Mineralium Deposita (1998) 33: 391–405

ARTICLE

B. K. Davis · J. F. M. Hippertt

Relationships between gold concentration and structure in quartz veins from the Hodgkinson Province, northeastern Australia

Received: 24 August 1997 / Accepted: 14 October 1997

Abstract The Hodgkinson Province is a tract of multiply deformed Silurian-Devonian rocks in north Queensland, Australia. Gold-bearing quartz veins from the West Normanby Goldfield in the northern Hodgkinson Province were emplaced during the Permian D_4 event, broadly coeval with regional granite emplacement. Taylors Fault, a major structure that formed during D_2, hosts the veins which infill dilatational jogs opened during sinistral-normal reactivation of the fault in D_4. Veins contain graphitic laminations that formed when fault planes segmented wallrocks adjacent to the veins, producing tabular clasts that were tectonically sliced into the reefs. Laminations are the result of progressive shear strain, associated with continued movement on the faults, which caused strain-enhanced dissolution of silicate minerals and residual graphite enrichment in the clasts. This process produced graphite-coated shear planes that delimit zones of grain size reduction in the veins. Laminations commonly contain stylolites, which nucleated on pronounced sinuosities of the shear planes due to progressive shortening during D_4. Gold particles have preferentially nucleated in zones of relatively coarser-grained quartz adjacent to the shear planes, where shortening strain caused microfracturing and allowed fluid access. Gold may have been introduced with the quartz, but was redistributed within the reefs and localized along the laminations by the effects of synchronous, progressive deformation. Regionally, gold deposits show close spatial relationships with granite plutons of the Permian Whypalla Supersuite. Relationships in the West Normanby Gold Field support a regional model of reef emplacement and gold mineralization during the Permian D_4 event.

Editorial handling: J. Walshe

B.K. Davis (✉)[1]
Department of Earth Sciences,
James Cook University of North Queensland,
Townsville, Queensland, Australia, 4811
Fax: 61-77-251501; email: Brett.Davis@jcu.edu.au

J.F.M. Hippertt
CNPq Researcher, Departamento de Geologia,
Universidade Federal de Ouro Preto, Morro do Cruzeiro,
Cep 35400-000, Ouro Preto, MG, Brazil
Fax: 55-31-5512334; email: hippertt@degeo.ufop.br

Present address:
[1]c/- Terra Search, P.O. Box 981, Castletown,
Hyde Park, Queensland, Australia, 4812
email: terrasch@ultra.net.au

Introduction

The Hodgkinson Province of north Queensland, Australia, is an extensive north-northwest trending trough of multiply deformed Siluro-Devonian sediments and volcanics within the Tasman orogenic system (Tasmanides) and is dominated areally by the multiply deformed Hodgkinson Formation. Hodgkinson Formation comprises a thick, monotonous succession of turbiditic greywacke-siltstone-shale, slate, minor volcanics, conglomerate, chert and rare limestones of deep marine origin (Arnold and Fawckner 1980; Bultitude et al. 1990). These rocks have been intruded by a number of granitic bodies of variable size (Fig. 1), generally of Early Permian age, which have been grouped geochemically into supersuites (Bultitude and Champion 1992).

Many areas within the Hodgkinson Province, particularly within the Silurian-Devonian Hodgkinson Formation, have been exploited for gold (e.g. de Keyser and Lucas 1968), much of which has been alluvial. The presence of gold hosted by in situ veins is relatively restricted and has confined previous studies of primary controls on gold mineralization to several areas within the Hodgkinson Province where hardrock mining has been undertaken. The most detailed of these studies was by Peters et al. (1990) and focused on several mines in the Hodgkinson Gold Field (Fig. 1) in the centre of the province. Similar studies for the northern portion of the Hodgkinson Province have not been published. The most significant northern deposits in Hodgkinson Formation are located within the West Normanby Goldfield

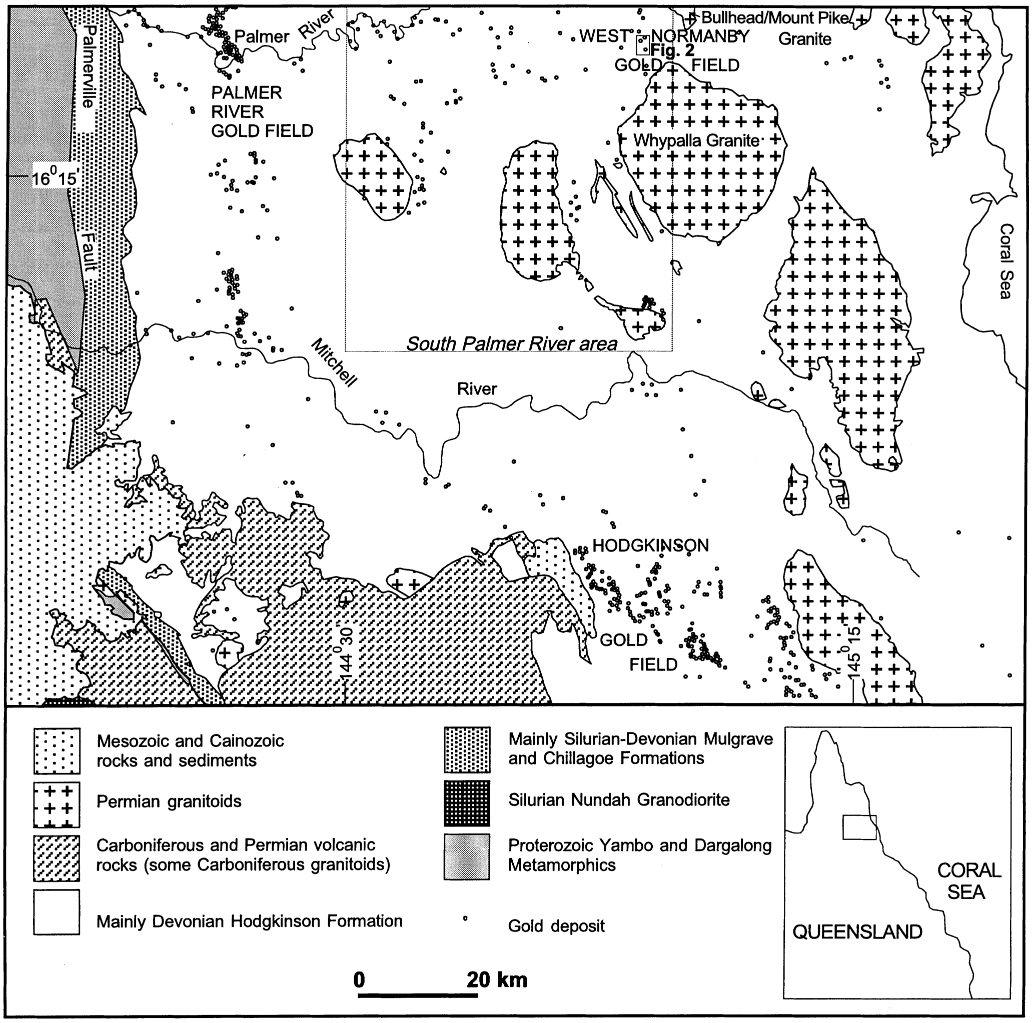


Fig. 1 Location of the Hodgkinson Province in Queensland, Australia, showing the major goldfields and individual gold deposits. The *South Palmer River area* is indicated and the West *Normanby Goldfield* is located in the *northeast corner* of this between the *Whypalla Granite* (south) and the *Bullhead/Mount Pike Granite*

of the South Palmer River region approximately 80 km south of Cooktown. A number of gold mines, including Maddens Mine and Brothers Mine, are located near the head of the West Normanby River and comprise underground development in the Hodgkinson Formation (Figs. 1 and 2).

Deposits in the southern portion of the West Normanby Goldfield display an intimate spatial relationship with an approximately north-northwest/south-southeast trending structure herein termed Taylors Fault (Fig. 2). Several mines incorporating underground development are situated along this structure, in addition to minor prospects defined by small open pits several metres across. Sinistral movement is interpreted for Taylors Fault based on an almost two kilometre displacement of steeply dipping lithological packages (Fig. 2; see later).

Hardrock mineralization in the Hodgkinson Formation of the West Normanby goldfield is associated with quartz veins, and known occurrences define a roughly north-south trending belt that is approximately 20 km long. The West Normanby Gold Field displays a close spatial association with several Permian granitoids (Fig. 1), which Bultitude and Champion (1992) included within the Whypalla Supersuite based on mineralogical and geochemical similarities. The southernmost mine of the West Normanby Goldfield is Brothers Mine, which is located approximately 5 km from the northern end of the Whypalla Granite (Fig. 1), the largest granite within the Whypalla Supersuite. Unnamed prospects at the northern end of the field lie within several kilometres of the Mount Pike Granite/Bullhead Granite.

This study focuses on the southern end of the West Normanby Goldfield and concentrates on structural characteristics of the main gold-bearing lenses from Maddens Mine and, to a lesser degree, Brothers Mine. The internal geometry of the reefs, in particular the microstructure, has been documented and a history comprising vein formation and deformation is proposed. Microstructural and prospect-scale structural controls on the localization and concentration of gold mineralization are also proposed and an attempt has been made to place the timing of mineralization within both the

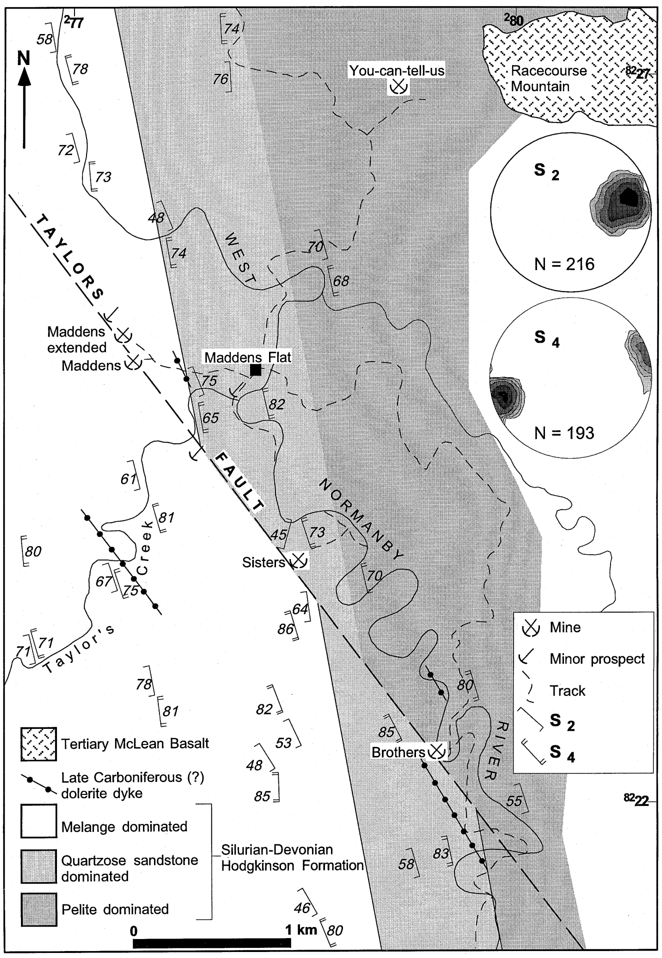


Fig. 2 General geology of the southern end of the West Normanby Gold Field. Lithologies have been grouped into broad packages based on dominant rock type. Bedding is not represented because it is commonly disrupted, particularly in the melange package. In zones of relatively coherent bedding, S_0 is generally subparallel to S_2. Note that only hard rock deposits are shown and that they all lie along the *Taylors Fault* except for *You-can-tell-us*. You-can-tell-us is interpreted to be on a structure subparallel to Taylors Fault. *Grid is* Australian Map Grid, zone 55

local deformation history of the mine area and the regional deformation history of the Hodgkinson Province.

