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Dave Craw
Doug MacKenzie

Macraes Orogenic Gold Deposit (New Zealand)

Origin and Development of a World Class Gold Mine

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Preface

Almost all schist terranes of the world host some gold-bearing quartz veins, and most of these have been mined historically to some extent. From the early Middle Eastern civilisations, and particularly during the time of the Roman Empire, mining of these veins has yielded gold in variable quantities in the ancient world. The same style of mining activity, with remarkably similar approaches and technology, persisted and spread throughout the world to the early 20th century. A small proportion of the vein systems were sufficiently continuous and gold rich to permit long-term mining, and some famous mines now extend for kilometres below the surface. However, most of the old mines extend only a few metres or tens of metres into the basement rocks before petering out as the physical and technological issues of following the veins overcame the value of the gold that was being extracted. Hence, remnants of these abandoned small, shallow historic mine workings are a common feature of the landscape in these schist terranes.

The presence of these historic workings has been a powerful attractor for subsequent exploration activities, especially at times of rising gold prices in the latter parts of the 20th century and on into the present century. The principal exploration target has remained the quartz veins themselves, by analogy with the few long-established mines. However, modern technology now allows practical and economic gold extraction from weakly mineralised rocks adjacent to the quartz veins as well as the quartz veins themselves. This increases the size of the exploration targets, and the volume of potential mineable rock, albeit with much lower gold grades than was historically economic. The result of these technological changes is the evolution of a new gold mine type in schist terranes: large tonnage, low grade operations in which the gold-bearing quartz veins are a relatively minor part.

Refractory and preg-robbing ore have traditionally caused issues of low gold recovery in orogenic gold deposits. These issues arose at the modern Macraes deposit, but recovery improved with introduction of new pressure oxidation technology. Modern mines have to work under stricter environmental regulations than in the past, and sensitive surrounding inhabitants ensure that environmental standards remain high. In particular, arsenic is a significant issue around orogenic gold mines, especially large mines like Macraes. However, judicious water and tailings management can limit the environmental footprint.

These new technological developments make all the small shallow historic mines of particular interest for modern exploration. Most will not yield new mines, but this can only be determined by active exploration and associated applied research. This book provides geological context and structural and geochemical frameworks for a successful project that turned what was a small set of schist-hosted quartz veins exposed in old mine workings into the world-class Macraes gold mine. Many of the key geological and geochemical features of the formation processes and resultant ore types at Macraes have direct effects on metallurgical characteristics and downstream environmental issues, and these practical and economic aspects are also incorporated into the narrative.

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This book, and the research reported in it, would not have been possible without the enthusiasm, funding, and extensive logistical support provided to us by Oceana Gold Ltd and its precursor companies, which have conducted exploration since 1985 and operated the mine since 1990. Senior staff who facilitated that support include Paul Angus, John Bywater, Mark Cadzow, Quenton Johnston, Marshall Lee, and Jonathan Moore. Hospitality and useful knowledge on site were ably provided by Ben Baxter, Hamish Blakemore, Debbie Clarke, Simone Creedy, Sean Doyle, Mark Mitchell, and Bill Yeo. Richard Norris, Iain Pitcairn, and Damon Teagle helped to provided new insights into the Hyde-Macraes Shear Zone and orogenic mineralisation processes in general. Additional discussions with Andrew Allibone, Mike Begbie, Katy Evans, Allan Hall, Jim Mortensen, Nick Mortimer, Rick Sibson, Ian Turnbull, Phaedra Upton, and Steve Windle were invaluable in helping us develop ideas about the deposit. Much of the useful information reported here was gathered by research students whom we helped to supervise, including Ben Cave, Lauren Farmer, Nick Goodwin, Anicia Henne, Shirley Hu, Philip Jones, Scott McKeag, Dusk Mains, Lisa Milham, and Brigitte Petrie. Financial support for most of our work has been provided by the New Zealand Government Ministry for Business, Innovation and Employment, and its precursor the Foundation for Research, Science and Technology, in the form of research contracts for definition of gold-forming processes and footprints, ancient and modern, in the South Island. Helpful suggestions from an anonymous reviewer improved the presentation of the manuscript.

Contents

Chapter 1
Introduction: Macraes Mine as an Orogenic Gold Deposit

1.1 Orogenic Gold Deposits

Orogenic gold deposits have formed throughout the Earth's geological history, from Archaean to present (Goldfarb et al. 2005). Most of the mined deposits occur in greenschist facies metamorphic belts, and deposit formation has been intimately related to the metamorphic evolution of those metamorphic belts. The most productive gold-bearing quartz vein systems occur in Archaean cratons, such as the Yilgarn of Western Australia, and the Abitibi of Canada, where they are hosted by so-called greenstone belts dominated by metabasic rocks (Goldfarb et al. 2005). In contrast, Phanerozoic orogenic deposits are mainly hosted in metasedimentary schist belts (Bierlein and Crowe 2000). These schist belts have formed as accretionary complexes at convergent tectonic margins, and they typically consist of thick stacked piles of variably deformed and metamorphosed sediments that have accumulated above a subduction zone (Bierlein and Crowe 2000; Goldfarb et al. 2005).

Orogenic gold deposits are structurally controlled features, typically focused in fault zones (Fig. 1.1; Goldfarb et al. 2005). The deposits form where flow of hydrothermal fluids in the middle crust has been controlled by the structure(s). The fluids deposit quartz and sulphide minerals along the structure, particularly in extensional sites where fault motion has created wider cavities. These depositional processes occur between 200 and 400 °C and 5–15 km depth. The hydrothermal fluids are at least partly derived from metamorphic processes occurring in the host schist terrane, although many of the deposits have formed after the immediate host schist has been uplifted from metamorphic depths (Goldfarb et al. 2005). However, fluid flow and faulting generally occur together, so that early-formed veins can become deformed by on-going structural activity.

Gold occurs either as free particles within the quartz veins, or is enclosed within the sulphide minerals (typically pyrite and/or arsenopyrite) as microparticles, nanoparticles, or in solid solution. In addition to the deposition of the gold-bearing

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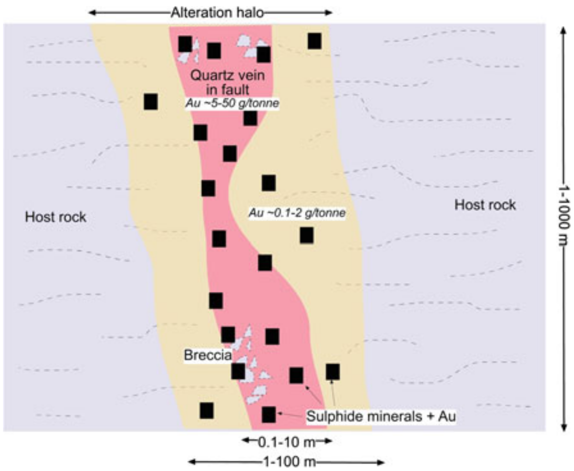

Fig. 1.1 Schematic orogenic gold deposit, showing the principal features and the range of scales at which they occur

quartz veins, some hydrothermal fluid penetrates into the immediate host rocks and causes alteration of the pre-existing minerals. This alteration halo can also receive sulphide minerals and gold as part of the alteration processes (Fig. 1.1). Fluid-rock interaction reactions can be instrumental in causing metal deposition, so that gold and sulphides are commonly concentrated near to the margins of the quartz veins and in brecciated host rocks formed during fault-driven deformation (Fig. 1.1).

1.2 Alluvial Gold and the Otago Goldfield

The Otago goldfield, in which the Macraes deposit occurs (Fig. 1.2) developed as an alluvial goldfield following a large gold rush that was initiated in 1861. More than 8 million ounces of alluvial gold have been recovered from this goldfield since 1861 (Williams 1974), and numerous short-lived alluvial operations still occur sporadically in the goldfield. Numerous gold-bearing orogenic veins were discovered in the basement rocks by the historic miners during their various alluvial exploration activities. Many of these were mined at shallow levels, and those mines ceased when the base of a supergene enrichment zone was reached (Craw et al. 2015). Historic production from orogenic veins was trivial compared to the alluvial deposits.

Orogenic deposits in the Macraes area were first discovered by alluvial miners seeking source(s) for the nearby alluvial gold (Chap. 2). The contribution of eroded parts of the Macraes deposit to the regional alluvial gold endowment is not known, but is probably large. Current exploration and mining activities at Macraes show that this deposit vastly overshadows all other known orogenic systems in the goldfield. The balance of orogenic versus alluvial production in the Otago goldfield is in the process of being eclipsed by the modern development of the Macraes mine. Hence, this single deposit has the potential to transform the Otago area from a primarily alluvial goldfield to a largely orogenic goldfield.

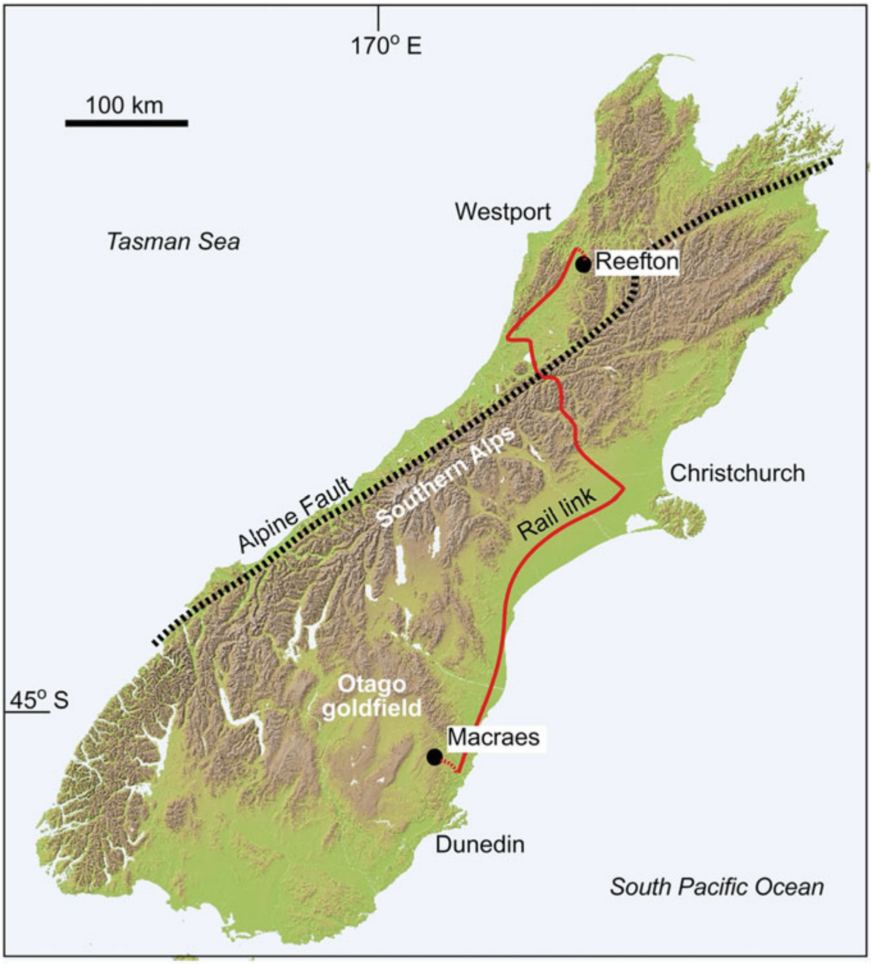

Fig. 1.2 Digital elevation model image of the South Island of New Zealand (from geographx.co.nz) showing the location of the Macraes orogenic gold mine and the Otago goldfield. Sulphide mineral concentrates were transported by road (*red dotted line*) and rail (*red solid line*) from the Reefton orogenic gold mining area in the northern South Island to Macraes from 2007–2015 to augment the ore feed in the Macraes processing plant

1.3 Macraes Deposit Exploration and Mining History

The Macraes orogenic deposit, in the province of Otago in southern New Zealand, is relatively unusual in having a shallow dip, but otherwise has most of the characteristics of orogenic deposits outlined in Fig. 1.1. Historic mining focused on quartz veins (Fig. 1.3a, b). The structure of the main part of the deposit was assumed to be simple, with two sub-parallel quartz veins that were believed to be

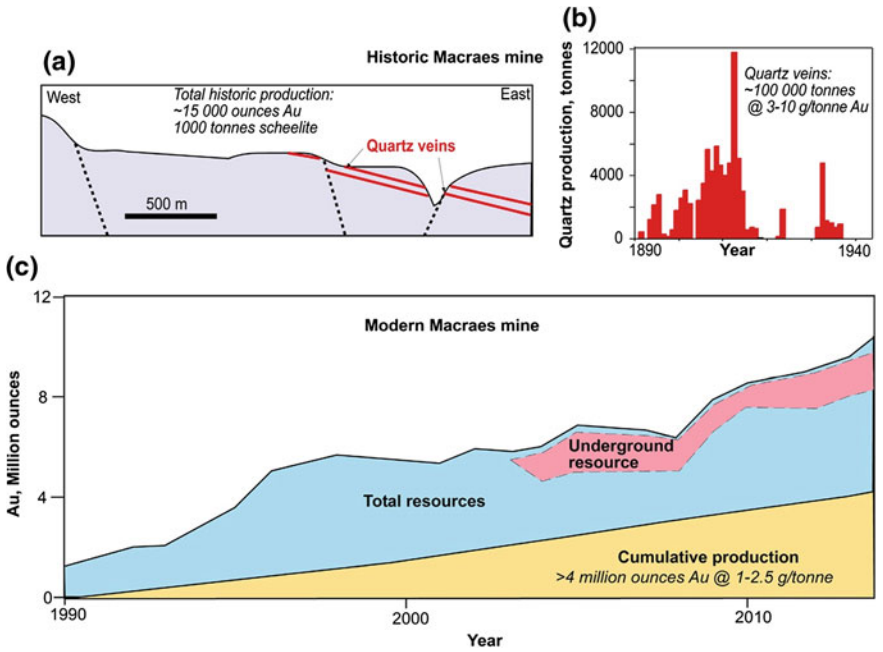

Fig. 1.3 Historic and modern production and resources at Macraes. **a**, **b** Inferred cross section, grades and production of historic workings (summarised from Williamson 1939). **c** Resources and production for the modern Macraes mine (adapted from Moore and Doyle 2015)

continuous over hundreds of metres (Fig. 1.3a). In addition, there were numerous outlying small quartz vein exposures in the area, most of which were gold-bearing (Williamson 1939; Williams 1974). Early mining occurred in shallow surface pits and short underground drives, all of which extracted quartz for crushing and gold extraction in nearby processing plants. Production was small, and <100,000 tonnes of quartz were processed to yield ~15,000 oz of gold over 50 years (Fig. 1.3a, b). The quartz veins locally contain scheelite ($CaWO_4$), and this was a significant product from the mines at times of high tungsten prices, particularly during wars (Williams 1974).

The near-surface veins have been variably oxidised, typically down to ~50 m. The oxidation of sulphide minerals liberated encapsulated microparticulate gold, and the associated supergene processes facilitated increases in gold particle sizes in the oxidised rocks (Craw et al. 2015). This relatively coarse free gold was readily extracted by the historic miners from the crushed ore, partly via gravity settling and partly via mercury amalgamation. However, once the miners penetrated to unoxidised rocks, they found that there was little or no coarse-grained gold and that nearly all the gold was encapsulated in sulphide minerals, pyrite and arsenopyrite. Attempts were made to liberate this gold by roasting sulphide concentrates, but this was not pursued to any significant extent before the mines closed in the 1940s (Fig. 1.3b; Mains and Craw 2005).

1.4 The Modern Macraes Mine

Renewed exploration of the gold potential of the Macraes area occurred in the 1980s, accompanied by drilling that was focused in what is now the central part of the mineralised structure (Fig. 1.4). Associated geological mapping led to the conclusion that many of what were originally seen as scattered quartz vein occurrences were in fact part of a major regional structure, now termed the Hyde-Macraes Shear Zone, that is traceable for more than 30 km along strike (Teagle et al. 1990). This structure contains numerous quartz veins, but these are discontinuous on the 1–10 m scale. However, hydrothermal alteration in the adjacent host schist has also deposited gold-bearing sulphides, albeit at lower gold grade than the associated quartz veins. Nevertheless, the structural package that includes veins and mineralised host rock is locally >150 m thick. It is this structural package that has become the focus of modern mining, which now extends intermittently for over 10 km along the Hyde-Macraes Shear Zone (Fig. 1.4).

Modern mining began in 1990 with open pits developed in the thickest part of the shear zone. Satellite open pits have been developed, and still are being developed, along strike (Fig. 1.4). When the modern Macraes mine opened in 1990, the defined resource was little more than 1 million ounces of gold, but this has progressively increased with along-strike exploration to >10 million ounces (Fig. 1.3c; Moore and Doyle 2015). During this time, actual production now exceeds 4 Moz of that total resource (Fig. 1.3c). In addition to the open pits, mining at the largest open pit, Frasers (Fig. 1.4) has been extended down-dip as an underground mine along the highest grade part of the mineralised structure, and this has contributed ~1 Moz of gold to the total resource (Fig. 1.3c).

In addition to the Macraes ore production, sulphide mineral concentrate from an orogenic gold mine at Reefton (Fig. 1.2) was transported 700 km across the Southern Alps mountains by road and rail, to be processed at Macraes. This additional input occurred between 2007 and 2015, and added about 10 % to the Macraes-derived sulphide concentrate that was being processed (Milham and Craw 2009).

Fig. 1.4 Aerial view of the modern Macraes mine in 2015 (from GoogleEarth). The main mining area is between Frasers and Golden Point, where excavations have been almost continuous along strike. Satellite pits have contributed relatively small amounts of ore. Pit names are derived from small historic workings

Spare capacity available in the Macraes processing system offset the long-distance transport costs and enabled establishment of the Reefton mine without the expense of full gold extraction facilities on site.

References

Bierlein FP, Crowe D (2000) Phanerozoic orogenic lode gold deposits. In: Gold in 2000, Hagemann SG, Brown PE (eds), Reviews Econ Geol 13: 103-140

Craw D, MacKenzie DJ, Grieve P (2015) Supergene gold mobility in orogenic gold deposits, Otago Schist, New Zealand. NZ J Geol Geophys 58: 123-136

Goldfarb RJ, Baker T, Dube B, Groves DI, Hart CJ, Gosselin P (2005) Distribution, character and genesis of gold deposits in metamorphic terranes. In: Hedenquist JW, Thompson JFH, Goldfarb RJ, Richards JP (Eds.) Econ Geol 100th Anniv Vol, 407-450.

Mains D, Craw D (2005) Composition and mineralogy of historic gold processing residues, east Otago, New Zealand. NZ J Geol Geophys 48: 641-647.

Milham L, Craw D (2009) Two-stage structural development of a Paleozoic auriferous shear zone at the Globe-Progress deposit, Reefton, New Zealand. NZ J Geol Geophys 52: 247-259

Moore J, Doyle S (2015) Resource definition in the world-class Macraes gold mine, New Zealand. Proceedings, PACRIM 2015, Aust Inst Min Metall, pp 557-566.

Teagle DAH, Norris RJ, Craw D (1990) Structural controls on gold-bearing quartz mineralisation in a duplex thrust system, Hyde-Macraes Shear Zone, Otago Schist, New Zealand. Econ Geol 85: 1711-1719

Williams GJ (1974) Economic Geology of New Zealand. Aust Inst Min Metall Monog 4

Williamson JH (1939) The geology of the Naseby Subdivision, Central Otago. NZ Geol Survey Bull 39

Chapter 2
Regional Geological Setting of the Otago Schist

2.1 Mesozoic Accretion

The basement rocks of the South Island of New Zealand consist of a diverse set of terranes that accumulated on the Pacific margin of Gondwana during the Mesozoic (Fig. 2.1a–c; Mortimer 2004). The Otago Schist belt that hosts the Macraes mine (Fig. 2.1a, b), formed as part of this Mesozoic convergence (Fig. 2.1c). At that time, what is now the New Zealand landmass and associated submerged continental crust was attached to the edge of the Australian portion of Gondwana (Mortimer 2004). This Pacific-facing continental margin was an elongated convergent tectonic boundary with active subduction, continental arc magmatism, and terrane collision (Fig. 2.1c). The Otago Schist formed as part of a wide (>100 km) accretionary complex above the subduction zone (Fig. 2.1b, c).

The accretionary complex includes two principal metasedimentary terranes, Caples and Torlesse terranes (Fig. 2.1b, c) as well as several other subordinate terranes within the complex (Mortimer 2004; MacKenzie and Craw 2005; Cooper and Ireland 2013). Terrane accretion resulted in stacking, thickening, and pervasive deformation in the metasedimentary rocks that accumulated above the subduction zone (Fig. 2.1c). These processes led to formation of a thick metamorphic pile, which became the Otago Schist belt, primarily during the Jurassic and Early Cretaceous (Fig. 2.1a–c; Mortimer 2004; Gray and Foster 2004). Terrane boundaries, and the Caples-Torlesse terrane boundary in particular, have been deformed and metamorphosed within the metamorphic pile (Fig. 2.1b).

Subduction-related Mesozoic arc magmatism occurred in what is now the far west of the South Island, to form the Median Batholith (Fig. 2.1c; Mortimer 2004). A notable feature of the Mesozoic plate boundary is the great width of the accretionary complex, which distanced metasedimentary accretion from the subduction-related arc magmatism (Fig. 2.1c). This has resulted in clear separation of magmatic

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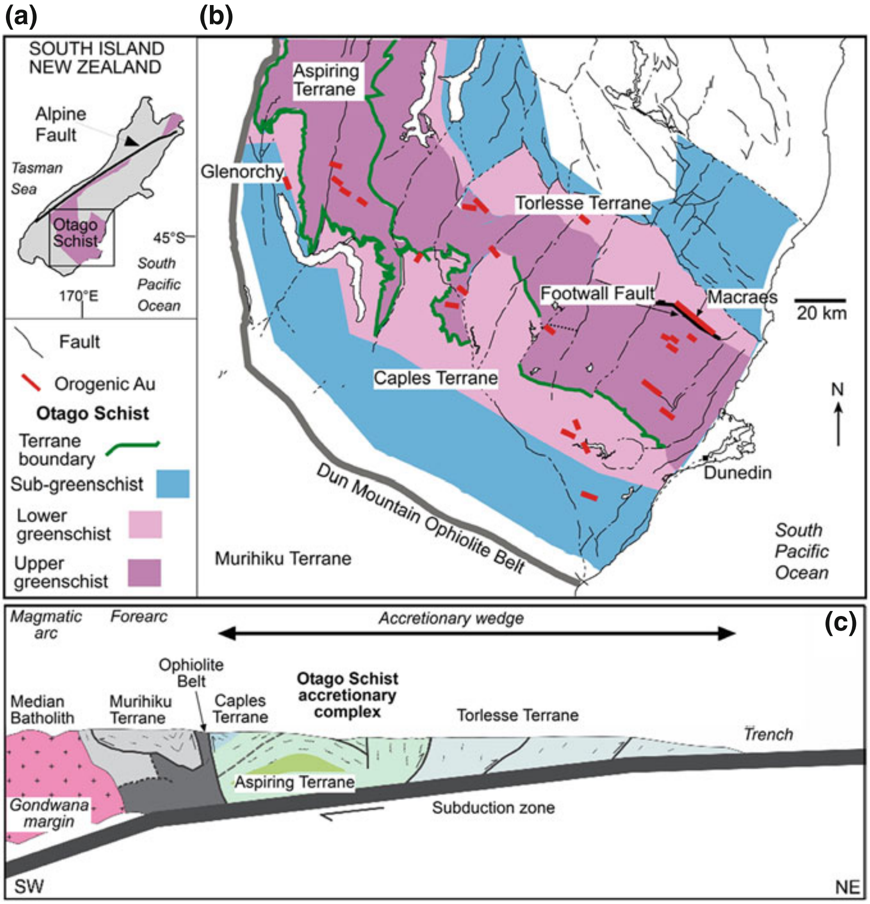

Fig. 2.1 Location of the Macraes mine within the Otago Schist as part of a Mesozoic accretionary complex. **a** Otago Schist belt in the South Island of New Zealand. **b** Metamorphic and terrane map of the Otago Schist belt. **c** Reconstruction of the Early Cretaceous plate tectonic geometry of the Pacific margin of Gondwana (modified from Mortimer et al. 2016)

processes from the accretionary complex. This lack of syn-metamorphic magmatism in the accretionary complex is a distinct feature of the Otago Schist belt that is not found in most other Phanerozoic gold-bearing metasedimentary terranes.

2.2 Otago Schist Lithology and Structure

The schist protoliths on both sides of the belt are dominated by greywacke (lithic sandstone) with interlayered argillites in thick turbidite sequences that have poorly developed stratigraphy (Fig. 2.2a; Mackinnon 1983; Mortimer 2004). The Torlesse

Terrane rocks (Fig. 2.2a) are generally more quartzofeldspathic than the volcanogenic Caples Terrane rocks, but these distinctions are subtle. Hence, the whole schist belt is made up of a compositionally uniform rock mass that differs mainly in metamorphic grade and degree of recrystallisation, and primary lithological variations are subordinate. Minor interlayered mafic horizons (1–100 m scale) occur throughout the belt, and these are more abundant in the Aspiring Terrane that is exposed on the western side of the belt (Fig. 2.1b). These mafic horizons do not make up more than 10 % of the schist pile locally, and are almost completely absent from the lower greenschist facies rocks near to the Macraes mine.

Polyphase recumbent folding, with associated fold axial surface cleavage development, has created pervasive flat-lying foliation that dominates much of the schist belt (Fig. 2.2b). Subsequent differential exhumation has formed a broad antiformal structure in the flat-lying foliation, with the highest grade rocks (upper greenschist facies) in the core of the antiform (Fig. 2.1b, c). Metamorphic grade decreases from the core to the northeast and southwest, where original sedimentary features are recognisable in the low grade (sub-greenschist facies) portions of the metasedimentary terranes. Boundaries between metamorphic zones are now extensively faulted, disrupting what were originally more continuous metamorphic transitions on both sides of the belt (Mortimer 2000; Henne and Craw 2012).

Greenschist facies rocks are fully recrystallised, so that no bedding or clastic textures are preserved. Syn-metamorphic quartzofeldpathic segregations, including

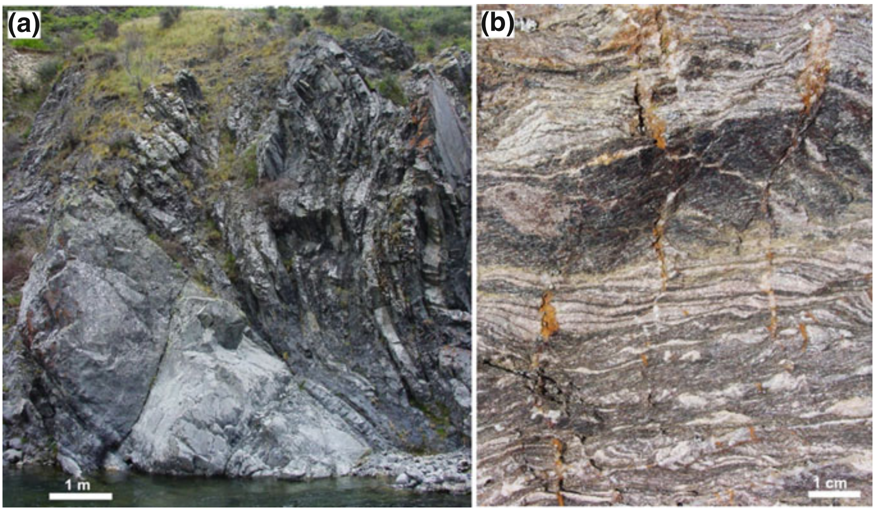

Fig. 2.2 Otago Schist structure and lithology. **a** Outcrop of low grade (sub-greenschist facies) Torlesse Terrane protolith dominated by steeply-dipping bedding that has been folded and steepened. Paler and resistant beds are greywacke (sandstone); recessive darker beds are argillite. **b** Close view of lower greenschist facies schist that is dominated by pervasive flat-lying foliation and metamorphic segregations. Remnants of more and less micaceous layers (*dark* vs. *light*, respectively) reflect original lithological variations in the protolith

some veins, have developed in greenschist facies rocks and dominate the rock fabric at the 1–10 cm scale (Fig. 2.2b). Segregations are separated by micaceous laminae containing quartz and muscovite (Fig. 2.2b). The quartzofeldspathic segregations have either formed parallel to the pervasive foliation or have been rotated into near-parallelism with that fabric during progressive ductile deformation. The development of these segregations has further obscured the subtle lithological variations within the schist, although more and less micaceous horizons are still recognisable on the 0.1–10 m scale (Fig. 2.2b).

2.3 Uplift, Exhumation, and Extension

Early-formed parts of the accretionary complex were metamorphosed and underwent uplift and exhumation while the more distal parts of the complex were still accreting. Hence, debris eroded from the uplifted portions contributed to the accreting sedimentary pile in the Jurassic and Cretaceous (Mortimer 2004; Cooper and Ireland 2013). At the same time, topographically uplifted parts of the evolving schist belt were undergoing extension while the deeper parts were still being compressively deformed (Mortimer et al. 2016). In the currently-preserved schist belt, it was the lower-grade flanks that were exhumed first, in the late Jurassic and Early Cretaceous (Gray and Foster 2004). The rocks that now constitute the higher-grade core of the belt continued to undergo ductile deformation into the middle Cretaceous, after what are now the lower grade flanks of the belt had been exhumed (Gray and Foster 2004).

Localised extension in the shallower parts of the accretionary complex in the Early Cretaceous evolved to more regional scale extension as the plate tectonic setting changed in the middle and Late Cretaceous. During this time, subduction ceased and extensional breakup of Gondwana became the dominant tectonic process (Mortimer 2004). The regional extension culminated in the separation of New Zealand continental crust, that now included the accretionary Otago Schist, from the Australian continent in the Late Cretaceous (Mortimer 2004). This regional extension led to development of a network of normal faults across the exhumed Otago Schist belt, with extensive erosion of faulted topography resulting in localised thick sedimentary accumulations in the middle Cretaceous (Craw 2010). Some of the normal faults were shallow-dipping, and these contributed to exhumation of the higher-grade core to form the antiformal structure that now dominates the geometry of the belt (Fig. 2.1b; Deckert et al. 2002).

Regional extension continued through the early Cenozoic, and the exhumed schist belt subsided beneath the sea until the late Oligocene or early Miocene (Landis et al. 2008). Reconfiguration of the plate tectonic setting in the SW Pacific Ocean at that time was marked in the South Island by development of the transpressional Alpine Fault (Fig. 2.1a). Regional deformation associated with this new plate boundary caused reactivation of many of the normal faults as reverse structures. This deformation resulted in uplift and renewed erosion across the schist belt.

The uplift and erosion is most pronounced near to the Alpine Fault, where a range of high mountains, the Southern Alps, has formed on the eastern side of that fault. The rejuvenated topography becomes progressively more subdued farther east, where much of the terrain is dominated by an exhumed and deformed Late Cretaceous-middle Cenozoic basement unconformity surface (Landis et al. 2008). In the vicinity of the Macraes mine, the topography is dominated by this unconformity surface that forms broad uplands incised by narrow steep streams (Fig. 1.4).

2.4 Hyde-Macraes Shear Zone

The Hyde-Macraes Shear Zone, which hosts the Macraes mine, is a major regional structure within the eastern part of the schist belt (Figs. 2.1b, 2.3a–c). The shear zone formed in lower greenschist facies schists as they were being uplifted through the brittle-ductile transition (Craw et al. 1999). Hence, early development of the shear zone was dominated by ductile features, including folding, mineral recrystallisation and reorientation, and mylonitic deformation (Craw et al. 1999; Petrie et al. 2005). The ductile features were progressively overprinted by more brittle compressive structures, including cataclasites and fault gouges, (Craw et al. 1999). The shear zone is a shallow-dipping thrust structure that is sub-parallel to the shallow-dipping metamorphic foliation on the northeastern limb of the regional schist antiform (Fig. 2.3c).

The earliest deformation in the shear zone occurred under lower greenschist facies metamorphic conditions, with recrystallised mineralogy similar to that of the host rocks. This deformation was accompanied by hydrothermal fluid flow and gold mineralisation. Fluid flow was pervasive, along grain boundaries and microshears, through large volumes of rock (Fig. 2.3b, c). The structural upper limit of this shear-hosted fluid flow is as yet poorly defined, although the shear zone is variably mineralised over several hundred metres thickness in places (Fig. 2.3b). As the rocks became more brittle, fluid flow and mineralisation processes continued, with progressively lower temperature mineralogy prevailing, and fluid flow became more focussed in cataclastic zones and fractures, still over a large thickness of rock.

The structural base of the shear zone is now defined by a prominent but narrow post-mineralisation normal fault, the Footwall Fault (Fig. 2.3a–c). This extensional structure has juxtaposed lower greenschist facies rocks, which host the mineralised shear zone, on to unmineralised upper greenschist facies rocks (Fig. 2.3a–c). The Footwall Fault is part of the regional set of extensional structures that was initiated in the middle Cretaceous, and has contributed to exhumation of the higher-grade schist core (Deckert et al. 2002; Craw 2010). Because of this post-mineralisation truncation of the lower part of the Hyde-Macraes Shear Zone, it is not possible to determine the original shear zone thickness.

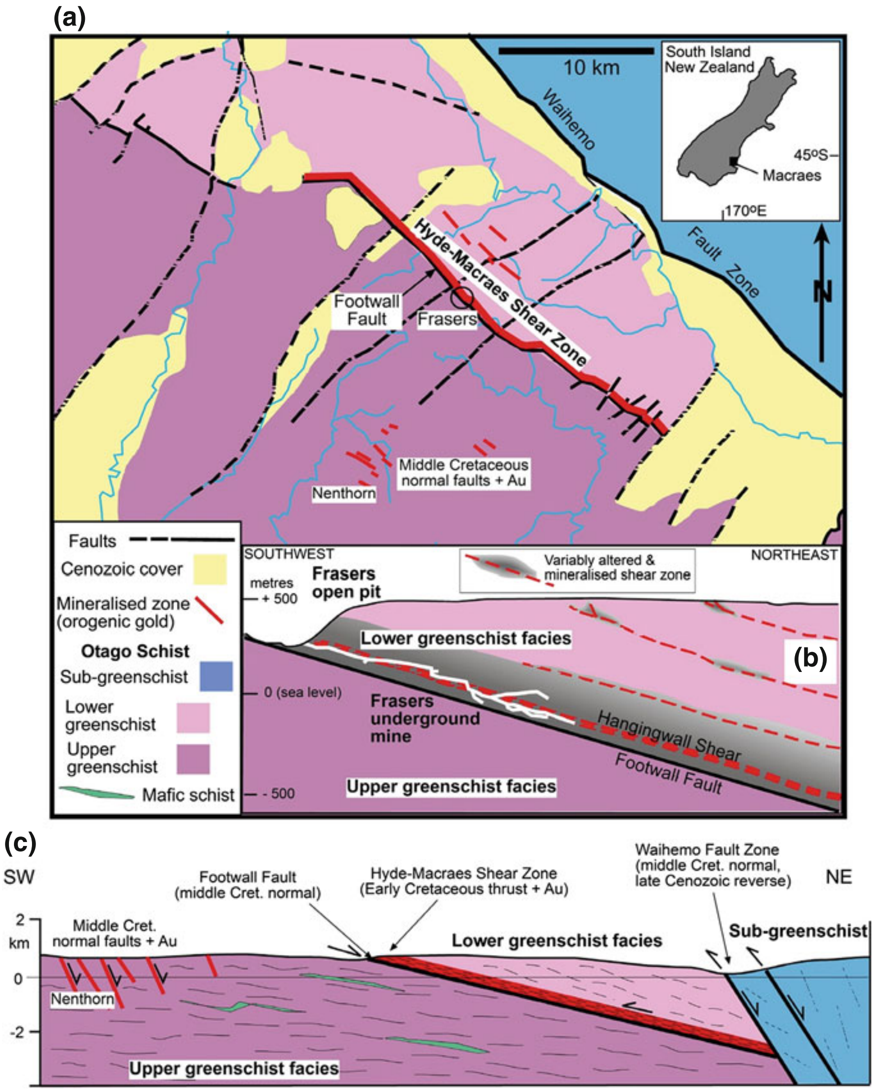

Fig. 2.3 Geological setting of the Macraes mine in the Hyde-Macraes Shear Zone. **a** Geological map of the Macraes area. **b** Cross section through the Frasers open pit and underground mine. **c** Regional cross section across the Hyde-Macraes Shear Zone near to the Frasers open pit

2.5 Mesozoic Geochronology

There were two distinct pulses of orogenic gold mineralisation (Mortensen et al. 2010) during the Cretaceous evolution of the Otago Schist belt: Early Cretaceous (135–140 Ma) and middle Cretaceous (110–100 Ma). The earlier event, which included Macraes, was intimately linked to the latter stages of metamorphism of the schist, and the later event was linked to regional extensional processes (Fig. 2.4a). The lower greenschist facies rocks on the flanks of the schist belt were being uplifted through the brittle-ductile transition while the upper greenschist facies core of the belt remained ductile and was still undergoing high grade metamorphism (Fig. 2.4a).

The relative timing of the specific structural features relevant to formation and deformation of the Hyde-Macraes Shear Zone has been determined radiometrically on available rocks, and these data are summarised in Fig. 2.4b. The lower greenschist facies host rocks for the shear zone were exhumed and cooled below argon and strontium closure temperatures (between 300 and 400 °C) in the Late Jurassic (160–140 Ma). Widespread recumbent ductile folds of early-formed foliation in these rocks were formed before this exhumation and cooling, and pre-date the formation of the shear zone. Rocks of the shear zone itself recrystallised and cooled by ~130 Ma, and the shear zone structures were superimposed on the pre-mineralisation ductile folds (Fig. 2.4b). In particular, precise $^{40}Ar/^{39}Ar$ dating of hydrothermal muscovite from the Macraes deposit suggests that mineralisation occurred at 135–136 Ma (Mortensen et al. 2010). These geochronological results are in accord with structural and mineralogical inferences that suggest that the shear zone formed in the latter stages of exhumation of the hosting lower greenschist facies rocks.

