

# The architecture of the central Victorian goldfields

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## Abstract

The central Victorian goldfields share comparable host rocks and deformational histories. The result is similar folding and faulting styles, quartz veining and gold mineralisation. Yet despite these similarities, the architecture of each goldfield differs. Significantly, variations in the presence and number of thick shales governed the structural styles that developed. Bendigo, Fosterville and Lockington all have linked limb-thrust faults that propagated from bedded, laminated quartz veins in thick shales. In contrast, Ballarat East did not have thick shales to accommodate slip during folding and the fault styles differ. Nerrina formed on a large west-dipping fold limb and is largely devoid of faults. Differences in structural style at each goldfield produced varying favourable sites for mineralisation.

## Introduction

Central Victoria is a world-class orogenic gold province where faults and folds within Ordovician turbidites host gold and associated mineralisation. Such turbidites occur across most of Victoria and in the field comprise monotonously interbedded sandstones and shales, although facies variations and lateral discontinuity of individual beds are characteristic at a local scale. Boucher et al (2008a, b, c, d) and Boucher and Makin (2009) demonstrated the importance of stratigraphy in controlling the structural styles and veining at Bendigo, Ballarat East, Fosterville, Lockington and Nerrina (Figure 1). This paper is a summary of those discussions.

The studied areas include the two largest goldfields in Victoria: Bendigo and Ballarat produced 22 and 12 million ounces of primary and alluvial gold respectively. The Ballarat goldfield



FIG 1 - Location map showing the turbidite-hosted goldfields discussed in this paper.

comprises the Ballarat East, Ballarat West and Nerrina districts. Data used here came from the southern Ballarat East and Nerrina workings. Historically Fosterville was a small goldfield; however, it has recently been opened up as a significant gold producer. This study considers only the western line of workings at Fosterville. The Lockington discovery was made beneath the Murray Basin in 2005.

## Stratigraphic studies in mineral exploration

Many recent advances in petroleum geology can be applied to the study of mineral deposits in sedimentary rocks. New turbidite depositional models and sequence stratigraphy concepts have assisted in understanding the host-rock environments of the central Victorian goldfields.

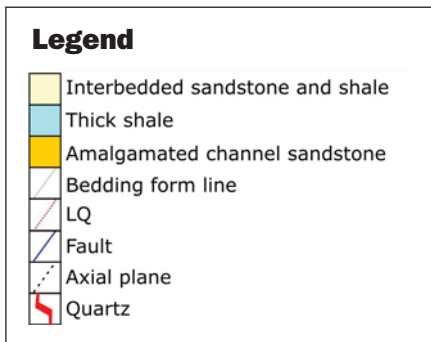
Stratigraphic research began in central Victoria in an attempt to correlate lithological packages between drill holes. Local companies have adopted a detailed sedimentological logging system in order to capture the data required for successful correlation. At an early stage such work was found to be important in determining fold geometries, fault positions and offsets, and gaining a better understanding of vein formation (Boucher, 2004; Boucher and Thomas, 2005). Unfortunately, more

work is needed to fully understand these issues and the controls on fluid flow and mineralisation. While companies have embraced the logging system (data collection), very little interpretation work has been done despite the recognition in recent years that a better understanding of mine geology and mineralisation controls is needed.

## Turbidite facies

Turbidite beds average 30 cm thick and lithological logging on a 10 cm scale is necessary to enable successful correlation. Recent research by petroleum companies exploring modern turbidites has provided great insight into depositional processes. Hemipelagic shales, along with channel sands and their accompanying overbank deposits, are clearly recognisable in mine successions throughout central Victoria. Original channel sands occur as typically coarse and very coarse amalgamated (stacked) sandstones. Overbank deposits are represented by interbedded fine- to medium-grained sandstones and shales that are colloquially referred to as 'shale-topped sands' (STS). STS make up the majority of the stratigraphy throughout central Victoria and the monotonous nature of the interbedded sandstone and shale sequences makes correlation difficult.

