Structural and Tectonic Constraints on the Origin of Gold Deposits in the Ballarat Slate Belt, Victoria

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Abstract

Tightly folded, early Palaeozoic turbidites in the Ballarat slate belt of central-western Victoria are hosts to a major gold province. Gold is typically located in reefs formed after the principal cleavage and fold development. The majority of the auriferous reefs occur in reverse faults and in saddle reefs, which are believed to have formed due to the 'locking' of folds in response to a transition from ductile to brittle deformation modes during a single progressive deformation. The gold introduced into the slate belt was liberated during a prograde metamorphic event in deeper crustal levels. This metamorphic event ultimately produced the anatexis responsible for the many late to post-tectonic, Early to Late Devonian granites in the Ballarat slate belt, and was induced either by Early-Mid Devonian tectonic thickening of the crust, or by anomalous heatflow associated with mantle magmatic activity.

Résumé

Des turbidites étroitement plissées de la ceinture d'ardoise Ballarat du début de paléozoique dans le centre-ouest de Victoria renferment une province aurifère importante. L'or se retrouve généralement dans des filons qui se sont formés après le développement des plis et clivages principaux. La majeure partie des filons aurifères se trouve dans des failles inverses et dans des gîtes en charnières que l'on croit s'être formés à la suite d'un figement des plis en passant d'un mode de déformation ductile à cassant durant un épisode de déformation progressif. L'or introduit dans la ceinture d'ardoise fut libéré au cours d'un épisode de métamorphisme progressif des couches profondes de l'écorce terrestre. Ce métamorphisme a finalement produit une anatexie qui a donné lieu aux nombreux granites du dévonien moyen et supérieur, tardi- et post-tectoniques, de la ceinture d'ardoise de Ballarat et fut provoqué, soit par un épaississement de la croûte au dévonien inférieur ou au dévonien moyen ou encore par un échange de chaleur anormal associé à de l'activité magmatique dans le manteau.

INTRODUCTION

The State of Victoria was a prolific producer of gold in the late 19th and early 20th centuries, with a total production of almost 2,450,000 kg (Whiting and Bowen, 1976). The vast proportion of this gold, much of which was recovered from Tertiary alluvial deposits, was originally derived from auriferous quartz reefs in Cambrian and Ordovician turbidites of the Ballarat slate belt in central and western Victoria (Fig. 1). Although numerous mining reports provide a great deal of information about the structural geometry of these auriferous reefs, the tectonic and metallogenic evolution of this important gold province is poorly understood, and the relationships between gold deposition, regional deformation and granite genesis within the slate belt remain the subject of controversy. In this paper, we review the structural setting of the gold deposits in order to establish a basis for understanding of the metallogenic evolution of this gold province.

The discussion presented herein is based largely on a review of the relevant available data concerning the gold deposits in this region, and with one exception the discussion is based on previously published work. This exception concerns the Avoca-St. Arnaud region near the western margin of the Ballarat slate belt (Fig. 2), a region of distinctive character which has received little attention in the previous literature. References to the geology of gold deposits in the Avoca region are based on our own, as yet unpublished, studies.

REGIONAL TECTONIC FRAMEWORK OF THE BALLARAT SLATE BELT

Victoria forms the southeastern corner of the Australian continent, and its geology is dominated by the Palaeozoic Lachlan foldbelt system (Fig. 1). This system is composed principally of low grade metamorphic marine sedimentary successions of Cambrian to Middle Devonian age, with subordinate volcanic rocks, and numerous Devonian granites (cf. Fig. 2).

Cambrian basic to intermediate metavolcanic and interflow metasediments (termed greenstones) are the oldest known rocks in Victoria. The greenstones are exposed in a series of meridonal axes separated by younger sedimentary basins termed the Ballarat, Melbourne and Omeo Troughs (Fig. 1). The greenstones preserve evidence of evolution in an oceanic arc environment, suggesting that the intervening sedimentary basins evolved as back-arc basins floored by oceanic crust (Crawford *et al.*, 1984). However, the existence of Proterozoic continental crust beneath the Victorian Palaeozoic successions is suggested by the isotopic signature of the Devonian granites (Compston and Chappell, 1979; McCulloch and Chappell, 1982). Consequently, the nature of the fundamental basement of the Lachlan foldbelt in Victoria remains enigmatic.

From the Middle Cambrian, sedimentation in Victoria was controlled by the behaviour of the three major basins (Fig. 1). The Ballarat Trough preserves turbidites of presumed Late Cambrian age as well as a complete Ordovician succession. The Melbourne Trough preserves a conformable sequence ranging from the Late Ordovician through to the end of the Early Devonian. The Omeo Trough is dominated by Late Ordovician turbidites but also preserves relics of Silurian and Devonian volcano-sedimentary successions.

All pre-Middle Devonian Palaeozoic successions in Victoria have been folded into upright, north-trending folds, and intruded by late to post-tectonic granites ranging in