In contrast, the underlying upper greenschist facies rocks did not cool below argon closure temperatures until at least 120 Ma (Gray and Foster 2004). These rocks remained ductile, with isoclinal folding and associated muscovite recrystallisation, after the Hyde-Macraes Shear Zone had formed at shallower structural levels (Fig. 2.4b). These relatively young ductile fold structures were superimposed on at least one generation of recumbent ductile folds that are temporally equivalent to the pre-mineralisation folds in the lower greenschist facies rocks (Fig. 2.4b). The young ductile folds in the upper greenschist facies rocks are at least partially the deeper-level expression of the same compressional deformation that formed the Hyde-Macraes Shear Zone as a thrust structure near to the brittle-ductile transition in the Early-middle Cretaceous.

The Footwall Fault and associated extensional structures in the Macraes area were initiated at ~112 Ma (Tulloch et al. 2009; Craw 2010), after cessation of mineralisation in the Hyde-Macraes Shear Zone. Steeper gold-bearing normal faults in the upper greenschist facies core of the schist belt, including the Macraes area (Fig. 2.3a, c), formed in a second pulse of gold mineralisation in the middle to Late Cretaceous (as young as ~100 Ma; Fig. 2.4b, Mortensen et al. 2010). These faults are entirely brittle extensional structures, and are genetically unrelated to the hydrothermal system of the much older Hyde-Macraes Shear Zone (Fig. 2.4a).

The Early Cretaceous gold mineralisation at Macraes was coeval with formation of a regional scale swarm of extensional quartz veins in the Glenorchy area (Fig. 2.1a; Mortensen et al. 2010). Some of these veins fill normal faults and have been mineralised, primarily with scheelite and minor gold (Hay and Craw 1993; Begbie and Sibson 2006). Host rocks are lower greenschist facies and

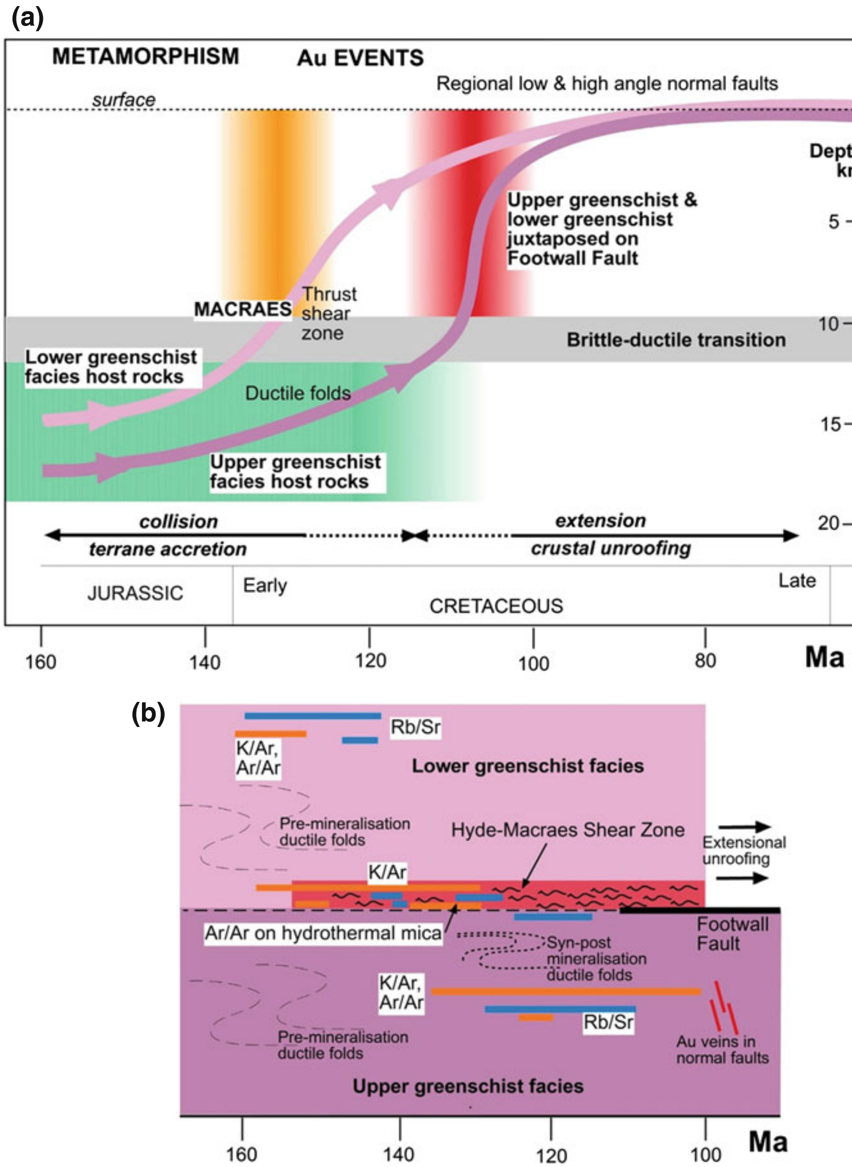

Fig. 2.4 Schematic representations of relative timing of geological events and orogenic gold mineralisation in the Otago Schist belt (modified from Mortensen et al. 2010). **a** The early pulse of mineralisation was associated with the latter stages of greenschist facies metamorphism, and the later stage of mineralisation was associated with regional extension The Macraes deposit formed during differential uplift of the lower and upper greenschist facies rocks. **b** Summary of geochronology associated with the Hyde-Macraes Shear Zone and the relative ages of various structures in the surrounding rocks (from Adams and Graham 1997; Craw 2002; Gray and Foster 2004; Mortensen et al. 2010)

sub-greenschists facies Caples Terrane schists that are broadly similar to those at Macraes. Mineralisation was a late metamorphic process, as at Macraes, but vein emplacement occurred at a higher structural level above the brittle-ductile transition.

2.6 Cenozoic Geological History of Macraes Area

Tectonic extension in the Macraes area continued through the Early Cenozoic, resulting in subsidence and erosion to a low relief land mass in the area. Numerous normal faults formed an orthogonal grid of northwest and northeast striking structures that disrupted the basement structures (Fig. 2.1). In particular, a set of northeast striking structures cut across the Hyde-Macraes Shear Zone, locally offsetting it on a scale of tens to hundreds of metres (Fig. 2.5a, b). These cross-faults may have been partly controlled by pre-existing structures in the shear zone itself.

A thin veneer of fluvial sediments accumulated locally, primarily in faulted depressions. Some of these sediments contained placer gold derived from erosion of orogenic deposits in the basement, possibly including the Macraes deposit. Groundwater-driven alteration of the basement rocks underlying the sediments resulted in a clay-altered and variably oxidised zone that extended up to 100 m below the basal sediment unconformity. This altered zone was readily eroded as on-going fault-related deformation exposed the basement on fault scarps. Quartz-rich sediments and placer gold were progressively recycled into younger deposits. Remnants of quartz-rich Eocene fluvial sediments are still preserved near the Macraes mine, and represent the end result of recycling processes that started in the middle Cretaceous (Craw 2010).

The groundwater-driven basement alteration beneath the sedimentary veneer caused oxidation and localised supergene enrichment of gold in orogenic deposits in the basement, including the Macraes deposit (Craw et al. 2015). The supergene gold has coarser particle size (Fig. 2.5c) than the primary hydrothermal gold at Macraes, which is typically micron scale particles enclosed in sulphide minerals. The supergene gold is also highly irregular in shape, and is distinctly different from the flakes of placer gold that have been recycled from older sediments (Fig. 2.5c).

Tectonic and topographic rejuvenation of the Macraes area in the Late Cenozoic occurred mainly via reactivation of the pre-existing normal faults, including the cross-faults that cut the Hyde-Macraes Shear Zone. These faults were reactivated as reverse faults, again with offsets on a scale of tens to hundreds of metres, including the prominent Macraes Fault (Fig. 2.5a, b). Alkaline basaltic volcanism accompanied the onset of late Cenozoic rejuvenation of the area, mainly in the early Miocene. Lava flows associated with this volcanism contribute to the thin veneer of young cover rocks, and their relative competence have protected the veneer from erosion in places. Some open pit mining has cut through the volcanic veneer to mineralised rocks below.

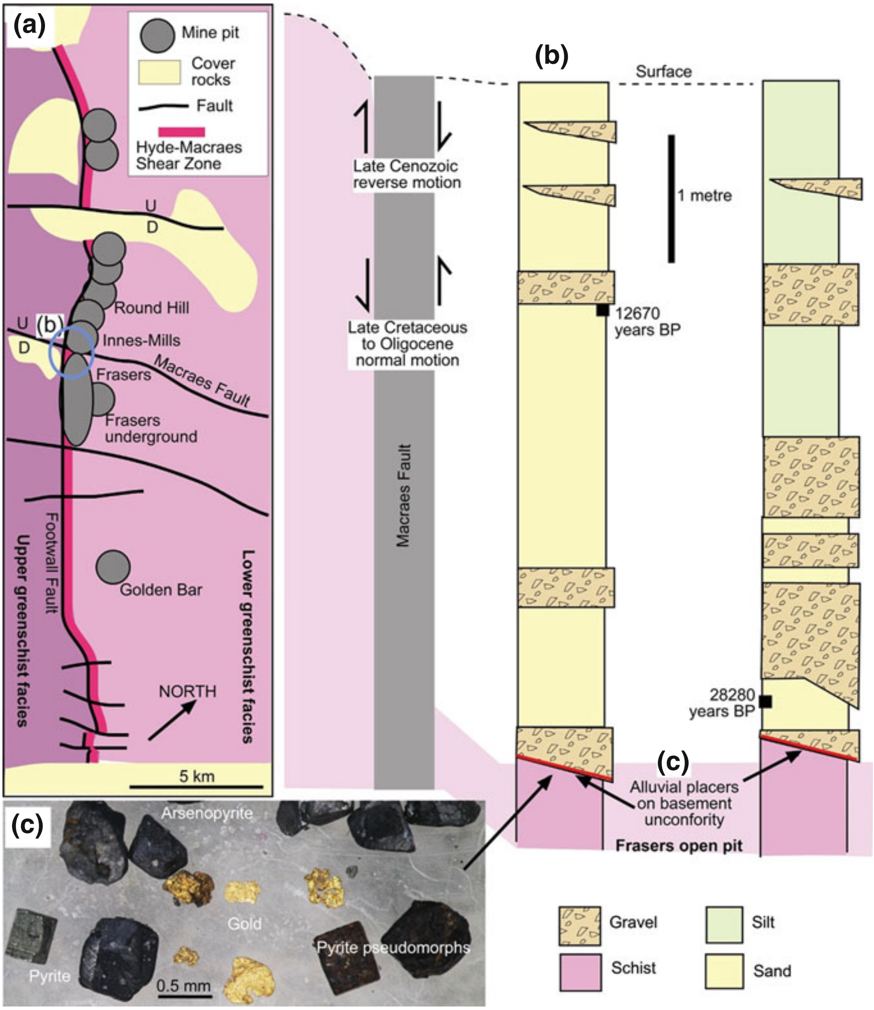

Fig. 2.5 Cross-faults cutting the Hyde-Macraes Shear Zone. **a** Sketch map showing the principal cross-faults, including the Macraes Fault. **b** Schematic section across the Macraes Fault, with the Late Pleistocene sediments (carbon dates indicated) that were on top of Frasers Pit, on the downthrown side of the fault (modified from Craw and Chappell 1999). **c** Detrital gold, pyrite, and arsenopyrite from the base of the Late Pleistocene sediments in (**b**). Gold flake at bottom centre is recycled from Eocene placers, whereas the other irregular gold particles are of supergene origin in the Hyde-Macraes Shear Zone

Cross-fault reactivation in the Macraes area was a Late Pleistocene effect, as indicated by radiocarbon dating of sediments that were deposited on what is now the Frasers open pit (Fig. 2.5b). These sediments were locally derived, from the rising reversed fault scarp nearby, and include some supergene gold, pyrite, and arsenopyrite, and their oxidised pseudomorphs, as well as some flaky gold derived from nearby Eocene sediments. Placer gold in the Late Pleistocene sediments (Fig. 2.5b, c) was mined for a short period as Frasers open pit was being excavated in the late 1990s. Similar gold-bearing sediments on the downthrown side of the Macraes Fault were mined historically immediately to the southwest of what is now Frasers open pit (Fig. 2.5a).

2.7 Absence of Syn-mineralisation Magmatism

There is no field evidence for magmatic intrusion into the metasediments that host the Hyde-Macraes Shear Zone during the Late Jurassic to Early Cretaceous metamorphism of the Otago Schist belt. The shear zone was immediately underlain by a thick pile of upper greenschist facies rocks that were exhumed by the Footwall Fault, and there are no intrusive rocks in this higher grade core of the schist belt in the Macraes area. Further, the Aspiring Terrane underlies at least some of the upper greenschist facies schist package and this has been exhumed to deeper levels than most of the schist belt by Cenozoic uplift and erosion in the western mountains (Fig. 2.1). Even this deeper structural level has no evidence for igneous intrusion into the schist belt. Xenoliths in Miocene alkaline basalts erupted in the Macraes area consist of metamorphic and mantle rocks, but no igneous rocks from intrusions at depth.

The first evidence for post-metamorphic magmatism in the accretionary complex, in the middle Cretaceous, occurs as small remnants of silicic tuff and ignimbrite (112 Ma) associated with regional extensional structures related to the Footwall Fault (Tulloch et al. 2009) that were emplaced >20 million years after the shear zone was mineralised (Mortensen et al. 2010). Magmatism that was approximately coeval with Early Cretaceous shear zone mineralisation did occur in the Median Batholith to the west of the accretionary complex (Tulloch et al. 2009), but the nearest intrusions were >150 km away from Macraes, in entirely different tectonic setting in different terranes (Fig. 2.1).

References

Adams CJ, Graham IJ (1997) Age of metamorphism of Otago Schist in eastern Otago and determination of protoliths from initial strontium isotope characteristics: NZ J Geol Geophys 40: 275-286

Begbie MJ, Sibson RH (2006) Structural controls on the development of fault-hosted scheelite-gold mineralization in Glenorchy, northwest Otago: In Geology and Exploration of New Zealand Mineral Deposits, Christie AB, Brathwaite RL (Eds) Aust Inst Min Metall Monog 25: 291–298

Cooper AF, Ireland T (2013) Cretaceous sedimentation and metamorphism of the western Alpine Schist protoliths associated with the Pounamu Ultramafic Belt, Westland, New Zealand. NZ J Geol Geophys 56: 188-199

Craw D (2002) Geochemistry of late metamorphic hydrothermal alteration and graphitisation of host rock, Macraes gold mine, Otago Schist, New Zealand. Chem Geol 191: 257-275
Craw D (2010) Delayed accumulation of placers during exhumation of orogenic gold in southern New Zealand. Ore Geol Rev 37: 224-235
Craw D, Chappell DA (1999) Evolution and sulphide mineral occurrences of an incipient nonmarine sedimentary basin, New Zealand. Sed Geol 129: 37-50
Craw D, Windle SJ, Angus PV (1999) Gold mineralisation without quartz veins in a ductile-brittle shear zone, Macraes Mine, Otago Schist, New Zealand. Mineral Deposita 34: 382-394.
Craw D, MacKenzie DJ, Grieve P (2015) Supergene gold mobility in orogenic gold deposits, Otago Schist, New Zealand. NZ J Geol Geophys 58: 123-136
Deckert H, Ring U, Mortimer N (2002) Tectonic significance of Cretaceous bivergent extensional shear zones in the Torlesse accretionary wedge, central Otago Schist, New Zealand. NZ J Geol Geophys 45: 537-547
Gray DR, Foster DA (2004) $^{40}Ar/^{39}Ar$ thermochronologic constraints on deformation, metamorphism and cooling/exhumation of a Mesozoic accretionary wedge, Otago Schist, New Zealand. Tectonophysics 385: 181-210
Hay, R. and Craw, D. (1993). Syn-metamorphic gold mineralisation, Invincible Vein, NW Otago Schist, New Zealand. Mineral Deposita 28: 90-98
Henne A, Craw D (2012) Synmetamorphic carbon mobility and graphite enrichment in metaturbidites as a precursor to orogenic gold mineralization, Otago Schist, New Zealand. Mineral Deposita 47: 781-797
Landis CA, Campbell HJ, Begg JG, Mildenhall DC, Paterson AM, Trewick SA (2008) The Waipounamu erosion surface: Questioning the antiquity of the New Zealand land surface and terrestrial fauna and flora, GeolMag 145: 173-197
MacKenzie DJ, Craw D (2005) Structural and lithological continuity and discontinuity in the Otago Schist, Central Otago, New Zealand. NZ J Geol Geophys 48: 279-293
Mackinnon TC (1983) Origin of Torlesse and related rocks, South Island, New Zealand. Geol Soc America Bull 94: 967-985
Mortensen JK, Craw D, MacKenzie DJ, Gabites JE, Ullrich T (2010) Age and origin of orogenic gold mineralisation in the Otago Schist belt, South Island, New Zealand: Constraints from lead isotope and $^{40}Ar/^{39}Ar$ dating studies. Econ Geol 105: 777-793
Mortimer N (2000) Metamorphic discontinuities in orogenic belts: example of the garnet-biotite-albite zone in the Otago Schist, New Zealand. Int J Earth Sci 89: 295-306
Mortimer N (2004) New Zealand's geological foundations. Gondwana Res 7: 261-272
Mortimer N, Craw D, MacKenzie DJ, Mortensen J, Ring U, Pitcairn I (2016) Cretaceous tectonics and regional gold mineralisation in the Otago Schist, New Zealand. Aust Inst Min Metall Monog (in press)
Petrie BS, Craw D, Ryan CG (2005) Geological controls on refractory ore in an orogenic gold deposit, Macraes mine, New Zealand. Mineral Deposita 40: 45-58
Tulloch AJ, Ramezani J, Mortimer N, Mortensen J, van den Bogaard P, Maas R (2009) Cretaceous felsic volcanism in New Zealand and Lord Howe Rise (Zealandia) as a precursor to final Gondwana breakup. Geol Soc London Special Paper 321: 89-118

Chapter 3
Structure and Lithology

3.1 Large Scale Structure

The Hyde-Macraes Shear Zone is several hundred metres thick, although the most-mineralised part is in the lower portions of the zone (Fig. 3.1a, b). In this lower portion, the uppermost well-mineralised shear is called the Hangingwall Shear in the various excavations that have been developed (Fig. 3.1a, b). However, there are scattered historic mine sites structurally above this Hangingwall Shear, and deep drilling from near these sites has intersected some weakly mineralised zones. One satellite pit for the modern mine, the Golden Bar open pit, was developed in the uppermost part of the shear zone where some historic underground mining had occurred. Despite the extensive mining and exploration of the area, the uppermost limit of shear-hosted hydrothermal alteration and mineralisation is poorly defined.

There is a distinct structural and lithological contrast between the lower greenschist facies rocks that host the Hyde-Macraes Shear Zone, and the upper greenschist facies rocks that now structurally underlie the shear zone across the post-mineralisation Footwall Fault (Fig. 3.1a–e). The lower greenschist facies rocks have chlorite zone mineralogy dominated by quartz, albite, muscovite and chlorite, and metamorphic grain sizes are typically <0.1 mm. Syn-metamorphic ductile folds that were formed throughout the schist belt during Jurassic foliation development have been overprinted by more localised folds and shears associated with the Hyde-Macraes Shear Zone (Fig. 3.1d, e).

In contrast to the lower greenschist facies rocks, the underlying upper greenschist facies rocks are relatively coarse-grained (0.1–0.3 mm) and some rocks have almandine garnets and/or biotite. Jurassic syn-metamorphic ductile folds and composite metamorphic foliation, of equivalent generations to those in the lower grade rocks, have been overprinted by a younger phase of ductile folds with a weak fold axial surface cleavage (Fig. 3.1c). These latter ductile folds formed at essentially the same time as, or may even post-date, the syn-mineralisation folds and shears of the structurally overlying Hyde-Macraes Shear Zone (Fig. 3.1c–e).

D. Craw and D. MacKenzie, *Macraes Orogenic Gold Deposit (New Zealand)*,
SpringerBriefs in World Mineral Deposits, DOI 10.1007/978-3-319-35158-2_3

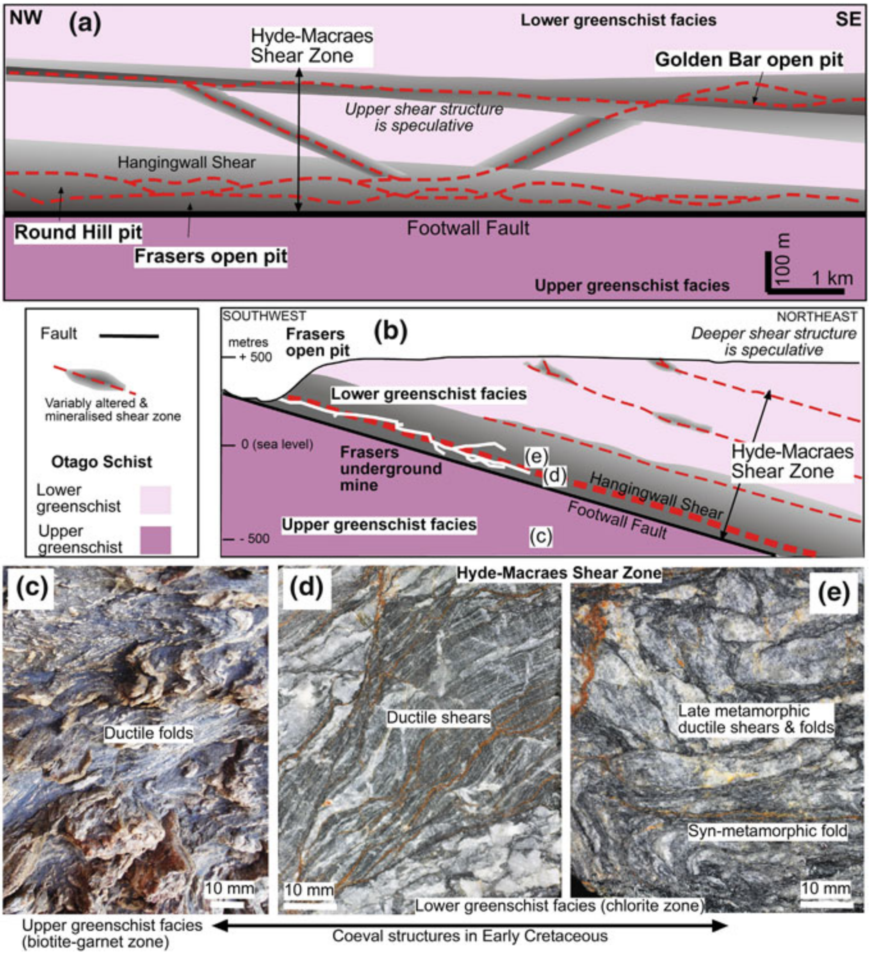

Fig. 3.1 Large-scale structure of the Hyde-Macraes Shear Zone and adjacent rocks (partly modified from Jones et al. 2007). **a** Schematic long section along the strike of the shear zone, showing the inferred thickness and variable shear development above the younger Footwall Fault, and the prominent Hangingwall Shear structure within the shear zone. **b** Cross section perpendicular to section in (**a**). **c–e** Typical deformation structures formed at the same time during shear zone development below the shear zone in higher grade rocks (**c**), within the Hangingwall Shear (**d**) and at the top of the Hangingwall Shear (**e**)

3.2 Unmineralised Rock Types

Unmineralised rocks all have the same lower greenschist facies mineral assemblage, but the proportions of these minerals vary widely, reflecting primary lithological variations (Fig. 3.2a–d). These primary lithological variations are dominated by original sedimentary grain size variations, between sandstone (greywacke) and

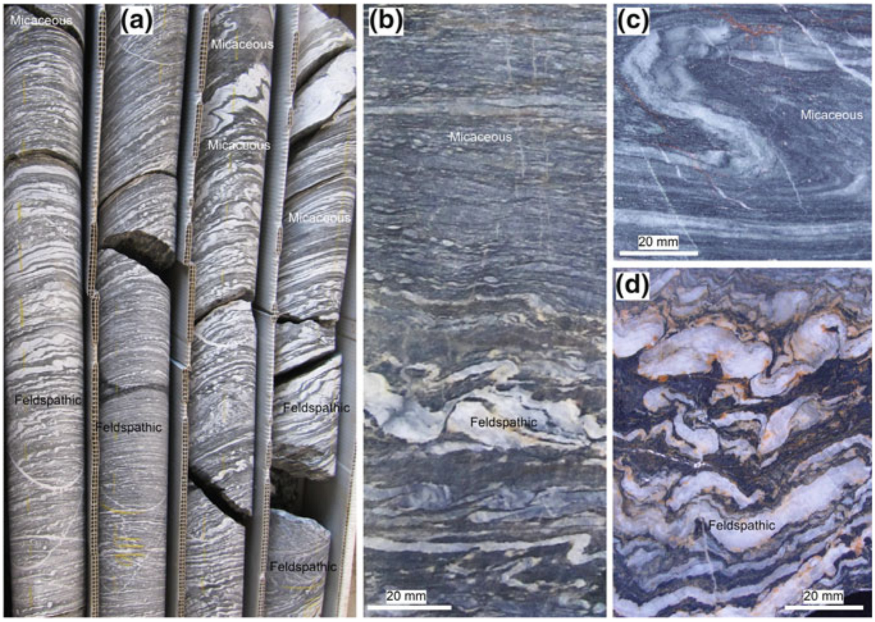

Fig. 3.2 Unmineralised lower greenschist facies schists above the Hangingwall Shear, showing two principal lithological end-members: micaceous and feldspathic schists. **a** Typical core view of interlayering of different schist types. **b** Boundary between two schist types. **c** Micaceous schist with a synmetamorphic (pre-mineralisation) fold. **d** Feldspathic schist with synmetamorphic (pre-mineralisation) folds

argillite (Fig. 2.2). However, subsequent metamorphic segregation, foliation development, and ductile folding have accentuated some aspects of this primary variation and obscured others, leading to complex interlayering of rock types at all scales from centimetres to tens of metres.

There are two principal end-member schist rock types recognisable at hand specimen scale, although most rocks at the outcrop scale consist of interlayered combinations of these schist types (Fig. 3.2a–d; Table 3.1). Fissile micaceous schists (Fig. 3.2a–c) are structurally relatively incompetent and form poor outcrops. These rocks are dominated by the micaceous metamorphic fabric, which anastomoses around quartz-albite lenses. More massive schist rock masses and outcrops are dominated by feldspathic schists that have a smaller mica component (Table 3.1). Feldspathic schists, some of which contain only minor quartz, have abundant quartz-albite segregations that form a rigid network through the rock and dominate the rock fabric (Fig. 3.2a, b, d). These feldspathic rocks have behaved in a structurally competent manner compared to the micaceous schists during syn-mineralisation deformation in and near the Hyde-Macraes Shear Zone.

A rare conglomeratic schist occurred in an unmineralised massive pod within the Round Hill open pit, and this rock provides good illustration of the metamorphic

Table 3.1 Summary comparison of lithologic and structural features of end-member rock types in Frasers open pit (partly modified from Petrie and Craw 2005)

	Feldspathic schist	Micaceous schist	Black sheared rock
Dominant minerals	Quartz + albite (>50 %); subordinate muscovite, chlorite	Muscovite (>30 %), chlorite; subordinate quartz + albite	Muscovite (>30 %) with graphite (∼1 %); subordinate quartz; minor albite, chlorite
Metamorphic grain size (mm)	0.1	0.1	0.1
Metamorphic structural elements	Pronounced quartz/albite and mica laminae	Weak quartz/albite and mica laminae	Weak quartz/albite and mica laminae
	Weak-moderate foliation	Strong composite foliation	Strong composite foliation
	Prominent quartz rodding lineation		
Late metamorphic structural elements	Open to tight folds	Tight folds	Well-defined muscovite and graphitic shear fabric
	Weak cleavage from recrystallised muscovite	Well-defined cleavage from recrystallised muscovite	Variably rotated porphyroclasts of disrupted quartzofeldspathic laminae
	Near-pervasive subtle alteration	Near-pervasive subtle alteration	Sericitised albite; graphitisation of shear fabric
Mineralised rocks	Mineralised microshears; abundant silicification	Sulfide replacement of silicates; common silicification	Sulphide replacement of silicates; minor silicification
	Cataclastic overprint	Cataclastic overprint	Cataclastic overprint; slickensided shears

structural features of the lower greenschist facies schists in general (Fig. 3.3). The rock is made up of deformed feldspathic clasts on the 1–5 cm scale that are still recognisable despite the thorough metamorphic recrystallisation. Original clastic textures have been fully recrystallised in all other schists. In this conglomerate, the clasts are most apparent in a face cut perpendicular to the strong metamorphic stretching lineation (Fig. 3.3a). Clasts have been largely obscured by the stretching, and are difficult to discern in the stretching direction (Fig. 3.3b) and on the foliation surface. However, some distinctive green fuchsite-bearing clasts are recognisable on the foliation surface despite deformation parallel to the pervasive metamorphic foliation (Fig. 3.3c). The Cr enrichment associated with these rare fuchsite clasts is of geochemical significance because there has apparently been Cr mobility during hydrothermal alteration and mineralisation in the shear zone (see Chap. 6).

An additional distinctive end-member rock type, black sheared rock (Fig. 3.4; Table 3.1), occurs only within the Hyde-Macraes Shear Zone. This rock is

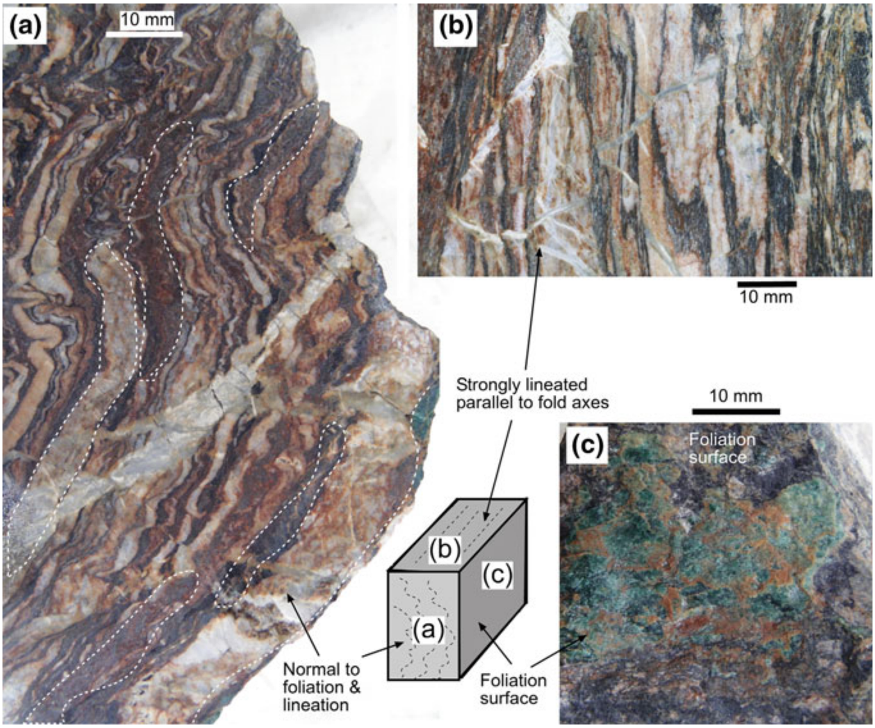

Fig. 3.3 A rare conglomeratic feldspathic schist (unmineralised) interlayered with variably mineralised rocks within the shear zone (Craw and Angus 1993). Inset shows orientation of views in relation to principal structures. **a** Face cut perpendicular to syn-metamorphic fold axes and a prominent rodding lineation. Some deformed conglomerate clasts, mostly feldspathic, are indicated with *dotted outlines*. Part of a fuchsite clast is on the edge (*right*). **b** View of lineated surface perpendicular to fold axes. **c** View of foliation surface with a fuchsite-bearing clast smeared parallel to the foliation

commonly, but not always, mineralised and occurs interlayered with the other schist types. The rock is invariably sheared to some extent, so that the shear fabric generally dominates over metamorphic foliation (Fig. 3.4). The most prominent feature of this rock is its elevated graphite content, which locally exceeds 3 %. The graphite occurs interspersed with muscovite, which is the dominant mineral (Fig. 3.4d). Historically, the graphite was assumed to be of primary sedimentary (organic) origin and the black rock reflected an original stratigraphic feature (e.g., McKeag et al. 1989). However, subsequent research has shown that this graphite was introduced during late metamorphic hydrothermal activity into what was typical micaceous schist. This topic is outlined in more detail in Chap. 7. The black sheared rock is an important feature of the shear zone for structural and economic reasons, and various physical and mineralogical aspects of this rock are a recurring theme throughout the following descriptions of the Macraes gold deposit.

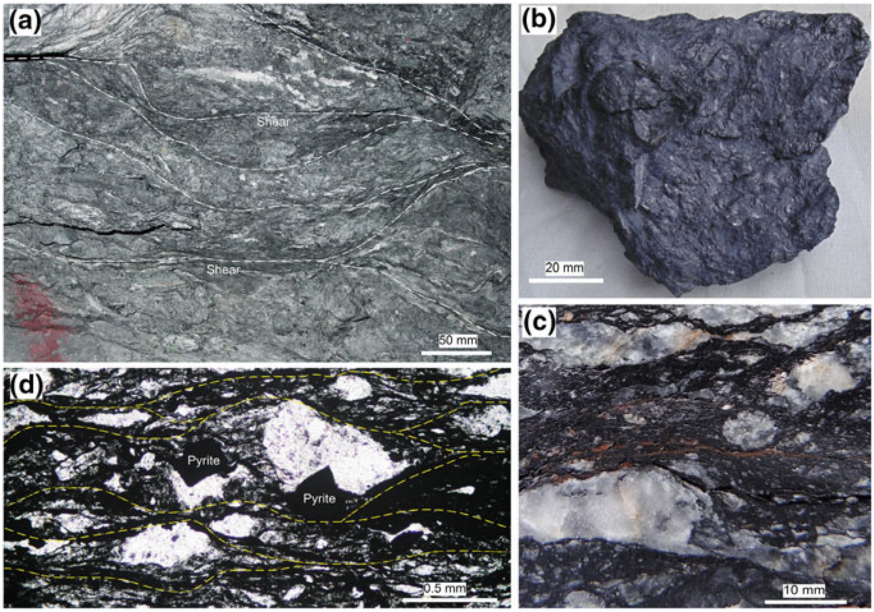

Fig. 3.4 Black sheared rock in the Hyde-Macraes Shear Zone. **a** Outcrop in Frasers underground mine. Principal shears are dashed. **b** Hand specimen view. Shiny patches are slickensided microshear surfaces. **c** Cut face of a hand specimen. Horizontal fabric is dominated by shears that have obscured the metamorphic foliation, and anastomoses around white quartz-rich lenses. **d** Thin section view (plane polarised light). Principal microshears through the predominant muscovite matrix are *dashed*. These microshears anastomose around disrupted quartz-rich porphyroclasts (*white*). Graphite (*black*) is concentrated in microshears, and mineralisation-related pyrite porphyroblasts (*black, labelled*) have replaced silicates in and adjacent to microshears

3.3 Mineralised Rock Types

Mineralised rocks, their structures, their minerals, their paragenesis, and their chemical compositions are discussed in detail in following chapters. However the key features of mineralised rocks relevant to lithology are introduced here in relation to the unmineralised rocks described in the previous section. Mineralisation in the Hyde-Macraes Shear Zone occurred by two distinctly different processes, leading to different types of mineralised rocks. The dominant mineralisation process involved replacement of original silicate minerals by new hydrothermal minerals, with little or no volume change. The other principal process, vein emplacement, involved infilling of open cavities in the rock by hydrothermal minerals. Vein emplacement was volumetrically minor in the shear zone, but is economically significant because most of the highest gold grades occur in veins.

Replacement reactions were structurally controlled, and those structures were in turn controlled by the original schist rock types described in the previous section. Micaceous schists and associated black sheared rock were sheared parallel to the metamorphic foliation during formation of the Hyde-Macraes Shear Zone, and hydrothermally-driven replacement occurred along those shears. Sulphide minerals pyrite and arsenopyrite have replaced silicates to form porphyroblasts that grew across the metamorphic foliation and early shear fabric (Figs. 3.4d and 3.5a). Gold is associated with these sulphides. In addition, some albite was replaced by hydrothermal muscovite, increasing the muscovite content of the rock and facilitating further shear development and associated sulphide replacement reactions.

