Miner Deposita (2007) 42: 449–463
DOI 10.1007/s00126-006-0072-8

ARTICLE

Clive E. Willman

Regional structural controls of gold mineralisation, Bendigo and Castlemaine goldfields, Central Victoria, Australia

Received: 8 November 2005 / Accepted: 18 May 2006 / Published online: 15 July 2006

Abstract The Bendigo and Castlemaine goldfields are classic examples of structurally controlled orogenic gold deposits in the Bendigo Zone of central Victoria, SE Australia. Detailed mapping and biostratigraphic interpretation has led to a better understanding of the regional structural controls of this type of gold-quartz mineralisation. Mineralised quartz veins are hosted by the Castlemaine Group, an Early-to-Middle Ordovician turbidite succession at least 3,000 m thick. Gold deposits are controlled by low-displacement faults that are clustered into several belts (the goldfields) indicating a regional structural control. The timing of mineralisation overlapped with that of the major period of deformation including folding, cleavage development and regional faulting. The Bendigo and Castlemaine goldfields are located in an area termed the Whitelaw thrust sheet bounded by two unmineralised, high-displacement, regional-scale faults. Mapping has revealed an interrelationship between the regional-scale faults, regional structural style and goldfield location. The goldfields lie immediately west of the boundary between the upper and lower portions of the thrust sheet and are characterised by symmetric folds with sub-horizontal to synclinal enveloping surfaces, relatively low co-axial strains and moderate cleavage development. The non-gold-bearing areas immediately east of each goldfield correspond with the lower part of the Whitelaw thrust sheet and are characterised by higher non-coaxial strains, stronger cleavage and folds with wide west-dipping limbs giving rise to easterly vergent sections and steeply west-dipping enveloping surfaces. That mineralisation was an integral part of the thin-skinned style of deformation in the central Bendigo Zone is indicated by timing relationships and the interrelationship between local-scale mineralised structures and regional-scale features such as large-displacement unmineralised faults, regional variations in fold style and overall thrust sheet geometry. The work supports previous models that suggest mineralised fluids were focussed along a linked system of deep-seated faults. The primary conduits may have been major regional-scale ‘intrazone’ faults, which are inferred to sole into detachments near the base of the Castlemaine Group. It is proposed that these structures linked with minor intrazone faults and then with networks of low-displacement mineralised faults that were strongly controlled by folds. The location of minor intrazone faults was probably controlled by internal thrust sheet geometry. The distribution of gold deposits and of gold production suggests that maximum fluid flow was concentrated along the eastern margins of networks of low-displacement faults.

Keywords Orogenic gold · Structural control · Lachlan foldbelt · Bendigo · Castlemaine · Victoria · Australia

Introduction

Bendigo is the major goldfield within a world-class orogenic gold province in the Bendigo Zone of central Victoria, SE Australia (Fig. 1). The province includes several smaller but significant goldfields such as Ballarat, Castlemaine, Maldon and Daylesford along with numerous minor goldfields. Bendigo is rightly famous for its spectacular examples of structurally controlled gold-quartz vein systems and for its substantial total gold production of 697 tonnes (t) (540 t from veins and 157 t from placers). The Castlemaine goldfield lies along strike from Bendigo, about 37 km to the south; however, its total gold production is much lower at 173 t (27 t from veins and 146 t from placers; Phillips et al. 2003). Together they have produced 35% of Victoria’s gold (Phillips et al. 2003).

While the mine-scale structural controls of gold mineralisation in the Bendigo Zone are well-known (Pabst 1919; Hermann 1923; Thomas et al. 1977; Sharpe and MacGeehan 1990; Cox et al. 1995; Schaubs and Wilson 2002), there has been little detailed structural

Editorial handling: F. Bierlein

C. E. Willman (✉)
GeoScience Victoria, Department of Primary Industries,
P.O. Box 4440, Melbourne, Victoria 3001, Australia
e-mail: Clive.Willman@dpi.vic.gov.au

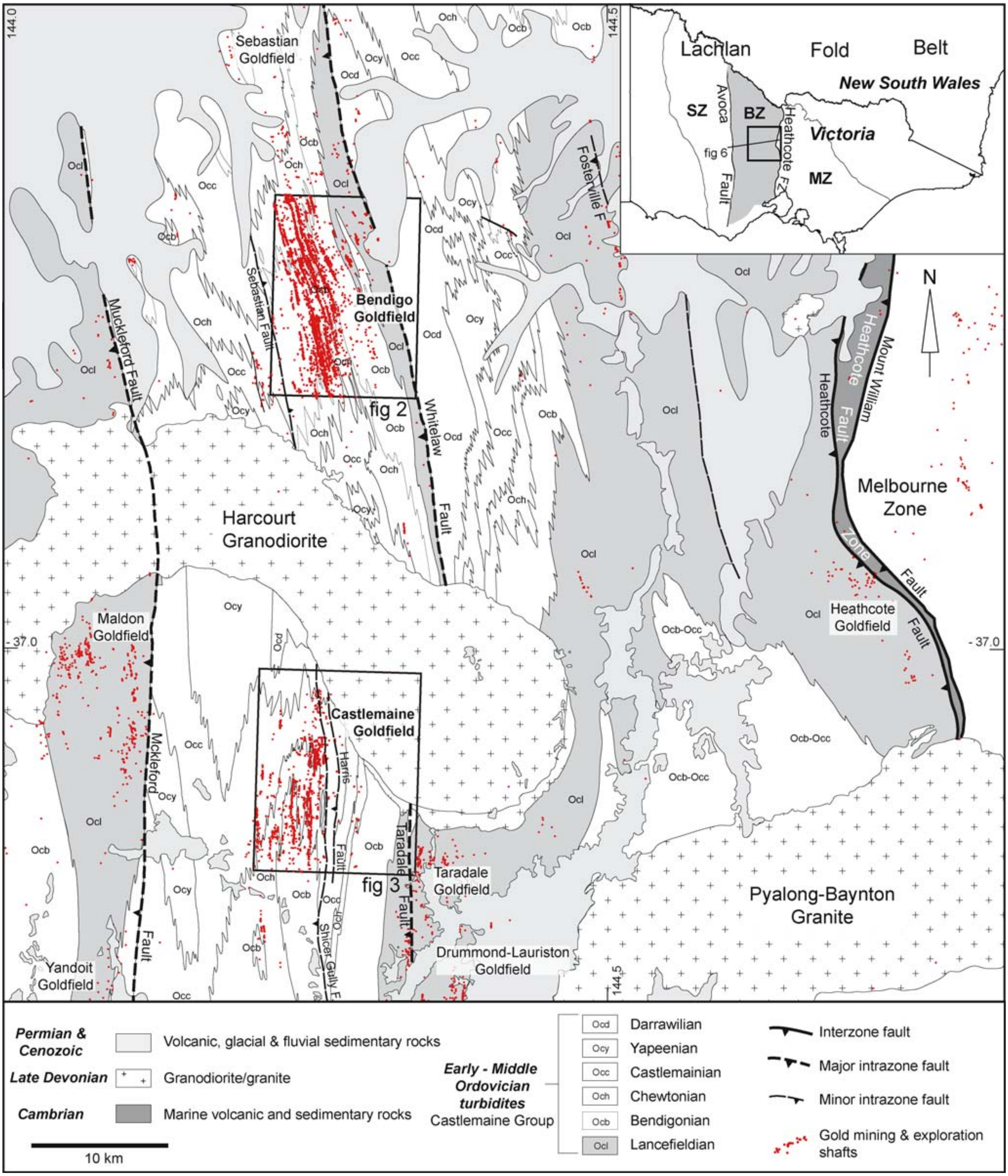


Fig. 1 Geology of the central and eastern Bendigo Zone showing distribution of biostratigraphic zones and gold mining/exploration shafts. The *two boxes* indicate the location of the detailed goldfield maps in Figs. 2 and 3. *Inset map* shows the location of the study area, structural zones and the location of the cross-section in Fig. 6 (*SZ* Stawell Zone, *BZ* Bendigo Zone, *MZ* Melbourne Zone). Regional geology after Edwards et al. (1998a,b) and Willman et al. (2002). Shaft location data are from the Department of Primary Industries

mapping that places the goldfields in their regional structural context (Thomas 1939). At the simplest analytical level, the clustering of gold deposits suggests that regional structural controls are important, given that the host rocks are broadly homogeneous in composition and metamorphic grade across the Bendigo Zone. However, no clear regional structural control has previously been identified although a relationship between high-displacement unmineralised regional faults (crustal scale) and low-displacement mineralised faults has been suggested by Cox et al. (1991a,b). In other orogenic gold belts, there are similar problems in defining the crustal-scale fault networks that have controlled orogenic mineralisation (Groves et al. 2003).

