

Late metamorphic structural zones in the Otago Schist: prospective hosts for gold mineralisation

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Abstract

The Otago Schist is crossed by numerous deformation zones that formed in the latter stages of metamorphism and uplift of the metamorphic belt. These deformation zones are long (tens of km) linear features at the regional scale, and are generally narrow (km scale or less). Many of these structural zones separate schist domains with different rock types and structural/metamorphic histories. The Hyde-Macraes Shear Zone is one such deformation zone, and this zone hosts the active Macraes gold mine. The Rise & Shine Shear Zone, 80 km NW of Macraes, is also enriched in gold and has been mined historically. Mineralisation in both these shear zones occurred during the transition from ductile to brittle deformation as the schist belt was uplifted from greenschist facies metamorphic conditions. Recrystallisation of quartz and micas in the early stages was overprinted by cataclasis, with sulfide and gold precipitation throughout. Many of the other late metamorphic deformation zones formed under similar greenschist to sub-greenschist facies conditions, with similar overprinting of recrystallisation textures and folds by more brittle textures such as breccias. Under these conditions, originally regionally pervasive deformation at the highest metamorphic grades was evolving towards more focussed high strain zones at lower temperatures and pressures. Shear zones initially focussed fluid flow along microshears and mineral grain boundaries, resulting in 1 to 100 m scale alteration and replacement in the host schist, with only local development of quartz veins. Fluid flow was not controlled by open fractures, and the rate of fluid movement was probably slow and pervasive. After uplift into the brittle regime, the schist belt underwent tectonic extension. Extension was accompanied by development of swarms of steeply dipping veins, with localised mineralised normal faults. Hydrothermal fluid flow throughout this uplift history was a normal consequence of late stage devolatilisation of the metamorphic belt. Hence, all late metamorphic deformation zones should be considered prospective for gold accumulation.

Keywords: *gold, tectonics, metamorphism, extension, mesothermal, orogenic, uplift*

Introduction

The success of Macraes mine development in east Otago has prompted interest in exploration for a similar style of mineralisation elsewhere in the Otago Schist. The Macraes deposit formed in a shear zone that was active as the host schist passed through the brittle-ductile transition during uplift of the schist belt (Craw 2002). Hence, structural zones that developed at about the same stage in the uplift history of the schist must be considered prospective. Another significant feature of the Macraes deposit, compared to most other known mineralised structures in Otago, is the comparative rarity of quartz veins associated with the mineralisation process. Mineralised rocks in many parts of the deposit at Macraes are essentially hydrothermally altered schist, with only minor mineralised quartz.

This paper focuses on these distinctive characteristics of the Macraes deposit, and examines this key stage in the evolution of the Otago Schist on a regional scale, in order to highlight the types of structures that have developed and their fluid flow characteristics through that uplift history. We describe development of focused structural zones from more diffuse pervasive synmetamorphic deformation, and the changes in structural style as the schist belt passed into the brittle regime nearer the surface. We examine this structural evolution in the context of the overall geological history of the schist belt. The aim of this paper is to provide a regional context for exploration programmes aimed at the Macraes style of deposit. We make reference in this paper to the Rise and Shine Shear Zone, an auriferous zone that has some geological similarities to the Macraes deposit, and more detailed comparisons between these deposits are described in a companion paper (MacKenzie et al., this volume).

General geology

The Otago Schist (Fig. 1) consists of variably deformed Paleozoic to Mesozoic metasedimentary schists, with minor mafic metavolcanic horizons. The schists formed during Mesozoic Rangitata Orogeny collision between two metasedimentary terranes: Caples Terrane and Torlesse Terrane (Fig. 1). An intervening packet of schists, the Aspiring lithologic association (Fig. 1) has geochemical similarities to the Torlesse Terrane, but has a higher proportion of metavolcanic and pelitic schists (Craw 1984; Mortimer and Roser 1992). Metamorphic grade increases from subgreenschist facies on the margins of the belt to a core of greenschist facies rocks (Fig. 1). The core consists of lower greenschist facies schists (chlorite zone) and upper greenschist facies schists (garnet-biotite zone). Macraes gold-bearing rocks occur at the boundary between lower and upper greenschist facies rocks, in a major regional structure, the Hyde-Macraes Shear Zone (Fig. 1). Likewise, the Rise & Shine Shear Zone occurs adjacent to this boundary, farther to the NW (Fig. 1). The schist belt has been cut by numerous Cretaceous and Tertiary faults and gold-bearing quartz vein systems (Fig. 2). All gold-bearing systems have substantial As and S enrichment, and some have W and/or Sb enrichment as well.