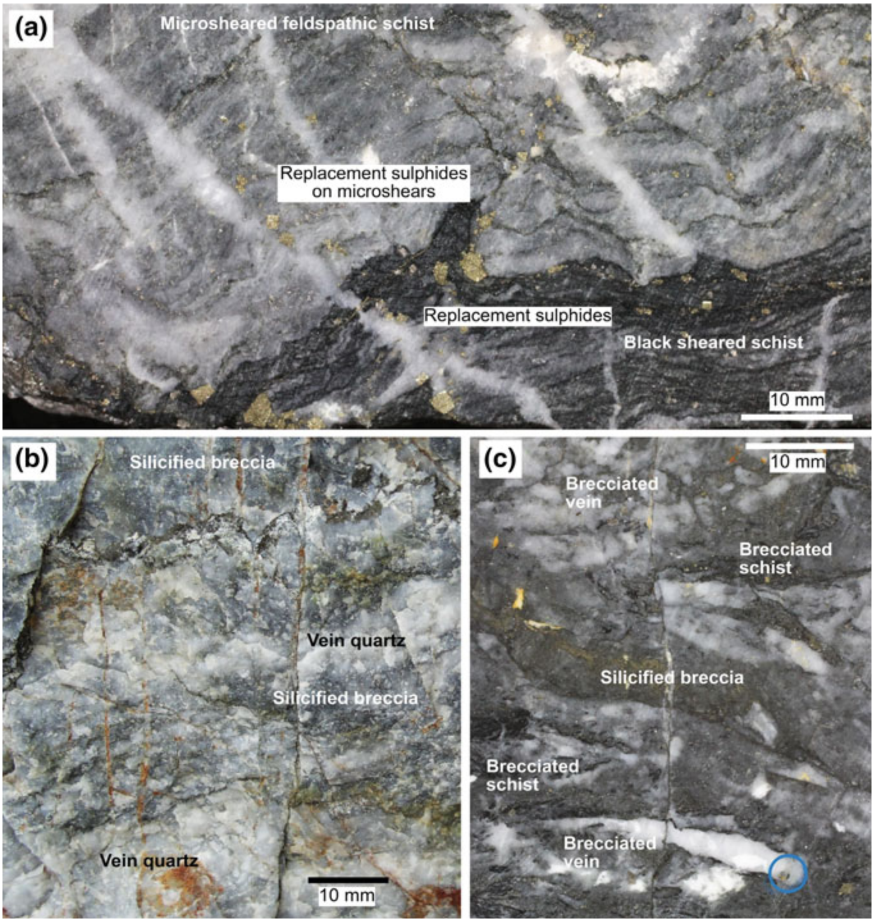

Fig. 3.5 Typical mineralised rock types. **a** Replacement mineralisation, with sulphides (*yellow*) replacing silicates along shears in black sheared rock (*bottom*) and microshears in partially silicified felsdpathic schist (*top*). **b** Vein mineralisation, with diffuse boundaries between vein quartz (*white*) and silicified and veined breccia (*grey*). **c** Mineralised breccia with clasts of schist (*dark*) and vein quartz (*white*). Grey matrix is silicified breccia. A grain of visible gold is at right end of large quartz clast at bottom (*circled*)

Feldspathic schists have behaved differently from micaceous schists during deformation and associated replacement mineralisation. The greater competence of feldspathic schists resulted in irregular networks of spaced microshears that cut across the rocks, rather than just following the metamorphic foliation as in micaceous schists. Replacement sulphides have formed in and adjacent to these microshears, and are dispersed throughout the rock (Fig. 3.5a). Addition of hydrothermal quartz as a replacement mineral (silicification) was widespread through feldspathic rocks, controlled by the network of microshears. Similar silicification has affected some micaceous schists, but to a lesser extent than the feldspathic schists.

Vein formation was dominated by introduction of quartz into open structures. Most veins are thin and discontinuous on the metre scale, and individual veins longer than 20 m are rare. Most vein formation involved some brecciation of adjacent host rock, and quartz-cemented breccias are an essential part of the structure of veins (Fig. 3.5b, c). Breccias are variably silicified, with silicification commonly so advanced that original host rock silicates have been largely replaced, leaving diffuse grey zones in the vein quartz (Fig. 3.5b). Likewise, the immediate host rocks to veins are commonly silicified so that boundaries are diffuse. Silicification has greatly enhanced the competence of some rocks, so that they responded structurally in a similar manner to massive feldspathic schists during progressive mineralisation-related deformation in the shear zone.

3.4 Structure Within the Hyde-Macraes Shear Zone

The metamorphic foliation is generally parallel or sub-parallel to the lithologic variations throughout most of the lower greenschist facies schists within and above the Hyde-Macraes Shear Zone (Fig. 3.2). Relict syn-metamorphic fold hinges locally distort the rock fabric occur on the 10–100 m scale, although most folds are rootless with strongly attenuated limbs that are parallel to foliation. Apart from these relict fold hinges, foliation and lithological variations are broadly planar and shallow-dipping in the upper parts of the Hyde-Macraes Shear Zone and in the overlying schist (Fig. 3.6a). These planar rocks are variably disrupted structurally down-section by open to tight folding and shears associated with the shear zone (Fig. 3.6a–d), although most of these disrupted rocks are unmineralised or only incipiently mineralised.

The lithological variations outlined above played an important role in controlling the geometry of the shear zone, at all scales from centimetres to tens of metres. In particular, micaceous schist horizons have controlled the location of individual shears, and these anastomose around more massive rock packets that are typically dominated by feldspathic schists. The shears had a thrust sense of motion, and duplex thrust systems developed locally, with stacking of rock packets along several shears (Teagle et al. 1990; Petrie and Craw 2005; Jones et al. 2007). Within

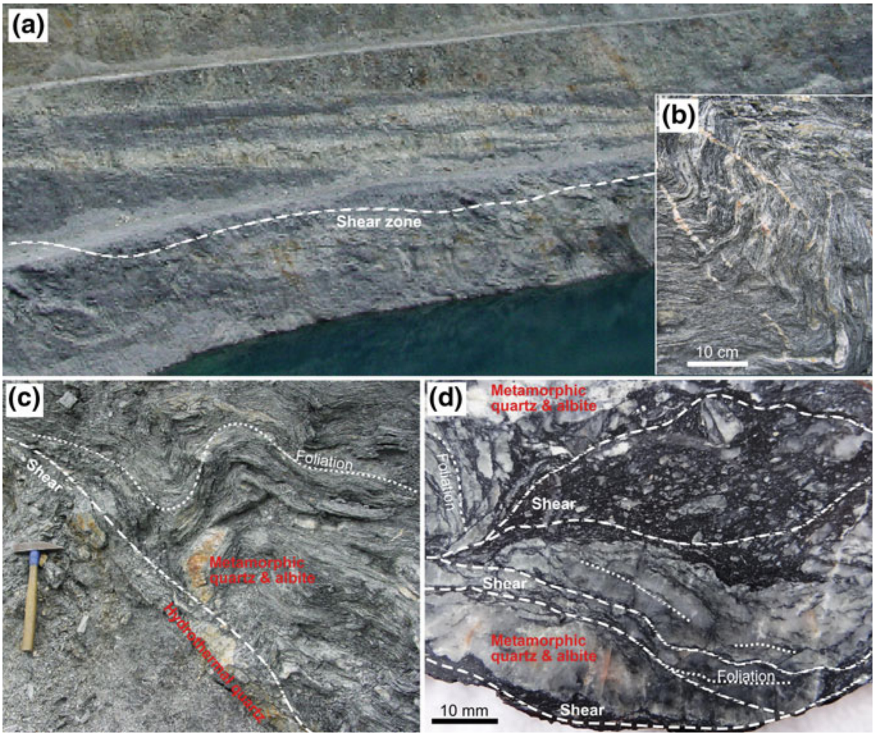

Fig. 3.6 Structure at the top of the Hyde-Macraes Shear Zone, as exposed in Golden Bar open pit. Dashed lines show shear surfaces that disrupt the sub-parallel foliation (*dotted*). **a** Largely planar foliation, with foliation-parallel lithological variations, overlie the uppermost mineralised shear (*dashed line*). **b** Outcrop of micaceous schist with shear-related folds immediately above the shear zone. **c** Outcrop of folds and sheared rocks at the uppermost shear. **d** Mineralised black sheared rock within the shear zone

these duplex stacks, on-going thrusting caused shears to develop in more massive rocks as well, and slices of these were incorporated into the duplexes as well.

The uppermost duplex system in the shear zone occurs in the Golden Bar pit (Fig. 3.7a–c). This zone is only 10–20 m thick, and is focused on micaceous schists. Some of these micaceous schists have graphite addition, to form black sheared rocks (Fig. 3.6d). The uppermost duplex zone is part of larger-scale thrust stacking complex that has at its base a well-defined shear containing abundant black sheared rock ~50 m below the duplex (Fig. 3.7a). Between these two prominent foliation-parallel shears, several flat quartz veins have filled horizontal fractures. These quartz veins emanate from the base of the upper duplex zone and extend to the lower black shear (Fig. 3.7a, c).

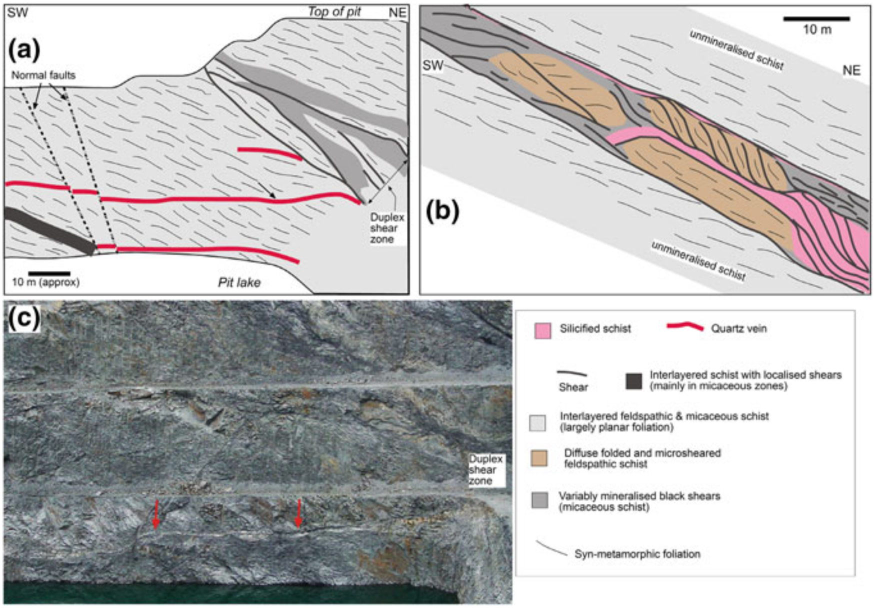

Fig. 3.7 Structure of the mineralised rocks at Golden Bar pit at the top of the Hyde-Macraes Shear Zone (modified from Jones et al. 2007). **a** Principal lithological variations and structures. **b** Detailed view of a duplex shear zone in a. **c** Photograph of pit wall in a, with duplex shear at *right*, and a large flat quartz vein indicated with *arrows*

3.5 Hangingwall Shear

Deeper within the Hyde-Macraes Shear Zone, the feature called the Hangingwall Shear in many of the mine pits has many of the same structural attributes as the duplex system in the Golden Bar pit, but has much larger scale. This shear and subordinate shears structurally below it form a duplex thrust system that has been closely stacked in packages up to 150 m thick in the central part of the shear zone. Above this complex thrusted package, the schists are broadly planar in a similar manner to those above the upper duplex at Golden bar pit. However, some zones of structurally-controlled mineralised rocks extend above the Hangingwall Shear, and these have been mined in places although most are relatively low grade.

The Hangingwall Shear consists of variable amounts of black sheared rocks which are generally strongly mineralised. Most mining has focused on this shear and associated rocks below it (Fig. 3.8a, b). Individual shears are discontinuous along strike, and the name "Hangingwall Shear" has been applied to the uppermost mineralised shear within each pit, based on the presence of economic gold grades. There is generally not direct continuity of this uppermost shear between pits, and typically one well-defined mineralised shear dies out laterally and another takes its place structurally higher or lower, on a scale of ~10–20 m. Nevertheless, the

Fig. 3.8 The Hangingwall Shear (black sheared rocks, *arrowed*) in the lower, most mineralised, part of the Hyde-Macraes Shear Zone in Frasers open pit. Other colour variations in the pit walls reflect lithological variations. **a** Shear dips down the northwest wall of the pit. Frasers underground mine portal is at centre left. **b** Closer view of the area indicated in (**a**), with the Hangingwall Shear bending around pods of massive (mainly feldspathic) unmineralised schist

Hangingwall Shear is a useful practical concept for mining purposes, as a well-mineralised upper structure always occurs near the top of the structurally complex thrust zone.

Even within individual pits, the Hangingwall Shear is a complex structure, with lateral variations strongly affected by host schist lithology. Massive schist pods on the 10–50 m scale have caused formation of undulations in the Hangingwall Shear, and led to thrust stacking with several subordinate shears in the underlying rock packets. The schists above the Hangingwall Shear are dominated by metamorphic foliation, with some syn-metamorphic fold hinges. Below the shear, most rocks have some degree of shear-related fabric, which dominates in black sheared rock and some micaceous schists, and affects some feldspathic rock types with microshears, especially on the margins of massive pods.

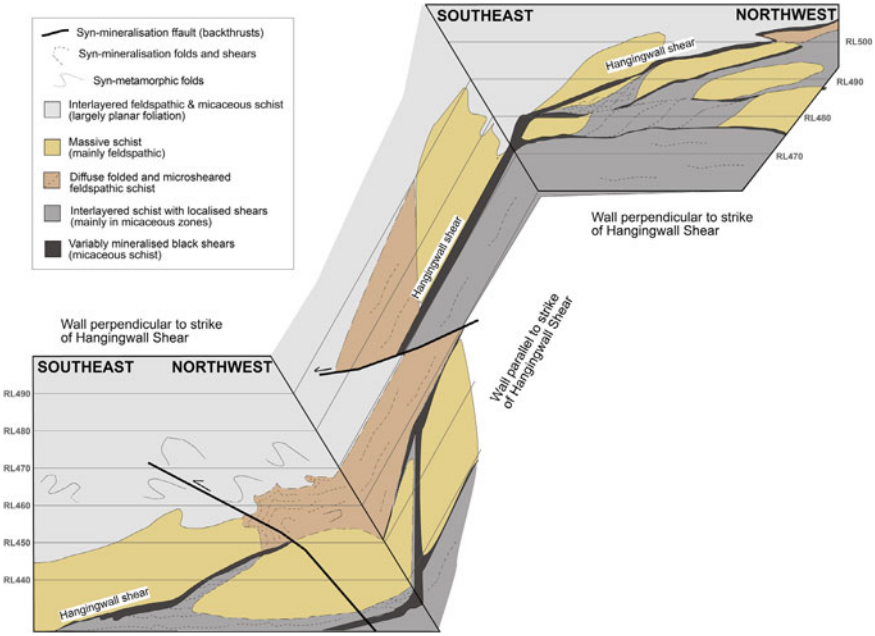

Fig. 3.9 Composite section of Frasers open pit walls showing the structural and lithological variations in the vicinity of the Hangingwall Shear (modified from Petrie and Craw 2005). Mineralisation was focused in and near the black sheared rocks of the Hangingwall Shear and the stacked and anastomosing shears beneath it. RL is height above sea level

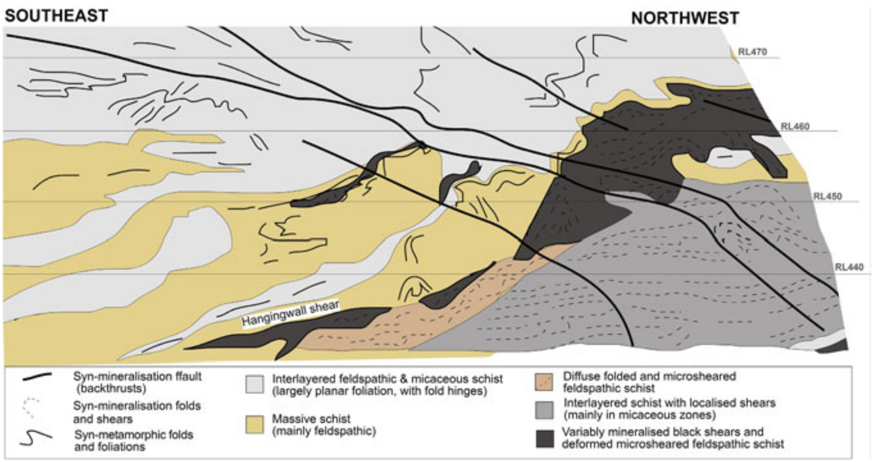

Fig. 3.10 Detailed structural and lithological variations in a Frasers open pit wall (modified from sketch by B Petrie; Petrie and Craw 2005), where mineralisation was focused on the Hangingwall Shear and the immediately underlying rocks. Hangingwall Shear locally changes into a complex folded zone that involves micaceous schist, black sheared rock, and microsheared feldspathic schist up-dip to right

The Hangingwall Shear and surrounding rocks in the parts of Frasers open pit illustrate the above features (Figs. 3.9 and 3.10). The Hangingwall Shear is a broadly continuous shear structure in this pit, but the thickness of black sheared rock varies along strike and down dip. The Hangingwall Shear incorporates differing proportions of microsheared feldspathic rocks as well as micaceous schists along its length (Figs. 3.9 and 3.10). Mineralisation along all these sections of the Hangingwall Shear occurred via replacement reactions in these different rock types (as in Fig. 3.5), and quartz veins were almost completely absent.

References

Craw D, Angus PV (1993) Mafic/ultramafic clasts in deformed biotite zone metaconglomerate, Macraes mine, Haast Schist, New Zealand. NZ J Geol Geophys 36: 395-398.

Jones P, Craw D, Norris RJ (2007) Golden Bar gold deposit as an extension of the Hyde-Macraes Shear Zone, east Otago, New Zealand. NZ J Geol Geophys 50: 271-281

McKeag SA, Craw D, Norris RJ (1989) Origin and deposition of a graphitic schist-hosted metamorphogenic Au-W deposit, Macraes, East Otago, New Zealand. Mineral Deposita 24: 124-131

Petrie BS, Craw D (2005) Lithological controls on structural evolution of mineralised schist, Macraes gold mine, Otago, New Zealand. NZ J Geol Geophys 48: 435-446

Teagle DAH, Norris RJ, Craw D (1990) Structural controls on gold-bearing quartz mineralisation in a duplex thrust system, Hyde-Macraes Shear Zone, Otago Schist, New Zealand. Econ Geol 85: 1711-1719

Chapter 4
Mineralised Structures

4.1 Mineralised Flat Veins

Veins containing gold and/or scheelite were the principal target of historical mining in the Hyde-Macraes Shear Zone (Chap. 1). Veins are still an important component of the ore in the modern mine, as the highest gold grades typically occur in veins, and almost all of the scheelite occurs in veins. There are two principal vein structures in the mineralised rocks: flat veins, and laminated veins. These were formed coevally and have similar mineralogy and some similar textures (Chap. 5). However, these two types of veins formed under different local stress regimes, have distinctly different geometry, and are typically found in different parts of the shear zone.

Flat veins are either horizontal or gently dipping (Fig. 4.1), typically <20° to the northeast, and lie sub-parallel to the shear zone as a whole. The veins have formed parallel or sub-parallel to the metamorphic foliation and the syn-mineralisation shears that have been controlled by that foliation, and veins commonly follow shears as they anastomose around more competent rock types (Chap. 3). Most of the veins occur within shears, and they are commonly called “shear veins”. However, some of these flat veins extend beyond shears into less-mineralised rocks between shears (Fig. 4.2). Initial formation of veins involved vertical extension of the rock mass, consistent with general thrust-related stress orientations (Fig. 4.2). However, laterally continuous extensional flat veins, such as those in Fig. 4.2a–c, are rare, and most flat veins are traceable for less than 20 m.

The extensional sites in which the flat veins have formed have been filled mainly with quartz, commonly with several sub-parallel vein generations (Fig. 4.1a). Most veins contain brecciated fragments of host rocks, commonly combined with brecciated fragments of earlier-formed veins, and these breccias have been cemented by quartz to form veined rock masses 0.5–5 m thick (Figs. 4.1 and 4.2). Hydrothermal replacement reactions have caused widespread silicification of breccias within the veins, and silicification of some adjacent rocks, contributing to overall vein

D. Craw and D. MacKenzie, *Macraes Orogenic Gold Deposit (New Zealand)*,
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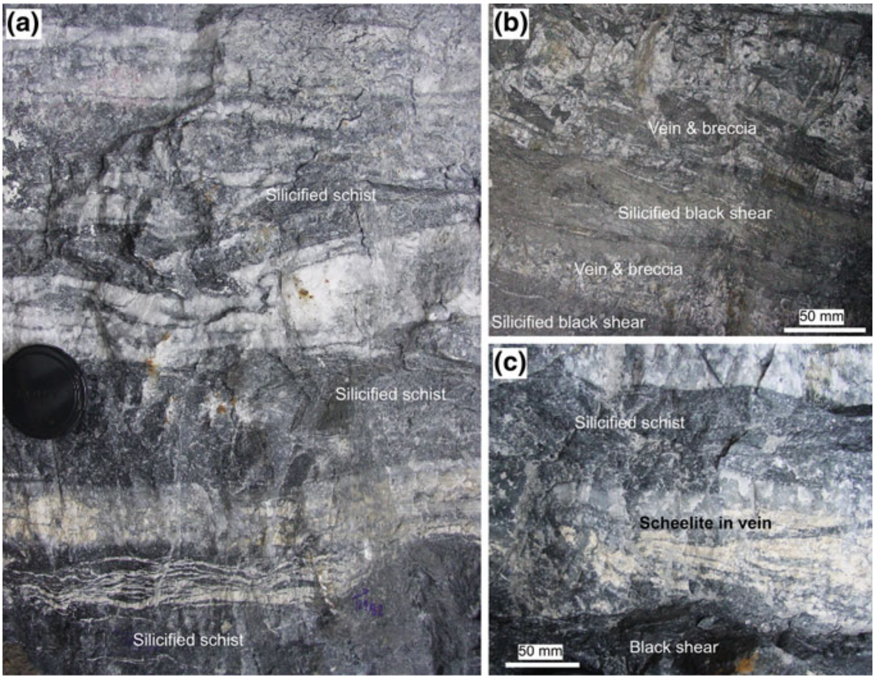

Fig. 4.1 Shear-parallel quartz vein structures in the Hyde-Macraes Shear Zone. **a** Typical near-horizontal composite vein structure, with multiple generations of veins and breccias. Lens cap is 50 mm. **b** Cemented host rock breccias emplaced into silicified rock. **c** Combination of veins and silicified breccias, surrounded by sheared micaceous schist

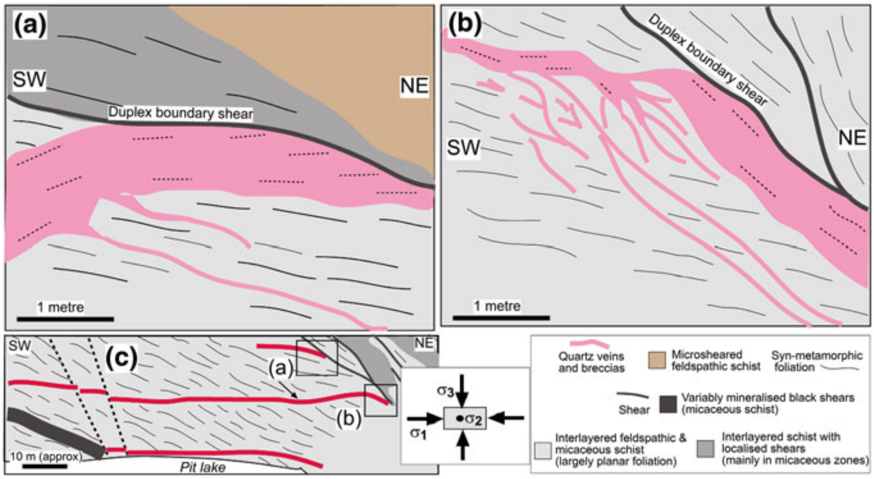

Fig. 4.2 Geometry of shear-related veins in Golden Bar open pit (modified from Jones et al. 2007). Veins emanate from shears associated with a duplex system (**a**, **b**), with which they are initially *parallel*, and extend almost *horizontally* to an underlying shear (**c**). Inferred principal stress orientations for extensional opening of flat veins is indicated

thickness (Fig. 4.1). The end result of these progressive vein mineralisation processes is a complex and rheologically competent rock mass within the shear zone, around which shearing continued to occur.

4.2 Mineralised Laminated Veins

Laminated veins have a more orderly structure than flat veins, and consist of multiple parallel laminae that have formed parallel to near-planar fracture walls (Fig. 4.3). Laminated veins cut steeply across the metamorphic foliation in host rocks, and mostly occur in host rocks that have undergone little or no shearing and only minor hydrothermal alteration. The laminated veins occur in swarms that die out laterally to scattered occurrences, but at least some laminated veins occur through most mineralised parts of the shear zone. The laminated veins are most abundant below the Hangingwall Shear, and locally extend down to the Footwall Fault where the base of the laminated vein swarms have been truncated by that fault.

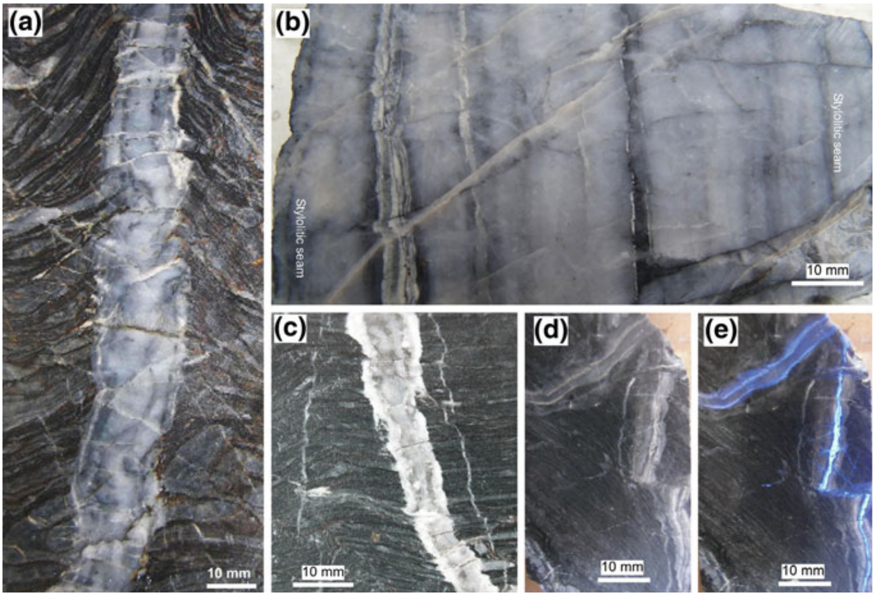

Fig. 4.3 Laminated veins that cut the host schist at a high angle. **a** Vein has been emplaced into a syn-mineralisation fold hinge. **b** Close view of laminations in a large vein. **c** Small laminated vein has two sub-parallel microveinlets on its margins. **d**, **e** Disrupted laminated veins have scheelite in some laminae (*purple* with UV light in e)

Individual laminae range from 1 to 10 mm wide, and these have accumulated to form veins that range from 10 mm to 1 m wide (Fig. 4.3). The different laminae consist of differing amounts of calcite, sulphides and scheelite, and the quartz in each lamina may have different grain sizes and textures, leading to wide variations

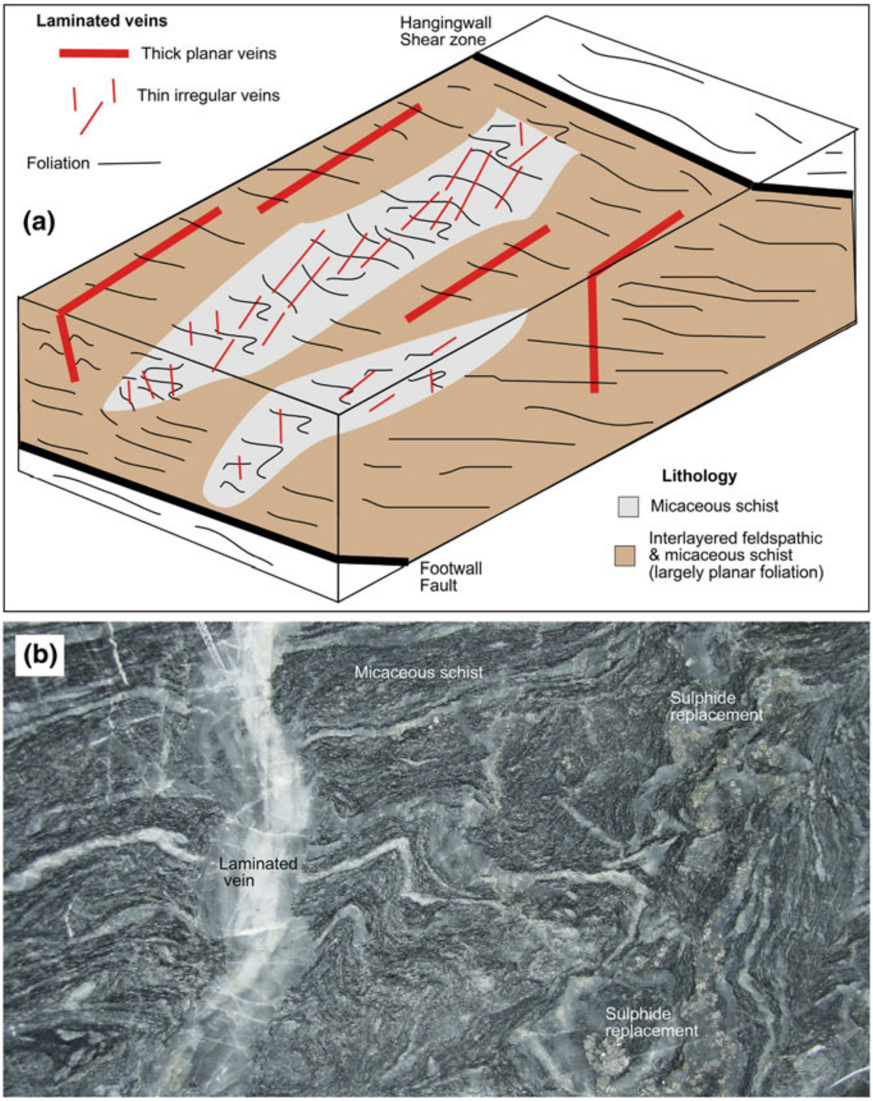

Fig. 4.4 Lithological control on emplacement of laminated veins. **a** Sketch block diagram of lithological variations and geometry of laminated veins beneath the Hangingwall Shear. **b** Irregular, thin laminated veins and associated replacement mineralisation in micaceous schist

in appearance of the laminae. Most veins are symmetrical, with distinctive laminae occurring in a similar position on either side of a central vein core (Fig. 4.3). Some darker laminae reflect zones of brecciated host rock fragments that have been extensively silicified. The rock breccia fragments, where recognisable, are typically narrow and long, parallel to the vein walls from which thin slices have apparently been peeled during opening of the hosting extensional fracture.

Some veins fill normal faults that dip 60°–80°, and some veins have been controlled by fold axial surface fractures in upright folds formed during shear zone evolution (Fig. 4.3a). Competent massive schists, especially feldspathic schists, host the largest fault-controlled veins, which are commonly planar and can be continuous for >10 m. These vein-hosting normal faults are commonly widely spaced, from 2 to 10 m apart (Fig. 4.4a) and have little or no associated alteration of their immediate host rocks. In contrast, micaceous schists host more numerous and closely spaced but smaller laminated veins (Fig. 4.4a). Many of these veins in micaceous schist are thin and relatively irregular and discontinuous, with variable amounts of silicification and sulphidation of the immediate host rocks (Fig. 4.4b).

4.3 Mineralised Shears

Mineralisation of shears was focussed primarily in black sheared rock, especially in the principal shears such as the Hangingwall Shear (Chap. 3). Mineralised shears formed at the same time as the veins described in the previous sections, and the differences in mineralisation style result directly from the different host rock types. Hence, there is commonly a close spatial relationship between mineralised shears and flat veins on the metre scale. Flat veins are almost invariably accompanied by some mineralised sheared rocks, mostly black shears (Fig. 4.1b, c). However, large volumes of variably mineralised black sheared rock occur without any significant vein formation in some parts of the shear zone (Chap. 3).

Mineralised black shears were initiated in micaceous schists, and ductile shear deformation was initially controlled by the metamorphic foliation (Fig. 4.5a). With progressive deformation, microshears cut across metamorphic quartz-albite laminae, disrupting and fragmenting these laminae to form lensoidal porphyroclasts, some of which became rotated during on-going shearing (Fig. 4.5). Porphyroblasts of hydrothermal sulphides (millimetre scale) overgrew the evolving shear fabric, but were then deformed and rotated by further shear deformation (Chap. 3; Fig. 4.5a).

Hydrothermal alteration of albite to fine grained muscovite enhanced the phyllosilicate-rich component of the rocks, and facilitated further shear development. With continuing deformation, the metamorphic fabric became almost completely overprinted by shear fabric, and locally some mylonitic shear textures developed (Fig. 4.5b). Microshears pervaded all quartz-rich parts of the rocks, which eventually became disrupted and incorporated into the black sheared rock.

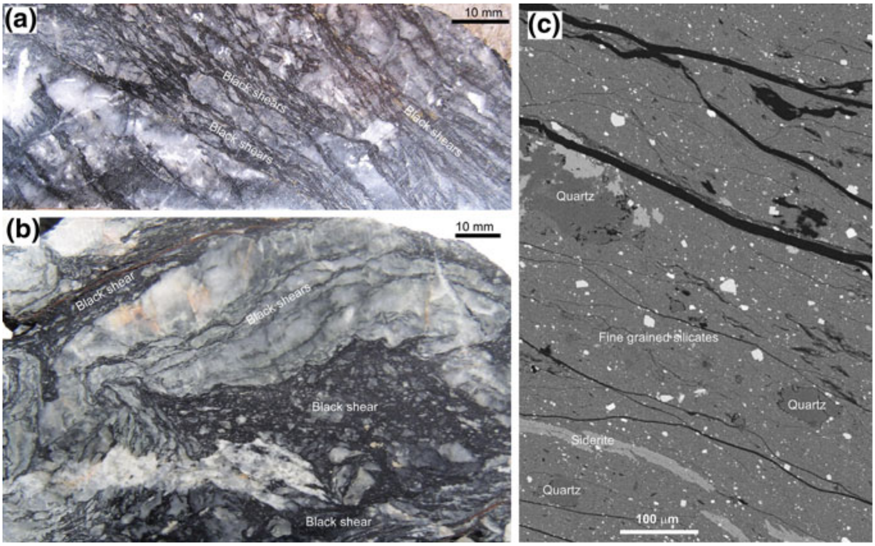

Fig. 4.5 Evolution of black sheared schist. **a** Incipient development of shears in micaceous schist. Shears are partly controlled by metamorphic foliation but anastomose around quartz-albite segregations. **b** Metamorphic foliation has been essentially obliterated, and rock is dominated by a shear fabric. Large quartz-rich metamorphic segregations (*top*) are cut by evolving anastomosing shears. Shears have evolved to mylonitic zone in centre, with lensoidal porphyroclasts of disrupted quartz-rich metamorphic segregations. **c** SEM backscatter image of fine grained mineralised mylonitic black shear. Principal microshears are defined by *black lines* (cracked and filled with mounting glue during sample preparation). Sheared silicates are *dark grey* (quartz porphyroclasts are labelled) and deformed sulphides are *white*

Ultimately, mineralised black sheared rocks developed mylonitic texture with relict porphyroclasts of quartz and sulphides floating in a matrix dominated by fine grained (micron scale) muscovite (Fig. 4.5c). Some additional hydrothermal sulphides were incorporated into the mylonitic shears, but most sulphides became irregularly shaped, cracked, and fragmented to fine grain size (Fig. 4.5c).

4.4 Syn-mineralisation Deformation of Veins

Progressive deformation of mineralised rocks has disrupted early-formed veins and deformed them with the hosting rock. Veins and silicified breccias were broken and boudinaged (Fig. 4.6a) or folded and sheared (Fig. 4.6b). Flat veins in shears, in particular, have been strongly deformed and disrupted, and fragments extended along the shear (Fig. 4.6c). Most such veins have been rotated into parallelism with

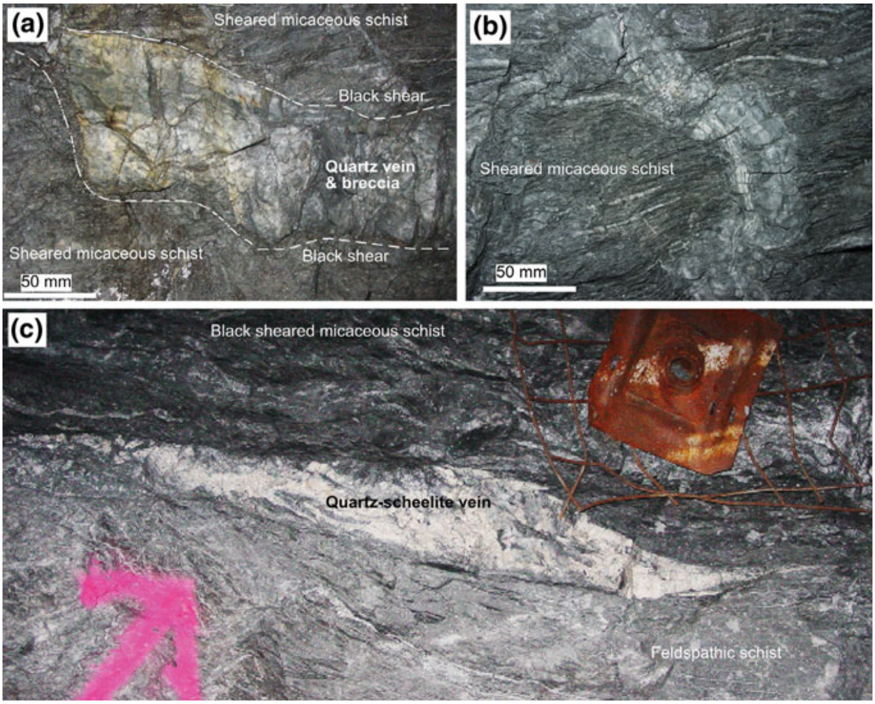

Fig. 4.6 Deformed quartz veins in the Hangingwall Shear, Frasers underground mine. **a** Flat vein in the shear zone has been broken and boudinaged, and is now surrounded by sheared micaceous schist and black sheared rock. **b** Laminated vein has been folded and offset by shears. **c** Flat vein at the boundary between micaceous and feldspathic schist has been sheared, boudinaged into a lensoidal shape, and internally brecciated

the hosting shear, irrespective of original orientations. Internally, deformed veins became sheared and brecciated, after which they were commonly re-cemented with quartz.