Prospect geology and structural setting

Host rocks to the auriferous veins are Hodgkinson Formation and comprise a siliciclastic turbiditic sequence of fine-grained graphitic mudstones, thin-bedded to laminated siltstones and fine- to medium-grained arenaceous units. The overall trend of bedding is approximately north-south and is commonly overturned with moderate to steep dips to the west. Tectonic melange (e.g. Hammond 1987; Davis 1994) is a common contributor to the sequence, and consists of phacoids of more quartzose material within a sheared mudstone matrix. Bedding in zones of melange varies from weakly segmented horizons through to completely disrupted lithologies characterized by block-in-matrix texture. Melange zones vary from approximately half a metre to hundreds of metres in width. The elongation of clasts within the melange defines a moderately NNW-plunging lineation due to modification of the phacoids by deformation that post-dated melange formation.

The sequence of rocks exposed in the mines is interpreted to have been affected by four ductile deformation events and a series of faults and shear zones. A similar deformation history is developed across much of the Hodgkinson Province, with a regionally pervasive foliation evident across most tracts of sedimentary rock, particularly the adjacent South Palmer River region (Fig. 1). This fabric has been defined S_2 by numerous workers (e.g. Halfpenny and Hegarty 1991; Davis 1994; Davis and Forde 1994), and is commonly overprinted by subsequent events, which have produced a similarly oriented composite fabric. In the central Hodgkinson Province S_2 is represented by an intense north-south trending foliation that is commonly parallel to bedding and axial planar to moderately to steeply plunging folds of all scales (Halfpenny and Hegarty 1991; Davis and Forde 1994). Consequently, S_2 is a good regional marker fabric and allows for tentative correlation of the early tectonic history from area to area. The dominant pervasive foliation in the vicinity of the mines shows similar characteristics to that for adjacent areas in the Hodgkinson and is interpreted to be S_2 (equal area net in Fig. 2). Based on this interpretation the first deformation, D_1, is implied. D_2 folds are generally from 10 to 50 cm in amplitude and have variable plunges. They are much rarer than in other areas of the Hodgkinson to the south. D_3 produced sporadically developed, mesoscale, recumbent folds of lithology and S_2 that generally have an axial planar crenulation cleavage, S_3. D_3 folds generally have interlimb angles of 70 to 100 degrees and vary from 10 to 80 centimetres in wavelength. D_4 produced an extensively developed crenulation cleavage, S_4, that is commonly differentiated and defines an excellent marker fabric for structural correlation. S_4 is subvertical and trends approximately NNW-SSE (equal area net in Fig. 2). Consistent asymmetry of the differentiated crenulations suggests an east-side-up sense of shear. D_4 folds are common, open and rarely exceed 20 cm in wavelength or amplitude.

Metamorphic grade across the West Normanby Goldfield is lower greenschist and porphyroblastic rocks are uncommon. Porphyroblast growth is restricted to carbonate (ankerite?) and porphyroblast-matrix microstructures indicate syn-D_4 growth.

Several generations of veins, apart from those forming the reefs, are apparent. Generally these are much thinner than the gold-bearing reefs and have been emplaced at various stages during the structural history of the area. The earliest recognizable set is obvious as extremely deformed and attenuated veins that are generally one to two centimetres wide. Segmentation of these veins is common and some surface outcrops display numerous isolated quartz clasts that originally comprised individual veins. These veins are most obvious in surface outcrops because of their distinctive 'sugary' grey-black appearance. Milky quartz veins up to 10 cm thick cross-cut S_2 but show the effects of D_3 deformation in the adit of Maddens Mine. A subsequent phase of quartz veining occurs as one to two centimetre wide veins oriented at a low angle to the axial plane of D_4 folds immediately outside the entrance to Maddens Mine. These veins are interpreted to have been emplaced syn-D_4.

The gold-bearing reefs consist of several phases of silica injection (see later). This is commonly attested by a brecciated texture of milky quartz in hand specimen, which has been sealed by at least one later phase of clearer quartz. Deformation characteristics in the reefs are most apparent at the micro-scale and are discussed later. At least one stage of veining post-dates emplacement of the reefs and is represented by shallowing dipping veins that are generally several millimetres wide. These are best developed in the more quartz-rich sediments, which were more easily fractured during the latter stages of the structural history.

Faults

The dominant population of faults and shear zones across the mining field strikes approximately 30° anticlockwise of the approximately north-south striking regional structural grain and are steeply dipping to subvertical. A population of late minor faults with subvertical, east-west orientations is locally represented. Underground development has also exposed numerous faults and shear zones and most trend at a low angle to the pervasive country

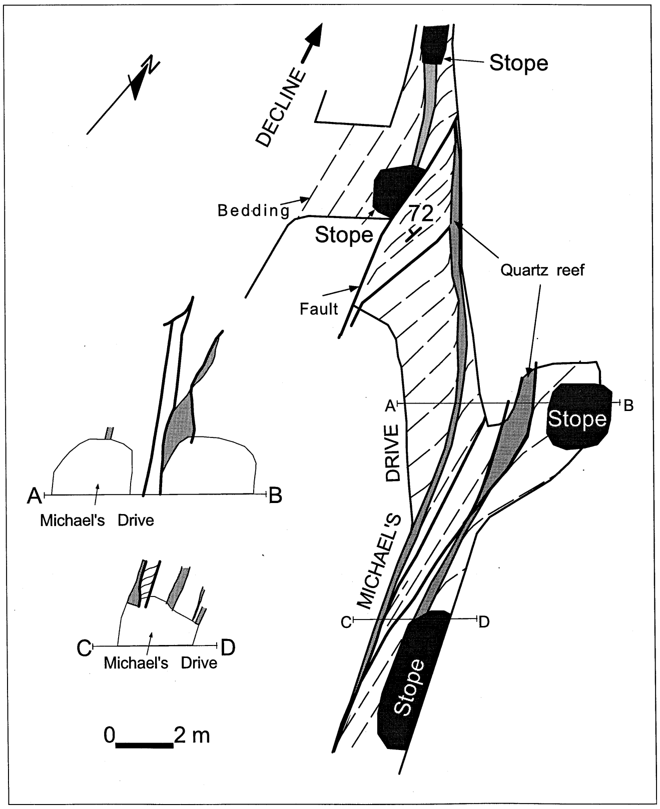


Fig. 3 Map of the back of one of the main ore drives (*Michael's Drive*) in Maddens Mine. Note that the reefs cut bedding at an acute angle and that their strike is consistently anticlockwise of that of bedding. Bedding displays progressive curvature into parallelism with the reef boundaries, which are commonly defined by faults. Sections *A-B* and *C-D* indicate fault geometries in vertical section

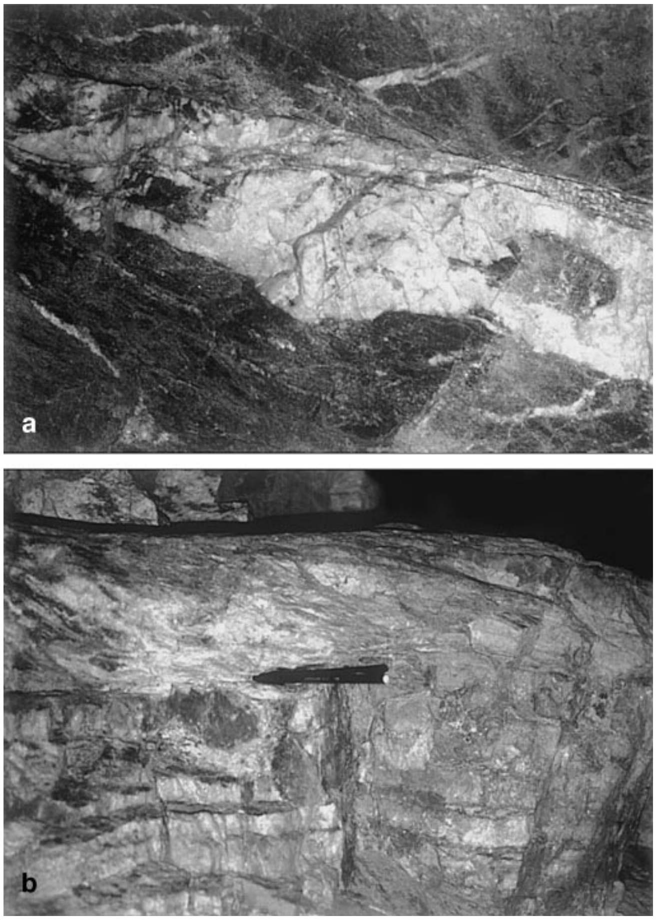


Fig. 4a,b Photographs from auriferous reefs in Michael's Drive, Maddens Mine. **a** Vein showing variation in thickness and inclusion of wall rock clasts. The clast on the *right hand side* of the photo displays partial silicification and no obvious association with shear planes. This is interpreted to be due to inclusion during brecciation and vein opening. Numerous, smaller unsilicified clasts in the *left hand side* of the vein have been entrained via a different mechanism involving tectonic slicing. Note that carbonaceous shear planes anastomose through this zone, beginning parallel to the bottom side of the vein and then defining a sigmoidal geometry through the centre of the vein before becoming parallel to the upper edge of the vein again. The shear fabrics on the upper margin have created a zone of lamination. Reef width is 40 cm at its widest portion. **b** Laminated vein in the *lower half of the photo* with intensely sheared country rock on its margin. The *pen* is parallel to the vein contact. The shear fabric in the country rock indicates sinistral shear

rock fabric, which is a combination of bedding and cleavage (Fig. 3). Dips vary from vertical through to approximately 35°, with dips greater than 50° being most common. Fault thickness is highly variable, ranging from centimetres to several metres. Boundaries of shear zones vary from regions of distributed shear, marked by overall decreasing shear intensity, through to knife-sharp contacts. Some structures are entirely brittle and are represented by angular clasts of quartz and/or country rock within a cataclastic, clay-dominated matrix.