Schist uplift history

The Otago Schist was uplifted from metamorphic depths during the latter stages of the collisional Rangitata Orogeny and subsequent extension (Mortimer 1993; Deckert et al. 2002). The approximate uplift trajectories for upper and lower greenschist facies rocks are indicated in Fig. 3, calibrated with recent geochronological data (Little et al. 1999; Forster and Lister 2002; Gray and Foster 2004). Rapid unroofing of the metamorphic rocks began near the Jurassic/Cretaceous boundary (Fig. 3; Little et al. 1999). Key stages in this uplift history that are relevant to gold mineralisation in Otago are indicated in Fig. 3, and described in the following sections. Uplift through the brittle-ductile transition was an important stage for gold mineralisation at Macraes and Rise & Shine, but we also describe evidence for fluid flow preceding and post-dating these structures.

Metamorphism

Metamorphism of the metasedimentary rocks resulted in complete recrystallisation of detrital minerals to a uniform mineral assemblage: quartz, albite, muscovite, chlorite, epidote, titanite and calcite. The greenschist facies schists have a well-defined foliation and are generally segregated into quartz-albite-rich and muscovite-chlorite-rich layers on the mm to cm scale. The foliation is generally flat-lying through most of the core of the belt. This foliation is polygenetic, resulting from several phases of ductile deformation and isoclinal folding. Juxtaposition of large crustal blocks such as the Caples Terrane, Aspiring lithologic association, and Torlesse Terrane during greenschist facies metamorphism resulted in further foliation development and recrystallisation, with some metamorphic retrogression (Craw 1998), in ductile shear zones (Fig. 3).

