Contents

NewGenGold 2021
Perth, Western Australia
November 9 - 10

Victoria – Laying the groundwork for an integrated systems approach to tectonics and mineralisation

Ross Cayley (presenter), Cameron Cairns

Geological Survey of Victoria

1/17 Spring St, Melbourne, Victoria, Australia, 3001

Contact:

Ross Cayley, Senior Geologist

Geological Survey of Victoria

1/17 Spring St, Melbourne, Victoria, Australia, 3001

Ross.Cayley@ecodev.vic.gov.au

Abstract

Victoria's goldfields have produced ca. 80 moz of gold. A significant proportion of production has been from hard rock orogenic gold deposits. Three regional deep 2D seismic reflection surveys acquired by the Geological Survey of Victoria (GSV) and collaborative partners in 2006, 2009 and 2018, have delivered a 1,278km traverse of the Delamerian and Lachlan orogens. The result is a geological systems (crustal-scale) workflow that has led to a paradigm shift in understanding the geological architecture of Victoria and south-east Australia and an improved predictive capacity for mineral systems, including orogenic gold deposits. Victoria's deep seismic surveys have been meticulously planned in the areas of best bedrock exposure and control, most of which was determined during a period of new generation geological (structural) mapping in the 1990s and early 2000s. The benefit is that well established geological relationships and overprinting criteria can be applied, which reduces ambiguity in the interpretation of the seismic data. The new generation mapping benefited from the integration of modern statewide potential field geophysical datasets, which allowed the informed interpretation from the seismic reflection data to be extended into areas of poor exposure and resulted in value-add outputs such as regional 3D models. The pre-competitive datasets and applied geoscience research undertaken has directly contributed to a renaissance in mineral exploration, investment, and discovery in Victoria. This paper and presentation will outline the motivation, strategy and workflow for regional deep 2D seismic reflection acquisition, and provide an insight into key results of the applied geoscience research program, including how the deeper understanding of Victoria's geological architecture has improved mineral exploration targeting, particularly for orogenic gold, including in the northern extensions of the Bendigo, Stawell and Melbourne zones where simulations predict that there may be an estimated 75 moz of gold yet to find under cover. Ongoing exploration and production success, including at the world-class Fosterville gold deposit, suggest that there may be significant upside in relatively shallow historical gold workings of forgotten goldfields, especially in light of an improved geological systems understanding.

Introduction

Victoria is currently experiencing unprecedented mineral exploration activity with A$183.8 million spent on mineral exploration in FY2021, which accounted for almost 6% of the national mineral exploration spend from just 3% of Australia's land mass. Victoria's growth in mineral exploration spend has outpaced the national trend during multiple quarters in recent years (Figure 1). A significant proportion of Victoria's surge in exploration spend has and remains focussed on orogenic gold. Exploration drill metres have increased more than 300% from FY2015 to FY2021, with more than 400,000m completed in FY2021. More than half of the exploration drilling in FY2021 was completed on exploration/retention licences, which is the first time since FY2015 that early-stage exploration drilling has exceeded exploration drilling on mining licences. The amount of diamond drilling on exploration and retention licences has been increasing since FY2015 and comprised almost half of the total metres in FY2021. The surge in mineral exploration investment has resulted in many new inbound domestic and international explorers with an appetite for drill testing targets generated by modern geochemical and geophysical surveys.

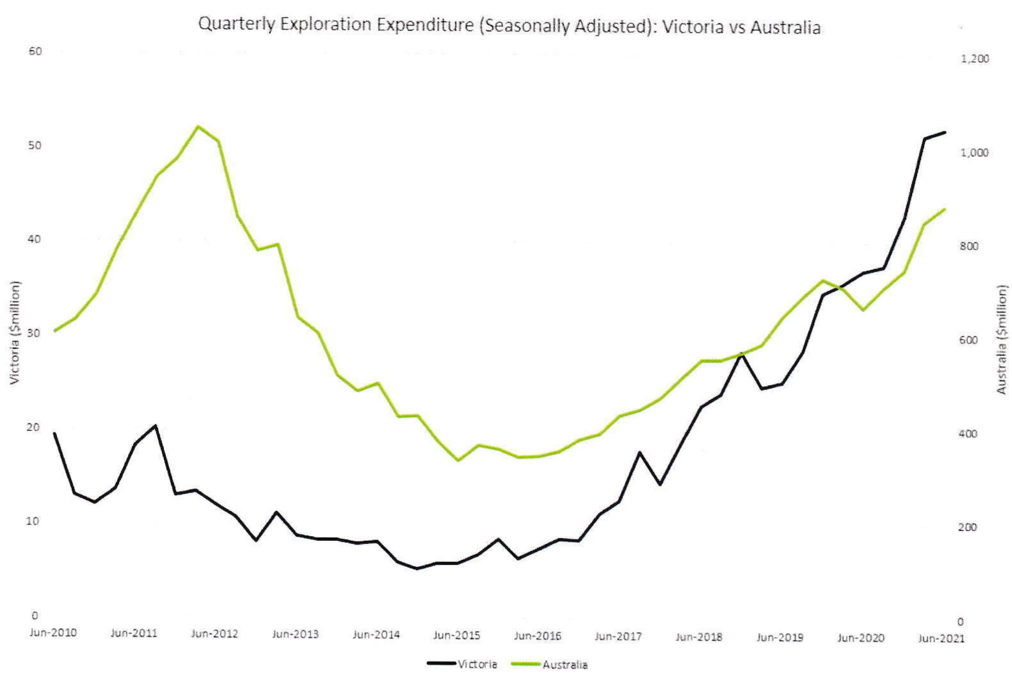

Figure 1: Exploration spend for Victoria and Australia. Source: Australian Bureau of Statistics

The resurgence of gold exploration in Victoria follows the discovery in 2016, 800m from surface, of the Swan Zone at the Fosterville gold mine in north-central Victoria (Figure 2). In 2017 the reporting of an intersection of 15.15m @ 1,429 g/t Au from a depth of 345.55m in diamond drill hole UDH1817 stunned the global mineral exploration and investment community. This was the best reported gold equivalent intersection for any commodity in the world for the year (RSC, 2017). At the end of 2018, the Swan Zone hosted an impressive mineral reserve of 2.34 moz @ 49.6 g/t Au, while remaining open down-plunge (Verity et al., 2019). Development of the Swan Zone resulted in annual production of 619,366oz @ 39.6 g/t Au (98.8% recovery) at Fosterville for 2019 followed by 640,467oz @ 33.9 g/t Au (98.9% recovery) in 2020 (Kirkland Lake Gold Inc., 2021). Recent exploration and production success at Fosterville has transformed a marginal asset within a goldfield of very modest historic oxide production (28,000oz Au 1894-1903) into one of the highest grade, lowest cost underground gold mining operations in the world. At the end of 2020 Fosterville marked approximately 8.8 moz production from a current endowment of almost 12.5 moz (Edgar, 2021, Kirkland Lake Gold Inc., 2021). The growth of Fosterville has highlighted the potential of Victorian orogenic gold deposits, especially following some high-profile setbacks after unsuccessful attempts to sustain modern production at the famed Bendigo (26 moz) and Ballarat (12 moz) goldfields in the late 1990s/early 2000s, where coarse-grained gold has proven difficult for resource estimation (e.g., Dominy, Platten & Raine, 2003).

However, this 'overnight success' was 165 years in gestation, underpinned by the vast 19th century gold production from Victoria (e.g., Phillips et al., 2003, Mudd, 2007) and the latent potential of the geology, but leveraged off advances in modern geoscience. In some ways, 2016 finally delivered on the promise of 25 years of systematic geoscience data acquisitions and systems analysis of Victoria, within the context of south-east Australia's geological evolution. Geological systems understanding has crossed a modern threshold in Victoria to deliver sufficient predictive capability to renew the confidence to invest in the search for extensions to historic goldfields and for new discoveries within a world-renowned gold province (Figure 2). Victoria was Australia's top ranked jurisdiction by gold production until as recently as 1987, when overtaken by Western Australia (Mudd, 2007), although the production grade of Victoria's deposits remains superior when Australia's two premier orogenic gold provinces are compared (Figure 3).

This paper very briefly outlines of the history of gold exploration and production in Victoria, some of the reasons resulting in the stagnation of the industry for over 100 years following early spectacular successes, before focussing on the scientific rationales and the applied geoscience research, including methodologies and key findings, by the Geological Survey of Victoria (GSV) and co-workers that have contributed to its recent revival.

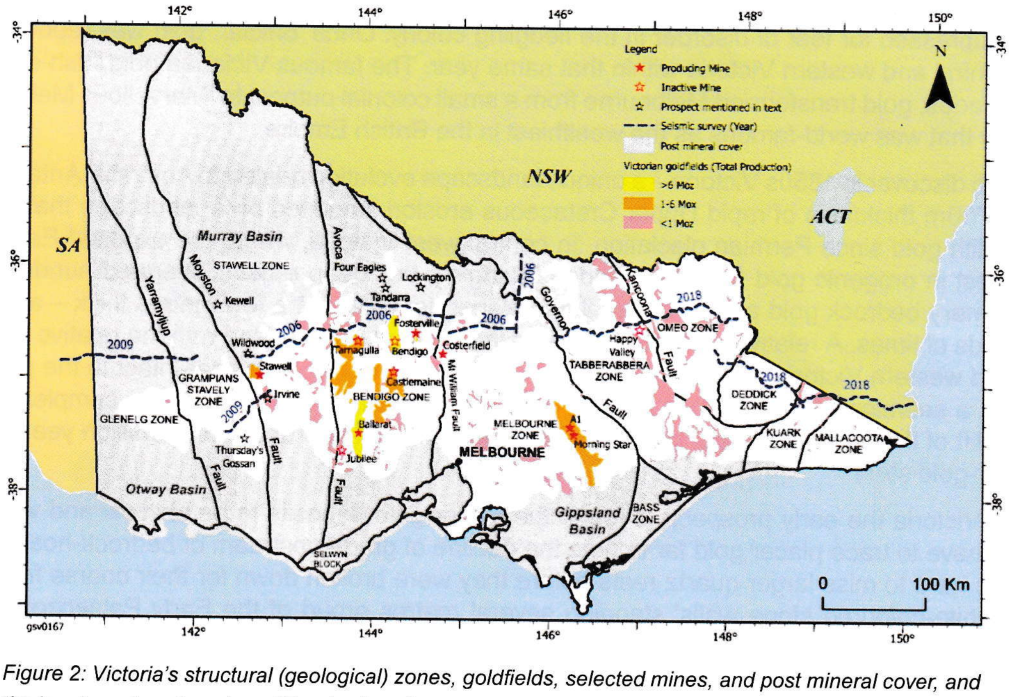

Figure 2: Victoria's structural (geological) zones, goldfields, selected mines, and post mineral cover, and the location of modern deep 2D seismic reflection transects designed to investigate the geology of the Delamerian and Lachlan orogens