This ongoing deformation and re-cementation of veins led to formation of rheologically competent massive pods of quartz-rich rock on the metre to ten metre scale (Figs. 4.1 and 4.7). These pods consist of complexly interdigitated hydrothermal veins and breccias that have been repeatedly brecciated, re-cemented and silicified. The pods grew in size and complexity with progressive deformation, as adjacent rocks became brecciated, silicified, and incorporated into the siliceous masses. The siliceous pods were flanked by anastomosing shears in more micaceous schists, and deformation in these shears focused strain on to the margins of siliceous pods, where abundant microshearing has imposed a new fabric that is locally graphitic (Fig. 4.7b, c). On-going silicification extended into some sheared micaceous

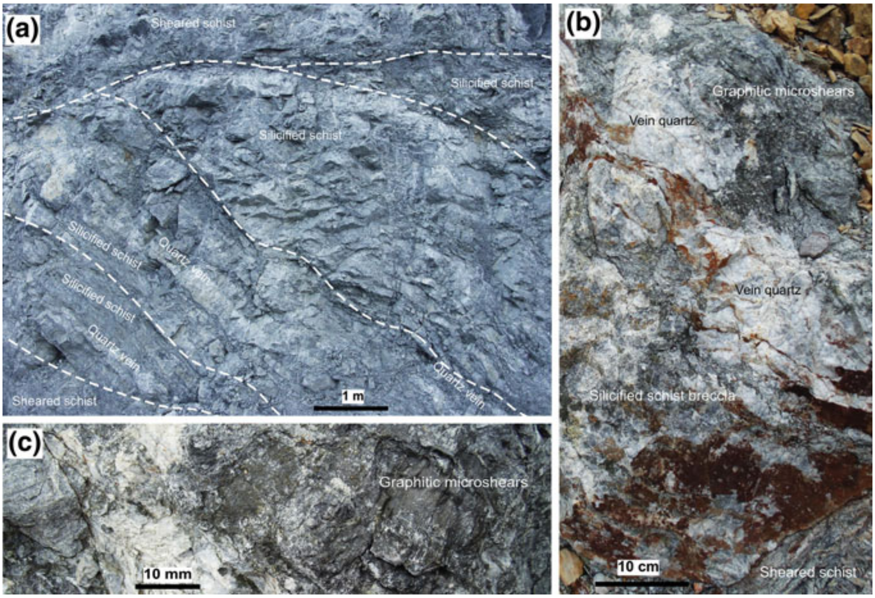

Fig. 4.7 Complex composite vein and silicified schist pod at Golden Bar open pit. The pod has evolved to form a competent rock mass around which more micaceous schists have become sheared. **a** Overall geometry of the pod. **b** Internal structure and sheared margins. **c** Close view of microsheared margin

schists and black sheared rock, so that even these fissile rocks became silicified and added to the width of the siliceous pods (Fig. 4.1b).

At small scales (centimetres to microns), microshears developed in deforming quartz-rich rocks, allowing hydrothermal fluids to penetrate and react, causing some recrystallisation and replacement of the pre-existing rocks. The most prominent result of this process is a network of dark stylolitic seams, that occur to some extent in most deformed quartz rocks (Fig. 4.8). The seams commonly nucleated on partially silicified host rock fragments, which became further silicified and obscured by dissolution and reprecipitation reactions along the seams, leaving a mica-rich residue. Seams generally contain some hydrothermal sulphides that have replaced pre-existing vein quartz and host rock silicates (Fig. 4.8). Stylolitic seams in sheared flat veins are highly irregular in orientation (Fig. 4.8a), although they help to define an imposed shear fabric near to the boundary with sheared micaceous schists (Fig. 4.7b, c). Stylolitic seams also occur in laminated veins, where they follow boundaries between individual laminae and are almost planar in shape (Fig. 4.3b).

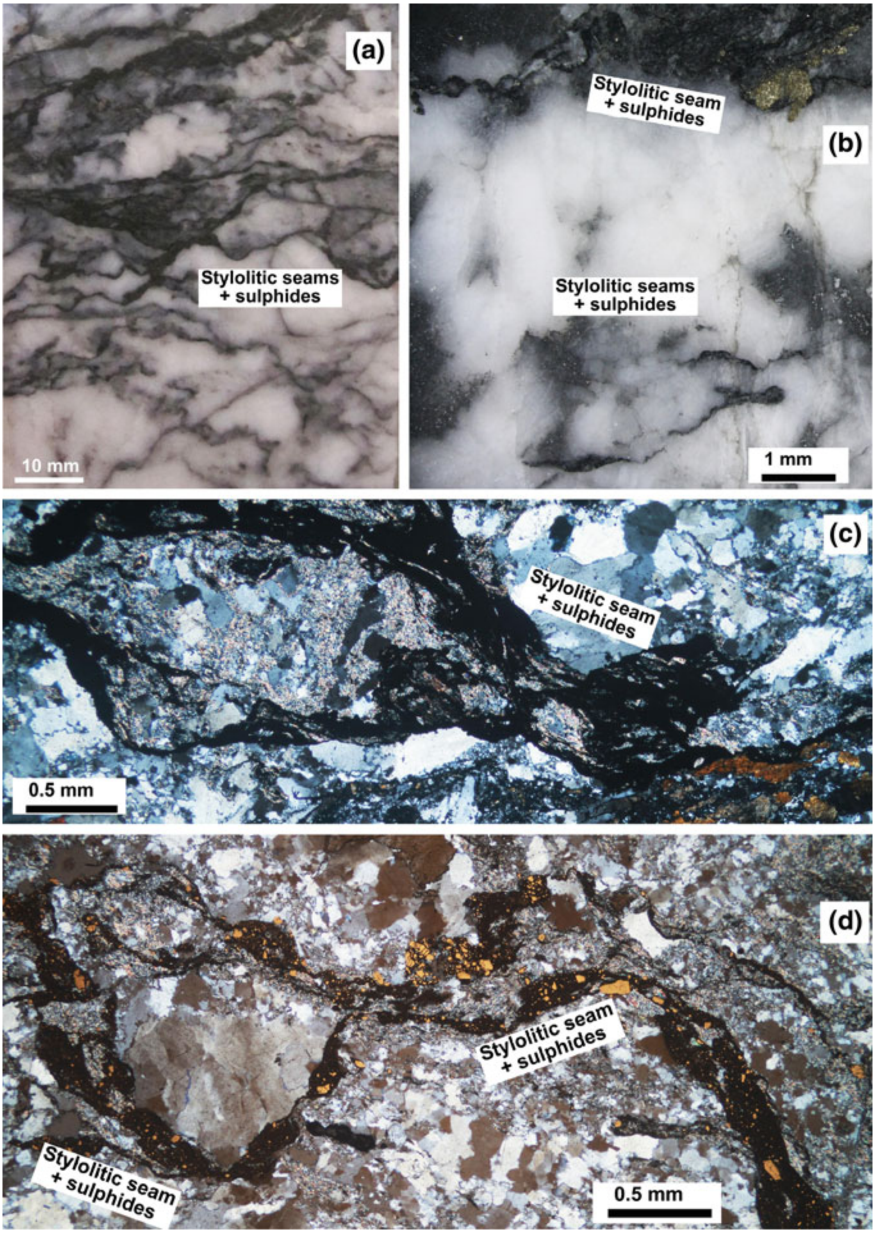

Fig. 4.8 Stylolitic seams (*black*) in quartz veins and silicified schist. **a**, **b** Hand specimen views of seams. **c**, **d** Microscopic view of seams cutting silicified schist with some vein quartz. Crossed polars, with incident light in (**d**) to highlight associated sulphides (*yellow*)

4.5 Formation of Laminated Veins

The laminated veins have formed at a high angle to the thrust-related shears of the Hyde-Macraes Shear Zone, including the Hangingwall Shear (Fig. 4.4a). These extensional veins have opened on normal faults and extensional fractures during the overall compressional, thrust-related, deformation in the shear zone. The orientation of this extensional opening and vein-filling is distinctly different from the flat veins typically associated with thrust motion (Fig. 4.2). Since the laminated veins are a common part of the mineralised system in the shear zone, they must reflect some common process that has occurred during thrust shear motion.

The relationship between these laminated vein orientations and the thrust shear structures and inferred thrust movement direction is summarised in Fig. 4.9. The inferred thrust direction is based on shear orientations and associated thrust-related folds. These features imply west to southwest directed thrust motion in the main mineralised zone of the mine, e.g., in Frasers open pit (Fig. 4.9). This is essentially up-dip in the present shear zone orientation. The thrust direction at the far north-western end of the shear zone has a more southerly component, as the shear zone strikes nearly east-west in that area, but thrust motion was up-dip in that area as well (Teagle et al. 1990). The laminated veins have strikes that are almost parallel to the thrust movement direction, and vein opening direction was sub-parallel to the strike of the shear zone (Fig. 4.9).

The apparent contradiction between extensional laminated vein orientations and shear zone thrust orientations has arisen because of structural and lithological inhomogeneities along the strike of the shear zone (e.g., Figs. 3.9 and 3.10). Subtle changes in rheological contrasts have led to formation of lateral ramps, which form steps in the structure along the strike of the shears, at which extensional fractures formed. A prominent lateral ramp in the Round Hill open pit was an important locus for abundant laminated veins (Fig. 4.10a). These lateral ramps and other associated structures were responsible for localised stress-switching, whereby the minimum

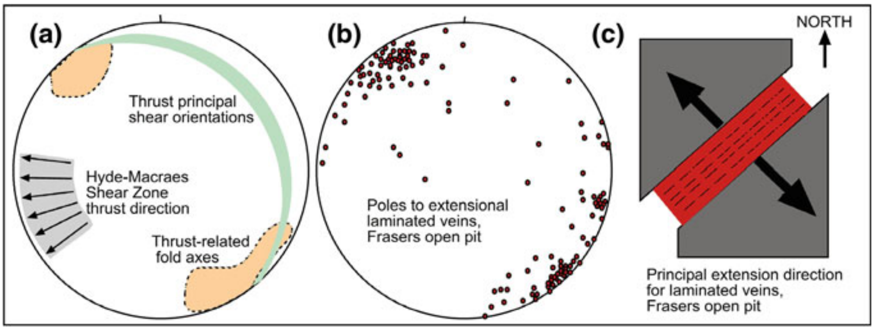

Fig. 4.9 Geometry of emplacement of laminated veins (Begbie and Craw 2006; Upton et al. 2008). **a** Overall geometry of Hyde-Macraes Shear Zone thrust structure and related folds. **b**, **c** Geometry of laminated vein opening in Frasers open pit

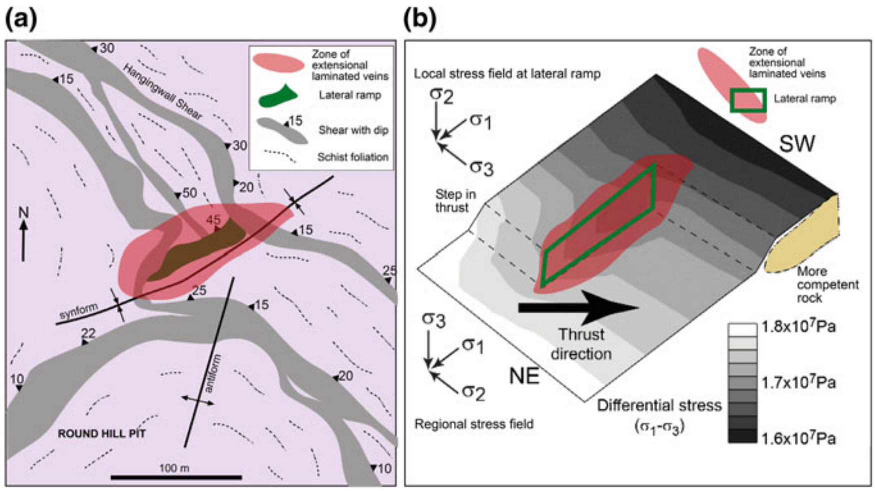

Fig. 4.10 Model of structural control of laminated vein emplacement associated with stress-switching near to, for example, a lateral ramp (modified from Angus 1993; Upton et al. 2008). **a** Map of a lateral ramp and related structures in Round Hill open pit, which was the site of abundant laminated veins. **b** Results of a numerical model that shows stress switching from regional σ_3 vertical to local σ_3 horizontal in the vicinity of a lateral ramp during thrust motion with σ_1 remaining *horizontal* throughout

and intermediate principal stresses (σ_3 and σ_2) became interchangeable over short distances within the shear (Fig. 4.10b). The maximum principal stress, σ_1 remained in constant orientation, reflecting the regional thrust-related compressional deformation throughout (Fig. 4.10b).

4.6 Evolving Rheological Contrasts

Many of the structural features of mineralised rocks that are outlined above have been controlled to some extent by rheological contrasts during progressive deformation in the Hyde-Macraes Shear Zone. These rheological contrasts were initially dominated by primary lithological variations, dominated by the differences between feldspathic and micaceous schists (Chap. 3). However, structural and hydrothermal processes during deformation and mineralisation have enhanced some of these contrasts, so that there was progressive evolution towards ever greater rheological contrast within the shear zone. These processes are summarised and contrasted, as softening and hardening processes, in Table 4.1.

The syn-deformational softening processes were focussed on micaceous schists and the related black sheared rocks. The most important contributors to this softening were hydrothermal reactions that altered metamorphic albite to muscovite, and added graphite to the resultant muscovite-domianted microshears. In contrast, the more

Table 4.1 Summary of hydrothermal processes accompanying formation of mineralised structures, which have led to changes and enhancement of rheological contrasts in the Hyde-Macraes Shear Zone

Feature	Syn-deformational softening	Syn-deformational hardening
Lithological control	Fissile micaceous schist	Massive feldspathic schist
Metamorphic structure	Metamorphic foliation	Quartz-albite metamorphic segregations (folded)
Shear deformation features	Muscovite rotation and recrystallisation forms shear fabric	Quartz veins and breccias
Breccias	Micaceous schist brecciation and ductile attenuation	Quartz cement in schist, breccias
Hydrothermal alteration	Alteration of albite to muscovite	Silicification, sulphide replacement
Hydrothermal mineral addition	Graphite	Scheelite, quartz
Principal locus and products	Black shears, mylonitic shears	Sheared flat veins, laminated veins
Permeability control	Grain boundaries, microshears	Brittle extensional fractures, microfractures
Fluid flow	Slow, pervasive, continuous	Locally rapid, episodic
Metallic minerals	Au; sulphides	Scheelite; Au in veins; Au and sulphides in stylolitic seams

massive feldspathic schist with abundant hard quartz-albite segregations, tended to fracure and become veined by hydrothermal quartz. This vein emplacement was also accompanied by silicification, further hardening the rock. Veins and silificified zones apparently protected the albite from hydrothermal alteration to muscovite. The massive siliceous rocks were commonly brecciated and re-cemented, becoming ever more silicified and rheologically more competent, leading to further fracturing and re-cementation and expansion of the hardened zones (Fig. 4.7).

The contrasting rheological softening and hardening processes also affected the hydrothermal fluid flow through the Hyde-Macraes Shear Zone. Fluid flow occurred mostly along the various shears, which are the most continuous structural features in the shear zone. This shear-hosted fluid flow was controlled by the shear fabric: microshears and associated grain boundary discontinuities in the micaceous rocks. Fractures were rare or absent from these rocks. The rheologically hard rocks were more readily fractured and open cavities formed, at least on the millimetre to centimetre scale, during progressive deformation. However, these fractures and associated breccias had limited lateral continuity (metres to tens of metres), governed by the scale of the hardened rock masses which were mainly podiform (Chap. 3; Fig. 4.7). Hence, fluid flow along these fractures, while more rapid than that along the micaceous microshears, was of strictly limited spatial scale. This fluid flow was temporally episodic as fractures opened and then were resealed by vein formation and breccia re-cementation.

4.7 Cataclasite

All the above mineralised structures formed under ductile or near-ductile conditions during the late metamorphic lower greenschist facies syn-deformational hydrothermal processes. As the rocks cooled further, many of the mineralised structures were overprinted by more brittle, cataclastic structures. This cataclastic overprint was still part of the Hyde-Macraes Shear Zone thrust-related deformation, and was partly controlled by the earlier-formed structures. In particular, black sheared rocks and micaceous schists were prone to later cataclasis, but some more competent feldspathic rocks were involved as well (Fig. 4.11). The overprinting deformation was highly localised, and caused additional brecciation and comminution of rocks, but with little or no formation of a new shear fabric. There was little hydrothermal activity associated with the cataclasis, although some remobilisation of sulphides, scheelite, and gold occurred (Chap. 5).

Additional cataclasis occurred associated with post-mineralisation deformation, initially during regional extensional deformation that produced with the Footwall Fault and related normal faults that cut across the shear zone (Fig. 2.5). This cataclasis was focussed on particular fault planes that cut the shear zone, and these cataclasite zones are typically on the metre scale. However, some such zones have secondary structures, still with normal sense of offset, that follow black sheared

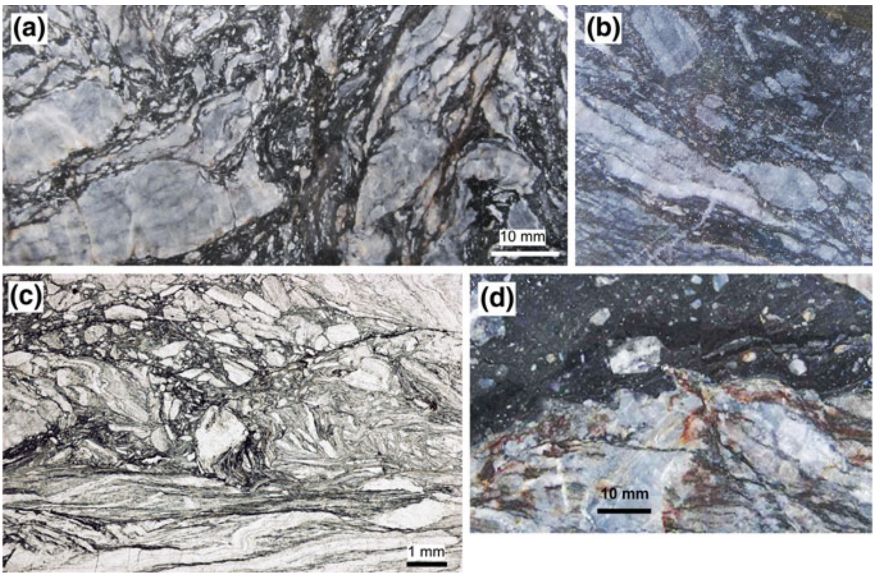

Fig. 4.11 Cataclasites formed in the latter stages of mineralisation, as the rocks became more brittle. **a**, **b** Minor cataclastic overprint on black sheared rock. **c** Cataclastic overprint on weakly mineralised feldspathic schist. **d** Strong cataclastic overprint on black sheared rock (*top*) while adjacent feldspathic schist is largely unaffected

rocks and other shears initially related to the thrust shear zone. Late Cenozoic reactivation of many normal faults has added a further cataclastic generation to the fault zones, some of which are now made up of several metres of soft gouge.

References

Angus PV (1993) Structural controls on gold deposition in the Hyde-Macraes Shear Zone at Round Hill, Otago, New Zealand. Proc Ann Conference, NZ Branch Aust Inst Min Metall, 11 pp

Begbie MJ, Craw D (2006) Geometry and petrography of stockwork vein swarms, Macraes mine, Otago Schist, New Zealand. NZ J Geol Geophys 49: 63-73

Jones P, Craw D, Norris RJ (2007) Golden Bar gold deposit as an extension of the Hyde-Macraes Shear Zone, east Otago, New Zealand. NZ J Geol Geophys 50: 271-281

Teagle DAH, Norris RJ, Craw D (1990) Structural controls on gold-bearing quartz mineralisation in a duplex thrust system, Hyde-Macraes Shear Zone, Otago Schist, New Zealand. Econ Geol 85: 1711-1719

Upton P, Begbie M, Craw D (2008) Numerical modeling of mechanical controls on coeval steep and shallow dipping auriferous quartz vein formation in a thrust zone, Macraes mine, New Zealand. Mineral Deposita: 43: 23-35

Chapter 5
Mineralogy and Paragenesis

5.1 Hydrothermal Alteration Halo

The hydrothermal alteration halo associated with the gold mineralisation in the Hyde-Macraes Shear Zone is a subtle feature that extends for tens to hundreds of metres beyond ore grade rocks. However, since the hydrothermal alteration occurred under lower greenschist facies conditions in lower greenschist facies rocks, the mineralised rocks can contain the same major silicate minerals as the unaltered host rocks: quartz, albite, muscovite, and chlorite (Fig. 5.1). Consequently, the alteration halo is difficult to recognise in hand specimen or outcrop, and is generally cryptic at the microscopic scale as well. The structures described in previous chapters are the principal indicators of mineralisation in the field, and some additional definition of altered rocks can be gained from geochemistry (Chap. 6). However, the subtle mineralogical changes outlined in this chapter provide some insight into the nature of the mineralising system, especially when viewed in the context of the structural evolution (Fig. 5.1).

The most widespread mineralogical changes in the alteration halo involve decomposition of silicate accessory minerals titanite and epidote (Fig. 5.1). These minerals form <2 % of the unmineralised rocks, and are typically fine grained (<50 microns), so their presence or absence requires detailed petrographic examination. Hydrothermal alteration has transformed titanite to rutile, essentially in situ so that there was minimal change to rock textures. Epidote decomposed to carbonate minerals (calcite, siderite) and Al-bearing phyllosilicates, and these alteration mineral products have been locally mobile within the rocks during alteration. The other principal mineral reaction during this hydrothermal alteration involved precipitation of graphite in the black sheared rocks. This process was more focussed into particular structures than the titanite and epidote decomposition reactions, and occurred mainly in sheared micaceous schists.

Sulphide minerals are widespread through the shear zone, and are an important indicator of the most mineralised rocks in the mine. Pyrite is the most common

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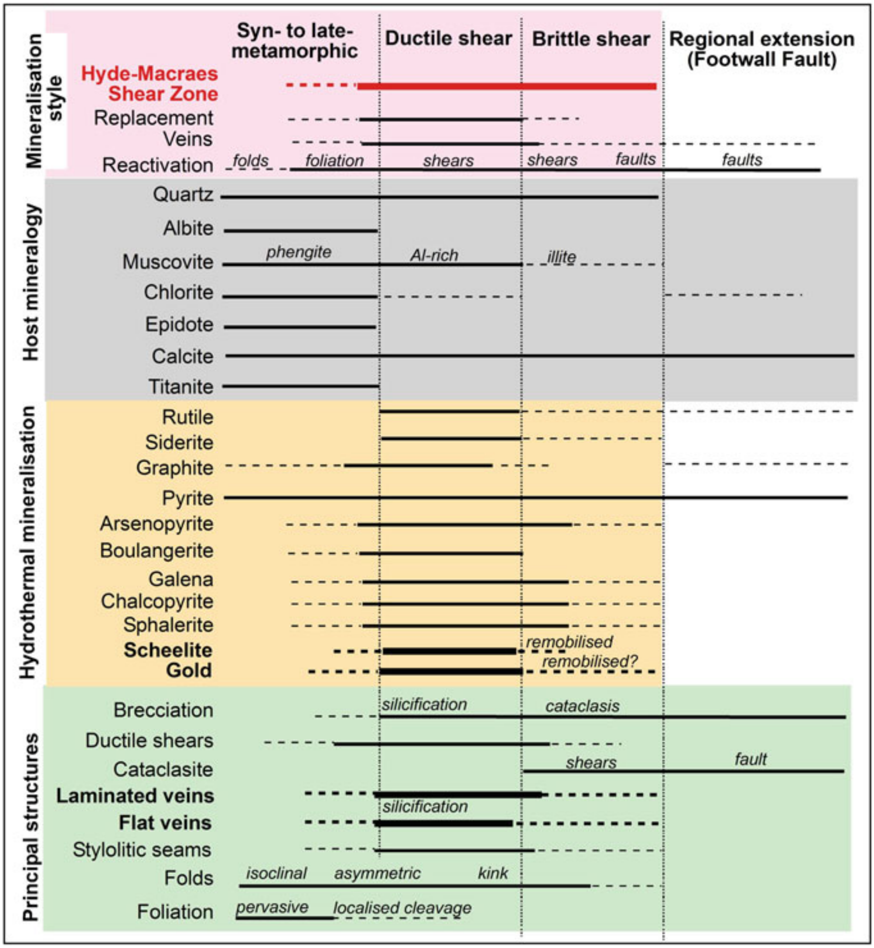

Fig. 5.1 Paragenetic chart that summarises the mineralisation style, mineralogy and structures through the evolutionary history in the Hyde-Macraes Shear Zone (modified from MacKenzie et al. 2016)

sulphide mineral throughout the shear zone, with a wide range of textures. However, pyrite is also an accessory in unaltered host rocks, especially micaceous schists, and the distinction between metamorphic and hydrothermal pyrite is subtle on the periphery of the alteration halo. Arsenopyrite has more restricted distribution than pyrite, and typically occurs only in gold-enriched rocks in the most-altered parts of the shear zone. Other sulphide minerals (Fig. 5.1) are present as accessories only. Chalcopyrite, sphalerite and galena are common but volumetrically insignificant, and typically occur as micron-scale inclusions in pyrite and arsenopyrite.

5.2 Early Stages of Structural and Mineralogical Paragenesis

Within the overall alteration halo, mineralisation is closely associated with shear structures, and the co-evolution of these structures and hydrothermal minerals is an important part of the formation of the ore deposit. The style of mineralisation changes with time as hydrothermal replacement, alteration, and vein formation occur in association with progressively less ductile structures (Fig. 5.1). At the same time, previously-formed features were commonly reactivated. The hosting shear structures were also affected by the rock types in which they have formed (Chaps. 3 and 4). Incipient development of shears was controlled by the pre-existing metamorphic fabric of the host schists (Fig. 5.2). In micaceous schists, the metamorphic foliation was the most important hosting feature. In contrast, early shears in feldspathic schists were controlled by syn-metamorphic folds of metamorphic segregations, and associated fold axial surface cleavage (Fig. 5.2). Pyrite

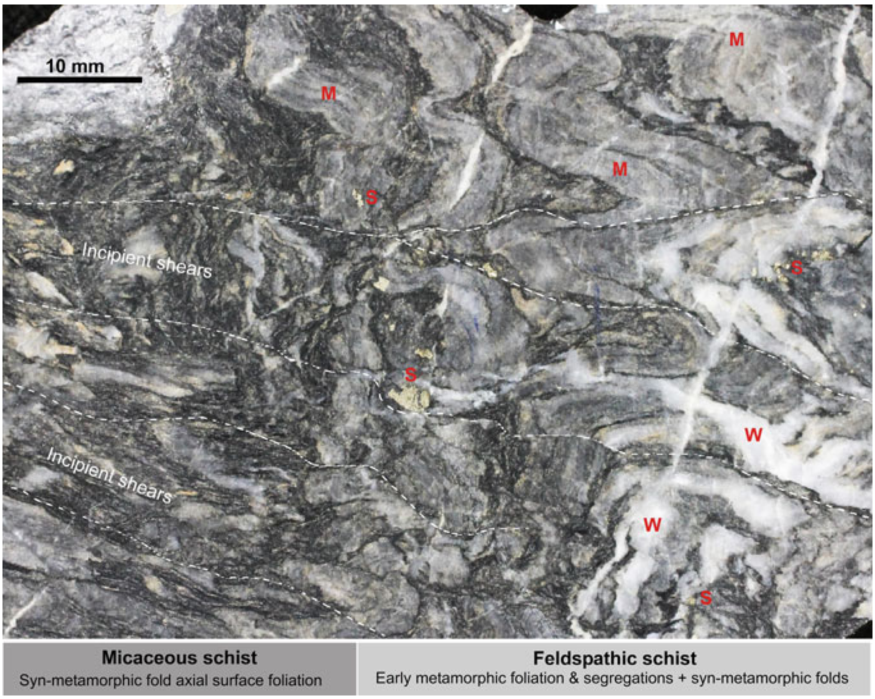

Fig. 5.2 Earliest stages of development of shear structures in the Hyde-Macraes Shear Zone. Development of shears (*dashed*) is controlled by pre-existing metamorphic features, which are different in micaceous schists (*left*) from feldspathic schists (*right*). Early white quartz veins (W) have filled fractures in metamorphic quartz-albite segregations (M) in feldspathic schist. Minor sulphides (S, mostly pyrite) replace silicates adjacent to shears

recrystallisation and pyrite addition via replacement reactions occurred in both rock types (Fig. 5.2), but only minor gold was introduced at these early stages of shear development.

Hydrothermal quartz veinlets were introduced, particularly into feldspathic schists where the metamorphic quartz-albite segregations fractured during deformation. These early vein formation processes were commonly focused where metamorphic fold hinges had thickened the segregations, at the centimetre to metre scales. The earliest quartz is distinctively white in hand specimen (Figs. 5.2 and 5.3), reflecting abundant micron-scale fluid inclusions in coarse-grained (millimetre scale) quartz. Minor silicification was associated with this early quartz veining, but this occurred mainly on the millimetre scale. Some pyrite, and rarely scheelite, occurs in this early white quartz, but gold is not enriched.

With increasing strain, the shear fabric became more pervasive and started to dominate the rocks, although the shears were still controlled by the pre-existing metamorphic fabric (Fig. 5.3). Shears in micaceous laminae anastomosed around more competent parts of the rock, including patches with early white hydrothermal

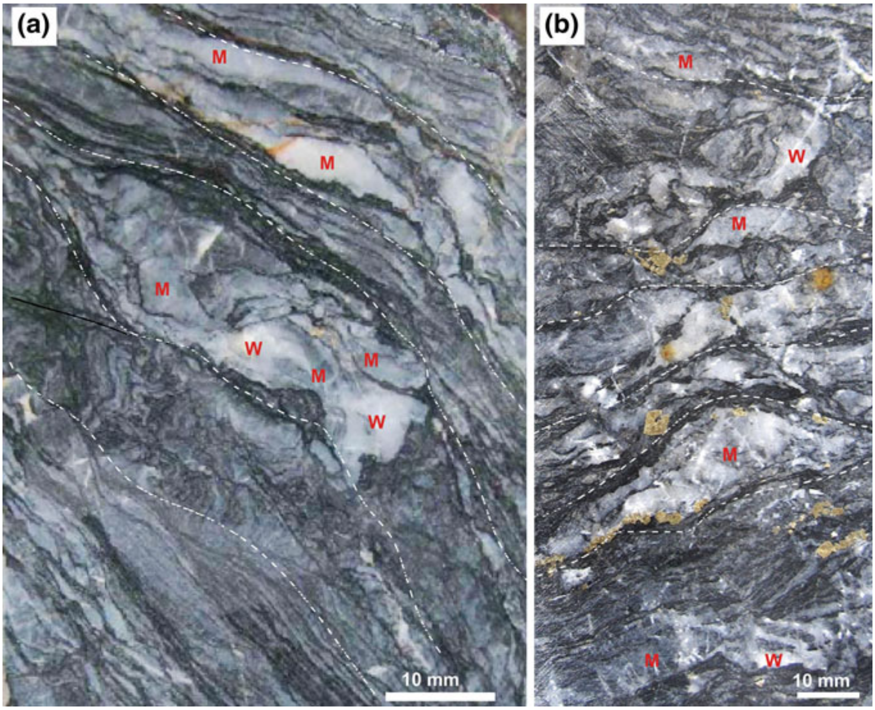

Fig. 5.3 Early shear structures (*dashed*) begin to dominate the fabric of host schists in the Hyde-Macraes Shear Zone, and white hydrothermal quartz (W) fills fractures in metamorphic laminae (M). **a** Shears follow micaceous segregations in feldspathic schist. **b** Black shears with some hydrothermal graphite have developed within micaceous schist. Abundant syn-mineralisation pyrite porphyroblasts (*yellow*) have overgrown some of the black shears

quartz. Initial addition of graphite enhanced some micaceous shears. Pyrite recrystallisation and addition continued to occur, resulting in porphyroblasts within the evolving micaceous shears. This pyrite was accompanied by other sulphides, especially minor arsenopyrite, and the first significant gold enrichment occurred during this stage of shear development. Pyrite and other sulphides were also added along microshears in the more quartz-rich parts of the rocks, including microshears that crosscut the earliest white quartz.

Shear fabric became progressively dominant in the micaceous rocks, and sulphide porphyroblasts became more abundant as mineralisation progressed to form what are now ore grade rocks. Arsenopyrite became increasingly common and formed porphyroblasts and finer grains within the shear fabric (Fig. 5.4a, b). Early-formed porphyroblasts of pyrite and arsenopyrite became fragmented as on-going deformation disrupted the sheared rocks, ultimately leading to mineralised mylonitic textures (Fig. 5.4c). Arsenopyrite remained subordinate to pyrite in most mineralised rocks, typically by a factor of 1:2, but locally dominates in higher grade ore zones. Other sulphide minerals remained at accessory levels, scattered through the rocks and encapsulated in pyrite and arsenopyrite.

Quartz veins continued to form in competent rocks adjacent to sheared micaceous rocks, with common interlayering of quartz-rich and micaceous mineralised zones on the metre scale. Early-formed white quartz almost invariably dominated the quartz vein complexes volumetrically, but that white quartz hosted only minor sulphides, rare scheelite, and negligible gold. Some of the white quartz has well-developed and variably zoned prismatic habit (Fig. 5.5a). The early white quartz was commonly overprinted in the most mineralised veins by several generations of fine grained quartz which is grey, or locally almost translucent, in hand specimen. This grey quartz locally infills fractures and open cavities, but most commonly occurs as recrystallisation and/or replacement of the white quartz (Fig. 5.5a–c). Importantly, sulphides and gold in mineralised rocks almost invariably occur within patches of grey quartz. The same generation of mineralisation that was responsible for grey quartz formation was also responsible for widespread silicification (Chap. 4). Sulphide mineral and gold introduction occurred during this silicification. Some of this silicification extended into adjacent sheared micaceous schists, with gold and sulphides (Fig. 5.4c).