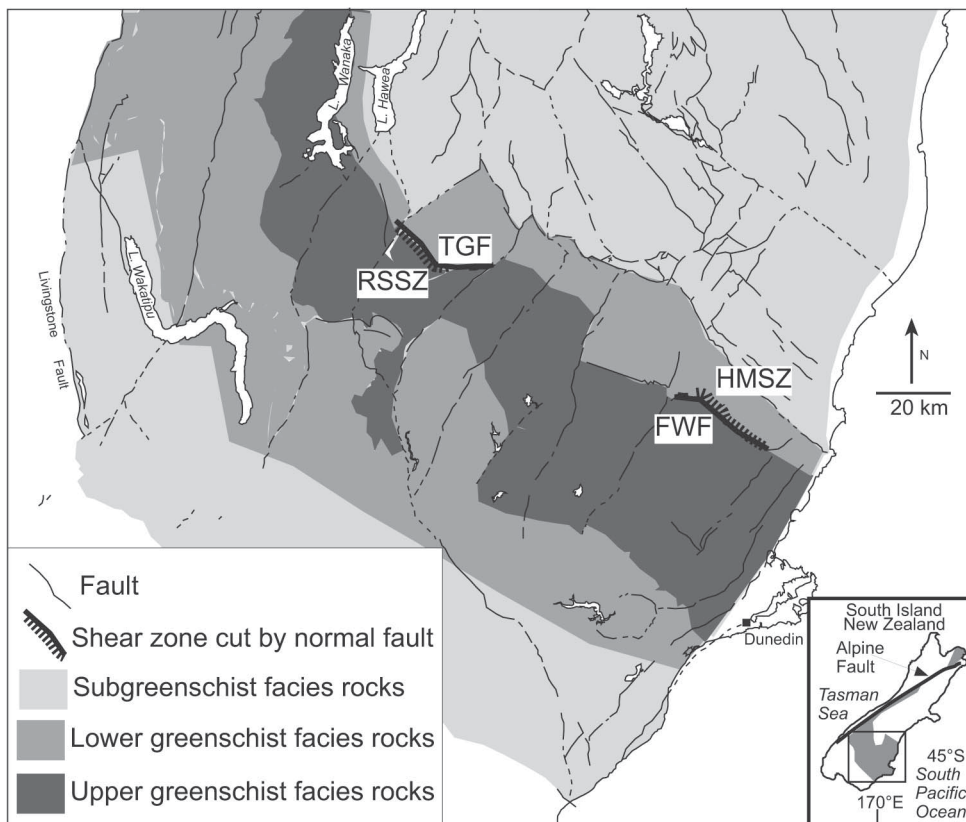


Fig. 1. Regional geological map of the Otago Schist, partly after Mortimer (1993), showing the principal metamorphic zones. The auriferous Hyde-Macraes Shear Zone (HMSZ) is truncated by the Footwall Fault (FWF) and the Rise & Shine Shear Zone (RSSZ) is truncated by the Thomsons Gorge Fault (TGF).

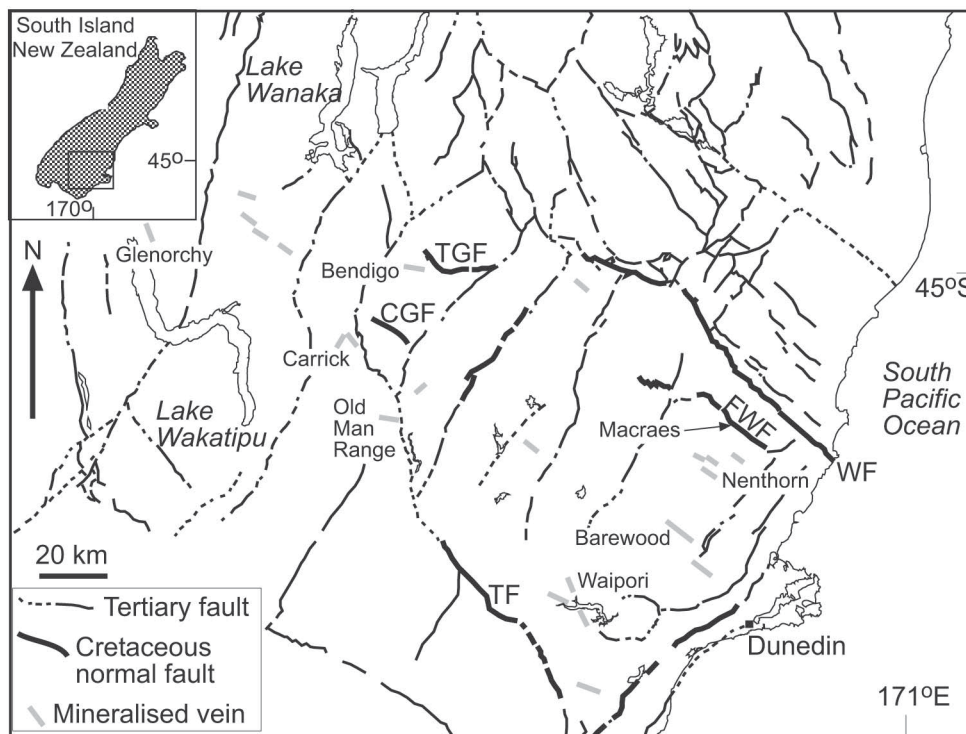


Fig. 2. Regional map of the Otago Schist belt, partly after Mortimer (1993), showing the principal post-metamorphic faults. Cretaceous normal faults are shown with heavy lines. CGF = Cromwell Gorge Fault (Deckert et al. 2002); TF = Tuapeka Fault.