This paper examines the regional structural setting of the Bendigo and Castlemaine goldfields, both located in the central part of the Bendigo Zone (Fig. 1). The object of this study was to remap the two goldfields, and most importantly, to extend detailed mapping east and west of the goldfields to examine their structural characteristics in the context of the surrounding less mineralised areas. The study also aimed to place the goldfields in the regional structural framework and to address questions such as: 1) why do gold deposits form clusters (the goldfields)? 2) does stratigraphy control the location of goldfields? and 3) is there a relationship between goldfield location and regional-scale structures such as unmineralised high-displacement faults?

Regional setting

The Ordovician Castlemaine Group forms the host rock to all the orogenic gold deposits of Bendigo and Castlemaine. This 3,000+ m thick pile of turbiditic sandstone and mudstone (now slate) forms the upper part of the basement to the Bendigo Zone, a major structural zone in the southeastern Lachlan Fold Belt (VandenBerg and Stewart 1992; Gray et al. 2003). The turbidites are underlain by up to 2.5 km of oceanic crust comprising Early to Middle Cambrian tholeiitic basalt, andesite, boninite and volcaniclastic rocks that are only exposed in major fault zones (Crawford et al. 2003).

The Castlemaine Group ranges in age from the Early to Middle Ordovician and consists of a very uniform and well-bedded sequence of marine turbiditic sandstone and mudstone interbedded with hemipelagic black shale and rare thin beds of limestone (Willman et al. 2002). Sandstone beds are usually <1.5 m thick and are often grouped together as packages averaging 10 to 20 m thick. Lithostratigraphic units are difficult to recognise because of the monotonous nature of the sequence. However, the group has been subdivided into six biostratigraphic stages (Lancefieldian, Bendigonian, Chewtonian, Castlemainian, Yapeenian and Darriwilian) and 19 zones using graptolites preserved in black shales (VandenBerg and Cooper 1992).

Most of the Early Palaeozoic sedimentary rocks in southeastern Australia were strongly deformed in the Late Ordovician to Silurian in a subduction-related collisional setting (Gray and Foster 1998). Deformation of the Bendigo Zone from the Late Ordovician to Early Silurian (Benambran Orogeny of VandenBerg et al. 2000) is evidenced by folding, faulting and cleavage development resulting in east–west shortening of up to 70% (Gray and Willman 1991a). The Castlemaine Group was tightly folded into chevron-style folds (F1) with wavelengths from tens to hundreds of metres. They are remarkably strike persistent and have profiles that are also persistent with depth. Folds are associated with a well-developed axial plane cleavage (S1). Groups of F1 folds form regional-scale anticlinoria and synclinoria that show pronounced domal culminations and basinal depressions associated with fold-plunge reversals (Fig. 1); these have been recognised by combining structural and biostratigraphic analysis (Thomas 1939; Cherry and Wilkinson 1994; Willman 1995; Edwards et al. 1998a,b; Willman et al. 2002).

Deformation of the Castlemaine Group and the underlying Cambrian sequence during the Benambran Orogeny was accompanied by significant faulting. The observed relationships between regional-scale faults and their proximity to belts of highly strained rocks has been used as evidence for thin-skinned tectonics involving a fold and thrust structural style (Sandiford and Keays 1986; Cox et al. 1991a; Gray and Willman 1991a,b).

High-displacement regional scale faults (interzone faults) form the boundaries to the Bendigo Zone (Fig. 1); the Avoca Fault to the west and the Heathcote Fault Zone to the east (Gray and Willman 1991a,b; Cayley and McDonald 1995; Gray and Foster 1998). These faults contain slivers of Cambrian oceanic crust and have throws in excess of 10 km (Gray et al. 2006). A seismic profile across the Heathcote Fault Zone indicates it has a listric profile (Gray et al. 1991).

Faults within the Bendigo Zone occur at several different scales from the low-displacement mineralised faults (throws <100 m) to the intrazone faults with throws up to 2 km (Gray and Foster 1998). Major intrazone faults are reverse faults with throws >1 km and strike lengths up to 150 km (e.g. Muckleford and Whitelaw-Taradale faults: Gray and Willman 1991a,b; Gray and Foster 1998). They are generally unmineralised. The hanging walls of major intrazone faults contain the oldest parts of the Castlemaine Group (Fig. 1) and show evidence for high strain (XZ>30:1); for example, vertical mineral lineations in slates, pyrite pressure fringes, intensified S1 cleavage and low F1 fold interlimb angles compared to areas more than 1 km away from major faults, which have lower total strain usually in the range 2.5:1<XZ<5:1 (Gray and Willman 1991b). These features indicate that major intrazone faults developed synchronously with folding and cleavage (Gray and Willman 1991b). There is no evidence for high strain in their footwalls. The areas between major intrazone faults show a general westward younging of stratigraphy so that the oldest parts of the sequence are exposed in the hanging walls of the faults and the youngest parts are exposed in the footwalls (Figs. 1 and 6).

Minor intrazone faults truncate F1 folds and do not show evidence for high strains in their hanging walls (e.g. Shicer Gully, Harris and Sebastian? faults). They are unmineralised reverse faults with throws from several hundred meters to 1 km (Cherry and Wilkinson 1994; Willman et al. 2002). There is no evidence for mining along the Shicer Gully Fault although it is marked in some places by a zone of quartz veining up to 20 m wide.

Low-displacement mineralised faults are reverse faults with throws less than a hundred metres and usually only tens of metres. They are frequently associated with significant quartz veining, with or without gold mineralisation (e.g. Wattle Gully Fault in Fig. 3). The paths of low-displacement faults are strongly influenced by fold shape—they formed in the late stages of folding associated with fold lock-up (cf. Ramsay 1974; Cox 1995).

Later deformation after the Early Silurian is mainly restricted to fault reactivation and associated localised cleavages (S2) or rare strike-slip faults that postdate mineralisation and have northwest or northeast trends (e.g. Spring Gully Cross Fault in Fig. 3). Much of this later deformation was probably associated with the Middle Devonian Tabberabberan Orogeny, which deformed the Melbourne Zone; its only significant effect in the Bendigo Zone was along its eastern margin (VandenBerg et al. 2000). This event postdates the major phase of mineralisation at Bendigo and Castlemaine (Bierlein et al. 2001a).

Both the Muckleford and Whitelaw faults have been reactivated since their initiation during the Benambran Orogeny (Cherry and Wilkinson 1994; Willman et al. 2002) The Harcourt Granodiorite overprinted both faults in the Late Devonian, thereby separating their northern and southern segments (Fig. 1). Later reactivation of the Muckleford Fault cut the Harcourt Granodiorite and thereby rejoined its two older segments. The Taradale Fault is inferred to be the (pre-Harcourt Granodiorite) southern segment of the Whitelaw Fault; however, Cenozoic reactivation of the northern segment of the Whitelaw Fault failed to link with the Taradale Fault (Willman et al. 2002).

Metamorphism and mineralising fluids

Metamorphic grade in the Castlemaine Group within the Bendigo Zone varies from epizonal (greenschist facies) in the west to anchizonal (prehnite-pumpellyite facies) in the east (Offler et al. 1998). Using b lattice parameters and illite crystallinity of K-white micas in Ordovician slates, Offler et al. (1998) found that moderately high pressures (0.4 GPa) and a moderately low geothermal gradient (26°C/km) prevailed during regional metamorphism, which accompanied the main cleavage-forming event and folding. The entire area between the Muckleford and Whitelaw-Taradale faults, including the Bendigo and Castlemaine goldfields, lies within the epizonal field.

