Structural Constraints and Localization of Gold Mineralization in Leather Jacket Lodes, Ballarat, Victoria, Australia

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Abstract

Gold mineralization at the Ballarat East deposit, central Victoria, Australia, is hosted in lodes that are historically known as “leather jackets.” These are quartz-dominant vein arrays related to low-displacement, W-dipping faults (≤45°) that transect the core and/or eastern limb of tight, asymmetric N-S-trending anticlines. The leather jacket lodes typically have dip extents from 5 to 65 m, widths of ≤20 m, and strike lengths up to hundreds of meters, but their along-strike continuity is disrupted by oblique, low-displacement listric faults known as “cross courses.” The gold lodes are characterized by distinct phases of sulfide paragenesis with minor gold + arsenopyrite + pyrite defining the early sulfide stage. Late-stage coarse gold was precipitated with galena + sphalerite ± pyrrhotite ± chalcopyrite (late pyrite also occurs). The gold mineralization events are linked to low-strain mineralized fracture networks, which are closely related to the final deformation stages and the amplification of the major folds enclosing the lodes. This amplification produced domal fold culminations, with plunges ≤30°, and localized minor parasitic folds with shallower plunges (≤10°). A network of dilation sites, on the W-dipping faults, preferentially developed in the cores of anticlines, particularly in zones where there are changes in strike of bedding or fault bifurcation and refraction through contrasting sandstone and interbedded packages of sandstone and shale.

Numerical three-dimensional simulations were undertaken to test our geologic observations and replicate conditions controlling the emplacement of the leather jacket lodes. Two different scenarios were investigated: first, to determine how changes in the local stress field orientation influences dilation and fluid infiltration; secondly, to test variations in fault geometry during the last stages of deformation—that is, within the final 2% of shortening, when most of the mineralized sites were created. Results show that strain and fluid flow localized along refracted sections of faults and around changes in dip, specifically on the shallower dipping sections within subvertical sandstone units. This is consistent with the observation that high-grade gold-bearing quartz is associated with localized changes in fault dip in thicker sandstone and sandstone-shale packages. There was also a component of strike-slip motion and near-field NW-to-SE or N-to-S stress fields, which can be attributed to the development of a component of out-of-plane motion during the development of fold culminations. The preferred model for the distribution of the high-grade auriferous vein arrays defining the leather jacket lodes is one of fold amplification and extension parallel to the fold axes, which produced an increasing out-of-plane relaxation. The main fluid conduits responsible for the leather jacket style of mineralization involve infiltration along steep bedding-parallel faults and veins that link up with the arrays of low-displacement W-dipping faults.

Introduction

The gold lodes at Ballarat East present particular challenges for both mining and exploration targets because they represent a very discontinuous style of quartz vein development in comparison to many other orogenic gold deposits in central Victoria, such as those found in the Bendigo goldfield (Willman, 2007; Wilson et al., 2013) or the Castlemaine goldfield (Cox et al., 1991; Willman, 2007). In common with the other gold lodes in central Victoria, the Ballarat East gold deposit is dominated by narrow quartz veins with disseminated gold particles (Dominy et al., 2008), and it shares similarities in terms of relative timing and being hosted by Ordovician turbidites within the Bendigo zone (Fig. 1). These host rocks are compressed by an initial deformation (D1) into upright, N-S-trending folds (Willman, 2007) in response to an E-W shortening during the Late Ordovician to Early Silurian Benambran orogeny (455–440 Ma). In spite of these similarities, Ballarat poses particular problems because of inherent geometrical, geologic, and grade complexities along strike. At the Bendigo deposits the auriferous quartz reefs are closely associated with open, upright, chevron-shaped folds (wavelengths ~400 m) and steep-dipping (~70°) limb thrusts (Leader and Wilson, 2013). These reefs have along-strike extents of many kilometers and a regular repetition in the hinges of anticlines across the gold-producing district (Willman, 2007). In contrast, the lodes in the Ballarat East deposit are confined to a set of closely spaced (wavelengths ≤200 m) asymmetric, tight to isoclinal anticlines with overturned eastern limbs. Within these folds there are quartz-rich en échelon vein array networks linked to vertically stacked W-dipping faults (≤45°), which have limited along-strike continuity (≤200 m). Furthermore, the final stages of mineralization at Ballarat are related to a N-S extensional event, which disrupts the areas of earlier mineralization. In contrast, the reefs at Bendigo are overprinted by an E-W...
crenulation cleavage related to N-S compressional event, which produces dilatant jogs and controls the areas of high-grade mineralization (Leader and Wilson, 2013).

The majority of the orogenic gold deposits in central Victoria are intimately associated with faults, which accompany the major folding events and provide fluid pathways that facilitate gold deposition (Willman et al., 2010; Wilson and Leader, 2014). Fluid infiltration and deposition of the coarse gold observed at Ballarat East (Dominy, 2006) are intimately related to such faulting events. Faults in the Victorian crust occur in two distinct regimes: a deep system accompanied by slow convective flow in the basement (Willman et al., 2010), and a shallow fault system with faster convection and flow into an overlying turbidites, such as at Ballarat East (Wilson and Leader, 2014). Although there are conflicting models proposed to explain the origin of the gold (e.g., Bierlein

Fig. 1. Geologic map and representative structural data from the Ballarat East goldfield. (A) The Ballarat East (BE), Ballarat West (BW), and Nerrina (NG) deposits are located within domal culminations of the Ballarat anticlinoria, in the hanging wall of the Williamson Creek fault (modified after Taylor et al., 1996). The position of the Canadian and Eureka gullies has been suggested to correspond with the surface trace of the postulated Blue Whale fault, which is interpreted to be a shallow (≤ 40°) W-dipping fault zone. The Late Devonian Mount Egerton Granite intrudes the zone between the Blue Whale and Williamson Creek faults. The Williamson Creek fault defines a boundary between the basal Lancefieldian and overlying Bendigonian section of the lower Ordovician Castlemaine Group. (B). Location of the Bendigo zone in Victoria. (C-G). Equal-area lower hemisphere projections of structural data shows that parasitic folds are doubly plunging asymmetric E-verging folds that are cut by generally W-dipping faults, with a range of fault, joint, and vein geometries discussed in text.
and McKnight, 2005; Large et al., 2009; Phillips and Powell, 2010), the timing of the gold mineralization in any of these models involves metamorphic devolatilization from deeper crustal sources, which occurs syn- to postpeak metamorphism (Wilson et al., 2009). A recent model proposed for the formation of the Victorian deposits suggests that the gold is sourced from the surrounding turbidites (Large et al., 2009). This model requires orogenesis to redistribute gold and other metals from the local sedimentary rocks into quartz veins. Other workers have more recently argued that the gold is externally derived from deeply sourced auriferous metamorphic fluids that have been focused along faults into a restricted vein network (Fairmaid et al., 2011; Wilson et al., 2013).