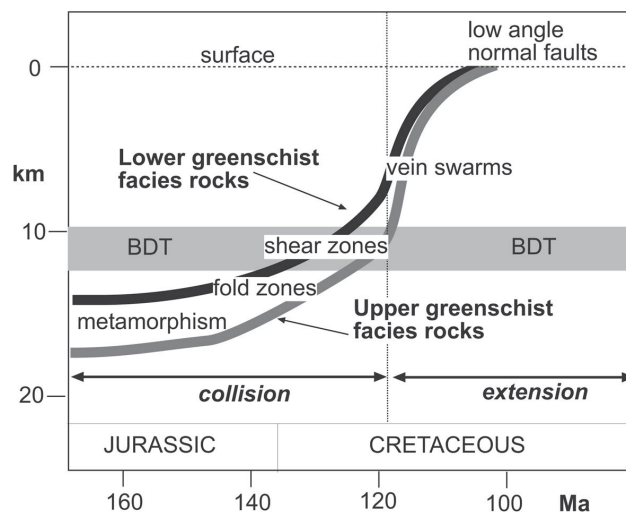
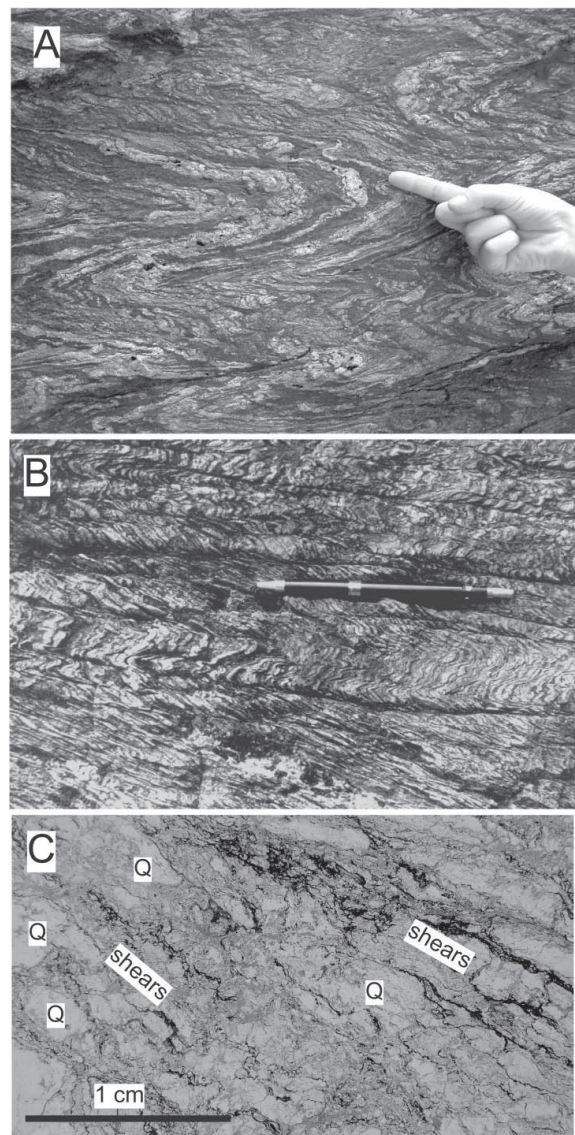


Fig. 3. Uplift trajectory diagram for the Otago Schist through time from initial collisional tectonics to Cretaceous extensional tectonics. Lower greenschist facies rocks (heavy black line) follow a slightly different uplift trajectory from upper greenschist facies rocks (heavy grey line) until the latter stages of uplift when they were juxtaposed. Structural regimes relevant to fluid flow zones along the uplift trajectories are described in the text.

Fig. 4. Photographs of typical late metamorphic folds from fold zones cutting across the Otago Schist (MacKenzie and Craw 2005). A. Manorburn Generation folds, with rounded hinges and weakly developed late stage cleavage parallel to the fold axial surface. B. Poolburn Generation folds, with more angular hinges and well-defined spaced cleavage on tight fold limbs. The spaced cleavage has controlled some fluid flow (subparallel to pen scale). C. Transmitted light photomicrograph of brecciated rock from a Poolburn Generation fold zone, with a matrix of hydrothermally



recrystallised chlorite around fragments of dismembered quartz-albite veins (Q). Opaque material is rutile (altered from metamorphic titanite), which defines late metamorphic shears.

Fold zones

During the early stages of uplift, the flat-lying foliation was deformed by ductile and semiductile folds (Fig. 4A, B). These folds are almost ubiquitous in the northwestern part of the belt, in the Aspiring and Wanaka lithologic associations (Fig. 5; Craw 1985). Mesoscopic folds are best developed in hinge zones of km scale folds in those areas. Farther east, these folds typically occur in well-defined structural zones, 1-2 km wide, that are not all clearly related to fold hinges (Fig. 5; MacKenzie and Craw 2005). At least two generations of these fold zones occur in central Otago, with the more angular folds (Fig. 4B) cutting across folds with rounded hinges (Fig. 4A) (MacKenzie and Craw 2005). Fold zones locally disrupt foliation and lithological layering in the schist, but no offset has occurred of structural markers such as metavolcanic layers or earlier fold zones (Fig. 5; MacKenzie and Craw 2005).