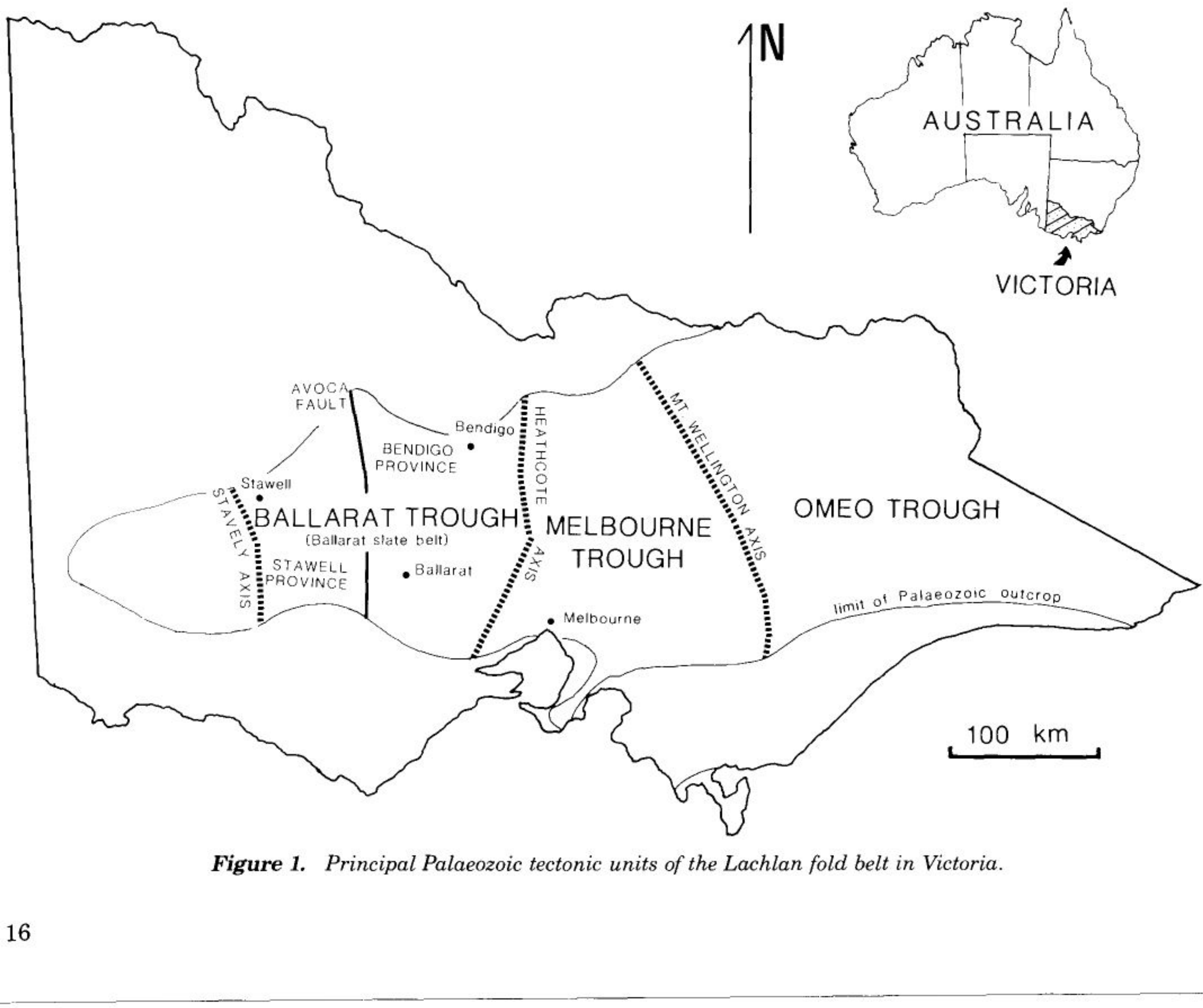

Figure 1. *Principal Palaeozoic tectonic units of the Lachlan fold belt in Victoria.*

age from the Early or Middle Devonian to Early Carboniferous (Vandenberg, 1978; Richards and Singleton, 1981). Only locally is there evidence for more than one generation of folds (Beavis, 1967). Post-fold thrusting on steeply dipping to vertical, north-trending fault surfaces is common, particularly in the Ballarat slate belt (Beavis, 1967, 1976). The mineralogy of the Palaeozoic metasediments reflects a low temperature-low pressure metamorphic regime. Assemblages typically range from sub-greenschist to greenschist, but locally attain cordierite-sillimanite grade in metamorphic terrains associated with granitic complexes. The north-trending folds can, in most cases, be demonstrably associated with an Early to Middle Devonian (Tabberabberan) deformation (Thomas, 1953a). The absence of sediments younger than Ordovician in the Ballarat slate belt has led to the suggestion that these rocks were folded during the Late Ordovician and/or Early Silurian, during the so-called Benambran deformation (Spencer-Jones and Vandenberg, 1976; Vandenberg, 1978). However, pervasive folding of western Victoria at this time is difficult to rationalise with the presence of a conformable sequence in the Melbourne trough ranging from the Ordovician through to the Early Devonian, and we prefer an Early Devonian age for deformation in the Ballarat slate belt. This age assignment is supported by evidence that some Early Devonian granites in the western part of the Ballarat slate belt (in the Stawell province) have schistose metamorphic aureoles (Richards and Singleton, 1981). Folding cannot be younger than Early Devonian because the Grampian Group, which lies unconformably above the early Palaeozoic turbidite successions in Western Victoria, is itself intruded by an Early Devonian granite (Richards and Singleton, 1981).

STRUCTURE OF THE BALLARAT SLATE BELT

Macroscopic structure of the Ballarat slate belt

The Ballarat slate belt consists of two distinct provinces, termed the Stawell province and the Bendigo province (Fig. 2). Both provinces host significant gold deposits. The Stawell province in the western half of the slate belt consists of unfossiliferous turbidites of presumed Late Cambrian age (Thomas *et al.*, 1976) with an estimated thickness of 730 m (Vandenberg, 1978). The evidence for a Cambrian age is based largely on the presence of intercalated metabasalts (greenstones) at Stawell (Clappison, 1960) and at Ararat (Roedder, 1977), in sequences which are presumed to be the oldest exposures in the Stawell province. The Stawell province is separated from the 1800 m thick fossiliferous Ordovician turbidite sequence of the Bendigo province (Vandenberg, 1978) by a north-trending lineament which has been variously termed the Avoca hiatus (Beavis, 1976), the graptolite line (Richards and Singleton, 1981), and the Wedderburn line (Vandenberg, 1978). Our own unpublished studies in the Avoca region suggest that this lineament is a fault, which we refer to here as the Avoca fault (Fig. 2). Further work is in progress to resolve the nature of the lineament.

The preservation of a superb Ordovician graptolite sequence (Harris and Thomas, 1938) in the Bendigo province has allowed for the elucidation of the detailed structure of this region (Thomas, 1939). The principal structures are doubly plunging, upright folds with wavelengths up to 3-10 km (Thomas, 1939). These folds define a dome and basin pattern elongated in the north-south direction (Fig. 2). In profile, the enveloping surface of the fold train dips shallowly west (Thomas, 1939). The consequent west-younging is restricted to relatively small fault-bounded blocks because of numerous west-dipping to near vertical, north-trending faults which expose successively older sequences to the west. Such faults include the Muckleford, Whitelaw and Avoca faults (Fig. 2). These faults define the largest scale, or first order, fault structures in the Ballarat slate belt. Vertical displacement on the Muckleford and Whitelaw faults is in the order of 1,000-1,500 m (Thomas, 1935; Beavis, 1967). It is probable that the Avoca fault involved a considerably larger relative vertical displacement, possibly on the order of 5 km, during an oblique sinistral wrench episode (our own unpublished data).