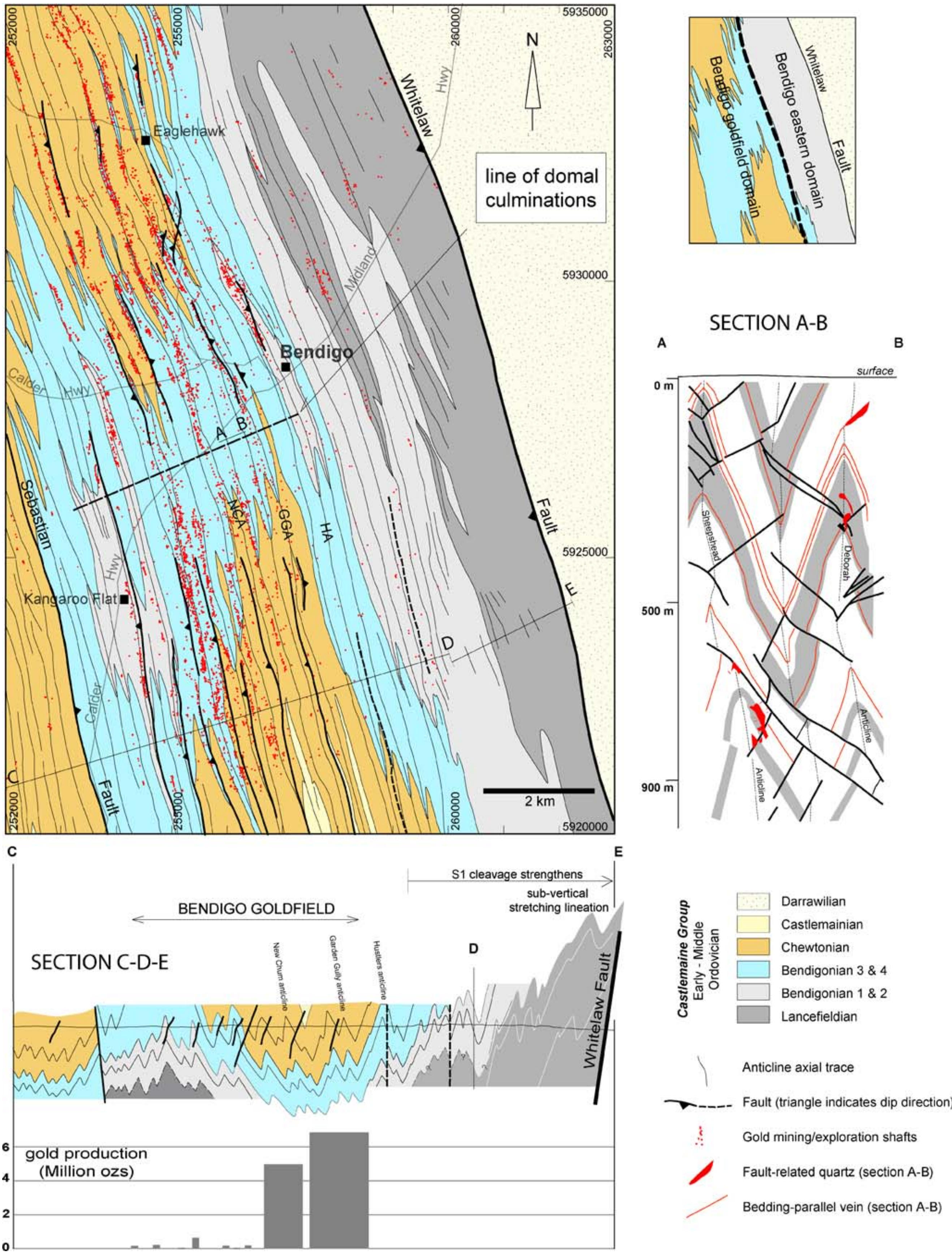
Geochemical studies suggest that mineralising fluids were derived from a deep-seated source generated by metamorphic devolatisation (Gao and Kwak 1995; Cox et al. 1995). The fluid had low-salinity water with carbon dioxide and lesser H_2S, nitrogen and local methane (Phillips et al. 2003). The fluids were focussed into fault zones and then precipitated quartz and metals under conditions of high but fluctuating fluid pressure involving repeated fault valve behaviour (Cox et al. 1991b; Cox 1995; Sibson 2004). The gold source is unknown but it may be the Cambrian mafic succession that underlies the Castlemaine Group beneath an inferred major mid-crustal detachment (Keays 1987).

Fig. 2 Bendigo goldfield. Structural and biostratigraphic *map* ▶ showing trend of anticlinal axes, location of gold mining shafts and main faults. Cross-section *AB* shows detail of mine-scale mineralised structures (redrawn from a plan by Bendigo Mining Ltd). Cross-section *CDE* shows variation in structural style. The *bar graph* indicates variation of gold production across the goldfield. *HA* Hustlers Anticline, *GGA* Garden Gully Anticline, *NCA* New Chum Anticline

Timing of deformation and mineralisation

The timing of deformation and metamorphism has been constrained by Ar–Ar data for the growth of metamorphic mica in cleaved slates (S1 cleavage) and of white micas in quartz veins associated with gold mineralisation (Foster et al. 1998, 1999). The data indicate that deformation was initiated at about 455 Ma continuing to as late as 420 Ma in the Bendigo Zone. However, dating of white micas in mineralised veins indicates a major phase of mineralisation was introduced at 440 Ma and field relationships show that this phase was late in the evolution of the F1 folds. Hence, the main phase of F1 folding and Sl cleavage development is probably 455–440 Ma. Low-displacement mineralised faults were formed towards the end of this period. The younger 420 Ma dates probably reflect fault reactivation.

Mine-scale structural relationships broadly indicate that the timing of gold mineralisation in the Bendigo Zone was protracted and overlaps with folding and cleavage development (Cox et al. 1991b; Willman and Wilkinson 1992). The timing is supported by radiometric dating (Bierlein et al. 1999; Bierlein et al. 2001a; Gray et al. 2002). Direct dating of mineralisation is based on Ar–Ar determinations from hydrothermal micas associated with mineralised quartz veins (Bierlein et al. 1999) and Re–Os dating of arsenopyrite at Bendigo (Arne et al. 2001). Indirect dating is based on U/Pb and K/Ar dating of igneous intrusions that show overprinting relationships with gold-quartz veins (Arne et al. 1998; Bierlein et al. 2001b). Mineralisation occurred in three distinct time phases between Late Ordovician and Late Devonian; the main gold mineralisation event occurred near the end of the Benambran Orogeny at about 440 Ma, a second minor event occurred at about 420–400 Ma and a third minor event occurred at about 385–365 Ma. Most gold production in the Bendigo Zone is probably derived from mineralisation associated with the 440 Ma event. This includes both the 'saddle reefs' and fault-hosted quartz reefs at Bendigo and Castlemaine.



5935000
252000
255000
260000
263000
N
Eaglehawk
Whitelaw
Hwy
line of domal culminations
Midland
5930000
Bendigo
Calder Hwy
A B
Sebastian
NCA
GGA
HA
Fault
5925000
Kangaroo Flat
Hwy
E
D
Calder
C
Fault
2 km
5920000
Whitelaw
Bendigo eastern domain
Fault
Bendigo goldfield domain
SECTION A-B
A
B
surface
0 m
Sheepshead
Deborah
500 m
Anticline
Anticline
900 m
C
E
S1 cleavage strengthens
sub-vertical stretching lineation
BENDIGO GOLDFIELD
SECTION C-D-E
New Chum anticline
Garden Gully anticline
Hustlers anticline
D
Whitelaw Fault
gold production (Million ozs)
6
4
2
0
Castlemaine Group
Early - Middle Ordovician
Darrawilian
Castlemainian
Chewtonian
Bendigonian 3 & 4
Bendigonian 1 & 2
Lancefieldian
Anticline axial trace
Fault (triangle indicates dip direction)
Gold mining/exploration shafts
Fault-related quartz (section A-B)
Bedding-parallel vein (section A-B)