Both fold styles have had pressure solution processes and mica recrystallisation associated with folding, especially on fold limbs. High-strain portions of folded zones have a new cleavage fabric developed parallel to the fold axial surface. Locally, shearing, brecciation and hydrothermal alteration have occurred associated with development of this new fabric (Fig. 4B, C).

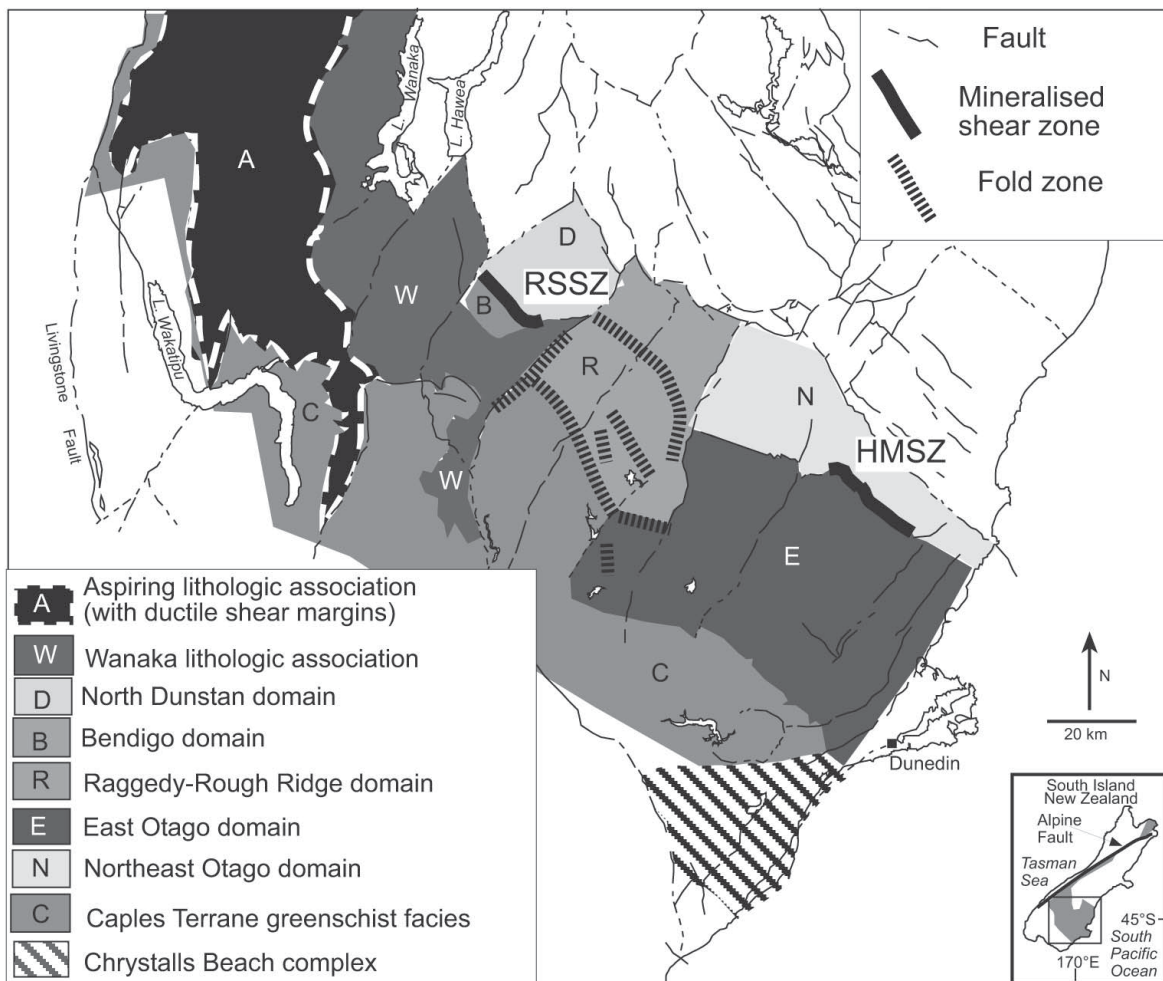


Fig. 5. Regional map of Otago Schist, showing principal structural and lithological domains and fold zones, and intervening structural boundaries (after MacKenzie and Craw 2005).