Shales rarely exceed 10 m thick. When they do, they not only make good marker beds for correlation, but commonly host bedded, laminated quartz (LQ) veins that link to important faults and are major hosts for gold mineralisation. Often LQ veins occur near the tops of the thicker shales. These thick shales are the best for regional correlation. LQ veins occur in shales that are as little as 2 m thick although, as a general rule, the thinner the shale the less displacement occurs on the associated LQ vein. For the purposes of this paper,



a shale will be considered a 'thick shale' if its thickness exceeds 2 m and it therefore has the potential to host LQ veins.

## Stratigraphic successions

Figures 2–8 are representative cross-sections at the different goldfields. Mine stratigraphies are well established at Fosterville, Bendigo and Ballarat East where hundreds of holes have been drilled over large areas. There are less data for Lockington and Nerrina, where 31 and 11 holes respectively have been drilled. However at Nerrina information is available from extensive surface mapping and accessing those adits that remain open.

The early miners and authors such as Dunn (1893) and Hermann (1923) recognised the significance of lithological packages at Bendigo and elsewhere in central Victoria. It is not possible to review the details here, but Willman (2006) provides an excellent summary. There is no formalised stratigraphy at any of the studied areas. Informal mine stratigraphies are used at Bendigo and Ballarat East and a sequential numbering system is applied at Fosterville, Lockington and Nerrina.

## Channel sands

Sandstones representing channel sands are seen in all studied areas although these comprise a small percentage of the overall stratigraphies (Figures 2–5, 7 and 8). Typical channel-sand deposits are just over 10 m thick and where present make good marker units. At

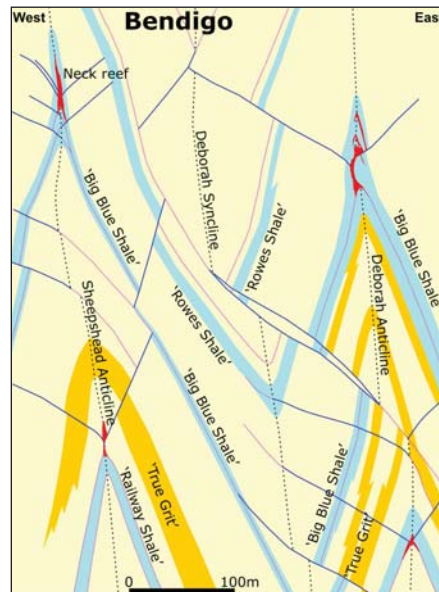


FIG 2 - Representative cross-section at Bendigo.

Bendigo, Fosterville, Lockington and Nerrina, the channel-sand deposits are coarse- to very coarse-grained amalgamated sandstones. However at Ballarat East, the sands were mostly medium-grained, suggesting a differing provenance. This contrasts with the coarser-grained sands immediately to the north at Nerrina.

Former channel sands show considerable lateral variation. At Fosterville, the channel-sand deposits can be correlated over at least 4 km with very little thickness change before they disappear abruptly at the former channel margin on the 7100 mN section (Figure 5). At Bendigo, the channel-sand unit splits into two towards the east. This suggests the channel may have initially migrated westwards before turning back towards the east. It is likely that the furthest the channel moved to the west was just beyond the present position of the Sheepshead Anticline, as represented in Figure 2.

At Ballarat East the 'Big Sandstone' has been recognised on the west limb of the Scandanavian Anticline (Figure 3) to disprove an early hypothesis that massive shearing accompanied large displacement along the axial plane of the fold? The 'Big Sandstone' dies out towards the north. The 'Little

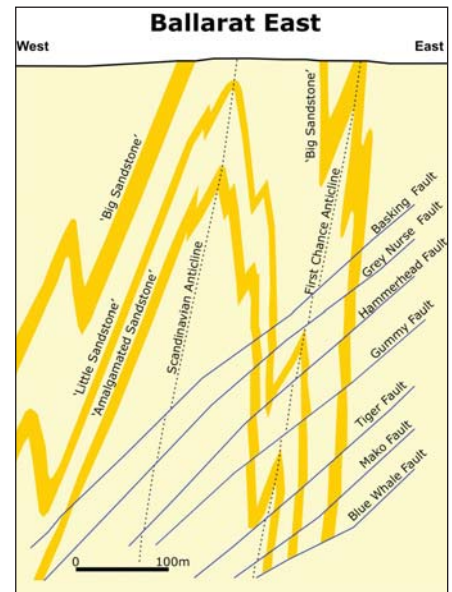


FIG 3 - Representative cross-section at Ballarat East.