The first order faults do not contain auriferous reefs and thus are distinct from the smaller (second order), predominantly west-dipping reverse faults which host the major gold deposits throughout the Ballarat slate belt (see below). The age of the first order faults is poorly constrained. The Muckleford fault displaces Pleistocene basalts (Thomas, 1935), but its principal movement predated the emplacement of the Late Devonian Harcourt granite (Beavis, 1976). Our own observations indicate that the Avoca fault involved sinistral strike-slip movement which produced refolding and crenulation of the adjacent Cambrian sediments in the Avoca region. Thus, movement on this fault must have been, in part, younger than the main folding event. Beavis (1967) has suggested that both the Muckleford fault and the Whitelaw fault were initiated during folding, an interpretation supported by theoretical considerations which indicate that folding in the Ballarat slate belt was accompanied by listric reverse faulting (see also Cox *et al.*, 1983a). These considerations are based on the evidence that folding and cleavage development in the Ballarat slate belt occurred in response to a very large sub-horizontal east-west shortening. Talent and Thomas (1973) estimated the average dip on bedding in the Bendigo region is 70°, implying total shortening in the order of 65% (assuming a buckle fold mechanism). Even greater total shortening is indicated by the estimate (Stephens *et al.*, 1979; Cox *et al.*, 1983a) that cleavage development involved up to 30% removal of bulk rock volume by dissolution of quartz from cleavage planes. Such extreme crustal shortening is unlikely to have affected the basement of the slate belt, because, if it had, the consequent crustal thickening might have induced erosion of the 5-12 km deep crustal levels preserved in the Ballarat slate belt. Differential shortening between slate belts and their basements is a common feature in 'thin-skinned' terrains (Boyer and Elliott, 1982). Such displacement is typically accompanied by the development of a decollement at the base of the slate belt from which listric reverse faults splay upwards in the direction of tectonic transport (Boyer and Elliott, 1982). The growth of these listric reverse faults, which may eventually become vertical, is coeval with the formation of folds and cleavage in the intervening fault-bounded sedimentary envelopes. Thus, it is possible that the first order faults in the Ballarat slate belt were initiated as listric reverse faults during folding in response to an easterly migration of the slate belt across its basement.

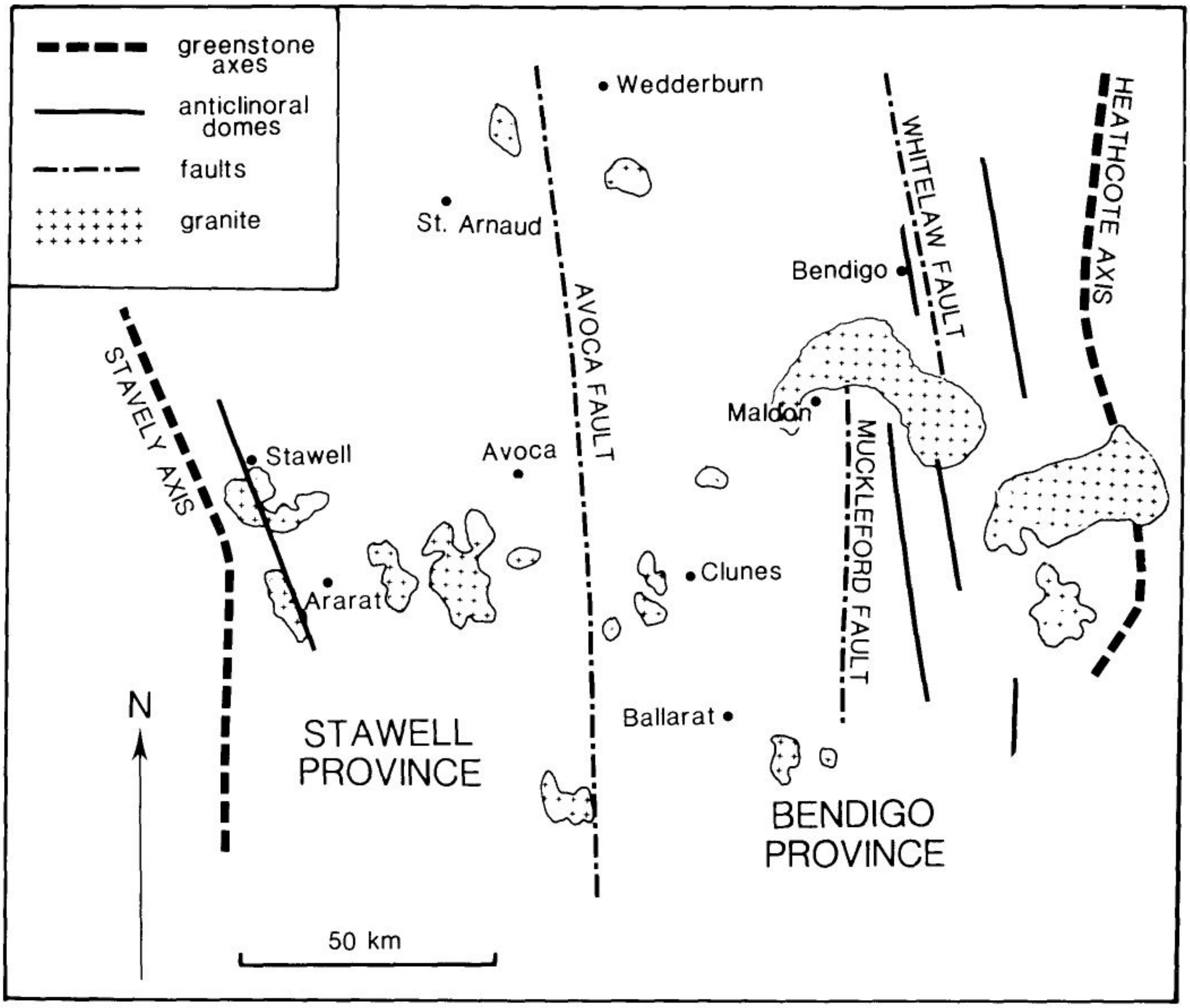

Figure 2. *Simplified geology of the Ballarat slate belt, showing the location of the principal goldfields (after Thomas, 1953a) and the major structural features.*

Distribution and mineralogical character of gold deposits in the Ballarat slate belt

Auriferous quartz reefs are not randomly distributed in the Ballarat slate belt. Rather, they tend to occur in a series of narrow, north-trending linear zones separated by relatively large tracts of unmineralised country (Thomas, 1953a). The principal goldfields are, from west to east (Fig. 2): the Stawell-Ararat and St. Arnaud-Avoca fields of the Stawell province, and the Ballarat-Wedderburn, Steiglitz-Maldon, and Blackwood-Bendigo fields of the Bendigo province.

Within individual reefs, the distribution of gold is extremely variable. There is a strong positive correlation between the presence of graphite in the host rocks and gold content of the quartz reefs (Stillwell, 1917). This feature is most pronounced in the Ballarat-Wedderburn field where the largest gold accumulations were found where reefs cut thin carbonaceous units known as 'indicators' (Thomas, 1953a). This association has long been attributed to the effect of graphite in limiting the gold solubility of the ore-bearing solutions (Stillwell, 1917). Consequently, graphite is regarded as a critical factor in the localisation of gold within the Ballarat slate belt.