Bifurcation and anastomosing of shear zones and faults is extremely common, with some structures exhibiting splays every few metres. Magnitudes of fault movements have been restricted in plan view, as attested by minimal offset of marker units affected by them. This suggests that the large displacement on Taylors Fault is probably due to individual faults accommodating only partial amounts of the overall movement, with these minor movements summing to give the major displacement. Faults commonly display intimate spatial relationships with quartz veins, which appear to simply be attenuated or thinned in plan rather than being displaced by significant distances. Individual structures in vertical section truncate the reefs or displace them over distances of metres to tens of metres. The greater amounts of displacement in section than in plan, the common occurrence of steeply plunging slickensides on fault planes, and the common asymmetric geometry of shear planes internal to the fault boundaries when viewed in vertical sections at a high angle to the fault zone, all suggest that fault movement vectors were steeply oriented. Taken in conjunction with the sinistral shear sense on Taylors Fault this suggests that the overall fault movement was moderately to steeply oblique.

Faults commonly define one or both margins of the auriferous reefs (Figs 3 and 4). Generally, faults in the country rock trend parallel to the reef margins but commonly acutely cross-cut them. Alternatively, the faults commonly bifurcate, with the splays cross-cutting the reef. In both cases the veins are attenuated and thinned, commonly with the production of sigmoidal fabrics within the reefs (Fig. 4). Generally, quartz within the faults appears ductilely deformed but in some rare cases it constitutes deformed clasts within an extremely sheared matrix of country rock.

Bedding trends display a consistent geometry relative to the faulted reef margins. In all plan views the strike of bedding is consistently 10° to 30° clockwise of the strike of the reefs, with the two commonly becoming subparallel on the reef margin. This suggests that, although magnitudes of fault movement on individual splays were relatively less in plan, the sense of shear was consistently sinistral on faulted vein margins. This accords with the sinistral sense of offset on Taylors Fault (Fig. 2). The sense of displacement of the reefs and lithology, the asymmetry of segmented reefs and the deflection of markers such as bedding and foliation into the faults and shear zones, overwhelmingly indicates east-side-up senses of movement in vertical exposures approximately normal to the trends of faults. Individual faults that dip moderately to the west are interpreted as being splays that link, and are bounded by, steeply dipping structures subparallel to the margins of the overall fault system. The east-side-up sense of movement is the same as that for the D_4 deformation.

Reef morphology

Mesoscale structure of the reefs

Quartz veins hosting the gold mineralization are milky white and strike sub-parallel to lithological layering or acutely cross-cut it. Vein widths are generally one metre or less and commonly vary dramatically over short distances along strike or up and down dip. Variation in thickness is commonly the result of margin-parallel shear zones, especially in areas where the faults cross-cut the veins (e.g. Fig. 3). Marked thinning of the veins has also been noted where there is no shear zone influence. Broad-scale flexures of the veins are also apparent. In some cases this folding is attributable to the influence of variably oriented faults and bedding, whereas other segments may reflect genuine post-vein (D_4?) folds. Generally, the amount of displacement on cross-cutting faults is small in plan, and veins tend to be attenuated and thinned rather than experiencing marked offsets. Bifurcation of the veins is common and dominantly occurs where the reefs are less than 50 cm wide. Best examples of bifurcation have been noted where the veins display marked thinning that is unrelated to faults. In these areas the splays define terminations of the reef or individual reef segments. Intersection of host rock bedding and S_2 shows a consistent asymmetry, with country rock fabrics adjacent to the reef margins displaying progressive changes in orientation such that they always intersect the veins at low angles (less than 20°).

Laminations and reef microstructure

Veins typically display laminations that may be up to a centimetre apart and range to five millimetres in thickness (e.g. Figs. 4 and 5). On the hand specimen scale, the laminations appear as planar zones characterized by a dark grey or black colour separated by milky white, pure quartz domains. Thinner veins display laminations across their width whereas thicker reefs tend to have laminations confined to their margins. Elongate, tabular clasts of country rock are occasionally included in the veins, generally close to the wallrock contact, and the extremities of these clasts commonly display continuity with vein laminations (Fig. 5). Lamination mineralogy is dominated by graphite with minor carbonates and sulphide. Sulphides are dominated by arsenopyrite and stibnite, with minor chalcocite and covellite, and rare galena and sphalerite. The dark colour of the laminations is principally due to the concentration of graphite (e.g. Cox 1995).

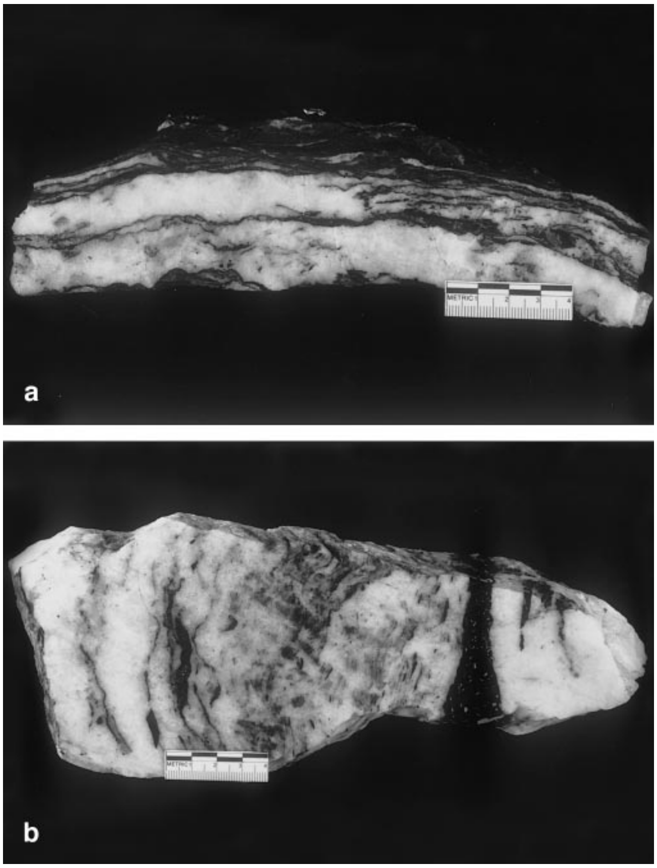


Fig. 5a,b Samples from Brothers Mine showing lamination evolution. **a** Laminations and elongate clasts of wall rock are obvious on the *right hand side* of the photo. Note the lamination in the approximate centre of the vein, which evolves from an elongate, intensely deformed tabular clast (*above left hand side of scale bar*) through to a discrete graphitic lamination that displays some stylolitization. This clast would have originally been much larger. The upper margin of the vein is a complex zone of intensely sheared country rock, lamination and attenuated quartz. **b** Sample displaying well-developed inclusion bands due to incremental opening and entrainment of tabular wall rock inclusions during crack-seal processes. Note that the larger inclusions *above the scale bar* are continuous with laminations that have a distinctly different appearance to the inclusion bands. This is interpreted to be the result of both the size of the clasts and the action of subsequent shear, which has attenuated them and caused graphite accumulation via dissolution of other clast components such as quartz. The flecks obvious in the large clast are arsenopyrite crystals

Laminations commonly coincide with the impingement of shear zones on the vein walls (Figs. 4 and 6). In the vicinity of the vein contact the laminations extend parallel to the vein margins and display continuity with mesoscopic fault planes in the country rock. These fault planes are subparallel to the vein margins at the contact or intersect them at very acute angles. With increasing distance from the vein margins the faults attain angles of up to approximately 30° to the trend of the veins (see earlier).

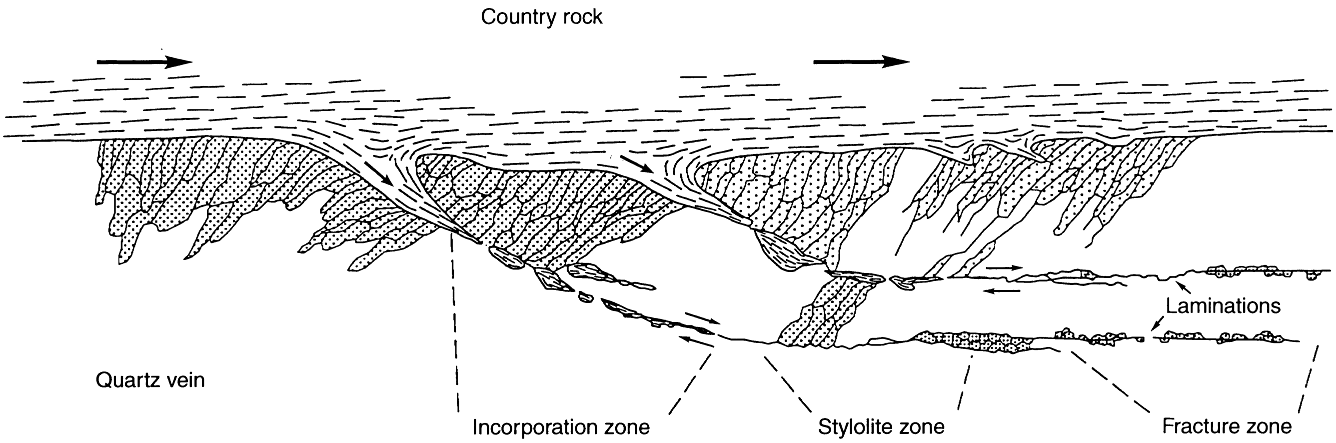


Fig. 6 Sketch illustrating detail of a vein margin on a microscale. Laminations are continuous with domains where the country rock protrudes into the vein along oblique shear zones. The microstructure of the lamination changes from a zone of stretched microclasts (*Incorporation zone*) immediately adjacent to the country rock impingements and passes through the *Stylolite zone*, where the laminations acquire a stylolitic aspect, before finishing in the *Fracture zone* in the lamination termination. The fracture zone is also characterized by the presence of fine-grained aggregates of recrystallized quartz immediately adjacent to the fractures. Long dimension of the sketch is approximately 5 cm

Study of the vein margins indicates that many laminations initiate where the country rock protrudes into the veins along the fault planes (Fig. 6). The laminations become progressively thinner away from the country rock protrusions and commonly acquire a stylolitic aspect. This change in character, from laminar to stylolitic, commonly corresponds to a disappearance of calcite and sulphides from the lamination planes. The stylolitic domains display a transition into planar zones of fracture with increasing distance away from the protrusions. These fracture zones comprise elongate, fine-grained quartz crystals (30 to 40 microns long, 5 microns thick) that fill the fracture gap and that have grown with their c-axes in the fracture plane. Figure 6 shows the transition between these different longitudinal domains along an individual lamination: the *incorporation zone* close to the country rock passing to the intermediate *stylolite zone* and then to the *fracture zone* at the lamination termination.