Sandstone' and the 'Amalgamated Sandstone' do not represent true channel sands but they are sufficiently thick and characteristic to allow correlation. Little is known about the channel-sand deposits at Lockington and Nerrina as they have only been penetrated by a few drill holes.

There are several locations where sandstones become thicker and coarser-grained, suggesting that a channel environment may have been close by. This situation occurs beneath 'Rows Shale' towards the north-west of the Bendigo goldfield (Figure 2), in the 'Little Sandstone' and the 'Amalgamated Sandstone' at Ballarat East (Figure 3), in the hanging wall above 'FOSH6' at Fosterville (Figure 4) and above 'Dimocks Mains Shale' at Nerrina (Figure 8).

## Thick shales

Thick (>2 m) shales are found in all studied areas except at the southern end of the Ballarat East goldfield (Figure 3). While historic mining identified the 'Twelve Foot Slates' and the 'Seven Foot Slates', these actually contain interbedded sandstones (Boucher et al, 2008b). However, to the north of the section shown in Figure 3, the 'Big Slate' widens to 15 m. It is not

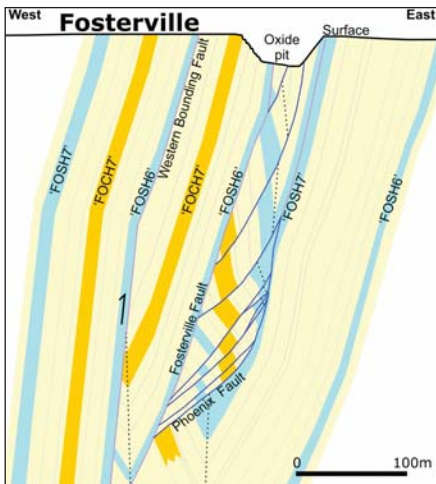


FIG 4 - Cross-section 8200mN at Fosterville.

known if the 'Big Slate' is equivalent to the 'Dimocks Main Shale' seen further north at Nerrina (Figure 8). The latter reaches 25 m in thickness. It is very rare to get shales exceeding 10 m in central Victoria. The notable exceptions are the 'Dimocks Main Shale' and 'FOSH13' at Fosterville which exceeds 75 m (Figure 6). The Lockington sequence contains far more shale than any other, although individual shale units rarely exceed 10 m.

Black shales commonly contain disseminated sulfides and have long been considered an important host for gold mineralisation in central Victoria. Some of the first modern exploration was conducted by Western Mining Corporation in the 1960s on ELs 3, 4 and 5. IP surveys were carried out to identify pyritic black shales hopefully associated with gold mineralisation at Bendigo, Ballarat and several other goldfields. Despite their perceived importance, black shales are rare in central Victoria. In the studied areas, they occur only rarely at Fosterville ('FOSH6') and as thin beds within some of the Bendigo shales, most notably the 'Big Blue Shale'.

At Fosterville and Lockington, all of the thick shales contain bedded LQ veins. A notable LQ vein at Fosterville occurs as part of the Western Bounding Fault (Figures 4 and 5). This large-displacement thrust has repeated the entire hanging wall sequence. Many thick shales at Bendigo contain

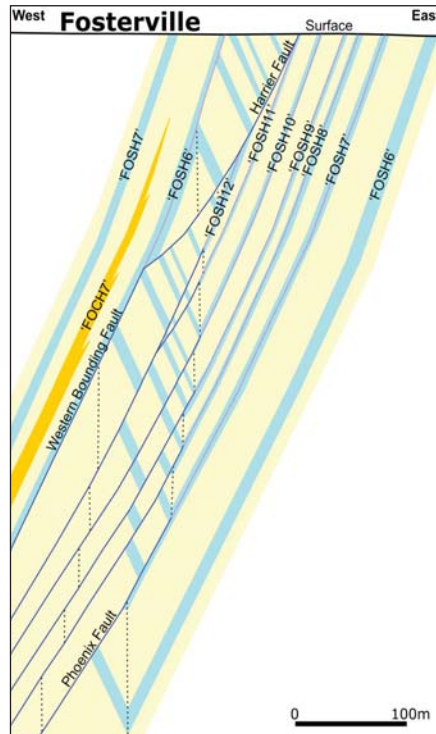


FIG 5 - Cross-section 7100mN at Fosterville.