The Ballarat East deposit (56 t Au) is the largest of three deposits within the Ballarat region (Fig. 1), with extensive mining occurring during the later 19th and early 20th centuries, before closing down in 1918, with renewed gold production commencing in 2005 at the Woolshed Gully mine (Williams and Sykes, 2008), where 5.7 t Au averaging about 6.2 g/t Au has been mined between 2005 to 2015, and is still ongoing. Historically, mine exploration on the Ballarat East line was accomplished by tracking thin pyritic horizons, termed “indicators,” to the intersection with predominantly W-dipping (≤45°) quartz lodes known as leather jackets (Fig. 2A, B). Indicator beds were believed to indicate enrichment of gold at the intersection with quartz veins (Lidgey, 1894). A long-held belief, based on the proximity and coarseness of nuggety gold, was that the indicator beds, which contain pyrite and carbonaceous material (Baragwanath, 1923), may be the source of gold (Gregory, 1907). Subsequently d’Avergne (1990) inferred that indicator beds represent bedding-parallel cataclasites, equating to slip surfaces or faults, on the limbs of the isoclinal folded sequence, which acted as a conduit for mineralization that hosts the quartz lodes. The historic subdivision of quartz lodes and veins in the Ballarat goldfield (e.g., Baragwanath, 1923) has been based on their orientation and relationship to bedding: (1) fissure lodes (bedded lodes); (2) verticals (breached hinges or axial planar faults); (3) leather jackets (Fig. 2; namely, bedding oblique, W-dipping reverse faults); (4) spurs or subhorizontal tension vein arrays, and (5) stockworks usually associated with thin bedded faults or shallow-dipping veins in the hinge of folds. However, many of these vein types are transitional or a combination of different stages of vein development (Fig. 3).

In this paper we provide a robust structural framework based on orientation and timing relationships between folds, faults, and the mineralized veins to understand the origin of the leather jacket style of mineralization. Using detailed underground mapping, drilling information, and surface outcrops we were able to develop a coherent chronology of the deformation, vein development, and mineralization events for the Ballarat East deposit (Table 1). Observations from the vein and fault movements are used to develop a model for gold-bearing vein formation with respect to the structural evolution of the deposit. By using explicit modeling we demonstrate how our understanding of the local geometries of faults and stress field controls the localization of the gold mineralization.

Local Geology

Stratigraphic setting

The host rocks to the Ballarat goldfield belong to the basal Lancefieldian succession of the Early Ordovician, Castlemaine Group (VandenBerg et al., 2000), which consists of thin- to medium-bedded packages of sandstone, mudstone, and black shale. These beds contain lithofacies associations inferred to have been deposited as channelized deposits in a turbidite fan (Boucher et al., 2008). At a mine scale these units have historically been named on the basis of their physical properties. For example, the three major sandstone units are defined as “Big,” (≥10 m wide), “Little,” and “Amalgamated,” which are all important hosts of quartz veining and gold mineralization. Similarly, the shales, which have a prominent cleavage, are referred to by their prospective empirical widths, the “Four-Foot slate” and the “Twelve-Foot slate,” while those shales known to have the potential for gold mineralization are termed the “Mundic” (pyritic) slate and “Indicator slate” (Osborne, 2008). The oldest shale stratigraphic unit identified at Ballarat East is the Barone shale (Fig. 4) while the Duchess shale unit is located higher up in the sequence; however, these units are difficult to correlate along strike and change dramatically at a mine scale with additional complexity in correlation introduced because of folding and later faulting. At the mine scale there is a change in lithology (Boucher et. al., 2008) from sand-dominated beds predominantly in the south to shale-dominated units in the north. Packages of interbedded shale and sandstone units occur in the central region of the goldfield (Fig. 4).

Structural and metamorphic setting

The Ballarat East goldfield is dominated by N-trending tight folds and cleavage development, and lies on the eastern limb of a regional anticlinorium known as the Ballarat anticline (Taylor et al., 1996). A striking feature of most folds is their strong E-verging asymmetry, noncylindrical nature and subvertical or overturned eastern limbs (Fig. 3A). Wavelength and amplitudes range between ~50 to 200 m with interlimb angles ranging from ~0° to 30°. Bedding (S0) and cleavage (S1) relationships suggest that fold axial surfaces are typically inclined to the west (Figs. 1C, D, 3A) and their intersection produces a prominent lineation (Fig. 5A), which enables fold plunges to be readily identified. The main deformation, producing the folds and steep W-dipping limb thrusts (>80°), is recognized as the D1 stage of deformation (Table 1). With further compression, there is a progressive transition into an episode of fold amplification and brittle fracturing (D2) accompanied by the evolution of discrete sets of mineralized veins (D3), whose timing relationship depends on the geometry of the earlier folds.

The major folds identified in the Woolshed Gully mine from W to E are known as the Norwegian, Sulieman, Scandinavian, First Chance, Oregon, and Exchange anticlines (Fig. 3A). However, their persistence with depth is sometimes difficult to ascertain because of the truncation by W-dipping faults. In the mine area there are major fold plunge reversals; in the southern area of the mine the folds are S plunging at ≤30°, with northerly plunges in the north (Fig. 4). The folds are cut by linked faults that locally may be (1) bedding-parallel, (2) cleavage-parallel, or (3) multiple sets of...
Fig. 2. Interpreted cross sections of the main Ballarat East goldfield. (A). Historic section of mine workings that illustrates the W-dipping leather jacket lodes (from Brown and Hogan, 1932). (B). Distribution of the major W-dipping leather jacket faults with respect to the main sandstone horizons (modified after Boucher et al., 2008). (C). Schematic cross section, illustrating the different vein-forming environments and distribution of alteration and slip surfaces seen in units such as the Amalgamated sandstone.
stacked W-dipping reverse faults (~45°, Fig. 2B, C), and the very occasional E-dipping fault, all of which have developed at different times and predominantly affect fold crests and upper limbs. The dominant W-dipping faults (Fig. 1F) are related to the leather jacket lodes and tend to be best developed in the core and eastern limbs of the chevron folds (Fig. 2), but die out both downdip and along strike, and may be widely variable in their strike and dip. These include a subpopulation...
of faults that dip at ~80° toward an azimuth of 220° (Fig. 1F). The folds are also offset by several major NE- to ENE-trending faults that have dextral/normal displacement of up to several hundred meters (Fig. 4). These offsetting faults were historically known as “cross courses.”

The gold-bearing lodes at Ballarat East are located within and adjacent to the W-dipping faults (Fig. 1F) as steep E-dipping quartz vein arrays (Figs. 1G, 2). Their along-strike continuity is short (≤200 m) and confined to what are known as “compartments,” which are bounded by major ENE-striking cross-course faults (Fig. 4). These faults have an important control on the number of ounces/vertical meters mined as they offset and control the distribution of many of the mineralized quartz veins. Cross-course faults range from small joint-like cracks with <10-cm vertical displacement to damage zones up to several meters in thickness with >100 m of lateral displacement (Table 2). The smaller faults generally have NE or NW strikes, with ankerite infilling, are cut by E-W-trending joints (Fig. 1E), and overprint an early set of dikes (Fig. 5D). In general, the NE-trending cross-course faults dip either NW or SE with a movement sense that is predominantly right-lateral (dextral) with minor (<3 m) reverse dip-slip movement. The NW-trending cross-course faults dip SW and display left-lateral (sinistral) strike-slip displacement with minor dip-slip movement.

The amount of movement on several of the larger ENE-trending faults can be constrained by offset of the more contiguous fold hinges, stratigraphic units, and the W-dipping faults. Piercing point analysis (Ragan, 1973) of several faults (Table 2) shows that movement on these faults is dominated by dip- rather than strike-slip offset. In each case the northern side of the fault has gone down relative to the southern side so that progressively shallower parts of the stratigraphy are present at the same level toward the northern end of the deposit in the Carlton, Golden Point, and Llanberris compartments. Based on historic data each compartment has different ounces/vertical meter (OVM) of contained gold.
deposit (Fig. 4). Mineralized vein arrays at shallower levels toward the southern end of the deposit are located at greater depths toward the northern end of the deposit. These larger faults can comprise heavily fractured quartz vein material and country rock in a puggy clay matrix.

