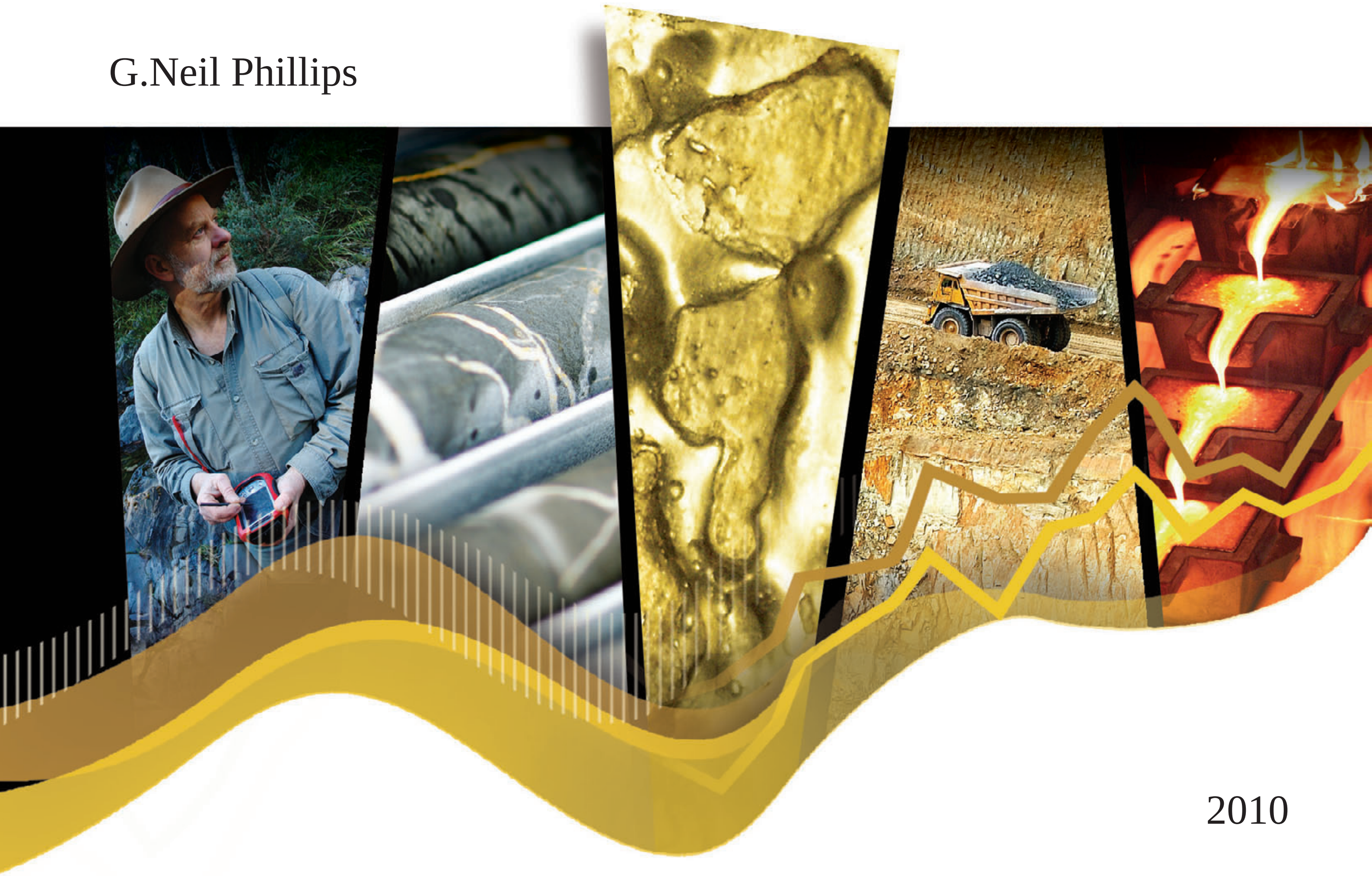
DEPARTMENT OF
PRIMARY INDUSTRIES

Victorian Gold Province Australia

A Contemporary Exploration Guide

G.Neil Phillips



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Many figures are drawn from existing publications, especially those of GeoScience Victoria and its staff. Except where specifically mentioned, figures are from Formation of gold (unpubl.) and Geology of GOLD, and access and permission to use these here is acknowledged.

Preface

A Contemporary Exploration Guide is written for geologists who are likely to be outside Victoria and possibly outside Australia. The target reader is one who is able to influence or decide where a company's exploration focus will be, potentially an exploration or new ventures manager. Some exploration experience is assumed such as a broad-based knowledge of the industry, but not necessarily technical knowledge relating to gold deposits or knowledge of Victorian geology.

The *Guide* avoids esoteric debate and much geological data where these do not materially influence exploration, but does not shy away from highlighting alternative ideas where they might provide an astute explorer with an exploration advantage. The report is deliberately reference-heavy to provide the opportunity to take any of the ideas farther, and much previous descriptive work has only been lightly summarised here as it is readily available in the literature.

In any exploration process, there needs to be confidence that gold is there to be discovered, and this confidence comes from understanding the nature of the primary gold province, the variety of possible styles of goldfields, an understanding of the terrain including its later modifications, and the ability to select appropriate methods to explore for the deposits. Ultimately, any decision to explore for gold in Victoria will be based on the belief that there is gold to find, that a Reserve can be established, that the deposit can be mined, and a profit is likely. If the exploration process can be facilitated and made more productive by some innovative ideas, the case for exploration in Victoria is enhanced. Little attempt is made here to provide a detailed exploration plan as this must be influenced by a company's philosophy and targets, regional geomorphology, the community, regulations, costs and land availability.

Although the report is focused on the State of Victoria, it necessarily includes the larger scale context. The Cainozoic Murray Basin provides a barrier to northward extension of surface exploration methods from central Victoria, but the subsurface Victorian Gold Province itself extends well into New South Wales and north-eastern Tasmania: much can be gleaned by including some data from these parts of the Province. Nature has formed all parts of this well-endowed gold province as one, and only later divided it with a major river and strait of water.

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Introduction

The State of Victoria was one of the world's leading sources of gold during the 1850s. In the half century that followed, the benefits of gold mining funded much of the earliest infrastructure and architecture of Melbourne, Ballarat, Bendigo and many other locations in southeast Australia (Blainey, 1963, 1984; Bate, 1988; Hughes & Phillips, 2001).

The opportunity exists today for a major find similar to those of the past, and possibly under cover. It is also likely that there are deposit types that were either unrecognised during the 19th century or were recognised but were uneconomic at the time. For various reasons, Victoria completely missed the 1980s global gold boom and has had modest sustained exploration activity since, despite some producing operations in existing goldfields. As such, there is a real chance of applying modern exploration methods in relatively untested areas within a major gold province.

The heart of the Victorian Gold Province is an area 50–200 km north and west of Melbourne embracing Bendigo (22 Moz), Ballarat (13 Moz), Castlemaine (5 Moz), Stawell (4 Moz), and many smaller goldfields (Phillips *et al*., 2003; Fig. 1). However, the gold-endowed Palaeozoic sequence extends 500 km southward into Tasmania, and northward into New South Wales.

The nature of mining in the 1850s was such that gold grades of 15–30 g/t were necessary to be profitable, and narrow vein mining was the optimal method of the time. Today, the larger mines like Stawell and Fosterville successfully exploit grades around 5 g/t and individual ore blocks can be 10–20 m thick and hundreds of metres long. Today, there is a complete spectrum from disseminated deposits like the upper weathered parts of Fosterville, to those that are relatively high grade (10 g/t) but notoriously nuggety such as Bendigo.

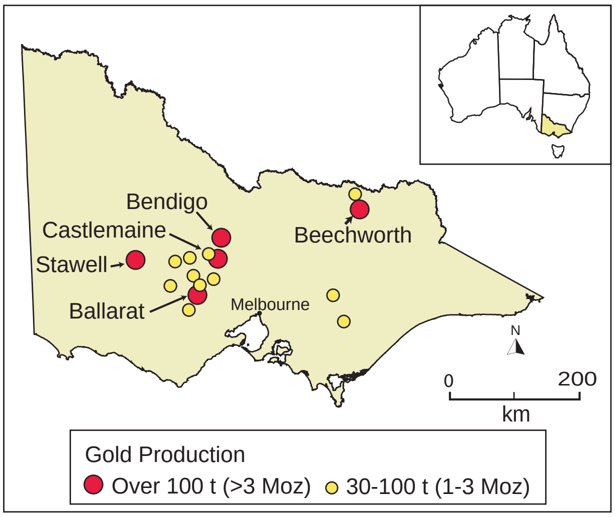


Figure 1. Map of Victoria showing all goldfields that have produced 1 Moz gold. There are very few places around the world that have sixteen ~ 1 Moz deposits in such a small area. The five largest goldfields have each produced over 3 Moz gold, and Bendigo a remarkable 22 Moz (data from Hughes, written comm., 2007; Phillips, 2007).

The hosting sequence for gold deposits is the Lachlan Fold Belt comprising a Palaeozoic metasedimentary succession of sandstone, siltstone, shale and slate with intrusive igneous rocks (VandenBerg *et al*., 2000). This turbidite package has been multiply deformed and metamorphosed to widespread (sub)-greenschist facies assemblages with local amphibolite facies. Various terms have been used for this type of rock package and its mineralisation including slate-belt, shale-greywacke, turbidite, flysch, and sediment-hosted gold mineralisation.

Primary gold mineralisation is structurally controlled, related to quartz veining, associated with sulphide minerals, and surrounded by carbonate alteration. In detail, goldfields tend to be removed from the largest structures. Most deposits are gold-only deposits (the dominant economic commodity is gold), but there are a few base metal occurrences with subordinate gold (e.g. volcanogenic massive sulphide types). The age of gold mineralisation is broadly constrained by the age of the host rocks, which ranges from Cambrian to Devonian in different parts of the State, the age of hosting structures, and by the age of post-tectonic granite intrusions which mostly overprint gold mineralisation. The post-tectonic granites are well dated, and show that the introduction of primary gold mineralisation had essentially ceased by the end of the Devonian period (360 Ma).

Virtually all pre-Carboniferous rock types of the Lachlan Fold Belt are gold mineralised in some part of Victoria, but the amount of gold produced from each different rock type is extremely variable. A large proportion of the gold is hosted by the metasedimentary shale-sandstone sequence especially close to Ordovician black slates. Intrusive Devonian mafic rocks are also hosts for goldfields of 1 Moz size. Granites of all types are insignificant as hosts to gold despite making up 20% of the Palaeozoic outcrop in Victoria.

There are some gaps and uncertainties in Victorian geology, the resolution of which might open new opportunities for understanding and discovery of gold. The more striking of these include the role of weathering and its effects on gold deposits, metamorphism, and the nature of thermal processes during the Palaeozoic. There is also a need to merge and synthesise the timing relationships generated from field relations with some of the geochronological information; this may also entail changing some existing interpretations as their supporting data become superseded.

This Guide does not replace other recent summaries of Victorian geology and Victorian goldfields. It collates selected basic information, and provides directions for further reading.

The Victorian Gold Province today offers a challenge to explorers who can use their geological information effectively to see opportunities that other explorers may have overlooked. Much of the geological data and some excellent field mapping are already in place, thanks largely to the Victorian Government initiatives including the Gold Under Cover Project. Existing gold mining operations have demonstrated to the community and government that gold mining can be socially and environmentally viable. Imagination, determination and perseverance are required to capitalise on this solid base, and to discover not just a single deposit but a series of new goldfields. Very commonly it is not the first explorer in an area that makes the large discovery.

1. Nature of the Victorian Gold Province

1.1 Gold endowment

General reference: ***Gold*** chapter in Birch (2003 Ch. 13, 377–432).

Australia had produced 11,573 tonnes of gold to the end of 2007, and has a further 5839 t as economic identified resources (GeoScience Australia; Fig. 2; Appendix 1). The bulk of this production has come from the Archaean rocks of Western Australia. All-time production from central Australia (South Australia and Northern Australia) is approximately 600 t from Pine Creek, Tennant Creek and Tanami goldfields with the remainder of the Proterozoic rocks being less productive to date (except for Telfer, endowment ~ 1500 t Au; and very substantial low grade endowment at Olympic Dam ~2000 t Au). The remaining 5000 t has come mostly from the Palaeozoic of eastern Australia where there is an additional 2000 t of economic demonstrated resources (EDR) identified suggesting an endowment in excess of 7000 t in eastern Australia. The greatest concentration of the historic Palaeozoic gold production has been from the Victorian gold province (Fig. 3).

Within the Palaeozoic sequences of eastern Australia, the bulk of production has come from the Lachlan Fold Belt, with subordinate contributions from the Thomson, New England and Delamerian fold belts.

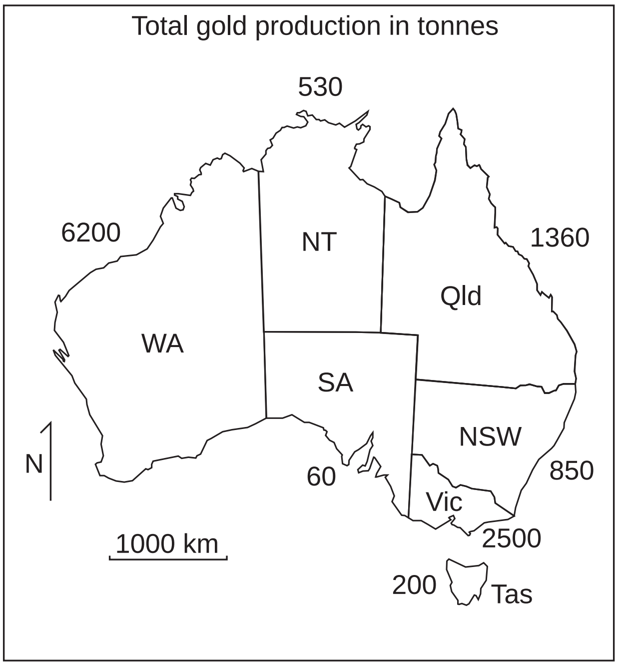


Figure 2. Map of Australia showing all-time gold production for each state, expressed in tonnes of gold (figures rounded, and to end 2007). The Yilgarn craton of Western Australia, NE Queensland, and the geographically smaller Victorian Gold Province have been the main sources of gold.

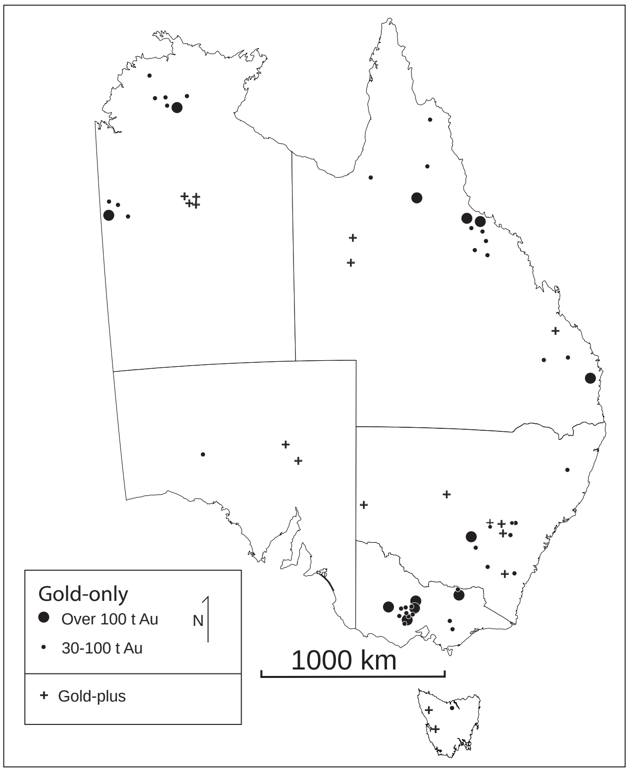


Figure 3. Map of eastern and central Australia with all 30 t (1 Moz) producers (with allowance for Reserves). The Victorian gold province is an unusually concentrated area of significant goldfields. The gold-plus deposits involve additional commodities, and except for Mt Morgan, Tennant Creek and parts of Cobar, many would be uneconomic as stand-alone gold operations (figure produced in co-operation with State Geological Surveys and Mines Departments).

The Victorian Gold Province comprises 7000 large and small mines and prospects, and most of the gold production in Victoria has come from gold-only deposits, i.e. those in which gold is the main economic commodity and in which base metals are uneconomic (Fig. 4). The largest ‘gold-plus’ deposit is the Benambra volcanogenic massive sulphide Cu–Zn deposit in Silurian volcanic rocks (Allen & Barr, 1990; Table 1). Under particular market conditions, antimony has been a by-product at a few deposits, most notably Costerfield. There is nothing yet to match the Cadia valley deposits in central New South Wales (> 20 Moz Au with economic copper), but there is a small copper–gold deposit at Bethanga (3 t Au). Maps of gold distribution in the Victorian gold province show that most deposits coincide with areas of outcrop of Palaeozoic rocks, and larger goldfields are close to many medium and small occurrences.

Classifying the different gold deposits of Victoria needs some care. The majority, but certainly not all, are quartz-vein related, surrounded by sulphide and carbonate alteration, and are structurally complex, with gold in or adjacent to the veins. In other parts of the world, they might be described by their host rock as sediment-hosted, slate-belt, or dyke-hosted, and by their formational process as orogenic (or the misleading *mesothermal* terminology).

Despite comprising 20% of the Palaeozoic succession and their emplacement being close in space and time to gold, granites have been host to approximately 0.4% of Victoria's gold production.

The timing of gold is well constrained by field relations, and primary hydrothermal gold is restricted to pre-Carboniferous rocks (Phillips, 1991). The most common host rocks are Ordovician in age. Gold postdates the initiation of major structures that host deposits, and although there is mesoscopic-scale evidence for the folding of quartz veins, in general, most of the gold-only mineralisation is not significantly deformed on a macroscopic scale despite the smaller-scale folds and faults. The relationship of gold mineralisation to granites provides further timing constraint: some Devonian granites contain minor auriferous quartz veins, whereas other (especially Late) Devonian granites truncate and have contact metamorphosed gold mineralisation (Hughes *et al*., 1997). Devonian dyke swarms are gold mineralised in western and central Victoria (Bierlein *et al*., 2001). To achieve greater detail of timing of the gold introduction, the ideal circumstances would be for clear field relationships and appropriate (SHRIMP Pb–Pb zircon) geochronology, but this optimal situation can be difficult to reproduce at several important goldfields.

Goldfield	Production [1] (tonnes)
Bendigo	697
Ballarat	408
Castlemaine	173
Stawell	127
Beechworth	120
Creswick	81
Walhalla	68
Maldon	65
Woods Point	52
Clunes	47
Beaufort	36
Maryborough	32
Daylesford	32
Avoca	32
Berringa (Scarsdale)	30
Chiltern	28
Mt Egerton	27
Rutherglen	27
Ararat	20
Fosterville	17
Tarnagulla	13
St Arnaud	13
Benambra (Currawong)*	12
Harrietville	11
Dunolly–Moliagul	10
Taradale–Lauriston	10
Steiglitz	8
Tallangallook	8
Mt Wills–Wombat Creek	8
Freeburgh	7
Smythesdale–Haddon	7
Bright–Wandiligong–Porepunkah	7
Rushworth–Whroo	6
Glen Wills	6
Inglewood	4
Nagambie	4
Blackwood–Trentham	4
Carngham – Snake Valley	4
Cassilis	3
Bethanga	3

Goldfield	Production [1] (tonnes)
Buckland River	3
Omeo	3
Mitta Mitta	3
Tallandoon	3
Costerfield–Redcastle	2
Diamond Creek	2
Reedy Creek	2
Alexandra	2
Moyston	2
Wehla	2
Dargo–Grant	1
Myrtleford	1
Granya	1
Corryong	1
Redbank–Stuart Mill–Kingston	1
Wedderburn	1
Mafeking	1
Heathcote	1
Minimum from these goldfields	2299
Total from Victorian gold province: approximately 2500 tonnes Au	
Date of compilation 2008	

[1] based mostly on compilations and re-interpretations by Martin Hughes for World Gold 2007, with 2008 amounts updated from Geology of Victoria (Birch, 2003).

* Benambra is the largest 'gold-plus' deposit, most others listed are 'gold-only'.

Fosterville has an endowment of >100 t Au including Resources.

Table 1. Gold production from the Lachlan Fold Belt in Victoria. General geological descriptions of the larger goldfields can be found in Birch (2003, Ch. 13) and Phillips & Hughes (1996). Alluvial gold has been added into primary source production (Appendix 2).

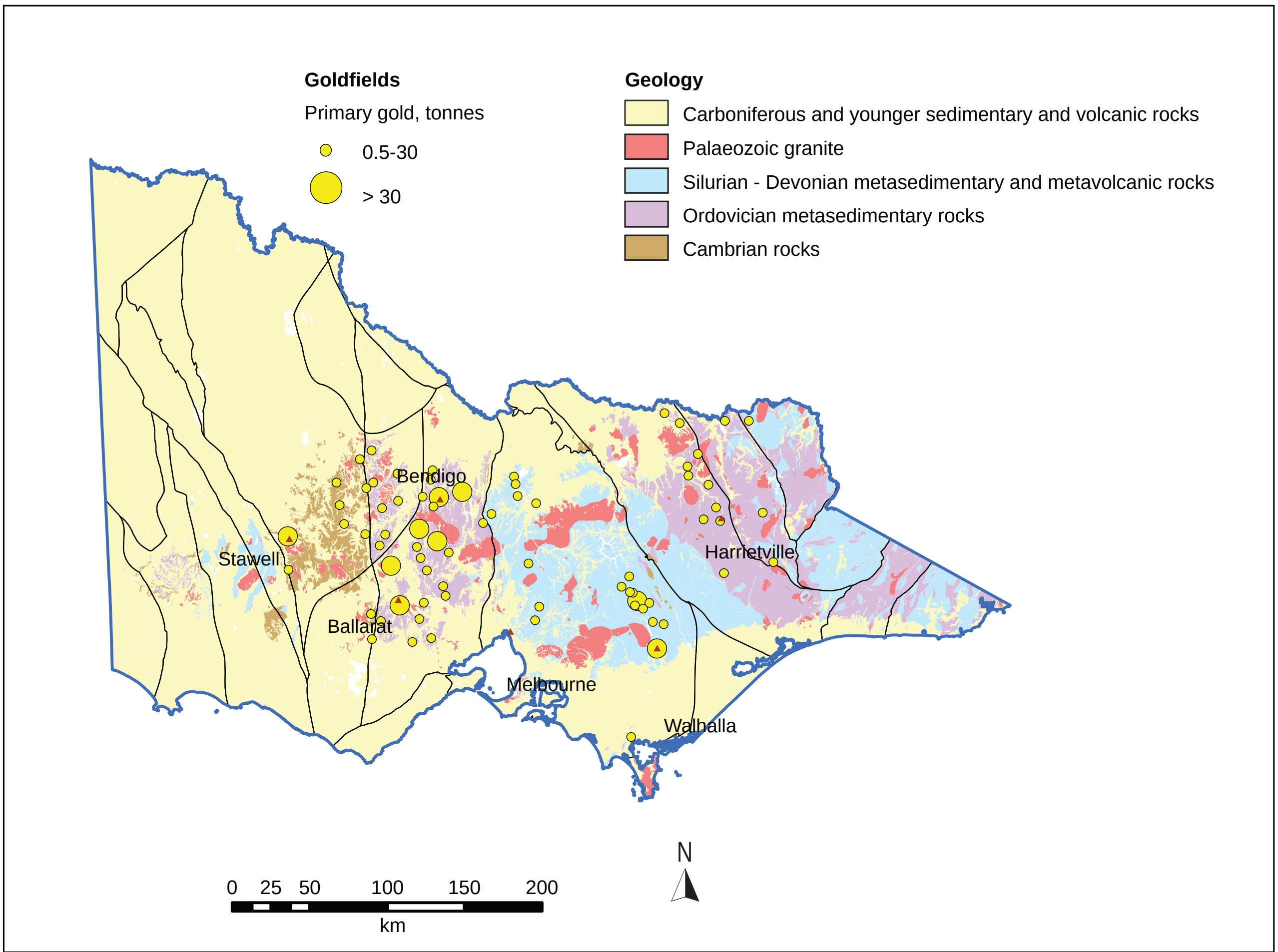


Figure 4. Goldfields of the Victorian Gold Province with primary production exceeding 0.5 t. This map highlights the correspondence between small and large goldfields (though not universal), and the restriction of most discoveries to areas of outcropping Palaeozoic rocks. Also shown are the major lithological subdivisions of the Palaeozoic Lachlan Fold Belt succession in Victoria.

