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Stratigraphic Controls on Structures And Mineralisation in Central Victoria 1: Bendigo

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Abstract

This is the first in a series of papers discussing the stratigraphic controls on structures and mineralisation in Victoria. Veins, joints and faults exploit natural planes of weakness along bedding and cleavage within turbidites. Major faults are continuous across folds. When the faults dip in the same direction as the limb of the fold, slip will preferentially occur along bedding. This is usually within a thick shale and often the fault is seen as a laminated quartz vein. Limb thrusts occur when bedded faults cross the hinge and penetrate through the opposing limb. Symmetrical folding at Bendigo allows west-dipping and east-dipping linked faults systems to cross, interact and provide sites for vein development and gold deposition.

Introduction

Central Victoria is a world class orogenic gold province. Faults and folds within Ordovician turbidites host gold and associated mineralisation. Turbidites occur across most of Victoria and in the field are seen as monotonously interbedded sandstones and shales. At Bendigo nuggety gold is hosted by quartz veins within fault- and fold-related structures. Bendigo is the largest goldfield in Victoria, with a recorded production of 22 million ounces of gold. Bendigo Mining is continuing efforts to reopen the goldfield.

This paper is the first in a series on the stratigraphic controls on structures and mineralisation for the gold deposits shown in Figure 1. These studies draw on work done by the senior author at each of the deposits alongside site staff.

The first stratigraphic project was initiated by Bendigo Mining in 2001 but has since been developed mostly at Fosterville and Ballarat. At these deposits it was found that many common ingredients occur: namely turbidite host rocks, folding and fault styles, and mineralisation types.

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Figure 1. Location map showing the turbidite hosted deposits discussed in this series of papers.

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However, despite the similarities, there are significant differences at each deposit. This series of papers will discuss separately how the stratigraphy controls the development of structures and mineralisation at each location.

Previous work

The early miners and authors such as Dunn (1893) and Hermann (1923) recognised the significance of some of the lithological packages at Bendigo and elsewhere in Victoria. This short paper cannot review the details, but Willman (2007) excellently summarises knowledge of the goldfields to the present time. It is fair to say that most studies of the goldfields of Victoria have been strongly biased towards faulting and folding styles.

Stratigraphic research in central Victoria began in an attempt to correlate lithological packages between drill holes, but it was soon found to be important in determining fold geometries, fault positions and offsets, and to gain a better understanding of vein formation (Boucher 2004, Boucher & Thomas 2005). Throughout central Victoria, companies have adopted a detailed sedimentological logging system to capture the data required to enable successful correlation.

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 Victoria. Channel sands are typically coarse and very coarse amalgamated sands. Overbank deposits are interbedded fine to medium grained sands 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 monotonously interbedded sandstones and shales make 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 veins that link to important faults and are major gold hosts. Often laminated quartz veins occur at the top of the thicker hemipelagic shales. It is possible that these positions are maximum flooding surfaces following major marine transgressions as carbonaceous shales would be expected to develop when clastic input is lowest. These thick host shales should therefore be the best for regional correlation. In contrast, shales that form distal to channels rather than during a major marine transgression will have highly variable thicknesses and won't necessarily have the carbonaceous facies that will develop laminated quartz veins.

In theory, a channel should exist between two thick hemipelagic shales. However, at mine scale it is most common that only STS facies are seen with the channel itself being away from the local mine area. Otherwise, the channel sands can be near the base, top or centre of the STS succession and the position of the channel sands can provide a good reference for correlation.

Local informal mine stratigraphy has been developed at most locations throughout Victoria. This series of papers will continue to use the informal names. 'Shale' is a widely used term throughout central Victoria and is used in this series to describe all siltstones and claystones. However, genuine claystones are rare in the turbidites of central Victoria.

Bendigo stratigraphy

The mine stratigraphy at Bendigo comprises several significantly thick shales, channel sands and overbank deposits (Fig. 2). All units are diachronous. The upper boundaries of the thick shales provide the best regional correlations. Several important shales occur within the succession and host significant laminated quartz veins (Fig. 2). An exception is the laminated quartz vein within the 'Kingsley Formation' which occurs in a thin shale between two thick sands. The 'Big Blue Shale' has been traced for over 8 km to the northern part of the field. Bendigo Mining define the 'Big Blue Shale' as only that shale above a significant laminated quartz vein which lies on a thin sand bed within the shale. However, toward the north and east, the overall shale package reaches 35 m in width and where the thin sand dies out, the laminated quartz vein and associated structures and mineralisation does too. 'Rowes Shale' is over 20 m thick to the southwest and thins to only one metre to the northeast where channel sands begin to develop instead. The 'Western Shale' is found variably between 10 and 20 m above the 'Big Blue Shale'. Less is known about the deeper 'Railway Shale' and 'Emily Shale'. Correlating the 'Railway Shale' between the the Sheepshead and Deborah anticlines is difficult because two shaley intervals occur to the northeast and it is uncertain which one is the 'Railway Shale'.