In addition to quartz, auriferous veins typically contain ankerite and accessory sulphides. In the Bendigo province the typical sulphide assemblage is pyrite-arsenopyrite, whereas the typical sulphide assemblage in the St. Arnaud-Avoca field in the Stawell province is pyrite-galena-sphalerite-chalcopyrite. Auriferous reefs in the St. Arnaud-Avoca field are also typified by a much greater proportion of sulphides than the auriferous reefs of the Bendigo province. Two styles of mineralization occur at Stawell itself: (1) pyrite-arsenopyrite in quartz reefs within Cambrian turbidites and (2) heavily disseminated pyrite-pyrrhotite-arsenopyrite mineralization in sheared mafic volcanic tuffs. While both Au and As are reported to form haloes around gold deposits in the Bendigo province, extending 15-20 m and 100 m from the auriferous reefs, respectively (Bowen and Whiting, 1975), no such haloes exist at Avoca (our own unpublished data). Mineralization at Avoca is accompanied by a zone of intense carbonate porphyroblast development which extends up to 1 km across strike from the auriferous reefs (Green, 1983). In contrast, only minor carbonate porphyroblast development is associated with auriferous reefs in mines such as the Wattle Gully Mine near Chewton in the Bendigo province (our own unpublished observations). The contrasting sulphide assemblages and variable halo development of mines in the two provinces may be due to the depths at which these deposits formed and, in particular, the temperatures of metal deposition. In a study of metal zoning in the Broadlands geothermal field, New Zealand, Ewers and Keays (1977) demonstrated that the principal cause of metal zoning was temperature: base metal sulphides occur at depth whereas precious metal sulphides containing very low concentrations of base metals are found at shallower levels. This interpretation is in agreement with the generally higher metamorphic grade of the Stawell province (lower greenschist to upper greenschist facies) when compared with the Bendigo province (sub-greenschist to lower greenschist facies).

Fluid inclusion studies at Avoca (Green, 1983) and Wattle Gully Mine (Cox *et al.*, 1983b) indicate that both aqueous and CO_2 or CH_4 fluids were present during auriferous reef formation. Salinities of aqueous solutions are generally low and homogenisation temperatures are consistent with trapping at temperatures of 250-300°C.

Structure of auriferous reefs in the Ballarat slate belt

The structure of auriferous reefs in the Ballarat slate belt has received considerable attention, both in reports of mining during the late 19th and early 20th centuries (published in the Bulletins and Memoirs of the Geological Survey of Victoria) and in more recent reviews (Thomas, 1953a; McAndrew, 1965; Bowen and Whiting, 1975; Whiting and Bowen, 1976). In this section, we briefly review the principal structural types of auriferous reef in the Ballarat slate belt with the emphasis on evidence pertaining to the timing of reef formation.

While there is a great variation in the morphology of auriferous reefs in the Ballarat slate belt (Thomas, 1953a; McAndrew, 1965), the great proportion of gold occurs in two principal types of auriferous reef, termed fault reefs and saddle reefs, respectively. Fault reefs are found in all gold fields, whereas the saddle reefs are largely restricted to the Bendigo field.

The auriferous fault reefs typically occur in reverse 'strike-faults', that is, in reverse faults which parallel the strike of the lithological layering. Typical fault reef geometries are illustrated in Figures 3 and 4. Most mineralised strike-faults dip west at 45-70°, although east-dipping reverse faults are common. In some goldfields auriferous reefs are found in conjugate sets indicating that faulting accompanied east-west shortening (Thomas, 1953a). Individual fault reefs, which are typically less than 2-3 m thick, show considerable variation in thickness and morphology along the fault plane. Variation in the vein thickness reflects different degrees of dilation and is due to local variations in the attitude of the fault plane to the finite displacement

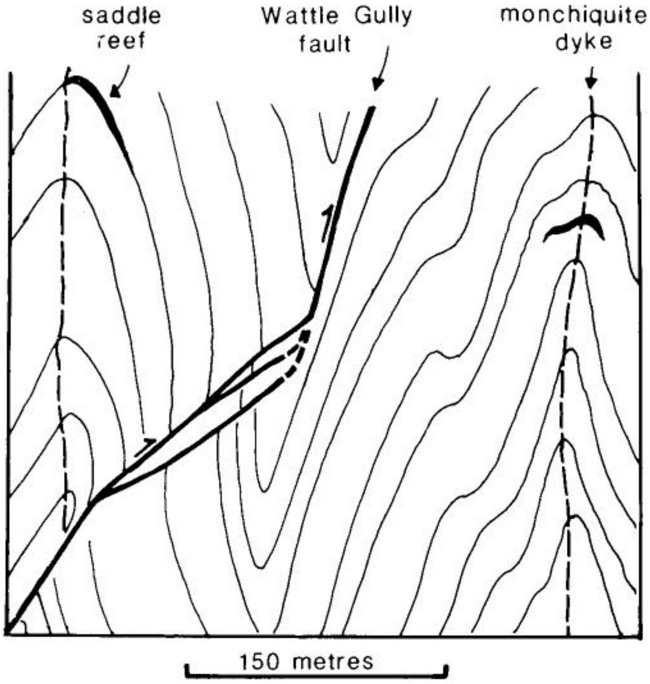

Figure 3. Cross-section of the Wattle Gully Mine in the Bendigo field (after Thomas, 1953c) showing the Wattle Gully fault, a reverse strike-fault, which hosts the auriferous reefs. Note the displacement of fold axial planes by the reverse faults. The saddle reefs are associated with bedding plane faults.

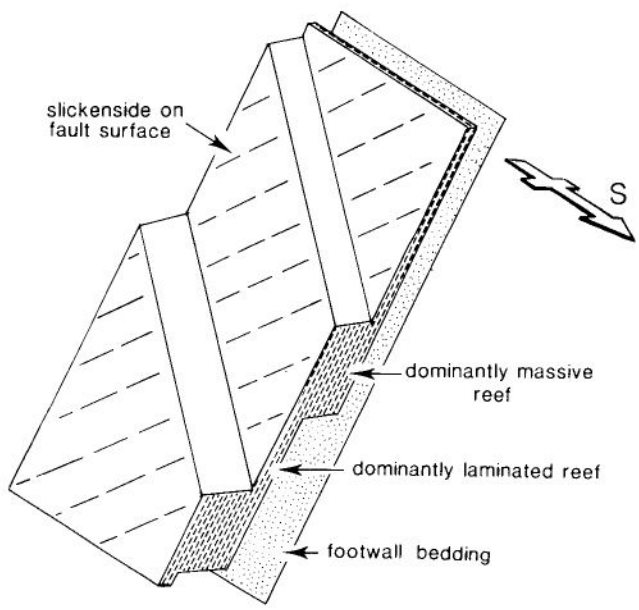

Figure 4. Diagrammatic block diagram of the Fiddlers Reef in a reverse strike-fault at the Roberta mine, Avoca, showing relationship between beddng and fault orientation, vein thickness and morphology (see also Fig. 5), and movement direction as indicated by slickenside trajectories.

direction (Cox *et al.*, 1983b). Typically, the faults are steepest where they parallel bedding as they pass upwards from a syncline to an anticline (Fig. 3). In such settings, reefs are relatively thin if not non-existent. Maximum reef thicknesses are typically associated with an abrupt shallowing of the fault plane where it breaks across the strata to the adjacent syncline (Figs. 3 and 4).