1.2 Geographic limits and extent

The Victorian Gold Province has been defined as that portion of central Victoria east of the Moyston Fault and west of the Kiewa–Kancoona fault system. It is also restricted to rocks older than Carboniferous in age. This definition arose from careful inspection of the distribution of gold deposits in the Lachlan Fold Belt of Victoria and noting that all medium to large deposits were within these bounds (Phillips & Hughes, 1995, 1996). Although gold occurrences are known in the Palaeozoic rocks of Victoria outside these boundaries, there were no cases of known gold-only occurrences that would be economic in today's climate (but, of course, this does not rule out the possibility of discovering different gold deposit styles, e.g. porphyry-related Cu–Au).

The geological importance of the Moyston Fault and of the Kiewa–Kancoona fault system was not fully appreciated when the Province was delineated. Their fundamental importance has been brought to light by subsequent geological mapping (Cayley & Taylor, 2001; Morand *et al.*, 2004), and by interpretation of the 2006 seismic reflection line of the Victorian Geotraverse study. The Moyston Fault is at or near the Lachlan–Delamerian Fold Belt boundary (Miller *et al.*, 2005), whilst the Kiewa–Kancoona fault system is a structural zone boundary along which there has been substantial strike-slip displacement. During the same period of study, the Governor Fault towards the east of the Victorian Gold Province has become better understood and recognised as a major tectonic boundary.

Outcrop expression of the Victorian Gold Province is terminated to the north by the Cainozoic Murray Basin sediments, to the south by Bass Strait, and by a cover of Cainozoic volcanics and Mesozoic sedimentary rocks, although minor goldfields occur in Palaeozoic inliers on the south coast at Mornington and Foster. Some continuity of Palaeozoic rocks beneath these cover rocks is already demonstrated, and some of the Lachlan Fold Belt gold deposits of NSW and Tasmania are likely to be part of the same Victorian Gold Province.

Scale is important in fully appreciating the Victorian Gold Province. Between the Moyston and Kiewa–Kancoona bounding fault zones is a 400-km-wide belt of Palaeozoic metasedimentary rocks containing important gold deposits. In a north–south direction, the Province might extend 500 km north and a similar distance south but with much less gold production. At a different scale, individual goldfields have

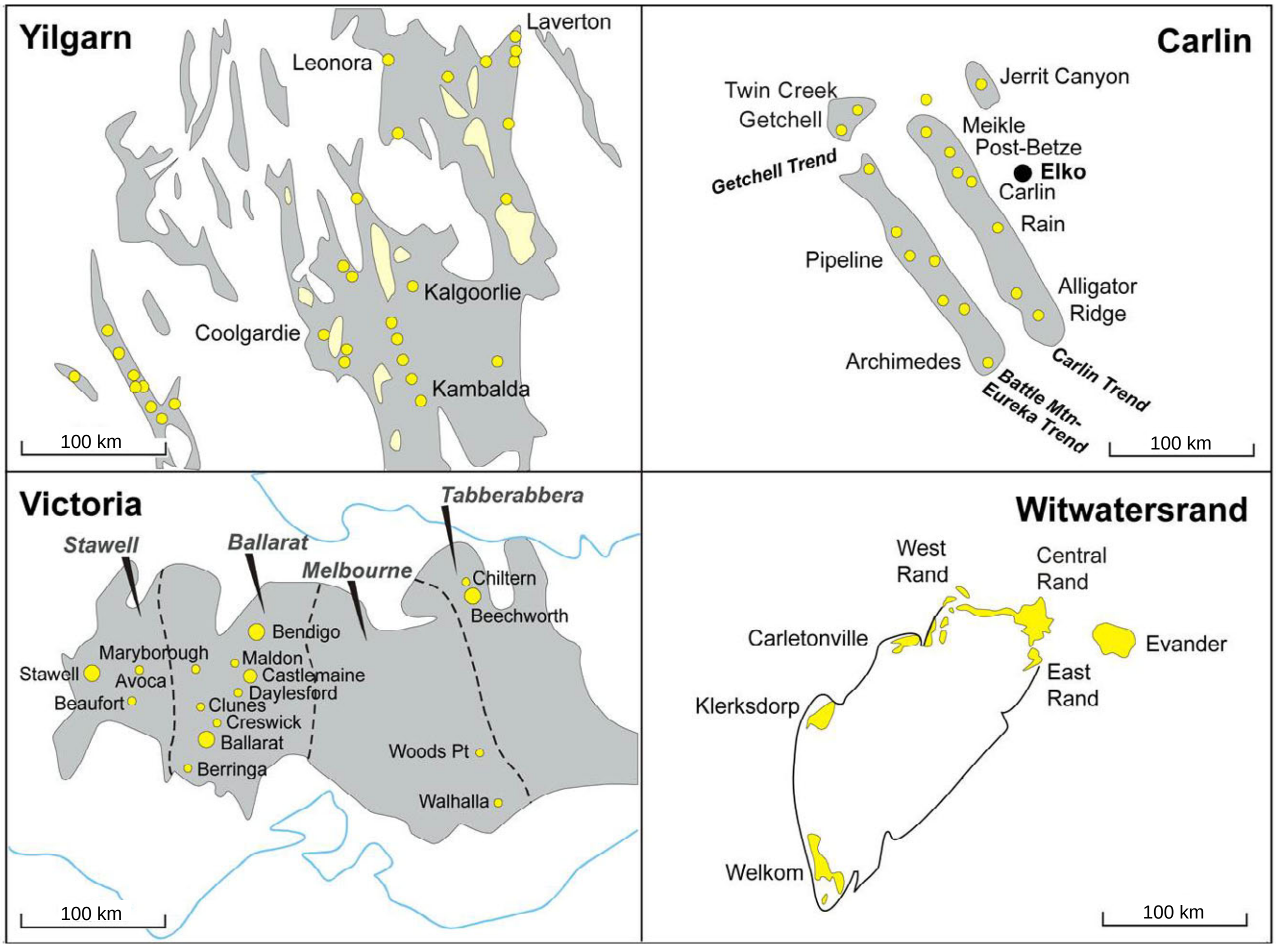


Figure 5. Map of four gold provinces on a common scale (after Phillips & Powell, in press). This compilation suggests that the scale of the Victorian gold province is not unusual for major gold provinces. Overall controlling causes of the gold mineralisation are therefore likely to be on a regional scale, with more subtle variations within the provinces (mineralogical domains) and on the district scale (individual goldfields).

dimensions ranging from hundreds to thousands of metres The giant Bendigo goldfield, for example, is 15 km north–south and 5 km east–west. Specific deposits are contained within mineralised areas that are 1–2 km wide, and tens of kilometres long characterised by abundant quartz veining, alteration and anomalous gold values. These mineralised areas are inferred to be the expression of fracturing that has tapped auriferous fluids from deeper crustal levels and established channelised flow regimes (Cox *et al*., 1991, p. 166). On a larger scale, the Tabberabbera structural zone in eastern Victoria has quite discrete, mineralised, linear features surrounded by essentially barren intervals of negligible quartz veining. For example, passing through Chiltern and Harrietville is an area 5–10 km wide and up to 200 km long near the eastern margin of the Tabberabbera structural zone in which goldfields occur, but most of the rest of the Tabberabbera structural zone has produced little gold (Phillips & Hughes, 1996, p. 291).

Although the Victorian Gold Province has its own distinctive features, it also shares many with other gold provinces. Palaeozoic slate belts with similar stratigraphic and sedimentological characteristics to the Victorian Gold Province are important hosts for major gold deposits elsewhere in the world with some well-known examples including Tien Shan Fold Belt of Uzbekistan and western China (Muruntau 5290 t Au; Kumtor deposit 600 t), Russian Far East (Goryachev & Edwards, 1999), and New Zealand's South Island (Macraes > 100 t; Craw *et al*., 2006). Just as for Victoria, most of these examples are classified as 'gold-only' meaning their sole economic commodity is gold; base metals are at levels too low to extract, and silver is produced with gold but on its own is quite uneconomic. Less gold occurs in otherwise similar geological settings in Wales, the Carolina slate belt in USA, Meguma terrain of Nova Scotia, Broken River area of north Queensland, Pine Creek geosynclines of Northern Territory, and the Andean Palaeozoic from Mendosa northward through Argentina, Bolivia and Peru.

There is enough commonality amongst the 7000 large and small mines and prospects of the Victorian Gold Province (especially on the mineralogical domain scale) to indicate that processes that operated to form the province were on a large scale (ten to hundreds of kilometres). This scale is similar to the scale of other gold-only provinces, including the Carlin province of Nevada (USA), Eastern Goldfields of Western Australia, and the Witwatersrand goldfields of South Africa (Fig. 5).

1.3 Mineralogical domains

Mineralogical domains represent a fundamental subdivision of the Victorian Gold Province based on the type and proportions of sulphide ore minerals present in the gold deposits, in addition to the ubiquitous quartz and carbonate gangue minerals (Fig. 6). As such, the subdivision can only be made where there are a number of gold deposits with at least some form of record of their mineralogy. The scheme was developed during the 1990s to distinguish patterns of ore mineral suites across the gold province (Hughes *et al*., 1997). The original scheme largely survives except for addition of the Leviathan Creek subdomain in the east (Hughes, 2004), and its usefulness has been demonstrated by subsequent mineral studies and field mapping by GeoScience Victoria. The Costerfield mineralogical domain has been extended into northeast Tasmania (Hughes, 2004; see also Reed, 2001).

Characteristics of the mineralogical domains include:

- Stawell–Ararat: pyrite–arsenopyrite with greater fraction of sulphide minerals as a proportion of the ore
- Landsborough–Percydale: elevated Ag–Pb, low fineness gold
- Ballarat: pyrite–arsenopyrite, includes many important deposits such as Bendigo and Ballarat goldfields
- Costerfield: pyrite–arsenopyrite–stibnite, gold of fine grain size
- Woods Point: pyrite–arsenopyrite like Ballarat domain
- Leviathan Creek subdomain of the Costerfield domain: pyrite – arsenopyrite, stibnite, and Pb–Zn–Cu rich
- Chiltern: pyrite–arsenopyrite like Ballarat domain
- Bethanga: elevated Ag–Cu–Pb–Zn, elevated sulphide minerals, lower gold fineness
- Buchan: elevated Ag and sulphide minerals
- far east Victoria (Kuark and Mallacoota structural zones including porphyries near Orbost): has few significant gold deposits, with elevated sulphide minerals (M. Hughes, written comm., 2008).

These mineralogical domains have sharp boundaries that typically coincide with major fault systems, with the Costerfield domain as the single exception—it overlaps with the Ballarat domain (but these may be of different age; Hughes, 2004).

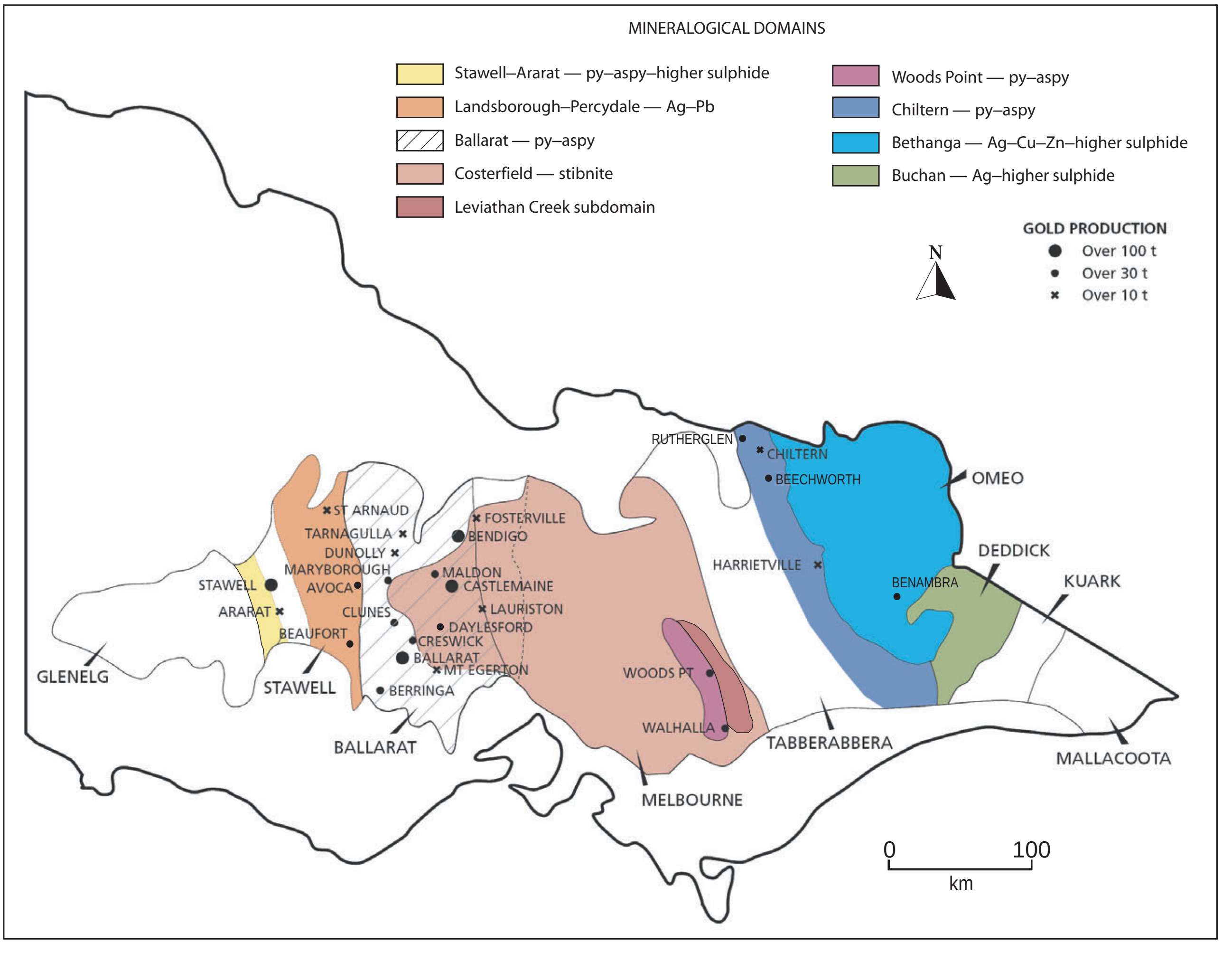


Figure 6. Map of the mineralogical domains of the Lachlan Fold Belt in Victoria (after Hughes *et al*., 1997; Hughes, 2004). Domains are based on the mineralogy of gold deposits, and are influenced in part, by the composition of the gold-bearing fluids. Structural zones are indicated with an arrow, e.g. Glenelg.

The four pyrite–arsenopyrite domains (with no stibnite or elevated Cu–Pb–Zn–Ag; Stawell–Ararat, Ballarat, Woods Point, Chiltern) all contain one or more gold deposits over 1 Moz, and these domains account for most of the gold production. Furthermore, these four domains include all the 1-Moz goldfields with the exception of those in the hanging wall of the Avoca Fault for which no primary source is known (i.e. Avoca and Beaufort goldfields).

Although our understanding of the reasons for the existence of the mineralogical domains is incomplete, it is likely that variations in ore fluid salinity could account for the variations in silver and base metal contents (Appendix 3).

1.4 Current understanding of the formation of Victorian gold deposits

Victoria is a gold province that has produced 2500 tonnes of gold since mining commenced in 1851. Much of the production has come from alluvial sources downstream from readily recognised primary gold sources. The primary gold deposits are mostly quartz vein related in metasedimentary rocks, and have associated carbonate and sulphide alteration haloes (Fig. 7). The number of 'reef mines', estimated at around 7000, reflects the very widespread nature of mineralisation and also the era of initial gold exploitation by small prospector groups. Only a small fraction of these occurrences are very large (e.g. Bendigo 700 t Au production, with substantial further resources).

Primary gold is restricted to rock units that are Devonian or older, and although most of the rock types contain some gold mineralisation, it is the metasedimentary turbidite sequence that accounts for most production and the larger goldfields. Various names apply to these gold deposits including slate-belt hosted, turbidite-hosted, sedimentary-hosted, orogenic, 'mesothermal', and gold-only (Appendices 4 & 5).

There is some general agreement that the early Palaeozoic setting of the sequence hosting the Victorian Gold Province was that of a convergent margin, though there is some uncertainty about the location and role of subduction zone(s). The overall Palaeozoic rock package is one of Cambrian mafic rocks, Ordovician to Devonian clastic metasedimentary rocks including turbidites, capped by post-Middle Devonian non-marine sediments and mainly felsic volcanics. Linking gold introduction into the tectonic framework requires knowledge of the timing of gold.

Three phases of deformation are relevant to the gold province: Benambran Orogeny (Late Ordovician to Early Silurian), Bindian Orogeny (Silurian–Devonian boundary), and Tabberabberan Orogeny (Middle Devonian). The Benambran and Tabberabberan orogenies involved mostly east–west compression, whereas the Bindian Orogeny resulted in a significant strike slip component.

Evidence from the larger Victorian goldfields indicates that some early-formed mineralised veins have been folded. Despite this small-scale deformation, most of the larger vein systems broadly retained their original larger-scale geometry (see Cox *et al*., 1995; Willman, 2007). Displacement of mineralisation by late faults is known from some places (Wilson & Watchorn, 1998; Miller & Wilson, 2002).

Field relationships that directly link orogenic events to gold introduction are not always present and this has generated a little uncertainty in some of the larger goldfields. However, it is clear from many goldfields that deformation and gold introduction are pene-contemporaneous in that gold fluids used actively-deforming structural pathways, and quartz veins are folded in places and locally overprinted by cleavage.

Two scenarios for the timing of gold introduction are presented in Phillips *et al.* (2003): the *major Ordovician gold scenario* involves three periods of gold introduction from Middle Ordovician to Middle Devonian (section 13.3.13 of Geology of Victoria), whereas the *major Devonian gold scenario* involves a single diachronous period of gold introduction in the Silurian and Devonian (section 13.3.12).

The *major Ordovician gold scenario* is of three periods of gold introduction commencing towards the end of the Middle Ordovician (460 Ma, Bierlein *et al*., 1999), or end of the Late Ordovician (VandenBerg *et al*., 2000, fig. 2.44). The major introduction is inferred to be the first of these. In this scenario gold mineralisation can have occurred prior to, during and after the folding and metamorphism in a single goldfield (e.g. Ballarat). This scenario has been based on observations that link the introduction of mineralised quartz veins to episodes of regional deformation (folding and cleavage development), palaeogeography, dated unconformities and an understanding of the relative ages of accretion of different terranes within the Lachlan Fold Belt, tied to Ar–Ar geochronology.

The alternative *major Devonian gold scenario* infers that major gold introduction in the Victorian Gold Province occurred during the Silurian and Devonian, broadly synchronous with a period of intense igneous activity and elevated geothermal gradient (Phillips *et al*., 2003 p. 405; Appendix 5). The two main differences with this scenario are that it is not built on Ar–Ar dating and it does not infer the major gold introduction to be during the Ordovician period.

These two alternative scenarios place differing importance on the thermal regime, deformation and tectonic setting during the Ordovician, Silurian and Devonian periods: one interpretation suggests that the major gold introduction was during the Middle–Late Ordovician at a time of relatively low geothermal gradient and turbidite sedimentation, the other assumes major gold introduction during the period of high geothermal gradient and synchronous Devonian magmatism. The two interpretations also lead to different conclusions as to the tectonic setting at the time of major

Figure 7. Gill Reef at Bendigo goldfield. Copyright Bendigo Mining Ltd.

gold introduction; for the Ordovician alternative, a Western Pacific style oceanic tectonic setting is suggested (Gray *et al*., 2003); whereas for the Silurian–Devonian alternative, a western US foreland setting of asthenospheric upwelling and thermal erosion is favoured (Cas *et al*., 2003).

The source of the gold-bearing fluids is commonly thought to be from devolatilisation in the crust during regional metamorphism generating low-salinity fluids (Appendix 6). The seismic lines from the Victorian Geotraverse are especially pertinent here as they indicate that the gold-rich Bendigo structural zone is underlain by inferred mafic rocks that are significantly thicker than elsewhere, and hence that these mafic rocks were not subducted during Palaeozoic convergence (Cayley *et al*., in prep.). The interpretation of the seismic profile also confirms the presence of a Precambrian basement (Selwyn Block) under central Victoria. This is important because it illustrates that the geological history, tectonic setting, and potentially the controls on metallogeny vary significantly across the width of the Lachlan Fold Belt. Some areas have undergone substantial crustal thickening during accretionary orogenesis (e.g. the Bendigo structural zone) whereas other areas are essentially intracratonic, for example the foreland basin succession of the Melbourne structural zone that overlies the Selwyn Block , where crustal thickening was considerably less (Cayley *et al*., in press).

2. Geological and tectonic setting of the Victorian Gold Province

Two major references provide comprehensive coverage of Victorian Palaeozoic geology:

Tasman Fold Belt System in Victoria (VandenBerg *et al.*, 2000);

Geology of Victoria (Birch, 2003).