bedded LQ veins, although one of the more significant LQ veins above 'Rowes Shale' occurs in a thin shale between thick sandy beds (Figure 2). There are some localised thick shale developments at Bendigo that contain short, but important, LQ veins. There are no thick shales at Ballarat East and there are no significant LQ veins. Interestingly, there are no LQ veins at Nerrina, even though there are thick shales. The 'Dimocks Main Shale' and the shales further west contain massive bedded veins. The western Nerrina shales are bounded by thickly-bedded sandstones. In contrast, the STS on either side of the thick shales below the 'Dimocks Main Shale' are shale-rich and the massive bedded veins are less frequent.

### Stratigraphic controls on the development of veins, faults and folds

As a result of the recent more detailed lithological logging there is now a greater understanding of the development of quartz veins in central Victoria. Most notable are the veins that align with cleavage/jointing within beds. Veins commonly exploit

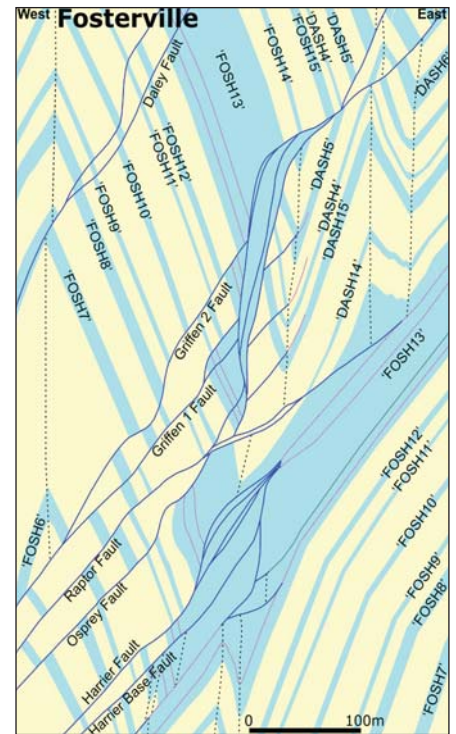


FIG 6 - Cross-section 5400mN at Fosterville.

planes of weakness along axial-planar cleavage in shales and spaced cleavage/radial jointing in sandstones. Hence veins are commonly vertical in shales and perpendicular to bedding in sandstones (Figure 9). These vein styles are found at Bendigo, Fosterville, Lockington and Nerrina. However, at Ballarat East the veins are differently orientated (Figure 10) and more of the quartz is associated with faults than elsewhere.

An important vein type throughout most of central Victoria is the bedding-parallel LQ vein. These formed during early folding and were continually reactivated during subsequent folding. Occasionally extra dilation occurred at the hinge to create simple saddle reefs. With continued folding, slip could translate up the bedding planes, then up the axial planes to produce neck reefs (Figure 2). More commonly, when the folds locked up, faults propagated from LQ veins, across the hinge and through the opposing limb (Figure 2). Such a fault was termed a limb thrust by Ramsay (1974). However, there have been various names used to describe such faults in central Victoria, such as strike reef/slide (Pabst, 1917), dilatant jog



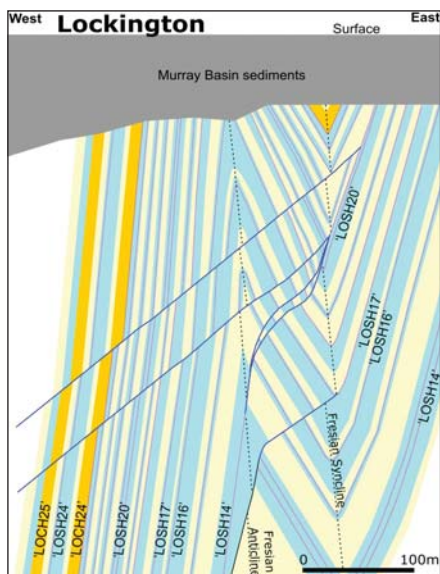


FIG 7 - Representative cross through Lockington.