The laminations represent the boundaries of zones of grain size reduction (generally a few millimetres wide) in the vein material; that is, there is generally a marked difference in grain size across individual laminations. Consequently, the overall laminated domains comprise a sequence of alternating bands of two contrasting grain sizes (Fig. 7). The fine-grained bands comprise recrystallized polygonal grains corresponding to shear bands on which the fault offset within the reefs was accommodated. A relatively low finite strain in these bands is indicated by the common presence of relic quartz grains and development of asymmetric shape fabrics at angles close to 45° to the shear band boundaries. These fine-grained bands are herein referred to as *active* bands in reference to their behaviour during lamination development. They contrast with the *passive* bands, which correspond to the relatively undeformed domains between the shear bands. Consequently, we interpret the laminations as discontinuities that separate bands of ductile deformation. Carbonate and graphite selvedges, which are common along the lamination planes, tend to occur external to the zone of grain size reduction (that is, in the passive domains).

This classification in terms of active versus passive bands is particularly important for describing the spatial distribution of the sulphide and gold particles in the laminated domains (see later). When observed at the microscale, the laminations tend to occur in sets of two, with each set defining an individual shear band. Lamination zones comprised of four, six and eight microscale laminae are the most common. These relationships are particularly clear when the laminations are thin, parallel and regularly spaced. However, the distinction between passive and active bands is occasionally complicated by bifurcation of the laminations.

Reef mineralogy and microstructural controls on gold distribution

The gold-bearing quartz veins consist of several generation of quartz associated with minor amounts (< 10%) of carbonates (ankerite and calcite) and sulphides (Nethery 1994). Pyrite, arsenopyrite and stibnite are the most common sulphides with tetrahedrite, boulangerite, covellite, chalcocite, galena and sphalerite occurring as minor components (Nethery 1994; M. Lindsay, personal communication 1996). Arsenopyrite appears to be the most common sulphide present within wallrock clasts entrained within the reefs, particularly at Brothers Mine (Fig. 5). In contrast, stibnite is the dominant sulphide associated with the gold particles. In this section, we describe the different morphological varieties of quartz and their spatial distribution, as well as the morphology and spatial distribution of gold and sulphides.

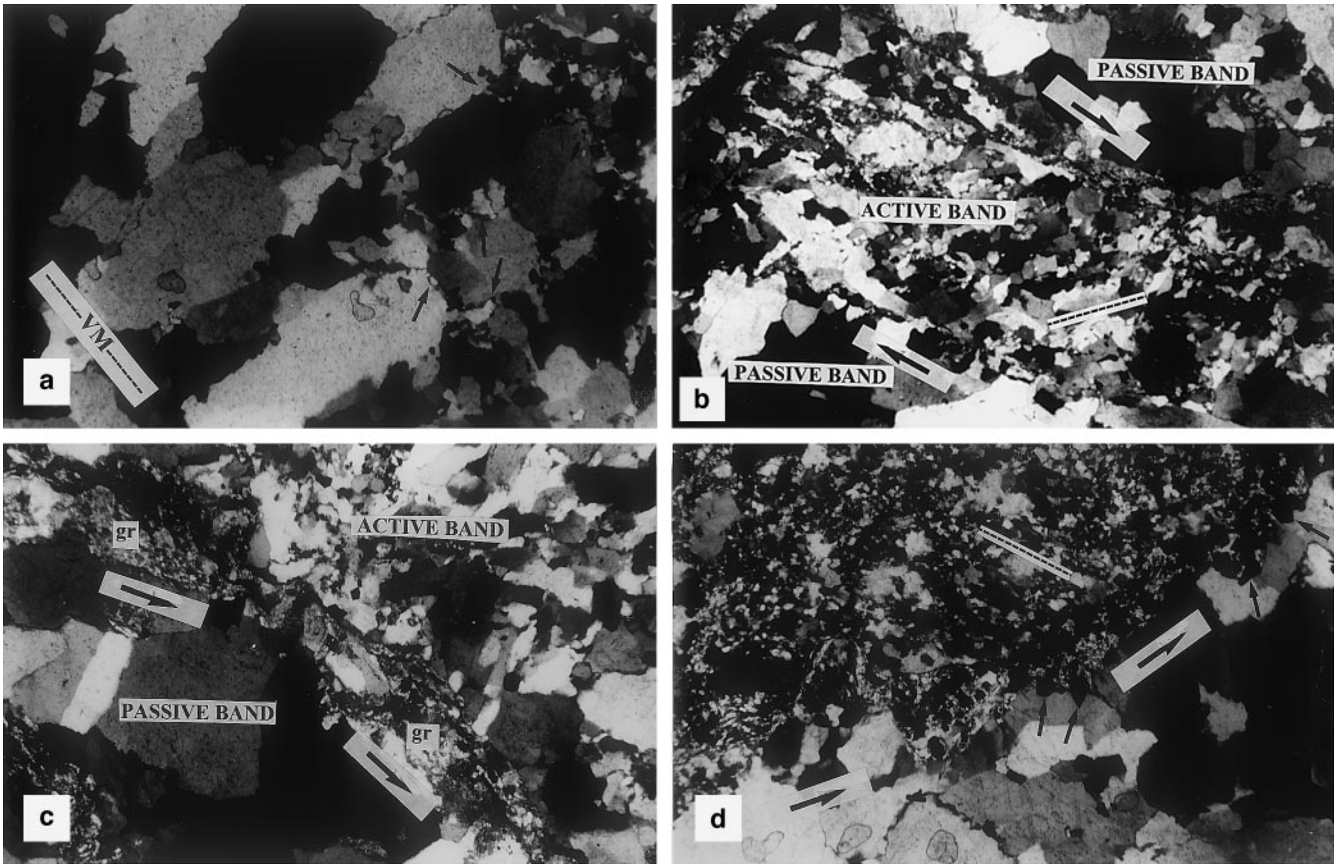


Fig. 7a–d Quartz microstructures in the laminated veins. **a** Photo showing large elongate quartz grains with their maximum dimensions at high angles to vein margins. These grains are interpreted to represent the first event of vein formation. Such microstructures are common in the non-laminated, central domain of the reefs. Note that incipient recrystallization has occurred and is defined by the development of small polygonal quartz grains along grain margins (*arrows*). The orientation of the vein margin (*VM*) is indicated. Base of photo is 1.8 mm. **b** Detail of a fine-grained active band (shear zone) between two passive bands. The active band is limited by two laminations. Graphite occurs along the individual laminations. Note incipient oblique morphological fabric in the active band (*interrupted line*) consistent with a dextral shear sense in this view. Base of photo is 0.75 mm. **c** Detail of a graphite-rich, individual lamination (*gr*) separating active and passive bands that have markedly different grain sizes. The incipient, oblique shape fabric in the active band is consistent with a sinistral shear sense in this view. Base of photo is 0.45 mm. **d** Detail of the contact between active and passive bands showing concentration of arsenopyrite crystals (*arrows*) along the contact plane. Note the small grain size (15 to 20 microns) of the dynamically recrystallized quartz within the active band. Oblique shape fabric indicates a relative sinistral sense of shear. Base of photo is 1.9 mm

Quartz

Figure 7 illustrates the different morphological varieties of quartz in the reefs. The two principal varieties occur as elongate grains and polygonal grains, generally in distinct domains within the veins. The elongate quartz grains are commonly quite coarse (60 to 400 microns) and typically have c-axes oriented parallel to their maximum dimension and at high angles to the reef margins. Grains with these characteristics commonly occur within quartz veins that have been produced via direct precipitation from solution during fracture infilling. Consequently, the elongate grains are interpreted to have nucleated on the fracture margins and grown towards the opposite wall, with the direction of fastest growth (which is parallel to the c-direction for quartz) tracking the separation trajectory of the fracture walls (see Cox and Etheridge 1983; Ramsay 1980). However, subsequent deformation and recrystallization of the vein material has obliterated the geometry of the original fractures, preventing any inference on the antitaxial or syntaxial nature of the grain growth process. At least two generations of large, elongate grains with these characteristics were identified. The oldest generation (Fig. 7a) is of more general occurrence and comprises the main reef. These grains show evidence for superimposed crystal-plastic deformation in the form of strong undulose extinction and development of subgrains. The youngest generation is restricted to secondary infill of some transverse fractures perpendicular to the reef wall, that commonly cross-cut the lamination, and appear much less strained optically.

The polygonal grains (20 to 220 microns; Fig. 7c, d) occur in roughly elongate domains that are widespread throughout the reefs. Most fine-grained aggregates have a well-defined planar geometry and constitute the active bands between adjacent laminations. Conversely, the coarse-grained aggregates do not display any consistent geometry or location within the vein. Gold and sulphide particles are normally associated with these coarse-grained polygonal aggregates.