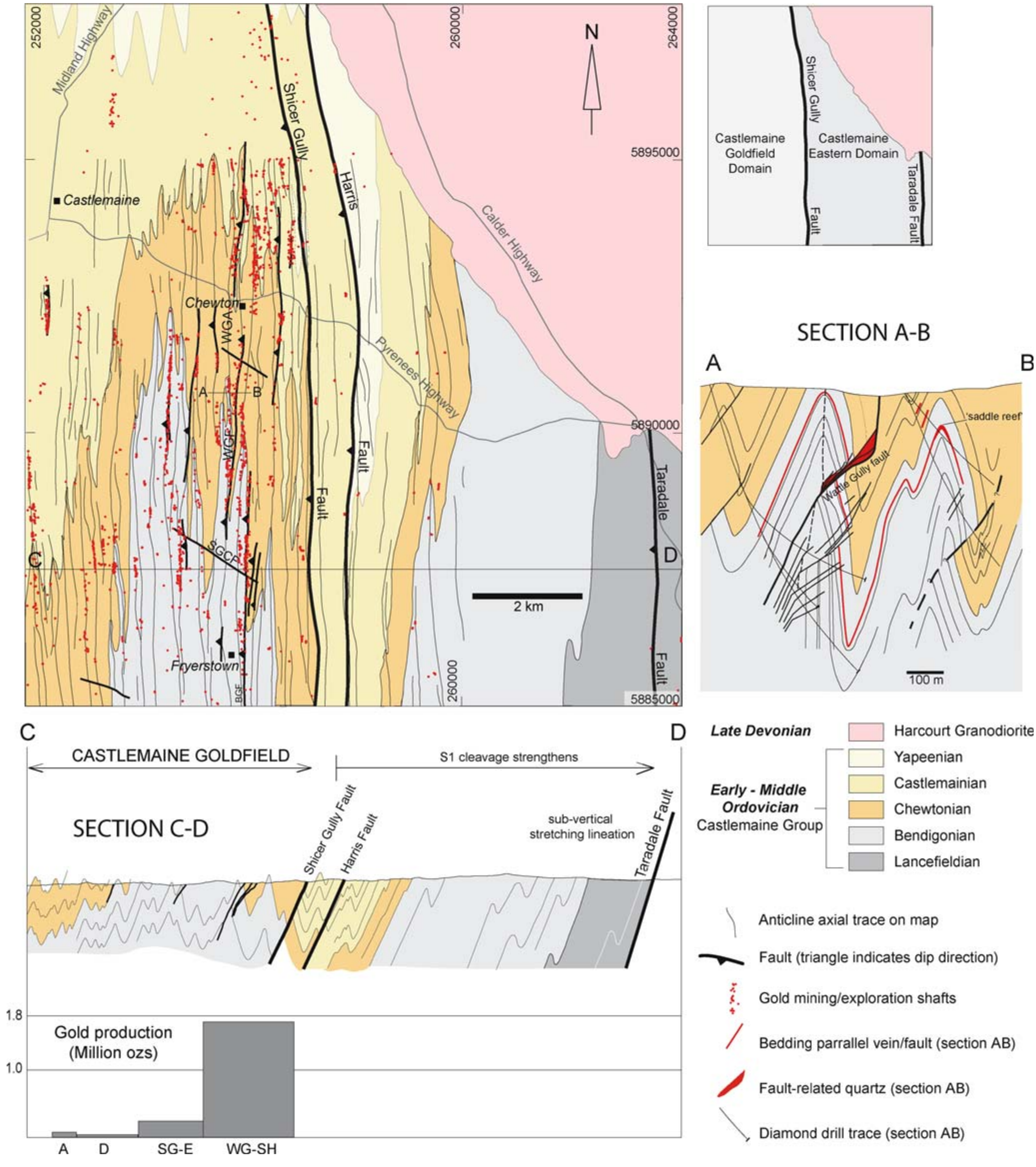


Fig. 3 Castlemaine goldfield. Structural and biostratigraphic *map* showing trend of anticlinal axes, location of gold mining shafts and main faults (*WGA* Wattle Gully Anticline, *WGF* Wattle Gully Fault, *SGCF* Spring Gully Cross Fault). Cross-section *AB* shows detail of mine-scale mineralised structures in the Wattle Gully mine (modified by Alexander Resources Ltd. after an unpublished plan by TF Potter). Cross-section *CD* shows variation in structural style. The *bar graph* indicates variation of gold production across the goldfield (*A* Ajax mines, *D* Devonshire mines, *SGE* Spring Gully–Eureka mines, *WG-SH* Wattle Gully-Specimen Hill mines)

Minor Late Devonian deposits with a gold-stibnite mineralogy occur east of Castlemaine at Belltopper Hill but the total production is quite small (Willman et al. 2002).

Mapping and construction of sections

Structural and biostratigraphic mapping at 1:2,000 and 1:5,000 scales was conducted over an area of 120 km^2 at

Bendigo and 80 km^2 at Castlemaine (Figs. 2 and 3). Despite generally poor outcrop, the Castlemaine Group contains prominent packages of sandstone beds averaging 10–20 m thick that form excellent although discontinuous structural markers. In combination with numerous other exposures in creeks, along roads and in railway cuttings, it has been possible to map most F1 fold axes. The main object of the mapping was to build a series of accurate cross-sections across each goldfield and into the adjacent unmineralised areas (Figs. 2 and 3). Interpretive geological maps at 1:10,000 scale were constructed by combining structural, fossil and sandstone lithofacies data. More than 1,200 fossil localities at Bendigo and 156 at Castlemaine were used to define up to eight biostratigraphic zones, or groups of zones, within the Castlemaine Group. Several hundred old mine plans provided an important constraint on the positions of faults, fold axes and fold forms. The thicknesses of biostratigraphic zones were established in areas of best data and were found to be constant over the area of each goldfield. The final interpretative maps were constructed using serial cross-sections at a spacing of 1 km and the biostratigraphic boundaries reconciled against the map face to achieve a three-dimensional solution. The maps presented in Figs. 2 and 3 are summary maps of the 1:10,000 scale interpretative maps (Willman and Wilkinson 1992; Willman 1995).

Mineralised structures of the goldfields

Faults are the dominant structural control of auriferous quartz veins. The most important faults are early-formed *bedding-parallel faults* and *low-displacement strike-parallel faults*. Folds play a significant role in controlling the paths of faults and a lesser role in creating dilation at fold hinges to form *saddle reefs*.

Bedding-parallel faults are concordant with bedding planes, and down-dip lineations show that displacement was reverse dip-slip. These narrow but persistent faults are characterised by chloritic fault pug, which is usually accompanied by laminated (or 'ribbon') quartz up to 25 cm thick. The veins are commonly auriferous. The faults and veins formed early during fold growth and were folded about F1 folds as they tightened; laminated veins are sometimes found to be overprinted by S1 cleavage (Sharpe and MacGeehan 1990; Willman and Wilkinson 1992). The average stratigraphic spacing of bedding-parallel faults at Bendigo is about 9–13 m (Jessell et al. 1994; Fowler 1996). Localised extension vein arrays may occur adjacent to bedding-parallel faults (Sharpe and MacGeehan 1990).

Mineralised *low-displacement strike-parallel faults* are host to most of the gold-quartz mineralisation in the Bendigo Zone. Displacements are generally less than 100 m and commonly only tens of metres. Strike lengths vary from a few hundred metres and up to several kilometres. Quartz either occurs as fault-fill quartz or as extensional vein arrays adjacent to faults. Most mineralised faults are west-dipping reverse dip-slip faults (Fig. 3, section AB) but east-dipping reverse faults are common at Bendigo (Fig. 2, section AB). The geometry of strike-parallel faults is usually strongly controlled by that of host F1 folds (Cox et al. 1991b); the faults are often rooted along pre-existing bedding-parallel faults above which they truncate the host anticlinal hinge zone to form 'limb thrusts'. This geometry is consistent with the progressive development of mineralised strike-parallel faults during folding and subsequent fold lock-up (Ramsay 1974; Sharpe and MacGeehan 1990; Cox et al. 1991b; Willman and Wilkinson 1992; Schaubs and Wilson 2002).

The term *saddle reef* is used to describe a concentration of quartz veins at an anticlinal hinge. The common link between all forms of saddle reefs is the presence of a bedding-parallel vein. A saddle reef in some cases is simply a folded bedding-parallel vein with enhanced dilation at the hinge. The most productive saddle reefs are formed by 'limb thrusts' that truncated anticline hinges. The faults cut across the opposite fold limb where they are often associated with fault-fill quartz and extensional vein arrays.

Regional variation of structural style

The structural profiles and maps (Figs. 2 and 3) show that structural style varies across the regions that include the Bendigo and Castlemaine goldfields. Structural style is mainly characterised by variations in F1 fold geometry and also by variations in cleavage intensity and the development of vertical mineral lineations. In addition, Gray and Willman (1991b) measured total strains that developed during folding and cleavage development across the study areas.

Bendigo Goldfield

The *Bendigo goldfield domain* (Fig. 2) is characterised by symmetric and strike persistent F1 folds. The enveloping surface to F1 folds is sub-horizontal to gently synclinal. Folds plunge 5–10° north in the north and 5–15° south in the southern part of the goldfield. This plunge reversal occurs in the central part of the goldfield where individual anticlines form domal culminations (Fig. 2). The overall structure of the goldfield is, therefore, a doubly plunging synclinorium. Some folds are continuous for up to 20 km along strike, and mining has traced individual anticlines down to depths of 1.4 km, yet the half-wavelength of F1 folds averages only 150 m. The average interlimb angle is about 40°. This zone includes the major mineralised area. Early formed bedding-parallel faults are common. The total XZ strain ratio is <6.9:1 across the domain (Gray and Willman 1991b).