At the base of the current mine workings it has been postulated that there is a shallow-dipping (~40°) Blue Whale fault, developed within the hanging wall of the major crustal-scale Williamson Creek fault (Fig. 1A). However, an identification of the Blue Whale fault has not been conclusively established with current diamond drilling.

Metamorphic grade in the Castlemaine Group in the immediate vicinity of the underground workings is greenschist facies and lies within the epizonal field (Wilson et al., 2009), whereas, geochemical studies suggest that mineralized fluids were derived from a deep-seated source generated by metamorphic devolatilization (Fairmaid et al., 2011) and not in equilibrium with the host rocks. Previous studies at Ballarat have suggested that the gold mineralization events are broadly constrained between 460 and 400 Ma (Bierlein et al., 1999).

**Intrusive events**

At least three phases of dike emplacement are associated with areas of high-grade gold mineralization. Most dikes are recognized by their hydrothermal assemblages that include sericite, chlorite, kaolinite, and carbonate. The youngest generation
of dikes was derived from a mafic source (Brock, 2009) and postdates the main phase of mineralization and intrudes pre-existing structures. The earlier dike sets can be divided into an older set overprinting D1 quartz veins, and a younger unaltered generation that may be related to the intrusion of the Mount Egerton Granite (Brock, 2009), which crops out ~5 km east of the Ballarat East goldfield (Fig. 1). A 368 ± 4 U/Pb zircon age from these latter dikes (Arne et al., 1998) places a youngest estimate on the age of mineralization, whereas the results of 40Ar/39Ar dating of micas associated with the mineralization range between 460 and 400 Ma (Bierlein et al., 1999).

Lode distribution related to strike of folds

The along-strike distribution of quartz-bearing lodes at Ballarat East is highly variable in comparison to the uniform quartz-bearing reefs at Bendigo (Leader et al., 2013). The style of the leather jacket lodes at Ballarat East, named after the tassels that hang from the sleeve of a cowboy's leather jacket, are very discontinuous along strike and are closely controlled by the geometry of folds and their interaction with faults (Fig. 3A-C). The First Chance and Suliemen N-plunging (≤ 10°) fold pairs can be traced throughout the northern two thirds of the deposit. Southward, from the Golden Point compartment (Fig. 4), there is an increase in the number and complexity of parasitic folds developed, which include the Scandinavian anticline and First Chance Minor folds (Figs. 3A, 5B). The parasitic folds have shallower plunges (≤ 10° N) and have limited lateral extent (<300 m). Along the steep-dipping eastern limbs of each fold there are bedding-parallel reverse faults containing slickenside striations that pitch ~90°. Faults trend parallel to the N-S hinge line, and then progressively turn NNE (Fig. 3B) as they truncate the hinge zone. In hinge regions of major folds, where there is an initiation of parasitic folds, there are subtle strike changes in bedding of <10° and refraction of the bedding-parallel faults with the development of the leather jacket zones of mineralization (Fig. 2C). In plan view, the translation of the hinge is typically horizontal and right-handed, that is, a fold hinge is refracted to the right or in a dextral sense (Fig. 3B). These strike changes of the folds and faults coincide with increases in the width of the mineralized zones (Fig. 3C). Similar width increase of mineralized zones is also observed around fold hinges that refract to the left, or in a sinistral sense.

Table 2. Piercing Point Analysis (Ragan, 1973) of Movements on Major Cross-Course Faults Identified in the Woolshed Gully Mine

<table>
<thead>
<tr>
<th>Cross-course fault</th>
<th>Dip-slip</th>
<th>Strike-slip</th>
<th>Net slip</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seven Stars</td>
<td>&gt;74 m N side down</td>
<td>32 m dextral</td>
<td>81 m along (right-lateral)</td>
</tr>
<tr>
<td>Charlie Napier</td>
<td>68-99 m N side down</td>
<td>11-16 m dextral</td>
<td>72-103 m along (right-lateral)</td>
</tr>
<tr>
<td>Bull and Mouth</td>
<td>35 m N side down</td>
<td>4 m sinistral</td>
<td>36 m along (left-lateral)</td>
</tr>
</tbody>
</table>

The area containing the Mako leather jacket lode (Fig. 6A-E) is within an elliptical lens with up to four NW-dipping fault splays striking ~030°, and located east of the N-striking Mako fault (Fig. 6C). Within this there is a damage zone, ~10 m wide and 20 m in height, containing an array of subvertical or steep E-dipping quartz veins (5–20 cm wide) hosting coarse free gold. Vertical veins, which may be parallel to cleavage, are best developed where faults are proximal to the bedded fault with a horizontal separation of no more than 10 m (Fig. 6). In the marginal regions of subvertical vein development, veins are thinner, more laminated, have higher concentrations of arsenopyrite, and have W-dipping fault splays that preserve slickenside striations. In such areas the apparent displacement varies from left-lateral, through zero to right-lateral.

Lodes observed in cross section

In cross section, en échelon extension veins characterize the leather jacket lodes, and they are discordant to bedding and intimately related to the W-dipping faults (Fig. 6). Across fault planes, offsets of the extensional veins cannot be correlated with amount of fault displacement, as there is generally a major component of out-of-plane movement, as evidenced from the orientation of shallow-plunging slickenside lineations (Fig. 6A, B). Large irregular quartz masses or stockworks can be identified in the hanging wall of the faults (Fig. 6F), but along strike these grade into en échelon vein arrays (Fig. 6G). The majority of these lodes are preferentially located on the subvertical eastern limb of the folds, but depending on the intensity of the W-dipping faulting, bedding may locally become warped and display a variety of steep E or W dips (Fig. 6G).

Lodes that conform to a stockwork style of mineralization in cross section (Figs. 3D-F, 6F) are also intimately associated with parasitic folds. An example is the First Chance Minor anticline, which folds the Amalgamated sandstone, defining a tight N-plunging fold (10°–20°; Fig. 3D). Here the ore shoots and W-dipping vein arrays rapidly change style along strike, as follows:

1. Where a fault breaches the anticline (Fig. 3F).
2. Within the hinge of the folded Amalgamated sandstone (Fig. 3D). In the First Chance Minor anticline area there is an obvious lack of throughgoing fault, with veins forming...
a distinctive radial pattern emanating from the overlying black slate horizon. This radial arrangement of veins was also related historically to signify gold-rich veins (Baragwanath, 1923), and we attribute these to tensile fractures.

3. As subvertical veins originating from W-dipping reverse faults, which may develop as a throughgoing structure within the Amalgamated sandstone (Fig. 3E).

4. Veining occurs in an overlying thinly bedded package (<2 m wide) of sericite-carbonated altered black slate and sandstone, where V2 vein arrays (Table 1) are typically E dipping and extend from a western limb fault or antclinorium axis.

Bedding-cleavage intersection lineations (Fig 5A) indicate the First Chance Minor fold axis has a 10° to 20° northerly
plunge (Fig. 3G). There is a difference in the rake of the fold plunge and fault movement where there is a change from breached versus nonbreached fold hinges. Stockwork vein development occurs in sites of fault refraction in the vicinity of the fold hinge (Fig. 3D, E). Zones of faulting are related to a greater areal extent of alteration, for example, alteration observed in the slate that overlies the Amalgamated sandstone on the western limb of the First Chance Minor anticline (Fig. 3F). This slate has a high concentration of chlorite, graphite, siderite veinlets and hosts a distinctive bedding-parallel laminated quartz veins with up to 30% arsenopyrite and minor gold (Table 3).