The auriferous strike-faults typically contain two morphologically distinct types of reef (Fig. 5). Laminated reefs are the dominant reef type in the steeper narrower portions of the reef systems, where total dilation is relatively small (Thomas, 1953a). Each lamination may represent one individual dilation event, with the composite laminated reef formed due to many such dilation events during a crack-seal deformation regime. Cox *et al.* (1983b) estimated that the auriferous reefs in the Wattle Gully mine resulted from as many as 2000 individual dilation events per centimetre of vein thickness. However, in most cases the individual laminae in laminated reefs (defined by thin films of slate) are stylolitic in form, suggesting that laminated reefs have formed due to deformation superimposed on a previously unlaminated reef system. Massive reefs are typically associated with the shallowest portions of the fault system where total reef thicknesses are greatest, and dilation during individual opening events was most significant.

The saddle reefs of the Bendigo field have been the subject of considerable discussion and the general morphology of such reefs is well known (Thomas, 1953b; Hills, 1972, p. 250). Individual saddle reefs typically consist of a crescent shaped 'saddle' of quartz which parallels bedding in the hinges of anticlines (Fig. 6). The saddle reefs are frequently located near massive psammitic beds, an observation which has lead to the suggestion that competency contrasts during folding provided the major control on saddle reef formation (Thomas, 1953a; Hills, 1972). However, invariably the saddle reefs are formed at the intersection of a reverse fault with an anticline (Fig. 6) and it is probable that faulting played an important role in the formation of most saddle reefs.

The auriferous faults typically displace the axial planes of folds in the host slate, and reefs in such faults commonly contain fragments of slate with randomly oriented or re-oriented cleavage (Fig. 5). Thus, the formation of these reefs must postdate the folding and cleavage formation in the slate belt. The geometry of conjugate fault systems indicates the stress field during mineralisation was similar to that which operated during regional folding (Thomas, 1953a). Thus, it is possible that the faults formed after 'locking' of the folds in response to a change in deformation from a ductile to brittle regime during the one progressive

***Figure 5.** Fiddlers Reef in the Roberta Mine, Avoca, showing older laminated reef within massive reef. Note that the cleavage in slate inclusions is now more or less parallel to the laminations in the laminated reef. The cleavage in the country rock forms an angle up to 20° to these laminations.*

deformation. The auriferous saddle reefs have been cited as examples of reef formation accompanying regional folding and cleavage development (Hills, 1972). Such a conclusion would be difficult to avoid if the reefs exhibited a simple symmetric saddle morphology. However, this is not generally the case as most saddle reefs are asymmetric due to the controlling influence of bedded reverse faults (Fig. 6). Their common association with reverse faults suggests that the saddle reefs represent a variation of the fault reefs and thus postdate folding. Moreover, the occurrence of saddle reefs in the absence of faults is not sufficient to establish synfolding formation as it is possible that such reefs formed in response to dilation during a quasi-brittle deformation associated with, or following, the 'locking' of folds.

No gold deposits are known in granites in the Bendigo province, and a post-mineralisation emplacement of granites in this province is indicated at Maldon where auriferous fault reefs are truncated and metamorphosed by the Late Devonian Harcourt granite (Thomas, 1953a; Singleton, pers. comm.). In the Stawell province, where the granites are generally some 10-20 Ma older than the granites in the Bendigo province (Richards and Singleton, 1981), the relationship between mineralised fault systems and granite emplacement is not clearly defined. At Stawell, gold mineralisation apparently predated the emplacement of the Middle Devonian Stawell granite (Clappison, 1960). In the Pyrenees Proprietary Mine near Avoca, a dyke reportedly cuts across the fault-related reef without apparent displacement (Thomas, 1953a), although it is not recorded whether this dyke is a granite, or one of the Mesozoic monchiquite dykes which are abundant throughout the Ballarat slate belt (Stillwell, 1911). Elsewhere in the Avoca district, auriferous reefs have been reported in granite dykes (Thomas, 1953a), and granite dykes are strongly carbonated in the vicinity of the auriferous reefs (our own observations). Moreover, metamorphic biotite in the Avoca slates, which formed during a regionally pervasive contact metamorphic overprint, is partially retrogressed to chlorite-muscovite intergrowths in the vicinity of mineralised reefs. These observations suggest that mineralisation in the Stawell province postdated the emplacement of the oldest (Early Devonian) syn-tectonic granites, but predated the emplacement of the youngest (Middle Devonian) post-tectonic granites.