The *Bendigo eastern domain* is characterised by a west-dipping enveloping surface. F1 folds are asymmetric—they have longer west-dipping limbs compared to east-dipping limbs. Interlimb angles are lower (average ~30°) compared to the Bendigo goldfield domain and tend to decrease towards the east. Gold deposits are rare and small. The slates in this zone have a weak to moderate phyllitic sheen, suggesting metamorphic grade is slightly elevated compared to the Bendigo goldfield domain. S1 cleavage intensifies close to the hanging wall of the Whitelaw Fault and slates contain a sub-vertical mineral lineation within 2 km of the fault (Fig. 2, section DE). Total XZ strain ratio is about 9:1 across the domain but increases to >30:1 in the immediate hanging wall of the Whitelaw Fault (Gray and Willman 1991b).

Castlemaine Goldfield

The *Castlemaine goldfield domain* is characterised by symmetric F1 folds with a mostly sub-horizontal enveloping surface, which becomes steeply west-dipping along its western edge (Fig. 3, section CD). The domain represents the crest of a regional anticlinorium. F1 folds consistently plunge about 10° north and show a systematic increase in mean half-wavelength from 80 m in the west to 300 m in the east, averaging 100 m. There is a corresponding eastward decrease in fold complexity. In the west, folds are impersistent along strike and form complicated branching patterns, but as half-wavelength increases eastward, folds become relatively strike persistent. Interlimb angles vary from 30 to 45°, averaging about 40°, and axial surfaces are sub-vertical to steeply west-dipping. S1 slaty cleavage is sub-vertical or steeply west-dipping. The domain contains all the major mineralised structures, which are concentrated towards the eastern sector. Folds in the eastern sector are symmetric and highly persistent along strike in contrast to the more complex fold patterns found further west in the domain. Low-displacement mineralised faults are common in the domain; they are mostly west-dipping, with dips ranging from 45 to 70° and are strongly controlled by fold geometry and bedding.

Regional-scale mapping (1:25,000 scale) shows that the structural style seen in the *Castlemaine goldfield domain* continues westwards to the Muckleford Fault (Fig. 1), but mineralised low-displacement faults are less common (Willman et al. 2002).

The *Castlemaine eastern domain* is bounded to the west by the Shicer Gully Fault, contains the Harris Fault and continues eastward to the Taradale Fault (Fig. 3). There is no recorded gold production in the domain and except for the evidence of a few shallow mine diggings, the area appears to be largely devoid of gold-quartz mineralisation. The domain is characterised by an east-vergent fold style; F1 folds are asymmetric, with half-wavelengths varying from tens of metres to 800 m. The average width of west-dipping limbs (400 m) exceeds that of east-dipping limbs (130 m), which gives the enveloping surface a steep westerly dip (Fig. 3, section CD). Towards the eastern part of the domain, fold axial surfaces rotate slightly from sub-vertical to west-dipping (~75°) and east-dipping limbs are frequently overturned. Interlimb angles vary from 30 to 70°, with most about 30°. S1 cleavage intensifies from west to east and is steeply west-dipping. This cleavage intensity is especially evident in sandstone where the well-developed and relatively closely spaced P domains forms strong convergent fans about fold hinges and a high bedding/cleavage angle on limbs. This suggests that cleavage formed early in fold development and was subsequently rotated as beds steepened (cf Cox et al. 1991a; Yang and Gray 1994). A weak phyllitic sheen in slates near the eastern part of the domain suggests a slight eastward increase in metamorphic grade towards the Taradale Fault. An eastward increase in intensity of a vertical mineral lineation in slate corresponds with the intensification of S1 cleavage, suggesting that strain was higher in the *Castlemaine eastern domain* compared to the *Castlemaine goldfield domain*.

Relationship of gold distribution to structural style

The geographic distribution of old gold mines and associated gold production is considered to be a good approximation of the actual distribution of total gold endowment because intensive mining has provided a large statistical sample over a period of 150 years. For example, there are 5,400 mining and exploration shafts at Bendigo and 1,700 at Castlemaine. Using these data, the most obvious and striking feature of gold distribution in central Victoria is that auriferous vein systems are clustered together in elongate linear belts (the 'goldfields') that are parallel to the structural trend of the host rocks (Fig. 1). Conversely, there are wide areas between goldfields, within the same host rocks, that are almost totally barren of auriferous veins. These areas typically have less quartz veins compared with the goldfields. The elongate shape of goldfields is parallel to F1 folds and low-displacement strike-parallel faults, reflecting their strong control over mineralised structures.

The greatest gold production is derived from the eastern sides of both the Bendigo and Castlemaine goldfields (Figs. 2 and 3). Gold production was greatest in the eastern part of the *Bendigo goldfield domain* (bar graph in Fig. 2). Total primary gold production at Bendigo is about 17.4 million ounces (540 t) and 13.7 million ounces can be confidently assigned to known mineralised structures (Bendigo Mining data). The data shows that the most productive anticlines were the Hustlers, Garden Gully and New Chum anticlines, each with production exceeding 1 million ounces Au. These occur in a strip 1.7 km wide representing 11.8 million ounces, or at least 68% of Bendigo's total primary gold production. The less productive western portion of the goldfield is about 4.5 km wide where gold production is about 1.4 million ounces (~8% of total production). Gold production drops sharply to the east of the Hustlers Anticline where less than 0.2% of the total production was mined in the Bendigo eastern domain. Sharpe and MacGeehan (1990) noted that the western part of the goldfield is dominated by 'spur reefs' compared to the more productive eastern part, which is dominated by 'saddle reefs' and associated faults.

The Castlemaine Goldfield has a similar production trend across its 4-km width. Gold production was greatest in the eastern part of the Castlemaine goldfield domain, concentrated along a north–south sector less than 1 km wide (Wattle Gully-Specimen Hill mines) that has produced 1.7 million ounces Au or 83% of total historic production (bar graph in Fig. 3). West of here, gold production decreased sharply. The Spring Gully-Eureka mines produced 0.24 million ounces of Au (11.5%) and the most westerly groups of mines produced only 0.04 million ounces (Devonshire mines, 1.8%) and 0.075 million ounces (Ajax mines, 3.6%), respectively. In summary, 94.5% of gold was mined from a belt about 1.7 km wide along the eastern half of the goldfield, whereas the western half produced only 5.4%. There is no recorded gold production between the eastern margin of the Castlemaine Goldfield and the Taradale Fault in the area defined as the Castlemaine eastern domain.

At both Bendigo and Castlemaine, the eastern margins of the most productive portions of the goldfields coincide with the change from symmetric folds to asymmetric folds. At this point, the width of west-dipping limbs increases and the enveloping surface of F1 folds climbs steeply towards the east. The geographic centres of production of each goldfield coincide with structural culminations in the host anticlines. This association is best developed in the Bendigo Goldfield where all the major mineralised folds plunge gently north and south away from the central part of the goldfield (Fig. 2). The association at Castlemaine is restricted to the Wattle Gully Anticline, the most productive mineralised fold that lies in the centre of the goldfield (Fig. 3).

Does stratigraphy control the siting of goldfields?

Earlier workers argued that some parts of the Castlemaine Group, such as strata of Bendigonian age, were lithologically favourable for gold deposition (Dunn 1893; Thomas 1953). At Bendigo, many deposits occur in the Bendigonian 3 and 4 zones at the current exposure level; however, mining has extended to depths of 1.4 km, well below these zones and into the Lancefieldian. Herman (1923) carried out an extensive analysis of the relationship between the biostratigraphic zones and gold deposits at Bendigo and found that no direct correlation could be inferred. This is supported by the present study. The biostratigraphic regional map (Fig. 1) shows that at current erosion levels, gold deposits occur in all biostratigraphic zones from the Lancefieldian to Yapeenian. Some goldfields such as Maldon (Fig. 1) lie entirely within Lancefieldian sedimentary rocks. The distribution of deposits at Castlemaine demonstrates that the biostratigraphic zones have limited influence over the shape and location of the goldfield (Fig. 3). The goldfield lies near the culmination of a gently north-plunging anticlinorium and, therefore, the north-trending goldfield extends from Bendigonian rocks in the south through to the younger Yapeenian rocks in the north. This suggests that stratigraphic level in the Castlemaine Group has little influence over the distribution of deposits. Furthermore, the barren Castlemaine eastern domain contains the same stratigraphic succession with no significant differences in lithology or sand-to-shale ratio compared to the adjacent goldfield.

While there is little evidence for large-scale stratigraphic controls, local variations in the lithology of the Castlemaine Group play an important role in localising mineralised structures. At the mine-scale, the packaging of mudstone or sandstone into units up to about 30 m thick has influenced the location of bedding-parallel faults and the geometry of mineralised strike-parallel faults (e.g. Wattle Gully mine; Fig. 3 section AB). Sharpe and MacGeehan (1990) reported that some tension vein arrays ('spur zones') are confined to specific lithological units.