2.1 Continent-scale tectonic setting

Today, the Australian continent lies within the Australian tectonic plate and well removed from the currently active margins of that plate (Fig. 8). Victoria lies in the southeast corner of the continent.

The Australian continent can be divided into a Palaeozoic eastern region, with the rest being dominated by Archaean cratons that are marginal to the continent, and by Proterozoic fold belts that are more central (Johnson, 2005; Fig. 9). Younger sedimentary basins overlie and separate many of these older terranes. The western boundary of the Palaeozoic succession is referred to as the Tasman Line (Fig. 10) which divides the Palaeozoic Thomson and Lachlan fold belts to its east, from older rocks to the west of the line. Although shown near Adelaide in several representations (see Kennett *et al.*, 2004), and queried by some as to whether it has much value as a 'Line' (Direen & Crawford, 2003), the Tasman Line may be better positioned in western Victoria along the Moyston Fault (Cayley & Taylor, 2001). This fault is the boundary of the Delamerian and Lachlan fold belts. It is a major east-dipping fault in the Moyston goldfield (Cayley & Taylor, 2001) visible on seismic profiles. Miller *et al.* (2005) placed the boundary between the Delamerian and Lachlan fold belts farther east.

The Tasman Line also coincides with a drastic change in thickness of the lithosphere beneath the Australian continent, from 220 km to the west, to less than 140 km thick to the east of the line (Betts *et al.*, 2002; Kennett, 2003). Lithosphere thickness is a result of strength and buoyancy, and is the characteristic that may have the most influence on continental geology (Jackson *et al.*, 2008). Such great thicknesses (over 200 km) are typical of craton and shield areas globally, and help to reduce the temperature of the crust in cratonic areas (Jackson *et al.*, 2008). It follows that the thinner lithosphere under the Tasman Fold Belt System facilitates higher temperature crustal conditions.

The thickness of the Australian continental crust broadly matches the age divisions, with the Moho being at a depth of 35 km beneath the Archaean areas, 50–60 km beneath the Proterozoic of northern Australia, and 35–50 km beneath the Palaeozoic Lachlan Fold Belt of southeast Australia (Finlayson *et al.*, 1980; Betts *et al.*, 2002; Collins *et al.*, 2003). The Moho beneath the Lachlan Fold Belt is a broad transition zone of increasing seismic velocity with depth, and beneath Victoria the Moho is at the relatively shallow depth of 36–42 km (Cayley *et al.*, in prep.).

Three late Proterozoic to early Palaeozoic fold belts of eastern Australia impact directly on the development of

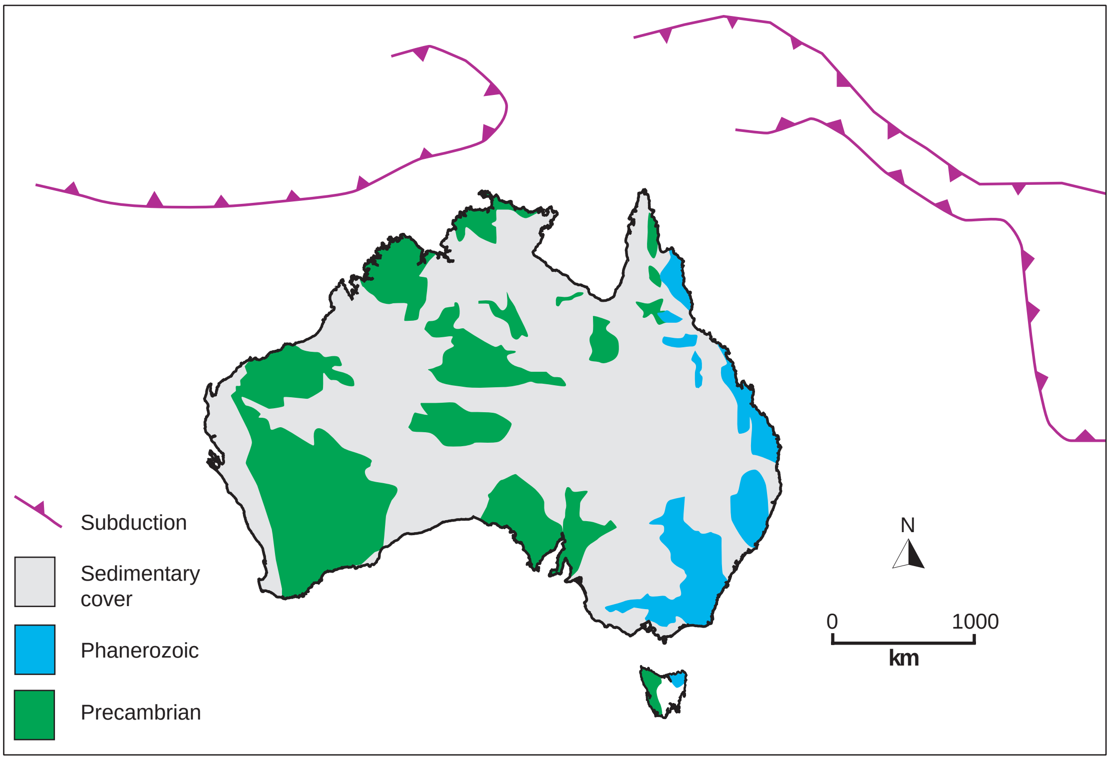
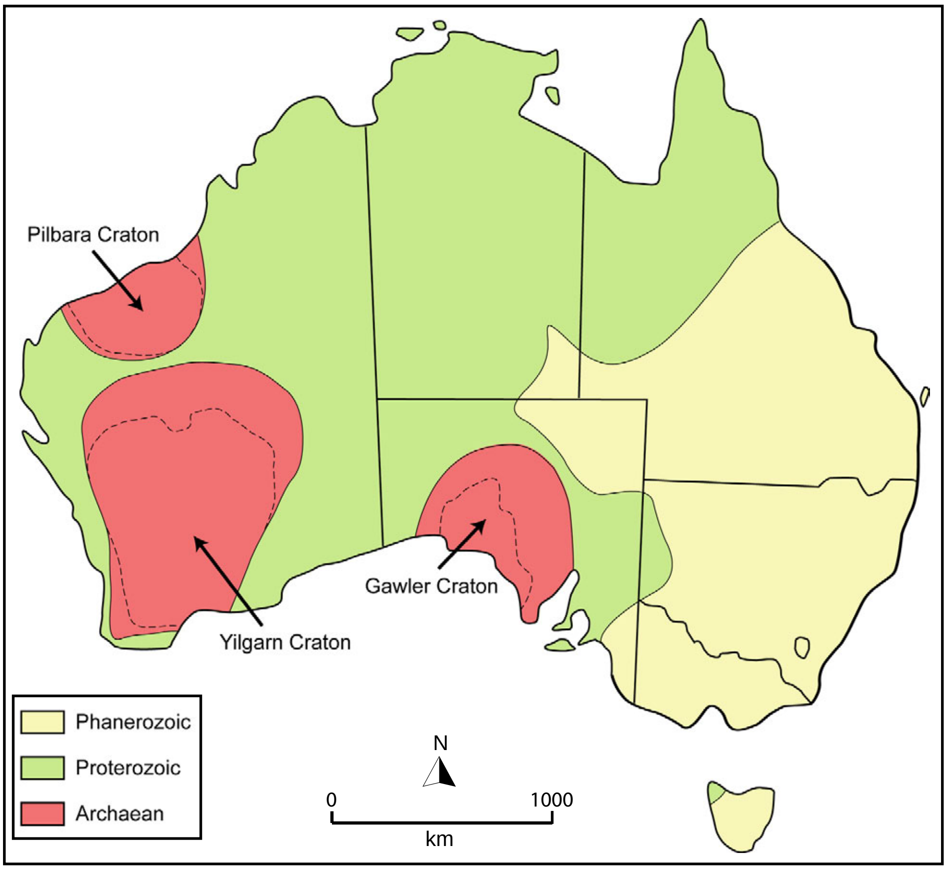


Figure 8. Map of Australia and SW Pacific region showing Australian continent, and various plate margins to the northwest and northeast (after Kennett, 2003).

Figure 9. Simplified map of Australia showing Archaean, Proterozoic and Phanerozoic areas (see Betts *et al*., 2002, and Johnson, 2005 for more details).



the Victorian gold province (Gray *et al*., 2003; Champion *et al*., 2009). To the west is the slightly older Delamerian Fold Belt that extends from the Archaean Gawler Craton into western Victoria and is generally poorly mineralised with respect to gold. The Delamerian Fold Belt comprises Proterozoic to Cambrian rocks and was deformed in the Late Cambrian (see Li *et al*., 2008 for the context during the late stages of Rodinian break-up). To the north lies the Thomson Fold Belt, in northern New South Wales and Queensland. The Lachlan Fold Belt, in which the Victorian Gold Province lies, extends across much of Victoria and New South Wales. To its northeast the Lachlan Fold Belt is adjacent to the late Palaeozoic to Mesozoic New England Fold Belt, in northeast New South Wales and southeast Queensland. Together these four fold belts are part of the Tasman Fold Belt System (VandenBerg *et al*., 2000), a large and complex accretionary system which formed along the margin of Gondwana from the Cambrian to Mesozoic.

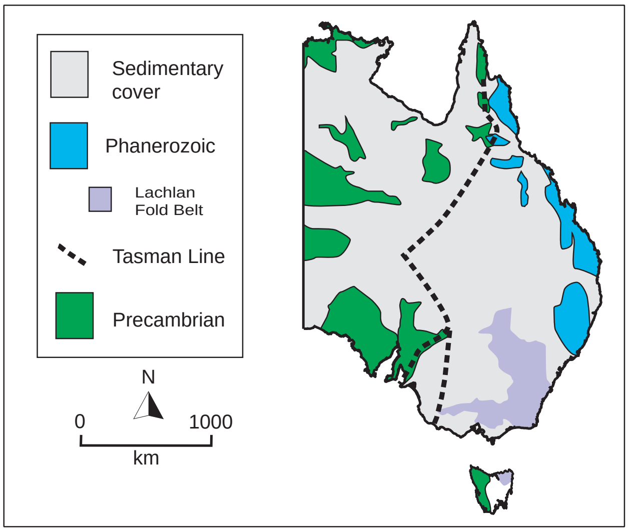


Figure 10. Map of eastern and central Australia showing the Tasman Line separating Proterozoic and Archaean cratonic areas to the west from Palaeozoic fold belts, including the Lachlan Fold Belt, in the east (after Kennett, 2003). This map shows the Tasman Line near Adelaide, and the alternative eastern position along the Moyston Fault as suggested by recent work. The Tasman Fold Belt System extends across most of the Palaeozoic east of the Tasman Line.

2.2 Terranes and structural/ tectonic zones

VandenBerg *et al*. (2000) identified two terranes in the Lachlan Fold Belt of Victoria, based on their different stratigraphic and structural histories before the Middle Devonian. The Whitelaw terrane, west of the Governor Fault, is characterised by east–west transport and compression, and contains most of the major goldfields. To the east, the Benambra terrane records north–south, orogen-parallel transport with strike-slip faulting, and includes fewer significant goldfields, e.g. Harrietville (11 t Au). The two terranes appear to have developed independently through the period of the late Precambrian until the Tabberabberan Orogeny, but by the close of this event, the two terranes were juxtaposed along the Baragwanath Transform (terminated and obscured now by the Governor fault; Fig. 11) in east-central Victoria (Willman *et al*., 2002). This juxtaposition across the Baragwanath Transform/Governor Fault is the major factor contributing to the considerable east–west width of the Lachlan Fold Belt in Victoria.

Subdivision of the Lachlan Fold Belt into structural zones is based on stratigraphy, structural and lithological character, and timing of the first major deformation (VandenBerg, 1978; Gray *et al*., 1988; VandenBerg *et al*., 2000). The Stawell, Bendigo and Melbourne structural zones in the west comprise the Whitelaw terrane; and the Tabberabbera, Omeo, Deddick, Kuark and Mallacoota structural zones comprise the Benambra terrane (Fig. 11). Reviews of the structural zones can be found in Gray (1988), VandenBerg *et al*. (2000) and Gray *et al*. (2003), and only four zones of special relevance to the Victorian Gold Province are summarised here.

Stawell structural zone

The western part of the Stawell structural zone includes Cambrian mafic volcanic and clastic sedimentary rocks, and eastward from here to the Avoca Fault are Cambrian to Ordovician metasedimentary rocks dominated by quartz-rich turbidites and mudstones that are phyllitic to slaty. Chevron-style folding about NNW-trending fold axes, and thrust faulting, has resulted in up to 70% shortening.

Bendigo structural zone

The Bendigo structural zone has Cambrian metavolcanic rocks overlain by dominantly quartz-rich Ordovician turbidites and siltstones. Deep seismic data indicate that the sediments are stacked to a depth of 15 km depth due to deformation similar to that in the Stawell structural zone. Faults and fold axes trend 10–20^{o} oblique (clockwise) from those farther west. A variable mix of sandstone and mudstone of Early–Middle Ordovician age is widespread across the zone. Late Ordovician sedimentary rocks are richer in black shale and are confined to the southeastern margin of the zone.

Melbourne structural zone

Small windows mainly in the east of the Melbourne structural zone expose the underlying Cambrian calc-alkaline metavolcanic rocks, but the zone is dominated by Silurian and Devonian clastic metasedimentary rocks of marine origin that are more than 10 km thick, overlying much thinner Ordovician turbidites, chert and shale. This sedimentary package is intruded by numerous granites of Devonian age, and by dykes, including the Woods Point Dyke Swarm. The sedimentary sequence is folded and faulted, with deformation gradually becoming more intense from west to east. There is no record of deformation in the Ordovician to latest Early Devonian sedimentation history, proving an absence of the early Palaeozoic deformation that affected adjacent regions.

Tabberabbera structural zone

Along the western margin of the Tabberabbera structural zone are Cambrian tholeiitic and boninitic metavolcanic rocks. The overlying Ordovician to Silurian sedimentary package consists mainly of turbidites and siltstones, and these are folded, faulted, and intruded by Devonian granite plutons, some of which are strongly magnetic.

2.3 Magmatism and metamorphism

The main Palaeozoic igneous activity within the Victorian Gold Province can be summarised as Cambrian metabasaltic (and minor felsic) rocks, and Devonian granites, felsic (and minor mafic) volcanic rocks, and dykes with a range of compositions. The Cambrian volcanic rocks have been described by Crawford *et al*. (1984).

The focus in this section is on the Devonian igneous activity, especially that which coincides with the Victorian Gold Province. Such rocks include widespread granite, volcanic cauldrons with rhyolite to rhyodacite and minor andesite, and dykes of ultramafic to felsic composition (Cas *et al*., 2003). East of the Kiewa–Kancoona Fault system, the granite activity is Silurian in age (VandenBerg *et al*., 2000). Several workers have described the nature of mid-Palaeozoic igneous activity in Victoria (Clemens & Wall, 1981; Marsden, 1988; Chappell *et al*., 1988; Coney *et al*., 1990; Hergt *et al*., 2003; Cas *et al*., 2003; Hughes, 2004). Granite plutons make up 20% of the Lachlan Fold Belt in Victoria, and felsic volcanic complexes of similar age a further 5% (Fig. 12). Dykes are best known from road cuttings and mines, suggesting they may be more abundant than even detailed maps indicate.

Granite

The exposed granites (which include granite *sensu stricto*, as well as granodiorite, and less abundant tonalite and diorite) can be subdivided into S- and I-types, with rare A-type plutons in the northeast and west (White & Chappell, 1988; VandenBerg *et al*., 2000). These granite 'types' are unevenly distributed, with large areas of I-type in the northwest and east of Victoria, and many S-types in the north-central and east. The youngest granites are in central Victoria, with older granites to both west and east. White and Chappell divided Victoria into granite 'basement terranes' whose boundaries were based on age composition. The 'basement terrane' boundaries are strongly oblique to some structural zone boundaries (e.g. Beaufort–Maryborough line, Hergt *et al*., 2003) and near-parallel to others. Using geophysics (mainly magnetics but also gravity), many plutons have been mapped under cover, especially to the north.

The depth of emplacement of individual plutons is variable, with primary muscovite in some granites in eastern and western Victoria reflecting relatively deep levels of emplacements (Wycheproof Granite, Mount Wills Granite). Other plutons have abundant miarolitic cavities indicating high to very high levels of emplacement (Warby Ranges, Clinton Rocks, Petrel Point, parts of the Strathbogie Granite, Mount Cole suite; White, 2002; Cayley & McDonald, 1995; Cayley & Taylor, 2001). Crystal

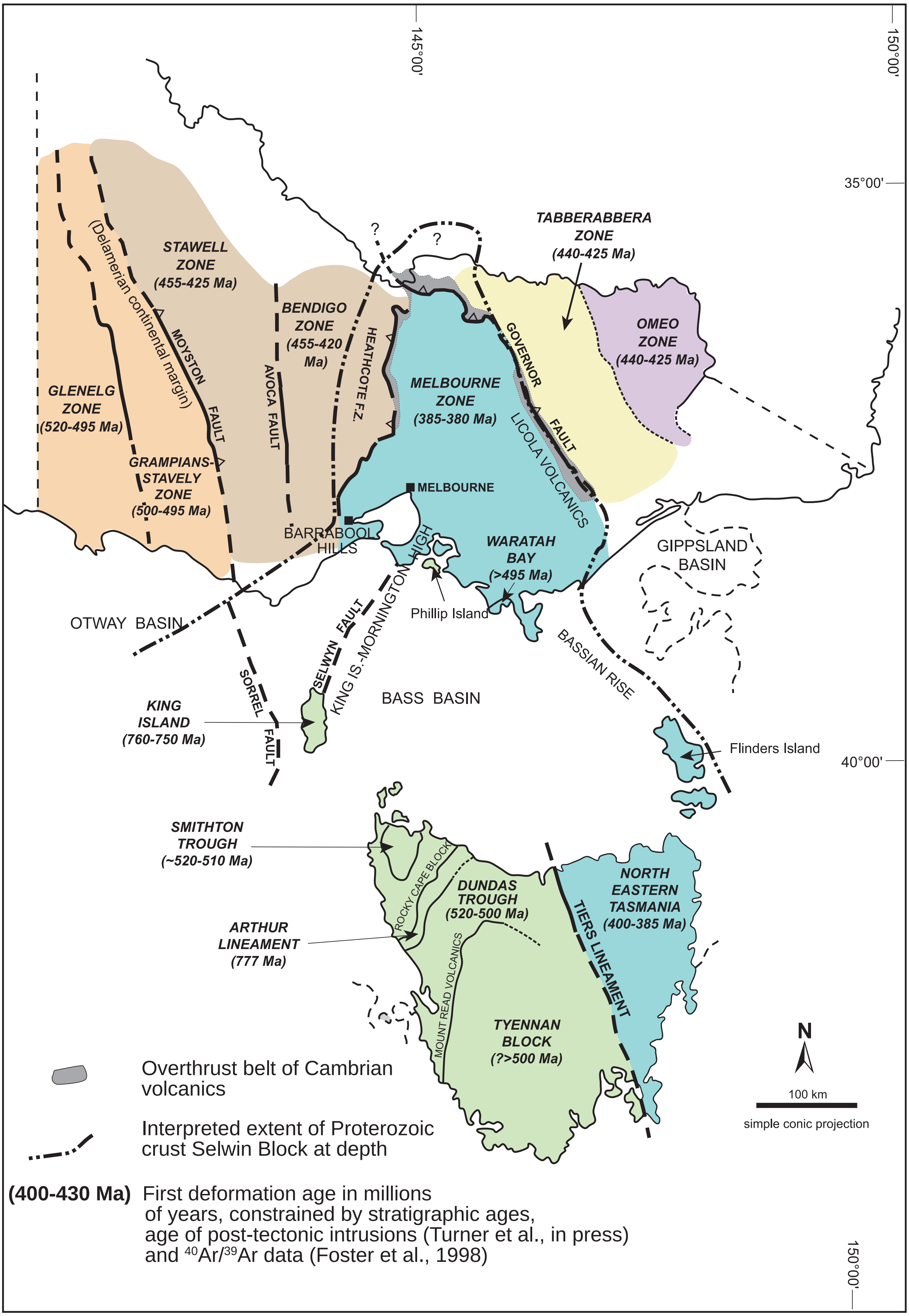


Figure 11. Map of Victoria and Tasmania showing the extent of the Lachlan Fold Belt, and boundaries of the structural zones across Victoria (after VandenBerg *et al*., 2000). The Whitelaw terrane is that part of the Lachlan Fold Belt between the Moyston Fault and Governor Fault, the Benambra terrane is the area east of the Governor Fault.

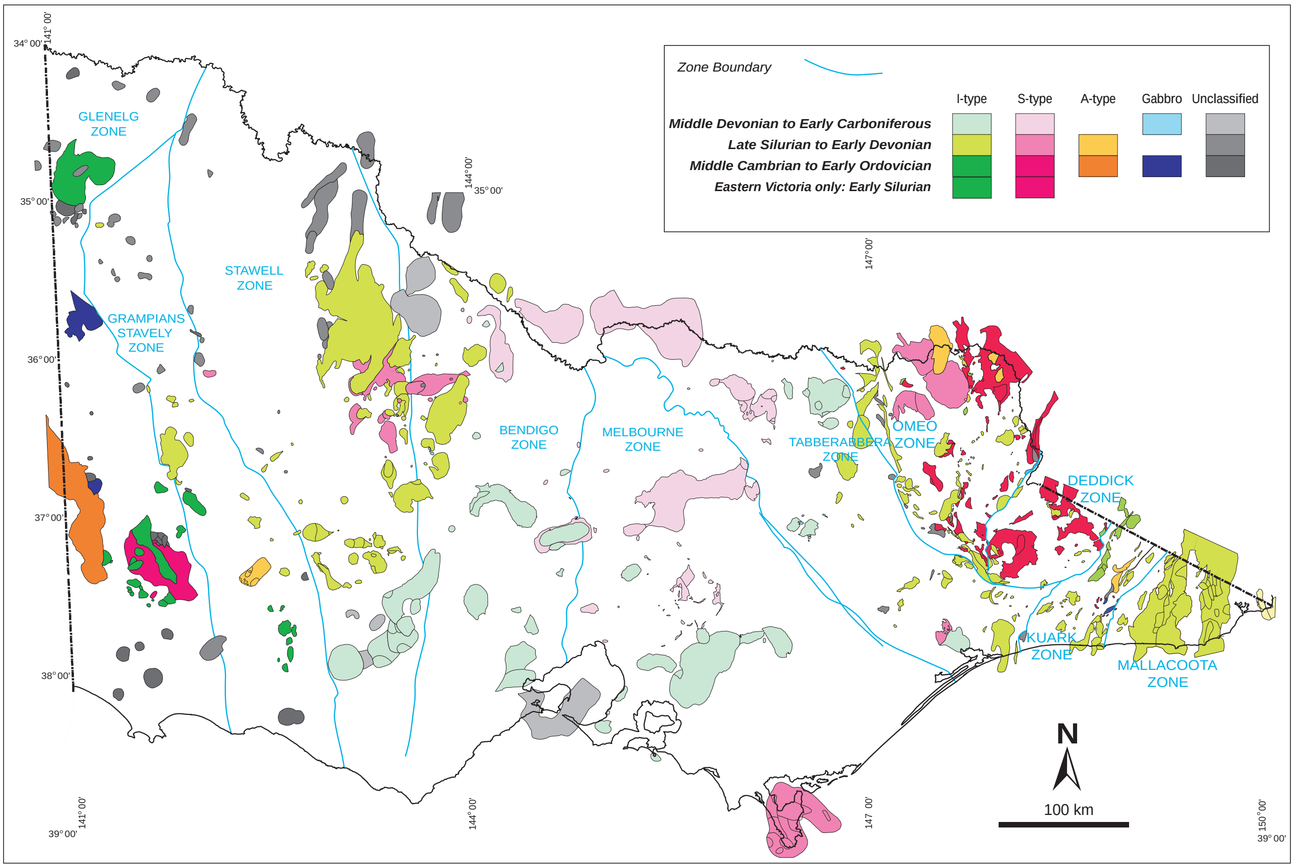


Figure 12. Map of granites in Victoria based on outcrop mapping and aeromagnetic data under cover (from VandenBerg *et al*., 2000).

terminations on quartz, feldspar, and tourmaline in these cavities may be as much as 10–20 cm long. This indicates that fluid had separated from a water-saturated magma at probably less than 3 km depth, either by decompression boiling or crystallisation of a near-anhydrous magma that raised the water content of the remaining magma (White, 2002). Large and/or zoned pegmatite bodies are uncommon in most Devonian plutons, although they are known from Everton, and at Tallangallook in the Strathbogie granite (Phillips *et al*., 2002, p. 60).