Shear zones

The Hyde-Macraes Shear Zone and Rise & Shine Shear Zone are well-defined structural zones that have involved a combination of folding, ductile recrystallisation, brecciation, and microshearing subparallel to the schist foliation. This deformation was compressional throughout, and led to low-angle thrust structures at Macraes (Teagle et al. 1990), and steeper-dipping fold and reverse fault structures in the Rise & Shine Shear Zone. Most of the deformation in the shear zones occurred along the pre-existing foliation. The micaceous layers, especially, became partially recrystallised to finer grain size, commonly with remobilised fine grained quartz, during that deformation (Fig. 6A, B). Titanite was replaced by rutile, and epidote by kaolinite and iron-bearing carbonate, during the deformation. In addition, sulfide minerals pyrite and arsenopyrite, with gold, were added along the foliation-parallel microshears (Fig. 6A). With increasing strain, the foliation became disrupted by development of numerous microshears with sulfide minerals and, in the Macraes deposit, abundant graphite (Fig. 6B; Craw 2002), so that the rock fabric became dominated by microshears rather than foliation. Microsheared rock was also folded on the cm to m scale, associated with larger shears in the shear zones (Fig. 6A). Most of this shear zone deformation was focussed in micaceous host schists, but some mineralisation occurred in feldspathic layers as well at the Macraes mine (Petrie et al. 2005). Some microshears were overprinted by cataclasis, especially at the Macraes mine where black shears are dominated by fine grained (micron scale) cataclastic micas, graphite, and sulfides.