The clustering of gold deposits

Each goldfield in the Bendigo Zone is comprised of numerous individual mineralised structures termed *quartz reefs* in this paper. These include bedding-parallel faults, strike-parallel faults, saddle reefs and tension vein arrays, each of which have strike-lengths up to hundreds of metres. The individual *quartz reefs* are clustered at two different scales (Fig. 4):

a) *Reef systems* are narrow clusters of quartz reefs at the subregional scale. They show a strong structural and spatial relationship to folds and are usually aligned along a single anticline. Reef systems consisting of sets of west-dipping en-échelon or anastomosing mineralised faults are usually confined to the east limb of a host anticline. Reef systems have strike lengths up to about 20 km and widths of tens to hundreds of metres.
b) *Goldfields* occur at the regional scale and are comprised of up to 20 adjacent reef systems. Goldfields have strike lengths up to 20 km but their widths are mostly less than 5 km. The length-to-width ratio of goldfields is usually greater than 2:1. For example, the Bendigo goldfield is comprised of at least 15 reef systems (parallel mineralised anticlines and/or fault zones) and has a strike length of about 20 km. The most

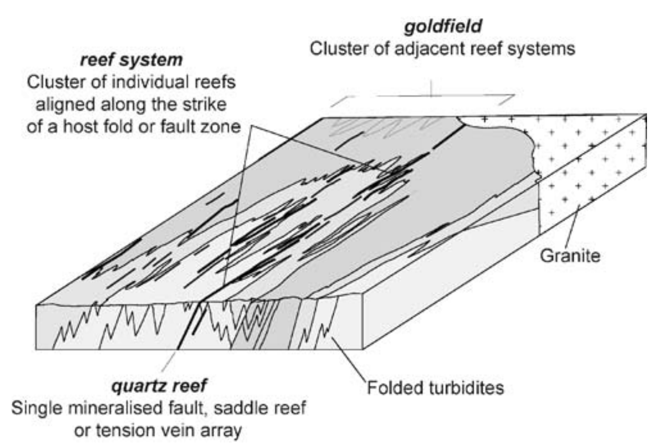


Fig. 4 Block diagram showing that individual mineralised structures (*quartz reefs*) are clustered at two scales forming *reef systems* and *goldfields*

productive portion of the goldfield (>99% total Au production) has a width of 4–6 km, but minor reef systems and other individual quartz reefs extend this width up to 8 km. The Castlemaine goldfield is comprised of at least six reef systems and is about 14 km long and 5 km wide.

The structural controls of individual quartz reefs and reef systems are well-understood at the subregional scale as they can be related to fold growth and subsequent fold lock-up (Willman and Wilkinson 1992; Schaubs and Wilson 2002). They represent the final trapping structures in an environment in which metal-bearing metamorphic fluids were circulating in the crust during the late stages of the Benambran Orogeny (~440 Ma). The discrete nature and elongate shape of goldfields implies that the structural plumbing system extends to the regional scale.

Discussion

Crucial to the understanding of orogenic gold deposits in the central Bendigo Zone is that the timing of mineralisation overlaps major deformation (folding, cleavage development and faulting) of the host turbidite sequence (Cox et al. 1991b; Willman and Wilkinson 1992; Gray et al. 2002). This resulted in mineralised structures that developed during the main and closing stages of fold growth. The earliest veins were bedding-parallel controlled by extensive flexural slip (Fig. 5a). As folding progressed to lock-up, the bedding-parallel veins were folded (Fig. 5b) and became the loci for later low-displacement mineralised strike-parallel faults that propagated from fold limbs and cut across fold hinges (Fig. 5c). This indicates that the development of individual quartz reefs and reef systems (Fig. 4) is directly linked to the structural evolution of folds and hence to the fold and thrust style of deformation characteristic of the central Bendigo Zone.

The clustering of quartz reefs and reef systems to form goldfields, and the elongate shape of goldfields parallel to regional structural trends, are strong evidences that region-scale structural controls are important (Cox et al. 1991b). The homogeneity of metamorphic grade and host-rock composition suggests that these are not significant factors affecting the siting of gold deposits in the central Bendigo Zone.

It has previously been suggested that the siting of central Victorian gold-quartz deposits was controlled by a linked system of thrusts that propagated into the Castlemaine Group late during crustal shortening, based on their timing and structural setting (Cox et al. 1991a,b). In a number of other gold belts, it has similarly been shown that high-displacement regional-scale faults are unmineralised but have a spatial relationship to low-displacement mineralised faults (Groves et al. 1990; Cox and Ruming 2004; Craw and Campbell 2004). The characterisation of the Bendigo and Stawell zones as east-vergent thin-skinned terranes (Cox et al. 1991a,b; Gray and Willman 1991a,b) provides a theoretical means to link the siting of reef systems and goldfields with regional variations in structural style and with major intrazone faults.

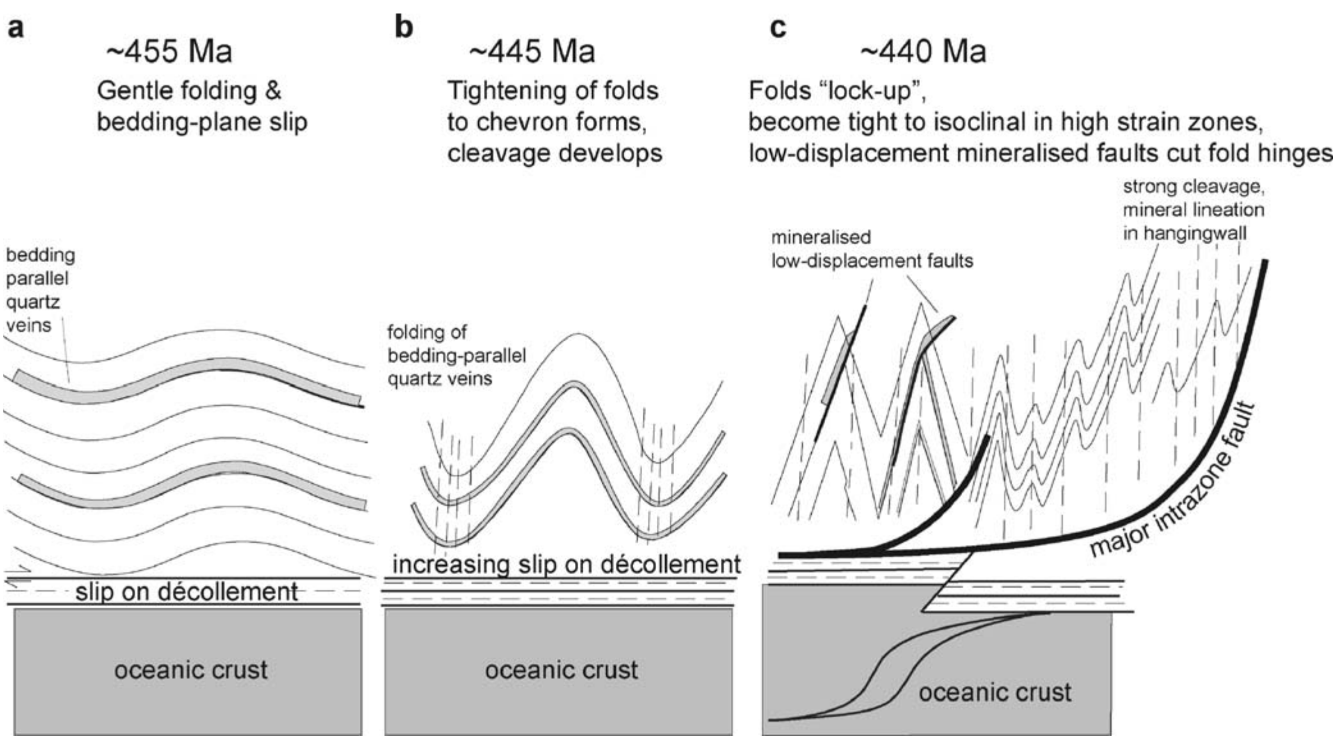


Fig. 5 Evolution of mineralised structures in the central Bendigo Zone. **a** Bedding-parallel faults and associated laminated quartz form in the early stages of fold growth. **b** Progressive folding and cleavage development deforms bedding-parallel veins and **c** low-displacement strike-parallel faults form during fold 'lock-up'. Modified after Gray et al. (2003)