Felsic volcanic rocks

Mid-Palaeozoic felsic volcanic cauldrons are concentrated in the Melbourne structural zone, extending from the vicinity of Melbourne itself for 200 km to the north and east (Cas *et al*., 2003). Most of the cauldron fill is ignimbrites, which overlie pre-collapse lavas and sediments. Composition is dominantly rhyolite and rhyodacite, with minor andesite and subordinate basalt. Some ignimbrites contain cordierite and/or garnet, similar to the Late Devonian granites. Cas *et al*. (2003) have ascribed the Late Devonian igneous activity to localised thinning of the previously thickened mantle lithosphere by an actively convecting asthenospheric mantle, and have drawn analogy with the Tertiary foreland setting of the North American Cordillera where igneous activity arose from asthenosphere upwelling and lithospheric mantle thinning (thermal erosion), all well inboard from the convergent margin.

The age of felsic volcanic cauldrons is constrained by fossils and statigraphy to be Middle to Late Devonian and similar to adjacent granite plutons; the felsic igneous rocks of central Victoria postdate the Tabberabberan Orogeny. The felsic volcanic rocks are compositionally, spatially and temporally similar to the granite plutons, and some genetic link has been inferred.

Devonian dyke swarms

There are extensive Devonian dyke swarms across the Victorian Gold Province. The dykes occur in groups that extend for many tens of kilometres along strike but are only a few kilometres wide. Dyke swarms occur near Landsborough, Moonambel, Maryborough, Walhalla–Woods Point–Eildon, Dargo, Angusvale–Wentworth River, and Harrietville (Bierlein *et al*., 2001; VandenBerg *et al*., 2000 p. 349, Cas *et al*., 2003; VandenBerg *et al*., 2006 p. 118; Willman *et al*., 2005). The largest is the Woods Point Dyke Swarm which covers an area of 6400 km^2, and trends for 150 km in a northwest direction. Except for the Angusvale Dyke Swarm, each of these areas has significant adjacent goldfields including auriferous quartz veins within dykes, but this relationship may be distorted as the dykes are easier to notice in old working than in surface settings.

Dykes have a wide range in composition, from felsic to ultramafic, and include hornblende peridotite, pyroxenite, hornblendite, gabbro, diorite, biotite leucodiorite and granite, with the majority being gabbro to diorite (Junner, 1921; Hughes, 1973; Arne *et al*., 1998; Bierlein *et al*., 2001; Bierlein *et al*., 2001; Phillips *et al*., 2003).

Individual dykes are generally less than a few metres thick, but some dykes locally bulge to 120 m thick and ½ km long and provide structural hosts for gold deposits. Many dykes trend subparallel to the regional strike direction and follow fold axes in cross-section (Phillips *et al*., 2003, fig. 13.18). Recent mapping indicates that some dykes in early 20th century reports have been difficult to confirm (Willman *et al*., 2005), but there is little doubt that they are widespread and difficult to detect where thin and weathered.

The age of some dykes is well constrained by field relations. The Woods Point Dyke Swarm postdates the Tabberabberan Orogeny (of ~375–380Ma), with dykes slightly oblique to the structural gain. The Angusvale Dyke Swarm similarly postdates the Tabberabberan Orogeny and is overlain unconformably by the latest Middle Devonian Avon River Group making the dykes around 375 Ma. There is an important trend of younging dyke ages from Landsborough eastward to Angusvale. Dykes in the west near Stawell (416–410 Ma), Landsborough (397 and 408 Ma) and Moonambel (393, 401, 403 Ma) are older than those from Tarnagulla (385 Ma), Maryborough (374 Ma), the Woods Point Dyke Swarm in the east (374 Ma; see Bierlein *et al*., 2001 fig. 2 for details), and Angusvale (~375 Ma). In summary, dykes indicate Early Devonian igneous activity in the west of the Victorian Gold Province, and Middle to Late Devonian age in the Melbourne and Tabberabbera structural zones.

Mesozoic 'monchiquite' dykes are quite common in the Victorian Gold Province, and some show a close spatial relationship to gold deposits. However, they postdate mineralisation and have exploited pre-existing mineralised structures. The dykes are not hydrothermally altered by the gold event and cross-cut both quartz veining and gold mineralisation (e.g. Central Deborah mine in the Bendigo goldfield), further indicating their late timing with respect to mineralisation.

Metamorphism

Regional metamorphism of the Lachlan Fold Belt of Victoria can be summarised as medium to high grade (amphibolite facies and partial melting) in the west of the Stawell structural zone and immediately east of the Tabberabbera structural zone. Greenschist facies grade is the highest reached in most of the Victorian Gold Province. In the greenschist facies areas, pressure during regional metamorphism is more difficult to constrain than temperature, and in the absence of quantitative estimates from mineral assemblages, the less quantitative illite crystallinity method has been used: this indicates medium pressures but without much guide to accuracy of the method (Offler *et al*., 1998; Appendices 7 & 8).

2.4 Tectonic setting of Victoria in the Palaeozoic

Current thoughts on the tectonic evolution of the Lachlan Fold Belt, as it applies to the Victorian Gold Province, are comprehensively summarised in Geology of Victoria (Gray *et al*., 2003). There is some agreement that convergent tectonics played a major part in the evolution, but considerable uncertainty regarding the location of any subduction zone(s), e.g. see Ferguson (2003). These authors suggest that there is agreement on several issues to do with Lachlan Fold Belt evolution:

- development was in a Western-Pacific style oceanic setting
- Ordovician turbidites were derived from the west or southwest from the Ross-Delamerian Fold Belt
- continental accretion was driven by plate tectonic processes including subduction
- subduction zone(s) lay somewhere to the east (i.e. Tabberabbera structural zone or farther east)
- an early extensional history is preserved in the Benambra terrane (cf. Whitelaw terrane)
- large listric thrust faults penetrate to the middle crust
- the Benambra terrane was translated southward in the Early Devonian to its present position.

However, some caution is warranted with these interpretations. Field work cannot resolve either timing of deformation or pressure during deformation so that these are based on Ar–Ar geochronology and illite crystallinity (e.g. Gray *et al*., 2003). Shortcomings in any one line of evidence may impact on the validity of tectonic reconstructions.

With respect to back-arc basin closure, the various authors discuss a double-divergent subduction model that effectively removes much evidence of the existence of a marginal sea; and an intraplate convergence 'vice' model in which the turbidites and oceanic lithosphere are deformed between the Delamerian orogen and the Selwyn block (Gray *et al*., 2003). The various merits of slab break-off, lithospheric delamination, and slab roll-back have been discussed (Vos *et al*., 2007. p. 519); and most conclusions will be dependent upon which aspects of the Victorian geological framework are adopted and which are questioned (e.g. geochronology, metamorphic pressures).

2.4.1 Interpretation of Precambrian basement under central Victoria: the Victorian Geotraverse, and the Selwyn Block

There has been a long history of speculation and varied evidence for the existence of a Precambrian continental basement beneath part of the Lachlan Fold Belt in Victoria. This evidence includes palaeogeographic reconstruction (Packham, 1973), pelitic gneiss xenoliths in Devonian

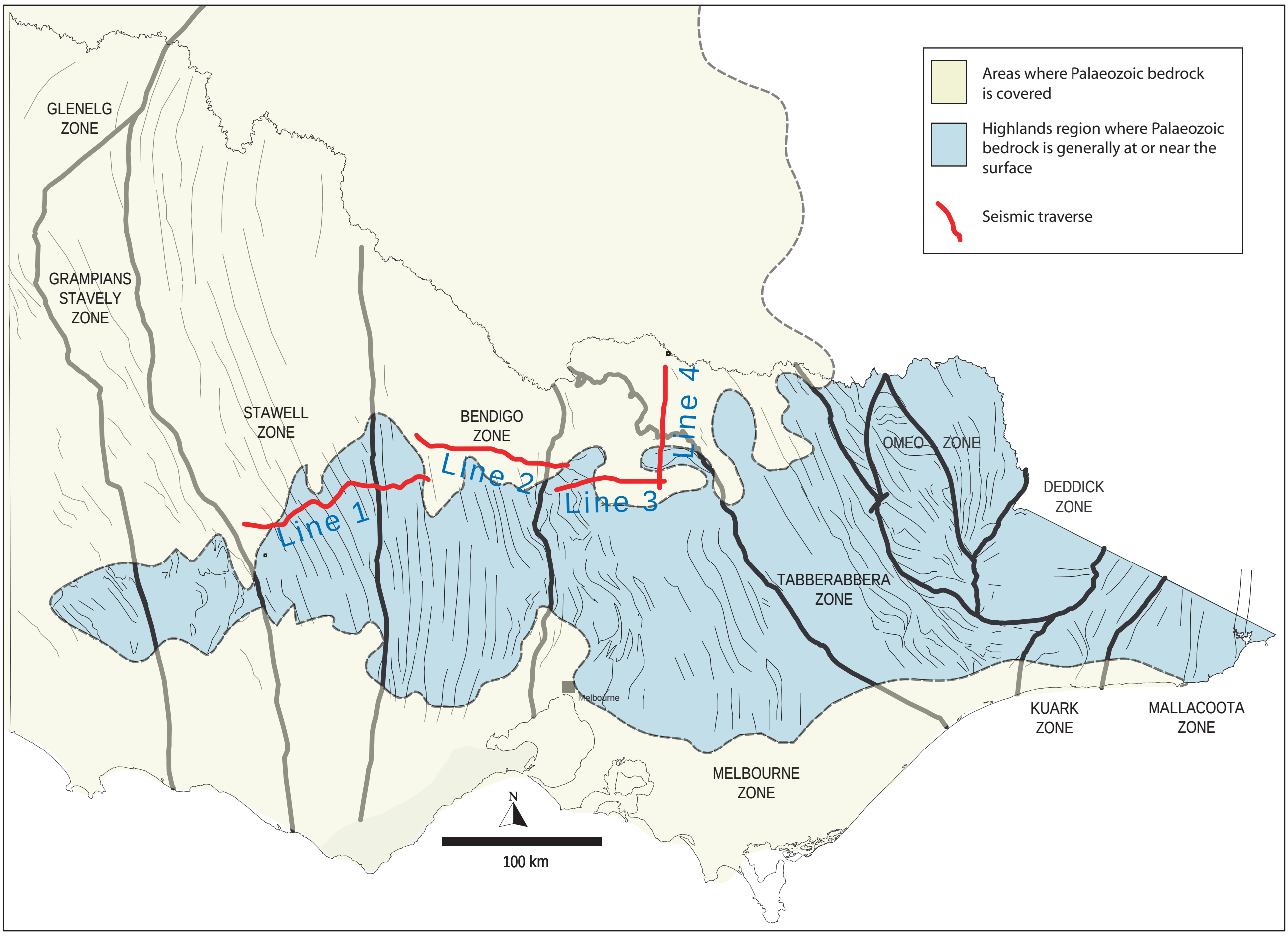


Figure 13. Map of Victoria showing the location of the four lines of the 2006 deep seismic reflection traverse on the northern fringe of Palaeozoic outcrop (Cayley *et al.* , 2008; see also Cayley *et al.*, in prep.).

granite (Phillips *et al.*, 1981, p. 61), sedimentological reconstruction (Cas, 1983), gneissic xenoliths in Devonian felsic volcanic rocks (Clemens, 1988) and, most recently, gneissic and gabbroic xenoliths with 600-Ma zircons in Cainozoic trachyte (Allchurch *et al*., 2008).

A geotraverse across northern Victoria has added considerably to the understanding of the region's crustal architecture and geological evolution, and has confirmed much of the mapping and recent geologic interpretations (Fig. 13; Appendix 9). The Victorian Geotraverse has built a multi-disciplinary synthesis around a deep seismic traverse (Cayley *et al.*, in prep.; Willman *et al.*, in press) supplemented with new geophysical data, and complimentary studies along the seismic line that include Palaeozoic to Quaternary geology (see numerous papers in Phillips & Ely, 2003).

Several unusual features of central Victoria have been attributed to a relatively rigid basement block beneath this area, referred to as the Selwyn Block (Fig. 14; VandenBerg *et al*., 2000; Cayley *et al*., 2002a). The Selwyn Block has been inferred to comprise metasedimentary and metavolcanic rocks with a veneer of Cambrian volcanic rocks, and to underlie the Melbourne structural zone and eastern part of the Bendigo structural zone. The rigid nature of this block preserved the Melbourne structural zone metasedimentary rocks from deformation in the Benambran and Bindian orogenies that deformed adjacent regions, and it was not until the Devonian Tabberabberan Orogeny that this succession was folded. The concept of the Selwyn Block has been supported by the 2006 seismic survey data which shows a horizontally layered basement block lying at depth, beneath the Silurian–Devonian sedimentary rocks of the Melbourne Zone.

The 'Selwyn Block' model explains a number of depositional, structural and intrusive features that are characteristic of the Melbourne structural zone but are largely absent in adjacent zones. These differences are depositional, structural and/or intrusive in nature. Thirteen separate features of the Melbourne structural zone are listed (Cayley *et al*., 2002b, p. 236–239) that are unusual for the Lachlan Fold Belt of Victoria, but are shared with the Lachlan Fold Belt in Tasmania. The opposing vergence of the Bendigo and Tabberabbera structural zones suggests a rigid block beneath the Palaeozoic metasedimentary sequence of the Melbourne structural zone (Cayley *et al.*, 2002a fig. 4).

Much of the Melbourne structural zone is non-magnetic or weakly magnetic including the plutons and dyke swarm. However, below the eastern part of the Melbourne zone is a long-wavelength magnetic body, unlike any features in

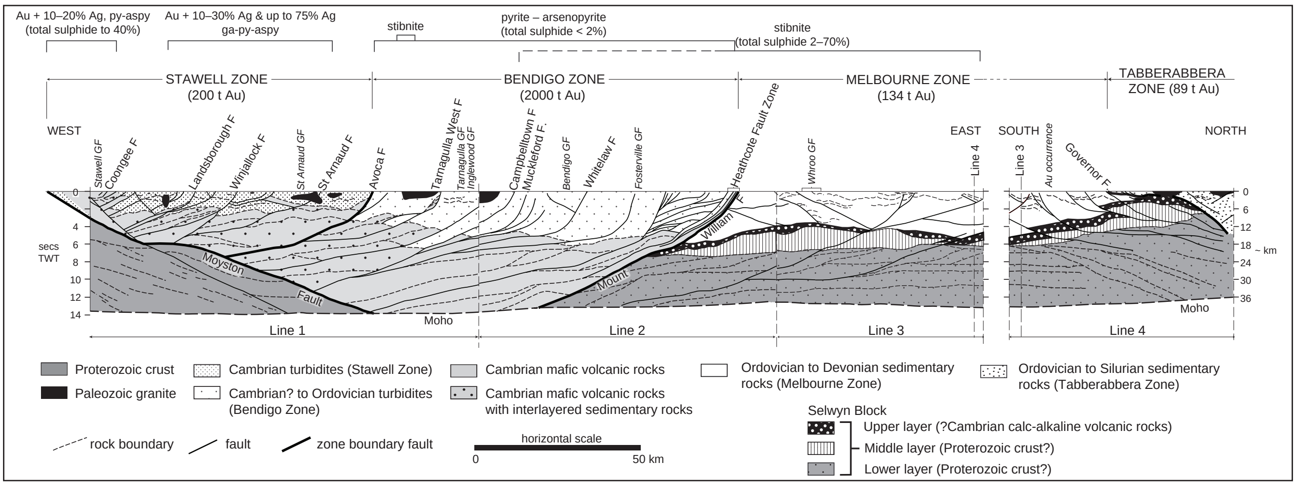


Figure 14. East–west cross-section along the seismic line shown in Figure 13 (Cayley *et al*., 2008). Note thickening of Selwyn block in the northeast; and that stibnite occurs as far west as the Avoca Fault.

the Bendigo or Tabberabbera structural zones, and several hundred kilometres in length trending NNW–SSE. This body has been modelled as a strongly magnetic sheet at 5–10 km depth of granitic (Meyers, 2002) or more likely serpentinised ultramafic composition (McLean *et al*., 2010).

2.4.2 Implications for gold mineralisation

Two scenarios for the introduction of gold mineralisation were presented earlier; in the *major Ordovician gold scenario* there were three periods of gold introduction from Middle Ordovician to Middle Devonian with the Ordovician introduction being the major one, whereas in the *major Devonian gold scenario* there was a single diachronous period of gold introduction after the Ordovician. Both scenarios can now be integrated with the tectonic evolution of Victoria.

In the *major Ordovician gold scenario*, gold mineralisation events in Victoria coincide with a shift from turbidites to black shale ± turbidites sedimentation, a period of stabilisation reflected by the Benambran Orogeny, post-cratonic rifting, and also east–west compression reflected in the Tabberabberan Orogeny. This scenario has gold mineralising events in Victoria spanning the Western-Pacific oceanic setting of the Ordovician period and the contrasting foreland setting of asthenospheric upwelling and thermal erosion postulated for the Middle–Late Devonian period. Despite the goldfields of the Stawell and Bendigo structural zones forming in a very different (Ordovician) tectonic environment to those of the Tabberabbera structural zone (Devonian) in this scenario, the difference is not obvious from the mineralogical domains which are based on characteristics of the goldfields (section 1.3).

The *major Devonian gold scenario* confines gold mineralisation to the foreland setting of a Silurian and Devonian time period of thermal perturbation with extensive metamorphic and igneous activity.

2.5 Is there anything unusual about the Lachlan Fold Belt in Victoria?

Worldwide, there are numerous Palaeozoic turbidite sequences, and although some have abundant gold deposits, most are not renowned for their exceptional gold production. In this context, there continues to be interest in determining whether there are unique or distinguishing features of the Lachlan Fold Belt in Victoria that might account for its exceptional gold productivity. One of the earlier broad-based studies that addressed this question was that of Coney and colleagues (Coney, 1992; Coney *et al*., 1990) who remarked upon:

- the exceptional width of the Lachlan Fold Belt perpendicular to any inferred convergent plate margin (600 km)
- the high proportion of granite and felsic volcanic rocks (20–25%)
- the east–west tectonic shortening of 50%, and even more in places
- absence of craton-directed thrust faults
- paucity of exposed high-grade metamorphic rocks
- absence of Archaean and Proterozoic inliers
- similarity of structural level across much of the fold belt.

Importantly, all these observations relate to the post-depositional history of the Lachlan Fold Belt, and not the depositional setting or process. The discovery of high-grade metamorphic rocks in the west, craton-directed thrusts and the Selwyn Block might remove three of the distinguishing features suggested by Coney (Cayley *et al*., 2002b).

Interestingly, there is little in the literature to suggest that the original Palaeozoic turbidite sequence of Victoria itself is exceptional in any way that could account for the Victorian gold province. Similar quartz-rich turbidite sequences are found on all continents, including several rich in black shales and of similar Palaeozoic age, e.g. Wales and Scotland (Berry & Wilde, 1978; VandenBerg *et al*., 2000, p. 379). Therefore, the turbidites are less likely to be the primary source of the gold, but rather a convenient host rock.

The exceptional width of the Lachlan Fold Belt is still pertinent as a possible factor as to why the belt is gold-rich, but some of this exceptional width is now attributed to juxtaposition of two different terranes across the Governor Fault (Baragwanath Transform), with both being gold-mineralised.

The importance of Devonian igneous activity is emphasised by the partial melting experiments of Clemens and co-workers who showed that many granites are not minimum melts, but are hot, dry and reducing, and reflect high T/P crustal conditions. Such conditions would be important during any crustal devolatilisation event.

Some things stand out as potentially important:

- Crustal melting has been important in Victoria (e.g. granites), but not in many other turbidite successions (e.g. Ordovician turbidites in Wales have few granite plutons and little gold).
- Some of the central Victorian granites are quite unusual in their mineralogy and chemical composition. For example, the high-level, cordierite-bearing Strathbogie Granite resembles the South Mountain Batholith of Nova Scotia, where the surrounding Palaeozoic turbidites contain several modest gold deposits.
- A high geothermal gradient, if demonstrated, would be very significant because it would have influenced thermal processes and indicated the energy source that drove hydrothermal reactions.
- The crust under the Victorian Gold Province is moderately thin.
- There has been minimal erosion since the Devonian in parts of central Victoria, such as where Devonian ignimbrites are preserved (Clemens, 1988).
- A layer several km thick of inferred mafic rocks underlies the Bendigo structural zone, indicated by the seismic traverse (Cayley *et al*., in prep.). Under different circumstances these mafic rocks may have been subducted.

One or more of the unusual characteristics may be important in the generation of the large gold province, and may be useful in larger scale exploration plans.

3. Exploration opportunities

It is not the intention of the *Guide* to provide a gold exploration plan, but it is possible to highlight a number of opportunities that arise from the geology of the Victorian Gold Province. Each exploration company will need to judge its own level of acceptable risk and whether it takes tried and tested geology only, or is prepared to follow some new and unproven ideas knowing it may be treading a new path.