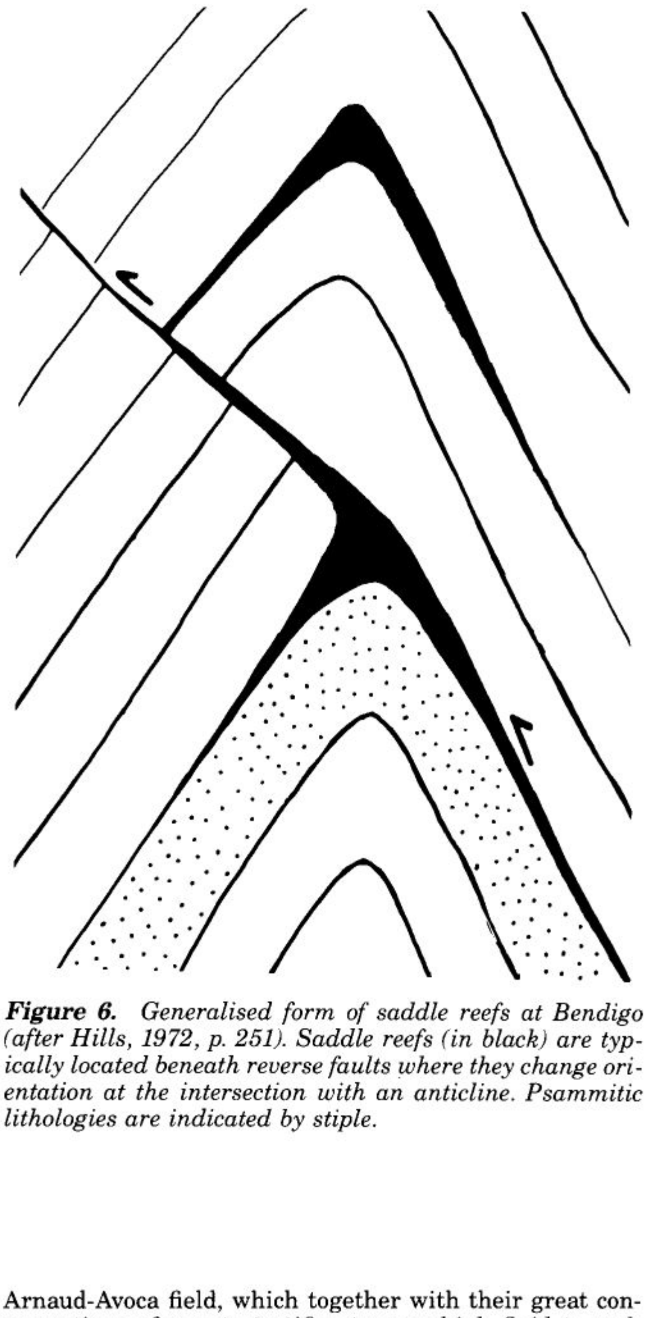

Figure 6. *Generalised form of saddle reefs at Bendigo (after Hills, 1972, p. 251). Saddle reefs (in black) are typically located beneath reverse faults where they change orientation at the intersection with an anticline. Psammitic lithologies are indicated by stiple.*

DISCUSSION

The timing of gold deposition in relation to deformation and granite emplacement in each of the two provinces of the Ballarat slate belt is summarised in Table I. In the following discussion we evaluate the tectonic setting of gold mineralisation in the Ballarat slate belt in light of the constraints imposed by these timing relationships.

As auriferous reefs formed after cleavage, it is unlikely that the gold in these reefs was derived from within the slate belt. This interpretation is consistent with the conclusion of Glasson and Keays (1978) who used mass balance and timing relationships to show that although 10% of the original gold content of the turbidites was liberated during cleavage development, this could not have been the source of the gold in the reefs. The spatial restriction of gold to relatively narrow north-trending zones suggests that the introduction of gold was strongly localised by strike-fault systems. These strike-fault systems locally show strong crenulation cleavage development, particularly in the St. Arnaud-Avoca field, which together with their great concentrations of quartz testifies to very high fluid to rock ratios during reef formation. As dewatering by cleavage formation had already ceased in the adjacent slates, the mineralised fault systems must have provided a focus for fluids liberated at deeper crustal levels. Therefore, it seems likely that the gold in the auriferous reefs in the Ballarat slate belt originated at deeper structural levels. Liberation of this gold is likely to have occurred in response to dehydration induced by prograde metamorphism of mid to deep crustal levels. The preferred timing relationships suggest this prograde metamorphic event immediately followed the culmination of the major deformation event.

Prograde metamorphism of the middle and lower crust during and after the waning stages of the major deformation episode is also indicated by the numerous late to post-tectonic granites in the Ballarat slate belt. The emplace-

Table I

Correlation of structural and igneous events with gold mineralisation in the Bendigo and Stawell provinces of the Ballarat slate belt. The range in ages of Early – Late Devonian granites for each of the two provinces is based on data presented by Richards and Singleton (1981).

	Cambrian	Ordovician	Silurian	Devonian	Carboniferous
Ma	575 – 509	509 – 446	446 – 416	416 – 367	367 – 289
STAWELL PROVINCE	{----}			(-----) <-> [-----]	
BENDIGO PROVINCE		{--------}		(-----) <-> [---]	

KEY

{-----}	sedimentation	<----->	auriferous reef formation
(-----)	folding and cleavage development	[-----]	granite emplacement

ment of the high level granites in the Bendigo province after gold deposition does not necessarily indicate that gold mobilisation and granite genesis are unrelated, as dehydration reactions will precede melting reactions during prograde metamorphism of water-saturated crustal rocks. Moreover, evidence that gold mineralisation in the Stawell province overlapped the emplacement of granites suggests a temporal connection between the thermal regimes resulting in gold liberation and granite formation.

In light of these considerations, we believe the origin of gold in the Ballarat slate belt, and elsewhere in Victoria, is deep-seated and intimately related to the generation of the late to post-tectonic granites. Possible sources of the gold are interflow sediments within the Cambrian greenstones, which are believed to lie at the base of the turbidite sequence. These interflow sediments have anomalously high gold contents; for example, pyritic carbonaceous shale from the Heathcote greenstone belt contain an average of 40 ppb gold (R.N. Robson, pers. commun., 1985). The high gold content of the interflow sediments probably relates to the significant proportions of boninites and other low-Ti lavas within the greenstone sequence in Victoria (Crawford *et al.*, 1984). Hamlyn *et al.* (1985) have demonstrated that boninites (including those from Victoria) have significantly higher platinum group element contents than any other normal lavas; it is believed that the gold contents of boninitic magmas were also higher. The gold in the interflow sediments may have been liberated during the prograde metamorphic event that generated the granite. Hence, gold mineralization in the Ballarat slate belt may be ultimately related to the presence of boninites and the presumed back-arc tectonic setting of the Cambrian volcanics.

The tectonic significance and the reason for the formation of post-tectonic granites in this, as well as other, foldbelts is not clearly understood, and a number of models for their generation have been proposed. In the following discussion we outline the two main models, but it is not possible to determine, on the basis of the available data, which of these models is more appropriate to the Ballarat slate belt. The models are presented in the hope that ensuing discussions on the origin of gold in Victoria will be based on more rigorous understanding of the tectonic evolution of Victoria, rather than, as has been the case in the past, on the descriptive aspects of gold deposits.

The first model assumes that prograde metamorphism was induced during tectonic thickening and subsequent heating through thermal re-equilibration of the crust. The timing of prograde metamorphism in middle and lower crustal levels beneath the slate belt, as indicated by the generation of granites and devolatilisation associated with the mobilisation of gold, implies a significant time lag (approximately 5-30 Ma) between the deformation responsible for tectonic thickening (as recorded by fold and cleavage formation), and the attainment of peak metamorphic temperatures. This deduction is consistent with models for the thermal evolution of tectonically thickened crust (Fig. 7; England and Richardson, 1977), which predict a time lag on the order of 10-20 Ma between maximum burial (which records the time of tectonic thickening) and peak temperatures for crustal levels at the likely depth of generation of Devonian granites in Victoria (approximately 15-25 km, Phillips *et al.*, 1981). A necessary consequence of rapid crustal thickening is that prograde metamorphism with attendant devolatilisation and anatexis in the deep crust will continue after erosion and cooling of upper crustal levels have commenced (Fig. 7).