5.3 Non-metallic Mineral Phase Equilibria

Mineralisation and associated hydrothermal alteration occurred while the host schists cooled through lower greenschist facies conditions (Chap. 2). Hence, the mineral transformations during the hydrothermal alteration are similar to those expected during normal metamorphic retrogression. Simplified phase equilibria for the main alteration reactions during this cooling process are summarised in Fig. 5.6a. The reactions reflect re-equilibration of the lower greenschist facies mineral assemblage in equilibrium with an aqueous fluid that had very low CO_2

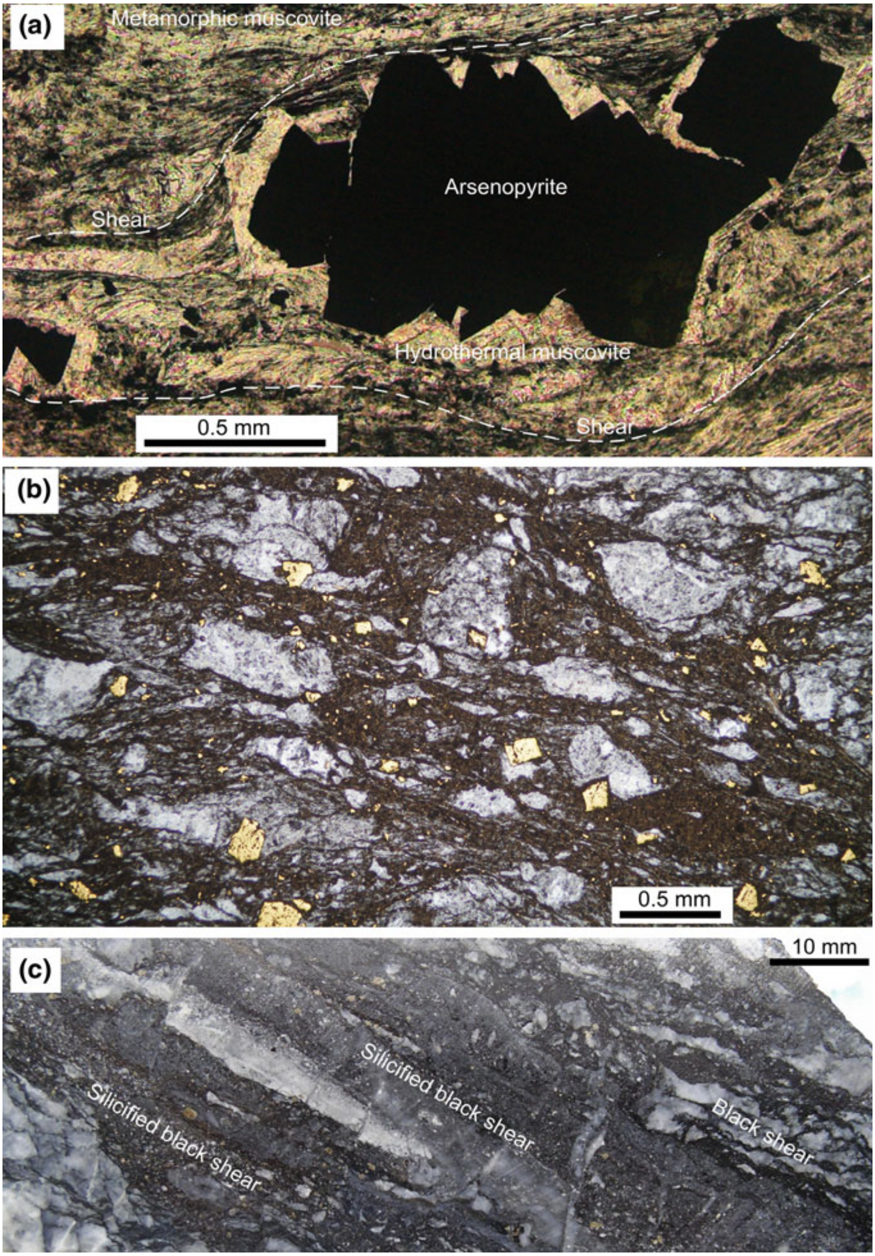

Fig. 5.4 Continued evolution of shears in micaceous schist to form ore grade rocks. **a** Thin section view (crossed polars) of metamorphic and hydrothermal muscovite, and a large porphyroblast of arsenopyrite. Microshears anastomose around the porphyroblast. **b** Thin section view, with combined plane polarised light and incident light, of pervasive micaceous shear fabric (*dark*), quartz-rich porphyroclasts (*white*), and scattered sulphide porphyroblasts (pyrite and arsenopyrite; *yellow*). **c** Mylonitic black sheared micaceous schist that has been variably silicified

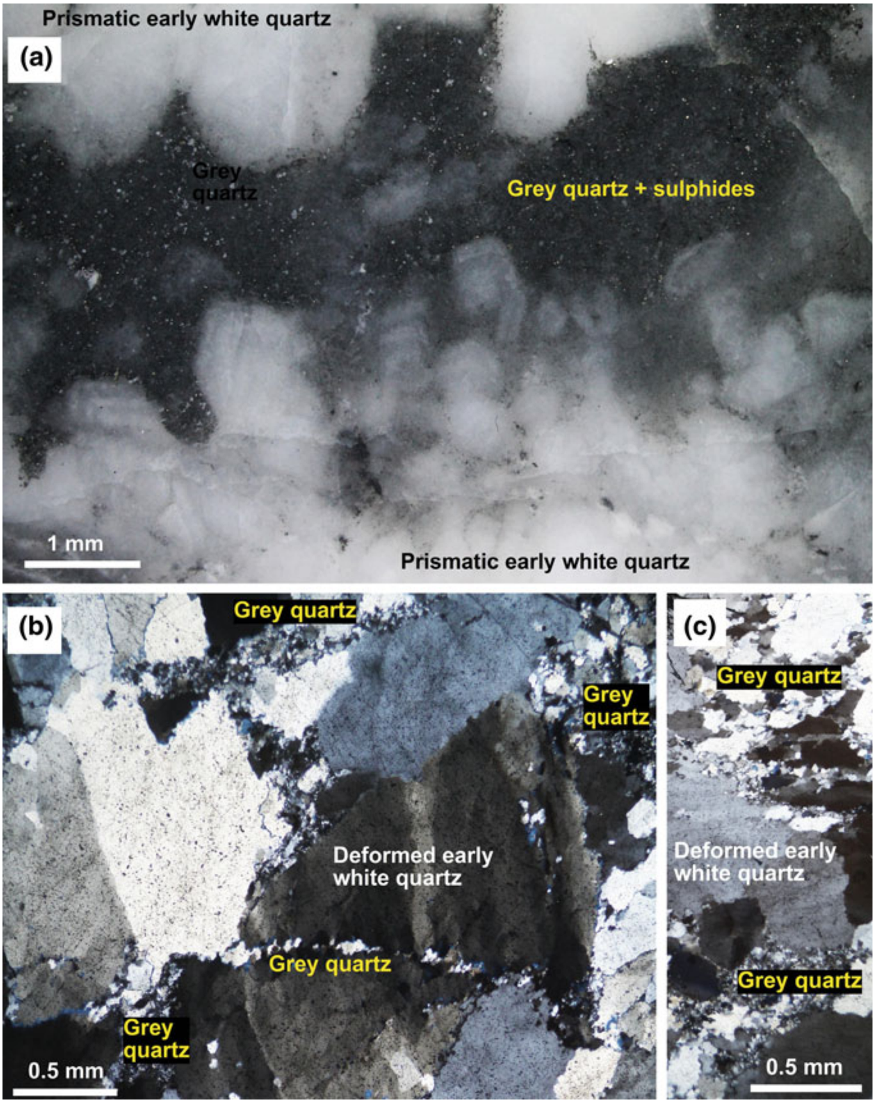

Fig. 5.5 Early stages of quartz vein formation in the Hyde-Macraes Shear Zone. Earliest *white quartz* is coarse grained and locally prismatic, and this is replaced and recrystallised by introduction of fine *grey quartz* along microfractures. **a** Hand specimen view of zoned prismatic *white quartz* that is partially replaced by *grey quartz* with scattered sulphides. **b** Thin section (crossed polars) of deformed coarse *white quartz* recrystallised to *grey quartz* in patches and along narrow fractures. **c** Similar rock to (**b**), but *grey quartz* patches predominate with some relict *white quartz* grains

content during mineralisation (as outlined in Chap. 7). At higher temperatures, such as in the upper greenschist facies and amphibolite facies schists that underlie the shear zone rocks in the Otago Schist belt, the metamorphic fluids had up to 10 mol % CO_2, although most greenschist facies fluid compositions were more aqueous than that.

Titanite, the almost ubiquitous greenschist facies titanium mineral, formed secondary rutile, calcite and quartz in a reaction that has been widely observed in metamorphic rocks and quantified experimentally (Fig. 5.6a). The stability of metamorphic epidote, which has a moderate Fe content in Otago Schist, is approximated in Fig. 5.6a by Fe-free zoisite and clinozoisite that define a stability range similar to that of titanite. The Fe released from alteration of the epidote results in formation of siderite, a widespread accessory mineral in the Hyde-Macraes Shear Zone mineralised rocks (Fig. 5.1). Graphite formation occurred in parallel with the

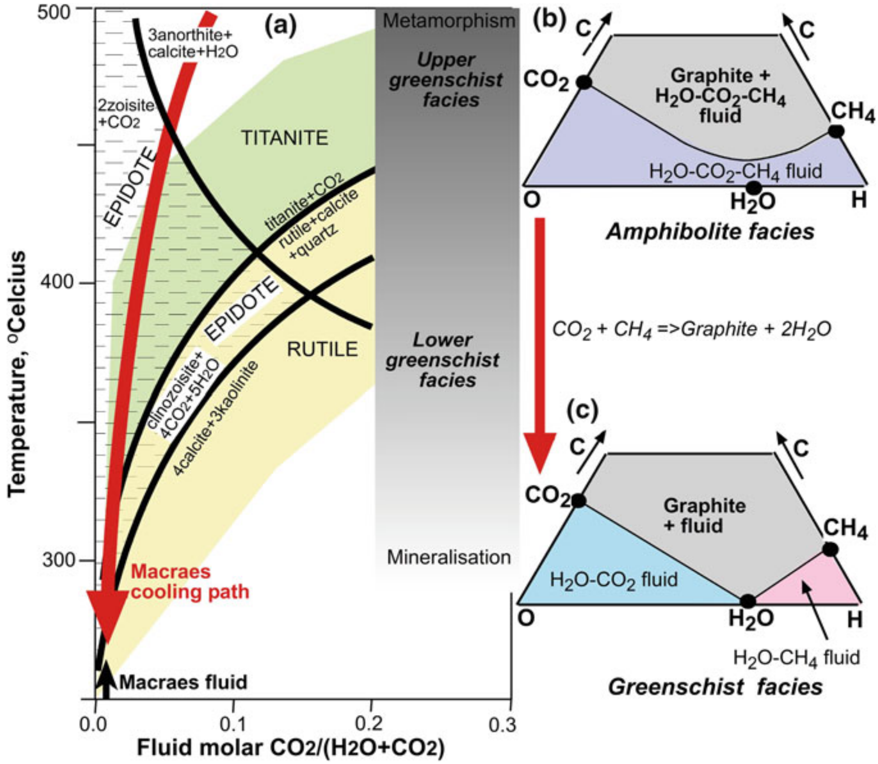

Fig. 5.6 Mineralogical phase diagrams relevant to hydrothermal alteration in the Hyde-Macraes Shear Zone during cooling through the greenschist facies. **a** Simplified reactions for alteration of titanite and epidote (modified from Craw 2002 and references therein). **b**, **c** Formation of graphite from carbonic metamorphic fluid during cooling (modified from Holloway 1984). The carbonic fluid contains coexisting methane and carbon dioxide at high temperature (**b**), but graphite precipitates as that fluid cools (**c**)

fluid-linked retrogression reactions that caused titanite and epidote destruction (Fig. 5.6). At high temperatures, CO_2 and CH_4 can coexist in a water-dominated fluid (Fig. 5.6b), but as that fluid cools, most of the CO_2 and CH_4 react to form graphite. Further discussions on the significance of this graphite are presented in Chap. 8.

White micas show a range of compositions in the Hyde-Macraes Shear Zone, reflecting different stages of recrystallisation during hydrothermal alteration. Host schist white micas are phengitic, with several weight percent FeO and MgO and linked lower Al_2O_3 and SiO_2 contents. These elemental substitutions in the white mica structural formulae are quantified in Fig. 5.7. Phengitic muscovite was recrystallised during hydrothermal alteration in the shear zone, resulting in a lower but still significant phengite content. These white micas in the micaceous shears have higher Al contents, replacing some of the phengite component. The white mica that formed by alteration of albite during shear zone development (Chap. 4) also has the

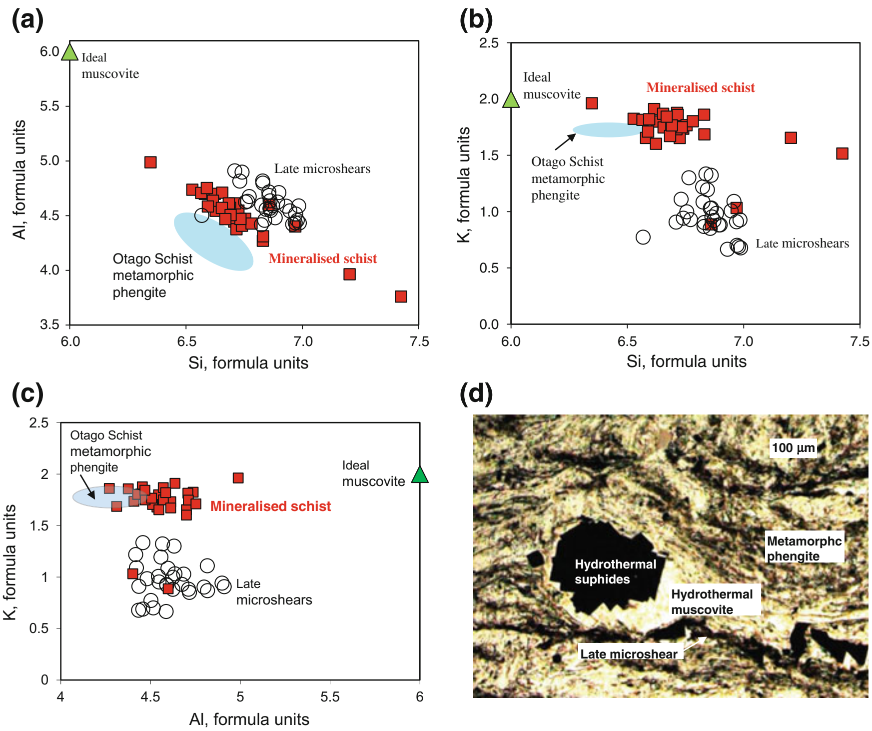

Fig. 5.7 Compositional variations of white micas in the Hyde-Macraes Shear Zone (data from Petrie and Craw 2005). **a–c** Plots of the mineral formulae parameters derived from electron microprobe analyses from metamorphic phengite, hydrothermal muscovite, and muscovite in late stage microshears. **d** Thin section view (crossed polars) of different textures of white micas, as in (**a–c**)

same Al-rich composition. The extra Al was derived from decomposition of epidote, and recrystallisation and/or replacement of chlorite during the early alteration.

Both metamorphic and early alteration white micas have almost a full complement of potassium in their structures (Fig. 5.7b, c). In contrast, late stage microshears that have formed within micaceous schists have lower potassium contents, and more illitic compositions (Fig. 5.7). Similarly, both metamorphic and early hydrothermal white micas in late stage cataclasites in micaceous shears and some mineralised feldspathic rocks show potassium depletion reflecting illitisation as the mineralisation temperature lowered and the rocks became more brittle (Fig. 5.1). Superimposition of later fault rocks during middle Cretaceous to late Cenozoic fault reactivation has led to extensive clay mineral alteration of fault rocks in narrow zones, but little change to the white micas associated with the main Hyde-Macraes Shear Zone mineralisation system.

5.4 Metallic Mineralogy

Pyrite is the most common metallic mineral in the Hyde-Macraes Shear Zone and related rocks, and pyrite has formed and recrystallised throughout the history of shear zone development and gold mineralisation (Figs. 5.1, 5.2, 5.3 and 5.4). Because of this complex history, pyrite grains are commonly texturally and chemically zoned internally. This zonation is a result of variable incorporation of trace elements in solid solution in the pyrite structure. The simplest type of zonation is concentric, with pyrite cores having different trace element compositions from outer and rim compositions. However, some pyrite porphyroblasts are composite and consist of intergrowths of grains with differing compositions.

In general, pyrite grain cores tend to contain lower concentrations of trace elements, because they formed in the earliest stages of shear development (Figs. 5.2 and 5.3) and have not been fully recrystallised during subsequent deformation and mineralisation. For example, the pyrite grain in Fig. 5.8a has essentially no gold in solid solution in its core, and low As and Ni contents as well. The bismuth content shows a more complex pattern, but the lowest Bi concentrations still occur in the core. In contrast, all these elements are enriched in the outer parts of the grain, and solid solution gold contents appear to be highest on the pyrite rim. More complex pyrite zonation is shown in the PIXE (proton-induced X-ray emission) image in Fig. 5.8b. Strong Ni enrichment in the centre of the grain occurs where the As content is lowest. Conversely, As-rich parts of the grain have low Ni, as do some low-As parts of the grain. Copper is enriched in the low-As part of the grain, partly in solid solution but mostly as micron-scale chalcopyrite inclusions.

Arsenic and antimony bearing minerals are an important indicator of the most intense mineralisation processes in the shear zone, and the geochemical signature of these minerals is discussed in more detail in Chap. 6. Arsenopyrite is by far the most important of these minerals (Fig. 5.4), and the first appearance of arsenopyrite during shear evolution is the strongest mineralogical indicator of related gold

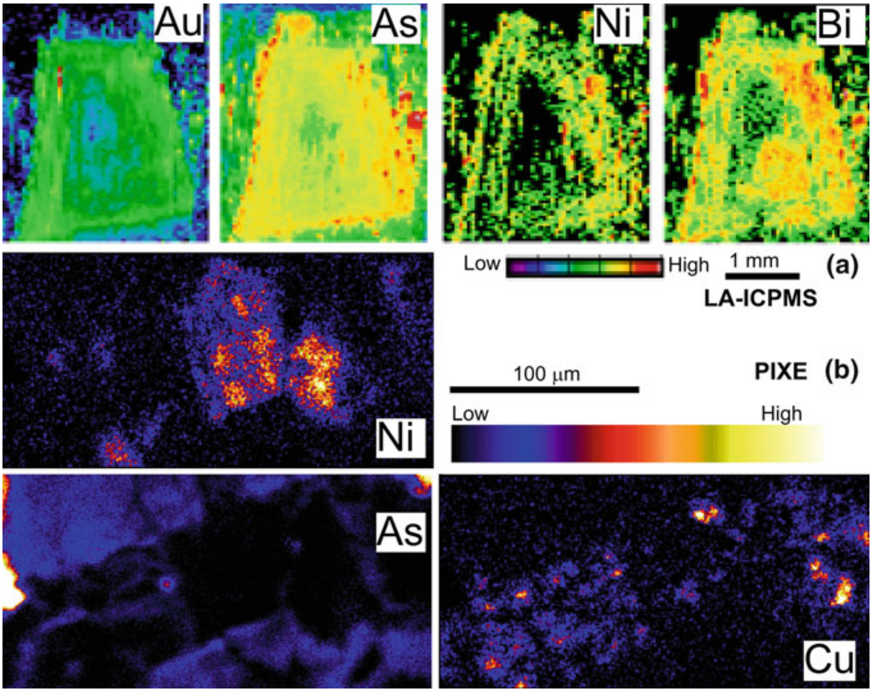

Fig. 5.8 Compositional zoning in hydrothermal pyrite at Macraes mine (modified from Large et al. 2012 and Petrie et al. 2005). **a** Laser ablation ICP-MS mapping of elements in a pyrite grain. **b** PIXE (proton-induced X-ray emission) mapping of elements in a pyrite grain (grain occupies whole of images apart from a small arsenopyrite grain at *left*)

enrichment. Arsenopyrite has generally consistent compositional range of 29–31 atomic % As where pyrite and arsenopyrite coexist in apparent equilibrium (McKeag and Craw 1989). Arsenopyrite without coexisting pyrite has similar but slightly higher As contents, up to 34 atomic % As. The arsenopyrite composition in equilibrium with pyrite is consistent with a lower greenschist facies mineralisation temperature between 300° and 400 °C (McKeag and Craw 1989; Craw and Norris 1991).

At the earliest stages of mineralised shear development, arsenopyrite is accompanied by boulangerite ($Pb_5Sb_4S_{11}$) and the two minerals are locally intergrown (Fig. 5.9a, b). Boulangerite remains a persistent accessory sulphide mineral throughout the evolution of the shear zone (Fig. 5.1). Even in the latter stages of shear development, as early-formed sulphides became brecciated, boulangerite was remobilised into late stage fractures (Fig. 5.9c, d). Despite the presence of this separate antimony mineral, there is also abundant Sb in solid solution in arsenopyrite grains (Fig. 5.9e). The solid solution Sb is zoned in arsenopyrite, and is locally as high as 2000 ppm (Petrie et al. 2005).

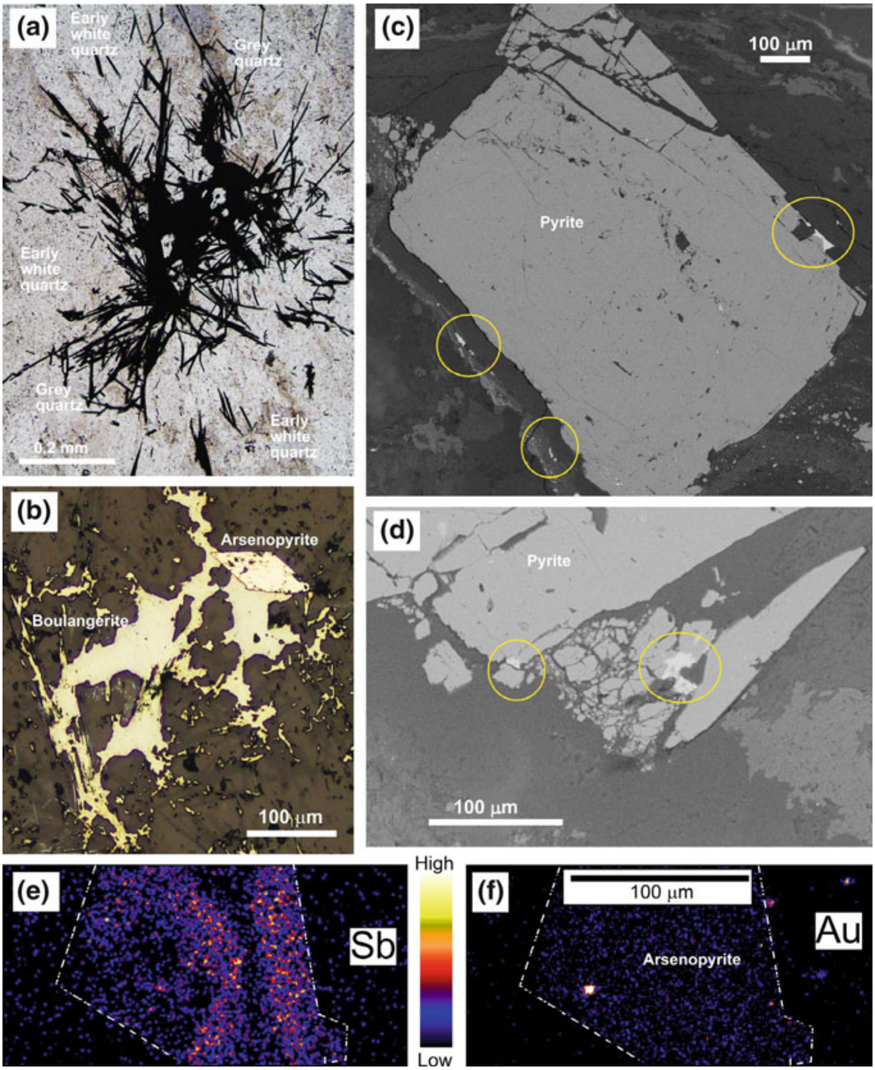

Fig. 5.9 Arsenic and antimony minerals. **a** Thin section (plane light) view of early stage boulangerite needles radiating from patches of *grey quartz* and cut across *white quartz*. **b** Incident light view of early stage boulangerite intergrown with euhedral arsenopyrite. **c**, **d** SEM backscatter images of late-stage boulangerite (*circled*) on the margins of variably brecciated pyrite in black sheared rock. **e**, **f** PIXE images (modified from Petrie et al. 2005) of an arsenopyrite grain showing antimony zoning (**e**) and a single encapsulated gold grain (**f**)

5.5 Gold

Gold was intimately associated with emplacement of sulphide minerals throughout the evolution of the shear zone, particularly where the sulphide mineral assemblage was enriched in As and/or Sb. Gold enrichment occurred during sulphide replacement reactions in host schist and veins, and within quartz veins, starting in the early stages of shear and vein development. Replacement-related gold and sulphides are volumetrically the most important in the shear zone, although gold grades are typically lower than in veins. Gold occurs in solid solution in the sulphides, at very low levels (typically <1 ppm), and as discrete native gold particles that dominate the gold inventory (Large et al. 2012). The gold has broadly uniform composition, with uniform 3 wt% Ag consistently across a range of textures, and variable Hg content between 1 and 4 wt% (MacKenzie and Craw 2005).

Gold in flat quartz veins is almost invariably hosted in fine grained grey quartz, which has formed from recrystallisation and replacement of earlier white quartz, and rare visible gold grains occur within this grey quartz and associated stylolitic seams (Figs. 3.5c and 5.10a). Likewise, rare coarse gold in laminated veins (Fig. 5.10b) is associated with sulphide-rich laminae and stylolitic seams that parallel those laminae. The vast majority of gold, possibly >99 % of it, occurs as micron scale inclusions in sulphide minerals (Figs. 5.8a, 5.9f and 5.10c–f) in predominantly replacement and recrystallisation textures. Most of the gold inclusions were incorporated during intial growth of the sulphide grains. In addition, some gold occurs on fractures (Fig. 5.10d), as coatings on the exterior surfaces of sulphide grains, and in the matrix of brecciated sulphides. This latter gold was remobilised from primary textures in the more brittle stage of shear zone development, and there is little evidence for addition of new gold into the shear zone after the main ductile stage of shear development (Fig. 5.1).

5.6 Scheelite

Scheelite occurs almost entirely within veins, both flat and laminated, in the shear zone, and scheelite emplacement was directly linked to the vein quartz emplacement into fractured rocks. Rare and volumetrically trivial grains of scheelite occur replacing silicates in the immediate host rock to some of these veins, within millimetres of the veins. Hence, scheelite emplacement was largely a cavity-filling process, in contrast to the essentially coeval replacement-dominated gold emplacement described above. The scheelite is almost pure $CaWO_4$, with very low Mo content (<1 wt%).

Scheelite commonly occurs in flat veins as coarse grained (cm scale) masses (Figs. 4.1c and 5.11) that can be up to 30 cm acoss. Scheelite also forms finer grained disseminated grains and cement in breccias within flat veins (Fig. 5.11b). The paragenetically earliest scheelite forms equant grains in white quartz associated

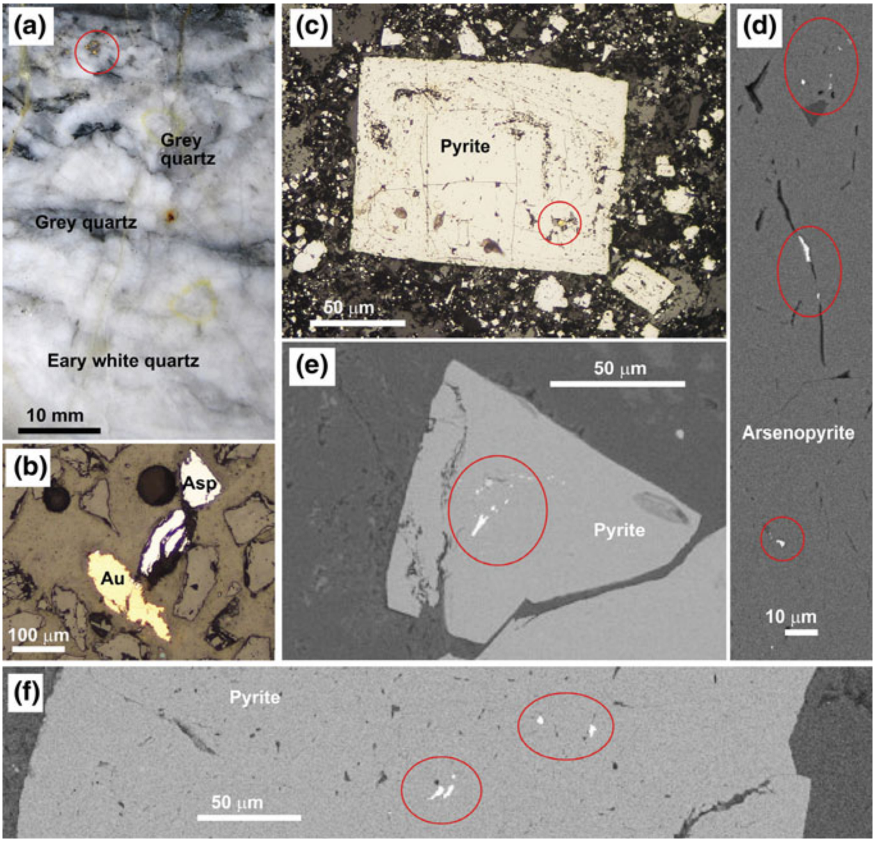

Fig. 5.10 Textures of gold (in *red ellipses*) in mineralised rock from Macraes mine. **a** Hand specimen with *white quartz* replaced by *grey quartz*. **b** Incident light view of a coarse gold particle liberated by crushing of a laminated vein. **c**. Incident light view of a gold particle encapsulated in a coarse zoned pyrite porphyroblast in black sheared rock. **d**–**f** SEM backscatter images of gold encapsulated in sulphide minerals

with incipient shear and vein development, but this is rare and volumetrically minor. Most flat vein scheelite occurs with grey quartz, locally replacing and veining early white quartz. Scheelite in laminated veins commonly dominates individual laminae, and can occur in multiple parallel laminae (Figs. 4.3e and 5.11c).

Scheelite grains and masses of grains are rheologically competent, and post-depositional deformation has caused brecciation and dispersal of the originally-emplaced textures. Scheelite breccia fragments in flat veins were recemented by later quartz after the fragments were variably dispersed laterally during deformation (Figs. 4.6c and 5.11a, d). Some laminated veins with scheelite laminae were folded, sheared, and disrupted and fragmented during deformation of the host schist (Fig. 5.11c). In detail, primary scheelite grains developed deformation lamellae and fractures during brecciation, dismemberment, and recementation (Fig. 5.11e).

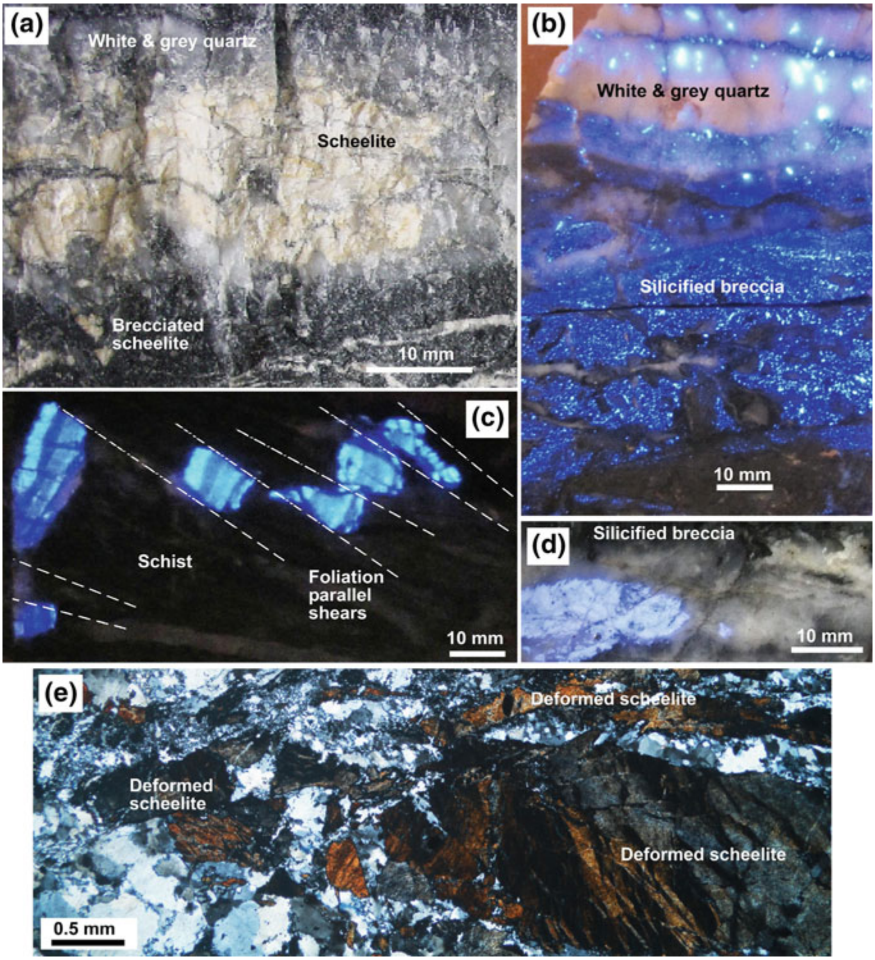

Fig. 5.11 Textures and paragenesis of scheelite. **a** Massive scheelite in a flat vein within the Hangingwall Shear. **b** Fine grained scheelite (*purple* in ultraviolet, UV, light) in veins and silicified breccia within the Hangingwall Shear. **c** Scheelite-rich laminated vein has been offset by foliation-parallel shears. **d** Deformed scheelite pod in a flat vein within silicified breccia. **e** Thin section view (crossed polars) of brecciated and deformed scheelite in a flat quartz vein

References

Craw D (2002) Geochemistry of late metamorphic hydrothermal alteration and graphitisation of host rock, Macraes gold mine, Otago Schist, New Zealand. Chem Geol 191: 257-275

Craw D, Norris RJ (1991) Metamorphogenic Au-W veins and regional tectonics: mineralisation throughout the uplift history of the Haast Schist, New Zealand. NZ J Geol Geophys 34: 373-383

Holloway JR (1984) Graphite-CH_4-H_2O-CO_2 equilibria at low-grade metamorphic conditions. Geology 12: 455-458

Large R, Thomas H, Craw D, Henne A, Henderson S (2012) Diagenetic pyrite as a source for metals in orogenic gold deposits, Otago Schist, New Zealand. NZ J Geol Geophys 55: 137-149

McKeag SA, Craw D (1989) Contrasting fluids in gold-quartz vein systems formed progressively in a rising metamorphic belt: Otago Schist, New Zealand. Econ Geology 84: 22-33

MacKenzie DJ, Craw D (2005) The mercury and silver contents of gold in quartz vein deposits, Otago Schist, New Zealand. NZ J Geol Geophys 48: 265-278

MacKenzie D, Moore J, Farmer L, Craw D (2016) Paragenesis of mineralisation in the Hyde-Macraes Shear Zone, East Otago. Aust Inst Min Metall Monog (in press)

Petrie BS, Craw D (2005) Lithological controls on structural evolution of mineralised schist, Macraes gold mine, Otago, New Zealand. NZ J Geol Geophys 48: 435-446

Petrie BS, Craw D, Ryan CG (2005) Geological controls on refractory ore in an orogenic gold deposit, Macraes mine, New Zealand. Mineral Deposita 40: 45-58

Chapter 6
Geochemistry of the Macraes Gold Deposit

6.1 Major Element Variations

The subtle hydrothermal alteration in the Hyde-Macraes Shear Zone, combined with the lithological variations on which the alteration was imposed, means that major elements do not provide a strong signal for mineralisation. The lithological variations reflecting different primary sedimentary rock types are variable on the 10 cm to 10 m scales, and the metamorphic segregation processes have caused lithological variations on the centimetre scale. Hence, selection of representative samples for analysis is fraught with problems, and the compositions of unmineralised host rocks can only be estimated from a statistical perspective, using large numbers of samples. Background rock analysis databases are available (e.g., Mortimer and Roser 1992), and these are used for comparison here, in addition to a set of analyses obtained from unmineralised rocks in Macraes mine excavations (McKeag et al. 1989; Craw et al. 1999; Craw 2002; Petrie and Craw 2005; Jones et al. 2007). To evaluate the effects of the subtle hydrothermal alteration in the context of the above background data, analyses of the most mineralised black sheared rocks have been selected (Fig. 6.1). These black sheared rocks have undergone the most advanced textural and mineralogical changes in the shear zone (Chap. 5).

Covariation of SiO_2 and TiO_2 in unmineralised rocks yields a negative correlation that reflects higher quartzofeldspathic component of sandstone protoliths. This was accentuated by metamorphic segregation processes that concentrated titanite in micaceous laminae rather than quartz-albite laminae. In the Macraes mine rocks, this negative correlation is readily recognisable in unmineralised rocks. Black sheared rocks fall into the same geochemical range despite their origin as micaceous schists because of variable amounts of hydrothermal silicification (Fig. 6.1a). Similarly, there is a negative correlation between Na_2O and K_2O in unmineralised rocks as a result of differing proportions of muscovite and albite, again reflecting both primary and metamorphic effects. Black sheared rocks

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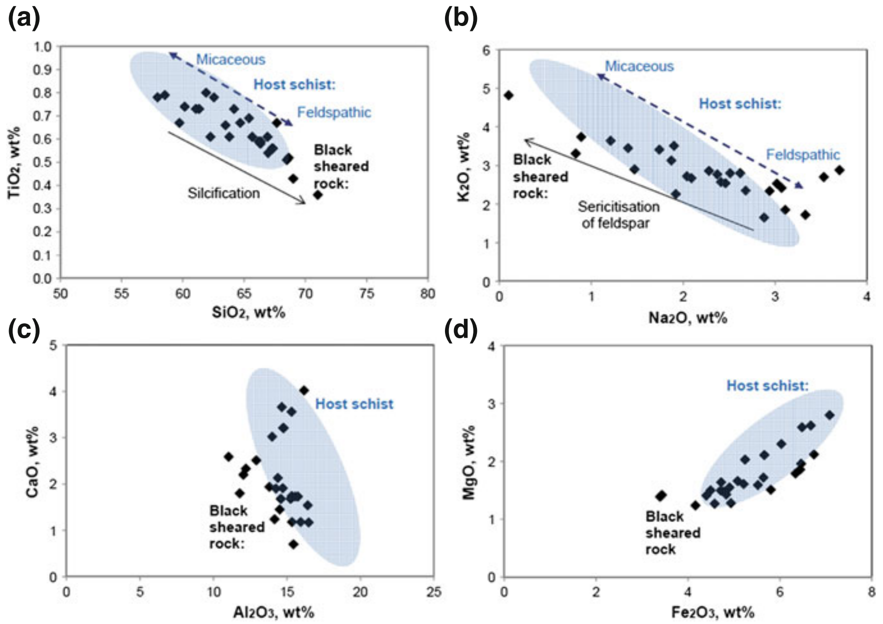

Fig. 6.1 Laboratory XRF analyses of major element variations for the principal rock types at the Macraes mine, compared to typical background Otago Schist compositions (*blue ellipses*). *Arrows* show principal hydrothermal alteration trends. Data mainly from Craw et al. (1999), Craw (2002) and Petrie and Craw (2005)

generally display the same negative correlation (Fig. 6.1b), because of initial micaceous origins, and because any albite present in the unmineralised precursors was altered to muscovite.

Epidote decomposition is one of the principal hydrothermal alteration reactions in the shear zone (Chap. 5), so both Ca and Al were mobilised to some extent during mineralisation. Nevertheless, the Al_2O_3 and CaO analytical data for black sheared rocks do not show major changes with mineralisation compared to host rocks (Fig. 6.1c). Also, despite the widespread replacement of silicates by iron-bearing sulphides (Chap. 5), there has been no overall change in the positive correlation between iron and magnesium that characterises unmineralised rocks (Fig. 6.1d). Chlorite is the principal Fe–Mg mineral in the unmineralised rocks, and any Fe and Mg mobilised by hydrothermal replacement of that chlorite has apparently been retained in the rocks.