Distribution of lodes along ore drives

In longitudinal sections, subparallel to fold axes, the quartz-rich lodes have the appearance of flat or gentle-dipping quartz sheets (Fig. 7A). In the PR385 ore drive (Fig. 7B) the quartz lodes are dominated by flat-lying V2 veins with visible native gold overprinted by W-dipping faults and shallow dipping V3 and V4 veins (Table 1). The V2 veins are also offset by SW-dipping cross-course faults. The footwall of the listric-shaped cross-course faults host a proliferation of mineralized V3-V4 veins and the presence of brecciated carbonate veins. These fault-vein relationships indicate that there is a component of extension with normal faulting of the variably dipping V2 veins (Fig. 7B) to produce both dextral and sinistral separation in plan view.

Within the lodes, striations are found along surfaces of the W-dipping faults. These striations are characterized by carbonate crystal fibers or grooves with thin coatings of graphitic fault gouge. Within the majority of the steeper dipping faults there may be two lineation sets; the first is a steep-pitching lineation consistent with flexural slip during E-W compression. The second set of shallow plunging striations indicates local N-S or NW-SE shortening. The magnitude of displacements on late brittle faults, which includes normal faults, is usually small (≤5 m). The majority of these faults have dips that are identical to bedding or older veins (Fig. 8), and hanging-wall transport directions can be defined using a combination of offset bedding, extensional veins and fault structures (Miller and Wilson, 2004). Hanging-wall transport on these faults shows two dominant directions either top-to-the N or top-to-the-S and varies considerably as they are localized on preexisting structures within the variably plunging folds. This variable N-S sense of transport is particularly obvious on brittle faults related to V2/V3 sphalerite + gold-bearing quartz-carbonate veins (Fig. 8). Contemporaneous with N-S transport is the development of conjugate sets of listric-shaped cross-course faults (Fig. 7B). Movement indicators such as slickenlines on cross-course faults are scarce, but using offset veins dextral and sinistral movements can be recognized. The shortening direction inferred from taking the acute separation angle between the dextral and sinistral fault planes can be attributed to an E-W bulk shortening (Fig. 8G).

Vein Chronology Related to Deformation History

To establish a rigid vein chronology is difficult as there is repeated overprinting, a complex variation of geometries in both two and three dimensions, with deposition of successive phases of quartz-carbonate and dike emplacement along

<table>
<thead>
<tr>
<th>Vein</th>
<th>Morphology</th>
<th>Mineralogy distinctive features</th>
<th>Structural setting and shortening direction</th>
<th>Grade</th>
</tr>
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<tbody>
<tr>
<td>V1</td>
<td>Width &lt;5-cm cleavage-parallel or-perpendicular tension veins (mode 1) strike N-S, subvertical or subhorizontal E-dipping</td>
<td>Qtz ± Ank (sometimes boudinaged)</td>
<td>Either— (1) Flexural slip on bedding accompanying D1 chevron folds (2) Vertical extension on refracted fractures in sandstone</td>
<td>Nil</td>
</tr>
<tr>
<td>V2</td>
<td>Width &lt;5 to 50 cm (mode 2 veins-normal offset), subvertical to moderately E-dipping</td>
<td>Qtz ± Asp, Py, Ank, Chl; may show Chl being replaced by Qtz</td>
<td>Fault and shear zones involving bedding-slip during flexural slip East to west shortening</td>
<td>Nil unless overprinted by later vein event</td>
</tr>
<tr>
<td>V3</td>
<td>Width &lt;1-m tension veins (mode 2 – variable normal and reverse offset), subhorizontal to moderately N- or S-dipping; rollover tips and tension gashes on V3, fissure lodes</td>
<td>Qtz ± Chl, Ank, Sid, Mus, Kao, Sp, Gn, Cpy, Po, and Au; “Bucky” quartz gradational to breccia veins with typical fresh green coloration, weathers to pale white clay at shallow levels</td>
<td>Reactivates and extends margins of V3 veins especially where proximal to strike-slip on early fault and/or footwall of cross-course faults; possibly responsible for fissure lode formation East to west shortening and Northeast + southwest extension</td>
<td>Variable 5–200 g/t</td>
</tr>
<tr>
<td>V4</td>
<td>Width &lt;5-cm tension veins (modes 1 and 2), subhorizontal to moderately N fault-dipping; cut across V2 and V3, merge into internal stylolites of V4 veins</td>
<td>Ank ± Qtz ± Sph, Gn and Au</td>
<td>Reactivates margins of V2 veins especially where proximal to strike-slip on D1 fault and / or footwall of cross-course fault Northwest to southeast + north-south shortening</td>
<td>High grade</td>
</tr>
</tbody>
</table>

Mineral abbreviations: Au = gold, Ank = ankerite, Asp = arsenopyrite, Chl = chlorite, Cpy = chalcopyrite, Gn = galena, Kao = kaolin, Mus = muscovite, Po = pyrrhotite, Qtz = quartz, Sid = siderite, Sph = sphalerite
preexisting structures. It is possible to broadly subdivide the gold-related veins into two stages. The first stage was related to an early, weak gold mineralization event that formed V1/V2 quartz veins (Fig. 9A-C) containing gold and arsenopyrite (Table 3). A structurally later event, but related to the main gold-bearing set of quartz and carbonate V3-V4 veins, represents the second stage. These V3-V4 veins host gold, sphalerite-pyrite, minor galena, and preserve abundant stylolites. The important structural control on all vein development is their association with faults that propagate across fold hinges and are either associated with bedding-parallel veins that link on opposing limbs of a fold or are veins that link with cross-course faults (Fig. 7B).

V1 veins

These veins are the earliest identifiable vein set and are either bedding-, cleavage-parallel, or tensional veins with tension fractures infilling perpendicular to bedding (Fig. 3G). These are attributed to “mode 1” or tensile fractures (Atkinson, 1987), related to tight E-W folding of the stratigraphy. On fold limbs these may be laminated (Fig. 10A-C) and accompanied with steep (>80°) bedding-parallel faults, generally characterized by graphite-rich gouge in zones of ≤1 m wide, sometimes referred to as “indicator beds” that may also contain finely laminated and folded quartz-carbonate veins and areas of sericite-chlorite-pyrite-arsenopyrite alteration. Veins of this generation may also occur as thin, vertical, cleavage-parallel and are unmineralized (Baragwanath, 1923), except where they are crosscut by later faults or vein sets. There are also arrays of subhorizontal or E-dipping V1 extensional quartz veins referred to as “spur veins” that are perpendicular to the margins of the steep W-dipping beds (>80°) (Fig. 2C). Offsets on these veins along known “indicator” units (e.g. Four-foot and Seven-foot shale) may be up to a meter or they may become folded (referred to as “rollovers”; Osborne, 2008) with local occurrences of visible gold.