While this thermal model, applied to the Early-Middle Devonian history of the Ballarat slate belt, adequately explains the observed temporal relationships between crustal deformation and thickening, metamorphism, gold liberation and granite genesis, a principal problem is that many of the granites in Victoria appear to have been generated at temperatures above that which could have been attained by simple thermal re-equilbration of the crust. For instance, Phillips *et al.* (1981) have estimated that the Strathbogie igneous complex, a late Devonian complex in the Melbourne Trough, resulted from anatexis attendant with granulite metamorphism at temperatures of 800-850°C at mid-crustal levels (approximately 15-25 km). Such temperature and pressure conditions imply an excessively high geothermal gradient for a tectonically thickened crust. Moreover, as the Strathbogie igneous complex was emplaced within 1-2 km of the present surface, the source region of the granite must have subsequently cooled at constant pressure. Isobaric cooling in the deep crust is

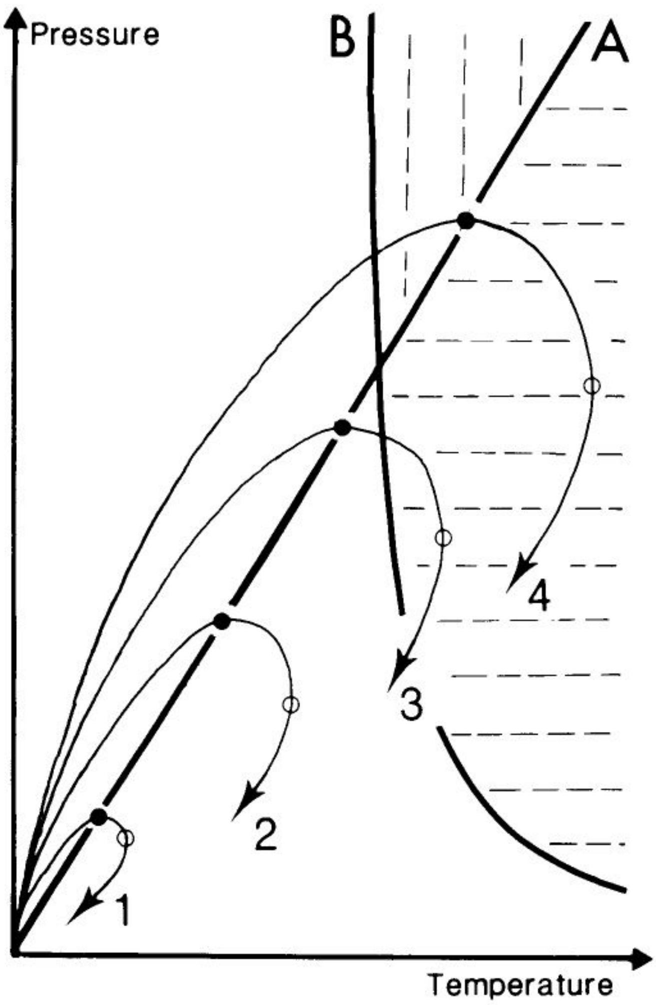

Figure 7. *Pressure-temperature trajectories for a crust undergoing rapid tectonic thickening by crustal shortening (after England and Richardson, 1977). Line A represents the locus of maximum pressures (solid circles) which are attained simultaneously at all crustal levels at the culmination of deformation. In contrast, maximum temperatures (open circles) are not attained synchronously at all levels. Rather, peak temperatures are attained at increasingly longer intervals after deformation the deeper the crustal level (compare trajectory 1 and 4). Line B represents the generalised form of the water saturated solidus for crustal rocks. Vertical dashed lines indicate the field in which syntectonic granites may be generated, while horizontal dashed lines indicate the field in which post-tectonic granites may be generated.*

difficult to reconcile with metamorphism induced by tectonic thickening of the crust (see discussion by England and Richardson, 1977, and Sandiford, 1985). Rather, it suggests that metamorphism was induced by exceptional or perturbed heatflow from the mantle.

These considerations raise the possibility that the prograde metamorphism responsible for granite genesis and gold liberation beneath the Ballarat slate belt resulted from additional heat input into the thickened crust, either by mantle underplating or by emplacement of mantle-derived melts into the crust at this time. Although no evidence of Mid-Devonian mantle-derived magmatism has been reported in the Ballarat slate belt, gold mineralisation in the Woods Point dyke swarm along the eastern margin of the Melbourne trough (Fig. 1) was associated with dykes of overall basaltic andesite composition. These dykes intrude turbidites of Siluro-Devonian age and are Middle Devonian in age (Green *et al.*, 1982). The dykes were emplaced during east-west extension immediately after folding about north trending fold axes, and prior to the emplacement of anatectic melts in cauldron subsidence complexes (Keays and Donnelly, 1984). Deformation continued after dyke formation to produce the classic ladder reefs of the dyke swarm (Edwards, 1953). It also produced mineralised reverse faults similar to those in the Ballarat slate belt (Edwards, 1953). Thus, it is suggested that mineralisation in the Woods Point province was initiated by the ascent of mantle-derived magmas into high crustal levels and that heat associated with the emplacement of these magmas produced anatexis in the middle and lower crust. While this model is difficult to evaluate for the Ballarat slate belt due to the lack of evidence for mantle magmatism in this region, the many similarities between the timing and tectonic environment of gold deposition in the two provinces suggests a genetic relationship.

In summary, the structural setting of the auriferous reefs in the Ballarat slate belt suggests that gold deposits formed during the waning stages of deformation during a Middle Devonian crustal shortening event. These structural relationships suggest that gold was liberated by dewatering of relatively deep crustal levels due to prograde metamorphism induced either by crustal thickening or by anomalous heat flow from the mantle at this time.

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REFERENCES

Beavis, F.C., 1967, Structures in the Ordovician Rocks of Victoria: Proceedings of the Royal Society of Victoria, v. 80, p. 147-182.

———, 1976, Geology of Victoria, Chapter 3: Ordovician: Geological Society of Australia. Special Publication, No. 5, p. 25-44.

Bowen, K.G. and Whiting, R.G., 1975, Gold in the Tasman Geosyncline, Victoria: in Knight, E.L., ed., Economic Geology of Australia and Papua New Guinea, Monograph No. 5, Australian Institute of Mining and Metallurgy, p. 647-659.

Boyer, S.E. and Elliott, D., 1982, Thrust systems: Bulletin of the American Association of Petroleum Geologists, v. 66, p. 1196-1230.

Clappison, R.J.S., 1960, The relationship of structure and ore deposition at Stawell goldfield, Victoria: Proceedings of the Australian Institute for Mining and Metallurgy, v. 195, p. 1-9.

Compston, W. and Chappell, B.W., 1979, Sr-isotope evolution of granitoid source rocks: in McElhinny, M.W., ed., The earth: its Origin, Structure and Evolution, London, Academic Press, p. 377-426.