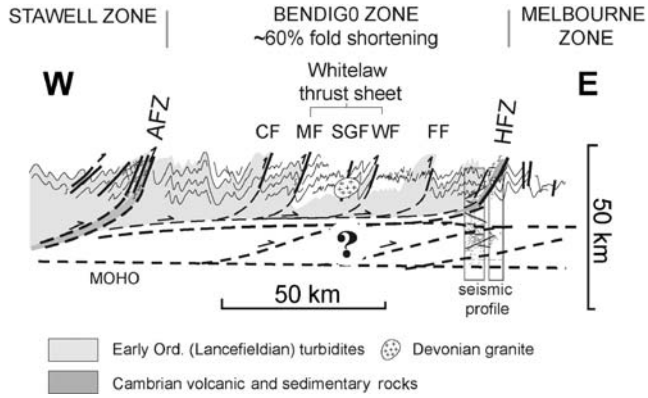


Fig. 6 Schematic regional cross-section across the Bendigo Zone showing inferred fold and thrust geometry and location of the Whitelaw thrust sheet. The *box* on the *right* shows the location of a deep seismic profile. *AFZ* Avoca Fault Zone, *CF* Campbelltown Fault, *MF* Muckleford Fault, *SGF* Shicer Gully Fault, *WF* Whitelaw Fault, *FF* Fosterville Fault, *HFZ* Heathcote Fault Zone. Modified after Gray et al. (2006). Section location is shown in Fig. 1 *inset map*

Gray and Willman (1991b) interpreted the deformed Castlemaine Group as a series of adjacent thrust sheets each bounded by high-displacement intrazone and interzone faults such as the Heathcote, Whitelaw–Taradale and Muckleford faults. The area between the Muckleford and Whitelaw–Taradale faults is one such thrust sheet (Whitelaw thrust sheet: Fig. 6). These faults are steep at the surface, but a deep seismic profile shows that the Heathcote Fault Zone flattens with depth, suggesting that other similar high-displacement faults may also have listric profiles (Gray et al. 1991). The thrust sheet model predicts that major and minor intrazone faults link at depth with interzone faults formed during east-vergent deformation of a sedimentary wedge (Figs. 6 and 7). The observed strain gradient across each thrust sheet suggests that the internal structure of the sheets is related to the major intrazone faults along their leading and eastern margins. The hanging walls of these leading faults are more highly strained compared to areas more than several kilometres to the west.

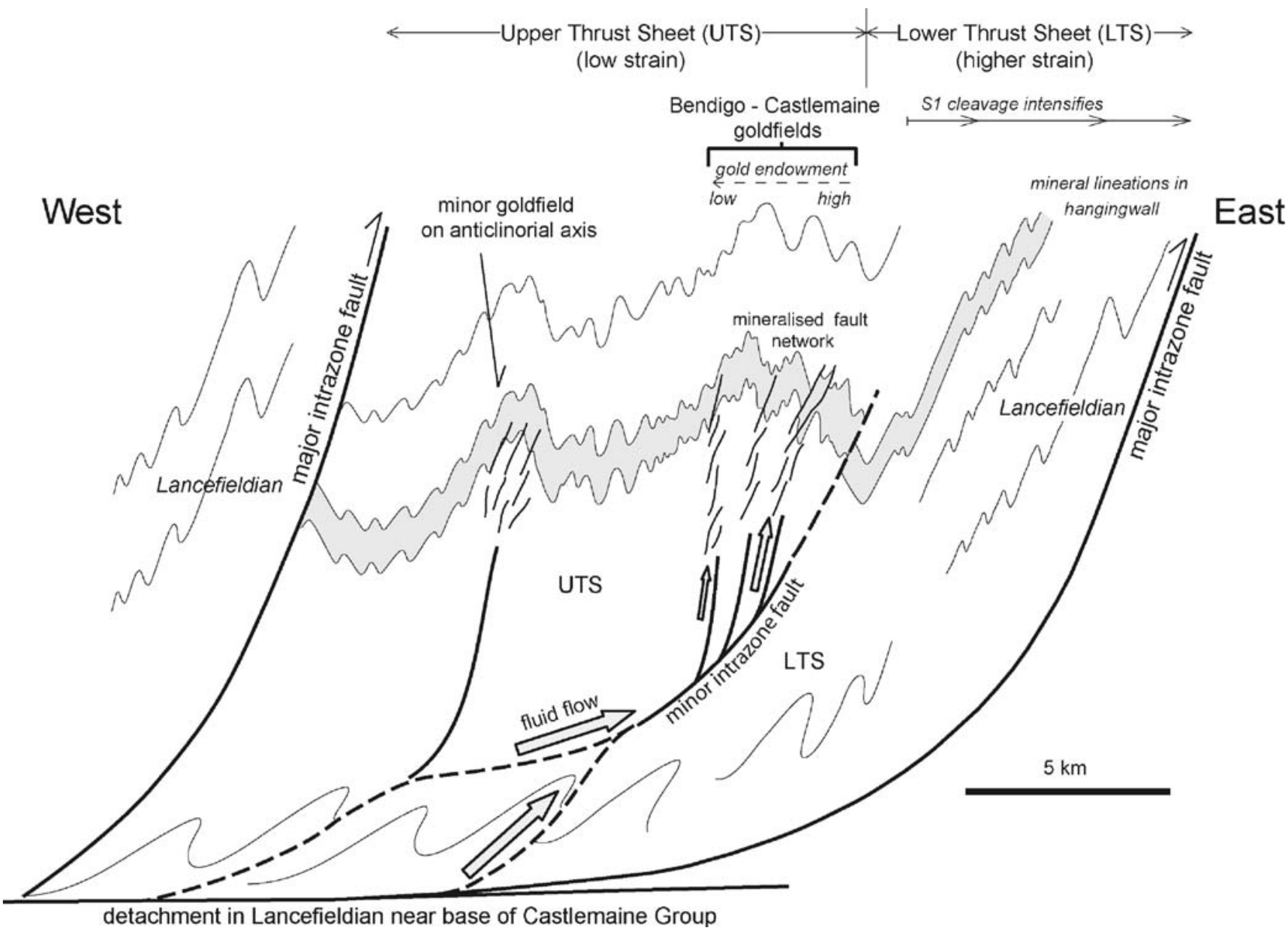


Fig. 7 Cross-sectional model of orogenic gold mineralisation in the central Bendigo Zone and its relationship to thrust sheet geometry. Structural style in the Castlemaine Group varies depending on proximity to the major intrazone fault at the leading (eastern) edge of the sheet. Gold deposits are clustered near the eastern margin of the upper Whitelaw thrust sheet. Networks of mineralised low-displacement faults are inferred to link with minor intrazone faults formed along the upper/lower thrust sheet boundary. Greatest gold endowment occurs along the eastern margin of the fault network coincident with the greatest fluid flow in the active fault network. Gold endowment decreases westward, as does the magnitude of fluid flow (indicated by the relative size of *block arrows*). *UTS* upper thrust sheet, *LTS* lower thrust sheet

Gray and Willman (1991b) subdivided the Whitelaw thrust sheet into upper and lower parts based on variations in fold geometry, cleavage intensity, lineation development, the magnitude of XZ strain and the incremental strain history. Lower parts of the thrust sheet have high strains characterised by non-coaxial deformation (the hanging wall of the Whitelaw–Taradale Fault), whereas upper parts of the thrust sheet have low-to-moderate strains characterised by coaxial deformation (Fig. 7). These features require that thrust sheet emplacement was synchronous with the development of major intrazone and interzone faults (Gray and Willman 1991b). Elsewhere in the Bendigo Zone and in the adjacent Stawell Zone, structural studies have shown similar relationships between high-strain zones and the hanging walls of major faults (Wilson et al. 1992; Cherry and Wilkinson 1994; Cayley and McDonald 1995; Cayley and Taylor 2001). Several goldfields in the Stawell Zone are located in the hanging walls of major intrazone faults (Cayley and McDonald 1995).

The Bendigo and Castlemaine goldfields occur within areas characterised by Gray and Willman (1991b) as 'upper' parts of the Whitelaw thrust sheet. Areas characterised as 'lower' parts of the thrust sheet are the gold-poor regions (Bendigo and Castlemaine eastern domains). The areas of maximum gold production at Bendigo and Castlemaine lie immediately west of the upper/lower thrust sheet boundary, suggesting it may have acted as a major fluid pathway. This pathway may include minor intrazone faults such as the Shicer Gully and Harris faults. The Shicer Gully Fault coincides with the upper/lower thrust sheet boundary, and the presence of quartz veining indicates significant fluid flow occurred along this structure.