The positions of the significant laminated quartz veins are indicated in Figure 2. Typically these are in the shales that are the least diachronous. The laminated quartz vein at the base of the 'Big Blue Shale' was significantly worked historically on the Sheepshead line and Bendigo Mining successfully located where it occurred on the Deborah line

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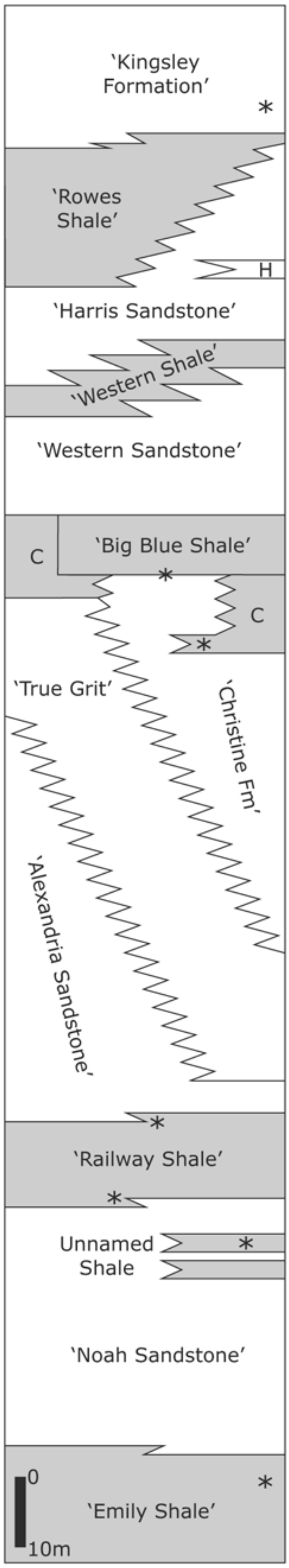

Figure 2. Stratigraphic column highlighting thick shale units and the position of major bedding parallel, laminated quartz veins (*). H = 'Harris Channel Sands' and 'C' = 'Christine Shale'.

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beneath old workings (Fig. 3). A localised reef was mined by Bendigo Mining in the small zone where thickening of the 'Christine Shale' enabled the development of a laminated quartz vein. Diachronous shales, such as the 'Western Shale' or 'Rowes Shale', do not contain the carbonaceous material that is most favorable for laminated quartz vein development. Historically, miners on the Bendigo goldfield sought the thicker shales knowing they hosted the significant laminated quartz veins and accompanying faulting and vein development at anticlines. Likewise, Bendigo Mining's exploration strategy developed in the late 1990's was significantly based on targeting the thicker shales, particularly where they met anticlines and limb thrusts developed.

The 'True Grit' is the only genuine channel sand within the defined mine sequence (Fig. 2). Mostly it occurs close to the 'Big Blue Shale'. However towards the northeastern part of the mine it occurs deeper within the succession and in some holes it occurs twice. This reflects meandering of the channel. The 'True Grit' is usually at least 10m thick and is composed of coarse and very coarse sands and granules with occasional shale flake breccia beds. In the northeast, sands within the 'Harris Sandstone' can be seen coarsening, thickening and become amalgamated indicating approach to a channel environment.

Stratigraphic controls on the development of veins, faults and folds

As a result of the more detailed lithological logging there is now a greater understanding of the development of quartz veins. Most notable are the veins that align with cleavage/jointing within beds. Veins commonly exploit 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 (Fig. 4).

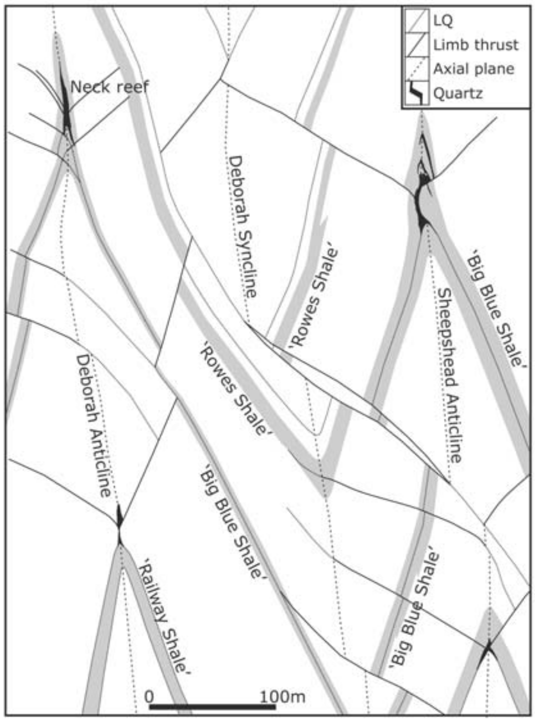

Figure 3. Composite cross section showing major thick shales which host laminated quartz veins (LQ's). Where LQ's cross axial planes, limb thrusts develop. Often neck reefs form where LQ's meet the hinge and slip occurs on the axial plane.