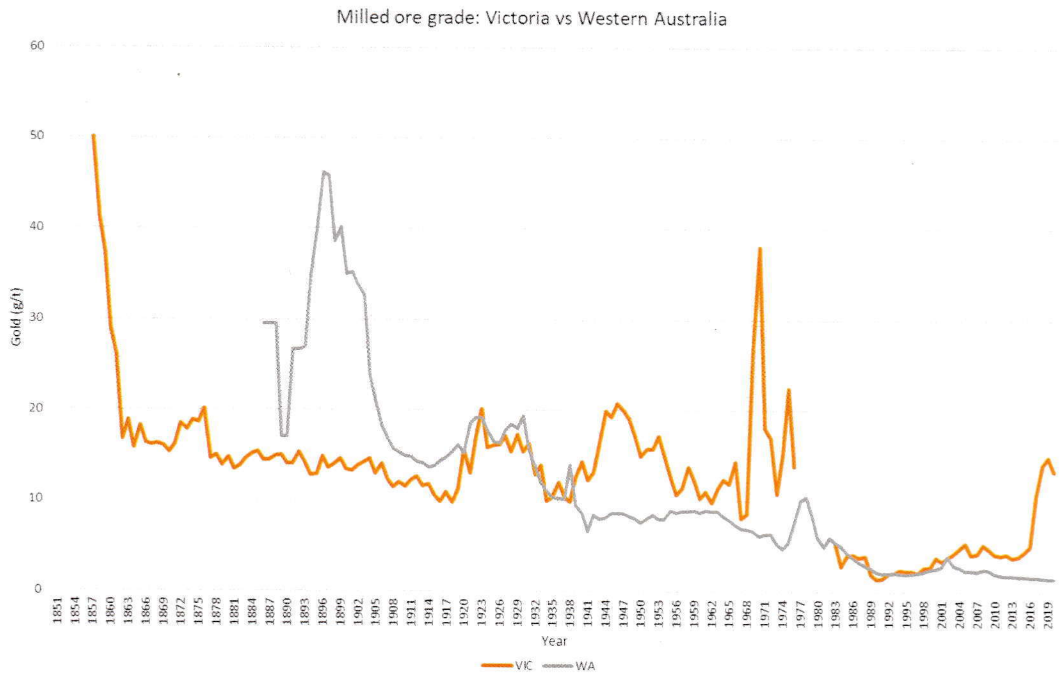

Figure 3: Milled ore grade, Victoria and Western Australia since gold discovery and production (Mudd, 2007, Mudd, unpublished)

Victoria – Discovery and early development of a world-renowned gold province

The official discovery of gold in Victoria was in 1851 at Clunes 117km north-west of Melbourne. Numerous accounts exist of 'unofficial' earlier (1840s) gold discoveries by European settlers as they moved into central Victoria, but they were supressed for fear of disorder in the fledgling colony. Once 'official', gold was reported from locations all over central and western Victoria within that same year. The famous Victorian gold rush era had begun. In just a few decades, gold transformed Melbourne from a small colonial outpost to 'Marvellous Melbourne', a vast multicultural city that was world-famous as the wealthiest in the British Empire.

Gold was easy to discover in 1850s Victoria – a unique landscape evolution related to Australia-Antarctica breakup included up to 700m thickness of rapid Upper Cretaceous erosion, imposed on a landscape that had likely accumulated regolith gold since Permian glaciation. In central-west Victoria, where the exposed Early Palaeozoic bedrock is richest in orogenic gold (i.e., the 'Golden Triangle'), this deep erosion liberated hundreds of metres thickness of primary bedrock gold and reworked it into placer deposits just a few metres thick – a concentration factor of hundreds of times. A relatively dry climate since the Palaeocene coupled with the relative tectonic stability of central and western Victoria has preserved these ancient placer deposits near-intact to the present-day. In eastern Victoria a seemingly lesser overall primary gold endowment, coupled with more complex, rejuvenated, and ongoing uplift of the Australian Alps, including throughout the last approximately 7 million years, has complicated the placer-gold story.

In central-west Victoria the early prospectors found the placer gold deposits to be shallow and very rich. Prospectors did not have to trace placer gold far to note the decline of grade upstream of bedrock-hosted quartz reef positions. It was hard to miss larger quartz reefs before they were broken down for their coarse free gold – they appeared as 'white-coloured stone walls' standing several metres proud of the Early Palaeozoic sedimentary host rocks. The quartz reefs were chased progressively deeper in a transition to small-scale open-cut and then underground hard rock reef mining.

The alluvial miners also followed the shallow placer deposits downstream noting their persistence beneath younger cover rocks as 'Deep Leads', buried ancient river courses that were mined using underground methods. 'Deep Lead' placer gold production rivals and sometimes far exceeds that won from hard rock sources, for example in goldfields like Ballarat, Ararat, Beaufort, and Myrtleford. Where this historical production discrepancy exists, it may be an indicator of unrealised primary gold discovery. A common theme across all the Victorian goldfields was the rapid depletion of shallow, easily won gold, and rapidly rising development and production costs in increasingly deeper mines working increasingly speculative geology.

Victoria's orogenic gold deposits

While the riches of Victoria's alluvial gold occurrences are well established, and intrusive-related gold occurrences (including historical production) are known, the focus of this paper is hard rock orogenic gold, it's form, location and distribution. This paper uses the scale of Schodde (2021) for gold deposit size: giant (>6 Moz), major (1-6 Moz) and moderate (<1 Moz) based on ounces produced. Endowment is noted where it is known and relevant.

The folded and faulted Cambro-Ordovician deep-marine sandstone and shale (turbidite) stratigraphy that hosts the bulk of Victoria's orogenic gold is extensive throughout eastern Australia from north Queensland to eastern Tasmania, yet only a relatively small part of central-west Victoria is currently known to host giant (e.g., Bendigo, Fosterville) and major (e.g., Stawell, Ballarat, Castlemaine, Walhalla) orogenic gold deposits. Moderate deposits occur across Victoria's geological/structural zones with production from deposits such as Costerfield (total production: ca. 813,000 oz: endowment ca. 1.28 oz Au or 2.4 Moz AuEq – end 2020), which is also Australia's largest producer of the critical metal antimony. Exploration of relatively shallow workings associated with moderate deposits in many of Victoria's historical goldfields is increasing as explorers search for the next Fosterville.

One of the big challenges of Victorian orogenic gold – discussed throughout this paper – is that the monotonous Early Palaeozoic folded low-grade metamorphosed sandstone and shale (and minor meta-igneous) host bedrock for known gold deposits and prospects, is virtually no different in appearance, lithology, age, metamorphic grade or structure (or geophysical characteristics) to adjacent non-mineralised rocks. Thus, it has proven very difficult to understand why the giant deposits (e.g., Bendigo, Fosterville) are where they are. Although this has always tended to focus exploration interest in the Bendigo Zone, without being able to understand exactly what localises the known goldfields, it has been near impossible to predict where undiscovered goldfields may be located, especially under post mineral cover. Complicating this is that alteration haloes associated with Victorian orogenic gold systems are subtle, narrow, and were not convincingly spatially and genetically linked to gold mineralisation until very recently (e.g., Arne et al. 2016). Even so, it remains possible to drill metres from a bonanza-grade ore shoot in central-west Victoria and remain unaware of the possibility of its existence.

Across the Bendigo Zone the commonality of low-grade metamorphosed sandstone and siltstone host bedrock and upright fold-dominated structure punctuated by west-dipping thrust faults within an area of common structural history means that most orogenic gold deposits look similar in cross section – maximum dilation occurs where fault segments have a locally low dip-magnitude, which generally occurs where a fault cuts across bedding with opposing dip (Figure 4). Because most faults dip west, dilation zones generally occur in the east dipping limbs of anticlinal closures, a relationship seen at Ballarat, Bendigo, Castlemaine, Fosterville and more recent discoveries under cover (e.g., Lockington and Four Eagles). In some places, including Bendigo, some quartz reefs in thickly bedded sandstone appear to have formed where more symmetrical, bedding-parallel faults converge towards pre-existing anticlinal closures. 'Saddle-shaped' zones of upwards dilation are centred on the anticlinal crests. In places these are multiply repeated down a single fold axis to depths >1,400 m (e.g., Hustler line of reef). The low dip-angles and upward-opening characteristics of the main ore shoots across the Bendigo Zone in particular, indicates opening during horizontally directed compression (transpression) with a vertically oriented minimum stress tensor. This stress condition is broadly consistent with the geometry of the upright folds that host the mineralised structures – the difference in appearance is due to the contrast in ductile and brittle strain regimes.

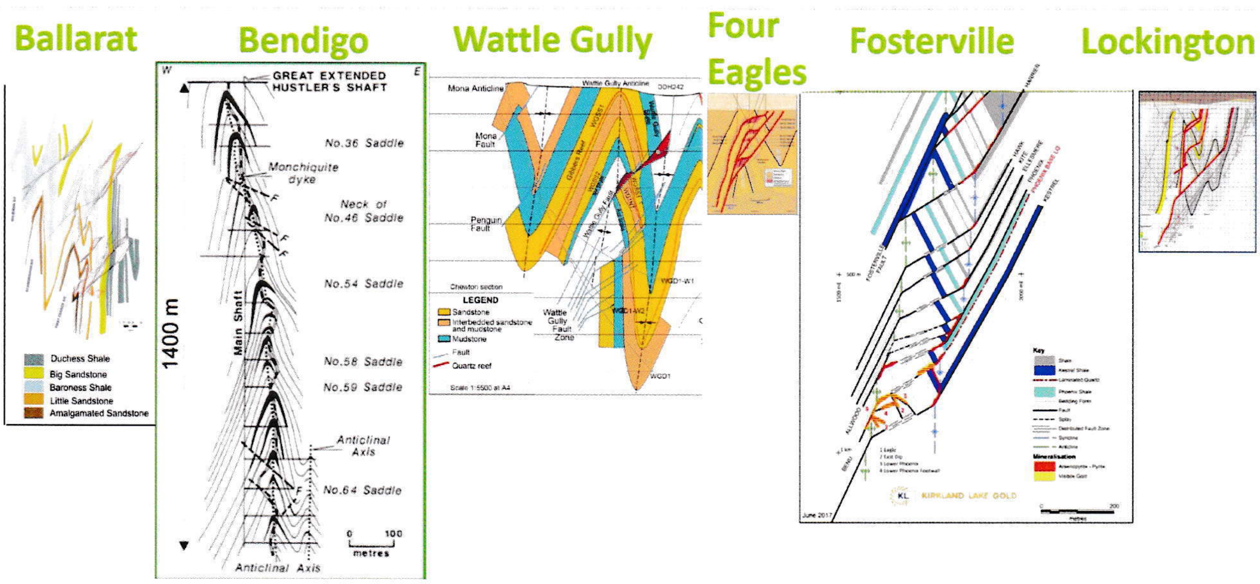

Figure 4: North-looking cross-sections at similar scale for selected mines at Ballarat (LionGold Corp, 2014), Bendigo (Herman, 1914), Castlemaine (Wattle Gully; Arne et al., 2016), Four Eagles (Charlton, 2019), Fosterville (Kirkland Lake Gold Inc., 2018), and Lockington (Goldfields, 2007)

Three orogenic gold events are currently recognised in Victoria: 455–440 Ma Benambran Orogeny (Stawell and early mineralisation in the Bendigo Zone), 420–410 Ma Bindian Orogeny (significant additional mineralisation at Ballarat, Bendigo and Fosterville), and 385–370 Ma Tabberabberan Orogeny (Costerfield and a second, bonanza event at Fosterville) (Wilson et al., 2020). Most rocks old enough to have experienced the orogenic gold events in Victoria often host mineralisation (e.g., Cambrian mafic igneous rocks at Stawell, Ararat, Avoca and Heathcote and the Ordovician sedimentary succession). Most granite rocks in Victoria are too young. Where fault reactivations associated with gold mineralisation are younger than granite, orogenic gold is known (e.g., Stawell Granite beneath the Great Western placer goldfield), although none have been associated with significant historical production. The Ordovician sandstone and siltstone units may be the most common host rock simply because the widespread sequence is common and of sufficient age to have been exposed to multiple deformations and orogenic gold events.

The multi-million-ounce Swan Zone, currently the highest-grade mineralised zone at Fosterville, with a reserve grade of more than 1 oz/t Au, is 2-5 m wide, dips west and is currently defined over 275m of strike and a vertical extent of 200 m (Kirkland Lake Gold Inc., 2021). The dimensions highlight how easy it could be to miss an extraordinary rich occurrence like this, especially considering the monotonous nature of the Ordovician metasedimentary sequence and limited wallrock alteration. Historic production profiles and current exploration results hint at the latent potential for brownfields discoveries in Victoria's goldfields. Poverty Reef at Tarnagulla, near the central-west margin of the Bendigo Zone, is where, despite incomplete production records, very high-grade gold is associated with transpressional strain to form steep plunging shoots with unexpected geometries in places (e.g., Bonanza Shoot ca. 360,000oz @ 92 g/t Au, Nick O'Time Shoot 53,000oz @ 29.1g/t Au, Krokowski et al., 2001). The intersection in mid-2021 of very high vein hosted gold (e.g., 11.10m @ 160.45 g/t Au from 190.40m downhole including: 0.60m @ 2,430 g/t Au from 190.40m and 3.00m @ 126 g/t Au – E79 Resources, 2021) beneath relatively shallow historical hard rock workings at the Happy Valley goldfield near Myrtleford, in the northern Tabberabbera Zone, is also testament to the potential for new high-grade discoveries in Victoria's forgotten goldfields.