The V2 veins are generally laminated and are found on fold limbs (Fig. 10A), and around fold hinges (Fig. 10B, C). The laminated character of these veins suggests that an ankerite- and quartz-rich fluid was introduced initially along bedding and was episodic, comprising several quartz/carbonate generations formed by successive opening events (Fig. 10C). Arsenopyrite is the most abundant sulfide within V1 veins and adjoining wall rock, as euhedral and sometimes twinned grains. Arsenopyrite occurs within and on the margins of quartz veins as massive clusters and crude laminations and is also a prominent alteration product in wall rocks, particularly sandstones. Pyrite is nearly as abundant as arsenopyrite and has a similar distribution in and around quartz veins but is most prominent in altered shales, which are sometimes referred as indicator beds.
Fig. 8. Extensional structures with corresponding sense of movement superimposed on preexisting V1 and V2 veins. Stereographic nets are equal-area lower hemisphere projections and show the hanging-wall transport direction at pole to fault. Faint lines depict veins or cleavage, thicker lines are faults. (A-B). Late N-dipping carbonate-quartz extension veins (V4) associated with gold and sphalerite splaying from southerly dipping faults (thick lines) that parallel V1 veins (WH189, pen for scale). (C). SE-dipping fault overprinting V1 and V2 veins on WH218 level (width of rock bolt platens 20 cm). This is offset by a bedding-parallel normal fault. (D). Enlargement of area with V1 and V2 veins crosscut by V3 carbonate-rich veins that lie on the faulted margin of a V1 vein. (E). Margin of V1 vein reactivated by fault that produces dilation sites in which extensional V4 veins are deposited. (F). Massive V1 vein in sandstone offset by normal fault that juxtaposes a shale unit containing a laminated V2 vein (WH218 level). (G). Orientation of cross-course faults identified in PR385 and 405 levels with sense of movement determined from offset bedding and V1-V2 veins. The E-W-shortening direction is inferred from their conjugate relationship.
V2 veins

These veins crosscut fold hinges and the S1 cleavage (Fig. 11A, B) and are generally quartz-filled mode 2 fractures (Atkinson, 1987) in which there is either minor (<1 m) normal or reverse displacements, and they carry little gold (Fig. 10D). The V2 veins offset V1 veins, and on overturned W-dipping bedding, dip at moderate and steep (45°–81°) angles and have a normal shear component with displacements of 5 to 15 cm (Fig. 8C). They are also spatially related to steep faults in altered shale (Fig. 8F) and generally refracted in sandstone units (Figs. 8C, 9C). V2 veins typically range from 5 to 50 cm in width and may persist along strike for up to 20 m as simple planar veins, but they are significantly modified by V3 and V4 vein development where they pass into cross-course fault zones. At Black Hill (Fig. 1), V2 veins coalesce into V3/V4 veins at a small gold-bearing cross-course fault (Fig. 10E). This cross-course fault at Black Hill splays from bedding with a curviplanar geometry to form a lateral ramp that truncates both bedding and quartz veins with ~10 cm of normal movement. Prominent bedding-cleavage intersection lineations at Black Hill indicate that the cross-course fault originates where the local folds plunge ~30° to the north (Fig. 10E).

V3 veins

Crosscutting the V2 veins are narrow, flat S- and E-dipping tension gashes, which are designated as V3 veins (Table 3). The V3-stage vein development appears to coincide with a major fault reorganization that was accompanied by the development of extensional dilation sites (Fig. 11C), two sets of slickenside striations, and the onset of a reverse and left-lateral (sinistral) motion. Moderately (10°–30°) E dipping V3 veins and major stockwork vein networks in hinge regions of preexisting folds dominate these vein types. The dip of these veins and their termination on bedding contacts suggest they formed as extensional fractures. Many of these veins can be interpreted as small-scale faults, but they are not due to shear failure, rather the result from shear displacements during opening and closing of tensile fractures.

The quartz in the V3 veins is composed of blocky or euhedral crystals, and superimposed on this quartz are also mineralized stylolites, which provide evidence for later fluid activity. In the center of some of quartz-rich areas are euhedral crystals with native gold that indicate open-space growth in free fluid. The sulfide assemblage of galena and sphalerite, although occurring less frequently than arsenopyrite, is evidently coeval with most of the gold within the V3 veins. Rutile, distinguished by an acicular habit, is also associated with sphalerite + galena ± pyrite. A further sulfide association of pyrrhotite and chalcopyrite occurs as massive zoned growths in association with sphalerite and gold.

Gold grades in the leather jacket lodes vary greatly both across the width and along strike from low, ~20 to 30 g/t to high >50 g/t (Table 3). Assays on niche samples along representative examples of leather jacket lodes indicate that the original V2 veins contain up to 57 g/t of gold, whereas overprinted V2/V3 veins recorded assays up to 225 g/t, but also several results of <1 g/t (e.g., PR385 ore drive; Fig. 7B). In the
Fig. 10. Early vein development at Ballarat East. (A). Bedding-parallel quartz veins and initiation of en échelon vein arrays on small displacement W-dipping faults (LLBD596 NOD1 38125 mN; width of photo 4 m). (B). Drill core sample of folded early laminated quartz-ankerite vein, where S_0 is at an angle to and deformed by S_1. (C). Cross-polarized photomicrograph showing detail of folded veins in (B) composed of quartz and ankerite. (D). Flat-lying laminated V_2 vein with arsenopyrite (WH237 level; scale on ruler is centimeters). (E). Geometry of veins and faults superimposed on N-plunging fold at Black Hill. Red box highlights region of lateral ramp, where cross-course fault splays from bedding.
Fig. 11. Timing relationships of veins and faults in shale sequences. (A). Quartz veins (V2) transecting hinge of fold with vertical cleavage in slate unit (PR385 south ore drive). The margins of the quartz veins are overprinted by V4 carbonates, sulfides, and visible gold. Transecting the cleavage are low-angle W-dipping normal faults, between which are pull-aparts with siderite, gold, and sulfides infillings (scale on ruler is centimeters). (B). V2 quartz vein on limb of fold in a cleaved slate. The margins of the quartz vein are faulted and overprinted by later arsenopyrite, gold, and siderite. (C). Boudinaged sericitic slate with a concentration of quartz with late kaolin + chlorite (green) in the boudin neck and crosscut by V2-V3 veins. The V2 veins are rotated into slate with a normal sense of shear. Thin V4 veins with siderite infilling crosscut earlier vein sets (near 25 cm ruler). Within the sandstone is a W-dipping fault with apparent normal movement (F-F) that is refracted into and becomes parallel to altered slate. The fault has N-over-S sense of transport to produce an apparent normal offset. (D). East-dipping carbonate-rich V4 veins overprinting earlier V2 quartz, whose margin contains a minor cross-course fault with a sinistral movement component, and crosscut by late E-W-trending vertical (J) extensional joints (Sovereign 469 south ore drive). The overall shear sense in this area is south to north. (E). V4 stylolite seams containing gold and sphalerite overprinting earlier quartz-rich vein. (F). Slickenside striations associated with V4 veins (mesh spacing 10 cm).
more mineralized regions, the bedding-fault intersection has a shallow plunge with bedding trending N-S. In contrast, in regions of the lode where gold grades are low, fault dips are more variable. Gold grades can also be high (>50 g/t) adjacent to cross-course faults where there are late veins or in the vicinity of altered dikes (Fig. 12).