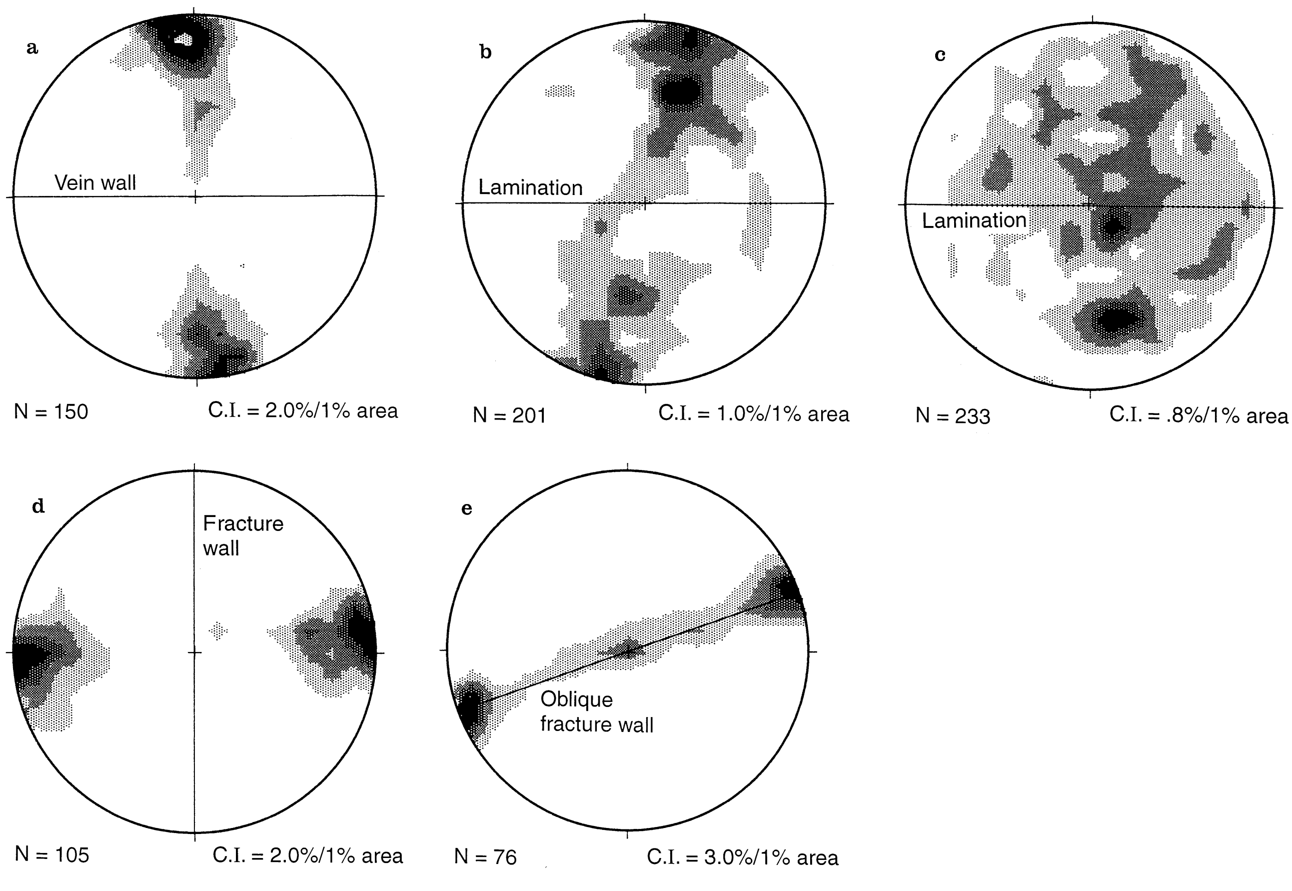
C-axes for quartz grains comprising these aggregates were determined using a Leitz 5-axes Universal Stage, on thin-sections cut perpendicular to the laminations and/or vein walls. The crystallographic orientation of the polygonal aggregates is not clear, but locally it reflects the influence of the pre-existing orientation of the original grains (Fig. 8). Some fine-grained aggregates show an incipient asymmetric crystallographic fabric relative to the lamination planes, indicating a component of shear along the laminations. Large polygonal grains commonly contain deformation bands and incipient subgrains, indicating that they formed synchronous with deformation (dynamic recrystallization). Polygonal quartz grains are commonly interpreted as resulting from crystal-plastic deformation and recrystallization under temperatures higher than 250 °C (e.g. Hirth and Tullis 1992; Hickey and Bell 1996).

Gold and sulphides

Most of the gold examined in polished thin sections occurs as rounded particles (3 to 20 μm) associated with, or included in, anhedral stibnite crystals (50 to 300 μm) that have grown between recrystallized, polygonal quartz grains (Fig. 9a). A minor proportion of gold (about 15%) occurs as anhedral/subhedral particles of gold only, which are surrounded by recrystallized quartz grains. The stibnite-gold particles have partially replaced the quartz grains, as indicated by the common protrusion of sulfide along internal quartz grain discontinuities such as fluid inclusion arrays.

The quantity of stibnite-gold particles decreases sharply both with the distance from the laminated domains and adjacent to the individual lamination planes, there being a zone of maximum concentration between 0.4 and 1 mm away from the lamination plane (Fig. 10). The 0.4 mm 'gold-absent' zone adjacent to the laminations indicates that the gold mineralization, although strongly associated with the laminated domains, does not produce a maximum concentration of gold-stibnite particles in the domains immediately adjacent to the individual lamination planes. We have noted the uncommon occurrence gold particles on the stylolitic portions of laminations,

Fig. 8a–c Equal area plots showing typical quartz c-axis fabrics in the reefs. Number of grains measured and contour intervals are indicated in all diagrams. **a** Coarse, elongate grains such as those shown in Fig. 7a in the central domain of the reefs. The *orientation* of the *vein wall is indicated.* **b** Fine, dynamically recrystallized quartz grains occur in the active bands between two consecutive laminations such as those shown in Fig. 7b. **c** Coarse, polygonal grains of the passive bands adjacent to laminations, such as in Fig. 7c. **d** Elongate grains infilling transverse fractures that cross-cut the laminations (see Fig. 11). **e** Tiny, elongated quartz grains infilling late oblique fractures (see Fig. 11)



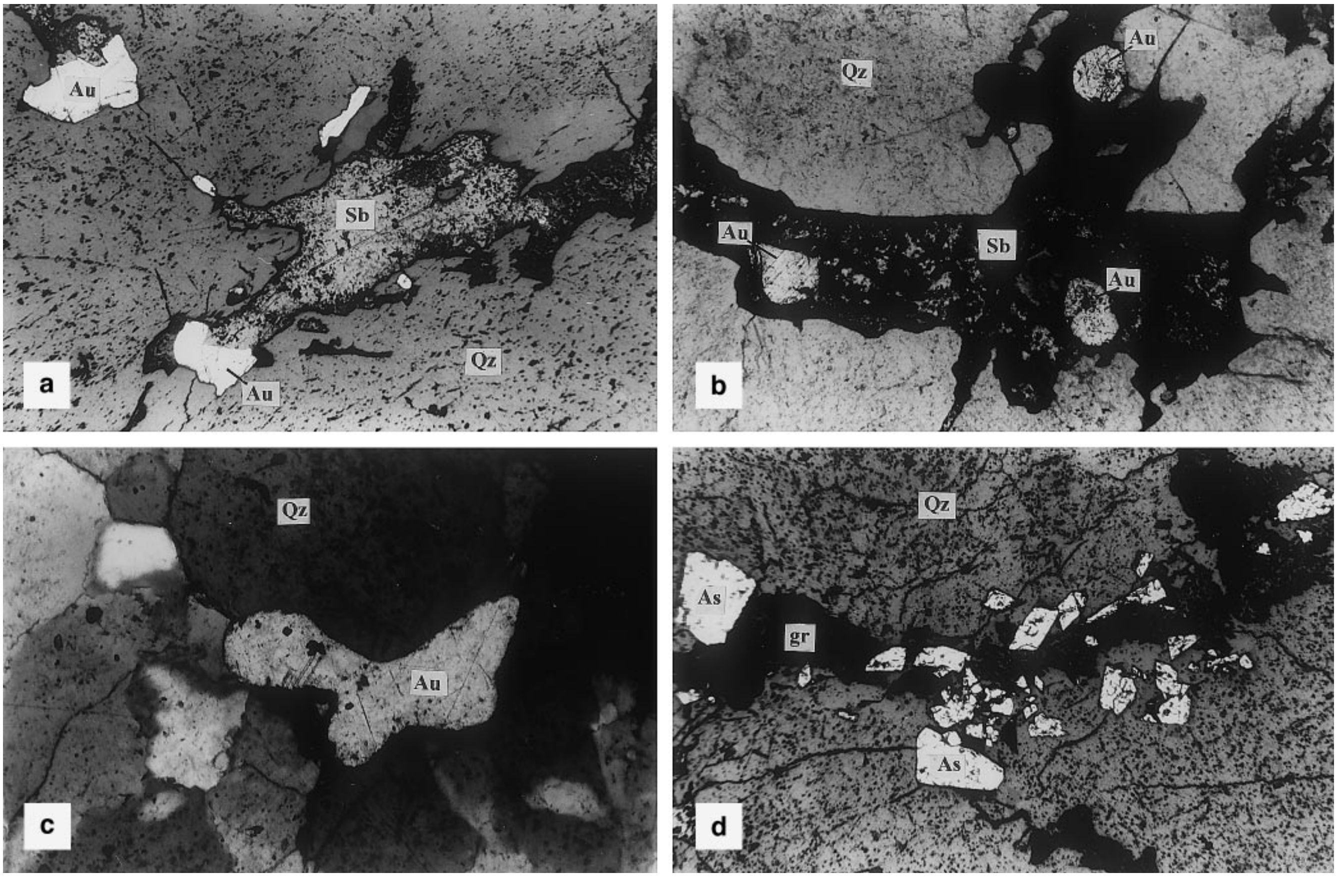


Fig. 9a–d Sulphides and gold in the reefs. **a** Interstitial stibnite(*Sb*)-gold(*Au*) particles between polygonal quartz grains. The quartz grain margins are emphasized. Non-polarized, reflected light. Base of photo is 180 microns. **b** Detail of a stibnite (*Sb*)-gold (*Au*) particle between quartz grains. The gold occurs as rounded particles inside the stibnite. Examination of a number of differently oriented thin sections suggests that the stibnite apophyses have advanced, and replace quartz, along grain boundaries and fractures, such as the two intersecting the botton edge of the photograph. Consequently, the quartz island to the left of the gold grain at the top of the photo is interpreted to be a relic included within the stibnite rather than a protrusion from a grain in the third dimension. Non-polarized, reflected light. Base of photo is 220 microns. **c** Detail of a large, pure-gold particle (*Au*) between polygonal quartz grains of a passive band. Crossed nicols, transmitted and reflected lights. Base of photo is 110 microns. **d** Arsenopyrite crystals (*As*) occurring along a graphite-rich (*gr*) lamination. Non-polarized, reflected light. Base of photo is 350 microns. (see Fig. 11)

suggesting deposition after stylolite formation. Also, uncommon occurrences of gold crystals occur in open spaces that commonly host euhedral quartz crystals (J. Taylor, personal communication 1996), and which appear to be associated with a late stage of brecciation.

Interestingly, arsenopyrite displays spatial relationships with laminations that are different to those for gold, with maximum concentration occurring adjacent to the lamination planes. Another important feature is the asymmetric distribution of both gold and sulphide particles relative to the lamination planes. These minerals are nearly always located in the passive domains external to zones of grainsize reduction. This is statistically demonstrated in the histogram of Fig. 10. To perform this statistical analysis we have considered the distribution of sulphide and gold particles counterweighted by their area in thin section. The minor particles optically visible were considered as a unit, and the others were quantified as multiples of this unit. Thus, the results reflect the volumetric distribution of gold and sulphides rather than the number of individual particles.

Discussion

Origin of the laminations – microstructural aspects

As noted already, laminations within the veins are parallel to, and continuous with, thin graphite-rich enclaves of country rock. In addition, areas of laminated vein material are also continuous with those where shear zones have impinged on the vein magins, suggesting that the laminations are associated with shearing of the vein-country rock contacts.