The geology of the Stawell goldfield in western Victoria differs from the common 'slate belt' hosted gold. The Stawell deposit (ca. >4 Moz) is located in the outer hangingwall of a highly-deformed, crustal-scale east-dipping thrust fault, the Moyston Fault (Cayley & Taylor, 2001, Cayley et al., 2011). The uplifted fault-hanging-wall geology includes large – up to multi-kilometre scale – steeply dipping, northerly-trending masses of Cambrian-age MORB-style metabasalt, fault-intermixed with metamorphosed sandstone and siltstone reminiscent of the central Victorian goldfields (Watchorn & Wilson, 1989). The steep sided kilometre-scale metabasalt dome at Stawell is known as the Magdala Antiform and the contrast in the rheology of this elongated mass of competent rock with the surrounding weaker metasediments has resulted in strain partitioning and dilation and the introduction of mineralised quartz veins into shear zones developed systematically along and above the antiform flanks (Figure 5). It was the predictability of the geology at Stawell that allowed almost thirty years of continuous operation after reopening by WMC in 1981, following careful research and systematic exploration, with mining reaching a depth of 1,600m. The distribution of the very different rock types can be imaged in geophysics, which was significant in arguably the first modern orogenic gold discoveries under Murray Basin cover in Victoria (e.g., Kewell, Wildwood, etc). However, like the Bendigo Zone the Stawell Zone is host to brownfield exploration opportunities. The Irvine discovery in late 2016, located in the Ararat goldfield approximately 20 km south of the Stawell deposit, is the first maiden (non-production) orogenic gold resource (304,300oz Au, Navarre Minerals, 2021) in Victoria for approximately two decades with the area exhibiting the same rock types and structural framework associated with the Stawell deposit (Cayley & Taylor, 2001).

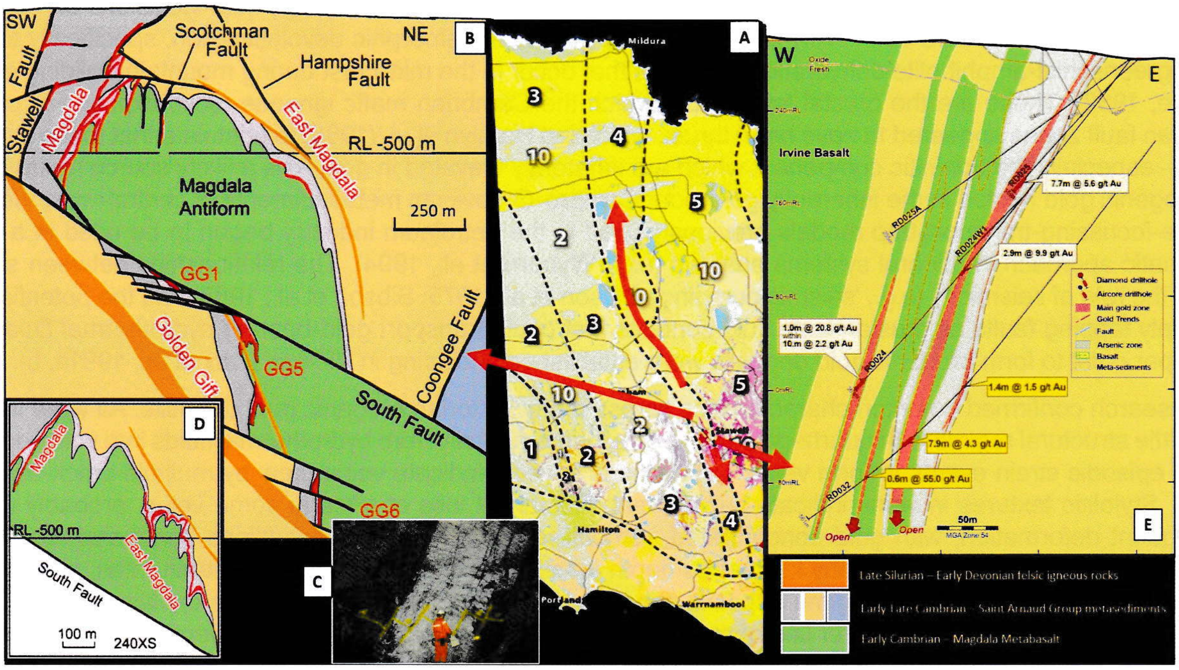

Figure 5: Western Victorian portion of the Mineral Systems Map of Victoria (GSV, 2014); (A) showing the location of the Stawell Goldfield in the 'Greenstone gold mineral fairway' (4) just east of the Moyston Fault. The Stawell Goldfield is centred on the Magdala 'Antiform', a north-plunging dome of competent metabasalt (B) with mineralised shear zones developed along and adjacent to its flanks, such as the multi-million ounce Magdala 'Central Lode System' (C). Mined to below 1600m, near 'Big Hill' the basalt crest narrows and rises to surface and shear-hosted mineralisation along the lobed eastern flank is the target of current operations (D); South of the Stawell Granite, similar geology hosts similar mineralisation, such as 'Resolution Lode' in the Irvine deposit (E). The 'Greenstone gold mineral fairway' is in the Moornambool Metamorphic Complex (Cayley & Taylor, 2001) a poly-deformed accretionary complex in the Moyston Fault hanging-wall – this is continental-scale, so potential exists for multiple repeats of this mineralisation style along the entirety of this structure in Victoria (indicated by additional red arrows). Image credits: Kirkland Lake Gold Inc. Ltd Can. NI 43-101 report 2016; Navarre ASX announcement 23 /12/2020

Growing understanding of Victoria's orogenic gold using the mineral systems 'source-focussing-transport-trap' approach

The 1980's was a significant time for geoscience with technical developments of that time laying important foundations for subsequent more effective orogenic gold exploration in Victoria. Definitive research on thrust-fault systematics (e.g., Boyer & Elliot, 1986), linkage of map-scale structure to plate-tectonic processes, and advances in geochemistry and sedimentology all led to a complete reappraisal of the tectonic setting of the Palaeozoic rocks in Victoria, including those hosting goldfields. It was recognised that the folded deep marine Cambro-Ordovician sandstone and siltstone belts of low metamorphic grade could be the conformable upper stratigraphy of allochthonous Early Cambrian oceanic terranes (VandenBerg, 1992) accreted to the eastern edge of Gondwana either by subduction processes (e.g., Crawford & Keays, 1978), or by involvement in continental collisions (e.g., Fergusson et al., 1986). This new insight replaced earlier, autochthonous, in-situ 'basin'-style interpretations.

Thus, northerly-trending belts of upturned Early Cambrian mafic igneous rocks exposed in central Victoria were reinterpreted as west-Pacific-style intra-oceanic arc and MORB-style oceanic volcanics (Nicholls 1965; Crawford & Keays, 1987), thrust to surface along major northerly-trending Late Ordovician fault systems that accompanied accretion (Gray et al., 1991). This work confirmed a clear distinction between the gold-poor Delamerian Fold Belt rocks of far west Victoria with links to the Neoproterozoic- Early Cambrian Gondwana passive margin of South Australia and late Cambrian orogenesis, and the gold-rich Cambro-Ordovician Lachlan Fold Belt rocks of central-west Victoria with evidence of oceanic provenance and no Cambrian orogenesis.

A rough first-order criteria for targeting orogenic gold exploration – Cambrian Gondwana 'not so good'; Lachlan Fold Belt oceanic 'good' – was emerging, but it had limitations – for example, Stawell Zone rocks, including the Stawell goldfield, were involved in Cambrian (Delamerian) orogenesis yet shared lithological similarities and oceanic provenance with the Lachlan Fold Belt. Interestingly, no Cambrian-age orogenic gold has been documented at Stawell – the earliest phase of deformation and crustal thickening was apparently unmineralised. The gold mineralisation at Stawell was introduced later during a structural event dated at ~440 Ma similar to the age of the earliest deformation and first phase of gold mineralisation hundreds of kilometres further east at Bendigo and Ballarat.

Also in the 1980's, theoretical studies underpinned by observation of (low salinity) fluid-inclusions and quartz-reef mineralogy and texture definitively linked orogenic gold to metamorphic devolatilization, specifically to prograde greenschist-amphibolite dehydration reactions that occur in the mid-crust during mountain-building events (Bohlke, 1982). These are the crustal levels from which the Cambrian mafic igneous rocks exposed in central Victorian fault zones appeared to have been thrust, which led Hamlyn et al. (1985) to postulate that these igneous rocks – especially the boninitic component which are inherently elevated in gold – as a likely source reservoir for the orogenic gold hosted in the inherently gold-poor Cambro-Ordovician metasediments of central-west Victoria. Source-focussing-transport-trap models previously used in the petroleum industry began to be used in a more systematic approach in mineral systems analysis (e.g., Wyborn et al., 1994). The relationships between stress, strain, the role of seismicity (e.g., 'seismic pumping'; Sibson et al., 1975; Sibson et al., 1988) and the potential role of deeply tapping faults as crustal-scale fluid conduits that could transport gold-bearing hydrothermal fluids into the upper crust to form orogenic gold deposits were established, including in Victoria (Cox et al., 1991a, b).

The research confirmed common characteristics across many Victorian orogenic gold deposits. All were formed in a brittle structural regime with quartz-gold precipitated incrementally from hydrothermal fluids into voids opened during episodic strain events to form veins. Laminations in veins indicate veins grew by multiple crack-seal episodes. Stylolitic textures in veins indicate subsequent substantial loss of silica in some veins, probably during subsequent deformation, with gold concentrated, remobilised or both. Since conditions conducive to a brittle structural regime can extend to many kilometres depth (contingent upon instantaneous strain rates, and on syn-orogenic erosion, etc) so brittle-regime deposits can also have great vertical extent. This explains the >1,400 m depth of development for the Hustler line of reef at Bendigo, more than 1,600m vertical depth extent for Stawell, and current depth extent of more than 1,000m at Fosterville (Figure 4) and flags the potential remaining in the many lesser-known Victorian goldfields only mined and explored to relatively shallow depths.

A regional-scale structural mapping and geophysics integration revolution

The monotonous Ordovician sandstone and siltstone turbidite stratigraphy of Victoria's goldfields is devoid of distinctive marker horizons, although contain a rich graptolite fauna preserved in thin graphitic black shale intervals. These intervals represent episodes of sediment starvation in the anoxic deep marine environment, so that pelagic material, including dead planktonic organisms, were able to settle out of the water column and accumulate without dilution by other sediment. The shale intervals represent compressed time, maximising the concentration of animal fossils. Though shale layers are thin and sparse in the Bendigo Zone they are regularly interspersed throughout the stratigraphy. The fossils contained within allow for fine biostratigraphic subdivision of the deformed stratigraphy at regional scale. Differences in biostratigraphic age reveal offsets of strata across major faults, and the absolute magnitude of fault displacements and the positions and amplitudes of major fold closures can be measured, and crustal shortening calculated (Gray et al., 2006).

Beginning in the late 1980s detailed 1:10 000-scale mapping of the Bendigo and Castlemaine goldfields (e.g., Willman & Wilkinson, 1992) established that rigorous structural mapping of fold closures and faults within the turbidite successions could complement and reproduce the structural form-surfaces indicated by biostratigraphy, and that regional-scale structures could be related directly to structures documented in historic gold mine plans. This breakthrough enabled the GSV to develop workflows for detailed structural mapping to constrain the regional-scale structure in parts of the monotonous widespread turbidite succession where graptolites were sparse (e.g., central and eastern Victoria) or absent (e.g., Cambrian successions west of Wedderburn and Ballan; e.g., Taylor et al., 1996).