**V4 veins**

Veins and stylolites propagate at dip changes and in subhorizontal sections of preexisting veins as thin (<5-cm) carbonate veinlets or thin quartz veins (Fig. 9E). These veins host gold and sphalerite and are defined as V4 veins (Fig. 11D). These veins generally dip 10° to 30°, with both N and S components of shear (Figs. 8A, B, 11D), and are most pronounced within shale units. Their distribution is sporadic and largely coincident with the oblique fault splays and minor cross courses. The V4 veins on intersecting V2/V3 veins coalesce into crustiform and stylolitic carbonate laminations or fractures that preserve slickenlines (Fig. 11E, F). In most instances V4 veins are defined by a distinctive mineral assemblage containing carbonate + pyrite + sphalerite + galena + coarse gold (Fig. 11E). The V3/V4 veins may also be associated with lenses of kaolinitic + chlorite, ankerite, goethite, and minor biotite (Brock, 2009). They are generally boudinaged and overprinted by gold-bearing quartz veins (Fig. 12A, B) that predate the V4 vein networks. They are frequently parallel to flat-lying V3 veins or associated with steep-dipping laminated veins and are overprinted by a cleavage. Along their contacts there is an abundance of sulfides that include arsenopyrite, pyrite, and minor amounts of galena and chalcopyrite and vermicular chlorite intergrowths with quartz and occasional gold grains (Fig. 12C, D).

**Ore-stage assemblages**

The uncertainties of previous genetic models proposed for the Ballarat gold deposits (Lidgey, 1894; Gregory, 1907;
Baragwanath, 1923) stem from a lack of understanding of the stratigraphy, structure, and timing of quartz veining. This study shows that the main mineralization overprints the D1 deformation features that include an initial episode of quartz veining (Table 1). Quartz appears to have been precipitated in V1 veins prior to most of the gold, sulfides, hydrous silicate, and carbonate minerals, which have been recognized in V2 to V3 veins, as grain boundaries between the earlier quartz, and other phases are not in equilibrium (Fig. 13).

The majority of the laminated quartz veins are also overprinted by later quartz veins, which may be accompanied by crustiform carbonate or sericitic alteration, sulfides, and gold within stylolites (Fig. 13A-D). This quartz displays undulose extinction and serrated grain boundaries when associated with stylolites (Fig. 13D, E). Coarse gold (>300 µm) occurs as both native gold and as gold inclusions in fracture networks (Fig. 13F-I) within sulfides (Dominy et al., 2008), in V3 to V4 veins and overprints earlier laminated veins. Although each vein type has a dominant sulfide and alteration association (Table 3), more than one association may be present in any particular vein type. Gold generally overprints arsenopyrite and pyrite and may be in equilibrium with galena and sphalerite, but is typically disseminated as coarse visible gold in quartz.

Fig. 13. Representative drill core (A-C), transmitted (D), and reflective light (E-I) images, showing assemblages and textural features associated with gold-bearing quartz veins. (A). Laminated veins overprinted by later quartz veins and intense crustiform siderite and calcite alteration. (B). Ankerite and crustiform calcite confined to the margin of earlier quartz vein. (C). Laminated vein oblique to S1 cleavage overprinted by stylolites containing galena and sphalerite. (D). Cross-polarized photomicrograph showing subgrain development in vein quartz and hydrothermal sericite precipitated on grain boundaries. (E-F). Comparative cross-polarized and reflected light photomicrographs showing spatial association of quartz, calcite, arsenopyrite, and gold. (G). Reflected light image showing galena and gold in equilibrium, from a V2 vein. (H). Galena and gold within fractures and overprinting an earlier arsenopyrite grain. (I). Zoned arsenopyrite in quartz matrix overprinted by a stylolite that contains carbonate and gold. Abbreviations: Asp = arsenopyrite, Cal = calcite, Gal = galena, Qtz = quartz, Ser = sericite.
Integrated Model for Au Mineralization at Ballarat East

A model that incorporates the structural and vein histories (Tables 1, 3) observed in ore drives can be intimately linked to flexural slip folding occurring during the deformation history (Fig. 14). As the noncylindrical folds change profile (Fig. 14) they amplify and trigger the development of small-scale faults in the fold cores and within the overturned limbs. The folds inevitably become what are known as fault-cored folds (Shackleton and Cooke, 2007). In a flexural slip model (Ramsay, 1974) fault development in this type of system is a function of acute fold tightening during E-W contraction. With ongoing contraction, on either side of the pinned portions of the folds, there is a component of out-of-plane motion (Fig. 14B), where displacement vectors on the faults deviate from the E-W contraction (Shackleton and Cooke, 2007). This type of system can explain key components of the overall kinematic development in the Ballarat East gold deposit, which we have deduced from the sense of slip associated with mineralized veins and on faults.

Our observations indicate that the W-dipping, subvertical eastern limbs of these folds (Fig. 14A) are regions where fluid pulses were able to permeate, as evidenced by an abundance of bedding-parallel laminated veins, sericitic- and sulfidic-bearing altered shales (termed historically indicator beds). The interaction of indicator-type slate units with mineralizing fluid facilitated much of the local gold deposition. The system absorbed the initial phase of deformation linked to folding via flexural slip (D_1) with bedding-parallel faults and low-angle extensional V_1 veins forming on the limbs of folds (Fig. 15, Table 1). Bedding-parallel movement horizons are almost entirely restricted to shale or siltstone lithologies, often at or near lithologic boundaries (Figs. 8, 10A).

The extreme tightening and amplification of the near-isoclinal, reclined folds (D_2-3) initiated failure in the hinge zones of...
the competent sandstone beds and sandstone-shale packages, resulting in the formation of W-dipping reverse faults (Figs. 14C, 15A), which are related to the leather jacket lodes. The faults that accompany the leather jacket lodes are generally initiated on subvertical fold limbs and ramp up to become crosscutting in the hinge zone or splay into a set of curved faults (Fig. 6), which terminate in a set of en échelon quartz veins (Figs. 3C, 6). Fault bifurcation is particularly prevalent near the hinge zone of parasitic folds, which coincides with the development of dilation jogs. The related dilatational sites, filled by the mineralized veins, are created by space problems that arise in the hinge zone, where parasitic folds plunge at a shallower angle or opposite directions to the geometry of larger folds. By this stage local strain distribution is no longer coaxial, with simple shear and cataclastic flow accompanied by strike-slip movements playing an important role on the fold limbs (Fig. 14C).

During the D2-3 deformation stages (Table 1), V1 veins are offset by step-like displacements parallel to bedding (Figs. 8C, 15B) with a movement sense consistent for flexural slip (Tanner, 1989). However, much of the strain was confined to the shale units (or indicator beds) with further extensional fractures accompanied by quartz stockworks (Figs. 3D, 6F). V2 veining is nucleated in the late stages of folding, when the
operation of flexural slip on bedding gave rise to area changes and extensional strain in the limbs. The competence contrast between multilayers of shale and sandstone was high, as indicated by the presence of faults and veins. In summary, continued flexural slip is interpreted to have resulted in the formation of further bedding-parallel V3 veins and steep dipping V4 veins oblique to bedding with an en échelon pattern related to flexural slip veins (Fig. 15B).

The field data also indicate that there was then a phase of extensional movement on the W-dipping faults with the formation of V1 veins and cross-course faults (Fig. 14 D, E), which have geometries that cannot be linked to a purely two-dimensional flexural slip interpretation (Fig. 15C). Earlier veins are overprinted by later low-angle V3 and V4 veins that reflect a switch back to both reverse and extensional movements on the W-dipping faults (Fig. 15D-F). The onset of this later stage of oblique reverse motion on W-dipping faults, with a component of predominantly sinistral transpression, is identified from the NW-SE and N-S movement and paleostress reconstructions (Figs. 8, 15G). This is interpreted to be coeval with a redistribution of strain occurring in the overall fold and fault system. This redistribution of strain was also accompanied by the development of dilatational sites suitable for deposition of gold, particularly in V3/V4 vein arrays, from overpressured mineralized fluids.