The apparent lack of change in major element concentrations with alteration can be summarised by direct comparison of all the elements in a black sheared rock to an inferred similar micaceous schist precursor. This is presented as an isocon plot in Fig. 6.2. Major elements (top right) fall close to the 1:1 line that indicates

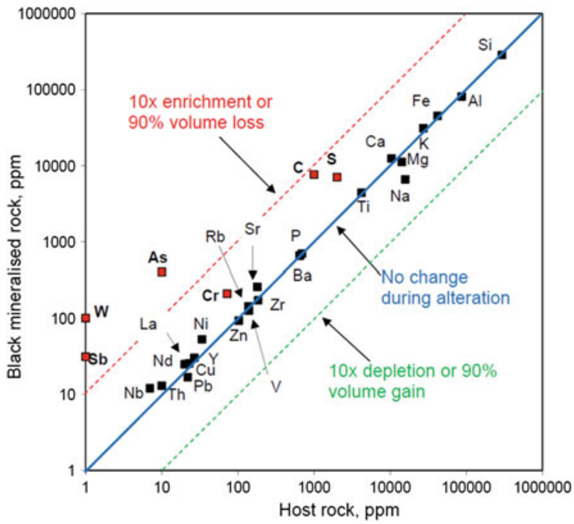

Fig. 6.2 Isocon plot comparing unaltered and altered black sheared schist at Macraes mine (modified from Craw 2002). Principal elements mobile during alteration are in *red* symbols

isochemical alteration. For this particular pair of rocks, there appears to have been minor sodium depletion, reflecting alteration of albite to muscovite. There is no evidence for volume gain by, for example, introduction of vein quartz to the mineralised rock. Conversely, there is no evidence for volume loss by, for example, displacement of major elements during sulphide mineral replacement. Aluminium and titanium, which are commonly considered to be immobile during hydrothermal alteration in general, have indeed remained immobile in the Macraes alteration processes.

6.2 Trace Elements

Most trace elements show the same sorts of relationships between unmineralised and mineralised rocks that occur with the major elements. Trace elements such as Zr, V and Y, which are commonly considered to be immobile like the major element Al, show no evidence for mobility at Macraes (Fig. 6.2). Likewise, Rb and Sr have remained immobile, following K_2O and CaO for which they commonly substitute. Even metals such as Cu, Pb, Zn that are common, although minor, in hydrothermal sulphides in the shear zone (Chap. 5) show no evidence for addition to the mineralised rocks (Figs. 6.2 and 6.3). Slightly lowered Cu and Zn contents of some black sheared rocks attest to minor dilution during silicification.

Chromium does show some evidence for enrichment during alteration of the black sheared rock depicted in Fig. 6.2, and this chromium enrichment is a widespread phenomenon in the Hyde-Macraes Shear Zone. Most host rocks have

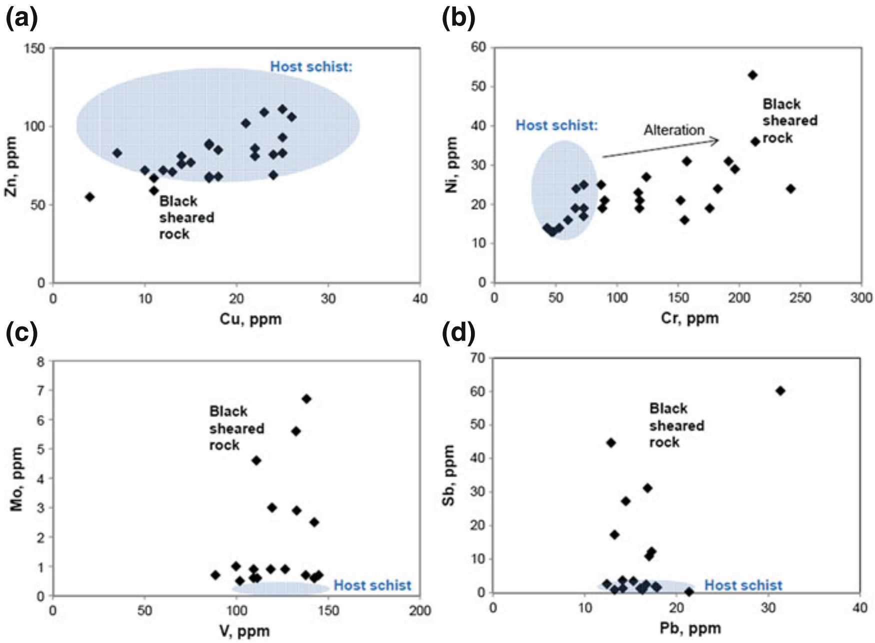

Fig. 6.3 Laboratory XRF trace element variations for variably mineralised black sheared schist at the Macraes mine, compared to typical background Otago Schist compositions (*blue ellipses*). Data mainly from Craw et al. (1999), Craw (2002) and Petrie et al. (2005)

<100 ppm Cr, and black sheared rocks range from these levels up to >200 ppm (Fig. 6.3b). More generally, Cr contents of mineralised rocks reach up to 500 ppm (Figs. 6.4b and 6.5). The rare occurrence of primary Cr enrichment in an unmineralised sample with a fuchsite-bearing conglomerate clast (Chap. 3) cannot explain the widespread Cr enrichment seen in the mineralised rocks. Rather, this Cr enrichment is related to the silicate replacement reactions that occurred in the mineralised rocks, and Cr has been mobilised from those silicates to be concentrated locally within the mineralised rocks, probably in hydrothermal muscovite. There has been minor Ni mobilisation at the same time (Fig. 6.3b), and at least some of that Ni was incorporated in hydrothermal pyrite (Chap. 5).

There has been slight enrichment in Mo in black sheared rocks during mineralisation (Fig. 6.3c). Molybdenum concentrations of Macraes hydrothermal pyrite are low but detectable (Large et al. 2012), and this pyrite is the principal repository for anomalous Mo. Scheelite does not typically occur in black sheared rocks, so Mo in solid solution in scheelite, common elsewhere in the world, is not responsible for the weak Mo anomaly in the Macraes black sheared rocks. Trace amounts of Mo do substitute in Macraes scheelite, however, so localised Mo enrichment of veined rocks does occur.

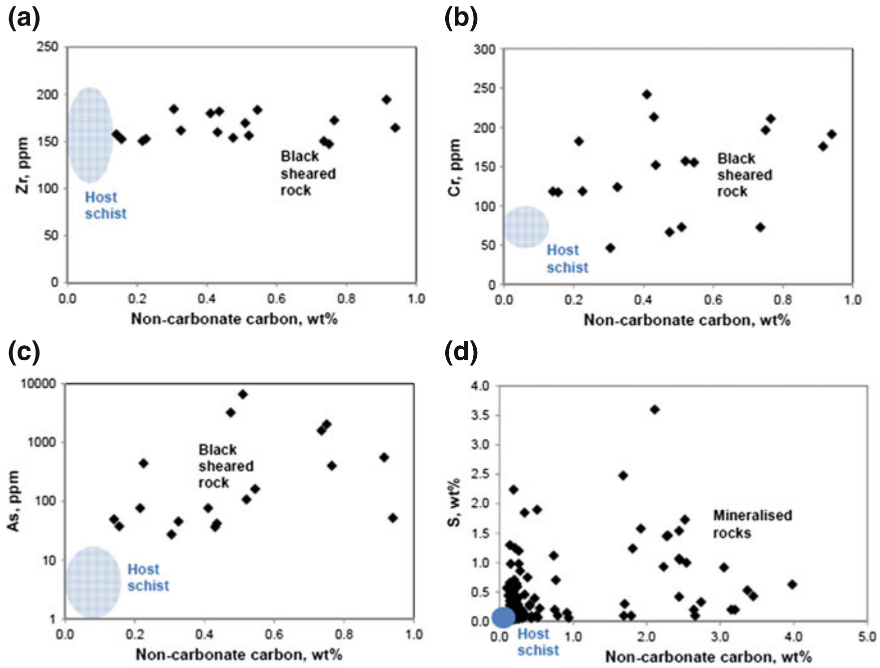

Fig. 6.4 Elemental variations for mineralised rocks with varying amounts of graphite (non-carbonate carbon analyses) at the Macraes mine, compared to typical background Otago Schist compositions (*blue ellipses*). Data mainly from Craw et al. (1999), Craw (2002) and Petrie et al. (2005)

6.3 Carbon and Sulphur

Carbonate contents of the mineralised rocks are highly variable because of the mobility of the common carbonate minerals calcite and siderite. Calcite is present as a metamorphic mineral in the host rocks, and is widespread as veins formed by all stages of mineralisation and post-mineralisation fluid activity (Chap. 5). Siderite is a product of hydrothermal alteration in the shear zone, but also became remobilised by subsequent fluid activity (Chap. 5). Hence, the carbonate contents of mineralised rocks, and changes in those carbonate contents with increasing alteration, have not been quantified. However, the non-carbonate carbon (graphite) content of altered rocks is a significant mineralogical feature of the shear zone, as discussed further in Chap. 8. This non-carbonate content has also been quantified extensively as part of ore characterisation for mineral processing (Chap. 9).

Direct comparison between black sheared rock and its inferred precursor (Fig. 6.2) suggests that carbon has been added to the rock while most of the other elements have remained unaffected by alteration. There is no evidence that the graphitic component of the rock has been concentrated by volume loss from this

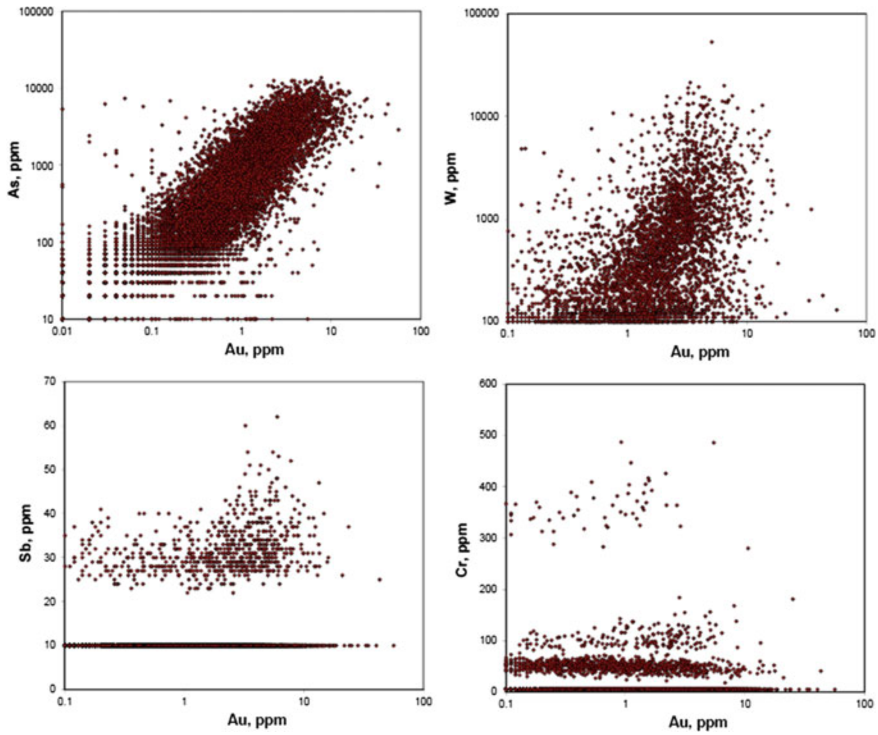

Fig. 6.5 General relationships between gold enrichment and As, W, Sb and Cr in mineralised rocks in the Hyde-Macraes Shear Zone. Gold analyses were by fire assay, and other elements analysed by portable XRF on the same material. Detection limit for portable XRF analyses is ~50 ppm for Cr, As, and W, and ~20 ppm for Sb

example of black sheared rock. This lack of volume loss is confirmed more generally in the shear zone by quantification of the concentrations of immobile elements in black sheared rocks compared to unmineralised host rocks. For example, Zr contents of host rocks are generally between 100 and 200 ppm, and all black sheared rocks have maintained this Zr concentration, irrespective of the amount of non-carbonate carbon present (Fig. 6.4a). In contrast, the non-carbonate carbon contents of black sheared rocks have weak positive correlations with elements associated with hydrothermal alteration and gold mineralisation. Chromium and arsenic, in particular, are enriched in rocks that have become enriched in non-carbonate carbon (Figs. 6.2 and 6.4b, c).

There is also a weak positive correlation between non-carbonate carbon and sulphur content of the black sheared rocks. Black sheared rocks typically, but not always, are enriched in sulphide minerals, especially pyrite (Chap. 5). Substantial amounts of hydrothermal sulphur (up to 5 wt%) have been added to the mineralised rocks compared to the generally low-sulphur host rocks. This sulphur addition accompanied the addition of hydrothermal non-carbonate carbon in black sheared rocks (Figs. 6.2 and 6.4d). Mineralised rocks dominated by veins do not show this relationship, and sulphur contents have risen without parallel increases in non-carbonate carbon.

6.4 Arsenic, Antimony and Tungsten

These three elements are the most significant additions to the hydrothermally altered rocks of the Hyde-Macraes Shear Zone (Figs. 6.2, 6.3 and 6.5). Arsenopyrite is the most important As mineral in highly mineralised rocks (Chap. 5), and this mineral is the principal repository for the weight percent levels of arsenic that occur in the most mineralised rocks (Fig. 6.5). This arsenopyrite is an important host for microparticulate gold (Chap. 5), so there is a positive correlation between As and Au in the shear zone overall (Fig. 6.5). Solid solution As in pyrite is important locally, and this solid solution As predominates in the earliest stages of shear development and hydrothermal alteration where pyrite is abundant and arsenopyrite is absent (Chap. 5). Arsenopyrite is the principal mineral to host Sb, in solid solution, in the most mineralised rocks (Fig. 6.5). However, boulangerite is a recurrent Sb-bearing accessory mineral in mineralised rocks as well (Chap. 5). Addition of Sb to form boulangerite was not accompanied by addition of Pb, which was derived from the host rocks during replacement reactions (Figs. 6.2 and 6.3d).

Tungsten occurs at low levels in solid solution in hydrothermal pyrite at Macraes (Large et al. 2012), and this W enrichment is responsible for the anomalous W contents of black sheared rocks (Fig. 6.2). Scheelite is the predominant W mineral in quartz veins, and is the host for the high levels of W in many Macraes mineralised rocks (Fig. 6.5). There is a weak positive correlation between W and Au in the mineralised rocks in the shear zone in general and this arises because many Au-bearing mineralised rocks, such as the black sheared rocks, do not contain scheelite and some scheelite-bearing quartz veins contain little gold. This localised separation of Au and W can be seen in more detail in analysed drill core profiles through the Hangingwall Shear (Fig. 6.6). When sampled at the metre scale, as in these profiles, high Au contents only rarely coincide exactly with high W contents. Sheared mineralised rocks enriched in Au in Fig. 6.6b, for example, have little W enrichment.

6.5 Gold Grades and Distribution

The gold contents of shear zone rocks have been measured routinely during mining, and a very large database has been compiled. Compilations of these data provide insights into the concentrations of gold in the rocks (gold grades), and the spatial distribution of these gold-bearing rocks. The central, most-mineralised, part of the shear zone has been the main focus for this compilation, and these data provide a

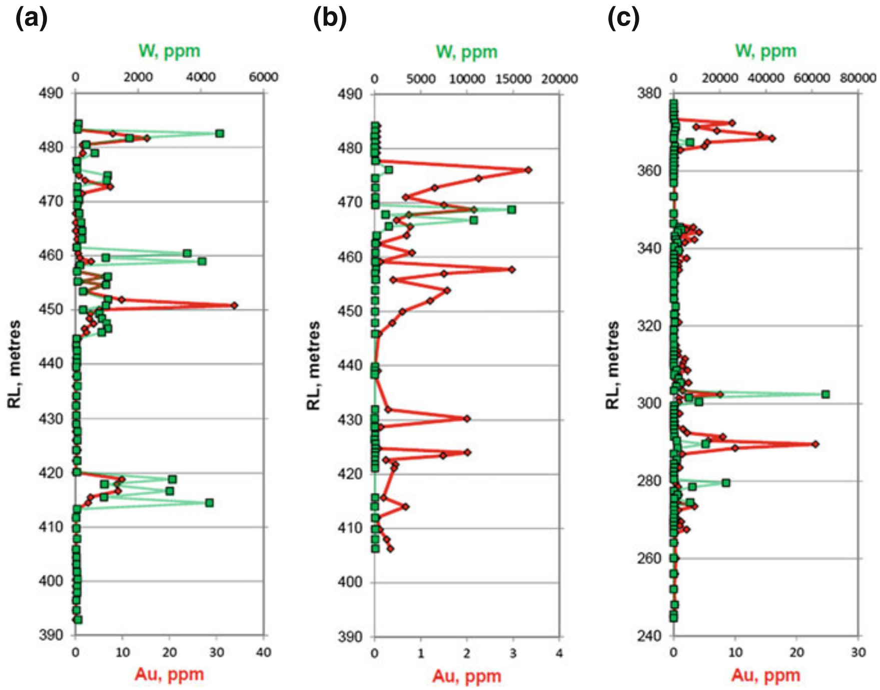

Fig. 6.6 Geochemical profiles for gold (fire assay) and tungsten (laboratory XRF) through the Hangingwall Shear (at top of each profile) at Round Hill open pit. RL is height above sea level. **a** Au-rich, W-poor profile with abundant veins. **b** W-rich profile with broad zones of Au-mineralised sheared schist. **c** W-rich profile with mixed sheared schist and veins, so Au-rich zones are near to, but not fully coinciding with, the W-rich zones

three-dimensional view of the gold-bearing portions of the altered rocks. The hydrothermal alteration zone extends for tens to hundreds of metres above these gold-enriched rocks, but gold contents of those altered rocks are generally very low and have not been investigated in detail.

On a large scale, the volume of shear zone rocks, in which gold contents are anomalous, changed substantially along strike (Fig. 6.7a). The Frasers open pit and underground mine had the greatest volume of mineralised rocks, and this decreased markedly immediately to the northwest, across the Macraes Fault. This cross-fault has a complex Middle Cretaceous to Pleistocene history, but may have developed by reactivation of some inhomogeneties within the Hyde-Macraes Shear Zone (Chap. 2). Northwest of this fault, the mineralised zone remained narrow for 2 km until it suddenly broadened again at the Round Hill open pit site. Rocks with relatively high gold grades are volumetrically minor within the overall mineralised package, but these higher grade rocks were most voluminous in the Frasers and Round Hill mining areas (Fig. 6.7b).

Within the narrower mineralised portion of the mined shear zone, there were two principal shear-dominated zones of mineralisation, and these were separated by

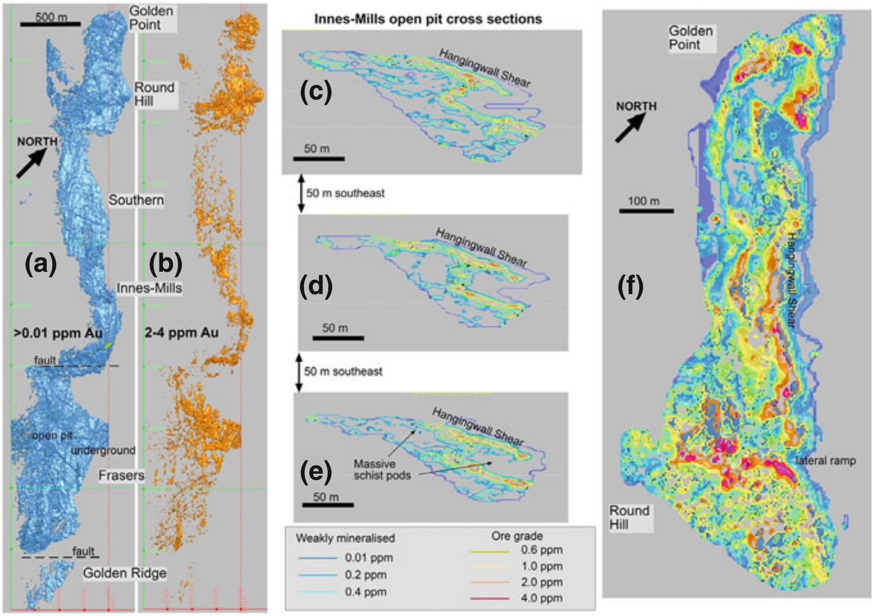

Fig. 6.7 Contoured gold contents (fire assay), from mine grade control data, of rocks in the Hyde-Macraes Shear Zone in the principal mineralised part of the shear zone. **a** Map view of extent of weakly mineralised rock. **b** Map view of distribution of gold-rich rocks. **c–e** Cross sections through the Innes-Mills open pit, drawn 50 m apart along strike, showing lateral and vertical gold grade variations. **f** Map view of a slice through the mineralised zone at Round Hill and Golden Point open pits. High grade zones have abundant quartz veins, including the lateral ramp in Round Hill pit (Fig. 4.10)

barren massive schist pods. This structure was laterally continuous on the 100 m scale only, and became more complex towards the northwest (Fig. 6.7c–f). Broadening of the mineralised zone at the Round Hill mine site was associated, at least in part, with a lateral ramp structure (Fig. 6.7f). This oblique structure linked several different mineralised shears, and was the locus for enhanced formation of a swarm of laminated veins (Fig. 4.10) that increased the gold content of that portion of the shear zone.

Southeast of the Macraes Fault, mining at the Frasers site focused initially on two sub-parallel mineralised shears (Fig. 6.8a) The uppermost of these shears was designated the Hangingwall Shear, although the exact structural relationship between this shear and the equivalent structure to the northwest (Fig. 6.7c–e) is not known. The main Frasers open pit was developed to follow the single Hangingwall Shear, and this was followed down-dip as an underground mine (Fig. 6.8). In addition, there was a thick zone of rock mineralised with laminated veins below the Hangingwall Shear in the Frasers open pit (Chap. 4), and this zone extended essentially to the Footwall Fault where it was truncated.

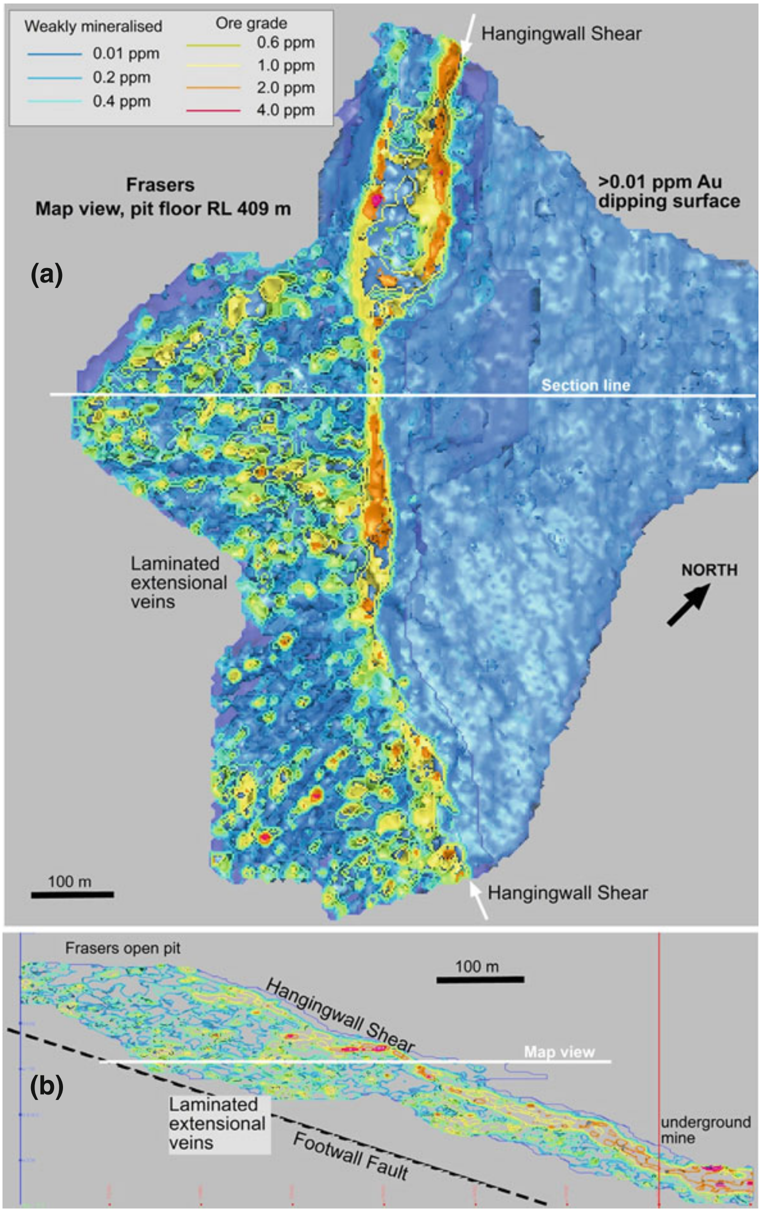

Fig. 6.8 Contoured gold contents (fire assay), from mine grade control data, of rocks in the Hyde-Macraes Shear Zone in Frasers open pit and underground mine. **a** Map view of the main mineralised zone (*left*), with dip extent of mineralised rocks below the mapped level to *right*. The Hangingwall Shear is the principal mineralised structure, but a subordinate shear at *top* was mineralised as well. Patchy elevated gold grades to southwest of the Hangingwall Shear is dominated by laminated veins with strikes perpendicular to the shear (Chap. 4). **b** Cross section through the open pit and underground mine

References

Craw D (2002) Geochemistry of late metamorphic hydrothermal alteration and graphitisation of host rock, Macraes gold mine, Otago Schist, New Zealand. Chem Geol 191: 257-275

Craw D, Windle SJ, Angus PV (1999) Gold mineralisation without quartz veins in a ductile-brittle shear zone, Macraes Mine, Otago Schist, New Zealand. Mineral Deposita 34: 382-394.

Jones P, Craw D, Norris RJ (2007) Golden Bar gold deposit as an extension of the Hyde-Macraes Shear Zone, east Otago, New Zealand. NZ J Geol Geophys 50: 271-281

Large R, Thomas H, Craw D, Henne A, Henderson S (2012) Diagenetic pyrite as a source for metals in orogenic gold deposits, Otago Schist, New Zealand. NZ J Geol Geophys 55: 137-149

McKeag SA, Craw D, Norris RJ (1989) Origin and deposition of a graphitic schist-hosted metamorphogenic Au-W deposit, Macraes, East Otago, New Zealand. Mineral Deposita 24: 124-131

Mortimer N, Roser BP (1992) Geochemical evidence for the position of the Caples-Torlesse boundary in the Otago Schist. J Geol Soc London 149: 967-977

Petrie BS, Craw D (2005) Lithological controls on structural evolution of mineralised schist, Macraes gold mine, Otago, New Zealand. NZ J Geol Geophys 48: 435-446

Petrie BS, Craw D, Ryan CG (2005) Geological controls on refractory ore in an orogenic gold deposit, Macraes mine, New Zealand. Mineral Deposita 40: 45-58

Chapter 7
Fluid Inclusions and Isotopic Signatures

7.1 Fluid Inclusion Compositions

Fluid inclusions in mineralised quartz veins in the Hyde-Macraes Shear Zone are broadly homogeneous in composition across the whole gold deposit (McKeag and Craw 1989; de Ronde et al. 2000). The water-rich, low-salinity fluid compositions at Macraes (Table 7.1) are similar to greenschist facies metamorphic fluids in the host Otago Schist belt (Craw and Norris 1991). These fluids are distinctly different from the more inhomogeneous, variably saline (up to 5 wt% NaCl equivalent), and variably CO_2-rich inclusions that characterise the younger (110–100 Ma), extension-related orogenic gold deposits that occur nearby (Chap. 3; McKeag and Craw 1989). Macraes fluid inclusions related to mineralisation are uniformly two-phase water at room temperature, whereas some of the younger deposits have coexisting two and three phase inclusions with evidence for CO_2 immiscibility and boiling.

In detail, the low salinity Macraes fluid inclusions show some salinity variations, from 0.2 to 3 wt% NaCl equivalent, indicative of some mixing of fluids of differing compositions within the mineralising system (de Ronde et al. 2000). The dissolved component of the fluid inclusions is dominated by chlorides, with minor amounts of other halogens (<1 %; Table 7.1). Sodium is the principal cation dissolved with the chlorides (de Ronde et al. 2000). Dissolved volatile components form <1 % of the fluid, with minor coexisting carbon dioxide, methane, and nitrogen (Table 7.1). Traces of hydrocarbons (<1 ppm combined) include C_2H_6, C_3H_4, and C_3H_6 (de Ronde et al. 2000). I/Cl and Br/Cl ratio of the mineralising fluid extracted from mineralised quartz is similar to, but more dilute than, brines in marine sediments (Table 7.1). These halogen ratios are distinctly higher than typical magmatic and/or mantle fluids, and the elevated I/Cl ratio indicates that there was extensive interaction between mineralising fluid(s) and host metasediments (Goodwin et al. 2016).

Mineralising fluid density was 0.90–0.94 g/cm^3, with most data near to 0.91 g/cm^3. Homogenisation temperatures of the two-phase inclusions are generally between 120° and 150 °C, although some higher and lower temperatures occur

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Table 7.1 Measurements and estimates of properties of the Macraes mineralising fluid based on fluid inclusion analyses and related mineralogy

Fluid property	Value range
Water content	>99 mol%
Water density	0.90–094 g/cm^3
Salts	Typically ~1 wt%, range 0.2–3 wt% NaCl equiv, chloride-dominated
I/Cl halogen ratio	10^{-5}–10^{-3}
Br/Cl halogen ratio	10^{-3}–10^{-2}
CO_2 proportion	0.1–0.8 mol%
CH_4 proportion	0.1–0.2 mol%
N_2 proportion	0.03–0.3 mol%
Homogenisation temperature	110°–190 °C
Trapping temperature	300°–400 °C (arsenopyrite geothermometer)
Inferred trapping pressure	2.5–4 kbar
Inferred depth of emplacement	10–15 km
^{2}H of inclusion fluid	−43 to −78 ‰
δ^{18}O of inclusion fluid	9–11 ‰ (calculated from quartz)
δ^{13}C of inclusion fluid	0 to −11 ‰ (calculated from calcite)
Fluid ^{40}Ar/^{36}Ar ratio	400–800
Fluid ^{132}Xe/^{36}Ar ratio	0.05–0.2
Fluid helium R/Ra ratio	0.02–0.04 (no detectable mantle He)

Data and interpretations from McKeag and Craw (1989), Craw and Norris (1991), de Ronde et al. (2000), and Goodwin et al. (2016)

(Table 7.1). These data, combined with mineralisation temperature estimates (Chap. 5) imply entrapment of the fluid inclusions at 2.5–4 kbars fluid pressure (McKeag and Craw 1989; Craw and Norris 1991). These estimates are consistent with the lower greenschist facies mineralisation conditions inferred from the deposit mineralogy and structural style (Chap. 5).

7.2 Fluid Inclusion Water Stable Isotopes

The δ^{18}O of the mineralising fluid, calculated from the δ^{18}O of the host quartz at 350 °C, shows a very narrow range of values, from +9 to +11 ‰ (Figs. 7.1a and 7.2; Table 7.1; de Ronde et al. 2000). This narrow range of fluid δ^{18}O is characteristic of fluid that has interacted extensively with the schist host rock, and is widespread in metamorphic-hydrothermal systems throughout the schist belt (Jenkin et al. 1994; Templeton et al. 1998; Menzies et al. 2014). Irrespective of the

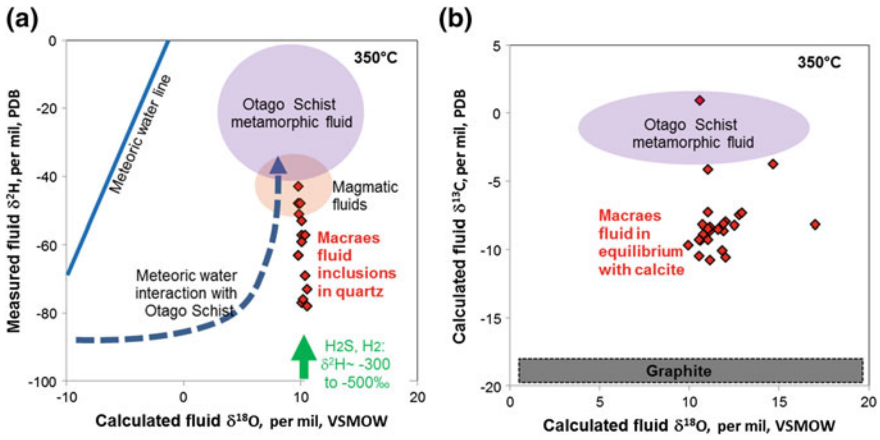

Fig. 7.1 Isotopic signatures of the mineralising fluid at Macraes mine, from direct measurements and calculated values from mineral data (adapted from McKeag and Craw 1989; McKeag et al. 1989; Craw and Norris 1991; Jenkin et al. 1994; Templeton et al. 1998; de Ronde et al. 2000; Craw 2002; and Menzies et al. 2014). **a** Fluid inclusions in quartz at Macraes compared to other potential isotopic reservoirs. **b** Calculated fluid in equilibrium with calcite, compared to host Otago Schist and graphitic carbon isotopic signature

initial fluid δ^{18}O ratio, fluid-rock interaction reactions rapidly exchange isotopes between oxygen-rich rocks and the fluid, resulting in homogenisation of oxygen isotopes in the hydrothermal system.

In contrast, fluid δ^{2}H (=δD) in measured fluid inclusions in quartz veins show a broad range of values, from −43 to −78 ‰ (Figs. 7.1a and 7.2; Table 7.1; de Ronde et al. 2000). This broad range is consistent with the range of salinities seen in primary fluid inclusions, and is not the result of incorporation of a component of younger secondary inclusions, which are rare in the deposit (de Ronde et al. 2000). Rather, the range of fluid δ^{2}H values is indicative of inhomogeneous mineralising fluid(s). The higher δ^{2}H end of the observed range has resulted from fluid interaction with the host rock, as for the oxygen data, and may indicate a trend towards a metamorphic fluid end-member (Fig. 7.1a). The absence of magmatic rocks in the surrounding geological setting (Chap. 2) precludes involvement of magmatic rocks in this fluid-rock interaction process.

The lower fluid δ^{2}H end of the range may be indicative of a meteoric water input into the hydrothermal system, as observed in a modern hydrothermal system in schists of similar composition near the active Alpine Fault to the west (Chap. 9). Similar evolution of fluid δ^{2}H and δ^{18}O ratios occurs in this modern system, as indicated in Fig. 7.1a (Jenkin et al. 1994; Menzies et al. 2014). The lowest fluid δ^{2}H in the Macraes data implies either high altitude (mountain) meteoric water incursion, as in the modern system (Menzies et al. 2014) or high latitude precipitation, or some combination of these. Alternatively, or as well, sulphidation reactions during

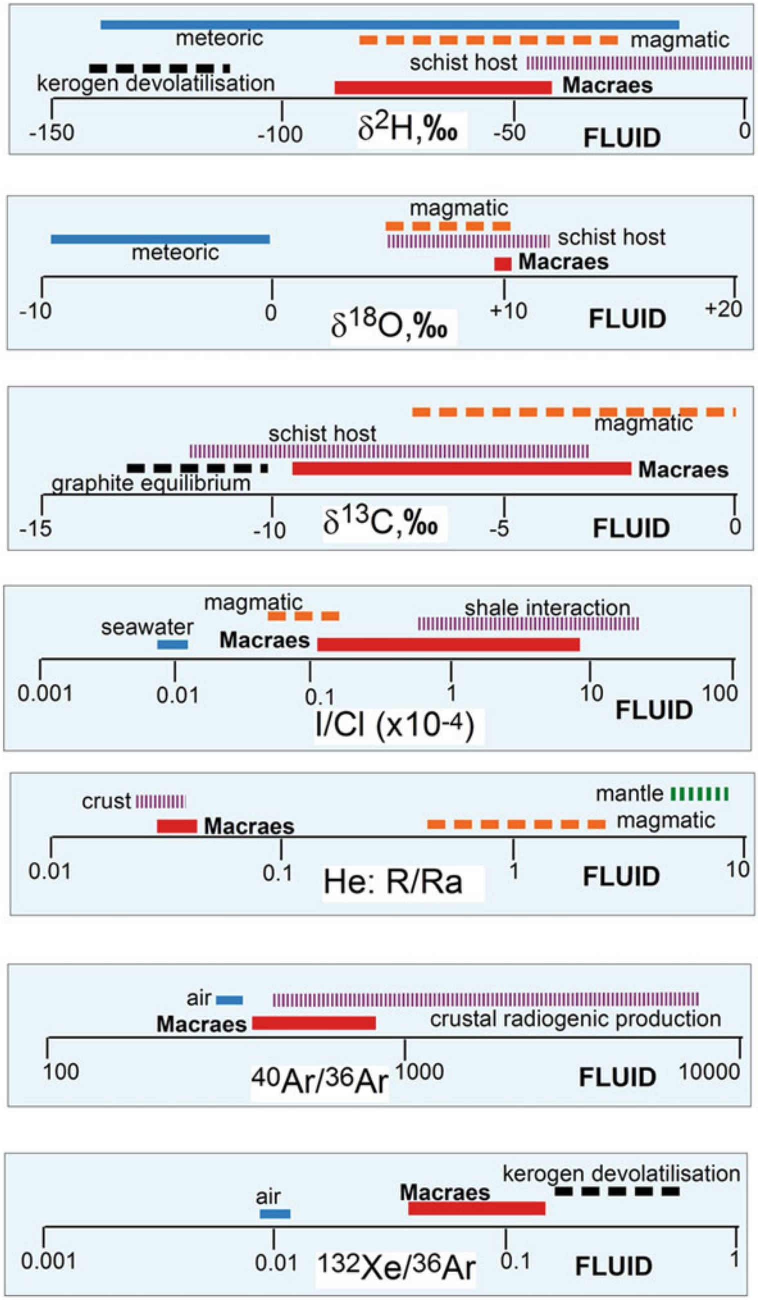

Fig. 7.2 Summary comparison of isotopic signatures of mineralisation at Macraes mine and other relevant isotopic reservoirs (adapted from McKeag and Craw 1989; McKeag et al. 1989; Craw and Norris 1991; Jenkin et al. 1994; de Ronde et al. 2000; Craw 2002; Menzies et al. 2014; and Goodwin et al. 2016)

hydrothermal alteration of the Hyde-Macraes Shear Zone may have contributed to a low water δ^2H end-member (Craw 2002):

$$2FeO(silicates) + H_3AsO_3(aq) + 0.5H_2(\delta D = -500\,‰) + 3H_2S(\delta^2H = -400\,‰)$$
$$=> FeS_2 + FeAsS + 5H_2O(\delta^2H = -300\,‰)$$

7.3 Fluid Inclusion Noble Gases

Most noble gas compositions in Macraes quartz fluid inclusions show broad variations in isotopic ratios that are indicative of mixing of fluids during mineralisation, and/or variable interaction between mineralising fluid(s) and host rock metasediments (Goodwin et al. 2016). Helium can leak from quartz-hosted fluid inclusions, and sulphide minerals provide more robust helium hosts. Fluids extracted from sulphide-bearing inclusions yield helium R/Ra values of ~0.03, indicative of crustal signatures, with no evidence for any mantle or mantle-linked magmatic component (Table 7.1; Fig. 7.2).

