POLYPHASE DEFORMATION AND THE STRUCTURAL CONTROLS ON ECONOMIC GOLD OCCURRENCES WITHIN THE BENDIGO GOLDFIELD, CENTRAL VICTORIA, AUSTRALIA

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STATEMENT OF CONTRIBUTIONS

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ABSTRACT

The Bendigo Goldfield is historically the largest producing goldfield within the Lachlan Fold Belt of southeastern Australia, and is a classic example of a structurally controlled turbidite-hosted gold deposit. Since 1993, Bendigo Mining Ltd. has been re-evaluating part of the goldfield and is in the process of developing an underground mine. The current development, which accesses eight auriferous reefs to a depth of ~800 m, presents a unique opportunity to re-examine the structurally controlled reefs, which characterise the central Victorian goldfields. The identification of multiple foliations, both proximal and distal to the mineralisation, prompted a reinvestigation of the deformation chronology, which revealed that the structural evolution of the goldfield was more complex than previously thought. A five-stage deformation chronology (D_1-D_5) based primarily on the recognition of overprinting tectonic foliations (S_1-S_5) is proposed. D_1 to D_3 represent distinct, yet progressive phases of ENE-WSW shortening possibly during the Benambran Orogeny (*ca.* 439-435 Ma), with D_2 corresponding to the peak of deformation and metamorphism. N-S directed shortening during D_4 indicates that a change in the principal shortening axis has occurred and as such, D_4 could represent the later stages of the Tabberabberan Orogeny (*ca.* 381-377 Ma). Deformation associated with D_5 suggests a period of NNW-SSE directed shortening, which may correspond to the younger Kanimblan Orogeny (*ca.* 360-340 Ma). A period of deformation and fault reactivation that post-dates both D_5 and Jurassic dykes has been recognised within the goldfield. However, the extent of this deformation remains unclear and no associated tectonic foliation has been observed.

At Bendigo, economic occurrences of gold are intimately related to the structural evolution of the goldfield and are associated with late-stage mineral phases, which post-date the syn-D_2 quartz veins such as the classic saddle reefs. On the basis of structural, microstructural and paragenetic observations it is proposed that the deposition of gold occurred during D_3, and more specifically, in association with the development of D_3 kink bands. The D_3 kinks vary in size from small-scale kink bands (S_3) on a millimetre-scale, through to large-scale kinks (F_3) at a kilometre-scale. The small-scale D_3 kink bands consist of four sets of conjugate extensional kinks, which exhibit an approximately orthorhombic symmetry about a sub-vertical axis, suggesting deformation in response to triaxial strain. Spatial analysis of historical production data has revealed a number of previously unrecognised high-grade trends. These trends coincide with the intersection axis between a kink band axial plane and bedding. It is proposed that these intersections control ore shoot geometry and location, because they also correspond to the orientation of historically worked ore shoots and those encountered more recently by Bendigo Mining Ltd. A new understanding of the controls on ore shoots has considerable implications for future exploration within the goldfield, and elsewhere in central Victoria.

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PROJECT OBJECTIVES

The aims of this project were to:

1. Investigate the deformation chronology preserved within the host rock at Bendigo;
2. Investigate the microstructural and paragenetic settings associated with gold, and determine the relative timing of gold in context with the deformation chronology;
3. Resolve the structural controls on auriferous mineralisation; and
4. To develop models that may assist near mine exploration and resource evaluation within the Bendigo Goldfield.

These aims were achieved through:

1. Structural analysis of surface exposure and more significantly, the new underground exposure;
2. Microstructural analysis of orientated thin-sections from orientated samples collected from surface and underground exposures;
3. Petrographic analysis of thin sections and samples from auriferous reefs exposed in the new underground development;
4. Analysis of historical production data and current mine assay data
5. Reviewing and integrating previous studies pertaining to structure and mineralisation with the findings of this study.

THESIS RATIONALE

Rationales for the four thesis sections are given below, along with a summary of the sections content:

SECTION A: A REVISED DEFORMATION CHRONOLOGY FOR THE BENDIGO GOLDFIELD, CENTRAL VICTORIA, AUSTRALIA: THE IMPORTANCE OF POST D_2 DEFORMATION EVENTS

The structural chronology preserved within the host rock at Bendigo is a contentious issue, with as many as three stages of deformation being proposed (Forde, 1989; Schaubs & Wilson, 2002). Early workers (e.g. Stone, 1937; Chace, 1949) refer to the possibility that gold deposition may have occurred during a later deformation. Despite such interpretations, the concept of polyphase deformation at Bendigo has commonly been ignored and may be one of the fundamental reasons why the distribution of gold, particular in three-dimensions, is poorly understood and frequently reported as erratic (e.g. Dominy & Johansen, 2004). Section A presents new geological and structural data that, in combination with a review of previous work (e.g. Forde, 1989; Gray & Willman, 1991c; Morand *et al*., 1997; VandenBerg *et al*., 2000; Schaubs & Wilson, 2002), has prompted a revision of the structural framework.