The sets of conjugate cross-course faults (Figs. 7, 8G) are intimately linked to the last stage of E-W shortening (D6, Table 1) and the episode of V3/V4 vein development (Table 3). Their intersection with bedding-parallel movement horizons is parallel to late movement direction and associated lineations, observed on V3/V4 veins and cross-course faults, and with the same sense of displacement. These structures can be considered to be equivalent to lateral ramps (Horne and Culshaw, 2001) and vary from centimeter-scale (Fig. 11D) to linked systems (Fig. 10E) to throughgoing faults that create the compartmentalization of the Ballarat East goldfield (Figs. 4, 14). Therefore, throughout the evolution of the Ballarat East mineralized system there is an apparent E-W compressive event (Fig. 14), with no evidence of the N-S compression observed at Bendigo (Leader et al., 2013). This hypothesis is tested in the following section with a series of numerical models that simulate variations in the distribution of strain and fluid flow associated with the changes in strike of the bedding-parallel faults as they cross fold limbs.

Numerical Modeling Methods and Design

In order to understand the importance of early-formed bedding-parallel faults and the role they play in controlling the initiation of the W-dipping leather jacket system of lodes, we have used an explicit modeling technique. This allows us to constrain and test the influence of changes to the stress field, and evaluate how the variations in fault geometry influence the development of dilatant sites and fluid flow (Fig. 16). As described above, the leather jacket systems are characterized by a combination of four structural features: (1) in plan view, fault-bedding relationships suggest that strike and dip of pre-existing bedding-parallel faults change during the late stages of deformation (Fig. 17A, B); (2) most leather jacket vein systems occur in thick sandstone units (Fig. 2B, e.g., Big or amalgamated sandstone); (3) leather jacket systems are related to ~45° W-dipping faults that are refracted as they transect thick sandstone units (Fig. 17D); (4) in a N-S-oriented long section the strike change occurs close to shallower plunging folds (e.g. First Chance Minor fold) adjacent to an anticlinal culmination defined by the double-plunging N-S-striking folds (Fig. 4).

In the numerical simulations, the geometric relationship between bedding and fault refraction was examined to quantify the optimal structural relationships for focusing dilation in the leather jackets during gold mineralization (Robinson et al., 2009). The process involved two stages of modeling. First, we constrained the orientation of stress fields using a static fault geometry and known gold distribution (as a proxy to dilation and fluid flow). This reverse engineering phase aimed to produce fault kinematics consistent with those inferred from structural observations and localize positive volume strain and fluid consistent with gold distribution (Fig. 17C). In a second phase of modeling, a wide range of fault-bedding relationships were evaluated under optimal stress field conditions identified in the first phase of modeling. Incremental changes to fault-bedding relationships were used to identify optimal geometric conditions for producing dilation, and sensitivity of dilation and fluid focusing to changes in fault attitude (Fig. 17E, F).

Model technique

FLAC3D (Fast Lagrangian Analysis of Continua; Itasca, 2001) was used to simulate deformation and fluid flow. In this code, deformation is coupled with fluid flow through the influence of fluid pressure on effective stress and the effect of deformation on permeability. FLAC3D uses the finite difference method to solve partial differential equations and thus simulate the behavior and evaluate the response of the physical materials according to the elastic-plastic Mohr-Coulomb constitutive law (Vermeer and de Borst, 1984; Zhang and Sanderson, 2002). As an explicit modeling method, a rectangular mesh of hexahedral elements represents each surface. In contrast, an implicit method is where the surface is defined by direct interpolation of input scalar datasets (Vollgger et al., 2015). Physical properties such as density, permeability, and porosity, and mechanical properties that determine how a material responds to elastic and plastic deformation are assigned to the hexahedra in order to represent the nature of the materials that are being modeled. The rate-independent elastic-plastic constitutive Mohr-Coulomb law governs the response of materials to deformation.

Deformation in the FLAC3D models involves the execution of a series of numerical time steps. One time step represents one revolution of a calculation cycle in which equations of motion are used to derive new velocities and displacements from stresses and forces that were derived from the execution of the previous cycle. The new velocities are then used to derive new strain rates, which are then used to calculate new stresses (Itasca, 2001). In FLAC3D fluid flow obeys Darcy’s Law, described by Bear and Verruijt (1987), and is driven by changes in the hydraulic head brought about by changes in pore pressure that result from positive volumetric (dilation) changes due to deformation.

Model design, boundary conditions, and material properties

In the first set of models a static geometry was tested under widely varying stress field conditions. The model consists of
a single fault that changes dip and strike as it crosscuts an upright sequence of slate and sandstone that also varies in strike (Fig. 17C). The model is based directly on the PR405 leather jacket vein system (Fig. 16) exposed at the 385/405 level. In the model, a single fault crosscuts a central sandstone unit at an angle of ~45° and dips toward 260°. Within the adjacent shale and sandstone units the fault dips more steeply and toward 235° to 245°. The models are placed at mean depths of 5 to 9 km (Robinson et al., 2009), which is consistent with the estimated depth of greenschist metamorphism in the Lachlan orogen (Wilson et al., 2009) and the estimated depths where fluids can reach near-lithostatic pressures (Sibson, 2000). Various stress field types were applied to the model (compression, sinistral transpression, dextral transpression) with incremental variation in compression directions through 180°. The second set of models uses a parametrized fault refracting through a sandstone unit where the angular relationship between the fault and bedding is systematically changed while the stress
The model is based on variations in dip and strike of the fault as it crosses from an interbedded sandstone-shale packages, refracts through a thick sandstone unit, and then passes back out into another sandstone-shale package (Fig. 17E-F). The magnitude of bulk shortening applied in these models was 2%, which is consistent with structures associated with mineralization (Fig. 8), where late fault reactivation records relatively small displacements (Figs. 14, 15). The fluid pressure conditions in the models were initialized at 75% of lithostatic pressure to ensure upward flow of fluid along the faults, which is consistent with mineralization models that propose fluids were sourced at depth (Fairmaid et al., 2011, Wilson and Leader, 2014). Furthermore, the depth of mineralization and the tensional vein arrays suggest that purely hydrostatic fluid pressure conditions were unlikely to have existed. The lower and vertical boundaries were impervious to fluid while fluid was free to flow out of the model at the upper boundary. The material properties applied to the rock units (Table 4) were adjusted to a point where the models best simulate what is observed in the field and are based upon values used in previous models for rock units in central Victoria.

**Numerical Model Results**

A summary of key results of the models is displayed (Figs. 18, 19) as a geometrical representation of shear strain, volume strain, and fluid-flow plots after 2% shortening, and is described below:

**Model set 1**

In assessing the potential stress field it is only those models producing a NW-over-SE hanging-wall transport that localize shear and volume strain that would be responsible for the development of dilatant sites around the central, low-angle, W-dipping fault segment. In particular, where a deformation
GOLD MINERALIZATION, BALLARAT, VICTORIA, AUSTRALIA

Table 4. Mechanical and Physical Properties Compatible with Field Observations that are Applied to the Models

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Notes: The properties are based on those used by Schaubs and Zhao (2002), Robinson et al. (2006), Leader et al. (2013), and Wilson and Leader (2014).