SMEDG and AIG

TERRY LEACH SYMPOSIUM 2008

SMEDG and AIG are organising a one day symposium, to be held at the Kirribilli Club, Milsons Point, Sydney, Australia, on Friday, 17th October 2008, to honour Terry Leach's contribution to mineral exploration.

The Application of Petrology to ~Geological Models in Mineral Exploration~

Terry's clients and colleagues will present exploration case histories reflecting on the contributions he made to specific exploration and mining projects.

For more information and proposed speakers see **www.smedg.org.au**

There will be opportunities to mount Trade Displays and to sponsor the Symposium at various levels. Contact details on the SMEDG website

An important vein type throughout most of Victoria is the bedding parallel, laminated quartz vein. Bedding parallel, laminated quartz veins form during early folding and are continually reactivated during subsequent folding. Some laminated quartz veins survive folding. Occasionally extra dilation occurs at the hinge to create simple saddle reefs. With continued folding, slip can translate up the bedding planes, then up the axial planes to producing neck reefs (Fig. 3). More commonly, when the folds lock up, faults propagate from laminated quartz veins, across the hinge and through the opposing limb (Fig. 3). This was defined by Ramsay (1974) as a limb thrust. However, there have been various names used to describe this feature in Victoria, such as dilatant jog, fissure reef, conjugate thrust, or low-displacement strike-parallel fault. Limb thrusts should theoretically dip at 45° in response to regional horizontal stress. However their paths are ultimately governed by where they meet another laminated quartz vein on the adjacent fold. Tension vein arrays can form on limb thrusts, most commonly in the sandstone beds, especially the thick channel sands. Tension veins commonly follow the pre-existing planes of weakness developed along the spaced cleavage/jointing within the sandstones (Fig. 4). As a result, some cleavage veins are linked to faults and others are not. It has not been established which veins systems are connected to mineralised "plumbing systems" and which veins are more likely to contain gold. It is difficult to establish from drilling alone how the veins link between holes and to the major structures which makes correlation difficult.

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From Your President

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and thereby recognising the relatively high costs associated with delivering geoscience courses, due at least in part to the cost of taking students into the field to develop their geological observation and interpretation skills, first hand. This is something on which there can be no compromise if students are to receive rounded and comprehensive education in geoscience.

This issue will be receiving considerable attention during the coming year.

Another challenge facing exploration and mining is its environmental credentials. The Federal government has ratified the Kyoto Protocol and initiated a national greenhouse gas emission reduction strategy. Professor Ross Garnaut, who is conducting this review and is scheduled to deliver his report to the government towards the middle of this year was reported in "The Australian" of December 12, 2007 as being of the view that coal fired electricity generation has no long term future in Australia.

International Energy Association (IEA) statistics show that Australia depended on coal for 80% of its electricity in 2006, when coal supplied 24% of the world's primary energy. The proportion of primary energy supplied by coal is projected by IEA to remain at this level until at least 2030, during which time world demand for energy will increase by 60%. The basic mix of energy sources in the next 20 years or so, based on IEA research is not going to change significantly. There is projected to be a decline in oil fired and nuclear energy generation, and a slight increase in energy generated using natural gas, but no increase in the proportion of energy generated using alternative technologies such as landfill gas or renewables including solar, wind and geothermal energy. There will be much more electricity generated from these sources, but no substantial increase in their contribution to the mix of the world's sources of energy. This appears to be contrary to Professor Garnaut's reported view.

If greenhouse gas emission cuts are to be achieved, we will need to rapidly develop practical and effective technologies to facilitate this. It doesn't matter whether, as individuals, we believe that humans are contributing to increased greenhouse gas concentrations in the atmosphere or we believe that it is the product of a normal, natural Earth process. Few would argue that if emissions that can be reduced without increasing the cost of energy markedly, and threatening economic development world-wide as a consequence, then it is a reasonable and sensible thing to do. Community perception of mining and geosciences generally can only be enhanced as a result.

For the first time in many years, we have a U.S. presidential candidate who has been reported by "New Scientist" as being an advocate of "Intelligent Design" in Mike Huckabee, one of the three leading Republican candidates. What would happen to government geoscience programs and science education in the U.S. with a president of this persuasion in the White House?