In central-west Victoria new mapping revealed a significant relationship – the largest goldfields such as Bendigo, Ballarat and Castlemaine are not located on the steep west-dipping regional-scale thrust faults, some of which exhibit kilometres of vertical displacement as constrained by biostratigraphic offsets, or even in the steeply-dipping stratigraphy of their proximal hanging-walls. The goldfields are located a few kilometres further west, in simply folded strata with a subhorizontal fold enveloping surface (Figure 6). Clear linkage between the orientation of fold-enveloping surfaces and the regional-scale faults – the fold enveloping surfaces progressively steepen towards parallelism with major faults in their hanging-walls – meant that the geometry of the fold enveloping surfaces could be used as a proxy for fault geometry at depth – the faults are listric – steep at the surface and flattening to a low dip-magnitude at depth. This observation led to theoretical models that postulated a 'thin-skinned' imbricate thrust-style of geology for Victoria, with fault structures known at surface soling into a mid-crustal detachment structure of some kind, above an unknown, possibly older substrate.

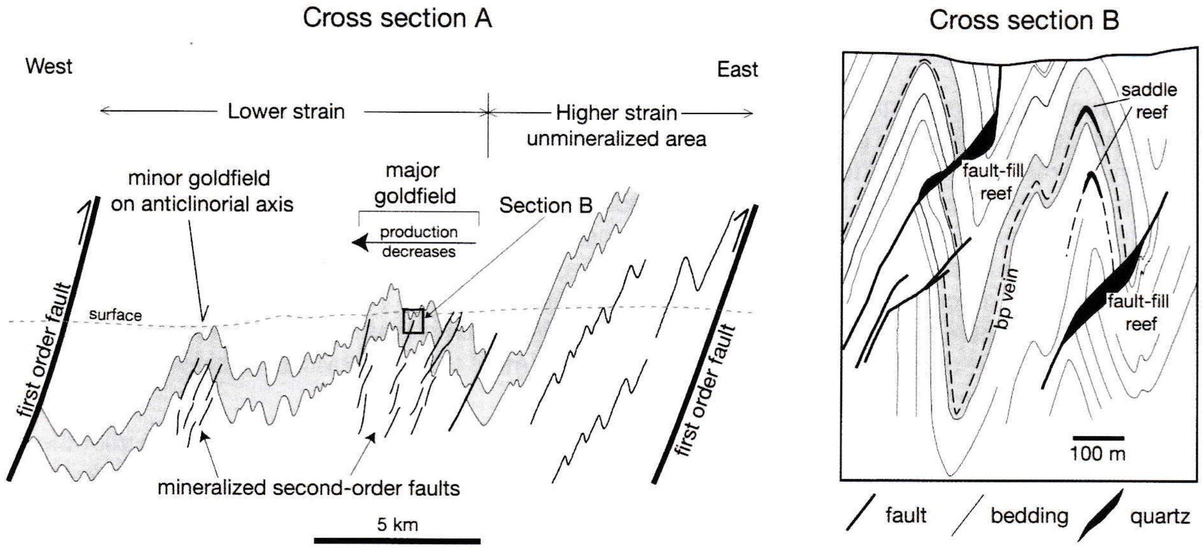

Figure 6: Stylised cross section of the Bendigo and Castlemaine goldfields adapted from Willman et al (2010), illustrating a key common feature - goldfields are hosted by geology with sub-horizontal fold enveloping surfaces. Steep fold enveloping surfaces in the hanging-wall of a regional scale faults (e.g., Whitelaw Fault, Bendigo, or Taradale Fault, Castlemaine) are unmineralised

The fault dip inflexion points at depth were postulated as a primary control on the location of Victoria's orogenic gold deposits, with gold-bearing fluids derived from metamorphic devolatilisation having leaked up dispersed subsidiary structures above the buried fault inflexion points (Willman, 2007; Willman et al., 2010 and references cited therein) due to the inability of the fluids to ascend along the high-angle upper segments of the regional scale faults – high-angle fault segments being held closed by the very compressive stresses that drove their reverse displacements and associated crustal thickening and prograde metamorphism (see Figure 8). This explains the offset location of some of the goldfields, the temporal links apparent between folding, faulting, and the earliest phases of orogenic gold mineralisation, and means that along-strike extrapolations of the major fault positions might potentially be used as a vector for new goldfields, including under cover, albeit offset to their hangingwall sides and developed intermittently. However, establishing fault positions away from areas of excellent exposure was very difficult and there was still no understanding of why the Bendigo Zone had the largest gold endowment while other areas of Victoria, apparently with near-identical turbidite sequences, did not.

The Victorian Initiative for Minerals and Petroleum (VIMP) (1993-2005) was the first concerted pre-competitive geoscience data provision initiative of the Victorian Government to support exploration investment. Led and delivered by the GSV, VIMP aimed to stimulate exploration by generating and providing access to consistent regional-scale geophysical and geological data. VIMP resulted in what arguably remains the best State-wide potential field geophysical coverage in Australia with 200-400m spaced airborne magnetic and radiometric data and nominal 1.5km gravity stations. Victoria's 1:250 000 geological map series was updated from 1997-1999. New generation 1:50 000 geological mapping of the Palaeozoic bedrock employed the structural mapping workflows described above. The new mapping products accounted for an area of 127,449km2 or 56% of Victoria's landmass. There was a growing expectation that all geophysical data should be reconciled against, and used to inform, field geological mapping. One objective was to transition from camp-scale thinking to crustal-scale geological systems thinking, recognising that systems such as orogenic gold are likely controlled at that larger scale. The new generation mapping and availability of improved geophysical datasets ultimately led to the development of Victoria's Seamless Geology (Higgins et al., 2014), the first geological map product of its type in Australia. Complex iterative mapping workflows evolved over several years, including the integration of potential field geophysics supported by effective data and image processing and display software.

Tectonic models and the start of effective crustal-scale geological systems thinking

The 1990s transition to 'geological systems' thinking in Victoria was marked by some key advances in understanding Victorian geology. One of the major contributions from the research community was recognition of the accretionary character of much of the oceanic succession (e.g., Powell, 1983; Collins & Vernon, 1992), which lead to subduction zone models for the Ordovician sequence in Victoria. The models proposed three underlying subduction zone systems operating simultaneously throughout the Ordovician-Early Devonian to explain structural vergence reversals in three major Ordovician-aged thrust systems across the width of Victoria, and the younger initial deformation age of geology in the middle (i.e., the Melbourne Zone). These subduction zone systems were postulated to have driven the observed shortening in a highly diachronous manner, culminating in Melbourne Zone accretion (Gray & Foster, 1998; Fergusson, 1998). Thus, most of the Ordovician turbidite sequences of Victoria were reinterpreted as forearc and/or accretionary wedges.

A major advance of these models is that they explicitly linked the tectonics of eastern Victoria with the coeval Macquarie Arc/accretion system recognised along-strike in New South Wales and provided a tectonic context for the accretionary characteristics observed in the Mallacoota, Tabberabbera, and Stawell zones. Mineral systems associated with modern subduction-accretion systems are well understood, so the new tectonic models suggested that mineral systems templates developed in modern settings in other parts of the world might be applied to Victoria to better understand and predict the positions of undiscovered mineralisation, including orogenic gold.

However, the multiple subduction model for the Ordovician was a poor fit for the simple layer-cake sedimentology and fold-dominated structure of the Bendigo and Melbourne zones in particular. The entire period of Bendigo Zone shortening coincides with an Ordovician-Silurian hiatus in proximal magmatism in western Victoria (Cayley & Taylor 1998), whereas the subduction zone model requires continent-dipping subduction accretion throughout, which should be accompanied by protracted proximal arc-magmatism. Thus, the subduction-accretion model appears weakest in the very places there the historic orogenic gold production is largest, and this geological uncertainty has arguably been the biggest impediment to exploration success. In eastern Victoria the multiple subduction model was a better fit but took no account of the influence of major Silurian strike-slip faults (Willman et al., 2002) and was inconsistent with critical palaeogeographic constraints.

Processing of the new Victorian potential field geophysics and mapping of a Cambrian unconformity beneath central Victoria subsequently showed that the Proterozoic-Cambrian craton of western Tasmania continues north beneath Bass Strait to underlie the younger Melbourne Zone as the Selwyn Block (Cayley et al., 2002). This model explains the Tasmanian affinity of Cambrian volcanic rocks (e.g., Jamieson Volcanic Group) exposed in fault windows eroded through thin overlying cover rocks of the eastern Melbourne Zone (VandenBerg et al., 1995). It also explains the lack of Ordovician deformation in the Melbourne Zone rocks themselves - these appear to have remained undeformed in a continental foreland basin setting into the early Devonian. The Selwyn Block model provides an alternative explanation for the presence and geometry of the major thrust-faults that overthrust the Melbourne Zone and have uplifted belts of Cambrian MORB-type igneous rocks from the lower parts of the adjacent Bendigo and Tabberabbera zones – rather than subduction-related thrusts, these faults could be craton-verging thrusts developed at the continent-ocean interfaces that mark the Selwyn Block margins.

Further west the classic accretionary wedge features in the western Stawell Zone were subsequently dated and shown to be Cambrian (Miller et al., 2005) and therefore related to Delamerian subduction-accretion further west. Thus, the Bendigo Zone, containing the most endowed orogenic goldfields, came to be seen as a region with oceanic-type geology sandwiched between Cambrian Gondwana continental crust to its west and the northern extension of Proterozoic-Cambrian western Tasmania continental crust to its east, that was shortened in a Late Ordovician setting apparently remote from the convergent plate boundary that was active in present day NSW (Cayley et al., 2011).

Victorian geological understanding was in an exciting state of flux with competing tectonic models with very different implications for mineral prospectivity and distribution, with academic debate on the potential sources for the gold, controversy around the transport mechanisms that might have delivered gold to sites of deposition, and debate on the scale of the orogenic gold systems. However, this created further uncertainty for mineral explorers. Using the new geoscience data and knowledge generated during VIMP the GSV determined that a regional-scale 2D deep seismic reflection survey might be a breakthrough dataset that could settle key aspects of tectonic model debates, which would in turn greatly reduce the ambiguity associated with orogenic gold exploration in Victoria. This survey was only enabled by collaborating with Geoscience Australia, the pmd*CRC and industry partners.

The 2006 central Victorian deep 2D seismic transect

Following a trial survey in central Victoria in 1989 that successfully imaged part of the Heathcote Fault Zone (Gray et al., 1991) a longer deep seismic profile was collected in the vicinity of Stawell in 1998 (Korsch et al., 2002). This survey confirmed an east dip for the regionally extensive Moyston Fault, which had been determined by Cayley & Taylor (2001) during new generation mapping by the GSV. The survey also imaged the dome of Cambrian mafic metabasalt (i.e., Magdala Antiform) that hosts the Stawell gold deposit. These results validated the new generation mapping workflows which, combined with new pre-competitive potential field data acquired as part of VIMP, informed the design, acquisition, and ultimately the interpretation, of the first regional-scale deep 2D seismic survey to span the full width of Victoria's most gold-endowed structural zones. The 400km transect traversed from Stawell in western Victoria to Violet Town in central Victoria, and north to near Cobram on the Murray River and the border with New South Wales (Figure 2).