The emplacement of veins subparallel, or at a low angle, to the lithological layering in the country rock has meant that any shear zones subparallel to the vein margins also have an orientation similar to that of the dominant country rock fabric. Entrainment of elongate, tabular country rock clasts during formation of the veins, owing to preferential breakage along the country rock layering, resulted in alignment of the clasts subparallel to vein margins. Subsequent shearing, which

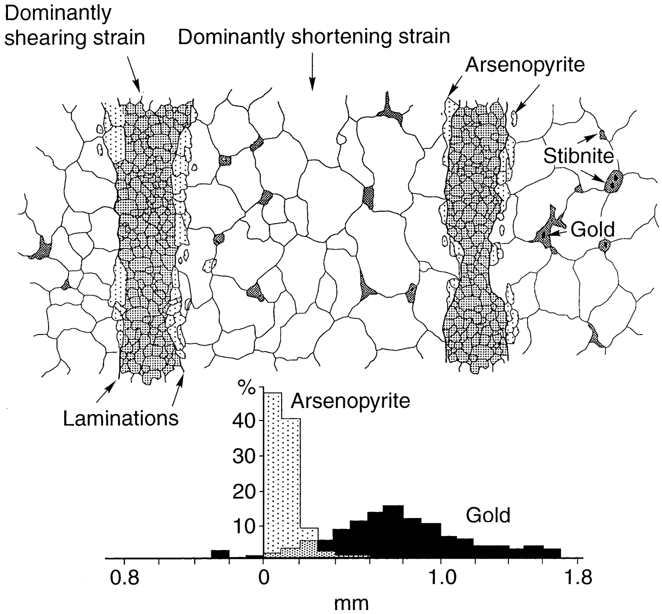


Fig. 10a,b Sketch illustrating the microstructure of the laminated margins of quartz veins. A distinct difference in grain size defines the boundary between passive and active domains. The active bands correspond to movement zones (shear bands) where the shear strain associated with the mesoscale faults was accommodated. The distribution of arsenopyrite and gold-stibnite particles is also shown. Base of sketch is approximately 5 mm. **b** Histogram showing the distribution (in volume) of arsenopyrite and gold-stibnite particles relative to distance from the individual laminations. Note that nearly all sulphide and gold occurs in the passive bands. Arsenopyrite is concentrated adjacent to the laminations. Gold-stibnite is concentrated in a zone between 0.4 and 1 mm away from the laminations

would have been easily accommodated by the preferably oriented, graphite-rich country rock layering, has been directed at a low angle to the vein walls. The contacts between vein walls and country rock correspond to sharp rheological discontinuities, hence localizing movement associated with fault planes. A common result of this is refraction of the fault planes toward parallelism with the vein-country rock contact. In addition, the graphite-rich country rock clasts in the interior of the veins would have produced a perturbation in the stress/strain field during progressive deformation, with consequent stress and strain concentration in the material immediately adjacent to the clasts (Handy 1990). This would probably contribute to the localization and propagation of the shear zones within the veins and explain the noticeable spatial association between laminations, country rock protrusions and country rock clasts.

Progressive shearing has caused removal of much of the original clastic quartz from within the country rock fragments due to shear enhanced dissolution (e.g. Bell and Cuff 1989; Hippertt 1994a), resulting in the residual concentration of the insoluble clast minerals (dominantly graphite and arsenopyrite) along the shear planes. In summary, we suggest that the country rock protrusions/clasts represent initial perturbations that have localized and initiated development of laminations in the veins, in continuity with mesoscale fault planes in the country rock.

Evidence for shear along the laminations is given by the development of recrystallized quartz grains with asymmetric preferential orientation of c-axes at high angles to the lamination planes (Fig. 8). Laminations correspond to lateral limits of longitudinal zones of grain size reduction, indicating that they represent margins of narrow shear zones with widths of the order of millimetres. The enhanced fluid circulation and associated dissolution expected to occur along shear zone margins (e.g. Selverstone et al. 1991; Hippertt 1994b) is probably also a major contributor to quartz removal and the residual concentration of very insoluble minerals such as graphite and arsenopyrite in the lamination planes (see O'Hara 1988).

The association of the laminations with zones of grain size reduction and development of recrystallized aggregates in the reefs contrasts with laminations produced by multiple crack-seal events such as those documented by Cox (1995), although the latter are common in Brothers Mine (Fig. 5). Our microstructural observations indicate that an interpretation for the stylolitic geometries in terms of dissolution due to orthogonal shortening is only a partial explanation for the presence of stylolites in the lamination zones. The laminations reported in this study normally separate domains with different microstructures, contrasting with the symmetry of the alteration zone observed on both sides of typical stylolites (Raynaud and Carrio-Schaffhauser 1992). Thus, the stylolitic aspect observed in some lamination terminations is interpreted as the initial stage of stylolite formation and begins as a sinuosity in the boundaries of the millimetre-scale shear zones.

Laminations and gold-stibnite mineralization

It is unlikely that the gold-stibnite mineralization in these reefs is associated with transport of an external source of Au through a syn-deformational fluid phase into the laminated domains. The mineralization is restricted to the laminated domains within the quartz veins, which represent continuations of country rock fault planes. These fault planes are generally gold-free, even when these fault planes cross-cut domains where the country rock is relatively more quartz-rich. Consequently, the spatial association between gold-stibnite mineralization and laminated zones may be interpreted as a result of remobilization/concentration of the gold originally contained within the quartz veins, due to quartz dissolution and consequent volume loss in the laminated zones. Our observations do not permit any inference on the degree of volume loss associated with the laminations. However, it was probably high, considering the enrichment of gold in the laminated zones, and assuming that no external gold has entered the system through the laminations. This interpretation is also in accordance with other studies from the

Hodgkinson Goldfield, which concluded that the antimony-gold-quartz mineralization postdated the main quartz-gold vein formation (de Keyser and Lucas 1968; Golding et al. 1990; Peters et al. 1990), although the chronological relationship between these two mineralizing events is not always evident (Peters et al. 1990).

Alternatively, gold defining the stylolitic geometries has actually been deposited on stylolites that formed very early in the evolution of the reefs. The presence of more than one generation of stylolites, with common cross-cutting geometries, supports this. Also, the transient nature of quartz dissolution and deposition along the shear zone during its evolution may have resulted in diachronous relationships between stylolite formation and gold deposition.

Although the gold concentration displays a strong temporal and spatial association with the laminations, the gold particles tend not to occur in the zones of grain size reduction between any two consecutive laminations comprising shear band margins (active domains). Instead, they are concentrated in the coarser-grained, passive domains (Fig. 10). We interpret this phenomenon to be a consequence of shear strain accommodation and grain size reduction in the active bands. Gold particles would not grow in these domains for similar reasons that porphyroblasts tend not to nucleate in zones of active progressive shearing that promote dissolution of minerals unable to accommodate shearing strain (e.g. Bell et al. 1986; Davis 1993, 1995). Our interpretation is that lateral migration of gold-bearing fluids into the passive domains through microfractures and grain boundaries has enabled nucleation and growth of gold particles between pre-existing quartz grains in the passive domains. This is in accordance with the propensity for orthogonal microfracturing in the passive domains due to their accommodation of dominantly shortening strain (e.g. Bell and Hayward 1991; Johnson 1990).

The association between Au and Sb in the laminated domains is also intriguing, as Sb is barely detectable in the country rocks and the older quartz-gold veins. However, stibnite is a common sulphide in shear zones hosted by the Hodgkinson Formation and which define domain boundaries in the Kingsborough area well to the south (Peters et al. 1990; Davis and Henderson, unpublished data). Interestingly, deposits of gold-free stibnite associated with shear zones of the Hodgkinson Gold Field are not reported in the literature, suggesting that the precipitation of stibnite was intimately linked to the growth of the gold particles. Indeed, the microstructural relationships indicate that the stibnite, at least in many cases, grew syntaxially on subhedral particles of gold (e.g. Fig. 9).

A potential explanation for the distribution of gold-stibnite mineralization is that the mineralized reefs at Maddens Mine represent the structural sites for mixing of two kinds of fluids (J. Walshe, personal communication 1997). These could have been represented by a background metamorphic fluid containing gold and arsenic in equilibrium with graphite, and a stibnite-bearing phase from another source such as a magmatic vapour. In the latter case the obvious source would be subsurface intrusives of the Whypalla Supersuite, with pressure release during deformation helping to focus fluids into the shear zone during movement on this structure. If this scenario were true then a second fluid pathway is required, the most obvious being bedding-parallel shears/faults that are common throughout the Hodgkinson Province but notoriously difficult to identify, especially on aerial photographs, due to their subparallelism with bedding and cleavage. However, this two-fluid model remains to be tested, and it is interesting to compare the deposits discussed here with the Nagambie gold deposit in central Victoria, where Gao et al. (1995) noted a similar gold-stibnite-arsenic mineralogy. They invoked scavenging of both gold and stibnite from host sediments, rather than sourcing from the adjacent S-type Strathbogie adamellite because gold deposits are generally related to I-type intrusives (Hattori, 1987 Chappell and White 1992). Similar problems exist for gold-stibnite mineralization in the Hodgkinson Province if the Whypalla Supersuite plutons are invoked as a source because of their S-type character (see later; Bultitude and Champion 1992).

History of vein formation and deformation

The microstructural relationships indicate at least five discrete stages in the history of vein formation and deformation, and are summarized in Fig. 11:

1. The oldest quartz generation is represented by quartz grains that are elongate along their c-axis direction and formed by direct precipitation during infilling of the main reefs (Fig. 8). These grains are randomly distributed throughout the reefs, and generally appear as relic porphyroclasts displaying undulose extinction and surrounded by a matrix of coarse-grained polygonal recrystallized grains.
2. This first generation of quartz was affected by ductile deformation that produced undulose extinction, subgrain development and recrystallization. No unequivocal crystallographic fabrics were identified in these recrystallized aggregates, preventing any inference on the kinematic framework. The finite strain associated with this first deformation event would have been relatively low, however, as indicated by the dimensions of the recrystallized grains and absence of crystallographic and morphologic fabrics.
3. The second ductile deformation event caused grain size reduction and produced lamination in the reefs, synchronous with movement on mesoscopic faults in the country rocks. This deformation stage reflects a non-coaxial kinematic framework, with development of planar aggregates of finer-grained polygonal quartz grains showing an asymmetric c-axis fabric. A significant component of stylolitization probably occurred in the later stages of this deformation due to shortening of anastomosing shear planes that developed earlier in the same deformation.