Model set 2

These generic models illustrate the effects of how geometric variance in the fault may have an impact on the localization of strain and fluid flow (Fig. 19D, F). In these simulations the same fault-bedding geometry was used, however, the dip and strike of different sections of the fault are varied while the stress field is kept constant. A total of 260 models were run (Robinson et al., 2009), the results of which were assessed based on identifying fault-bedding relationships that maximize dilation and fluid flow. The best results (Fig. 19) highlight the optimal fault orientations that localize fluid flow within the central sandstone. In order of relative importance these are: (1) dip of the fault within the outer sandstone-shale packages would have an optimal dip of 40° to 50°; (2) dip of fault in central sandstone would have optimal dip of 25° to 35°; (3) dip direction of fault within sandstone sequence would be 250° to 270°.

The results from assessing stress field after 2% bulk shortening, showing distribution of volumetric strain (dilation); shear strain and fluid flux plots. A green star means a good result based upon the localization of strain and fluid flux around the central, low-angle fault segment. (A-B). Strike of bed (black) and fault (blue) are kept constant, but compression direction was rotated from E-W, with best result at 120°. (C) Sinistral transpression with 1:1 strike slip to compression ratio, with an effective transport direction of ~135° produces a good result.

changes in dip when the effective transport direction is NW-SE in the range of 110° to 145°. With other orientations or with dextral transpression the dilation or fluid flow is not localized in the region where fault transects the central sandstone unit.
The results from the models are largely consistent with observed relationships between structures and gold distribution. Results in terms of fluid localization (i.e., around the change in fault dip) are also consistent with the observations made in the mine. With a small component of sinistral transpression, greater shear strain, volume strain (dilation), and fluid flux are localized on the bedding contacts. This is consistent with the observation of late subhorizontal slip on bedding-parallel fault planes being associated with the main phase of mineralized fluid infiltration that accompanies the V3 to V4 vein formation.

Discussion

Role of fold amplification

The major folds associated with mineralization at Ballarat East are double plunging with curvilinear fold hinges. This is particularly common throughout the central Victorian goldfields (Schaubs et al., 2006; Leader et al., 2013), where fold interlimb angles average 30° to 40° (Cox et al., 1991; Willman, 2007). However, the Ballarat East folds are tight to isoclinal (interlimb angles 0°–30°), which suggests there was significantly greater strain, and the slip directions within fold culminations would have become more complex because of the additional strain (e.g., Tanner, 1989; Horne and Culshaw, 2001). This complexity is seen in the core of these folds where low-displacement W-dipping faults, hosting the majority of mineralization, are concentrated toward the vertical or overturned eastern limb.

The formation of the cross-course faults is also consistent with fold amplification and the development of double plunging folds. Deformation parallel to the fold axes, between the cross-course faults, is interpreted to have been one of distributed extension (Fig. 14C, D). This extension was accommodated by initiation of the cross-course faults and sets of V3/V4 veins at a moderate angle to the plunging fold axis (Fig. 14C, D).
The extensional event created the dilation sites where the mineralized fluids could reside to form the V3/V4 networks. Few of these extensional veins show any signs of deformation and they are interpreted to have formed very late in the deformation history. These veins represent transient episodes of embrittlement, and the oscillation in the pressure of the fluid phase as seen by the presence of localized stylolites (Fig. 11E).

The fluid system

The distributions of bulk gold grades (Fig. 4) suggest that there was structural controlled fluid compartmentalization separated by major ENE cross-course faults. Between compartments the fault-cored folds and fractured hinges acted as along-strike fluid conduits with relatively good hydraulic conductivity and porosity. The less fractured rocks on the limbs were isolated from these structural fluid pathways. The distribution of quartz veins and gold grades also suggest that cross-course faults may have reduced fluid flow along strike.

As well as facilitating folding via flexural slip, the limbs of the large amplitude folds host bedding-parallel veins, hydrothermally altered early dikes (Fig. 12), and altered indicator beds. This suggests that the strata on the eastern limb also acted as an important vertical fluid conduit. The modeling and field observations indicate there is little to no cross-stratal flow until units are intersected by W-dipping leather jacket faults, which is an effective means of concentrating buoyant overpressured fluids near the crests of the anticlines. Fold kinematic effects (Fig. 14) lead to important spatial or temporal variations in connectivity and permeability and affect the movement, storage, and release of fluids in and adjacent to the faults. The evolving mechanical properties of the rocks not only control the number and distribution of fractures, but also control when these structures form during the folding process.

The numerical modeling results described here also demonstrate a geometric dependence on the localization of dilation and shear strain and, thus, the potential localization for fluid flow and consequently mineralization. In all models, strain and fluid flow are localized around refracted faults (Figs. 18, 19), particularly at the point of inflection between the steeper and the shallower fault sections. With fault strike changes, there was increasing strain and fluid fluxes occurring toward the northern end of a NNW-trending fault segment. However, when the SW-over-NE transport is applied, as a consequence of the out-of-plane movement (Fig. 14), strain and fluid flow concentrates at the southern end of the fault.

In the model we propose for the Ballarat East deposit, the fluid infiltration is time dependent (Fig. 14). A necessary precursor is the tightening of the anticlines before there was a significant relaxation phase where faults had dilated in response to an extensional episode associated with the out-of-plane movement during the final stage of an E-W contraction. This last stage of movement is evidenced by lineation orientations and displacement on bedded faults, early veins, and offsets on V3/V4 veins and cross-course faults, in an inclined N-over-S manner. This sense of movement is inconsistent with the expected sense of transport during flexural slip folding; occurring where folds are tight and where bedding on the eastern limb is subvertical. Accompanying this is incremental vein formation in which cyclic fluctuations of fluid pressure controlled episodic vein dilation and gold deposition.

Conclusions

In the Ballarat East deposit, different structural and auriferous compartments, separated by cross-course faults, are affected in different ways. Where there are no parasitic faults there is a small amount of mineralization and the area is dominated by V3 vein formation. Where there are changes in fold plunges involving parasitic folding, there is an abundance of V3/V4 veins, with high gold grades associated with late oblique strike-slip movement on the leather jacket faults and a NW-SE and N-S motion. The evolution of strike-slip movement on the leather jacket faults and distribution of high-grade mineralization appears to be associated with the tightening of the folds. Differing complexities in the form surface of the competent units facilitated a different near-field stress regime, which had the potential to focus fluids and mineralization. Despite the apparent structural complexities, changes in the form of the faults and veining are consistent with variation in the geometry of bedding that is associated with strike changes and plunge of the fold axis.

Although the W-dipping faults are historically reported to have reverse offsets of several meters, many faults have minimal reverse movement (<0.5 m), some even with an apparent normal sense. The normal movement we interpreted as a significant relaxation phase where faults had dilated in response to an extensional episode associated with the out-of-plane movement during the final stage of an E-W contraction. This last stage of movement is evidenced by lineation orientations and displacement on bedded faults, early veins, and offsets on V3/V4 veins and cross-course faults, in an inclined N-over-S manner. This sense of movement is inconsistent with the expected sense of transport during flexural slip folding; occurring where folds are tight and where bedding on the eastern limb is subvertical. Accompanying this is incremental vein formation in which cyclic fluctuations of fluid pressure controlled episodic vein dilation and gold deposition.

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