Other evidences that suggest a link between intrazone faults and the location of goldfields include:

1) Most quartz reefs in the Bendigo Zone are associated with west-dipping reverse faults, which have the same vergence as the regional intrazone faults. This suggests there is a structural continuum between mineralised faults, reef systems and unmineralised intrazone faults as a result of gross eastward structural vergence during the Benambran Orogeny.
2) The central part of the Bendigo Goldfield lies opposite (and west of) the area of maximum stratigraphic displacement along the Whitelaw Fault (Figs. 1 and 2). Furthermore, the anticlines in the central part of the Bendigo goldfield form a series of domal culminations plunging to the north and south away from a northeast-trending line in the centre of the goldfield (Fig. 2). This suggests that the plunge reversals are related to the maximum displacement along the Whitelaw Fault.

In summary, the overlap between the timing of deformation of the central Bendigo Zone (Whitelaw thrust sheet) and the formation of mineralisation indicates that mineralisation was an integral part of the thin-skinned style of deformation and the progressive development of the thrust sheet. This conclusion is supported by the mapping, which shows that the distribution of mineralised structures is related to variations in structural style and indirectly to the location of intrazone faults. The clustering of gold deposits into reef systems and goldfields immediately west of the upper/lower thrust sheet boundary suggests that thrust sheet geometry controlled the primary fluid pathways during deformation. The upper/lower thrust sheet boundary may have been an important crustal-scale pathway for transferring fluids from the base of the thrust sheet to higher levels. The structures that link major intrazone faults with low-displacement mineralised faults have not been identified: 1) they may be minor intrazone faults or, alternatively, 2) reef systems may have large enough vertical extents to create direct links with major intrazone/décollement structures. These two options are discussed below.

Option 1

The Shicer Gully Fault is an example of a minor intrazone fault that may have formed a link between the Taradale Fault and the network of low-displacement mineralised faults in the Castlemaine goldfield. However, there is no equivalent fault at Bendigo that is presently exposed at the surface along the upper/lower thrust sheet boundary. If one exists at Bendigo, it must be a blind fault. The most likely location of a blind fault would be beneath the eastern portion of the goldfield where gold production is greatest, close to the upper/lower thrust sheet boundary. In such model, fluid flow would have been focussed along major and minor intrazone faults that link with a basal decollement (Fig. 7). Fluids were only trapped in low-displacement faults that were capped by locally or regionally impervious rock packages, probably pelitic units within the Castlemaine Group (Willman and Wilkinson 1992; Schaubs and Wilson 2002).

However, Schaubs and Zhao (2002) used numerical modelling to argue that the presence of blind faults was not critical to the supply of fluids into Bendigo based on an earlier model by Willman and Wilkinson (1992). Schaubs and Zhao (2002) suggested that the capping effect of low permeability shale-rich units, which occur high in the Castlemaine Group at Bendigo, was important in elevating fluid pressures to form gold deposits below the cap. They found that a combined model of a low-permeability cap above the goldfield with the presence of high permeability major intrazone faults (e.g. Whitelaw Fault), resulted in the greatest fluid flow into the goldfield. However, the upper part of the Castlemaine Group is consistently more shale-rich across the entire central Bendigo Zone (Cox et al. 1991a; Willman et al. 2002) indicating that this is unlikely to be a major factor explaining the clustering of deposits and the elongate shape of goldfields.

Option 2

The vertical extent of reef systems is unknown, but the depth of mining at Bendigo (1.4 km along the New Chum Anticline) indicates the possibility that networks of low-displacement mineralised faults may extend to considerable depths along some host folds (Fig. 2, section AB). At Castlemaine, mineralised faults have been traced down-dip for up to 600 m by mining and drilling (Fig. 3, section AB), and west-dipping reef systems can be traced for over 5 km along the strike of host folds. However, it is not known whether the west-dipping fault networks at Castlemaine step across adjacent folds with increasing depth or recur as stacked faults on the one-fold limb. In any case, the data suggest that fault-fracture networks have significant depth continuity in both goldfields. There is also the strong possibility that some reef systems remain confined to a single-host fold for a depth of several kilometres. Folds clearly had an important structural role in controlling fluid flow during deformation as is well demonstrated by the reef systems at Bendigo (Fig. 2). Numerical modelling of the Deborah Anticline at Bendigo suggests that fold buckling processes provided an additional control over fluid flow by directing fluids along permeable sandstone layers towards the hinge area of the fold (Schaubs 1999). The interaction between fluid flow and fold-related structures suggests that individual folds may have formed very efficient self-perpetuating pathways for the upward movement of fluids resulting in near-vertical fault-fracture meshes.

It is proposed that a combination of options 1 and 2 provides the most likely model for the upwards movement of mineralising fluids during deformation. In this model, fluid flow at lower levels in the thrust sheet is directed along the upper/lower thrust sheet boundary, which is inferred to contain minor intrazone faults. As fluid flows towards the leading part of the upper thrust sheet (UTS in Fig. 7), it continues to be controlled by the upper/lower thrust sheet boundary until the boundary steepens. At this level, fluid flow is compartmentalised along adjacent sets of folds. The interaction between elevated fluid pressure and fold-related faulting produces fault-fracture meshes (reef systems) that grow upwards. Cap rocks consisting of low-permeability shales high in the Castlemaine Group help to produce supralithostatic fluid pressures resulting in the growth of quartz veins. Smaller goldfields are located in anticlinorial highs in areas distal to the upper/lower thrust sheet boundary.

An important implication of the protracted history of mineralisation, and its overlap with deformation of the thrust sheet, is that the crustal-scale fault architecture must have developed early in the structural evolution of the Bendigo Zone and continued to focus fluid migration into the goldfields over a significant period. The concentration of gold production along the eastern margins of the goldfields, and the associated westward decrease in production, may reflect the underlying architecture of faults that fed fluids to each goldfield. The pattern suggests a fault-geometry that allowed for a systematic reduction in fluid flow with increasing distance from a parent structure; for example, a west-dipping network of linked faults with maximum displacement and fluid flow concentrated along the leading (eastern) edge of the network (Fig. 7). A possible explanation of the pattern is that the connectivity of the fault-network was more difficult to maintain in the more distal (western) parts of the goldfield over time.

Goldfields in neighbouring thrust sheets show a similar spatial relationship to the leading intrazone faults as described for Bendigo and Castlemaine. The Maldon goldfield sits about 4 km west of the Muckleford Fault and the Heathcote goldfield lies in the hanging wall of the Heathcote Fault (Fig. 1). However, some smaller goldfields in the Bendigo Zone occur in different structural settings. The Daylesford and Blackwood goldfields, although characterised by west-dipping reverse faults close to regional anticlinorium axes, have no obvious relationship to overall thrust sheet geometry (Willman et al. 2002). The unusual Fosterville gold deposit (low-quartz and sulphide-rich) is hosted by a minor intrazone fault (Fosterville Fault, Fig. 1); however, mineralisation ages younger than 440 Ma suggests the fault was reactivated after the Benambran Orogeny (Arne et al. 1998). This indicates that there are a number of different structural pathways that resulted in goldfields of different sizes, both during the main 440 Ma mineralising event and during later minor events. There are also other factors that may have controlled the location of goldfields such as the possible presence of buried continental blocks such as the Selwyn Block of Cayley et al. (2002).

The relationship between goldfield location, position within the host thrust sheet and proximity to major intrazone faults should provide an important regional-scale parameter for future gold exploration in the northern parts of the Bendigo Zone, which are buried by Permian-Cenozoic cover rocks. The relationships at Castlemaine and Bendigo suggest that prospective areas will be located several kilometres west of the major intrazone faults such as the Whitelaw–Taradale Fault or possibly immediately west of minor intrazone faults such as the Shicer Gully Fault. An important factor that needs to be taken into account in applying this model is the relative timing of mineralisation compared to thrust sheet emplacement; younger phases of mineralisation will not necessarily be related to thrust sheet geometry. The relationship between goldfield location and thrust sheet geometry indicates that deep seismic surveys could make an important contribution to future mineral exploration in Victoria.

Acknowledgements Most of the field work for this project was carried out as part of the mapping program of GeoScience Victoria (formerly Geological Survey of Victoria). This work is published with their permission. Colleagues such as Eric Wilkinson provided guidance and support, David Byrne mapped an area of 40 km^2 in the central Bendigo area and Fons VandenBerg assisted with fossil identifications and biostratigraphic interpretation of the Bendigo area. Vladimir Lisitsin made constructive comments on the text. David Gray is thanked for ongoing support. Stephen Cox and Bruce Hobbs provided valuable guidance in the early stages of mapping. Garry Johansen and Rowland Hill of Bendigo Mining Limited provided production statistics and are thanked for numerous stimulating discussions on Bendigo's geology. Mine cross-sections were provided by Bendigo Mining Ltd and Castlemaine Goldfields Ltd.

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