The approach here is to understand the large-scale geological framework, and emphasise aspects of the geology based on reasonable genetic models for gold. I have used descriptions of Victorian goldfields (Phillips & Hughes, 1996; references in this *Guide*) and gold genetic models.

Figure 15. Drilling in box eucalypt forest near St Arnaud. Copyright Rex Minerals Ltd.

3.1 Prospectivity

The prospectivity of the Victorian Gold Province is high, with the potential for substantial new finds without recourse to any exceptional geological pleading. For example, by just considering new deposits that might be under modest cover, there is reason to believe that an additional 5000 t of gold could be found (Phillips *et al.*, 2001), or twice as much gold as that which has already been produced from the province. The GIS-based calculation of Phillips *et al*. looked at the area of outcropping Palaeozoic rocks and added the area where similar rocks were covered by 0–200 m of cover; it then allowed for areas where exploration was problematic (e.g. parks, irrigation areas, water catchments, intense land use) and excluded large areas of particularly unfavourable host rocks (e.g. felsic igneous rocks, Post-Devonian sedimentary basins). Using slightly different input parameters, Lisitsin *et al*. (2007) suggested the potential for an additional ~1000 t gold in the northern extension of the Bendigo structural zone, and ~ 1200 t gold in the northern extension of the Stawell structural zone (Lisitsin *et al*. in prep.). These estimates by Lisitsin *et al*. take into account gold in gold–quartz veins, and exclude alluvial production.

There are assumptions in both sets of calculations that may not be proven over time; for example, all Victorian gold deposits might outcrop strongly because of their quartz veining and hence would be mostly represented on hills and non-covered areas (Fig. 15). This would make the above estimates too high. Conversely, large gold deposits with appreciable sulphide component may be selectively weathered compared to their surrounds and be more abundant in topographically low areas. The experience working in the regolith of Western Australia suggests that both these factors can apply, and they are well illustrated by the mapping of shallower BOA (base of alluvium, i.e. cover) and deeper BOCO (base of complete oxidation) adjacent to gold mineralisation (Anand, 2000; Ely, 2000; Anand & Paine, 2002). Although the number of outcropping discoveries in WA may be decreasing, many important discoveries in the last 15 years have been made under minimal cover (e.g. Bronzewing, Kanowna Belle, Quarters, Thunderbox, Sunrise), or in weathered outcrop (e.g. Plutonic, Jundee).

The prospectivity analyses are not able to predict the amount of undiscovered gold in alluvial systems and the amount in primary deposits and it is likely that some of the primary gold being predicted in these studies has been eroded into alluvial systems.

In the end, however, the prospectivity studies do not say exactly where or how to explore, nor are they a guarantee of success—they simply provide a strong justification for exploring in the Victorian Gold Province if the target is gold.

Despite this geological potential and the considerable remaining untested areas, the economic return from Victorian gold over the quarter century since the start of 1979 has not been encouraging (Phillips, 2005b). This period has seen Economic Demonstrated Resources increase to 75 t and a cumulative production over that quarter century of 65 t (figures from Geoscience Australia, and Australian Bureau of Statistics). Yearly exploration expenditure directed to gold has been AUD$10–25M suggesting an investment of $400M over the quarter century, representing approximately $80 per ounce for the gold produced, or added to the resource inventory. The comparable amount for all Australia is $35 per ounce for the same period. These Victorian figures would suggest that the current approach to gold exploration in Victoria may not be sustainable. To attract continued exploration investment, the discovery rate in the Victorian Gold Province (using 'tonnes of gold per million dollars of exploration') needs to rise from 0.35 t per million dollars, to closer to the recent Australian average of 1.2 t per million dollars (Hogan, 2004). In terms of doing more of the current exploration, these figures are quite discouraging, and instead suggest that a different approach is needed. Factors worth considering include the percentage of budgets spent on drilling, regulatory costs, integration of commercial models with exploration, geological assumptions and methods being used, and training and experience of the geoscientists engaged in exploration.

3.2 Exploration opportunities

Opportunities for exploration in the Victorian Gold Province include:

1. extensions in and around existing primary goldfields
2. exploration around goldfields for additional styles of deposit, e.g. oxide ores that were previously uneconomic. In this category might also be included primary gold deposits upstream from known alluvial goldfields
3. extensions under cover from nearby outcrop where the outcrop offers strong geologic control
4. new discoveries in outcropping but weathered Palaeozoic bedrock
5. new discoveries under significant younger cover where geologic control from outcrop is of limited detail
6. new discoveries of 'typical' Victorian gold deposits that 'look different', perhaps because of higher metamorphic grade or strong modification by weathering
7. discoveries of completely new gold deposit styles.

These seven types of opportunity are not mutually exclusive, and some opportunities have several different components.

3.2.1 Extensions around established goldfields

A good place to explore for gold is in and around known goldfields, and this practice is well underway in Victoria. Stawell gold mine has relied on near-mine extensions to sustain production for many years and benefited from strong conceptual ideas backed by management support and action. Bendigo goldfield has also been the focus of near-mine exploration and has demonstrated how the proximity of a city of 80,000 people can be managed with care and effective communication. Similarly, recent mining at Ballarat has been focussed along a previously mined trend, but below and along strike of the mined-out parts. Operational difficulties at each of these locations have somewhat overshadowed the prospectivity adjacent to these established goldfields, but at Fosterville, Stawell, Ballarat and Bendigo some of the potential for additional mineralisation has been realised (Fig. 16).

For smaller goldfields, the opportunity lies in being able to distinguish which ones might become larger with exploration success. Here alteration, host rocks, structural setting and regolith context can be used to advantage. The evolution and growth of the Fosterville goldfield over the last two decades is perhaps the best example of recognising a much larger system from the geology of a very small historic goldfield. The large footprint of the mineralised area at Inglewood is a positive indicator, and multiple vein directions and regolith depletion at Rushworth are positive factors for potential at depth.

Figure 16. Kangaroo Flat mine site accessing the underground workings of the Bendigo goldfield. Copyright Bendigo Mining Ltd.

In several large alluvial goldfields (placer deposits), the source, which should be a similarly large primary goldfield, has not been located. Examples include Beechworth, Creswick, Chiltern, Ararat, Maryborough, Beaufort and Avoca. The full significance of these alluvial goldfields has only recently been recognised, due to the poor production records from early alluvial fields and the major ongoing compilation exercise to estimate their productions. In exploration parlance, this alluvial gold is an enormous surface geochemistry anomaly indicative of a primary source. Only a much better understanding of the geology (geomorphology, uplift history, and structure of the bedrock) will tell us whether the primary source is deeply buried, offset, or eroded.

Buried alluvial gold systems remain an additional new target, and although not the main topic of this *Guide*, may represent an economic proposition if remote mining techniques can be applied. These will also require new ways to evaluate Reserves and Resources.

3.2.2 Additional ore styles in known goldfields

In a single hydrothermal system, there are several factors in and near the site of deposition that can significantly influence the character of resulting gold mineralisation. Host rocks, structural geometry, controlling structures, and subsequent weathering can combine in different ways to produce mineralisation of different appearance. If each factor is considered on its own, exploration will proceed in one direction whereas an understanding of all the factors as part of a single larger system will lead to a different and probably more successful approach in exploration.

Maldon is an example of a major goldfield comprising quartz veins in Ordovician turbidites, and along strike there are much smaller occurrences adjacent to granite and pegmatite dykes. If the occurrences adjacent to granite had been found first, would exploration have ceased as the small deposits were mined out, or might it have continued by further exploration for different styles of mineralisation to become the considerably larger Maldon goldfield? In between the occurrences adjacent to granite and the typical Victorian style auriferous quartz veins well south of Maldon, are ores that have undergone contact metamorphism and been significantly modified (Hughes *et al*., 1997).

Fosterville is another example of one ore type being an indicator to deeper sulphide ore (described in 3.4). The reverse also applies that Fosterville-like targets might easily exist above and near major underground deposits such as Bendigo.

3.2.3 Extensions under cover from nearby outcrop

This is an important opportunity that is under-appreciated because the extent of thin regolith cover is misunderstood. Over a significant part of the central highlands, a thin veneer of soil lies above bedrock, and in lower areas the soil is transported and not always representative of what lies below. Many valleys in the highlands are broad enough to conceal primary mineralisation at a few metres depth. Radojkovic & Bibby (2003 p. 21 fig. 13) provide a fine example of a small palaeochannel in the middle of the city of Ballarat that might have remained unknown except for a major road cutting that cuts through it: although too small to conceal a major goldfield, this example illustrates the difficulty of mapping such features under even minor cover. Testing in palaeochannels similar to this can yield negative results even immediately above bedrock mineralisation, so that it is critical that exploration recognises all Cainozoic cover and explores beneath it with drilling.

A better understanding of the regolith and surficial features such as palaeochannels can provide additional opportunities. An excellent example outside Victoria is the discovery of the 2 Moz Quarters deposit at Mt Pleasant north of Kalgoorlie in Western Australia (Forster *et al*., 1997). At the time of discovery in 1996, the Mt Pleasant goldfield was already known for its high gold potential, and Quarters was targeted by a drilling program that filled gaps in previous drilling where bedrock was not properly tested. The Quarters discovery occurred 700 m from an underground mine and beneath a 30-m deep palaeochannel overlying 50 m of weathered Archaean rocks. An example of this type of target in Victoria would be the northward extension of the Ballarat West goldfield under swamp, sediments and basalt (M J Hughes, written comm., 2007).

3.2.4 New discoveries in outcropping but weathered Palaeozoic bedrock

This opportunity is often overlooked by those assuming that any outcrop areas would have been well prospected in the 19th Century. This conclusion may be correct for areas where auriferous quartz veins are prominent, but may not apply where regolith processes have removed vein quartz, carbonate alteration and sulphides to significant depth. There is good evidence in north-central Victoria that vein quartz is removed during regolith processes (e.g. Fosterville, Nagambie); this means that some areas of highly weathered outcrop may show little or no quartz but still overlie auriferous targets. Relatively unsophisticated structural and mineralogical approaches can be quite effective in assessing such areas, and in providing the encouragement and confidence to drill to fresh bedrock for gold geochemistry testing. Here an understanding of gold leaching and dispersion in the regolith is useful.

3.2.5 Beneath significant cover

The large area of Murray Basin cover north—and along strike from—central Victorian goldfields makes this an attractive and important exploration focus; and much of this ground is logistically easy to explore. Similar opportunities exist south of the uplands, under cover of post-Palaeozoic basalt and sediment though the basalt leads to difficulties with magnetic interpretation, and it can be very thick.

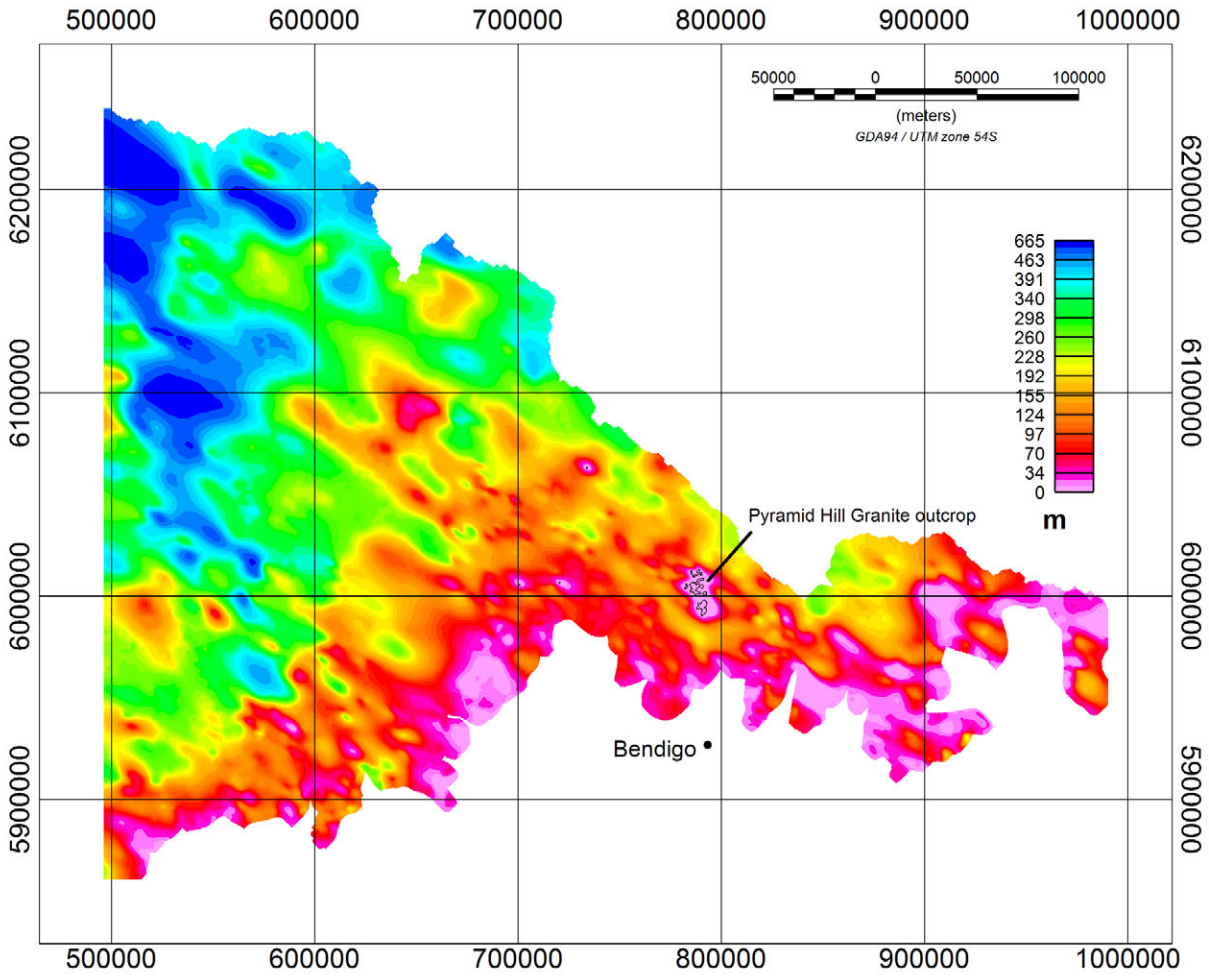
Technical successes from this type of exploration include Lockington and Tandarra north of Bendigo, where Murray Basin cover generally thickens northward but has numerous areas of thin cover well away from Palaeozoic outcrop (Fig. 17).

The thickness of cover above the auriferous Palaeozoic metasedimentary rocks is a particularly important consideration for this type of exploration, and although the Cainozoic Murray Basin sediments generally thicken toward the north, there is considerable variation in this pattern (Fig. 18). Hughes (2002) has drawn attention to Permian sedimentary fill in grabens beneath the Murray Basin that effectively increase overall cover depth by 60 m along one 50-km long graben. These graben fills may not be readily imaged by geophysical methods, but can be investigated prior to drilling using other methods (see Hughes, 2002). Early detection can lead to significant exploration cost savings.

The Cambrian mafic rocks provide an opportunity because they can be traced using aeromagnetic data for many kilometres from outcrop, under 100+ m of cover. Tracing

Figure 17. Tandarra exploration project north of Bendigo and under Murray Basin cover. The various components of the regolith are discernible from colour changes in drill material from the upper part of the drill hole. Copyright Perseverance Coporation - now Northgate Australian Venutres.

Figure 18. Geophysical interpretation showing inferred depth to basement in northern Victoria (McLean et al. 2009). The depth of Murray Basin sediment cover is relatively thin immediately north of the central highlands outcrop.



the mafic rocks of the Stawell goldfield northward using magnetic and gravity methods indicated favourable setting for a Stawell-type deposit at Kewell, where drilling intersected mineralisation in 2001. However, such exploration methods rely on the assumption that gold mineralisation is associated with volcanic rocks, as the Stawell deposit itself is hosted by metasedimentary rocks rather than basalt.

The extra costs of developing and profitably mining any discovery under cover mean that the options and costs of development need to be carefully assessed before an exploration program is begun. An extra cost is access to the mineralisation, either via a decline through overburden, or by digging an open pit. Another cost is the added work needed to evaluate such a prospect and demonstrate a reserve under such cover. If costs are not properly assessed prior to exploration, one may achieve a technical success that discovers mineralisation, that cannot be exploited economically. There are few local analogues of known mines that would be economic targets under Murray Basin cover, but one might be the Meikle deposit in the Carlin trend of Nevada USA (9 Moz Au, discovery hole 177 m @ 12 g/t Au from 428–605 m, grade ~ 20 g/t Au, small arsenic anomaly and subtle surface expression; Bettles, 2002).

3.2.6 Discovery of 'typical' Victorian gold deposits which 'look different'

Overprinting and/or alteration can dramatically change the appearance of a typical Victorian quartz vein deposit and make it much harder to recognise, and could therefore have been missed by early prospectors. High-grade metamorphism after gold mineralisation completely changes the mineral assemblage and mineralised structures, and affects the way a deposit might subsequently weather. Weathering also changes the mineralogy and structural features, but also leads to large-scale gold dispersion. Both high-grade metamorphism and weathering lead to a decrease of carbonate and sulphide mineral species, and may lead to a reduction of quartz veining.

3.2.7 Completely new gold deposit types

Some gold deposit types have not been found in Victoria, but are known from similar terrains and are potentially very attractive targets. These include:

- the Cadia–Ridgeway complex in porphyry intrusions and metasedimentary rocks in central New South Wales
- the possibility that Carlin-type gold deposits may occur in north-central Victoria has already been alluded to (Hughes *et al*., 1997) and such ideas have formed the basis for raising finance for new exploration (e.g. Nagambie, Fosterville). With the role of deep weathering in the Carlin province of Nevada, USA becoming recognised, there will be implications in future for what, beyond its weathering features, actually constitutes a 'Carlin-type' deposit (Phillips *et al*., 1998)
- Au–Mo systems are currently being explored in igneous rocks in northeast Victoria, and these have the potential to yield large-tonnage targets
- Large goldfields hosted in turbiditic metasedimentary rocks include Murantau (5000 t Au) and Sukhoi Log (900 t Au), and these may present analogues to guide exploration in Victoria.
- The Juneau goldfield in Alaska contains two multi-million ounce goldfields only a few kilometres apart and on opposite sides of a 700-km long structure. Juneau goldfield is in a metagabbro and Treadwell in a monzodiorite stock. The region's host rocks resemble those of the Lachlan Fold Belt; Victoria does not have a similar setting on a major structure. The change of plate motion (collisional to strike slip) implicated for these Alaskan gold deposits may provide insight to the triggers for Victorian gold mineralisation in the Palaeozoic (Goldfarb *et al*., 1991).
- The gold-plus deposits in the Mount Read Volcanics of northwest Tasmania may extend into western Victoria (e.g. Mount Ararat prospect), and this VMS-style is also known from the eastern margin of the Melbourne structural zone (e.g Rhyolite Creek prospect). In both cases, the targets would be gold and base metals, and the size of Mt Lyell and Rosebery, and the grade of Henty, indicate their worth (see Fig. 3).
- Although granites in Victoria are not host rocks for gold, it is worth remembering that intrusive rocks in the Townsville–Charters Towers district contain many million ounces of gold (Charters Towers, Mt Leyshon, Ravenswood, Mt Wright) of similar Palaeozoic age.
- The Broken River gold province of northeast Queensland has gold mineralisation related to turbidites of Palaeozoic age, and although small, may provide some insight to Victorian opportunities because of their similar regolith profiles superimposed on gold-only mineralisation (Vos *et al*., 2005).

The scenario of Victorian gold mineralisation being related to Devonian thermal, fluid, deformation and metamorphic processes is not universally accepted, but if correct, would introduce an overlooked opportunity for major gold mineralisation in rocks younger than Middle Ordovician age, and such finds might be more akin to some other global gold provinces where gold and high geothermal gradient settings are related.

3.3 The environment of Victorian exploration: regolith

Although this *Guide* concentrates on primary gold deposits, the Cainozoic history of Victoria impacts on many aspects of geology, exploration and gold deposit description. The most important factor is the sedimentary cover that obscures potential gold-bearing areas and provides an extra challenge to modern exploration. The importance of Cainozoic weathering is only gradually being understood and has been underestimated in many geological studies. It may require the rejection of some established ideas (see discussions in Hughes *et al*., 1998a & b; Phillips, 1998). Such revisions may create new exploration opportunities.

The Murray Basin has been a topographic low for much of the last 50 My (Brown & Stephenson, 1991). Within it, Quaternary tectonic movements have been mild compared to those in the neighbouring uplands. A change is postulated at the end of the Miocene from tilting, uplift and erosion before, and less intense modern deformation since 6 Ma (Sandiford, 2003). This neotectonic response may result from prior strike-slip movement on the Australia–Pacific plate boundary changing abruptly to transpression (Walcott, 1998).

The current surface character of the Victorian Gold Province is strongly influenced by neotectonics reflecting activity on the boundary between the Australian and Pacific plates, and has seen little change since the beginning of the Pliocene (Sandiford, 2002, 2003). The Victorian region is characterised by current east–west to southeast–northwest compression reflected in recent seismic activity (Sandiford, 2003).

Not many systematic regolith studies have been done in the Victorian Gold Province, despite their importance for gold exploration. The study at Ballarat–Creswick (Radojkovic & Bibby, 2003; see Appendix 8) provides a typical cross-section and records a much more complex regolith history than recorded in the older literature. Here, chlorite in relatively fresh material was weathered to kaolinite, muscovite to illite and kaolinite, and siderite to iron oxides including goethite and limonite staining. Weathering appears to be deeper in and around gold deposits, presumably because of fracturing, and because of the oxidation of sulphides to give acid ground waters that then reacted particularly with carbonate minerals.

Late Miocene to Recent basalt flows cover important parts of the Victorian gold province in the last few million years, including primary (e.g. Ballarat West goldfield) and alluvial goldfields. These igneous rocks are described by Price *et al*. (2003).

The importance of weathering and the regolith for Victorian gold exploration cannot be over-emphasised. Only one decade ago, the importance of the regolith was widely questioned and challenged but today it is clear that surface sampling, in the most part, is from the regolith, including the depleted zone which is developed across the goldfields as a pallid interval. Core from the Daylesford goldfield shows a good example of the depth of visible weathering. Hematite staining from surface waters occurs preferentially along the higher strain zones, to depths of 200 m (Phillips, 1998). At Ballarat, kaolinite extends from the surface to depths of 300–500 m, illustrating that deeper weathering in gold systems occurs along structures. More broadly, reported kaolinite alteration at other goldfields has not been demonstrated to be due to primary alteration rather than to weathering. Drilling just to the northwest of Ararat to below 100 m depth intersected a quartz-bearing zone with over 20% of cavities that was highly permeable contained flowing groundwater. This was at the gold target depth and the absence of anomalous gold around this target depth is likely to reflect supergene removal, so this hole failed to test its target for gold despite intersecting anticipated favourable geology. Immediately west of Ararat in a road cutting, a broad zone of quartz veining with carbonate has been thoroughly sampled for gold because of its ‘attractive mineralised’ appearance. However, gold values in the cutting have been so low that the area has not been tested by drilling, even though the cutting is probably in the regolith, i.e. depleted.