SECTION B: THE THREE-DIMENSIONAL GEOMETRY AND KINEMATICS OF KINK BANDS WITHIN THE BENDIGO GOLDFIELD, VICTORIA, AUSTRALIA

Although the analysis of experimentally derived kink bands has advanced understanding of kinking mechanisms, comparisons between the geometric properties of naturally occurring and experimentally derived kink bands frequently reveal inconsistencies (e.g. Anderson, 1968; Cudahy, 1986; Stubley, 1990; Kirschner & Teixell, 1996). There are two main discrepancies reported in the literature; the first is between the stress-strain relationships derived experimentally (e.g. Gay & Weiss, 1974) and those inferred from natural kink band systems (e.g. Anderson, 1968; Cudahy, 1986; Stubley, 1990), whilst the second relates to kink band geometry. Several studies of

naturally occurring kink bands report geometries that differ significantly from those derived experimentally (e.g. Stubley, 1990; Kirschner & Teixell, 1996). In such cases no single experimental or theoretical model can explain the development of the naturally occurring kink band system. Section B investigates the three-dimensional geometry of mm-scale extensional and contractional kink bands recognised in Section A. The geometric properties of the contractional kink bands are compared to those derived experimentally. Two-dimensional geometric parameters are presented for D_3 kilometre-scale kinks and a comparison is made with the mm-scale D_3 kink bands observed in thin section.

SECTION C: A NEW PARAGENESIS FOR LATE-STAGE MINERALISATION WITHIN THE BENDIGO GOLDFIELD, CENTRAL VICTORIA, AUSTRALIA: THE LATE TIMING OF GOLD

A number of early workers suggest that the deposition of gold within the Bendigo Goldfield postdates the major quartz bodies, sulphides and other gangue minerals (e.g. Stone, 1937; Chace, 1949). Forde (1989) also proposes a late orogenic timing for gold. However, other workers (e.g. Stillwell, 1950), particularly more recently, (Jia *et al*., 2000; Schaubs and Wilson, 2002) have suggested that gold was deposited throughout much of the deformation sequence and was simultaneous with several major phases of D_2 quartz veining. It is evident that a dichotomy exists between views that significant mineralisation occurred in D_2 and later events, and views that mineralisation is only post-D_2. Part of the reason for the disagreement is that few detailed paragenetic studies (e.g. Chace, 1949) have ever been published on Bendigo. Section C investigates the mineral paragenesis and microstructural settings associated with gold, and presents a new relative timing for gold in the context of the revised deformation chronology presented in Section A.

SECTION D: STRUCTURAL CONTROLS ON GOLD MINERALISATION WITHIN THE BENDIGO GOLDFIELD, CENTRAL VICTORIA, AUSTRALIA: DEVELOPING EXPLORATION POTENTIAL

It is acknowledged by a number of early workers in the Bendigo Goldfield that the controls on gold localisation and ore shoot formation are poorly understood (e.g. Dunn, 1896; Whitelaw, 1914; Chace, 1949; Thomas, 1953b). Some more recent authors suggest that the quartz veins are characterised by an erratic gold distribution, with little or no reference made to the possibility of deficient geological understanding (e.g. Wilkinson 1988b; Sharpe & MacGeehan, 1990; Johansen, 2001b; Johansen *et al*., 2003; Dominy & Johansen, 2004). Recent revisions to the deformation chronology (Section A) and the relative timing of gold (Section C) have demonstrated that the structural evolution of the goldfield is more complex than previously thought, and that gold is associated with a deformation event that was previously unrecognised. Section D investigates high-grade trends within the Bendigo Goldfield in an attempt to resolve the underlying controls on ore shoot formation, location and geometry.

The data used and presented in this thesis are based on fieldwork, hand specimen and thin section analyses, and some unpublished sources. Samples referred to in the text were catalogued and submitted to the research collections of the School of Earth Sciences at James Cook University. The main body of the thesis comprises four papers written for eventual publication in international scientific journals. Section A has been submitted to the Australian Journal of Earth Sciences. Section B will be prepared for submission to the Journal of Structural Geology, whereas Section C will be prepared for submission to the Australian Journal of Earth Sciences. Section D will be prepared for possible submission to the Canadian Institute of Mining and Metallurgy.