(Cox et al, 1991), fissure reef (Finlay and Douglas 1992), transgressive reef (Turnbull and McDermott 1998) and low-displacement strike-parallel fault (Willman, 2006).

Limb thrusts should theoretically dip at 45° in response to regional horizontal stress. However, their paths are ultimately governed by where they meet another LQ vein on the adjacent fold. Tension-vein arrays can form on limb thrusts, most commonly in the sandstone beds, especially the thick channel-sand deposits. Veins commonly follow the pre-existing planes of weakness developed along the spaced cleavage/jointing within the sandstones (Figure 9). Some cleavage veins are linked to faults and others are not. It has not been established which vein systems are connected to mineralised 'plumbing systems' and which veins are more likely to contain gold. It is difficult to determine from drilling alone how the veins link between holes and to the major structures.

Thick, amalgamated channel-sand deposits are favourable sites for vein development. Brittle failure occurs in the thick sandstones and accompanying vein development is common, especially near faults. Boucher (2004) demonstrated that the 'True Grit' unit on the Sheepshead Anticline is significantly thicker to

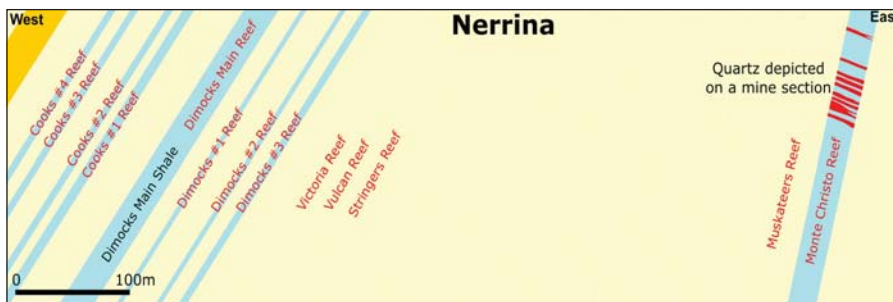


FIG 8 - Representative cross-section at Nerrina.

the north. Where the unit is thickest and shows good vein development, Bendigo Mining delineated small gold resources. However, these were found to be patchy and of low grade. To the south as the 'True Grit' thins, the veining diminishes also. Unfortunately, a lack of understanding of vein systems from drilling data means that resource delineation is difficult in channel-sand deposits. However, there is scope for lithostratigraphic correlation to elucidate the cleavage- and fault-related vein distribution in the channel sandstones. At Ballarat East the 'Big Sandstone' was extensively stoped historically where intersected by west-dipping faults and along its margins. However, no mineralisation is known to be associated with the channel sandstones at Fosterville, Lockington or Nerrina.

### Fold and fault styles

Classification of the folds and faults at each goldfield is shown in Table 1. Folds

are typically upright, subhorizontal, chevron folds. Folds normally plunge at less than 10° towards both the north and south; however, on rare occasions, such as near the southern end of the Fosterville lease, they plunge at up to 30°. Folds are generally tight or close with interlimb angles between 20° and 60°. Beds usually dip at more than 70° except at Nerrina where dips are as shallow as 50°.

Where LQ veins occur, accommodate slip and cross fold hinges, limb thrusts are the dominant fault type. This is seen at Bendigo, where the faults are both east- and west-dipping, and at Fosterville and Lockington, where the faults are west-dipping. However, at Ballarat East where there are no thick shales and no associated LQ veins, there are no limb thrusts. Here the folds are tighter (interlimb angle 20°) and it is likely that once the folds locked up, the faults cut through both of the steeply dipping limbs. At Ballarat East these faults