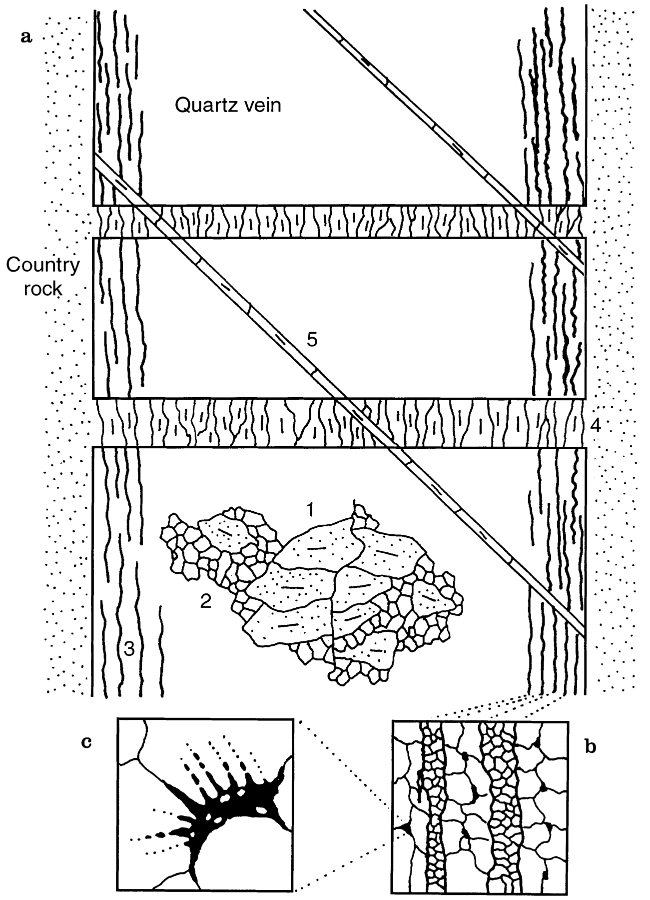


Fig. 11a–c Sketch summarizing the main stages (*numbered 1 to 5*) of the history of vein formation, deformation and mineralization. Stage 1 represents infilling of major veins through crystallization of large quartz crystals with c-axes perpendicular to the vein walls. These aggregates have generally been obliterated by a subsequent event of ductile deformation (stage 2) that produced undulose extinction, subgrain development and recrystallization of the pre-existing crystals. Stage 3 corresponds to lamination development via shearing along the vein margins. **b** Sketch shows detail of the laminated domains, where bands with different grain size exist (passive and active bands). The side of the square would be approximately two mm. The nucleation and growth of the gold-sulfide particles is also attributed to stage 3. **c** Sketch shows a detail of a gold-stibnite particle grown between quartz grains in a passive band, and the side of the square would be approximately 200 microns. The gold-stibnite partially replaces the quartz grains from the grain boundaries and along planes of fluid inclusions. Stage 4 is represented by a brittle event that produced fractures perpendicular to the main reefs. These fractures are filled with another generation of fibre quartz that has grown with c-axes perpendicular to the fracture walls. Stage 5 is restricted to narrow oblique fractures that cross-cut all the pre-existing structures

4. Transverse quartz veins, perpendicular to the reef margins, cross-cut all the previous structures (including the laminations). These veins reflect a later event of brittle deformation and were probably associated with shortening perpendicular to the reef margins. The cross-cutting veins comprise euhedral quartz crystals that have grown with c-axes perpendicular to the vein margins (crack-seal), and do not show any evidence of superimposed deformation.
5. The last identifiable deformation is expressed as very fine, oblique fractures (<20 μm wide) that cross-cut all the pre-existing structures. These fractures are infilled with tiny, elongate quartz grains that have grown with their c-axes parallel to the fracture plane. This crystal orientation could indicate that these last fractures opened at a slower rate than the transverse fractures described above.

Age of Taylors Fault and timing of vein formation

Despite the overprinting relationships we have recognized, which have allowed the history described to be resolved, the time of initial emplacement of the reefs is still tentative. The reefs cross-cut S_2 and hence post-date D_2. However, the age of Taylors Fault, which the reefs are intimately associated with, is more problematic. Numerous other faults in the Hodgkinson Province have similar orientations (e.g. Halfpenny and Hegarty 1991; Mossman 1:250 000 geological map, sheet SE 55–1), including major structures such as the Fiery Creek Fault, Hurricane Creek Fault and Cyclone Creek Fault in the South Palmer River region to the south (Halfpenny and Hegarty 1991; Davis 1993). Many of these have been interpreted to have formed during D_2, which has a possible mid- to late Carboniferous age (Bultitude et al. 1996), and reactivated during the Permian D_4 event (Davis 1994). Consequently, quartz reefs could have been emplaced during reactivation of Taylors Fault (see later).

The D_3 event has been interpreted by Davis (1994) as being temporally close to D_4, and also part of the Permian tectonic event, and several minor quartz veins display the effects of D_3 folding. Unfortunately, the poor development of D_3 structures has precluded unequivocal timing of the main reefs relative to D_3. Veins at the entrance to Maddens Mine have been emplaced parallel to the hinge-line of mesoscale D_4 folds of bedding. Some of these veins show local deviation from this trend, owing to emplacement controlled by bedding, but display the effects of D_4 folding where this has occurred. Numerous small-scale veins underground have also been affected by D_4. The small size of D_4 folds (generally only centimetres in wavelength) makes it difficult to assess the effects of D_4 on the major reefs, However, rare local development of mesoscale fold with steep axial planes in the vicinity of the reefs suggests accumulation of D_4 shortening strain against the reefs. Consequently, we interpret emplacement of the main stage of the reef to have occurred pre- or syn-D_4. Relationships such as those described for veins parallel to F_4 axial planes but also being folded suggest progressive emplacement over the course of the deformation (e.g. Robert and Brown 1986).

D_4 deformation was a result of east-west crustal shortening (Davis 1993, 1994; Davis and Forde 1994; Bultitude et al. 1996). Consequently, the orientation of Taylors Fault would have been favourable for accommodating sinistral movement, as supported by offsets of lithology. It is conceivable that reefs were emplaced in response to fault movements that were sinistral, and may represent sites of local opening (extensional jogs; e.g. Sibson 1985; MacKenzie and Craw 1993; Ferkous and Leblanc 1995). The normal, east-side-up sense of movement for Taylors Fault, which matches that for the bulk movement direction during D_4 supports this. Progressive deformation will have re-brecciated and deformed these reefs during evolution of the fault zone. Angular wall rock clasts are locally entrained within the veins indicating periods of brecciation (e.g. Forde 1991; Forde and Bell 1994). In addition, crack-seal textures (Ramsay 1980) and inclusion bands (e.g. Cox et al. 1995) are well developed in some samples from Brothers Mine (Fig. 5). This suggests fault-valve behaviour (Sibson 1985; Cox 1995) was probably important for development of the main reef stage, but that it occurred at different sites at any one time (e.g. Kontak and Smith 1993). That is, these sites will have been transient throughout the duration of reef and fault zone evolution, with the relative importance of crack-seal versus brecciation being controlled by the magnitude of opening and local fluid pressures. The presence of brecciated wall rocks that have been largely replaced by silica (e.g. Forde and Davis 1994), and more than one set of crack-seal textures that lie at high angles to one another at Brothers Mine, support these contentions. At the mine-scale, Taylors Fault consists of a series of interlinked brittle faults and ductile shears. Displacement across the zone comprising Taylors Fault would have been accommodated at different rates at different times on these structures, with displacement potentially switching from one strand to another (e.g. Cox et al. 1995; Keller et al. 1995). This will have emphasized the transient nature of reef formation and deformation, and caused shearing and lamination formation in some zones while others were opening and depositing quartz. A significant implication of this is that formation of similar lamination/mineralization relationships and textures may have actually formed at different times.

Stages 1 and 2 in the vein formation history listed probably occurred prior to the onset of D_4 deformation, or reflect reactivation of Taylors Fault at the initiation of D_4. Deformation would have been relatively coarsely partitioned initially and some zones of rock would have experienced little or no strain, explaining the relatively low strains expressed by the quartz fabrics. We interpret stage 3 to represent intense D_4 deformation. Progressive deformation will have repartitioned the deformation such that much of it will have been accommodated by the weakness provided by Taylors Fault, and by strain accumulation against the relatively rigid main reefs. It is difficult to constrain stage 4 but both it and stage 5 probably represent post-D_4 stress relaxation. Figure 11 summarizes these principal events of vein formation and deformation.

Implications for regional gold mineralization

In terms of understanding the timing of gold mineralization across the whole Hodgkinson Province, the mines discussed in this study support broad regional relationships noted between areas of mineralization and granite emplacement. Mineralization in the West Normanby Gold Field is spatially very close to the Permian Whypalla and Bullhead/Mount Pike Granites, and public domain gravity data suggest granite underneath this area. Historically, production of gold from zones of hardrock mineralization in the Palmer River Gold Field to the west (Fig. 1) was dominated by mines in the Maytown area. Rocks in the Maytown area are of higher metamorphic grade than those in the surrounding Hodgkinson Formation and commonly phyllitic (Bultitude and Donchak 1992), suggesting the possibility of subsurface granite. Similarly, the Mount Madden structural dome (Bultitude and Donchak 1992), which is a macroscale D_4 feature located directly west of the Permian Cannibal Creek Granite and south of Maytown, contains mica schists and has historically yielded significant quantities of large gold nuggets and hosted numerous small-scale hardrock workings. Gravity images, metamorphic grade variations and structural relations (Bultitude and Donchak, 1992; Davis unpublished data) indicate the presence of shallow subsurface granite here also. Another area renowned for nugget production, Campbells Creek, lies immediately adjacent to the Permian Koobaba and Kelly St George Granites in the central eastern portion of the South Palmer River area. Hard rock mines have also been developed in the vicinity of the Permian Tinaroo Granite at Gold Mine Creek. In all cases listed, the granite bodies belong to the Whypalla Supersuite (Bultitude and Champion 1992), which is the largest supersuite by area in the Hodgkinson Province.

Work by Davis (1993, 1994) focused on plutons of the Whypalla Supersuite in the central Hodgkinson Province and interpreted emplacement synchronous with a major crustal shortening event, D_4, in response to the Permian-Triassic Hunter-Bowen Orogeny (e.g. Carey and Browne 1938; Day et al. 1978; Collins 1991). The development of the R.B. Mine in Permian Normanby Formation west of Cooktown confirms gold mineralization in the Hodgkinson Province during the Permian. Consequently, we suggest that syn-D_4 granites emplaced during a major episode of crustal shortening, in particular those belonging to the Whypalla Supersuite, were integral to the major gold mineralizing event in Hodgkinson Province during the Permian, and that the mineralization in the West Normanby Goldfield is a reflection of this.

Notably, a number of workers (e.g. Hattori 1987; Chappell and White 1992; Matthai et al. 1995) have suggested genetic links between gold mineralization and intrusions. In these cases the igneous bodies have been I-type (Chappell and White 1992), and Blevin and Chappell (1992) concluded that mineral deposits related to granites in eastern Australia are mainly determined by the oxidation state and the degree of fractional crystallization of the associated granites. Chappell and White (1992) concluded that Cu and Au are more likely to be associated with oxidized I-type granites of intermediate composition. Given that plutons of the Whypalla Supersuite are S-type (Bultitude and Champion 1992), this suggests that granites belonging to this supersuite are probably not the source of gold in the Hodgkinson Province, but have been instrumental in supplying heat for fluid movement and Au concentration (e.g. Gao et al. 1995).

Conclusions

1. Mineralized reefs are sited within the Taylors Fault, which represents a major structure that formed during the regional D_2 and was reactivated during the regional Permian D_4. Transient fault-valve behaviour is implied and would have been reflected in similar transitory fault movement, fluid flow, and vein emplacement occurring at different sites at any one time.