The 2006 central Victoria deep 2D seismic reflection survey delivered excellent data that imaged contrasting geology to the base of the crust at approximately 35km depth (Figure 7). Fundamental faults and key rock types mapped at surface were imaged in the data – this was the breakthrough needed to extend surface understanding to crustal-scale. Key results that relate to orogenic gold (see Willman et al., 2010, Cayley et al., 2011) include:

- The geology of the Bendigo Zone was determined to be 'thick-skinned', not 'thin skinned' as previously interpreted. The stratigraphy and structures mapped at the surface can be traced unbroken into the lower crust and to the Moho, which means that the structural history mapped at surface can be applied to the whole crust.
- Dense Cambrian mafic igneous rocks exposed at surface in the Heathcote Fault are highly reflective and this distinctive pattern continues to the base of the crust. Reflective rocks extend west to occupy the whole middle and lower crust of the Bendigo Zone. Forward modelling and inversions at crustal scale, informed by directly measured density values of the various Bendigo Zone rock types, demonstrates a good match to observed gravity, providing confidence in the interpretation. One implication is that Cambrian oceanic igneous crust in the Bendigo Zone was not subducted during Ordovician crustal shortening – instead it was imbricated together with the overlying deep marine turbidite succession to create continental-thickness crust from an oceanic precursor. This is in marked contrast to the Stawell Zone, which the seismic data shows to be thinner and piggy-backed above the Bendigo Zone across the Avoca Fault, metasediment-dominated throughout but with irregular blobs of intermixed reflective Cambrian mafic igneous material at a range of scales. This appearance is a good match for the sediment-dominated melange of accretionary material, that includes Cambrian mafic igneous rocks host to the Stawell gold deposit, that have been uplifted to surface in the Moyston Fault hanging-wall. It confirms a Cambrian accretionary wedge setting for the Stawell Zone, linked to Cambrian continental(west)-dipping subduction. The coherent ocean crust that floored the Stawell Zone in the Cambrian is now subducted and lost from the continental crust - only off-scraped fragments of it remain.
- Structural linkage exists between the Bendigo Zone and the Stawell Zone – the Moyston Fault dips east beneath the Stawell Zone to also bound the lower western margin of the Bendigo Zone. Structural linkage extends east from the Bendigo Zone into the younger Melbourne Zone. Farther east, structures propagate from the Tabberabbera Zone into the younger Melbourne Zone. The structural linkages indicate the possibility of crustal-scale fluid interconnectivity (including hydrothermal gold-bearing fluids) between different structural zones. The geometries indicate that fluid flows would be outwards and upwards from the lower Bendigo Zone into the overlying Stawell Zone and adjacent Melbourne Zone, not the other way around.
- The fault networks have a V-shaped geometry across the width of the Stawell, Bendigo and Melbourne zones, converging to a common mid-point in the lower crust beneath the western Bendigo Zone. This indicates the possibility of a common source region at depth beneath the western Bendigo Zone for contemporaneous orogenic gold deposits that are widely separated at surface. For example, this can explain the common age of ~440 Ma for early gold deposits of the Bendigo Zone and the Stawell gold deposit despite the different host rocks, different structural history, and wide separation at surface.
- The mid and lower crust of the Melbourne Zone has a completely different seismic character to the mid- and lower crust of the Bendigo and Stawell zones – the diversity of character confirms a diversity of geological provenance at depth across the width of central-west Victoria. Exotic (continental-style) crust beneath the Melbourne Zone contrasts in character with the adjacent Bendigo Zone. The seismic data images crustal-scale faults that overthrust the Melbourne Zone from the west (Bendigo Zone geology uplifted in the Heathcote Fault Zone hangingwall), and from the north and east (Tabberabbera Zone uplifted in the Governor Fault hangingwall). The new seismic reflection data validated the Selwyn Block model developed by the GSV as informed by new generation mapping.

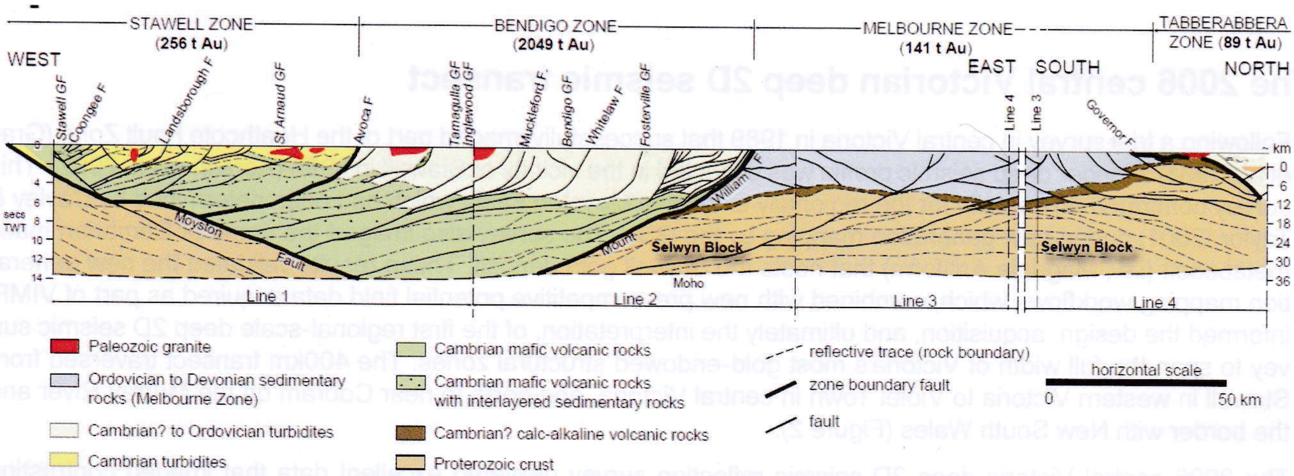

Figure 7: Interpreted cross-section of 2006 central Victorian deep 2D seismic transect data (after Willman et al., 2010).

Building on the new findings

The GSV Gold Undercover initiative (2006-2009) was undertaken to support and attract mineral exploration investment, in targeting potential gold in prospective bedrock concealed by post mineral cover in northern Victoria. The initiative delivered new pre-competitive geoscience data and knowledge in twenty-four reports, an exploration toolkit and two peer reviewed scientific papers in internationally recognised journals (see Willman, 2010).

Following successful seismic acquisition in 2006, it became feasible to construct a constrained crustal-scale 3D geological framework model of the Stawell, Bendigo and Melbourne zones to progress tectonic modelling and geological (mineral) systems thinking. GSV's 3D Victoria project delivered a 3D crustal-scale model of Victoria (Rawling et al., 2011). With 3D model construction complete, the crustal scale framework for central-west Victoria could be imported into numerical fluid flow and strain modelling software to inform conceptual tests such as: thrust-belt formation and geometry between converging crustal blocks with an intervening weak zone; listric fault inflection points under compressive stress as a control on orogenic gold fluid flow (Figure 8); how variations in stress-field orientation might change the positions of dilation zones and sites of orogenic gold deposition in pre-existing faults. The results validated and refined the concepts of the previous decade. Statistical examination of fault inflection point positions at depth within the Bendigo Zone 3D model showed a striking correlation with the surface positions of known goldfields – this indicated that the inflection points hidden at depth have been a critical control in the focus and the location of Victoria's orogenic gold deposits (see: Rawling et al., 2011). This goes some way to explaining why it has been so hard to target orogenic gold based on the geology of the host rocks alone – these are not the control on orogenic gold endowment – the primary control likely lies at depth.

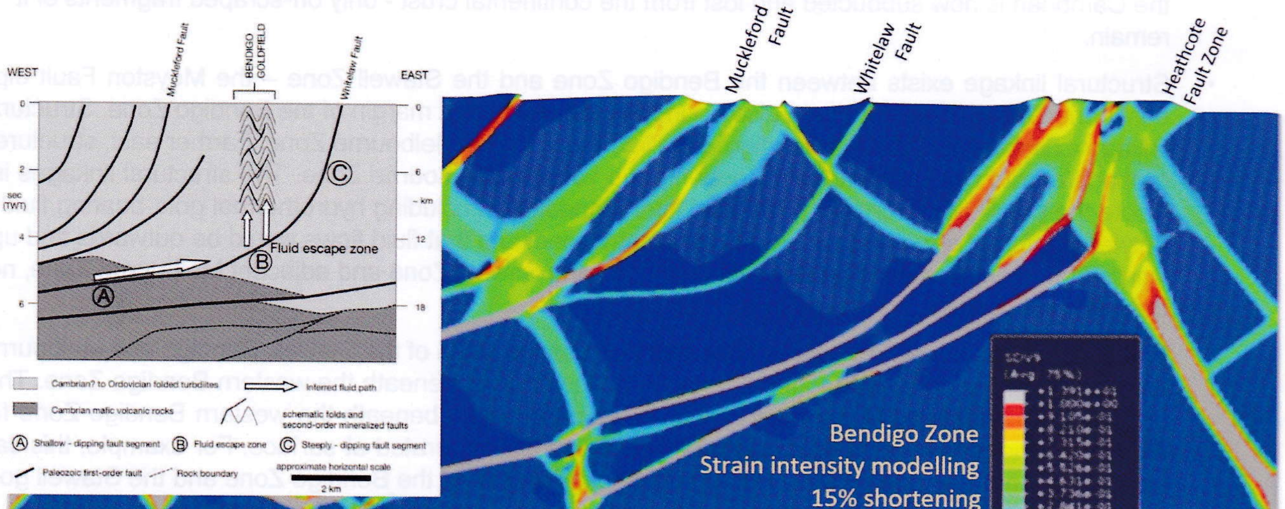

Figure 8: Central Bendigo Zone rock distributions and fault configurations from the 2006 seismic reflection survey (adapted from Willman et al., 2010; refer to Figure 7), showing the orogenic fluid flow concept, with low-angle faults at depth (A) open to fluid flow, while high angle portions of the same faults near surface (C) are held shut, so are poor conduits. Thus, fluids escape upwards via networks of subsidiary structures that are active above the fault inflection point (B). Numerical modelling of strain for the same fault network at matching scale (see Rawling, et al, 2011) shows high strain strongly localised within the mafic igneous rocks at depth (narrow grey bands). Strain becomes more distributed in the overlying metasedimentary succession with subsidiary structural networks implicated, particularly in fault hangingwalls – these could potentially accommodate fluid flow

Case study: Discovery of the Four Eagles gold deposit under cover

Pre-2007 local explorer Providence Gold and Minerals Ltd (Providence) had identified, north of Bendigo, low level gold mineralisation in the Mitiamo area east of the Whitelaw Fault using the fault inflection point concept, located according to the best existing interpretations of fault positions under cover based on strike-projections from the nearest bedrock outcrops and the Victorian aeromagnetic data. As part of the Gold Undercover initiative the GSV acquired detailed semi-regional ground gravity across the northern Bendigo Zone (see Haydon, 2008) to determine the location and strike extent of faults identified in the 2006 deep 2D seismic reflection survey in the northern extent of the Bendigo Zone where prospective rocks are concealed beneath the Murray Basin. Processing the imagery of the semi-regional ground gravity data (high pass filtered), presented in Moore & McLean (2009), showed that the surface positions of the mapped and seismic-imaged portions of the major faults were subtly expressed in the gravity data and could be traced north (Figure 9). A reinterpretation of the fault network, including the location of the Whitelaw Fault, resulted in a shift in targeting to the west by Providence and the discovery of Four Eagles orogenic gold deposit under 10-120m of cover in 2010. The current size of the gold footprint is approximately 6km long by approximately 2.5km wide and contains multiple north-south trending zones each of which have returned gold values of economic interest, including multi-ounce intersections and visible gold. The improved mineral exploration targeting and resulting discovery highlights the successful application of GSV's applied geoscience research workflow and the importance of foundational data and knowledge in regional-scale systems understanding.