Cox, S.F., Clepacha, J., Wall, V.J., Etheridge, M.A., Cas, R.A.F., Hammond, R. and Willman, C., 1983a, Lower Ordovician Bendigo trough sequence, Castlemaine area, Victoria – deformational style and implications for the tectonic evolution of the Lachlan fold belt (abstract): Geological Society of Australia, Abstracts, No. 9, p. 41-42.

Cox, S.F., Wall, V.J., Etheridge, M.A., Sun, S.S. and Potter, T.F., 1983b, Gold-quartz mineralization in slate belts: the Castlemaine-Chewton example: Geological Society of Australia, Abstracts, No. 9, p. 260-261.

Crawford, A.J., Cameron, W.E. and Keays, R.R., 1984, The association boninite low-Ti andesite-tholeiite in the Heathcote Greenstone Belt, Victoria, ensimatic setting for the early Lachlan Fold Belt: Australian Journal of Earth Sciences, v. 31, p. 161-175.

Edwards, A.B., 1953, Mines of the Walhalla-Woods Point Auriferous belt: in Edwards, A.B., ed., Geology of Australian ore deposits: Australian Institute for Mining and Metallurgy, Melbourne, p. 1061-1076.

England, P.C. and Richardson, S.W., 1977, The influence of erosion upon the mineral facies of rocks from different metamorphic environments: Journal of the Geological Society of London, v. 134, p. 201-213.

Ewers, G.R. and Keays, R.R., 1977, Volatile and precious metal zoning in the Broadlands Geothermal Field, New Zealand: Economic Geology, v. 72, p. 1337-1354.

Glasson, M.J. and Keays, R.R., 1978, Gold mobilisation during cleavage development in sedimentary rocks from the auriferous slate belt of Central Victoria, Australia: some important boundary conditions: Economic Geology, v. 73, p. 496-511.

Green, A.H., Donnelly, T.H., Jahnke, F.M. and Keays, R.R., 1982, Evolution of gold-bearing veins in dykes of the Woods Point Dyke Swarm, Victoria: Mineralium Deposita, v. 17, p. 175-192.

Green, N., 1983, Geology and geochemistry at Fiddlers Creek: Unpublished B.Sc. (Honours) thesis, University of Melbourne, p. 39.

Hamlyn, P.R., Keays, R.R., Cameron, W.E., Crawford, A.J., and Waldron, H.M., 1985. Precious metals in magnesian low-Ti lavas: implications for metallogenesis and sulphur saturation in primary magmas: Geochemica et Cosmochimica Acta, v. 49, p. 1797-1811.

Harris, W.J. and Thomas, D.E., 1938, A revised classification and correlation of the Ordovician Graptolite Beds of Victoria: Mining and Geological Journal, v. 1, p. 62-72.

Hills, E.S., 1972, Elements of Structural Geology, Second edition: London, Chapman and Hall, p. 502.

Keays, R.R., and Donnelly, T.H., 1984, Controls of gold mineralization in the Woods Point Dyke Swarm, Victoria: in Abstracts, 7th Australian Geological Convention, Sydney, p. 299-300.

McAndrew, J., 1965, Gold deposits of Victoria: in McAndrew, J., Geology of Australian Ore Deposits: 8th Commonwealth Mining and Metallurgical Congress, Melbourne, p. 450-456.

McCulloch, M.T. and Chappell, B.W., 1982, Nd isotope characteristics of S- and I-type granites: Earth and Planetary Science Letters, v. 58, p. 51–64.

Phillips, G.M., Wall, V.J. and Clemens, J.P., 1981, Petrology of the Strathbogie batholith: a cordierite bearing granite: Canadian Mineralogist, v. 19, p. 47-63.

Richards, J.R. and Singleton, O.P., 1981, Palaeozoic Victoria: igneous rocks, ages and their interpretation: Journal of the Geological Society of Australia, v. 28, p. 395-421.

Roedder, G.H., 1977, Structure and metamorphism in a contact aureole: the Ararat granitic intrusion: Unpublished Ph.D. thesis, University of Melbourne, 300p.

Sandiford, M., 1985, Granulite facies metamorphism at Fyfe Hills: implications for Archaean crustal thickness in Enderby Land, Antarctica: Journal of Metamorphic Geology, v. 3, p. 155-178.

Spencer-Jones, D. and Vandenberg, A.H.M., 1976, The Tasman geosyncline in Victoria – regional geology: in Knight, C.L., ed., Economic geology of Australia and Papua New Guinea, Monograph No. 5: Australian Institute of Mining and Metallurgy, p. 637-646.

Stephens, M.B., Glasson, M.J. and Keays, R.R., 1979, Structural and chemical aspects of metamorphic layering development in metasediments from Clunes, Australia: American Journal of Science, v. 279, p. 129-160.

Stillwell, F.L., 1911, Preliminary notes on Monchiquite Dykes of the Bendigo goldfield: Proceedings of the Royal Society of Victoria, v. 25, p. 1-10.

———, 1917, The factors influencing gold deposition in the Bendigo goldfield, Part I: CSIRO Bulletin, v. 4.

Talent, J.A., and Thomas, D.E., 1973, Stratigraphy and structure of the Palaeozoic of west-central Victoria: in McAndrew, J. and Marseden, M.A.H., eds., Regional Guide to Victorian Geology: School of Geology, University of Melbourne, 2nd ed., pp. 65-82.

Thomas, D.E., 1935, The Muckleford fault in the Guildford-Strangways area: Proceedings of the Royal Society of Victoria, v. 47, p. 213-224.

———, 1939, The structure of Victoria with respect to Lower Palaeozoic rocks: Mining and Geological Journal, v. 1, p. 59–64.

———, 1953a, Mineralization and its relationship to the geological structure of Victoria: in Edwards, A.B., ed., Geology of Australian Ore deposits: Australian Institute for Mining and Metallurgy, Melbourne, p. 971-985.

———, 1953b, The Bendigo goldfield: in, Edwards, A.B., ed., Geology of Australian ore deposits: Australian Institute for Mining and Metallurgy, Melbourne, p. 1011-1027.

———, 1953c, The Castlemaine-Chewton-Fryerstown goldfield: in Edwards, A.B., ed., Geology of Australian ore deposits: Australian Institute for Mining and Metallurgy, Melbourne, p. 1042-1053.

Thomas, D.E., Spencer-Jones, D., and Tattam, C.M., 1976, Geology of Victoria, Chapter: Cambrian: Geological Society of Australia, Special Publication, No. 5, p. 11-24.

Vandenberg, A.H.M., 1978, The Tasman fold belt system in Victoria: Tectonophysics, v. 48, p. 267–297.

Whiting, R.G. and Bowen, K.G., 1976, Geology of Victoria, Chapter 12: Economic Geology, gold: Geological Society of Australia Special Publication No. 5, p. 434–451.

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