2. Microstructural relationships indicate at least five discrete stages in the vein formation-deformation history at Maddens Mine. The first two stages occurred prior to, or synchronous with, the regional Permian D_4. Stage three is interpreted as representing intense D_4 deformation, and the final two stages probably reflect post-D_4 stress relaxation and vein emplacement.

3. Quartz veins contain graphitic laminations, which are the product of faulting processes that have tectonically sliced tabular clasts of country rock into the veins during progressive deformation. Progressive shear strain associated with faulting caused strain-enhanced dissolution of silicate minerals and concentration of residual graphite that defines the laminations.

4. Gold concentration displays a strong temporal and spatial association with quartz vein laminations. Gold is concentrated in zones that have not accommodated shearing strain during progressive deformation of the quartz. Nucleation of gold grains occurred dominantly between pre-existing quartz grains unaffected by shearing strain, but instead preferentially underwent shortening strain and microfractured, thereby supplying sites for fluid ingress and gold nucleation.

5. Gold mineralization is temporally and spatially related to plutons of the Whypalla Supersuite. However, gold was probably not sourced from these plutons, but was scavenged from elsewhere during fluid movement in response to crustal heating by the granites.

Acknowledgements Justin Taylor, Graeme Byrne and Terry Edwards of West Normanby Resources are thanked for providing access to mining leases and underground mines, and for their hospitality. Bob Bultitude provided important information on the regional geology of the Hodgkinson Province. Ken Davis has given freely of his time for a number of years during regional geological assessment of the Hodgkinson Province, and has been instrumental in the collection of samples and data. Ken Hickey and Mark Lindsay reviewed an early version of the manuscript. Mark Lindsay also provided additional structural information and the sample in Fig. 5a. Constructive reviews by John Walshe and an anonymous reviewer were greatly appreciated. Davis completed this work while holding an ARC fellowship. Hippertt acknowledges financial support from the Brazilian Research Council (CNPq).

References

Arnold GO, Fawckner JF (1980) The Broken River and Hodgkinson Provinces. In: Henderson RA, Stephenson PJ (eds) The geology and geophysics of northeastern Australia, pp 175–189. Queensland Division of the Geological Society of Australia, Brisbane

Bell TH, Hayward N (1991) Episodic metamorphic reactions during orogenesis: the control of deformation partitioning on reaction sites and reaction duration. J Metam Geol 9: 619–640

Bell TH, Rubenach MJ, Fleming PD (1986) Porphyroblast nucleation, growth and dissolution in regional metamorphic rocks as a function of deformation partitioning during foliation development. J Metam Geol 4: 37–67

Bell TH, Cuff C (1989) Dissolution, solution transfer, diffusion versus fluid flow and volume loss during deformation/metamorphism. J Metam Geol 7: 425–447

Blevin PL, Chappell BW (1992) Some controls on granite metallogeny: an eastern Australian perspective. Trans R Soc Edinburgh Earth Sci 83: 305–316

Bultitude RJ, Champion DC (1992) Granites of the Eastern Hodgkinson Province – their field and petrographic characteristics. Queensland Resource Industries Record, 1992/6

Bultitude RJ, Donchak PJT (1992) Pre-Mesozoic stratigraphy and structure of the Maytown region. Queensland Resource Industries Record, 1992/5

Bultitude RJ, Donchak, PJ, Domagala J, Fordham BG, Champion DC (1990) Geology and tectonics of the Hodgkinson Province, north Queensland. Proc Australasian Inst Mining and Metall Pacific Rim 90 Congr, Townsville, Queensland, Australia, PR 75–81

Bultitude RJ, Rees ID, Garrad PD, Champion DC, Fanning CM (1996) Explanatory notes to accompany Mossman 1:250 000 geological map, Sheet SE 55–1, 2nd edn. Department of Mines and Energy, Brisbane, Australia

Carey SW, Browne WR (1938) Review of the Carboniferous stratigraphy, tectonics and palaeogeography of New South Wales and Queensland. J Proc Linnean Soc NSW 71: 591–614

Chappell BW, White AJR (1992) I- and S-type granites in the Lachlan Fold Belt. Trans R Soc Edinburgh Earth Sci 83: 1–26

Collins WJ (1991) A reassessment of the 'Hunter-Bowen Orogeny': Tectonic implications for the southern New England Fold Belt. Aust J Earth Sci 38: 409–423

Cox SF (1995) Faulting processes at high fluid pressures: An example of fault valve behaviour from the Wattle Gully Fault, Victoria, Australia. J Geophys Res 100: 12841–12859

Cox SF, Etheridge MA (1983) Crack-seal fibre growth mechanisms and their significance in the development of oriented layer silicate microstructures. Tectonophysics 92: 147–170

Cox SF, Sun SS, Etheridge MA, Wall VJ, Potter TF (1995) Structural and geochemical controls on the development of turbidite-hosted gold quartz vein deposits, Wattle Gully Mine, Central Victoria, Australia. Econ Geol 90: 1722–1746

Davis BK (1993) Mechanism of emplacement of the Cannibal Creek Granite with special reference to timing and deformation history of the aureole. Tectonophysics 224: 337–362

Davis BK (1994) Synchronous, syntectonic granite emplacement in the South Palmer River region, Hodgkinson Province, Australia. Aust J Earth Sci 41: 91–103

Davis BK (1995) Biotite porphyroblast nucleation and growth: control by microfracture of pre-existing foliations in schists in the Robertson River Metamorphics, Australia. Geol Mag 133: 91–102

Davis BK, Forde A (1994) Regional slaty cleavage formation and fold axis rotation by re-use and reactivation of pre-existing

foliations: the Fiery Creek Slate Belt, North Queensland. Tectonophysics 230: 161–179
Day RW, Murray CG, Whitaker WG (1978) The eastern part of the Tasman Orogenic Zone. Tectonophysics 48: 327–364
De Keyser F, Lucas KG (1968) Geology of the Hodgkinson and Laura Basins, north Queensland. BMR, Aust Bull 84
Ferkous K, Leblanc M (1995) Gold mineralization in the West Hoggar shear zone, Algeria. Mineralium Deposita 30: 211–224
Forde A (1991) The late orogenic timing of mineralization in some slate belt gold deposits, Victoria, Australia. Mineralium Deposita 26: 257–266
Forde A, Bell TH (1994) Late structural control of mesothermal vein-hosted deposits in Central Victoria: mineralization mechanisms and exploration potential. Ore Geol Rev 9: 33–59
Forde A, Davis BK (1994) Crack-reaction veins from the Hodgkinson Formation, north Queensland, Australia. Geol Mag, 131: 49–56
Gao ZL, Kwak TAP, Changkakoti A, Hussein E (1995) Supergene ore and hypogene nonore mineralization at the Nagambie sediment-hosted gold deposit, Victoria, Victoria, Australia. Econ Geol 90: 1747–1763
Golding SD, Bultitude RJ, Peters SG, Myers IA, Dowling K (1990) Stable isotope constraints on genetic models for gold-quartz, antimony-gold-quartz, tin and tungsten-tin mineralization, Hodgkinson Province, northern Queensland. In: Proc Pacific Rim Congr 1990; an International Congress on the geology, structure, mineralization, and economics of the Pacific Rim. Australian Institute of Mining and Metallurgy, Parkville (Victoria), III, 325–335
Halfpenny RW, Hegarty RA (1991) Geology of the South Palmer River 1:100 000 Sheet area (7865), north Queensland. Dept Res Ind Record, 1991/6
Hammond RL (1987) The influence of deformation partitioning on dissolution and solution transfer in low-grade tectonic melange. J Metam Geol 5: 195–211
Handy MR (1990) The solid state flow of polymineralic rocks. J Geophys Res 95: 8647–8661
Hattori K (1987) Magnetic felsic intrusions associated with Canadian Archaean gold deposits. Geology 15: 1107–1111
Hickey KA, Bell TH (1996) Syn-deformational grain growth: matrix coarsening during foliation development and regional metamorphism rather than by static annealing. Eur J Min 9: (in press)
Hippertt JFM (1994a) Microstructures and c-axis fabrics indicative of quartz dissolution in sheared quartzites and phyllonites. Tectonophysics 229: 141–163
Hippertt JFM (1994b) Grain boundary microstructures in micaceous quartzite: Significance of fluid movement and deformation processes in low metamorphic grade shear zones. J Geol 102: 331–348
Hirth G, Tullis J (1992) Dislocation creep regimes in quartz aggregates. J Struct Geol 14: 145–159
Johnson SE (1990) Lack of porphyroblast rotation in the Otago schists, New Zealand: Implications for crenulation cleavage development, folding and deformation partitioning. J Metam Geol 8: 13–30
Keller JVA, Hall SH, Dart CJ, McClay KR (1995) The geometry and evolution of a transpressional strike-slip system: the Carboneras fault, SE Spain. J Geol Soc London 152: 339–351
Kontak DJ, Smith PK (1993) A metaturbidite-hosted lode gold deposit: the Beaver Dam deposit, Nova Scotia. I. Vein paragenesis and mineral chemistry. Can Mineral 31: 471–522
MacKenzie DJ, Craw D (1993) Structural control of gold-scheelite New Zealand. N Z J Geol Geophys 36: 437–445
Matthai SK, Henley RW, Bacigalupo-Rose S, Binns RA, Andrew AS, Carr GR, French DH, McAndrew J, Kananagh ME (1995) Intrusion-related, high-temperature gold quartz veining in the Cosmopolitan Howley metasedimentary rock-hosted gold deposit, Northern Territory, Australia. Econ Geol 90: 1012–1045
Nethery JE (1994) Maddens Flat gold mine: Appraisal Report – August 21, 1994. Unpubl Rep to West Normanby Resources Pty Ltd, 4 pages
O'Hara K (1988) Fluid flow and volume loss during mylonitization – an origin for phyllonite in an overthrust setting, North Carolina, USA. Tectonophysics 156: 21–36
Peters SG, Golding SD, Dowling K (1990) Melange- and sediment-hosted gold-bearing quartz veins, Hodgkinson Gold Field, Queensland, Australia. Econ Geol 85: 312–327
Ramsay J (1980) The crack-seal mechanism of rock deformation. Nature 284: 135–139
Raynaud S, Carrio-Schaffhauser E (1992) Rock matrix structures in a zone influenced by a stylolite. J Struct Geol 14: 973–980
Robert F, Brown AC (1986) Archaean gold-bearing quartz veins at the Sigma Mine, Abitibi Greenstone Belt, Quebec: Part I. Geologic relations and formation of the vein system. Econ Geol 81: 578–592
Selverstone J, Morteani G, Staude J-M (1991) Fluid channeling during ductile shearing: transformation of granodiorite into aluminous schist in the Tauern window, Eastern Alps. J Metam Geol 9: 419–431
Sibson RH (1985) Stopping of earthquake ruptures at dilational fault jogs. Nature 316: 248–251