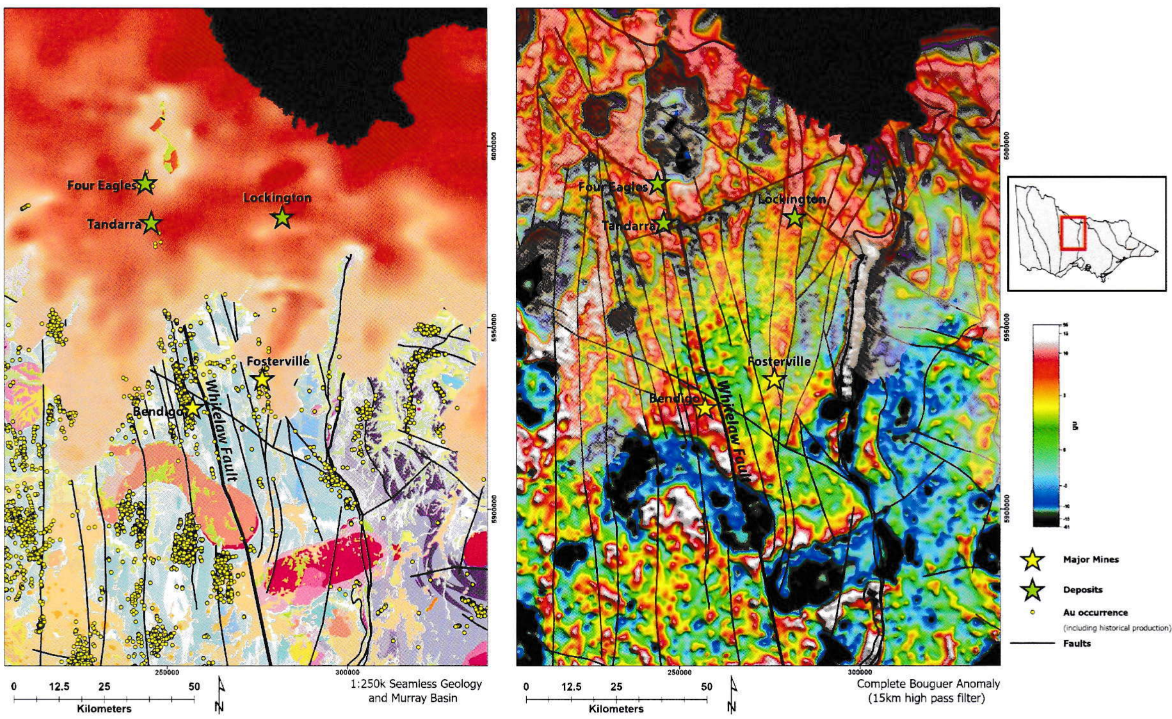

Figure 9: Left: 1:250 000 seamless surface geology of the northern Bendigo and Melbourne zones, including the extent and interpreted depth (pale shading = shallow; dark shading = deep) of post-mineral Murray Basin cover (McLean, 2010). Gold occurrences are shown in relation to mapped faults, note that historical occurrences typically stop at the boundary with the cover. Right: Image showing filtered (15km high pass) semi-regional ground gravity data. Locations of selected major mines and deposits are shown in relation to gravity anomaly trends utilised in the interpretation (and extension) of faults beneath the Murray Basin

Towards a refined and effective predictive capability for orogenic gold exploration in Victoria

Confidence in the tectonic setting of central-west Victoria from the Cambrian to the Silurian at last provided a firm foundation against which ideas for the strike-slip-dominated geology of eastern Victoria could be tested. The critical breakthrough came with the acquisition, by the Geological Survey of New South Wales (GSNSW), of modern aeromagnetic data across the Murray Basin in NSW. From this data it was immediately apparent that the Cambrian accretionary rocks of the Stawell Zone continued into NSW beneath the Murray Basin, but diverged from the east Gondwana margin to curve smoothly clockwise through more than 90° in strike, over hundreds of kilometres, before terminating at a high angle against a large, buried north-trending fault. This fault could be traced south in the data into Victoria where it coincided with the mapped position of the Kiewa-Kancoona fault system, a large Silurian-aged dextral strike-slip fault network. Thus, the new generation mapping of geology exposed along the Victorian portion of the Great Dividing Range could be used to constrain the hidden geological history of much of western NSW.

The result of this breakthrough was the Lachlan Orocline geodynamic model (Cayley, 2012; Cayley & Musgrave, in prep). A huge (hundreds of kilometres amplitude), Silurian-aged Z-shaped, vertically-plunging oroclinal fold is interpreted to have been superimposed over a previously linear Lachlan Fold Belt comprising subduction-accretion geology, caused by asymmetric subduction-rollback precipitated by the ingestion of the northern Selwyn Block apex of a buoyant microcontinent into the southern end of the Ordovician Macquarie Arc subduction zone. This concept has since been successfully modelled by Moresi et al. (2014). The Lachlan Orocline explains the distribution of orogenic gold and arc-related mineral systems throughout eastern Australia (Huston et al., 2015; Figure 10). The implications for Victorian orogenic gold, including predictive capability, include:

- The possibility that the mostly concealed northern Tabberabbera Zone may represent an extension to the gold-rich Bendigo Zone, folded clockwise around the northern apex of the Selwyn Block;
- An explanation for stress-field rotations, cross-faults, and second-generation vertically plunging folds at a range of scales previously mapped in the Tabberabbera Zone – this has implications for understanding the context of orogenic gold in places such as Buckland Valley, Myrtleford, Cassilis, and further afield;
- The origin of east-west trending structures mapped in the Melbourne, Bendigo and Stawell zones, some of which host orogenic gold (e.g., Jubilee Reef, Ballarat, 1887-1913 ca. 130,000oz at a mined grade of ~12 g/t gold).

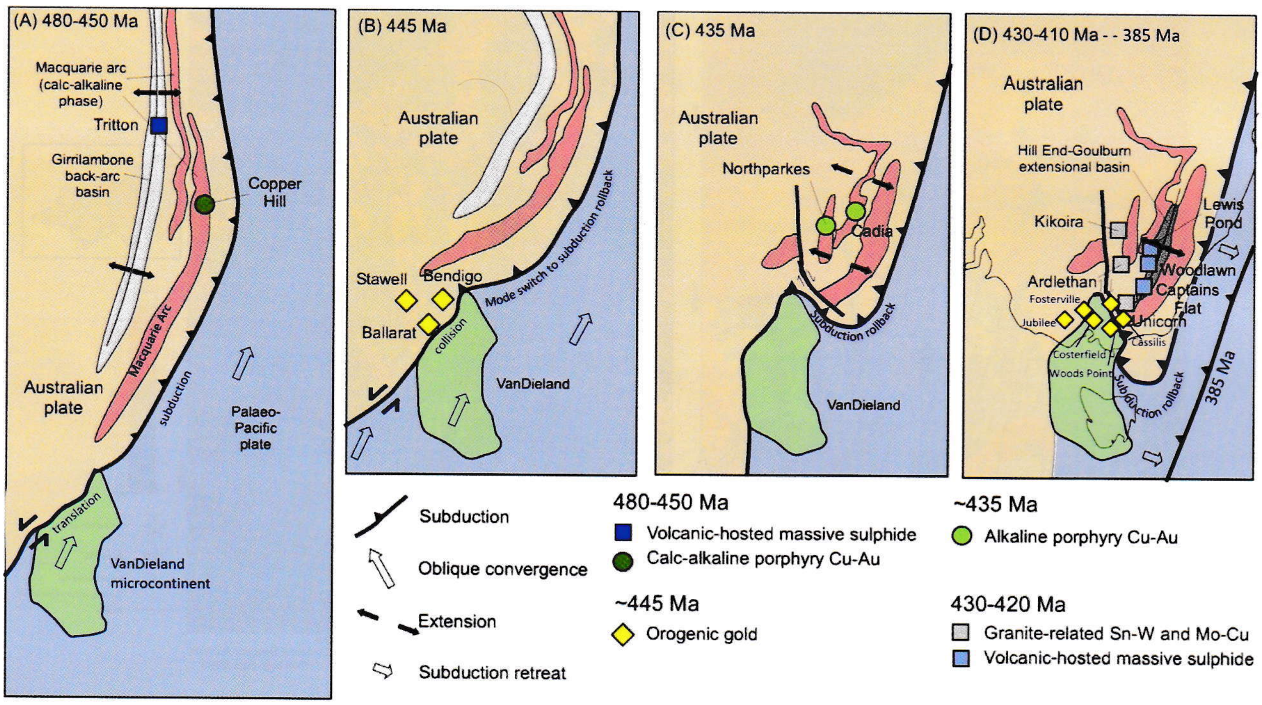

Figure 10: The Lachlan Orocline concept (Cayley, 2012; Cayley & Musgrave, in prep.) envisages the Ordovician proto-Lachlan Fold Belt as a simple linear subduction/accretion system (including the Macquarie Arc) developed along the east Gondwana margin (A). In the Late Ordovician, a microcontinent (VanDieland, comprising western Tasmania and the Selwyn Block; Cayley, 2011) embedded within the lower plate was drawn into the southern end of the subduction zone, congesting it (B). Oblique collision with amagmatic parts of the Gondwana plate south of the arc at this time formed the Bendigo Zone (and Bendigo Zone orogenic gold). With lower plate advance stalled by the buoyant microcontinent, the uncongested parts of the down-going slab fell into asymmetric roll-back, pivoting around the apex of the collider, dismembering, and translating the Macquarie Arc and forming a highly curved oroclinal trench (C; Moresi et al., 2014). As the northern and then eastern parts of Vandieland were drawn progressively into the trench, the collider was enveloped entirely by Gondwana crust, with widespread crustal thickening and related phases of orogenic gold mineralisation (D). Eventually the trench reorganised to become linear once more, with final phases of orogenic gold introduced (~385 Ma). Figure adapted from: Huston et al., 2015; Moresi et al., 2014, Cayley & Musgrave, in prep.

Geological systems analysis and the source of gold debate

It is widely accepted that two main candidates exist as source rocks for orogenic gold in Victoria – the Cambrian mafic igneous rock successions at depth (e.g., Hamlyn et al., 1985; Keays, 1987; Bierlein et al., 1998; Phillips & Powell, 2010; Wilson et al., 2013), and the overlying thick sequence of deformed Cambro-Ordovician sandstone and siltstone, specifically the sulphidic black shale components (e.g., Large et al., 2011, 2012; Tomkins, 2013; Zhong et al., 2015), that also host most of the orogenic gold deposits. Felsic granites are the other common early Palaeozoic rock type in the Victorian goldfields but are generally too young and considered a poor source rock candidate.

While the igneous and sedimentary candidates both have theoretical strengths and weaknesses, and most agree that it was metamorphic devolatilization reactions at depth that liberated gold and sulphur from source rocks into hydrothermal fluids that were subsequently transported towards surface to form the deposits (Goldfarb et al., 2005), vigorous academic debate continues as to the most viable source rock. This uncertainty has implications for area selection and exploration targeting. For example, deformed Cambro-Ordovician metasandstone, slate and shale successions are widely distributed across Victoria (and other parts of southeast Australia), which means that the black shale-as-source-rock model does not necessarily predict the position of the giant deposits.

Geological systems analysis may provide a practical solution to this ongoing debate, and a way forward for explorers. There is general acceptance that pyritic black shales across the Cambro-Ordovician metasedimentary succession in Victoria are a good potential source rock candidate for orogenic gold deposits, however regional geological mapping demonstrates that the relative abundance (volume) of black shale in Cambro-Ordovician metasedimentary stratigraphy in Victoria is anti-correlated with the size of historical orogenic (and placer) gold production. For example, the Bendigo Zone has the least amount of black shale (mapped at <5% total rock volume) of Victoria's geological zones but has the most recorded gold production by a significant margin. To the west, the Stawell Zone has a far greater amount of pyritic black shale, but when significant volumes of these rocks were first regionally metamorphosed to form amphibolite facies graphitic/pyritic-pyrrhotite schists in the Late Cambrian (e.g., the Rhymney Schist exposed in the Moyston Fault hanging-wall; Cayley & Taylor, 2001), no orogenic gold deposits were formed. We now understand that Cambrian deformation and metamorphism in the Stawell Zone occurred within an accretionary-wedge setting, related to the Stavely Arc. Hydrothermal fluids were evolved during Late Cambrian crustal thickening and metamorphism of the Stawell Zone but did not carry gold (i.e., metamorphism of the black shale did not liberate significant gold during orogenesis). The introduction of orogenic gold into the Stawell Zone came later (455-440 Ma) and coincident with the first deformation and crustal thickening of the shale-poor Bendigo Zone.