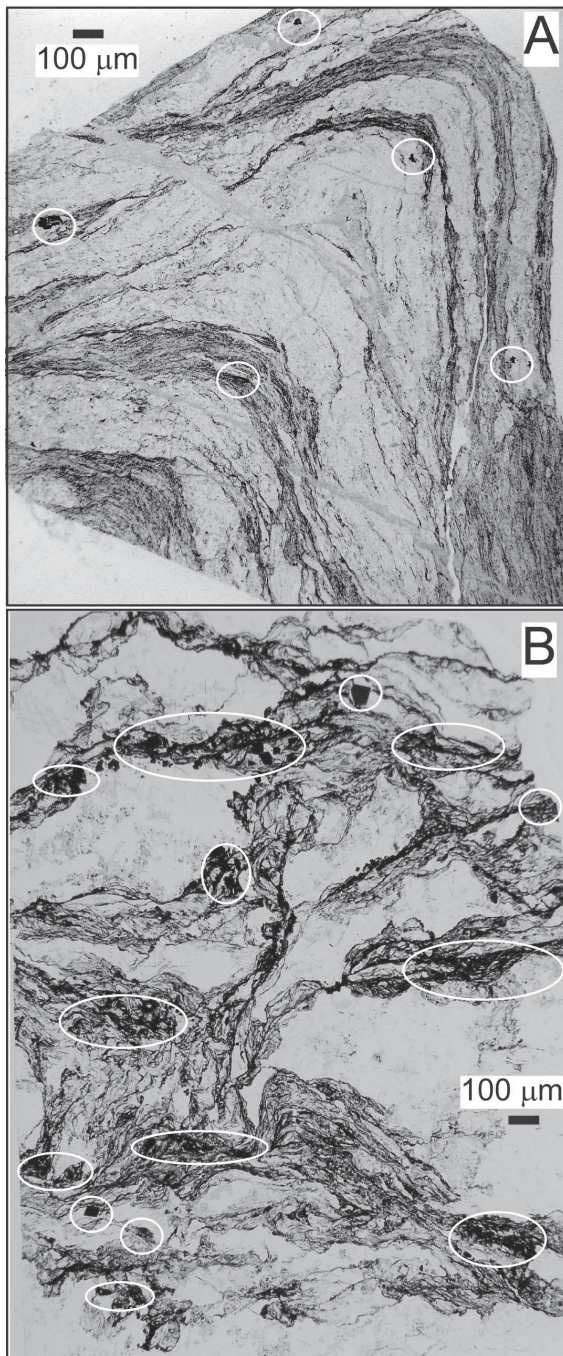


Fig. 6. Transmitted light photomicrographs of mineralised schist in shear zones, with hydrothermal sulphide grains circled. A. Folded mineralised schist from Rise & Shine Shear Zone, with dark microshears subparallel to folded foliation. B. Complexly deformed graphitic microshears from the Hyde-Macraes Shear Zone. Foliation has been strongly disrupted locally, but microshears are still largely subparallel to that foliation.

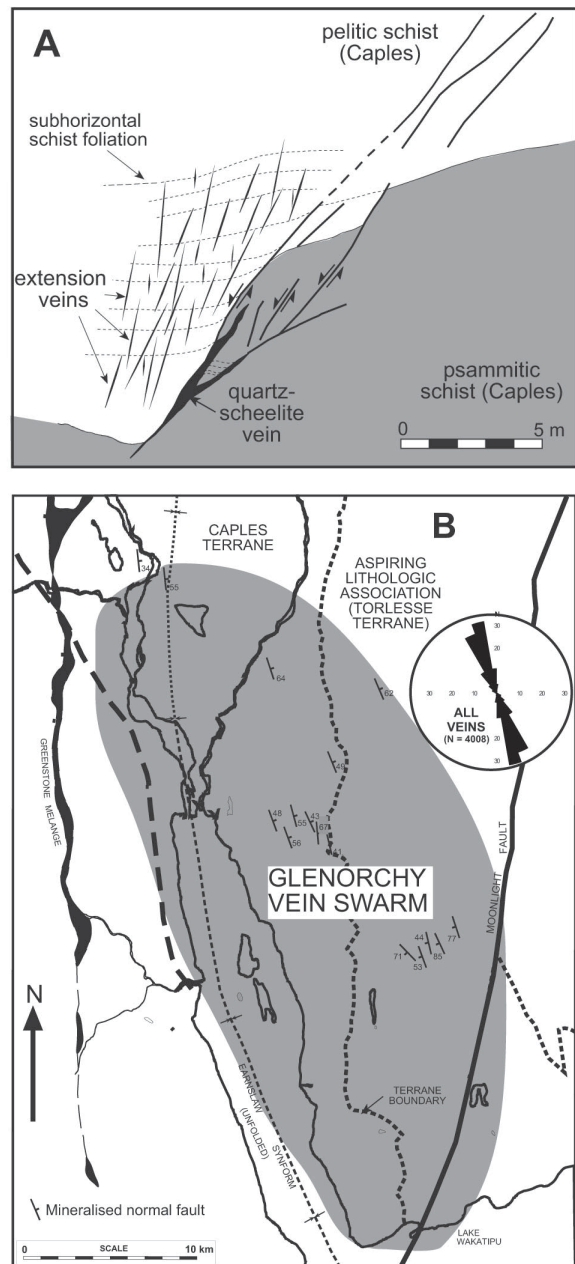


Fig. 7. Glenorchy vein swarm, NW Otago (after Begbie 2002; Begbie and Sibson 2005). A. Sketch of veins at the outcrop scale. A swarm of extensional veins has developed near the boundary between pelitic and psammitic schists. This lithological boundary has been faulted normally, and a larger mineralised vein has formed in association with that fault development. B. Map of the regional extent of the Glenorchy vein swarm. Inset rose diagram shows the orientations of extensional veins within the swarm.

Vein swarms

The exact timing of change from essentially regional collisional deformation to regional extensional deformation is debated, but is known to have been in the early Cretaceous (Fig. 3; Forster and Lister 2002; Gray and Foster 2004). One of the important features accompanying the onset of extension was the development of swarms of veins that cut the foliation at a high angle (Begbie 2002; Fig. 7A). These veins are small (typically 5-10 mm thick and less than 1 m long), but they are numerous (up to 10 per metre across strike). The veins have formed in a mesh or network of extension and extension-shear fractures. A well-defined swarm occurs in the Glenorchy area (Fig. 2, 7B), where it covers more than 1500 km². The veins have a uniform NNW strike (Fig. 7B) and steep dip (Fig. 7A).