It's certainly going to be an interesting year. ▲▲

Andrew Waltho

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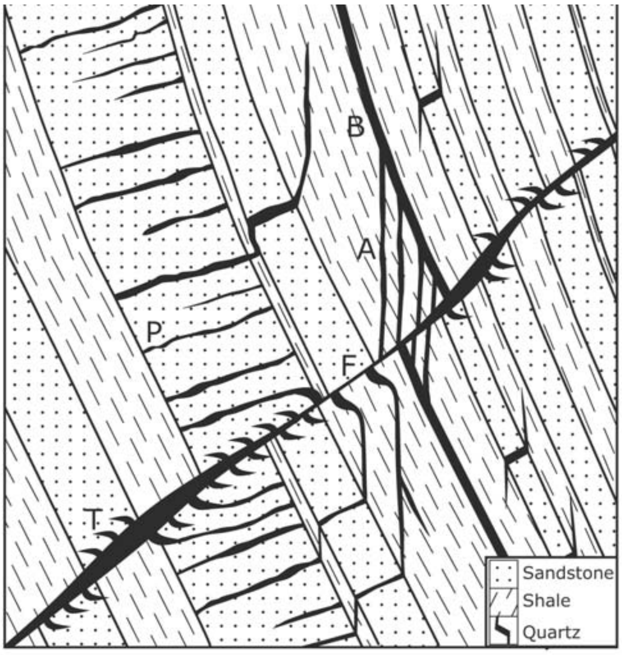

Figure 4. Lithological and structural controls on quartz veins found at Bendigo. Veins occur on faults (F), as tension vein arrays (T), following bedding (B) and aligned with axial planar (A) and radial (P) cleavage. Based on Rickard (1892).

Thick, amalgamated channel sands are favorable sites for vein development. Brittle failure occurs in the thick sands and accompanying vein development is common, especially near faults. Boucher (2004) demonstrated that the 'True Grit' channel sands are significantly thicker to the north than they are to the south on the Sheepshead Anticline. Where the sands are thickest and show good vein development, Bendigo Mining had small resources delineated within the sands. However, these were found to be low grade and patchy. To the south as the sands thin, the veining diminished also. Unfortunately, understanding vein systems from drilling data means that resource delineation in these facies is difficult. However, there is scope for lithostratigraphic correlations to assist to understand the cleavage and fault related vein distribution in the channel sands.

Folding and fault styles at Bendigo

Folds at Bendigo are symmetrical and upright with axial planes dipping steeply to the east. Hinge lines are usually sub-horizontal but plunge gently to the north and south producing a series of elongate domes and basins. Chevron folds have an interlimb angle of 50°. Saddle reef, neck reefs and limb thrusts all occur where laminated quartz veins intersect the hinges of folds. Neck reefs are better developed at Bendigo than in other goldfields and they can reach 30 m high and 3 m wide. Bendigo is famous for its saddle reefs, but limb thrusts are much more common than simple saddles. Displacement on limb thrusts rarely exceeds 40 m. Faults with as little as 5 m of displacement are often significantly mineralised. The symmetrical nature of the folding means that both east- and west-dipping limb thrusts develop at Bendigo. East-dipping faults commonly offset the west-dipping ones (Fig. 3).

Conclusions

Laminated quartz veins occur mostly within thick shales at Bendigo and provide sites for major reefs where they intersect anticlines, especially where they develop into limb thrusts. East- and west-dipping limb thrusts occur and are the primary exploration targets for Bendigo Mining. Elsewhere, channel sands provide good environments for brittle deformation and veining. However, their distribution varies with the migration of the channel. High resolution stratigraphic logging has enabled recognition of veins that form on cleavage within shales and sands. However, work needs to be done to link the "plumbing systems" of these veins to laminated quartz veins and faults in order to understand gold distribution. Detailed lithological logging throughout central Victoria has enabled good correlation and interpretation and provided a good understanding of structures and mineralisation. ▲▲

Acknowledgments

Numerous geologists over the last two decades have contributed a significant amount of research, data collection and modelling to assist to understand the geology and mineralisation of the Bendigo goldfield. Bendigo Mining continues to actively put significant effort in its attempts to understand the complex geology of the goldfield. The senior author is particularly indebted to Dean Turnbull who contributed a great deal of the structural analysis and target generation for Bendigo Mining, initiated the first stratigraphic study and provided over a decade of thoughtful discussions on the geology of Bendigo. He and Dave Garrard constructed the first series of regional cross sections that provided a bench mark for all subsequent work. Jim Jago, Allan Rossiter and Fons VandenBurg are gratefully acknowledged for their assistance in shaping the content of this series of papers.

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