“For the Victorian gold province, the shadow of deep weathering potentially hangs over many research projects (1998).”

… a quote reminding explorers that many samples had been collected from the surface and from dumps around shallow mines, and therefore come from the regolith. As a result, some mineral assemblages, whole-rock geochemistry, illite crystallinity and Ar–Ar results might be viewed with caution. The quote is also a reminder that underestimating the role of the regolith may mean that viable targets have been overlooked.

While Cainozoic weathering is of great interest, a completely unknown and potentially new frontier is that of Palaeozoic weathering after the Tabberabberan Orogeny. Many parts of the Victorian Gold Province may have been at or near the surface during the later Palaeozoic, especially the Costerfield mineralogical domain.

3.4 Case history of exploration success: Fosterville goldfield

Fosterville is an example of modern exploration success, first by identifying gold for a heap leach operation, and then by deeper drilling to justify an underground operation. The geological setting of Fosterville is summarised here, and then some of the key stages are described that led to the discovery of significant sulphide ores at depth (~ 2 Moz Au). Many lessons can be taken from the Fosterville example including the value of a well reasoned, technically-based argument to generate a deep drilling program, the role of challenging existing geological models, the application of regolith research, and the wealth of relevant information that can be gleaned from other gold provinces at virtually no cost. What looks so obvious after the event (‘everyone knew there was gold there, all that was needed was to drill beneath the pits’), took several years to evolve into a technically-supported and funded drilling program.

A well developed regolith profile contained sufficient weathered ore for the heap leach operation, and the weathered nature of Ordovician host rocks in the district contributed to Fosterville not being recognised as a significant goldfield until 1995 (Fig. 19).

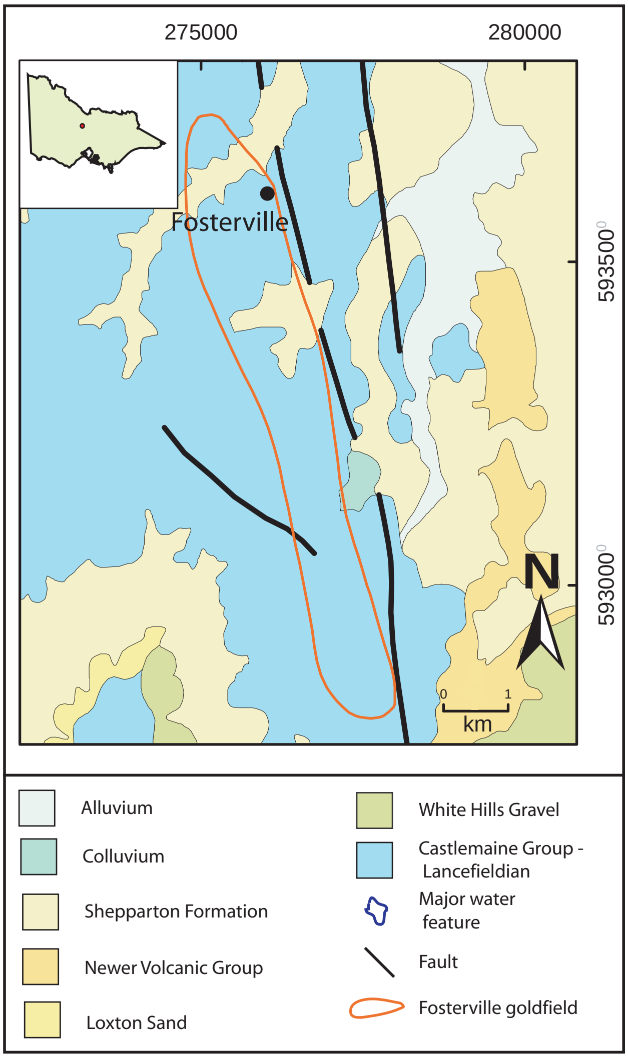


Figure 19. Geological map of the Fosterville district showing Ordovician metasedimentary rocks and considerable Murray Basin cover to the east (adapted from GSV 1:1,000,000 scale mapping).

Fosterville goldfield is 25 km northeast of Bendigo near the eastern margin of the Bendigo structural zone (McConachy & Swensson, 1990; Phillips & Hughes, 1996; Hughes *et al*., 1997; Arne *et al*., 1998a; Mernagh, 1998; Phillips, 1998; Zurkic, 1998; Bierlein *et al*., 2001; Phillips *et al*., 2003; Roberts *et al*., 2003; Boucher *et al*., 2008). Heap leaching of oxide ore from 1991–2001 produced 0.285 Moz (9 t). Mining of sulphide ores, initially from open pits and now from underground, commenced in 2003.

Gold production: total 17.8 t to end 2007 (1894–1903: 1 t; 1981 to 2005: 9 t heap leach; open pit sulphide operation ending 2007: 8 t). Resources in 2009: surface to 100 m depth 8.1 Mt at 2.0 g/t for 0.5 Moz; > 100 m depth 9.7 Mt at 4.4 g/t for 1.337 Moz, including a reserve of 3.6 Mt at 4.9 g/t for 0.56 Moz, with an underground cut-off of 3 g/t. Over twenty open pits have mined oxide ore since the 1990s, and this phase of mining ended in December 2007. Endowment is likely to be ~ 100 t Au.

Host rocks: Early Ordovician (Lancefieldian) Castlemaine Group turbidite sequence comprising mudstone, sandstone, black shale. Metamorphic grade is probably greenschist facies.

Igneous rocks: quartz porphyry dykes are emplaced in shear zones near the mineralisation. A Cainozoic basalt flow fills a stream 1–2 km to the east.

Structural setting: the Castlemaine Group is folded tightly about upright NNW-trending fold axes with a 300–500 m wavelength. The major NNW-trending Fosterville Fault dips steeply west and is one locus of mineralisation, and there are parallel faults to the east and to the west with known gold mineralisation. Movement on the Fosterville Fault has been interpreted as reverse and sinistral, with late strike-slip activity.

Ore geometry: a major factor in ore geometry is the considerable north–south elongation parallel to the Fosterville fault, other NNW-trending faults, and splays. Cross-faults and/or cross folds locally coincide with some better ore where they intersect the NNW trends (e.g. Daley Hill open pit in the south). Ore zones are generally around 5 m wide, continuous for 400 m strike length, and dip to the west. Deeper drilling below the base of the regolith demonstrates that sulphide-bearing mineralisation is organised in a number of ore shoots that plunge gently southward (e.g. 30° S). Phoenix shoot is known to extend down to a depth of 1 km. Maximum ounces per vertical metre of gold coincides with structural thickening through fault repetition of the ore shoot and its quartz veining.

Ore character: gold mineralisation is related to quartz veining in dark grey to black carbonaceous shale near sandstone. Quartz veins are common in and near the ore, particularly laminated veins. Gold is generally very fine grained (1–10 μm) and associated with arsenopyrite (80%) and pyrite (20%), with stibnite common especially near fault splays.

Alteration mineralogy: approaching ore positions, there is an increase in quartz veining, white mica, ankerite and siderite, and sulphide minerals, at the expense of chlorite and feldspar. This mineralogy is reflected in the whole-rock geochemistry by variable Na and K, and increase in CO_2, S, Sb, As, Ag and Au. Base metals are minor; and the sulphide assemblage is dominated by arsenopyrite, pyrite and stibnite, with minor sphalerite, galena, bournonite, boulangerite and tetrahedrite.

Fluid characteristics: fluid inclusions in quartz veins indicate a trapping temperature of 270 °C, low salinity, and an inferred depth of formation of 2.6–5.7 km. Sulphur isotope values are tightly bunched near and slightly below zero implying a reduced sulphur-bearing fluid (without placing much constraint on the source of sulphur). Hydrocarbons occur in and near the ore in sandstone adjacent to the Fosterville Fault.

Weathering and the regolith: in the upper few tens of metres of the ore deposit, the ore zone and its surrounds are pale cream to orange and generally devoid of quartz veining and sulphide minerals. The gold here is free-milling and can be extracted through heap leaching. These characteristics

Figure 20. Core from the Fosterville goldfield. The red-orange colouring is from iron carbonate that has oxidised since the core was drilled. The quartz veining in and around mineralisation in this unweathered material contrasts with ores in the regolith from the open pits which were devoid of quartz veining. This example shows that Fosterville is a primary quartz-vein related goldfield in which quartz has been lost during weathering in the regolith. Copyright Perseverance Corporation - now Northgate Australian Ventures.

are a consequence of weathering and represent the upper part of the regolith profile in which micas and chlorite have been converted to illite and kaolinite, with some iron oxides, during weathering. Gold is somewhat more dispersed in the regolith than at depth and is not locked in sulphide minerals. The base of the bleached zone is sharp and marked by the change from a pale upper section to an underlying black to grey rock; this boundary would be mapped as BOCO (base of complete oxidation) in many gold provinces. Importantly, this dark interval below BOCO is not unweathered, but instead represents the lower part of a regolith profile approximately 150 m thick. Some sulphide minerals are stable in the lower weathered interval below BOCO where carbonate and feldspar minerals have been partially leached. Gold from this lower zone is refractory. The base of weathering is several tens of metres deeper, not completely mapped, and an interval where sulphide and silicate minerals are no longer altered by meteoric waters. Cainozoic cover, which includes basalt, conceals parts of the Fosterville goldfield.

3.4.1 Discovery of deeper sulphide ore at Fosterville, and the role of geoscience

The full potential of Fosterville, including its sulphide ores, was demonstrated during deeper drilling in 2001–2 after a ten-year study of the geology and comparison with other deposits.

The evolution of ideas influencing the deep drilling program at Fosterville dates back to the late 1980s and early 1990s, particularly after the discovery of the Nagambie deposit. At this time, several gold occurrences in north-central Victoria were labelled ‘epithermal’ on the basis of their lack of quartz veining and kaolinite-bearing host rocks. This opened an opportunity for an entirely new type of gold deposit in the Victorian Gold Province that might be rich, with bonanza grades of large tonnage, and be highly profitable. Furthermore the shape of such deposits might mean greater near-surface tonnage without the great depth extent of the classical Victorian orogenic deposits. At the same time as these epithermal models were evolving, there was growing recognition of the existence of quartz veining, structural control, and an important overprint of weathering at Nagambie and Fosterville. By the mid 1990s, the bleached upper material mined at Fosterville was mostly regarded as a product of weathering, but the deposit was still considered atypical for the Victorian Gold Province, and labelled ‘disseminated’ because of a lack of quartz veining, and ‘epithermal’ being retained locally. Some disappointing drilling to 100–150 m depth was mostly within the deeper part of the regolith profile though this was not recognised during logging. Drilling in 1995 to 440 m depth intersected 55 m at 1.9 g/t but drilling to these depths was not followed up for six years. At the time, the quartz veining and carbonate alteration in this intersection was considered quite different from the more familiar mineralisation in the open pits.

Deep drilling was followed up after exploration funds were raised in 2001. However, by this time the geological rationale for deeper testing had changed significantly, with the existing deep intersections recognised as potentially the primary ore of what was seen in the pits. The prospect for considerable depth of the deposit, similar to other Victorian goldfields, was recognised.

Recognition that the two types of mineralisation were part of the same system was a simple shift of thinking but one that could justify the raising of further finance, and give confidence and purpose to a new exploration program.

Critical in re-interpreting the deeper intersections were several disparate ideas.

- It became understood that both the bleached upper material and lower dark refractory material were formed by weathering. The upper part was formed above the water table in oxidising conditions, the dark material below the water table in more reducing conditions. The transition from light to dark was similar to boundaries being mapped by the Co-operative Research Centre for Landscape Evolution and Mineral Exploration in other Australian terrains as BOCO (base of complete oxidation; Anand & Paine, 2002).
- Comparisons with the history of the Carlin gold province of Nevada, USA showed a similar thought pattern of early interpretation of deposits as ‘epithermal’ followed by recognition of structural control and the potential for much greater depth of ore. The Fosterville regolith profile was not as deep as in the Carlin goldfields, but similar in that there was upper bleached oxidised ore, lower black refractory ore, and the suggestion of primary ore with carbonate alteration and quartz veining. The Archaean Binduli

gold deposit just west of Kalgoorlie and the Palaeozoic Camel Creek deposit in NE Queensland exhibited similar regolith patterns to Fosterville and Carlin, indicating that this type of weathering of sedimentary-hosted gold deposits might be quite widespread.

- Research in Western Australia and several deposits in the Carlin Gold Province indicated that the lack of quartz veining in the bleached zone was not unusual even above deposits with strong primary quartz veining as the main host for gold. This indicated that the 'disseminated' character of Fosterville was better explained as a function of weathering than as a primary ore characteristic.
- The same geological rationale to that used to justify deep exploration at Fosterville has subsequently been used at Nagambie to raise finance and target primary ores beneath the regolith blanket.

Fosterville is one of a hundred Victorian examples where drilling beneath near-surface mineralisation was an obvious early idea; however, without recognising the significance of weathering, the importance of the subsequent two drilling results at Fosterville went unnoticed for some time. The case for raising finance to carry out follow-up drilling was primarily built around re-interpretation of the geoscience. It is not a case of saying 'we should drill beneath this mineralisation in the regolith', it is a case of explaining 'WHY!' in scientifically valid terms, and demonstrating that this prospect was better than 7000 other targets that could be drilled at depth in Victoria.

3.5 Conclusions—the improving economics for Victorian gold

The substantial historical production of the Victorian Gold Province has not been matched by recent exploration success. However, the geological framework and analysis of the prospectivity strongly suggest that the potential for major discoveries remains high. In terms of the world's major gold provinces and what perceptions might have been in 1979, the ensuing quarter century has been remarkably productive for most provinces, but not for Victoria.

Many of the facilities for gold exploration are already in place in Victoria including an outstanding geosciences database, excellent infrastructure, a strong legal system, and first-class educational and research institutions.

The approach for the future might sensibly involve first-class geoscience teams, adequate capital backing, clear and long-term management focus, and persistence. There is a need to re-examine current exploration methods given the discovery rate of recent years. More viable exploration plans could result from questioning some of the current geological assumptions. The focus of geological research also needs to be subject to review and, potentially, revision, as this has not generated the same level of rewards as have been generated in some other provinces, e.g. Yilgarn craton during the 1980s and 1990s.

There is little consensus about the reason why Victoria is so well endowed with gold, or what is special or different about the geological history of the Lachlan Fold Belt in Victoria from that of similar, non-productive regions. These questions might be better answered by stepping outside the Province and looking at global gold, and even at the chemistry of gold and its hydrothermal fluids. In this regard, some of the processes that operated during the Silurian–Devonian period in Victoria may stand out to an exploration manager as unusual, but not unlike processes seen in some other major gold provinces. This might be a starting point for re-examining some geological assumptions.

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Appendix 1: Terminology

Mineralogical domains: regions ranging from tens to thousands of square kilometres with gold deposits of similar mineralogical characteristics (Hughes *et al*., 1997).

Endowment: an approximation of the pre-mining amount of gold within a goldfield, usually compiled from total production and resources. A good geological guide to size.

Goldfield, deposit: the terminology here follows that of Cox *et al*. (1991) and Phillips & Hughes (1996, table 1).

Economic Demonstrated Resources / Economic Identified Resources: terms used to denote reasonably likely resources (see Geoscience Australia for details). Not the same as JORC figures.

All-time production: cumulative production since mining began (cf. annual production which is rarely used here).

Ounce/tonne: as an approximation, one tonne is 30,000 troy ounces, and one million troy ounces equals 30 t. Exact figures are 32,150 oz, and 31.10 t. Tonnes and million ounces are both used in this *Guide*.

Timescale: This *Guide* uses the most recent timescale (Pogson, 2009), which also shows the various other timescales used in the last 15 years or so.

Tasman Fold Belt System: term to describe the collection of Palaeozoic fold belts in eastern Australia that extends from North Queensland to Tasmania. This includes the Lachlan, Thomson and New England fold belts; some authors also include the Delamerian Fold Belt (see Figure 10).

Lachlan Fold Belt: Lachlan orogen is also used.

Central, eastern and western, as in central Lachlan Fold Belt: these terms are mostly avoided because they do not match well the literature across state boundaries and have led to some confusion, i.e. a large part of the western Lachlan subprovince is in eastern Victoria and is east of what is referred to commonly as central Victoria.

Terranes: Whitelaw and Benambra terranes were juxtaposed along the Governor Fault during Devonian stabilisation of Victoria.

Structural zones: a subdivision of the Palaeozoic rocks of Victoria based on stratigraphy, structural and lithological character, nature of the underlying crust, granite type, and distribution of volcanic rocks. Most authors refer to them simply as zones (e.g. Bendigo Zone). These are also called tectonic zones in some publications.

Ballarat zone / Bendigo structural zone: the zone between the Stawell and Melbourne structural zones is referred to as the Bendigo structural zone following VandenBerg *et al*. (2000), and this is synonymous with the Ballarat structural zone used in much of the international literature on the Victorian Gold Province (see Birch, 2003, p. 381 for further information).

Orogenies recognised in the Palaeozoic rocks of Victoria: Delamerian, Benambran, Bindian, Tabberabberan, Kanimblan.

Suites, supersuites, provinces, superprovinces: all these terms have been used to group granitic rocks in Victoria.

Basement terranes: used for groups of granites (Chappell & White, 1988), and not to be confused with terranes as in Whitelaw and Benambran terranes.

Beaufort–Maryborough line: a NE–SW trending line passing through the goldfields of Beaufort and Maryborough, and separating Early Devonian granite plutons to the west from Late Devonian granite plutons to the east (see Hughes *et al*., 1997, figure 1; Hergt *et al*., 2002).

Appendix 2: Alluvial gold as an indicator of primary goldfields

Over half of the historic Victorian gold production has come from alluvial workings. In most cases, this production can be traced back to reasonably certain source areas of primary gold mineralisation with transport distances ranging from a few hundred metres to a few kilometres. It was the understanding of this link between the alluvial deposits and primary gold mineralisation that led the early prospectors to some remarkable exploration successes in finding Bendigo (22 Moz primary), Ballarat (2 Moz primary), and other primary goldfields after the alluvial deposits were discovered—they were using what was essentially stream sediment geochemistry. In the alluvial examples where a primary source is not obvious even today (e.g. Ararat, Avoca, Beaufort, Creswick, Beechworth; Hughes *et al*., 2004), primary mineralisation may have been lost through erosion, or it may still represent a future opportunity under cover.

The seeming lack of logic behind the distribution and richness of primary and alluvial gold is well-illustrated by the Maldon and Castlemaine goldfields which are within 25 km of one another. These have yielded 90% and 15% primary gold, respectively, the remainder being alluvial gold.

This *Guide* is focussed on primary gold deposits and potential for their discovery. In assessing this potential,

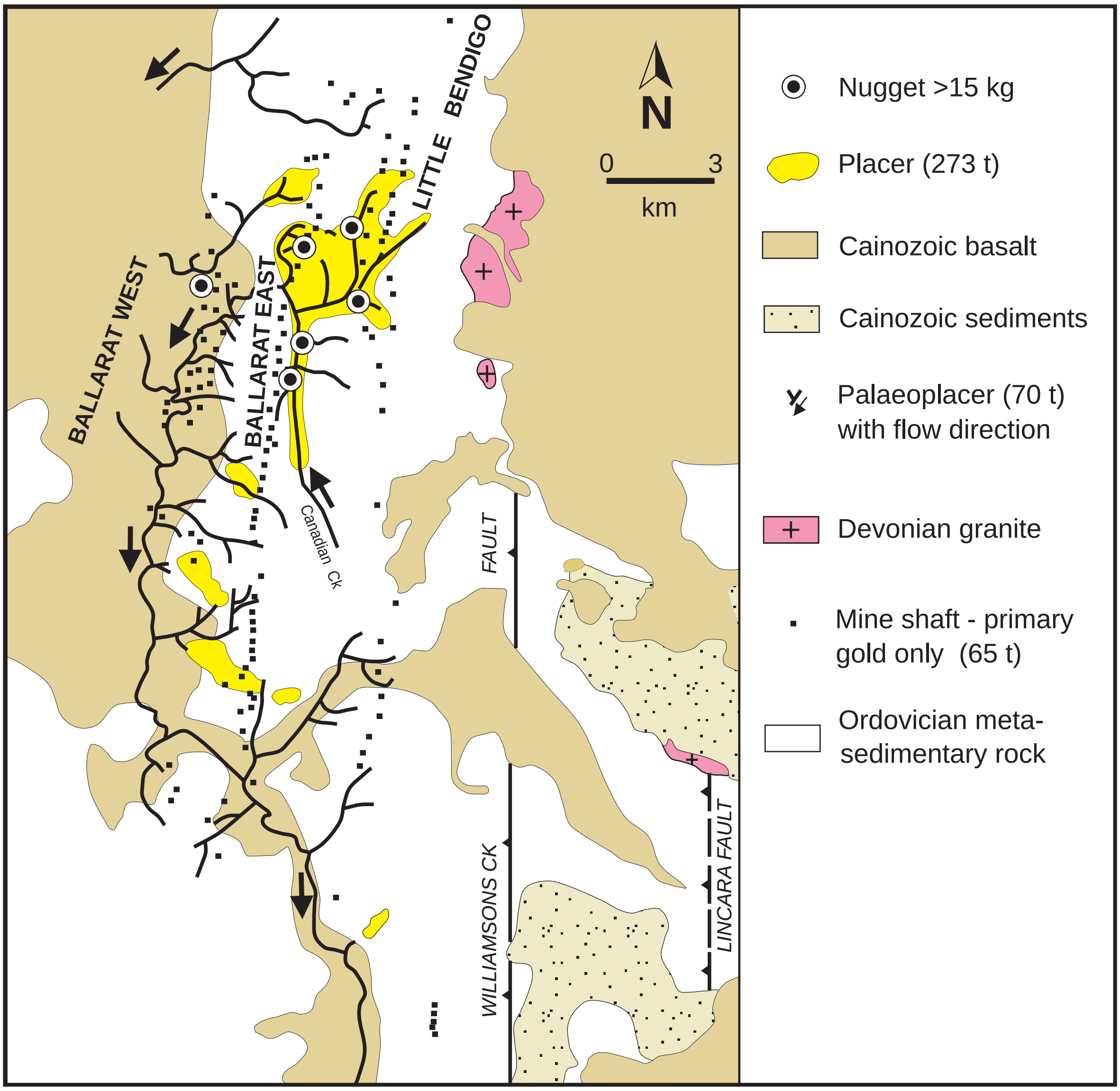

Figure A2.1. Map of the Ballarat goldfield showing the auriferous Palaeozoic window in Cainozoic basalt. Three north–south lines of primary mineralisation (Ballarat West, Ballarat East, and Little Bendigo) have provided the 65 tonnes of primary gold from deep mines. Placer gold found at the surface surrounds the ridge that forms the Ballarat East workings and toward Little Bendigo. Palaeoplacer gold was found by tracing the placer gold under basalt cover, and this in turn led to the discovery of the completely covered Ballarat West goldfield. The alluvial gold, which includes large nuggets, show a close spatial relationship to primary gold, and shows gold dispersion ranging from a few hundred metres to several kilometres (after Hughes *et al*., 2004; see also Taylor & Gentle, 2002; Hough *et al*., 2007).