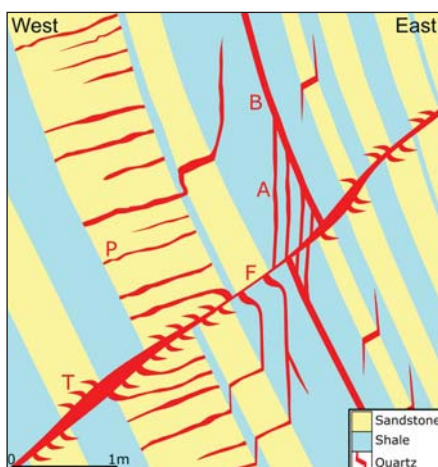


FIG 9 - Lithological and structural controls on quartz veins at Bendigo. Veins occur on faults (F), as tension-vein arrays (T), following bedding (B) and aligned with axial planar (A) and radial (P) cleavage. Based on Rickard (1892).

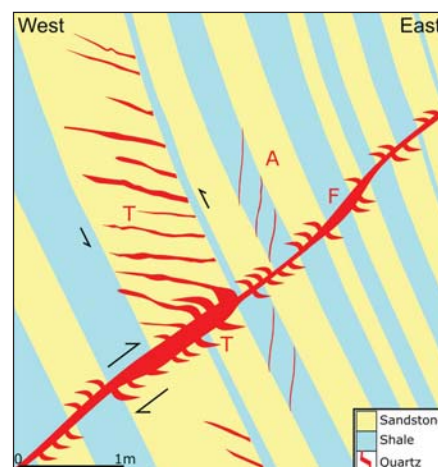


FIG 10 - Lithological and structural controls on quartz veins at Ballarat East. Veins occur on faults (F), as tension-vein arrays (T) and aligned with axial planar cleavage (A). Note there are no thick shales at Ballarat East.

	Lockington	Fosterville	Bendigo	Nerrina	Ballarat
Dip of axial surface	80°–90° (Upright)	80°–90° (Upright)	80°–90° (Upright)	80°–90° (Upright)	80°–90° (Upright)
Plunge of fold axis	0°–10° (Sub-horizontal)	0°–10° (Sub-horizontal)	0°–10° (Sub-horizontal)	0°–10° (Sub-horizontal)	0°–10° (Sub-horizontal)
Fold style	Chevron	Chevron	Chevron	Chevron	Chevron
Fold tightness	30°–40° (Close)	40°–60° (Close)	50° (Close)	Unknown	20° (Tight)
Fold amplitude	110 m	110–300 m	200 m	Very large	Variable
Fold wavelength	180 m	100–250 m	250 m	Very large	20–200 m
Fault style	Limb thrust and leather jacket	Limb thrust	Limb thrust	Leather jacket	Leather jacket
Fault displacement	<20 m	1–100's m	1–75 m	<10 m	1–100's m
Mineralised sites	Leather jackets	Limb thrusts	Laminated quartz veins, limb thrusts and associated veins	Bedding and cleavage parallel vein systems, leather jackets	Leather jackets and associated veins

TABLE 1 - Dominant structural features at each goldfield. Note that variations may occur and these are discussed in full in the text.

have historically been referred to as 'leather jackets'.

Similar faults occur at Lockington where a broad west limb dips steeply. Presumably here the stress could not be translated along LQ veins and instead conjugate faults formed in response to the horizontal regional compression. Small leather jacket-style faults occur at Nerrina. However, unlike similar faults at Lockington and Ballarat East, these faults are east-dipping where they cross west-dipping beds. Unusual faults are associated with the thickest shale at Fosterville (Figure 6). Here the faults split, anastomise, ramp up and sometime cut downwards through.

A notable feature of the Ballarat East goldfield is the presence of steeply dipping, conjugate, bedding-oblique faults (crosscourse faults) that show strike-slip and dip-slip displacement of up to 100 m. Crosscourse faults are rare elsewhere and not seen at Fosterville.

Fault displacements vary between goldfields. Limb-thrust faults at Bendigo (Figure 2) and Fosterville (Figures 4–6) show displacements of up to 75 and 150 m respectively. Although at Fosterville repetition of the succession must be the result of hundreds or thousands of metres of displacement on the Western Bounding Fault (Figures 4 and 5). Leather-jacket faults at Ballarat East (Figure 3) usually show offsets of less

than 10 m. However, displacement on the Blue Whale Fault is significantly greater. The few faults observed at Lockington have offsets of less than 20 m.