The most notable characteristic of the Bendigo Zone, different from the zones on either side and clearly imaged in the deep 2D seismic reflection data, is the presence of vast quantities of imbricated Cambrian mafic igneous rocks at depth - these form the entire middle and lower crust at depths where amphibolite facies metamorphism was inevitable (Figure 7). This difference with the Stawell Zone reflects the very different, apparently 'within-plate', tectonic setting of the Bendigo Zone in the Ordovician – instead of ocean crust being subducted during Bendigo Zone orogenesis it remained within the crust (Cayley et al., 2011). The massive volume of the Cambrian mafic igneous rocks indicates that liberation of gold and sulphur into hydrothermal fluids from them need not be efficient in order to explain the world-class endowment of the goldfields near surface. The deep 2D seismic reflection data has imaged a fault network with a geometry that could facilitate fluid transportation from these depths upward into the overlying rocks to explain the high gold endowment and formation of giant orogenic gold deposits in the Bendigo Zone, but also out into the adjacent Stawell and Melbourne zones where major and moderate deposits are known.

Additional regional deep seismic provides new opportunities

The success of the central Victorian survey (2006) encouraged deep 2D seismic reflection surveys in western Victoria (2009) and eastern Victoria (2018), in collaboration with Geoscience Australia, AuScope and the Geological Survey of South Australia (GSSA) and GSNSW respectively. The result is a complete traverse of the Delamerian and Lachlan orogens in southeast Australia in the region of best surface geological control (see Figure 2).

The 249km western Victoria deep 2D seismic reflection survey acquired in 2009 imaged the Stavely Arc and the regionally extensive crustal-scale Moyston Fault, which separates supra-subduction zone rocks with Cambrian Gondwana affinity to the west from accretionary rocks with Cambrian oceanic affinity to the east. The data and findings resulted in a new insight into the geological systems of western Victoria, including a greater understanding of Cambrian aged arc-related mineralisation that provided a new Australian exploration search space (e.g., Schofield, 2018, Cayley et al., 2018, Cairns et al., 2018). The systems analysis built on an existing framework for the adjacent Stawell Zone, including the location and timing of the orogenic gold mineralisation (e.g., Cayley & Taylor, 2001, Miller et al., 2005). The recent identification of structurally controlled massive to semi-massive quartz-sulphide mineralisation, including chalcopyrite, bornite and hypogene chalcocite at the Thursday's Gossan deposit with discovery hole SMD050 intersecting 32m @ 5.88% Cu, 1.00 g/t Au, 58 g/t Ag from 62m including 2m @ 40% Cu, 3.00 g/t Au, 517 g/t Ag within 12m @ 14.3% Cu, 2.26 g/t Au, 145 g/t Ag (Stavely Minerals, 2019) demonstrates that significant metals exist in the system and vindicates the proposal of a new (base metal) mineral exploration search space.

The Southeast Lachlan Crustal Scale Transect (Cayley et al., 2019, Cayley et al., in prep) was the most ambitious survey with 629 km of deep 2D seismic reflection acquired in 2018 through the heart of the Australian Alps to investigate the geological architecture of northeast Victoria and southeast NSW and how it has evolved over the past 500 million years. The survey was designed as a series of major geometrical tests of the Lachlan Orocline model including crossing both mobile limbs in places where mapping and other geophysical datasets suggest that they are still intact and linked. Mineral systems of NSW (e.g., base metal systems hosted by the Ordovician Macquarie Arc and by metasediment and metavolcanic successions to its west) and Tasmania (e.g., Beaconsfield-style orogenic gold, intrusive hosted tin) may extend into eastern Victoria. Orogenic gold, magmatic-related tin, volcanic hosted base metal deposits, and dyke swarms with elevated lithium and rare earth elements occur in eastern Victoria and understanding their geological context can focus mineral exploration efforts and potentially identify new mineral exploration opportunities.

Conclusions

The application of carefully planned regional deep 2D crustal seismic acquisition, in areas of best surface geological (bedrock) control, has been fundamental in adopting and progressing a geological systems approach in Victoria (and southeast Australia) that has improved target generation and early-stage mineral exploration. It is not uncommon for structures mapped at surface to be able to be traced to great depths in seismic reflection data – thus the better surface geological control can directly inform interpretation of lithology, structure, age and geological inter-relationships in the lower parts of a seismic reflection survey. The understanding gleaned from interpreting seismic reflection data can be extended into adjacent areas of poorer exposure using potential field geophysics. This approach has delivered on our objectives to develop an effective geological systems approach, creating crustal-scale frameworks which allow reappraisal of a whole range of other legacy geoscience datasets.

The Lachlan Orocline concept introduces insights for orogenic gold exploration in Victoria. Recognition that parts of the Fosterville deposit formed in response to north-south-directed stress (Wilson et al., 2020) is predicted by the Lachlan Orocline model, and this strain pattern can be recognised across the Bendigo, Melbourne and Stawell zones where it manifests as late, east-west trending mineralised structures. Historic examples such as Jubilee Reef southwest of Ballarat, the Rhymney and Plantaganet reefs near Ararat, the Kingston goldfield northeast of Stawell, and the Rushworth reefs and related structures are just some examples of historical workings in the structural/geological zones of Victoria that remain underexplored. The structures are not well imaged in Victoria's existing aeromagnetic data, given that acquisition was east-west lines to best image north-south trending stratigraphy. The potential continuation of the highly endowed Bendigo Zone into the northern Tabberabbera Zone requires further investigation.

The quirks of Victorian geology mean that it was relatively easy to find naturally exposed orogenic deposits when gold was first discovered. A more sophisticated understanding of the geology will be paramount for target generation and exploration of the many relatively shallow high grade historical workings throughout Victoria, even more so under cover where recent examples hint at the potential of greenfield discovery opportunities (e.g., Tandarra, Four Eagles, Lockington) with simulations suggesting that there may be approximately 75 Moz of undiscovered gold yet to find in the northern extent of the Stawell, Bendigo and Melbourne zones (Willman, 2010). The biggest learning from the recent successes in Victorian orogenic gold is: build understanding of the geological setting and then drill diamond, drill often and drill deep. Without the commitment and perseverance of systematic deeper drilling within a well-established stratigraphic framework, the world-class Swan Zone at Fosterville is unlikely to have been discovered.

Acknowledgments

Many GSV geoscientists past and present have contributed to the data and knowledge presented in this paper, the reference list below does not do justice to the long list of individuals involved. The deep seismic surveys could not have happened without collaborative partners: Geoscience Australia, AuScope, pmd*CRC, GSNSW, GSSA and select industry contributors in 2006. Gavin Mudd generously provided unpublished data for Australian gold production. Melanie Phillips compiled drilling statistics and Nikita Buck exploration expenditure. David Higgins prepared Figure 2. Figures 4 and 9 were adapted from recent publicly available GSV presentations on orogenic gold systems in Victoria by Rob Duncan and Phil Skladzien respectively.

References

Arne, D.C., House, E., Pontual, S. & Huntington, J. 2016. Hyperspectral interpretation of selected drill cores from orogenic gold deposits in central Victoria. Australia, Australian Journal of Earth Sciences, 63, 1003-1025.

Bierlein, F.P., Arne, D.C., Broome, J.M.N. & Ramsay, W.R.H., 1998. Metatholeiites and interflow sediments from the Cambrian Heathcote Greenstone Belt, Australia: sources for gold mineralisation in Victoria? Economic Geology, 93, 84-101.

Böhlke J.K., 1982, Orogenic (metamorphic-hosted) gold-quartz veins. U.S. Geological Survey Open-file Report, v. 82–795, 70–76.

Cairns, C.P., Cayley, R.A., Duncan, R.J., Haydon, S.J., Lewis, C.J., McLean, M.A., Meixner, A.J., O'Neill, C.D., Phillips, M.J., Schofield. A., Skladzien, P.B., & Taylor, D.H., 2018. The Stavely Arc uncovered - a new Australian mineral exploration search space. Stavely Project Report 5. Geological Survey of Victoria. Department of Economic Development, Jobs, Transport and Resources.

Cayley, R.A., 2011. Exotic crustal block accretion to the eastern Gondwanaland margin in the Late Cambrian – Tasmania, the Selwyn Block, and implications for the Cambrian-Silurian evolution of the Ross, Delamerian and Lachlan Orogens. Gondwana Research 19, 628 – 649.

Cayley, R.A., 2012. Oroclinal folding in the Lachlan Fold Belt: consequence of southeast directed Siluro-Devonian subduction rollback superimposed on an accreted Ordovician arc assemblage in eastern Australia. Geol. Soc. Aust. Ext. Abstract. 103, 34–43.

Cayley, R.A. & Taylor, D.H., 1998. Divergent double subduction: Tectonic and petrologic consequences: Comment and reply Geology, 26, 1052.

Cayley, R.A. & Taylor, D.H., 2001. Ararat 1:100 000 map area geological report. Geological Survey of Victoria Report 115.

Cayley, R.A., Taylor, D.H., VandenBerg, A.H.M. & Moore D.H., 2002. Proterozoic–Early Palaeozoic rocks and the Tyennan Orogeny in central Victoria: the Selwyn Block and its tectonic implications. Australian Journal of Earth Science, 49, 225–254.

Cayley, R. A., Korsch R. J., Moore D. H., Costelloe R. D., Nakamura A., Willman C. E., Rawling T. J., Morand V. J., Skladzien P. B. & O'Shea P. J., 2011a. Crustal architecture of central Victoria. results from the 2006 deep crustal reflection seismic survey. Australian Journal of Earth Sciences, 58, 123–156.

Cayley, R.A., McLean M.A., Skladzien, P.B., & Cairns, C.P., 2018. Stavely Project - Regional 3D Geological Model. Stavely Project Report 3. Geological Survey of Victoria. Department of Economic Development, Jobs, Transport and Resources.

Cayley R. A., Skladzien P.B., Cairns C.P., Haydon S., McLean M.A., Taylor D.H., Fomin T., Costelloe R.D., Kirkby A., Jingming D., Doublier M., Musgrave R., Stolz N., Spampinato G., Gilmore P., Greenfield J. & Rawling T.J., 2019. The Southeast Lachlan Crustal Transect – planning, acquisition and some preliminary results from a 629 km long deep seismic reflection profile across the Australian Alps, Mineral Exploration in the Tasmanides 2019, AIG Bulletin 69, Australian Institute of Geoscientists.

Cayley, R.A. & Musgrave, R.J., in prep. The giant Lachlan Orocline – a new geodynamic model for the Ordovician-Devonian evolution of Eastern Australia.

Cayley, R.A., Skladzien, P.B., Cairns, C.P., Haydon, S.J., McLean, M.A., Taylor, D.H., Fomin, T., Costelloe, R.D., Kirkby, A.L., Duan, J., Doublier, M.P., Musgrave, R.J., Stolz, E.M., Spampinato G., Gilmore, P.G., Carlton, A.A., Greenfield, J.E., Rawling, T.J., in prep, Geological interpretation of deep 2D seismic reflection survey lines 18GA-SL1, 18GA-SL2 and 18GA-SL3 undertaken as part of the Southeast Lachlan Crustal Transect. Geological Survey of Victoria. Department of Jobs, Precincts and Regions.

Charlton, K., 2019. The Four Eagles Gold Project: A gold discovery through systematic exploration under cover in the Northern Bendigo Zone, AIG Victoria Minerals Roundup, 8 November 2019, Macedon.

Collins, W.J. & Vernon, R.H., 1992. Palaeozoic arc growth, deformation and migration across the Lachlan Fold

Belt, southeastern Australia. Tectonophysics, 214, 381-400.

Cox, S.F., Etheridge, M.A., Cas, R.A.F. & Clifford, B.A., 1991a. Deformation style of the Castlemaine area, Bendigo-Ballarat zone: Implications for evolution of crustal structure in central Victoria. Australian Journal of Earth Sciences, 38, 151-170.

Cox, S.F., Wall, V.J., Etheridge, M.A. & Potter, T.F.M., 1991b. Deformational and metamorphic processes in the formation of mesothermal vein-hosted gold deposits - examples from the Lachlan Fold Belt in central Victoria, Australia. Ore Geology Reviews, 6, 391-423.