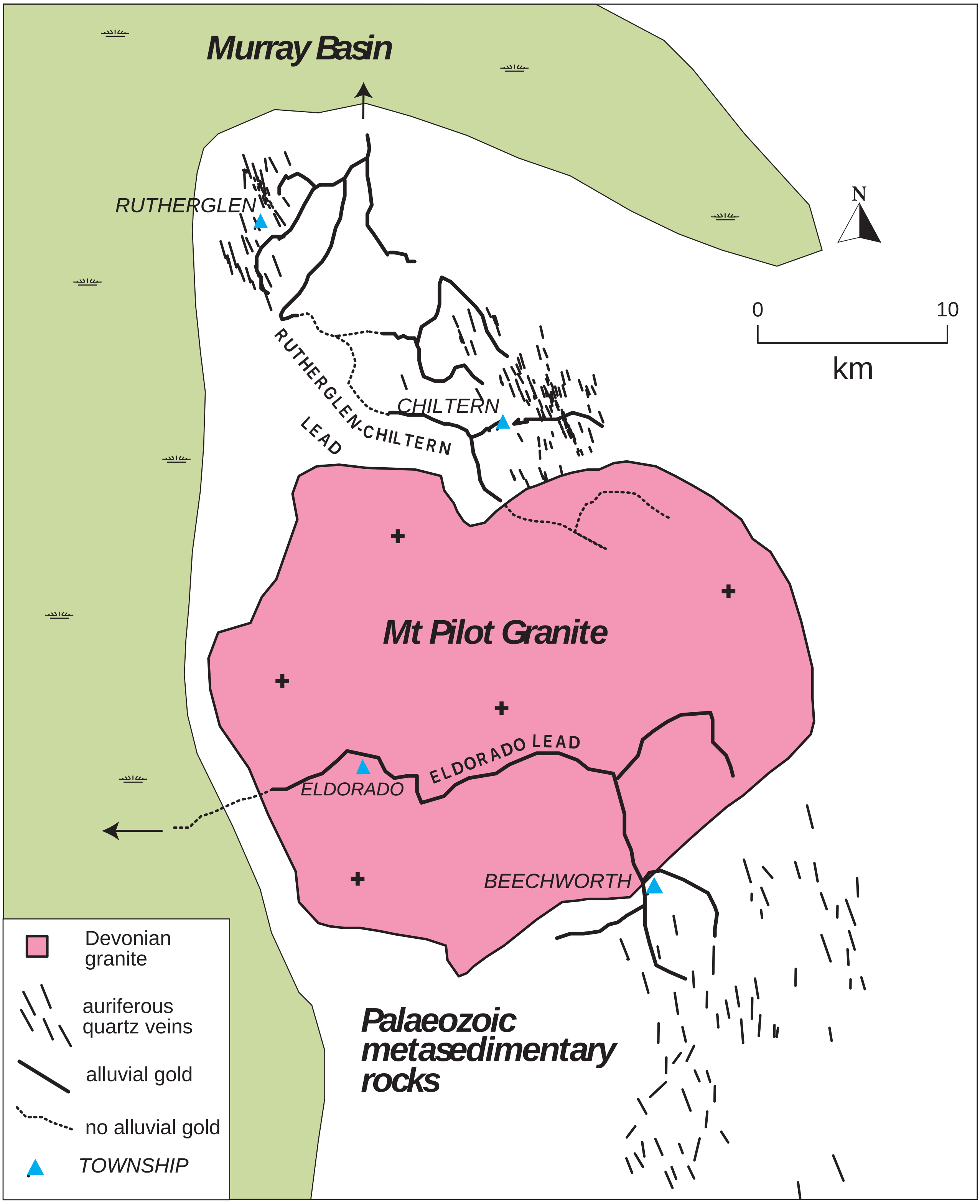

Figure A2.2. Map of the Beechworth–Chiltern–Eldorado–Rutherglen area of northeast Victoria. Primary gold mineralisation in quartz veins trends NW from Beechworth to Rutherglen via Chiltern, but this trend is interrupted by the post-mineralisation, Middle Devonian Mount Pilot Granite (~377 Ma). Alluvial gold has been followed downstream from each of these three primary goldfields for several kilometres. The Chiltern–Rutherglen lead system is devoid of gold upstream (i.e. SE) of the granite contact where there is no Palaeozoic source for gold; it is gold-bearing for almost 10 km downstream from the Chiltern and Rutherglen goldfields. The Eldorado lead contains gold for at least 20 km downstream of the granite contact, suggesting that detrital gold has been carried for at least this distance (after Hughes *et al*. 2004).

what is important is the original size of primary gold deposits, not their size after erosion which varies from place to place. To correctly represent (or *more* correctly represent) the size and distribution of Victorian gold deposits prior to erosion, it is valuable to add alluvial gold where its primary source is reasonably clear (Phillips 1991; Hughes *et al*. (2004)). This process is relatively robust given the close relationship between primary occurrences and alluvial gold (Figs A2.1, A2.2); but this will only provide a minimum size for original primary endowment of a source area. The benefits to explorers of this process were demonstrated by Phillips (2007, figure 2).

Appendix 3: Mineralogical domains and what they mean

Since the mineralogical domains are based upon the mineralogy of gold deposits, they are well defined where there are abundant gold deposits, but not mappable where gold deposit information is scarce or absent. Hence the domains are not well defined in the eastern part of the Stawell structural zone and western part of the Tabberabbera structural zone. The scale of the mineralogical domains is similar to that of the structural zones being 100 km or more long, aligned NNW–SSE with stratigraphy and major structures, and 20–100 km wide across strike. Additionally, oxygen isotope data from vein quartz is in accord with some of the mineralogical domain boundaries, suggesting they have different fluid sources or history (Hughes & Phillips, 2001).

The major differences in gold deposits reflected in the mineralogical domains do not closely accord with characteristics of granitic intrusions despite their similarity of scale. For example, the age change boundary from Late to Early Devonian granites (395 to 365 Ma, Beaufort–Maryborough line) cuts across mineralogical domain boundaries in the same fashion that it cuts across the structures. No consistent relationship exists between gold deposits and granite chemistry (S- or I-type,) reduced/oxidised, Ba or initial $^{87/86}$Sr values. There is a correspondence between Devonian reduced granites and the main goldfields, but with exceptions such as Stawell which is near magnetic (oxidised) granite.

Those mineralogical domains characterised by elevated (though uneconomic) base metals (i.e. Landsborough–Percydale, Bethanga, Buchan) probably reflect slightly more saline ore fluids though further data on this are still required. Possible sources for this salinity include magmatic, marine diagenetic, or evaporitic waters.

The consistency of mineralogical features of gold deposits in the Stawell–Ararat, Ballarat, Costerfield, Woods Point and Chiltern mineralogical domains indicates that gold

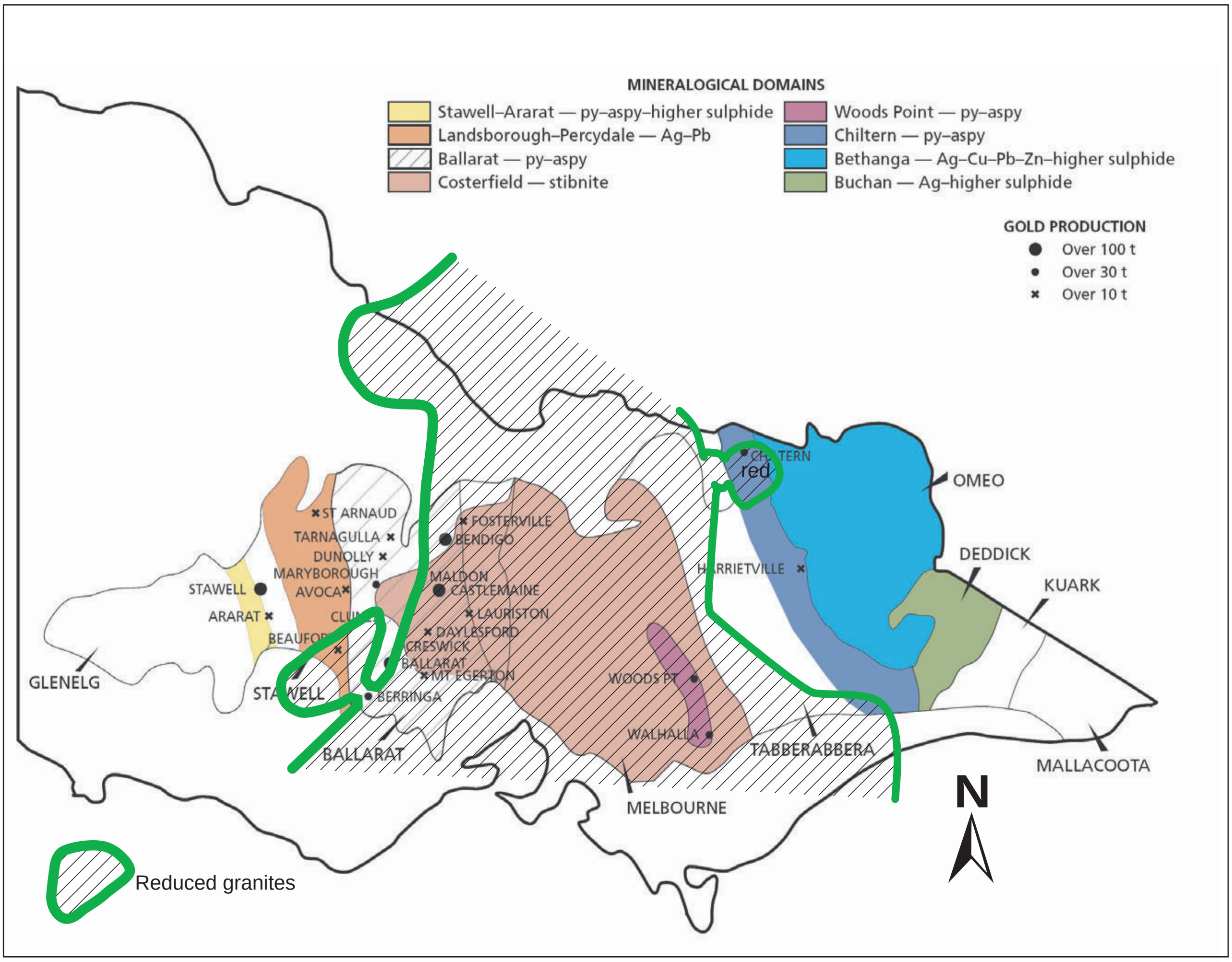

Figure A3.1. Overlay of the mineralogical domains and region with reduced granites in central Victoria (after Phillips *et al*., in press). There is a fair correspondence of the reduced granites with the Costerfield mineralogical domain (and the Selwyn block). These granites also coincide with most of the larger goldfields of Victoria, excepting those in the northwest such as Stawell and Maryborough. It should be noted though that the granites can be mapped even under cover using aeromagnetic data and the mineralogical domains are only mapped where there are gold deposits in outcrop. This mapping of granites under cover may help to extend the potential prospective terrain.

emplacement processes were similar across this area (i.e. the heart of the Victorian Gold Province). This consistency may be difficult to explain in any model that invokes the formation of the various goldfields at different times (i.e. some in the Ordovician, others in the Devonian) and in the two different tectonic settings that prevailed in those periods.

The scale of the mineralogical domains helps to understand the likely role of the voluminous granite intrusions. On a province scale, and even subcontinent scale, a strong geographic correspondence exists between the gold province and abundant high-T granites. However, on a local scale there is no close correspondence between goldfields and plutons, and in fact, the plutons are poorly gold-mineralised. These observations are compatible with the gold mineralising event, and partial melting in the crust, being two of the consequences of a single (Silurian-Devonian) thermal anomaly. This would explain the spatial and temporal association of gold and granites, but a lack of any direct genetic links (see Powell *et al*., 1991, fig. 3). Granite and gold may be different consequences of one thermal event. The observations might also be consistent with alternative explanations not considered here.

Appendix 4: Gold-only and gold-plus deposits

The primary subdivision used here relates to whether deposits produce gold alone, or are multi-commodity with co-product or by-product gold. This subdivision draws on strong global and chemical support: it is a way to divide virtually all the world gold production with very few exceptions necessary, and has a strong scientific foundation that links with different oxidation states of gold (Au^{1+} and Au^{3+}), different preferred ligands (reduced sulphur and chloride) and consequent ability to enrich base metals (low versus high base metals).

Although the gold-only / gold-plus subdivision can be applied globally and through geologic time, there are a few exceptions such as the Witwatersrand uranium which is postulated to be diagenetic in origin and separate from the gold introduction event, and some smaller Victorian deposits with elevated base metals though generally at sub-economic levels (e.g. St Arnaud, Bethanga, Cassilis), and antimony.

The gold-only / gold-plus subdivision draws its strength from simplicity and effectiveness, and also its linkage with rigorous chemical theory. This linkage is easily demonstrated in a few observations:

- gold has two stable oxidation states in nature, Au^{1+} and Au^{3+}
- redox conditions dictate the relative stability of these oxidation states
- Au^{1+} is one of the softest of all cations, preferring to bond covalently with soft anions
- soft anions in nature are limited, and include bonding through sulphur atoms (HS^- and H_2S)
- other soft cations include Sb, As, B, Hg and Te
- gold-only deposits originate from S-bearing low salinity fluids
- Au^{3+} is an intermediate to hard cation preferring to bond with intermediate to hard anions such as Cl^-
- intermediate to hard cations are widespread and include many metals such as Cu, Pb and Zn
- intermediate to hard base metal cations bond strongly with Cl so are transported effectively in saline fluids
- gold-plus deposits originate from saline fluids that are also oxidising.

Hence the gold-only / gold-plus subdivision can be reached by backward modelling from the natural distribution of gold deposits and their constituents, or from forward modelling from gold chemistry.

The classification scheme does not require determining the age or conditions of formation of a gold deposit (which is a major advantage compared to using terms like epithermal, epizonal, mesothermal, mesozonal, hypozonal, intrusion-related).

Global gold deposits				Chemistry of gold	
With base metals	*gold - plus*	Hard Class A	Cl - complexing Cu - Zn - Pb - Ag - Au	Saline oxidising fluid	Au^{3+}
No economic base metals	*gold - only*	Soft Class B	S - complexing Au >> Cu, Pb, Zn	Low salinity reducing fluid	Au^{1+}

Figure A4.1. The subdivision of gold deposits into gold-only and gold-plus can be arrived at by backward modelling from observations globally; the subdivision can also be reached by forward modelling from basic aqueous chemistry of gold and its two oxidation states (after Phillips & Powell, in press).

Appendix 5: Classification of Victorian Gold Province mineralisation

Approach and importance of classification

What constitutes a distinctive style of gold deposit is very much context-dependent. Geologists, miners, metallurgists, accountants and investors are all interested in differences between groups of gold deposits, but what each perceives as important differences to them may be simply variants of a common theme to someone with a different viewpoint. However, through these differences of approach and viewpoint, it is necessary to retain some economic perspective: for example, two gold deposits of the same style, one at the surface and another under 150 m of cover, represent very different exploration opportunities and targets.

This overview of Victorian gold deposits is biased towards geology and exploration, but still needs to address at least two questions. One question is primarily exploration-focused and to do with area selection and asks 'what are the fundamentally different ways in which Victorian gold deposits have formed?' (the subtext here is 'how can answers to this question guide future exploration?'). The second question is more to do with what deposits look like, and asks 'what geological processes account for this gold deposit being as it is?'. As will be discussed, there are several ways to modify essentially similar primary gold deposits after they have been formed to make them very different to the miner, metallurgist or accountant, and even the geologist.

Many of the global classification schemes of gold deposits in use have been found wanting. Some are based on doubtful premises, others fail to capture the breadth of possibilities globally, and others may not be especially informative when applied to the Victorian Gold Province.

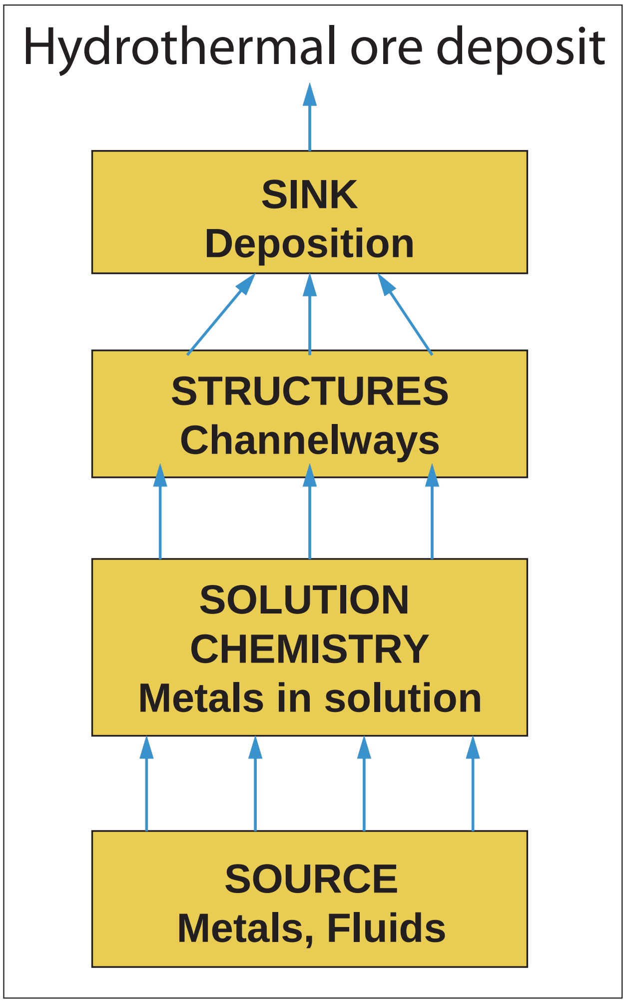

Figure A5.1. Generic ore formation scheme for a hydrothermal gold deposit incorporating a source area, a solution, focussing channelways, and a site of precipitation.

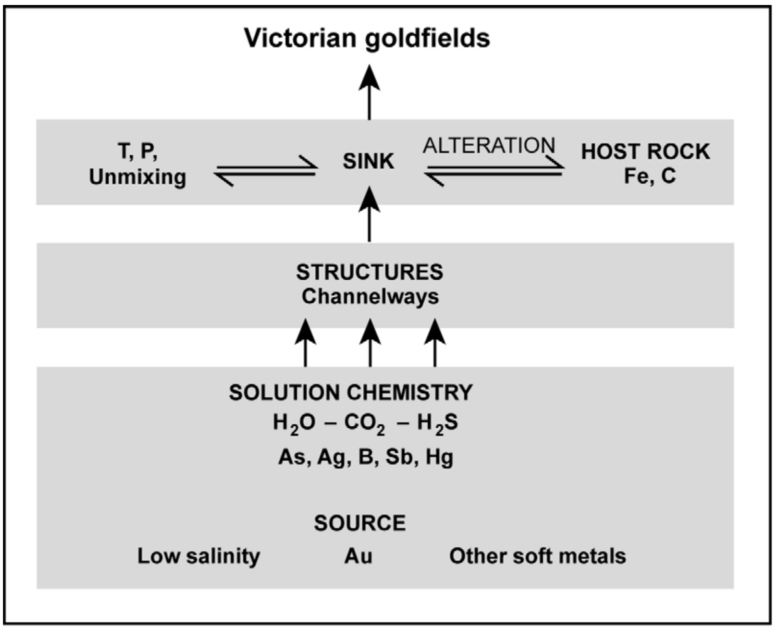

Figure A5.2. Modification of Figure A.5.1 for Victorian gold genesis (after Phillips & Powell, in press). This scheme becomes a starting point for developing practical parameters for exploration, including gold, alteration, host rock lithology and structure.

Some are noted and learned from, but not necessarily accepted as useful, robust, nor applicable to the Victorian Gold Province. As an example, there are a dozen recent definitions of an epithermal gold deposit, and some of the differences represent ad-hoc modifications over time. As applied to Palaeozoic rocks such as those in Victoria, the epithermal term is likely to generate some confusion and uncertainty.

A simple set of stages in the formation of a gold deposit (Fig. A5.1) becomes very useful for identifying those characteristics that are common across much of a gold province (e.g. fluid type, thermal perturbation) and those that vary between and within goldfields (host rock, structural setting, metamorphism, mineralogy; Phillips & Powell, 1993; Phillips, 1998). A set of guidelines for exploration of immediate practical value in the field can be developed from these figures (e.g. gold, alteration, lithology, structure, Figure A5.2).

One of the challenges in classifying gold deposits and erecting different styles is selecting the right level of detail: a system that is too broad will add little value, and a system that is too fine, in its extreme, needs a new substyle for each different deposit. In making a choice between these *lumpers* and *splitters*, the erring is on the side of the lumpers, and the result of this is shown in Figure A5.3.

Gold-only and gold-plus deposits

The primary subdivision used here relates to whether deposits produce gold alone, or are multi-commodity with co-product or by-product gold. This subdivision is discussed in Appendix 4.

Classification by host rocks

The secondary subdivision used for the dominant 'gold-only' group relates to the nature of the (main) host rocks of a gold deposit. The main examples are turbidite-hosted, and dyke-hosted, with subordinate granite-hosted.

Understanding the controls on some of the characteristics of gold deposits helps to select subdivision criteria. For example, the mineralogy of alteration zones reflects a combination of the auriferous fluid (potentially quite uniform), the host rock, the metamorphic grade, and in some studies is influenced by degree of weathering. As such, a high-level subdivision based on alteration mineralogy is likely to have difficulties and requires regular ad-hoc modifications.

In general, the uniformity that characterises the gold province is related to deep-seated processes, and the diversity between goldfields reflects features at or near the site of gold deposition (Phillips & Powell, 1993; Phillips, 1998). Structural geometry of mineralisation, host rocks, alteration mineralogy and weathering are functions of the deposition site.