Fold amplitude is often difficult to measure after reconstructing fault offsets. At Bendigo fold amplitude is consistently about 200 m. At Ballarat East and Fosterville the size of the folds varies and the largest fold has not been determined. There are limited data at Lockington and no fold closures have been seen at Nerrina. Overall fold wavelength is variable, although commonly around 200 m (Table 1).

### Sites and styles of gold mineralisation

The gold at Fosterville and Lockington occurs mainly within fine-grained, disseminated, needle-like arsenopyrite. Nuggety free gold occurs at the other goldfields.

At Bendigo, the linked limb-thrust systems are the primary sites of mineralisation, especially near the hinges of anticlines. Synclines are rarely prospective. Gold occurs in quartz veins associated with the limb thrusts and within the LQ veins, saddle reefs and neck reefs. Some isolated reefs occur where shales with associated LQ veins thicken. In contrast, at Fosterville and Lockington, the LQ veins are not mineralised. The mineralisation at Fosterville occurs on the limb thrusts, especially where

either of the footwall shale or the hanging wall shale is parallel to the fault. Where beds are oblique/oblique to the fault, mineralisation tends to be more patchy. At Lockington, mineralisation has been found on the leather jackets rather than the limb thrusts. The most favourable sites occur where such faults truncate sandstones.

A similar situation occurs at Ballarat East where the best vein development and gold mineralisation is present where the leather jackets cross thick sandstones, especially channel-sand deposits. Gold mineralisation also occurs on bedding-parallel shears on the margins of the 'Big Sandstone' and along thin indicator beds. Indicators are significant gold hosts at Ballarat East and were historically important. The general consensus is that they are thin (<1 cm) bedding-parallel faults. Reconstruction of the stratigraphic position of several indicators described by Lidgley (1894) shows that they occur within STS successions. It is possible that indicators are thinner analogues of LQ veins that occur in environments where there are no thick shales and where some bedding-parallel slip occurred during folding. There is potential at Bendigo to obtain gold from spurs within channel-sand units if these are carefully mapped. However, there is no mineralisation associated with the channel sandstones at Fosterville, Lockington or Nerrina.



At Nerrina, close to 1000 shafts have been mapped along the 'Dimocks Main Shale'. There are often several small shafts close together across the width of the shale. Gold occurs in bedding-parallel and cleavage-parallel veins and on small east-dipping faults within the shale. No similar mineralised shale system has been seen anywhere else in central Victoria, but a shale this thick is exceptional.

## Conclusions

There are many similarities across the central Victorian goldfields. Each occurs within a turbidite sequence with channel sandstones and, in most cases, thick shales. Folds are generally upright, subhorizontal, open or close, chevron folds. Faults form in response to regional stress and became bedding-parallel where they could. Despite these similarities, the geometry of each goldfield is significantly different. Bendigo shows both east- and west-dipping linked limb-thrust systems. Fosterville and Lockington exhibit similar linked-limb thrust faults; however, they are all west-dipping. Thick shales control the positions of these faults as they peel out of bedded, LQ veins at the hinges of folds. In contrast, Ballarat East does not have thick shales or LQ veins and is dominated by leather-jacket faults. This fault style is also seen at Lockington. Nerrina occurs on a large, undeformed west-dipping fold limb containing thick, mineralised shales. At each goldfield, vein systems are strongly controlled by lithology. Tension veins develop best in thick sandstones. Other veins exploit weaknesses caused by axial-planar cleavage and spaced cleavage/radial joints.

Given the variability in structural and mineralisation styles that arises from differing stratigraphies across the central Victorian goldfields, it is important that geologists avoid being model-driven and rely too heavily on observations they have made in other areas. The Fosterville system evolves differently to the south as the shales thicken (Figures 4–6). Nerrina is

across the freeway from Ballarat East but the geology is completely different. It is important that geologists monitor facies evolution as mining and section drilling progresses and are alert to likely changes in stratigraphy and structural style. Geologists should be keen to identify former channel margins and thick shale units. When such environments have been recognised the search for gold-bearing reefs can begin.

## Acknowledgements

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