Crawford, A.J. & Keays, R.R., 1978. Cambrian greenstone belts in Victoria: Marginal seacrust slices in the Lachlan Fold Belt of southeastern Australia. Earth and Planetary Science Letters, 41, 197-208.

Crawford, A.J. & Keays, R.R., 1987. Petrogenesis of Victorian Cambrian tholeiites and implications for the origin of associated boninites. Journal of Petrology, 28, 1075-1109.

Dominy, S.C., Platten, I.M. & Raine M.D., 2003. Grade and geological continuity in high-nugget effect gold-quartz reefs: implications for resource estimation and reporting, Transactions of the Institutions of Mining and Metallurgy, Applied Earth Science, 112(3), 239-259.

Edgar, W.B., 2021. The Fosterville Gold Deposit, its Geology and Place Amongst the World's Best Orogenic Goldfields, Society of Economic Geologists 100 Conference, 14-17 September 2021, Whistler.

E79 Resources, 2021. E79 Resources drills 11.10 m of 160.45 g/t gold at the Happy Valley Prospect, Victoria, Australia. viewed 27 September 2021, https://e79resources.com/news-release/e79-resources-bonanza-drill-results-at-the-happy-valley-prospect-victoria-australia/.

Fergusson, C.L., 1998. Cambrian-Silurian oceanic rocks, upper Howqua River, eastern Victoria: tectonic implications. Australian Journal of Earth Sciences, 45, 633-644.

Fergusson, C.L., Gray, D.R. & Cas, R.A.F., 1986. Overthrust terranes in the Lachlan Fold Belt, southeastern Australia. Geology, 14, 519–522.

Goldfarb R.J., Baker T., Dube B., Groves D.I., Hart C.J.R., & Gosselin P., 2005, Distribution, character, and genesis of gold deposits in metamorphic terranes, in Hedenquist J. W. Thompson J. F. H. Goldfarb R. J. Richards J. P., eds., Economic Geology. 100th Anniversary Volume 1905–2005: Littleton, Colorado, Society of Economic Geologists, 407–450.

Gray, D.R., Wilson, C.J.L. & Barton, T.J., 1991. Intracrustal detachments and implications for crustal evolution within the Lachlan Fold Belt, southeastern Australia. Geology, 19, 574-577.

Gray, D.R. & Foster, D.A., 1998. Character and kinematics of faults within the turbidite-dominated Lachlan Orogen: implications for tectonic evolution of eastern Australia. Journal of Structural Geology, 20, 1691-1720.

Gray, D.R., Willman, C.E., Foster, D.A., 2006. Crust restoration for the 1032 western Lachlan Orogen using the strain reversal, area 1033 balancing technique: implications for crustal components and 1034 original thicknesses. Australian Journal of Earth Sciences, 53, 329–341

Hamlyn, P.R., Keays, R.R., Cameron, W.E., Crawford, A.J. & Waldron, H.M., 1985. Precious metals in magnesian low-Ti lavas: implications for metallogenesis and sulfur saturation in primary magmas. Geochimica et Cosmochimica Acta, 49, 1797-1811.

Haydon, S.J., 2008. Bendigo-Mitiamo Gravity Survey. GeoScience Victoria Gold Undercover Report 7. Department of Primary Industries.

Higgins, D.V., Vandenberg, A.H.M., Morand, V.J. & D'Elia, F., 2014. Seamless Geology 1:50 000 geology dataset. Geological Survey of Victoria.

Keays, R.R., 1987. Principles of mobilization (dissolution) of metals in mafic and ultramafic rocks - the role of immiscible magmatic sulphides in the generation of hydrothermal gold and volcanogenic massive sulphide deposits. Ore Geology Reviews, 2, 47-63.

Krokowski de Vickerod, J., Cuffley, B., Evans, T., 2001. Tarnagulla Goldfield, Central Victoria, 1:10 000 Map Geological Report. Victorian Initiative for Minerals and Petroleum Report 71. Department of Natural Resources and Environment.

Huston, D.I., Mernagh, T.P., Hagemann, S.G., Doublier, M.P., Fiorentini, C., Champion, D.S., Lynton, J.A., Czarnota, K., Cayley, R.A., Skirrow, R., & Bastrakov, E., 2015. Tectono-metallogenic systems – the place of mineral systems within tectonic evolution, with an emphasis on Australian examples. Ore Geology Reviews, 76, 168-210.

Kirkland Lake Gold Inc., 2021. Fosterville Mine. viewed 27 September 2021, https://www.kl.gold/our-business/australia/Fosterville-mine/default.aspx.

Kirkland Lake Gold Inc., 2021. Resources & Reserves. viewed 27 September 2021, https://www.kl.gold/our-business/resources-and-reserves/default.aspx.

Korsch, R.J., Barton, T.J., Gray, D.R., Owen, A.J. & Foster, D.A., 2002. Geological interpretation of a deep seismic reflection transect across the boundary between the Delamerian and Lachlan Orogens, in the vicinity of the Grampians, western Victoria. Australian Journal of Earth Sciences, 49, 1057–1075.

Large, R.R., Bull, S.W. & Maslennikov, V.V., 2011. A Carbonaceous sedimentary source-rock model for carlin-type and orogenic gold deposits, Economic Geology, 106, 331-358.

Large, R., Thomas, H., Craw, D., Henne, A. & Henderson, S., 2012. Diagenetic pyrite as a source for metals in orogenic gold deposits, Otago Schist, New Zealand, New Zealand Journal of Geology and Geophysics, 55, 137-149.

Miller, J.M.L., Phillips, D., Wilson, C.J.L. & Dugdale, L. J., 2005. Evolution of a reworked orogenic zone: the boundary between the Delamerian and Lachlan fold belts. Australian Journal of Earth Sciences, 52, 921–940.

Mudd, G.M. 2007, Gold Mining in Australia: Linking Historical Trends to Environmental and Resource Sustainability. Environmental Science and Policy, 10, 629-644.

McLean, M.A., 2010. Depth to Palaeozoic basement of the Gold Undercover region from borehole and magnetic data. GeoScience Victoria Gold Undercover Report 21. Department of Primary Industries.

Moore, D.H. & McLean, M.A., 2009. The northern Bendigo Zone: interpretation of the Bendigo-Mitiamo gravity survey, including depths to basement. GeoScience Victoria Gold Undercover Report 11, Department of Primary Industries.

Nicholls, I.A., 1965. Studies on the mineralogy, geochemistry and petrology of the greenstones of the Heathcote district, Victoria, Australia. Unpublished MSc thesis, University of Melbourne.

Phillips, G.N., Hughes. M.J., Arne, D.C., Bierlien, F.P, Carey, S.P., Jackson, T. & Willman, C.E. 2003. Gold. In Birch, W.D. ed. Geology of Victoria, pp 377-433, Geological Society of Australia Special Publication 23, Geological Society of Australia (Victoria Division).

Phillips G.N. & Powell R., 2010. Formation of gold deposits: A metamorphic devolatilization model: Journal of Metamorphic Geology, 28, 689–718.

Powell, C.M.A., 1983. Tectonic relationship between the late Ordovician and Late Silurian palaeogeographies of southeastern Australia. Journal of the Geological Society of Australia, 30, pp. 353-373.

Moresi, L., Betts, P.G., Miller, M.S. & Cayley, R.A., 2014. Dynamics of continental accretion. Nature, 508, 245-248.

Navarre Minerals, 2021. Maiden gold mineral resources & exploration targets for Resolution & Adventure prospects, viewed 27 September 2021, https://wcsecure.weblink.com.au/pdf/NML/02358765.pdf.

Rawling, T.J., Osborne, C.R., McLean, M.A., Skladzien, P.B., Cayley, R.A. & Williams, B., 2011. 3D Victoria Final Report. GeoScience Victoria 3D Victoria Report 14, Department of Primary Industries.

Schodde R., 2021. Trends in gold exploration, Prospectors and Developers Association of Canada, 8-11 March 2021, Toronto.

Schofield, A. 2018. Regional geology and mineral systems of the Stavely Arc, western Victoria. Record 2018/002. Geoscience Australia, Canberra.

Sibson, R.H. Moore, J. Mc. M., Rankin, A.H, 1975. Seismic pumping—a hydrothermal fluid transport mechanism. Journal of the Geological Society, 131 (6), 653–659.

Sibson, R.H., Robert, F. & Poulsen, K.H., 1988. High-angle reverse faults, fluid pressure cycling and mesothermal gold-quartz deposits. Geology, 16, 551-555.

Stavely Minerals, 2019, Outstanding shallow high-grade copper discovery in first diamond drill hole at ultramafic contact fault, viewed 27 September 2021, https://57f74567-ce1b-45ab-a71b-954db2250d3b.filesusr.com/ugd/18fadc_e73dc843fdfd4bea98d5c738f1227f45.pdf.

Taylor, D.H., Whitehead, M.L., Olshina, A., & Leonard, J.G., 1996. Ballarat 1:100 000 map geological report. Geological Survey of Victoria Report 101.

Tomkins, A.G., 2013. On the source of orogenic gold. Geology, 41, 1255-1256.

Watchorn R.B. & Wilson C.J.L., 1989, Structural setting of gold mineralisation at Stawell, Victoria, Australia, Economic Geology, Monograph 6, 292–309.

Willman, C.E., 2007. Regional structural controls of gold mineralisation, Bendigo and Castlemaine goldfields, Central Victoria, Australia. Mineralium Deposita, 42, 449-463.

Willman, C.E., 2010. Gold Undercover - summary of geological findings: Exploring for buried gold in northern Victoria. GeoScience Victoria Gold Undercover Report 24. Department of Primary Industries.

Willman, C.E. & Wilkinson, H.E., 1992. Bendigo Goldfield - Spring Gully, Golden Square, Eaglehawk 1:10 000 maps geological report. Geological Survey of Victoria Report 93.

Willman C.E., VandenBerg, A.H.M. & Morand, V.J., 2002. Evolution of the southeastern Lachlan Fold Belt in Victoria. Australian Journal of Earth Sciences, 49, 271–289.

Willman, C.E., Korsch, R. J., Moore, D.H., Cayley, R.A., Lisitsin, V.A., Rawling, T. J., Morand, V.J., & O'Shea, P.J., 2010. Crustal-Scale Fluid Pathways and Source Rocks in the Victorian Gold Province, Australia: Insights from Deep Seismic Reflection Profiles. Economic Geology, 105, 895-915.

Wilson, C.J.L., Moore, D.H., Vollgger, S.A., & Madeley, H.E., 2020. Structural evolution of the orogenic gold deposits in central Victoria, Australia: The role of regional stress change and the tectonic regime, Ore Geology Reviews, 120.

VandenBerg, A.H.M., 1992. Kilmore 1:50 000 map Geological Report. Geological Survey Report 91.

VandenBerg, A.H.M., Willman, C.E., Hendrickx, M.A., Bush, M.D. & Sands, B., 1995. The geology and prospectivity of the 1993 Mount Wellington Airborne Survey area. Victorian Initiative for Minerals and Petroleum Report 2. Department of Agriculture, Energy and Minerals.

Verity, B., Fuller, T., Hitchman, S., Edgar, W., Jackson, A., Pittaway, N., 2019. Fosterville – A discovery story of perseverance. NewGenGold Conference, 12-13 November 2019, Perth.

Wilson C.J.L. Schaubs P. Leader L.D., 2013, Mineral precipitation in the quartz reefs of the Bendigo gold deposit, Victoria, Australia: Economic Geology, 108, 259–278.

Wyborn, L.A.I., Heinrich, C.A. & Jaques, A.L., 1994. Australian Proterozoic mineral systems: Essential ingredients and mappable criteria: Proceedings of the Australasian Institute of Mining and Metallurgy Annual Conference, Darwin, 5–9 August 1994, 109–115.

Zhong, R., Brugger, J., Tomkins, A. G., Chen, Y., & Li, W. (2015). Fate of gold and base metals during metamorphic devolatilization of a pelite. Geochimica et Cosmochimica Acta, 171, 338-352.