The ^{40}Ar/^{36}Ar ratios of fluids from Macraes quartz show a broad range, from 400 to nearly 800, indicating inhomogeneous fluid with a predominant radiogenic ^{40}Ar component from radioactive decay in crustal rocks. Xenon extracted from fluid inclusions in mineralised quartz has been relatively enriched in ^{132}Xe, with ^{132}Xe/^{36}Ar ratios up to 200 times greater than air (Table 7.1). These high ratios have arisen from extensive interaction between fluid and maturing organic material within the metasedimentary host rocks (Goodwin et al. 2016).

In contrast, the ^{21}Ne/^{22}Ne, air-normalised ^{84}Kr/^{36}Ar, and ^{131}Xe/^{132}Xe ratios for fluid inclusions are near to air or air-saturated water ratios, and imply some component of meteoric water in the Macraes mineralising system (Goodwin et al. 2016). The various noble gas data support the inferences from inclusion salinity variations, and water δ^2H and δ^{18}O ratios, that the mineralising fluid was inhomogeneous and involved at least two components (Figs. 7.1a and 7.2). One of the components was fluid that had interacted extensively with the host schist, and another component was meteoric water, possibly augmented by low δ^2H water from sulphidation reactions.

7.4 Calcite Stable Isotopes

The relatively uniform δ^{18}O ratio of the mineralising fluid, near to 10 ‰, is apparent in isotopic data calculated from calcite analyses in the Hyde-Macraes Shear Zone (Figs. 7.1b and 7.2). These estimates are less robust and more variable than the estimates derived from quartz, as calcite has been remobilised throughout the mineralisation and post-mineralisation history (Chap. 5). Nevertheless, the Macares estimates are similar to, and less variable than, estimates of metamorphic fluid $\delta^{18}O$ ratio derived from carbonates within the host schist (Fig. 7.1b).

The calculated $\delta^{13}C$ ratio for dissolved carbon in the mineralising fluid shows a broad range, from 0 to −11 ‰. This range has some overlap with values calculated for the host schist metamorphic fluid, but most fluid $\delta^{13}C$ values are considerably lighter than the host schist metamorphic fluid (Fig. 7.1b). This shift to lighter values is a result of partial equilibration, and re-equilibration, of fluids between calcite in the metamorphic host rocks and the graphite in the most mineralised rocks that has distinctly light $\delta^{13}C$ (Figs. 7.1b and 7.2).

7.5 Rock Isotopic Signatures

Nitrogen in the Otago Schist originally entered the metasedimentary pile in detrital organic matter, and is progressively released with increasing metamorphic grade to be incorporated into other minerals and the metamorphic fluid (Pitcairn et al. 2005). Liberated nitrogen commonly replaces potassium in phengites in these metamorphic rocks. This nitrogen, which is present at low levels (typically 100–400 ppm) in the micas, has $\delta^{15}N$ between 2 and 6 ‰ in Torlesse Terrane rocks that host the Hyde-Macraes Shear Zone (Fig. 7.3a). Nearby Caples Terrane parts of the Otago Schists have similar N concentrations and $\delta^{15}N$ values (Fig. 7.3a). Additional nitrogen, with similar isotopic signatures, remains in partially recrystallised organic material (Pitcairn et al. 2005). Mineralised Macraes rocks, which have abundant hydrothermal white micas as well as relict metamorphic phengite (Chap. 5), have nitrogen with $\delta^{15}N$ in those micas that overlaps with the range in the host rocks,

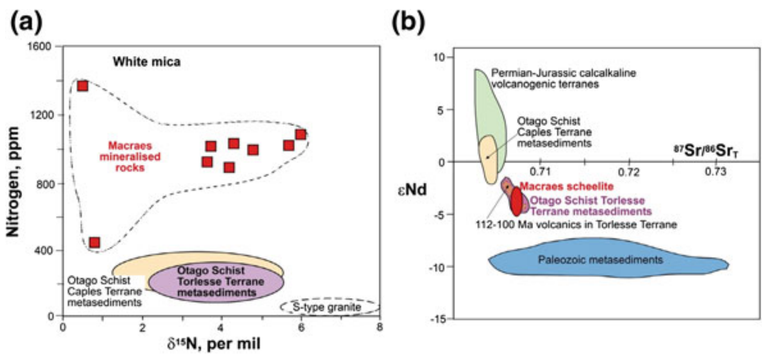

Fig. 7.3 Comparison of mineral and rock isotopic signatures in the Hyde-Macraes Shear Zone with host rock Torlesse Terrane and nearby terranes in southern New Zealand. **a** Nitrogen isotopic ratios and associated nitrogen contents of white mica separates (modified from Pitcairn et al. 2005). Strontium and neodymium isotopic signature of Macraes scheelite (data from Adams et al. 2005; Tulloch et al. 2009; Farmer et al. 2012)

albeit with some lighter values as well (Fig. 7.3a). These mineralised rocks have been strongly enriched in nitrogen, up to 1200 ppm, compared to the host rocks (Fig. 7.3a) during the mineralisation process.

Mineralisation processes, dominated by replacement reactions, have mobilised nitrogen from both the phengite and the remnants of organic matter into the Al-rich hydrothermal white mica that dominates the black sheared rocks. There is no evidence for any external source(s) of nitrogen, such as magmatism, within the Macraes hydrothermal system (Figs. 7.3a and 7.4). Similarly, sulphur from the disseminated metamorphic pyrite in the host rocks has been mobilised into the mineralised rocks of the Hyde-Macraes Shear Zone, with little or no change in isotopic signature. Macraes hydrothermal pyrite and arsenopyrite have $\delta^{34}S$ in a narrow range between 0 and −3 ‰, which overlaps the host rock $\delta^{34}S$ which ranges from +2 to −5 ‰ (Fig. 7.4).

The strontium and neodymium isotopic signatures of the Macraes scheelite closely overlaps the signature of the Torlesse Terrane host schist (Fig. 7.3b; Farmer et al. 2012). The Sr and Nd signature of mineralised rocks and host are distinctly

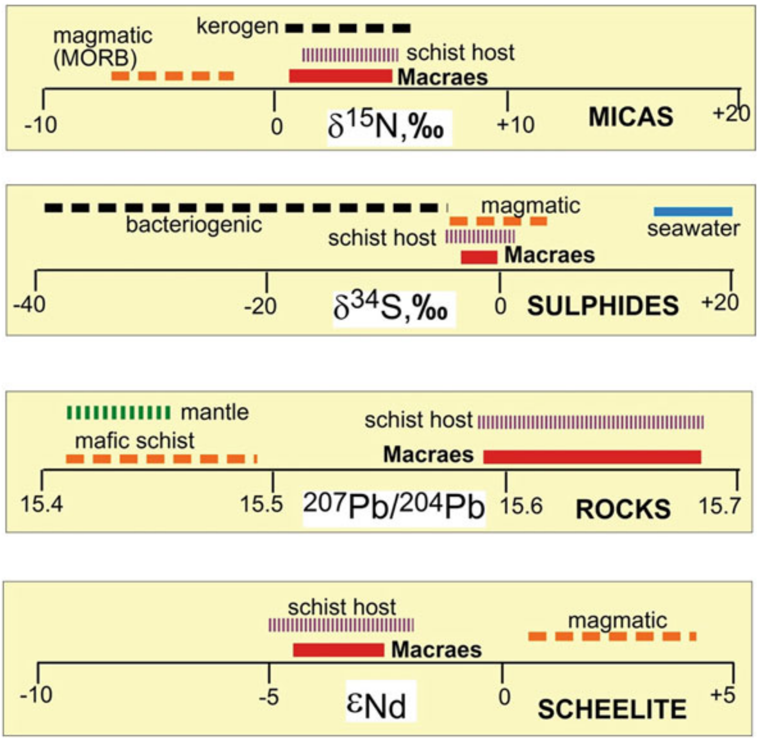

Fig. 7.4 Summary comparison of isotopic signatures of mineralised rocks and minerals at Macraes mine and other relevant isotopic reservoirs. Adapted from Craw et al. (1995), Pitcairn et al. (2005), Mortensen et al. (2010), Farmer et al. (2012)

different from the nearby Caples Terrane in the Otago Schist belt, and from other terranes in southern New Zealand (Fig. 7.3b). Any magmatic rocks derived from these terranes have similar Sr and Nd signatures to the hosting metasediments, as indicated by the sparse subaerial volcanic remnants of middle Cretaceous rocks resting on Otago Schist basement that were coeval with the younger phase of gold mineralisation (Figs. 7.3b and 7.4). However, the absence of magmatism coeval with Macraes mineralisation precludes a magmatic input into that stage of mineralisation. Instead, the abundant scheelite within the Hyde-Macraes Shear Zone has merely inherited the Sr and Nd isotopic signature of the host rocks with which the hydrothermal fluids had extensively interacted and replaced during mineralisation.

Lead isotopes show the same close relationship between host rock signature and the signature of mineralised rocks in the Hyde-Macraes Shear Zone that has been indicated by the other tracers outlined above (Figs. 7.4 and 7.5; Mortensen et al. 2010). The Macraes data fall almost entirely in a narrow cluster that overlaps the Pb evolutionary band of the Torlesse Terrane host rocks (Fig. 7.5). There is no indication from these data (Figs. 7.4 and 7.5) that any of the hydrothermal Pb at Macraes has been derived from metabasaltic rocks that occur locally within the Otago Schist metasedimentary pile (Chap. 2). While some Pb may have been extracted from the metabasalts, the vast majority of the Pb involved in mineralisation has been extracted from the metasedimentary rocks. This is consistent with the geochemical observations (Chap. 6) that Pb was not enriched during mineralisation, and has merely been remobilised from the host rocks during replacement reactions, largely to form hydrothermal boulangerite and galena (Chap. 5).

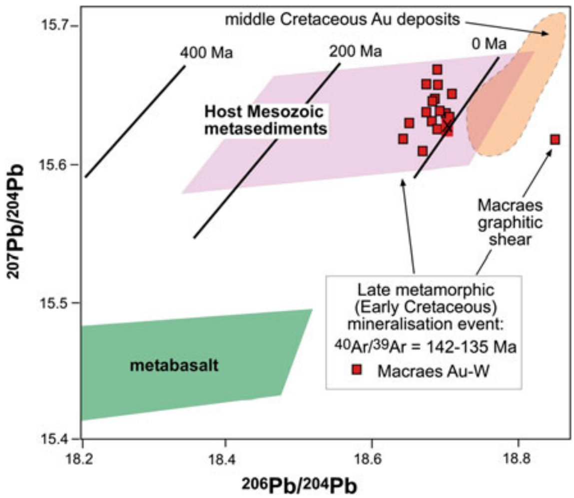

Fig. 7.5 Lead isotopic ratios for sulphides from Macraes mineralised rocks compared to the host Torlesse Terrane metasediments (depicted with Pb evolutionary trend) and the Pb signature of the younger phase of gold mineralisation in the region (summarised from Mortensen et al. 2010)

References

Adams C, Pankhurst R, Maas R, Millar I (2005) Nd and Sr isotopic signatures of metasedimentary rocks around the South Pacific margin and implications for their provenance. Geol Soc London Special Publ 246:113-141

Craw D (2002) Geochemistry of late metamorphic hydrothermal alteration and graphitisation of host rock, Macraes gold mine, Otago Schist, New Zealand. Chem Geol 191: 257-275

Craw D, Norris RJ (1991) Metamorphogenic Au-W veins and regional tectonics: mineralisation throughout the uplift history of the Haast Schist, New Zealand. NZ J Geol Geophys 34: 373-383

Craw, D, Hall, AJ, Fallick, AE, Boyce, AJ (1995) Sulphur isotopes in a metamorphogenic gold deposit, Macraes mine, Otago Schist, New Zealand. NZ J Geol Geophys 38: 131-136

deRonde CEJ, Faure K, Bray CJ, Whitford DJ (2000) Round Hill shear zone-hosted gold deposit, Macraes Flat, Otago, New Zealand: evidence of a magmatic ore fluid. Econ Geol 95: 1025-1048

Farmer L, Palin JM, Moore J, Teagle DAH, Stirling C (2012) The geochemistry and isotopic signature of scheelite from the Macraes orogenic gold deposit. Proc Ann Conference, NZ Branch Aust Inst Min Metall, pp 145-153

Goodwin NJ, Burgess R, Craw D, Teagle DAH, Ballentne CJ (2016) Noble gases fingerprint a metasedimentary fluid source in the Macraes orogenic gold deposit, New Zealand. Mineral Deposita. doi:10.1007/s00126-016-0648-x

Jenkin GRT, Craw D, Fallick AE (1994) Stable isotopic and fluid inclusion evidence for meteoric fluid penetration into an active mountain belt; Alpine Schist, New Zealand. J Metamorphic Geol 12: 429-444

McKeag SA, Craw D (1989) Contrasting fluids in gold-quartz vein systems formed progressively in a rising metamorphic belt: Otago Schist, New Zealand. Econ Geology 84: 22-33

McKeag SA, Craw D, Norris RJ (1989) Origin and deposition of a graphitic schist-hosted metamorphogenic Au-W deposit, Macraes, East Otago, New Zealand. Mineral Deposita 24: 124-131

Menzies CD, Teagle DAH, Craw D, Cox SC, Boyce AJ, Barrie, CD, Roberts S (2014) Incursion of meteoric waters into the ductile regime in an active orogen. Earth Planet Sci Letters 399: 1-13

Mortensen JK, Craw D, MacKenzie DJ, Gabites JE, Ullrich T (2010) Age and origin of orogenic gold mineralisation in the Otago Schist belt, South Island, New Zealand: Constraints from lead isotope and $^{40}Ar/^{39}Ar$ dating studies. Econ Geol 105: 777-793

Pitcairn IK, Teagle DAH, Kerrich R, Craw D, Brewer TS (2005) The behaviour of nitrogen and nitrogen isotopes during metamorphism and mineralisation: Evidence from the Otago and Alpine Schists, New Zealand. Earth Planet Sci Letters 233: 229-246

Templeton AS, Chamberlain CP, Koons PO, Craw D (1998) Stable isotope evidence for mixing between metamorphic fluids and surface-derived waters during recent uplift of the Southern Alps, New Zealand. Earth Planet Sci Letters 154: 73-92

Tulloch AJ, Ramezani J, Mortimer N, Mortensen J, van den Bogaard P, Maas R (2009) Cretaceous felsic volcanism in New Zealand and Lord Howe Rise (Zealandia) as a precursor to final Gondwana breakup. Geol Soc London Special Paper 321: 89-118

Chapter 8
Graphite and Shear Zone Evolution

8.1 Graphite in the Otago Schist Belt

Graphitic carbonaceous material is widespread in the Otago Schist belt, and the Hyde-Macraes Shear Zone is the most extensive and focussed of these occurrences. The graphitic material has two principal forms and textures: primary organic matter that became progressively metamorphosed in the schist pile, and hydrothermal graphite that occurs in cross-cutting structures. The two forms are linked, as the hydrothermal graphite was derived from the primary carbonaceous material by metamorphic remobilisation of carbon. Both types of graphite are present in the Hyde-Macraes Shear Zone, and have been intimately involved in formation of the gold deposit.

The primary graphitic material originated as micron-scale detrital fragments that are dispersed through the protolith sediments, especially the argillites (Henne and Craw 2012; Hu et al. 2015). The fragments are angular and original plant cell structures are commonly preserved in the lowest grade protoliths. With increasing metamorphic grade, this material became deformed and variably recrystallised, and was typically concentrated with metamorphic muscovite in the micaceous segregations and associated foliation. Some of the graphitic material also became incorporated into quartzofeldspathic laminae. All the metamorphic graphitic material remained fine grained (micron scale) and is dispersed amongst the silicates as dusty inclusions (Hu et al. 2015). Further recrystallisation and reorientation of the graphitic material occurred during syn-metamorphic and late-metamorphic folding and axial surface cleavage and microshear development. This latter texture is common in some micaceous schists that form host rocks to the Hyde-Macraes Shear Zone (Henne and Craw 2012; Hu et al. 2015).

Hydrothermal graphite has formed in a range of syn-metamorphic, late-metamorphic, and post-metamorphic structures throughout the Otago Schist belt (Henne and Craw 2012). This graphite is relatively coarse grained (>100 µm scale) and forms veins that are locally centimetre scale (Fig. 8.1). Some

D. Craw and D. MacKenzie, *Macraes Orogenic Gold Deposit (New Zealand)*,
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early-formed graphite has been disrupted by on-going deformation during evolution of the hosting structures, and slickensided graphitic shears occur in some structures (Fig. 8.1). The graphite forms more than 50 % of many of the veins, and is accompanied by quartz, chlorite, muscovite, and some quartz (Fig. 8.1). Pyrite occurs in some graphite veins, and rare pyrrhotite occurs in the host rocks and metamorphic veins as well. Graphitic veins in sub-greenschist facies rocks sharply crosscut the metamorphic fabric, although some veins are confined to particular rock types, especially argillaceous rocks and their metamorphosed equivalents.

Hydrothermal graphite in the Hyde-Macraes Shear Zone is finer grained (micron scale) than the lower grade material, and is focussed in microshears that are sub-parallel to the metamorphic foliation (Fig. 8.2; Chaps. 3, 4 and 5). Hence, the distinction is subtle between metamorphosed primary graphite and introduced hydrothermal graphite in the Hyde-Macraes Shear Zone, and both types occur within many micaceous schists. The hydrothermal graphite is commonly accompanied by hydrothermal rutile (Chap. 5), which adds to the dark colour of the shears (Fig. 8.2). Likewise, the graphitic shears in mineralised rocks also contain sulphide porphyroblasts, typically replacing pre-existing metamorphic and/or hydrothermal silicates. The end results of these changes is formation of black sheared rock (Chap. 3), and mineralised black shears (Chaps. 4, 5 and 6).

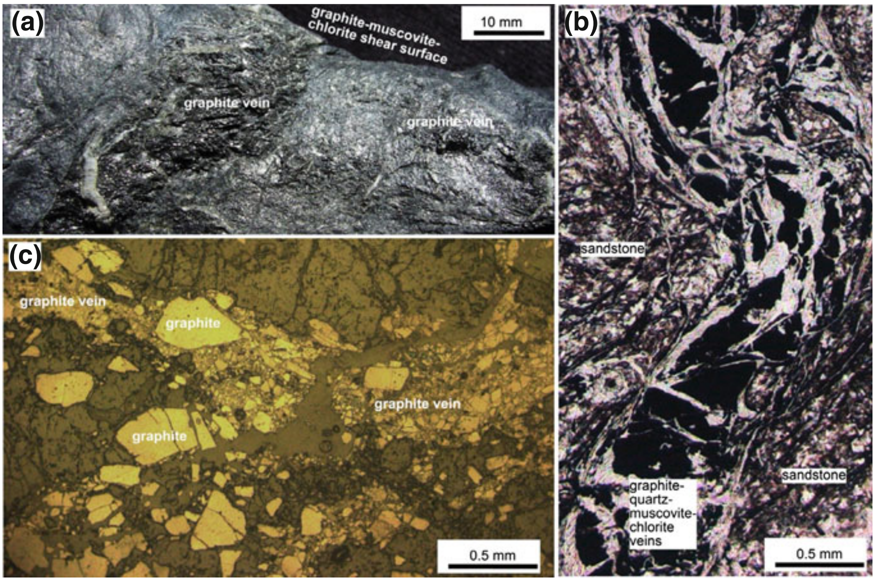

Fig. 8.1 Graphite veins in sub-greenschist facies protoliths of the Macraes host schist (modified from Henne and Craw 2012). **a** Centimetre scale graphite veins, with quartz and chlorite, in a shear zone with graphitic shear surfaces (*shiny*). **b** Thin section view (*plain light*) of a pure graphite vein (*black*) cutting weakly foliated sandstone. **c** Incident light view of graphitic veins with brecciated coarse single-crystal graphite clasts (*yellow-brown*) cutting across low grade quartz-rich schist (*dark grey*)

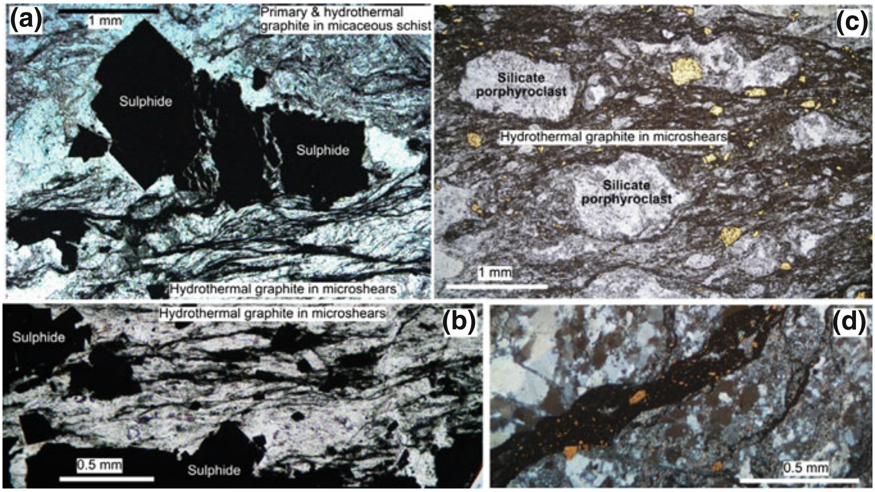

Fig. 8.2 Thin section images of graphite (*thin black seams*) in sulphide-bearing black sheared schists of the Hyde-Macraes Shear Zone. **a** Crossed polar view, with abundant metamorphic and hydrothermal muscovite (*shades of blue*) and sulphide porphyroblasts. **b** Plain light view of graphite seams in hydrothermal muscovite (*white*). **c** Plain light view with incident light to show disseminated sulphides (*yellow*) within the graphitic seams. **d** Crossed polars with incident light, showing graphitic stylolitic seams with fine sulphides (*yellow-brown*) cutting silicified schist

8.2 Mineralogical Characteristics of Graphitic Material

Primary and hydrothermal graphitic material became progressively more crystalline with increasing metamorphic grade of the host rocks. Reflectance in visible light becomes progressively higher, from <2 % in the lowest grade rocks to ~7 % in the Hyde-Macraes Shear Zone (Fig. 8.3). Reflectance of hydrothermal graphite in the most mineralised rocks at Macraes is slightly higher than the graphite in the host schists (Fig. 8.3; McKeag et al. 1989). Coarse grained hydrothermal graphite in sub-greenschist facies rocks shows strong reflectance anisotropy; for example the different shades of yellow reflected light in Fig. 8.1c are a result of this anisotropy. The increasing reflectances are a result of increasing crystallinity towards ordered graphite, although that is not fully reached in the Macraes deposit.

The increasing graphite crystallinity is also shown by increased ordering of the graphite structure as quantified by X-ray diffraction and Raman spectroscopy (Fig. 8.3; Landis 1971; Hu et al. 2015). Sub-greenschist facies graphite has strongly disordered structure, even in hydrothermal veins (Fig. 8.3). The Macraes graphitic material, in both mineralised and unmineralised rocks is distinctly more ordered than in the lower grade rocks, although there is still some disorder compared to crystalline graphite (Fig. 8.3). There are small differences in amounts of

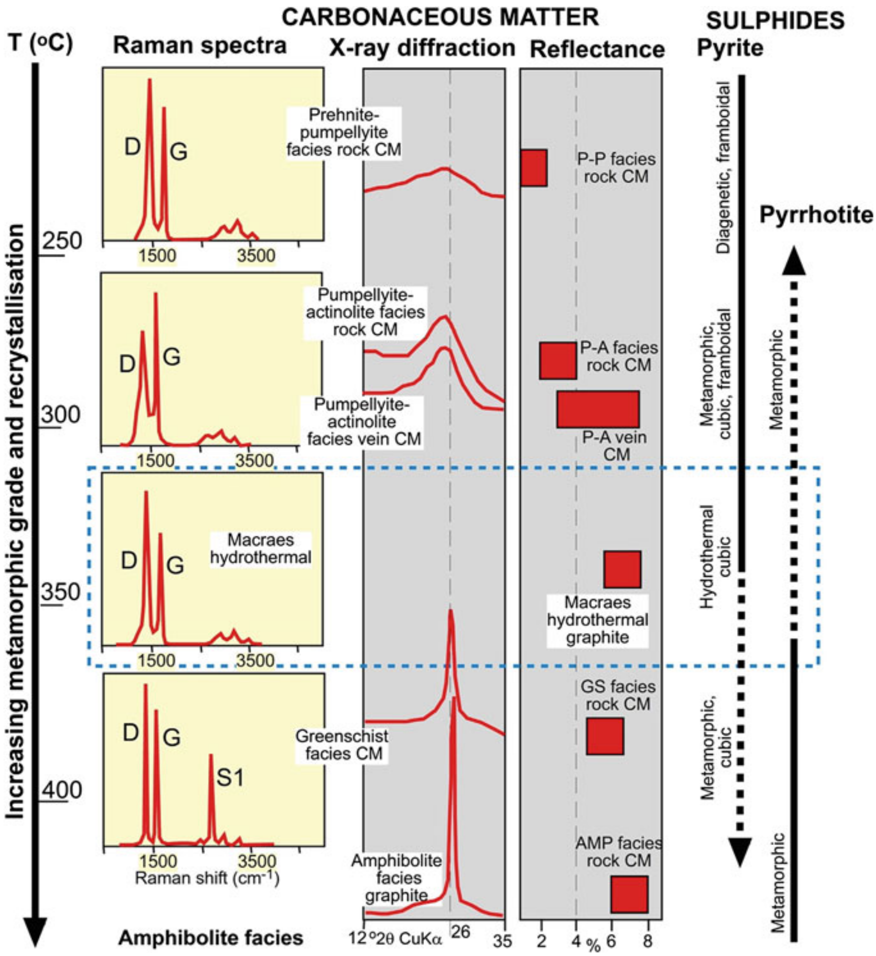

Fig. 8.3 Summary of the principal mineral transformations related to graphitic material in the Hyde-Macraes Shear Zone, its host schist, and its lower grade (sub-greenschist facies) protoliths (modified from Hu et al. 2015)

Raman-quantified disorder in the crystal structure between the metamorphic and hydrothermal graphite at Macraes, with the hydrothermal material showing more disorder (Fig. 8.4). In contrast, infrared analysis shows that the host rock graphitic material at Macraes has some remnants of attached hydrocarbon groups, whereas the hydrothermal graphite has little or none of these attached groups (Fig. 8.4).

Hence, distinction between the two graphite types at Macraes is possible with these techniques, whereas microscopic textures can be more equivocal in weakly mineralised rocks.

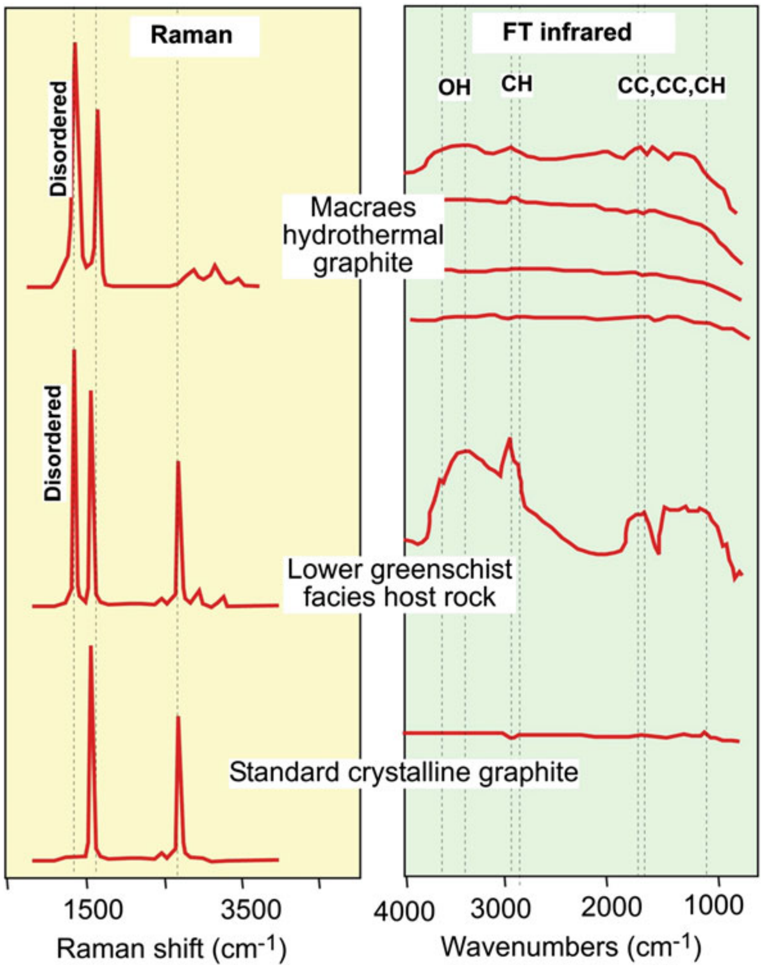

Fig. 8.4 Comparison of the Raman and Fourier Transform infrared characteristics of Macraes hydrothermal graphite, graphitic organic matter in the host rocks, and pure standard graphite (modified from Pitcairn et al. 2005 and Hu et al. 2015)

8.3 Chemical Relationships Between Graphite and Gold Mineralisation

Most of the structures with hydrothermal graphite in the Otago Schist belt do not contain elevated gold concentrations. Hence, the introduction of hydrothermal graphite and introduction of hydrothermal gold were separate processes during metamorphism and mineralisation of the schist belt. These two processes apparently coincided in the Hyde-Macraes Shear Zone, so this convergence is of considerable interest for understanding the genesis of the mineralised shear zone (Chap. 9).

There are three principal chemical reactions that lead to primary graphite remobilisation and formation of hydrothermal graphite during Otago Schist metamorphism (Henne and Craw 2012; Craw et al. 2015):

$$\text{Reduction of carbon dioxide}: CO_2 + 2H_2 \Rightarrow C_{graphite} + 2H_2O$$
$$\text{Mixing carbon dioxide and methane}: CO_2 + CH_4 \Rightarrow 2C_{graphite} + 2H_2O$$
$$\text{Oxidation of methane}: CH_4 + O_2 \Rightarrow C_{graphite} + 2H_2O$$

The second of these reactions was important for formation of hydrothermal graphite in the Hyde-Macraes Shear Zone, as minor remnants of coexisting methane and carbon dioxide are still detectable in fluid inclusions (Chap. 7; de Ronde et al. 2000). Methane was produced by on-going metamorphic devolatilisation of hydrocarbons bonded to remnants of primary graphitic material in schist host rocks (Fig. 8.4; Pitcairn et al. 2005). This methane migrated along the shear zone, which was preferentially developed in micaceous schists that contained most of this primary graphitic material (Fig. 8.5). Higher concentrations of CO_2 in the metamorphic fluid in other host rocks diffused into the shear zone. Fluid mixing, coinciding with lowering temperatures that limit the miscibility of carbon dioxide and methane, caused graphite precipitation from the fluid (Fig. 8.5; Chap. 5).

The presence of graphite in a host rock can act as a chemical reductant to cause precipitation of gold (Fig. 8.6a). If gold is in solution in the hydrothermal fluid as a reduced sulphur complex, any reduction reaction results in decrease of gold solubility by several orders of magnitude (Fig. 8.6a; Shenberger and Barnes 1989). Graphite-mediated reduction of the dissolved gold to metallic gold in this process at Macraes was accompanied by oxidation of graphite (Craw et al. 2007):

$$Au(HS)_2^- + C_{graphite} + H^+ + O_2 = Au + CO_2 + 2H_2S$$

Oxidation reactions also result in gold precipitation (Fig. 8.6a), so if host rock redox state was an important feature of the gold mineralising system in the Otago Schist in general, some of the more oxidised rocks, especially mafic schists (Fig. 8.6b), should also be mineralised in a similar manner. No evidence of this mineralisation of oxidised rocks has yet been found.

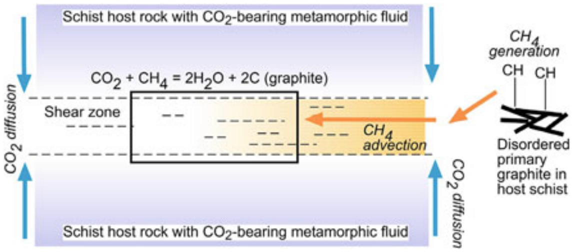

Fig. 8.5 Model for mixing of carbon dioxide and methane in water-saturated rocks of the Hyde-macraes Shear Zone under lower greenschist facies conditions (modified from Craw 2002 and Upton and Craw 2014)

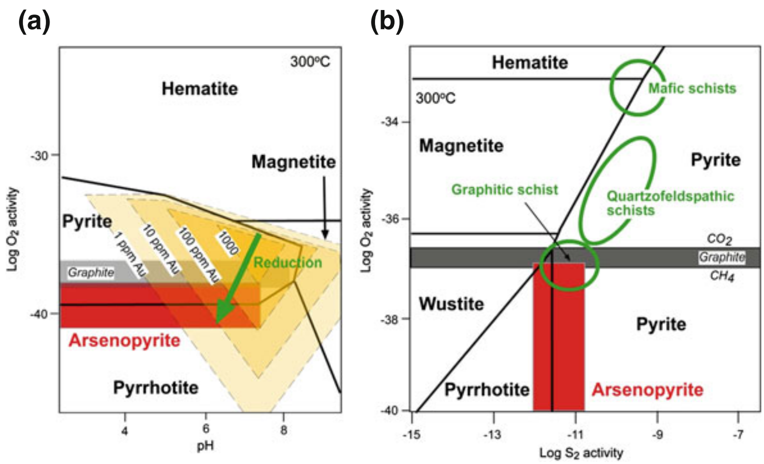

Fig. 8.6 Geochemical phase diagrams for principal iron-bearing minerals and graphite in the Hyde-Macraes Shear Zone and host rocks. **a** Relationships between iron minerals, graphite, and gold solubility (modified from Shenberger and Barnes 1989) with constant total dissolved sulphur of 0.01 m. Green arrow shows a fluid reduction pathway that causes gold precipitation. **b** Sulphur and oxygen activity controls on mineralogy (calculated with Geochemists Workbench software). *Green ellipses* show fluid conditions prevailing in different host rocks in the Otago Schist

Gold deposition is a volumetrically small part of the mineralising system in the Hyde-Macraes Shear Zone, which was dominated by sulphide mineral replacement of silicates (Chaps. 4 and 5). The solubility of gold as reduced sulphur complexes is strongly affected by the amount of dissolved sulphur, as well as redox conditions, and little affected by temperature (Shenberger and Barnes 1989). Hence, while the geometry of the gold solubility variations in Fig. 8.6a remain the same, the absolute solubilities change by an order of magnitude if the dissolved sulphur concentration decreases by an order of magnitude. It is this decrease in dissolved sulphur concentration, related to sulphide mineral replacement reactions in the shear zone, that has been responsible for gold deposition at Macraes. Replacement processes during mineralisation can be summarised by reactions that contribute iron from the host rocks to the sulphides, thereby maintaining constant iron concentrations (Chaps. 6 and 7; Craw 2002):

$$2FeO_{silicates} + H_3AsO_3(aq) + 0.5H_2 + 3H_2S => FeS_2 + FeAsS + 5H_2O$$

Sulphidation reactions of this type require low redox conditions in host rocks, such as in graphitic schists (Fig. 8.6b). These lower greenschist facies rocks commonly contain pyrite, with rare pyrrhotite, as part of the regional metamorphic transition from pyrite to pyrrhotite (Fig. 8.3).

8.3.1 Physical Relationships Between Graphite and Gold Mineralisation

Graphite is a soft mineral and acts as a lubricant within deforming shear zones in the Otago Schist, resulting in slickensided slip surfaces (Fig. 8.1a). In the Hyde-Macraes Shear Zone, addition of hydrothermal graphite to micaceous schists during deformation contributed to the reaction softening of the rock, allowing more focussing of shear strain into black shears (Chap. 4). This focussing of strain into the softer rocks resulted in enhancement of microshear development throughout the black sheared rocks, and it is this microshear development that facilitated hydrothermal fluid flow and sulphidation replacement reactions in the black sheared rocks (Chaps. 4 and 5). Hence, hydrothermal graphite introduction to the shear zone had physical effects, as well as chemical effects, on mineralisation processes.