Classification by age (and time of gold introduction)

In theory, subdividing deposits on their relative ages of formation is useful, but in practice this has proved one of the more contentious topics. Dating the age of gold mineralisation in any province is complex regardless of the accuracy of isotopic measurements, and in Victoria it is fraught with difficulties of field relationships, sampling, low metamorphic grade and fine-grained rocks, and interpretation. Perhaps the least equivocal

CLASSIFICATION TAG	BASIS	COMMENT
Gold-only	Negligible base metals	Simple, effective, usable
Gold-plus	Important co-products	Simple, effective, usable
Slate belt gold	Host sequence	Some generic use
Turbidite-hosted gold	Host sequence	Some generic use
Sediment-hosted gold	Host sequence	Means different things to different people
Shale-greywacke-hosted gold	Host sequence	Some generic use
Dyke-hosted	Host rock	
Intrusion-related gold	Broad spatial and genetic association	Poorly defined recognition criteria. Possibly not a distinct group at all
Orogenic	Synchronous with deformation, metamorphism	Broadly correct; covers many different ideas; some generic use
Epizonal/hypozonal	Based on depth and temperature of formation	Genetic basis is doubtful
Skarn gold deposit	Describes a mineral assemblage in a geological setting	Less useful, has undesirable genetic connotations
Epithermal	Originally defined by pressure and temperature range	Multiple definitions make current usage for older sequences prone to confusion

Table A5.1. Some of the classifications and names used to describe gold deposits.

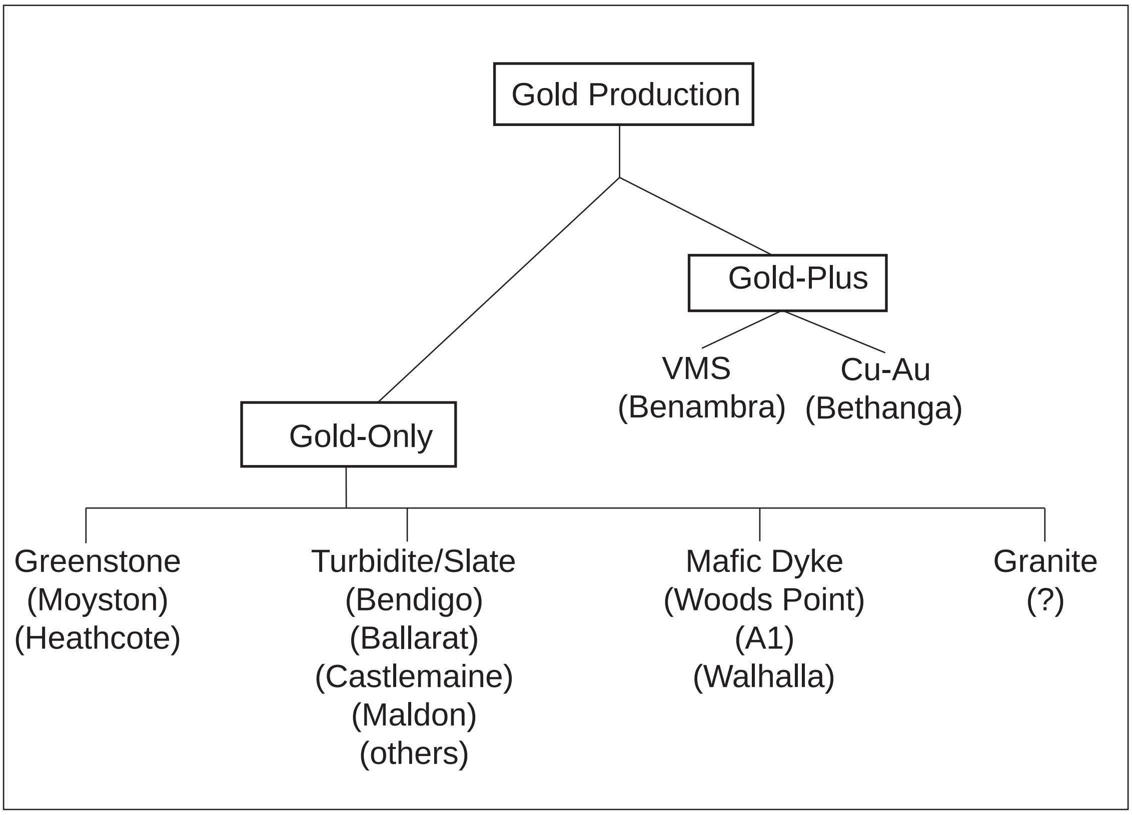

Figure A5.3. Simple goldfield classification system based first on commodity mix which reflects basic chemistry differences. Second-level classification is on host rock, and although not rigid or foolproof, this is useful because the host rock influences structure, mineralogy, grade and appearance of many ores. It is recognised that any mineralisation can cross host rock boundaries meaning that this lithological subdivision should not be applied too rigidly.

example of dating gold mineralisation in Victoria comes from field relationships involving mineralisation with granite plutons that are dated by Pb-Pb zircon (SHRIMP) methods: gold mineralisation either predates intrusion (e.g. Maldon, Hughes *et al*., 1997) or postdates it (e.g. Mafeking, Phillips, 1991; VandenBerg *et al*., 2000, p. 342). Some of the difficulties inherent in dating Victorian gold mineralisation arise from differences in interpretation of field relationships (Birch, 2003) or from using Ar-Ar (Re-Os) dating . Note that this *Guide* follows the latest timescale of Pogson (2009).

Thoughts on classifying different styles of gold deposit

Abstract from Metals and Exploration, towards 2000 Conference, Sydney Universities' Consortium Of Geology and Geophysics: Phillips, G N, Powell, R, 1992, Sydney.

Major gold provinces: lumpers and splitters

Over 80 percent of the World's primary gold (non-placer) has come from "gold-only" provinces defined as those in which gold is dominant over silver, copper, lead and zinc. Examples include the Witwatersrand of South Africa, Archaean greenstone belts, slate belts such as Victoria, and parts of epithermal provinces. Much of the remaining primary gold is won from gold - base metal deposits that include Au-Cu of the Proterozoic (Telfer, Trough Tank now Osbourne, Tennant Creek), volcanogenic massive sulphides, and Au-Ag systems in epithermal provinces.

In any single province, there is an enormous diversity of deposit characteristics, including host rock type, controlling structures, alteration mineralogy, ore orientation and associated mineralogy. Single mines can exploit ore from several different rock types, and from ore deposits of dramatically differing shapes. So widely acknowledged are these contrasts that the saying "Gold is where you find it" has evolved over time. However, such a saying does no credit to the enormous boost to exploration confidence that has followed successful or partially successful genetic models: at no time was this more obvious than in the 1980s especially in Australia.

Unfortunately, several classification systems for gold deposits focus on the differences, and whereas these are useful for mining, they help little in determining what the underlying causes of mineralization in a province may be. If we are to understand why some parts of the Earth's crust are extraordinarily mineralized (e.g. Victoria, Nevada), and others are not, then we need to look for the common features, rather than differences.

Features common to gold-only deposits appear to be their derivation from low salinity fluids, the ubiquity of some form of structural control, and contemporaneity between *times of elevated geothermal gradient, deformation and gold introduction.*

It becomes immediately clear that the features in common relate to crustal-scale phenomena, whereas the differences are much more local (i.e. the immediate depositional site). The features CRITICAL in a gold-only province are thus likely to be crustal in scale (e.g. not host rock, or specific structure).

Other classification schemes for gold-only deposits

Some genetic models of gold mineralisation have limited applicability to the Victorian Gold Province either because of inherent weaknesses, or they only apply to deposit types not found there. Six commonly invoked genetic models to account for gold formation are discussed here but they are unable to predict the auriferous fluid.

The continuum model, with implication of deposit formation throughout 25 km of crust, fails in high metamorphic grade domains where melting occurs, and the concept remains unsubstantiated at very low grades (Phillips *et al*., 2002). This renders the classification of gold deposits based on their depth of formation (the epizonal, mesozonal, hypozonal scheme of Gebre-Meriam *et al*., 1995), derived from the continuum model, of little use.

Syngenetic models involving gold enrichment on the seafloor invariably require elevated base metals and are more appropriate for gold-plus deposits where Cu, Pb and Zn are elevated, or even economic. Syngenetic and diagenetic models for Victorian gold face difficulties with fluid chemistry, with structural timing and in postulating remobilisation mechanisms.

Magmatic processes, in general, do not enrich gold strongly, and no magmatic model for gold-only deposits quantitatively predicts the fluid composition on goldfield, province and global scale. The lack of gold enrichment during most magmatic processes, the lack of significant gold deposits in Victorian granites, and the lack of diagnostic evidence being used to support a magmatic origin downgrades the likelihood of this postulate (see more detailed discussion in Hughes *et al*., 1997). Granite appears to have played no role in generating the source of gold or of the auriferous fluid, or the ultimate source of heat. Granite also does not present a particularly favourable host rock for fluid ingress, alteration or gold-only precipitation (note however, discussion of a Cadia-type target in Section 3.2.7).

Some Victorian occurrences have been identified as 'intrusion-related gold' but the class is not well defined in either what is meant by 'related' (e.g. source of fluids and metals, source of heat, or some form of geographic proximity), or what the special intrusion types might be, or even what process(es) might have led to gold-enrichment. So far, the identification of intrusion-related gold deposits has been by using non-diagnostic characteristics that are also found in many other gold types, e.g. spatial and temporal association with felsic rocks, sericite, sulphide, carbonate, tourmaline, Te, Mo, W and Bi-Cu (Bierlein & McKnight, 2005). None of the features are diagnostic of intrusion-related gold. Wonga deposit at Stawell has also been classified as intrusion-related, but the criteria being used to make the classification can all be found in many orogenic gold deposits (e.g. elevated Te, As, Mo, Bi, Se, Sb).

Epithermal gold mineralisation has been advocated for several deposits in northern Victoria including Fosterville and Nagambie (Ramsay *et al*. 1998 p. 141). An alternative interpretation of Fosterville as *weathered* opened up new opportunities at depth which have subsequently identified sulphide ores for a new mining operation (see Section 3.4).

The term 'disseminated gold deposit' has been used in the Victorian Gold Province literature to indicate a lack of quartz veining. In the case of Fosterville, the lack of quartz veins with mineralisation is a feature of the regolith only, and quartz veins are associated with primary mineralisation. Several of the Victorian examples described as 'disseminated' may be quartz-vein related beneath the weathered zone. Recent exploration around Nagambie has supported this strong change from 'disseminated' mineralisation in the upper regolith, to vein-related and/or structure-related mineralisation deeper down.

Mineralogical domains provide a descriptive subdivision of Victorian gold deposits based on ore mineralogy. Interpretation of what causes the difference between these domains is incomplete, but this does not prevent the subdivision highlighting some variations on the scale of tens of kilometres.

The Victorian goldfields are *orogenic* gold deposits (Böhlke, 1982) in that they are formed synchronous with regional deformation.

Scheme adopted for this report

The most suitable classification scheme of gold deposit styles depends very much upon the user. The miner will be interested in structures for stability, and mineralogy for rock hardness and abrasiveness; the metallurgist will be more interested in ore and gangue minerals and their physical and chemical properties; the economist will be interested in the overall gold grade and production costs. In exploration, understanding how deposits form is an early step in finding new ones, so gold genesis plays an important role in a classification scheme.

A major risk in developing a complex classification scheme is tying the scheme too much into a suspect geological framework (or one that might be revised). For example, schemes that are based on depth of formation (e.g. epithermal, continuum model) often require some sophisticated knowledge and reasoning to determine the depth, and there is always an inference that the inferred depth relates to gold introduction whereas it might reflect subsequent metamorphism.

In this *Guide*, the detail of classification is minimal and the primary grouping is gold-only, with a further emphasis on host sequence type and reference to the mineralogical domains. The gold-only grouping informs about deeper and regional characteristics common across a province (Phillips & Powell, 1993), and the host rock grouping and mineralogical domain inform on the deposit and mineralisation itself, and help to explain some of the diversity found within a province (Phillips, 1998).

Appendix 6: Metamorphic devolatilisation and the formation of gold deposits

Abstract from: On the importance of minding one's Ps and Ts: reflections on the past, present and future of metamorphic studies, Roger Powell conference at University of Melbourne, 11-12th June 2009, p. 17-18.

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A major goldfield of 1000 tonnes Au represents a substantial geochemical anomaly and poses some significant challenges in postulating a viable mode for its formation. The bulk of world gold production has come from gold-only ores in which gold is the main or only economic commodity. A viable genetic model for the gold-only ores needs to explain the strong segregation of gold from the much more crustally-abundant copper, lead and zinc, the extreme enrichment of gold by 3-5 orders of magnitude above its typical crustal abundance in most rocks of 1-2 ppb Au, the timing of mineralisation that is broadly synchronous with regional metamorphism as well as deformation (i.e. orogenic), and the occurrence of the larger goldfields within gold provinces that have dimensions of a few 100 km and include many tens or hundreds of large and smaller goldfields of broadly similar age, geological setting and relative metal concentrations.

A metamorphic devolatilisation model can explain the segregation, enrichment, timing, and character of provinces, and is developed here to explain the formation of gold-only deposits in three broad stages, i.e. the source of auriferous fluid, its migration, and the deposition of gold from this fluid.

The main part of the crust where the raw materials for fluid – H_2O and CO_2 – are present in abundance is in greenschist facies rocks, and sited in hydrous minerals including chlorite, and carbonate. When such rocks are heated further, they devolatilise, and the resulting fluid passes upwards in the crust, having the capacity to mineralise at shallower levels. The fluid is generated across the greenschist to amphibolite facies transition.

Importantly, a single process liberates H_2O, CO_2, S and Au from the source rock to generate the auriferous fluid. As this process operates on a grain-by-grain scale, it is highly effective in extracting not just H_2O and CO_2 but also S and, in turn, gold. Elevated gold concentration in solution is achieved by complexing with the reduced S, and by H_2CO_3 weak acid buffering near the optimal fluid pH for gold solubility. Favourable redox conditions for gold solubility are maintained where reduced sulphur and oxidised carbon (CO_2) species co-exist. The low salinity of the metamorphic fluid ensures low base metal concentrations in the fluid. This single extraction process differs from other genetic models where a fluid is generated somewhere else, then migrates to a volume of crust from which it may extract gold.

Migration of the auriferous fluid is initially via grain boundaries. At least minor strain is implied in this model as compaction of the rock is involved in the fluid departing the source. Subsequent migration is by shear zones and/or hydraulic fracture zones in rocks of low tensile strength. It is the geometry of the shear zones that ultimately dictates the kilometre-scale fluid migration paths and degree of fluid focussing into small enough volumes to form economic deposits.

Deposition of gold from the solution necessitates breakdown of the gold-thiosulphide complex and is especially facilitated by fluid reduction in contact with reduced carbon bearing host rocks and/or sulphidation of wallrocks to generate iron sulphides and gold. As such, black slate, carbon seams, banded iron formation, tholeiitic basalt and differentiated tholeiitic sills are some of the important hosts to major goldfields. Where the host rock is of suitable bulk composition, carbonation, sulphidation and muscovite/biotite alteration accompany gold. A primary role for fluid mixing, temperature decrease and/or fluid pressure decrease and boiling in gold deposition is not well established. The well-known correlation of gold with rock type argues for rock dominated systems, rather than fluid-dominated ones.

Essential factors in the devolatilisation model for gold-only deposits are hydrous source rocks with carbonate and sulphide components, and a thermal perturbation. Useful factors that favour larger goldfields and provinces include above average initial gold contents, focussing of structures, and Fe and/or C bearing host rocks. The largest goldfields appear to reflect the optimisation of several of these factors.

Much of what is seen and recorded at gold-only deposits today reflects subsequent modifications to this generic metamorphic devolatilisation process. Overprinting by deformation and higher grade metamorphism, and/or (palaeo)-weathering account for many of the most-obvious features of deposits including their mineralogy, geochemistry, geometry, small-scale timing features, and even mesoscopic gold distribution.

Appendix 7: Illite crystallinity work in metamorphic petrology

Muscovite crystallinity, expressed as a Kübler index, varies with metamorphic grade and other geological parameters. The b_o spacing of the muscovite lattice varies as a function of temperature and pressure, so that if temperature is known it may provide an estimate of pressure. In general, these are not particularly quantitative methods for determining metamorphic grade as they are not well calibrated and are influenced by several parameters that are mostly poorly known (e.g. temperature). Trends across a terrain may be useful but absolute T and P are generally associated with unconstrained errors. For this reason, muscovite crystallinity is not a method of first choice in metamorphic petrology, but rather one of last resort when other options are limited.

For the Lachlan Fold Belt in Victoria, muscovite (illite) studies have been reported by Offler *et al*. (1998) and Wilson *et al*. (2009). Kübler indices range from 0.20–0.25 in the Stawell Zone and 0.25–0.35 in the Bendigo Zone indicating higher temperatures in the Stawell Zone, compatible with the occurrence of metamorphic biotite and schistose fabrics there. A few values in the Melbourne zone range from 0.23 to 0.33 (Wilson *et al*., 2009). These two studies do not independently verify one another except in a general sense, they leave a little uncertainty as to the amount of weathering of the samples measured, and come to different conclusions on fault movements. The detailed regolith work of Radojkovic and Bibby (2003; Appendix 8) may help to explain some of the uncertainties.

One of the very few gold provinces in which muscovite crystallinity can be calibrated against independent metamorphic mineral assemblages is the Witwatersrand goldfield (Phillips & Law, 1994). Here, weathered samples were excluded by collecting from within mines from 2 to 4 km below the surface. The chloritoid–pyrophyllite–chlorite–quartz assemblage constrains temperatures to: Blyvooruitzicht (330–370 °C and Kübler Index = 0.20–0.32, with adjacent Western Deep Levels 330–370 °C and KI = 0.21–0.32), Cooke (370 °C and KI = 0.21) and West Rand (380 °C and KI = 0.19-0.21; Phillips *et al*., 1997). Calibrating the Victorian data against the Witwatersrand data suggests Stawell zone temperatures around 350–370 °C, Bendigo zone and western Melbourne Zone probably 330–350 °C.

It is suggested that the regional metamorphic temperature estimates of Offler *et al*. (1998) may be slightly low, those of Wilson *et al*. (2009) east of the Whitelaw fault may be slightly low, and the large area of diagenetic and unmetamorphosed rocks in the Melbourne Zone may be greenschist facies (> 300°C) but now with kaolinite formed by weathering. The muscovite pressure estimates are probably associated with significant errors.

Appendix 8: Regolith in the Ballarat goldfield

A regional regolith study of the Ballarat area

The Ballarat–Creswick area provides some interesting information about the behaviour of muscovite in the regolith (Radojkovic & Bibby, 2003), and perhaps suggests a different interpretation of illite crystallinity and weathering. During mineralogical determination of soil samples from the Ballarat area, Radojkovic & Bibby (p. 31) detected a change from "...highly crystalline illites/muscovites in the C-horizon samples, and the apparent dominance of the less crystalline smectitic and kaolinitic clays in the A and B1 horizons". They also noted intermediate crystallinity for B–C horizon samples. Such results collected by PIMA may not have the sensitivity of X-ray diffraction, but they do suggest strong mineralogical and crystallinity variations in the regolith over the Ballarat East goldfield. Hence, samples collected from different positions of the regolith at any single location might themselves have considerable variability.

In many ways, the Ballarat results confirm what might be expected—that there is some change in mica crystallinity brought about by weathering. The weathering of turbidites in central Victoria involves the removal of K from rocks and conversion of muscovite to illite and eventually to kaolinite. Thus the loss of K should lead to changes in the crystallography of the white mica and this might modify its crystalline state inherited from metamorphism.

Appendix 9: New evidence from the Victorian Geotraverse and seismic lines

A geotraverse across northern Victoria has added considerably to the understanding of the region's crustal architecture and geological evolution, and confirmed much of the mapping and recent geologic interpretations. The Victorian Geotraverse has built a multi-disciplinary synthesis around a deep seismic traverse (Cayley *et al*., in prep.; Willman *et al*., in prep.) supplemented with new geophysical data, and complementary studies that include Palaeozoic to Quaternary geology, gold geology and igneous petrology (see Phillips & Ely, 2003).

The seismic survey comprises four overlapping lines totalling 400 km, and images parts of the Stawell–Ararat, Landsborough–Percydale, Ballarat and Costerfield mineralogical domains, and the Stawell, Bendigo, Melbourne and Tabberabbera structural zones. The scale of the four lines and of the supporting Geotraverse components are ideal for understanding features at district to regional scale including the major structures, mineralogical domains, granites, vertical ordering of rock packages, structural zones, and the Victorian Gold Province itself. The seismic lines have confirmed many previous ideas based on field mapping and geophysical interpretation, but have thrown a new light on other unresolved problems. Importantly, they confirm the positions and dip directions of major faults (Moyston, , Avoca, Mt William, Governor faults) and indicate that these faults flatten with depth somewhat less than had been predicted. The results also do not show any major faults or folds converging on larger goldfields such as Bendigo—again supporting the mapping. The seismic results shed a new light on the thickness of the upper package of turbidites and on that of the underlying inferred mafic rocks beneath the Bendigo structural zone. It also reveals the probable presence of the Selwyn Block beneath and adjacent to the Melbourne structural zone. This confirmation makes it much more likely that the Geotraverse data will be used in exploration, and gives confidence in the whole Victorian geological framework.

The seismic traverse clearly identifies the Moyston Fault as a major east-dipping structure, with rocks of different character—the older, Delamerian Fold Belt—west of it. This is consistent with the interpretation of the Moyston Fault having 10–25 km of offset prior to the Devonian based on metamorphic pressure estimates (VandenBerg *et al*. 2000). The traverse also shows the Landsborough, Percydale, Avoca, Muckleford, Whitelaw, Fosterville and Mt William faults as significant west-dipping structures across the Stawell and Bendigo structural zones. As previously predicted from mapping, the faults are strongly listric, dipping steeply near the surface (60–70^{o}) and then more gently at depth. These continue to approximately 15–30 km depth before terminating against the Moyston Fault. This interpretation differs from previous interpretations that had the west-dipping faults flatten at the base of the turbidite package on a décollement above mafic rocks. West-dipping structures are also identified in the Melbourne structural zone, and the boundary with the Tabberabbera structural zone is confirmed as the gently north-dipping Governor fault.

There is a significant difference in the crustal package being inferred at depth along the seismic traverse. In the Stawell and Bendigo structural zones, an upper layer of sedimentary rocks overlies a lower layer of interleaved volcanic and sedimentary rocks (Willman *et al*., in prep.). The upper package in the Stawell and Bendigo structural zones is 15 km thick in the west, thickening to over 30 km beneath the Ballarat–Bendigo districts where a considerable thickness of mafic rocks is inferred (Cayley *et al*., in prep.). The Melbourne structural zone, in contrast, appears to have a multi-layered crustal structure of Palaeozoic rocks deformed by thin-skinned tectonics above a Proterozoic basement (the Selwyn Block). These interpretations have been extended northward under the Murray Basin and into New South Wales using teleseismic tomography (Rawlinson *et al*., 2008).