Veins in the Glenorchy swarm are filled with quartz and minor wall rock fragments. There has been negligible hydrothermal alteration of wall rock fragments or vein margins. Some normal faults in the vein swarm area were more extensively mineralised with sulfides, scheelite, and minor gold (Fig. 7A; Williams 1974; Begbie 2002; Begbie and Sibson 2005). The Glenorchy mineralised normal faults represent an early stage in the emplacement of normal-fault hosted mineralised quartz veins throughout the Otago Schist (Craw and Norris 1991).

Normal faults

Regional scale normal faulting became an important part of the structural evolution of Otago in the early Cretaceous, resulting in much of the present distribution of metamorphic zones. There has been hydrothermal activity along some of these faults (MacKenzie et al. 1998), in addition to the more localised mineralised structures mentioned in the previous section. Normal faults have been responsible for disruption of the uplifted metamorphic rocks into several large scale (tens of km²) domains that are internally geologically similar, but distinctly different from neighbouring domains (Fig. 3; MacKenzie and Craw 2005). The Caples-Torlesse terrane boundary through much of Otago has been obscured by these normal faults (Fig. 3).

Low-angle normal faults are relatively rare in Otago, but those that are present were active at this early to middle Cretaceous period (Deckert et al. 2002; Forster and Lister 2003). Low angle normal faults have been responsible for juxtaposing upper greenschist facies rocks against lower greenschist facies rocks in several places (Craw 2002; Deckert et al. 2002). The main significance of these low-angle faults to gold deposits is that they truncate the known mineralised shear zones, Hyde-Macraes Shear Zone and Rise & Shine Shear Zone, and juxtapose them against unmineralised rocks of different metamorphic grade (Fig. 2, 3).

Discussion and conclusions

Metamorphism resulted in partial dehydration of the rocks, with ca. 2 wt% water generated in the process (Norris and Henley 1976). This fluid presumably pervaded the rock along grain boundaries and was interconnected, as can be seen in geophysical imaging of the same rocks at 10-30 km depth beneath the modern collisional orogen east of the Alpine Fault (Fig. 1; Wannamaker et al. 2002). Metamorphic dehydration fluids beneath the modern collisional orogen have leached most of the arsenic and mobilised some gold from amphibolite facies rocks, and transported these elements to shallower levels (Campbell et al. 2004). Similar processes presumably occurred during the collisional Rangitata Orogeny, resulting in crustal-scale metal mobility from the deeper parts of the metamorphic pile (Pitcairn et al. 2003). In the absence of evidence for other fluid sources such as igneous bodies, this metamorphic dehydration process is the most likely source for the mineralizing fluid during schist uplift.

During the early stages of schist uplift, deformation-induced fluid flow through ductile rocks would have been slow (ca. 1 mm/year) and pervasive (Upton 1998). This slow rate of fluid movement will have persisted through to the brittle-ductile transition unless well-defined fractures

developed enabling faster fluid flow. Development of microshears in the mineralised shear zones at Macraes and Rise & Shine may have facilitated some more rapid fluid flow as the rocks passed through the brittle-ductile transition. This shear zone-related fluid flow would have been locally enhanced by fracturing that led to the minor quartz veins in these deposits. However, the bulk of fluid flow in these mineralised shear zones was via slow percolation along grain boundaries and microshears, leading to large volumes of hydrothermally altered and weakly mineralised rock. At Macraes, this fluid flow was along a low-angle structure, with a small vertical component of motion (Craw 2002).

Once the schists passed through the brittle-ductile transition, fracturing became more significant, especially with the onset of extensional deformation. Under these more brittle conditions, vein swarms formed in interconnected fracture arrays that facilitated fluid flow (Begbie 2002). Even here, the major permeability was parallel to fracture intersections, and had only a minor vertical component of motion (Begbie 2002). Through-going normal faults in this setting were most important for channeling fluids that led to mineralised vein systems. Fluid flow under these conditions may have been many orders of magnitude more rapid, but little interaction with host rocks occurred. Resulting volumes of mineralised rocks, essentially confined to veins, are small.

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