The key features of the physical processes that have generated the black sheared rocks in the Hyde-Macraes Shear Zone, and facilitated their mineralisation with sulphides and gold, are contained in a numerical model of graphitisation (Fig. 8.7; Upton and Craw 2008). The starting material is inhomogeneous rocks (Fig. 8.7, right column) that have differing strengths (structural competencies), and deformation of this rock mass results in focussed shear zones in the weaker portions, anastomosing around the more competent pods. Progressive addition of hydrothermal graphite, up to ~2 wt%, is facilitated by enhanced rock permeability in the deforming zones, and this graphite in turn enhances the shear strain rate in those deforming zones (Fig. 8.7, left column). Rock permeability is also enhanced by these processes, thereby

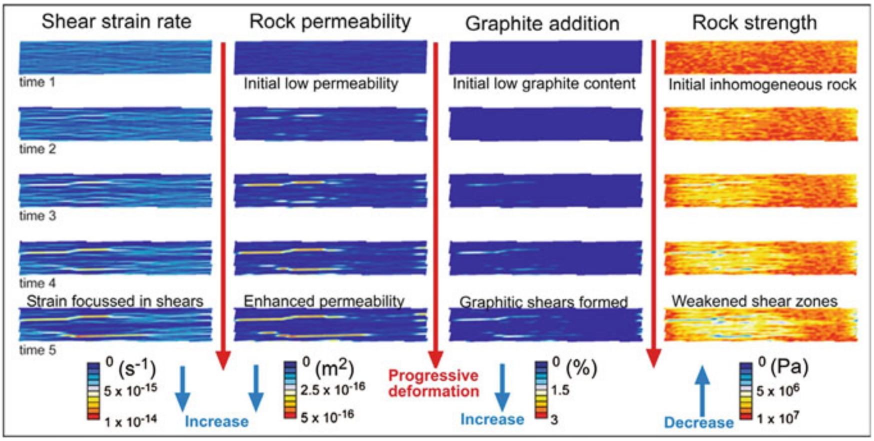

Fig. 8.7 Numerical model results (modified from Upton and Craw 2008) for deformation of inhomogeneous rocks and progressive introduction of graphite into the most highly strained shear zones. Rock parameters change progressively with time from top to bottom of the diagram

facilitating more fluid incursion and graphite precipitation in the weakened, rapidly straining zones. The positive feedback effects of the various parameters throughout these processes results in narrowly focused, highly strained, permeable, graphite-rich shears in which sulphidation reactions and gold deposition could occur via the chemical effects outlined above.

8.3.2 Geophysical Signature of Graphite

The combination of graphite and sulphides in the shear zone has resulted in a regional conductive geophysical anomaly (Fig. 8.8). The enhanced conductivity is dominated by graphite, which has been deformed into focused shears and commonly forms thin slickensided films on shear surfaces. There is therefore greater electrical connectivity along these thin films than between individual sulphide grains that form porphyroblasts and porphyroclasts along these shears. In addition, the shear fabric has enhanced the permeability of the shears compared to the adjacent more competent rocks, and subsequent saturation by an interconnected groundwater film further enhances electrical conductivity. Unfortunately, wet clay-rich cataclasite and fault gouge in younger cross-fault zones also have enhanced conductivity, obscuring the geophysical signal of the Hyde-Macraes Shear Zone (Fig. 8.8).

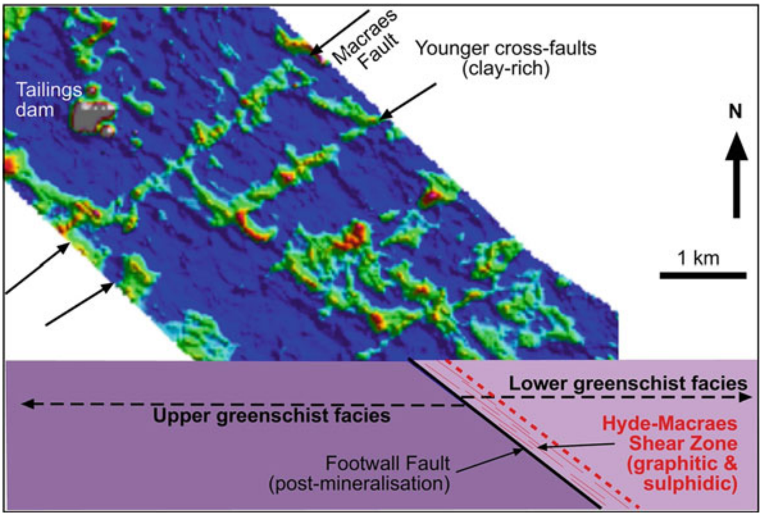

Fig. 8.8 Airborne conductivity across the Hyde-Macraes Shear Zone showing the relatively high conductivity anomaly (*greens* and *reds*) caused by graphite and sulphides in the shear zone

8.3.3 Regional Graphitic Shear Zone Evolution

All the processes discussed above converge to make the graphitic and gold-bearing Hyde-Macraes Shear Zone a well-defined feature on a regional scale. The shear zone developed as part of late metamorphic processes imposed on part of the still-deforming metamorphic schist pile, and none of those processes were unusual in themselves; the key feature of the shear zone is that an unusual convergence of these processes arose in a single structure on a regional scale. Mineralised structures such as the Hyde-Macraes Shear Zone are therefore of considerable economic interest, and the graphitic component is one of the most distinctive features.

Regional evolution of this mineralised shear zone has involved a combination of metamorphic, structural, geochemical and lithological factors, as summarised in Fig. 8.9a, b. At the outcrop scale, there has been strong lithological control on primary graphite remobilisation during metamorphism. Argillites were the most important source for primary organic carbon, and mobilisation of some of that carbon fed structures that evolved differently in argillites and sandstones. The micaceous schists and black sheared rocks derived from them in the Hyde-Macraes Shear Zone

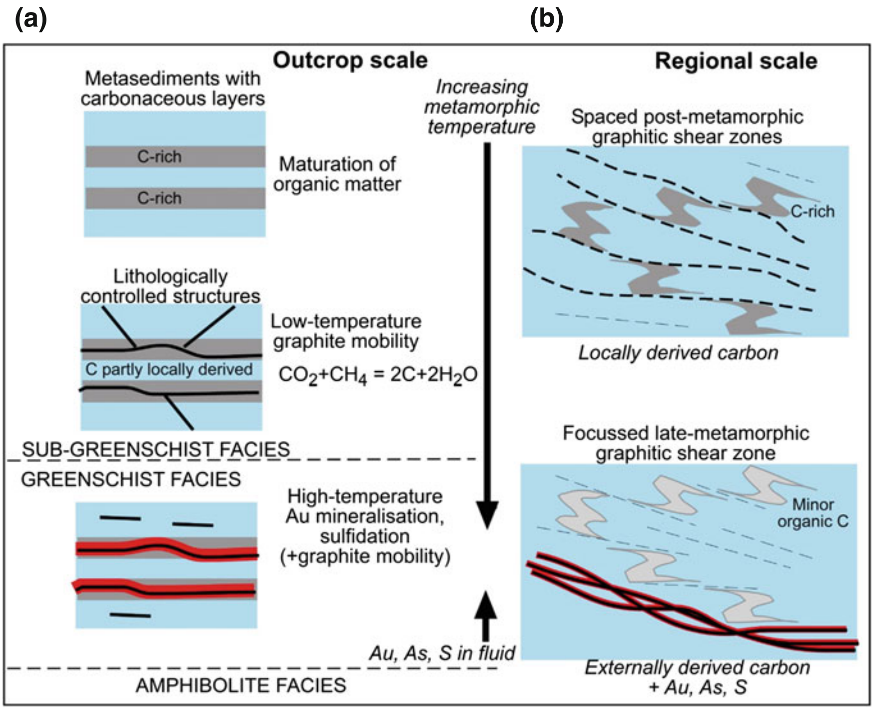

Fig. 8.9 Cartoon depiction of development of graphite-bearing structures with increasing metamorphic grade in the Otago Schist. Evolution of graphitic schists and introduction of gold occur during separate processes which can coincide in structures such as the Hyde-Macraes Shear Zone

formed from primary argillaceous layers, and became ideal host rocks for subsequent mineralisation. A separate gold-bearing hydrothermal fluid introduced metals into the previously-prepared micaceous rocks, with on-going deformation and further graphite addition and/or concentration.

At the larger scale, the Hyde-Macraes Shear Zone represents a major lithologically-controlled set of shear structures that has been focused into a relatively narrow zone as the host rocks cooled from more ductile metamorphic conditions. This focusing of shear structures occurred during a transition from more pervasive folding in the lower greenschist facies rock mass (Fig. 8.9b). The shear zone developed regionally as shears hosted in individual micaceous schist layers became connected to form a through-going structural zone. The shear development was facilitated by deformation that was being enhanced by the presence of primary and early metamorphic graphite in the micaceous schist, and was further enhanced as more graphite was introduced during hydrothermal mineralisation (Fig. 8.9).

References

Craw D (2002) Geochemistry of late metamorphic hydrothermal alteration and graphitisation of host rock, Macraes gold mine, Otago Schist, New Zealand. Chem Geol 191: 257-275

Craw D, Mortensen, J, MacKenzie D, Pitcairn I (2015) Contrasting geochemistry of orogenic gold deposits in Yukon, Canada and Otago, New Zealand. Geochem Explor Envir Anal 15: 150-166

Craw D, MacKenzie, DJ, Pitcairn, IK, Teagle, DAH, Norris, RJ (2007) Geochemical signatures of mesothermal Au-mineralized late-metamorphic deformation zones, Otago Schist, New Zealand. Geochem 7: 225-232

deRonde CEJ, Faure K, Bray CJ, Whitford DJ (2000) Round Hill shear zone-hosted gold deposit, Macraes Flat, Otago, New Zealand: evidence of a magmatic ore fluid. Econ Geol 95: 1025-1048

Henne A, Craw D (2012) Synmetamorphic carbon mobility and graphite enrichment in metaturbidites as a precursor to orogenic gold mineralization, Otago Schist, New Zealand. Mineral Deposita 47: 781-797

Hu S, Evans, K, Craw D, Rempel K, Bourdet J, Dick J, Grice K (2015) Raman characterization of carbonaceous material in the Macraes orogenic gold deposit and metasedimentary host rocks, New Zealand. Ore Geol Rev 70: 80-95

Landis CA (1971) Graphitization of dispersed carbonaceous matter in metamorphic rocks. Contrib Mineral Petrol 30: 34-45

McKeag SA, Craw D, Norris RJ (1989) Origin and deposition of a graphitic schist-hosted metamorphogenic Au-W deposit, Macraes, East Otago, New Zealand. Mineral Deposita 24: 124-131

Pitcairn IK, Roberts S, Teagle DAH, Craw D (2005) Detecting hydrothermal graphite deposition during metamorphism and gold mineralisation. J Geol Soc London 162: 429-432

Shenberger DM, Barnes HL (1989) Solubility of gold in aqueous sulfide solutions from 150 to 350°C. Geochim Cosmochim Acta 53: 269-278.

Upton P, Craw D (2008) Modelling the role of graphite in development of a mineralised mid-crustal shear zone, Macraes mine, New Zealand. Earth Planet Sci Letters 266: 245-255

Upton P, Craw D 2014. Modelling of structural and lithological controls on mobility of fluids and gold in orogenic belts, New Zealand. In: Garofalo PS, Ridley JR (eds) Gold-Transporting Hydrothermal Fluids in the Earth's Crust. Geol Soc London Special Publ 402: 231-253

Chapter 9
Genesis of Macraes as a Metamorphogenic Gold Deposit

9.1 Regional Metamorphic Mobilisation of Metals

The structural, geochemical, geochronological, and isotopic data presented for the Hyde-Macraes Shear Zone (previous chapters) all show that there was a close genetic relationship between mineralisation of the shear zone and metamorphism of the hosting Otago Schist belt. The principal mineralising fluid was derived from, and underwent extensive interaction with, the host rock of the Torlesse Terrane. Additional fluid inputs may have included meteoric water, but even this water had undergone extensive geochemical interaction with the host rocks. There is no evidence for coeval magmatism, either in the geochemical and isotopic data or in the regional geological reconstruction of the Otago Schist belt for the Early Cretaceous (Chap. 2). Hence, mineralisation in the shear zone required metamorphogenic mobilisation of the metals from the host schist belt in which the deposit now occurs.

Analysis of typical protolith greywackes and quartzofeldspathic schists across the schist belt shows that some metals were extracted from the schists during prograde metamorphism (Pitcairn et al. 2006, 2010, 2014). Hence, higher grade rocks have generally lower metal contents than low grade rocks, on a regional scale. Most notably, As and Sb contents decrease by an order of magnitude, and Au decreases to about half its low grade rock concentration. These metals change most significantly between greenschist facies and amphibolite facies. Changes in rock W contents are less clear, but the higher grade rocks have slightly lower concentrations than the low grade rocks (Fig. 9.1). Mercury has been extracted progressively with increasing metamorphic grade, starting in sub-greenschist facies conditions.

The metals that were extracted in this process were those that typically occur in orogenic gold deposits. This metal extraction was accompanied by rock dehydration, with loss of between 1 and 2 wt% water during prograde metamorphism from greenschist to amphibolite facies. Metamorphic processes must have generated large volumes of metal-bearing fluid within and beneath the greenschist facies

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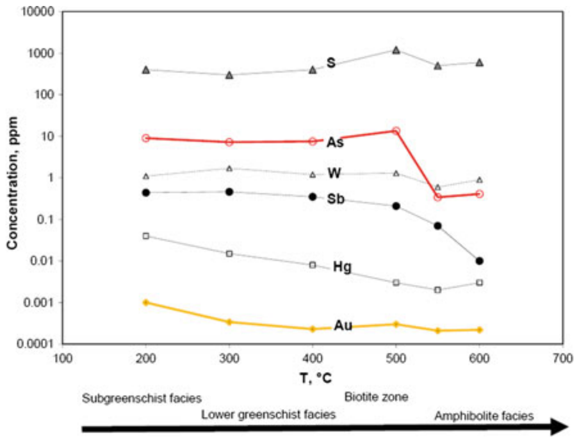

Fig. 9.1 Changes in average metal contents of Torlesse Terrane greywackes and equivalent schists with increasing metamorphic grade (modified from Pitcairn et al. 2006, 2014)

schists. Contents of metals such as Cu, Pb and Zn have remained unchanged within the rocks, and were not mobilised into this fluid. Total rock sulphur contents did not decrease during prograde metamorphism (Fig. 9.1), but there was abundant sulphur available in the rocks for formation of Au-sulphur complexes in the fluid.

9.2 Mineral Sources of Metals

Sub-greenschist facies greywackes and argillites that form the protoliths for the Otago Schist belt contain framboidal pyrite that was formed diagenetically within the sediments. These pyrite framboids contain relatively elevated concentrations of metals compared to the surrounding rocks. Significantly, the framboids typically contain ~1 ppm Au and W, ~100 ppm Ag and Mo, and ~1000 ppm As (Fig. 9.2; Large et al. 2012). Mineral recrystallisation during prograde metamorphism caused transformation of these framboids, first to coarser grained euhedral pyrite and then to pyrrhotite (Fig. 9.3; Henne and Craw 2012; Large et al. 2012). These transformations liberated the metals and made them available for dissolution in the metamorphic dehydration fluid being generated at the same time.

Metals held in solid solution in other primary minerals in the low grade protoliths were mobilised as recrystallisation and mineral transformations occurred. In particular, the transformation of detrital rutile to form metamorphic titanite was important for mobilising W (Fig. 9.3). Tungsten levels in the detrital rutile range up to 3000 ppm in the greywackes, whereas metamorphic titanite in low grade schists contains only ~100 ppm W (Cave et al. 2015). Initially, the W released from rutile was deposited almost in situ, as disseminated scheelite in syn-metamorphic quartzofeldspathic veins and segregations in pumpellyite-actinolite facies schists (Fig. 9.3; Craw and Norris 1991; Pitcairn et al. 2014; Cave et al. 2015). This tungsen was remobilised on a more regional scale in the upper greenschist facies (Fig. 9.3).

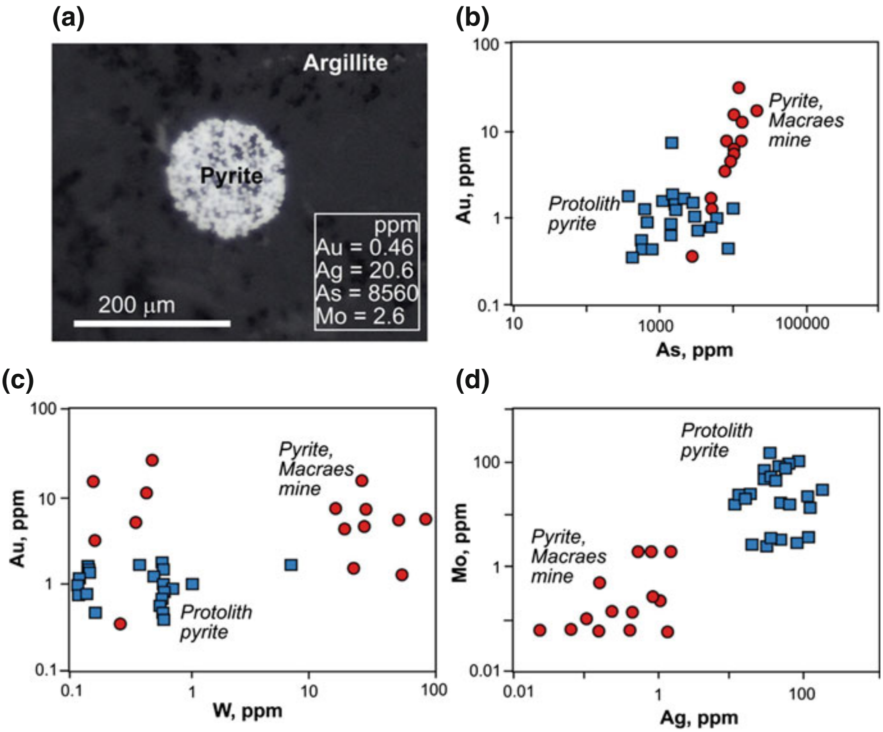

Fig. 9.2 Changes in metal contents of pyrite in transition from diagenetic framboids in low grade protoliths to mineralised porphyroblasts in the Hyde-Macraes Shear Zone (modified from Large et al. 2012)

9.3 Early Cretaceous Orogenic Reconstruction

Geochronological and structural data (Chap. 2) show that greenschist facies and higher grades of metamorphism and associated ductile deformation were still on-going as the Hyde-Macraes Shear Zone was formed and mineralised near to the brittle-ductile transition. Although the hydrothermal alteration in the shear zone represents retrograde reactions that occurred during uplift and cooling, the underlying rocks were still undergoing prograde metamorphic recrystallisation. Those metamorphic transformations at depth, in the transition between upper greenschist and amphibolite facies conditions, were the most potent for generation of metal-bearing fluids in the metamorphic pile, especially Au, As, Sb and W (Figs. 9.1 and 9.3). Hence, Early Cretaceous prograde metamorphic reactions at depth generated metalliferous fluid that contributed to retrograde metamorphic-hydrothermal reactions in the overlying lower greenschist facies rocks, with fluid flow controlled mainly by the more permeable Hyde-Macraes Shear Zone.

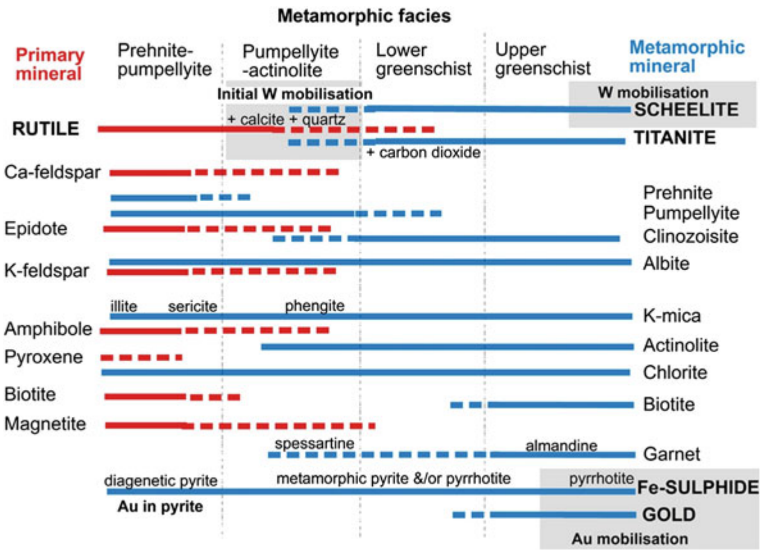

Fig. 9.3 Principal mineralogical changes during prograde metamorphism of Torlesse Terrane (modified from Cave et al. 2015), from primary (mainly detrital) minerals on *left* to metamorphic minerals towards *right*. *Grey areas* indicate important transformations for mobilising Au and W

The dynamic convergent tectonic and metamorphic orogen that resulted in the mineralised Hyde-Macraes Shear Zone is depicted in Fig. 9.4. Prograde metamorphism continues below the shear zone, contributing metal-bearing fluids to permeable structures at shallower levels, to form the Macraes deposit. Meteoric water incursion adds a contribution to the fluid near to, and below, the brittle-ductile

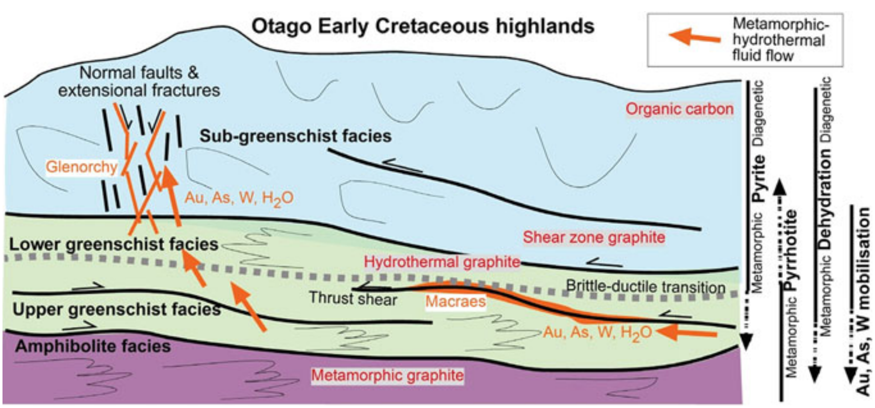

Fig. 9.4 Cartoon cross section reconstruction of the Otago Schist during Early Cretaceous mineralisation (modified from Mortimer et al. 2016). Glenorchy is a normal fault-hosted mineralised vein swarm coeval with the Macraes deposit (Mortensen et al. 2010)

transition zone (Menzies et al. 2014). Mineralising fluid continues to shallower levels locally, to form mineralised veins in more brittle structures, such as at Glenorchy (Chap. 2). These latter vein systems occur in extensional structures that formed within the convergent orogen at the same time as the thrust shear zone at Macraes (Mortensen et al. 2010). Coexistence of coeval thrust and extensional deformation regimes is a common feature of convergent orogens, especially those that have a component of transcurrent motion (Upton and Craw 2014a, b).

9.4 Modern Analogues for Orogenic Gold Mineralisation Systems

9.4.1 Analogues Around the World

Most active and recently-active convergent orogens produce linear mountain chains in which crustal scale fluid flow and associated surface hot springs are important components of the mountain environment. Fluid migration is driven by tectonically-driven processes and topographic relief, and most of these systems do not have directly-related magmatism. These systems, both active and quiescent, are found, for example, in the Himalaya, North American Cordillera, European Alps, and Pyrenees (Craw et al. 2002). Some of these tectonically driven hydrothermal systems have generated gold deposits. The oblique convergent orogen in Taiwan is one of the best modern analogues for an active orogenic gold mineralising system in an accretionary metasedimentary complex (Craw et al. 2010). There, late Cenozoic sediments, including carbonaceous shales, are being stacked into a thick metamorphic pile, with mountains up to 4 km high. Gold-bearing quartz veins have been emplaced by metamorphogenic fluids under a range of greenschist facies and lower grade conditions in the core of this orogen while metamorphism continues at depth. Meteroic water percolates extensively through the active orogen, including gold-bearing structures, and hot springs are common.

Similar processes to those in Taiwan are occurring in the Southern Alps of New Zealand, immediately to the northwest of Macraes mine (Fig. 9.5). The Southern Alps is a narrow, linear range of mountains that locally exceed 3 km in height, and is being uplifted along the transpressional Alpine Fault, a major plate boundary structure (Fig. 9.5). The Southern Alps differs from Taiwan in having reactivated Mesozoic accretionary complex rocks in the orogen, rather than young sediments. These reactivated Mesozoic rocks are the same Torlesse Terrane metasediments, and geochemically similar schists, that are host rocks for the Macraes mine. Hence, there are many lithological, structural and geochemical similarities between Macraes mineralisation and that occurring in the Southern Alps, and magmatic activity is absent from the Southern Alps, as at Macraes.

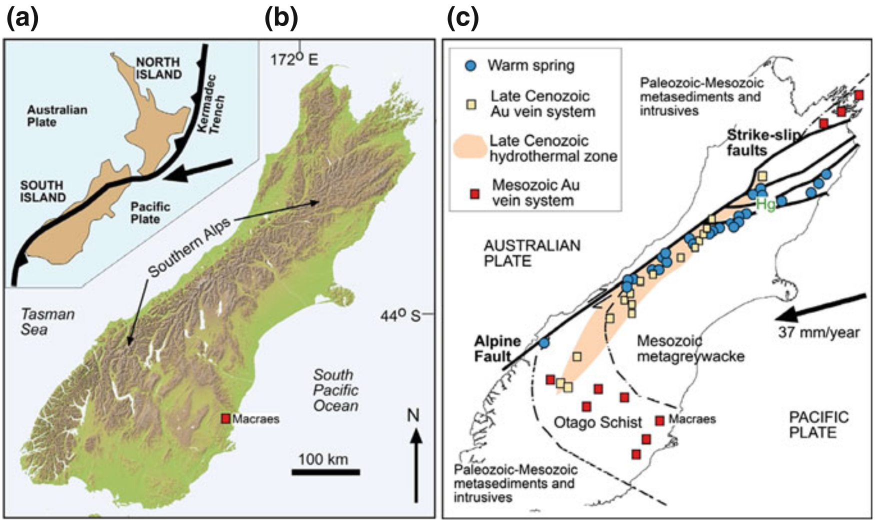

Fig. 9.5 Present tectonic setting (**a**) of the South Island of New Zealand along the Pacific-Australian plate boundary (Alpine Fault), with (**b**) the resulting mountain topography, and (**c**) associated tectonically driven gold-transporting hydrothermal system, with mercury anomalies at springs in some strike-slip faults at the northern end (**c**). Host rocks for the modern hydrothermal system are essentially the same as those for the Mesozoic deposits in Otago Schist including Macraes

9.4.2 Southern Alps and Macraes Style Mineralisation

The tectonic-hydrothermal system in the Southern Alps involves mixtures of metal-bearing metamorphic fluids being generated at depth, and deeply circulating meteoric water that is driven by the high topography (Craw 1997; Craw et al. 2002, 2009; Menzies et al. 2014). These processes have been occurring since the Miocene inception of the present plate boundary. Small orogenic gold deposits have formed at various times since the Miocene in a belt within the hydrothermal zone, and sub-parallel to a belt of warm meteoric springs (Fig. 9.5c). Some of these deposits, especially the southernmost ones (Fig. 9.5c), have been mined historically.

The Southern Alps orogen is being constructed by oblique convergence during which low grade Mesozoic metasediments are being pushed westwards at ~10 mm/year to form a thickened metamorphic pile with an extensive crustal root (Fig. 9.6a). Uplift along the Alpine Fault (up to 10 mm/year) and rapid erosion is exhuming high grade rocks, including amphibolite facies rocks on the western side of the orogen. A magnetotelluric survey has imaged the resultant fluid-rich zones beneath the orogen (Fig. 9.6b; Wannamaker et al. 2002). The green-yellow zones of lower electrical resistivity (higher conductivity) in Fig. 9.6b show that conductive zones with fluid, and possibly graphite, are focussed in the high grade metamorphic rocks being deformed and dewatered beneath the high mountains.

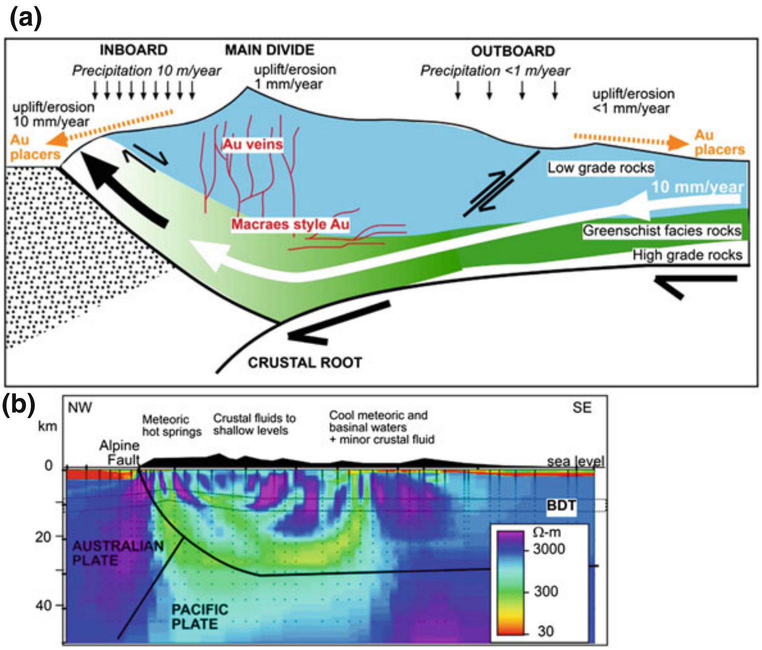

Fig. 9.6 Cross sections through the active plate boundary (**a**) and its hydrothermal system (**b**) as depicted with magnetotelluric resistivity data (modified from Wannamaker et al. 2002), with low resistivity zones (water and/or graphite rich) in *pale blues*, *greens*, and *yellows*

Metal-bearing metamorphic fluids, with a meteoric component, form plumes that are rising to form gold-bearing deposits at a range of structural levels beneath the mountains (Figs. 9.6 and 9.7a). The Macraes style of replacement-dominated hydrothermal gold mineralisation is forming in the deeper parts of this tectonic-hydrothermal system. Some small gold deposits with the Macraes style of mineralisation have been exhumed by erosion (Craw et al. 2009). In these deposits, the hydrothermal alteration has greenschist facies mineralogy, including biotite, and the mineralising fluids were essentially in equilibrium with the host rocks (Fig. 9.7c). Some of these deposits occur in close association with graphitic schist host rocks. Deformed and metamorphosed versions of this Macraes style of deposit (Fig. 9.7b), which are currently being carried into the main uplift zone, have not yet been exhumed.

9.4.3 Mineralisation Styles that Formed Shallower Than Macraes

Shallower-level deposit formation involved quartz veins, rather than replacement reactions, with chlorite-destructive hydrothermal alteration yielding ankeritic

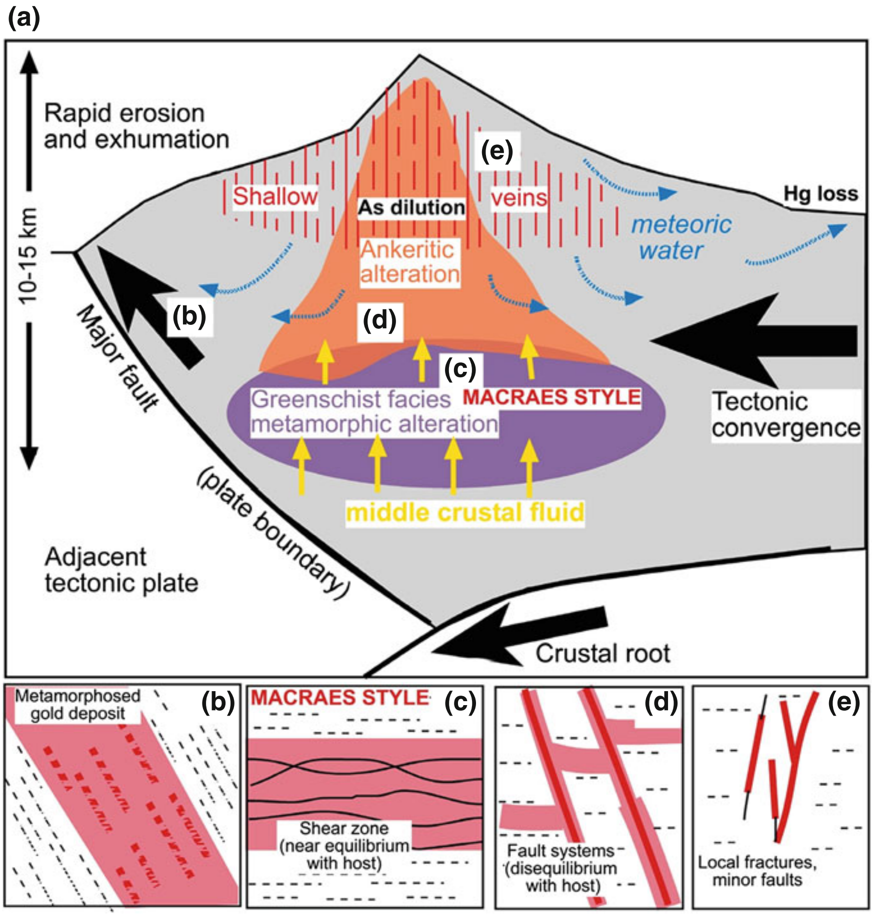

Fig. 9.7 Schematic cross section (**a**) through the active tectonic mountain-hosted hydrothermal system (based on Southern Alps, as modified from Craw et al. 2009) showing inferred zonation of mineral deposit styles, with projected location of Macraes style of shear-hosted deposit. Sketches (**b**) to (**e**) show styles of mineralisation, with veins in red and alteration in pink

carbonate in the wall rocks. At these shallower levels, the mineralising fluid was out of equilibrium with greenschist facies host rocks (Fig. 9.7d). Near-surface fluid flow has produced shallowest-level veins (Fig. 9.7e), with only minor gold mineralisation. These latter veins do not have significant wall rock alteration. It is notable that the vein systems with ankeritic alteration, and the shallow veins, have been emplaced into extensional fractures in the rock while the deeper parts of the orogen have continued to be deformed in a compressional manner (Upton and Craw 2014a, b).

Gold deposits die out at the northern end of the Southern Alps hydrothermal system where active fluid flow has now been captured by expansion of a zone of strike slip faults (Fig. 9.5; Craw et al. 2012). Warm springs in this region are controlled by these faults. There has been little exhumation in this area and the exposed rocks are low metamorphic grade Torlesse Terrane metagreywacke. No gold deposits have been exposed because of this lack of exhumation, but some of the warm springs have Hg enrichment in waters and sinter deposits (Fig. 9.5; Holley et al. 2010). These Hg anomalies reflect the mobilisation of Hg that arises throughout the metamorphic pile (Fig. 9.1).

References

Cave BJ, Stepanov AS, Craw D, Large RR, Halpin JA, Thompson J (2015) Release of trace elements through the sub-greenschist facies breakdown of detrital rutile to metamorphic titanite in the Otago Schist, New Zealand. Canadian Mineral 53: 379-400

Craw D (1997) Fluid inclusion evidence for geothermal structure beneath the Southern Alps, New Zealand. NZ J Geol Geophys 40: 43-52

Craw D, Norris RJ (1991) Metamorphogenic Au-W veins and regional tectonics: mineralisation throughout the uplift history of the Haast Schist, New Zealand. NZ J Geol Geophys 34: 373-383

Craw D, Koons PO, Horton T, Chamberlain CP (2002) Tectonically driven fluid flow and gold mineralisation in active collisional orogenic belts: comparison between New Zealand and western Himalaya. Tectonophysics 348: 135-153

Craw, D., Upton, P., MacKenzie, D.J. 2009 Hydrothermal alteration styles in ancient and modern orogenic gold deposits, New Zealand. NZ J Geol Geophys 52: 11-26

Craw D, Upton P, Yu B-S, Horton T, Chen Y-G 2010. Young orogenic gold mineralisation in active collisional mountains, Taiwan. Mineral Deposita 45: 631-646

Craw D, Upton P, Horton T, Williams J 2012. Migration of hydrothermal systems in an evolving collisional orogeny, New Zealand. Mineral Deposita *48:* 233-248

Henne A, Craw D (2012) Synmetamorphic carbon mobility and graphite enrichment in metaturbidites as a precursor to orogenic gold mineralization, Otago Schist, New Zealand. Mineral Deposita 47: 781-797

Holley EA, Craw D, Kim J (2010) Natural and mine-related mercury in an orogenic greywacke terrane, South Island, New Zealand. NZ J Geol Geophys 53: 103-114

Large R, Thomas H, Craw D, Henne A, Henderson S (2012) Diagenetic pyrite as a source for metals in orogenic gold deposits, Otago Schist, New Zealand. NZ J Geol Geophys 55: 137-149

Menzies CD, Teagle DAH, Craw D, Cox SC, Boyce AJ, Barrie, CD, Roberts S (2014) Incursion of meteoric waters into the ductile regime in an active orogen. Earth Planet Sci Letters 399: 1-13

Mortensen JK, Craw D, MacKenzie DJ, Gabites JE, Ullrich T (2010) Age and origin of orogenic gold mineralisation in the Otago Schist belt, South Island, New Zealand: Constraints from lead isotope and $^{40}Ar/^{39}Ar$ dating studies. Econ Geol 105: 777-793

Mortimer N, Craw D, MacKenzie DJ, Mortensen J, Ring U, Pitcairn I (2016) Cretaceous tectonics and regional gold mineralisation in the Otago Schist, New Zealand. Aust Inst Min Metall Monog (in press)

Pitcairn IK, Teagle DAH, Craw D, Olivo GR, Kerrich R, Brewer TS (2006) Sources of metals and fluids in orogenic gold deposits: insights from the Otago and Alpine Schists, New Zealand. Econ Geol 101: 1525-1546

Pitcairn IK, Olivo GR, Teagle DAH, Craw D (2010) Sulfide evolution during prograde metamorphism of the Otago and Alpine Schists, New Zealand. Canadian Mineral 48: 1267-1295

Pitcairn IK, Craw D, Teagle DAH (2014) The gold conveyor belt: Large-scale gold mobility in an active orogen. Ore Geol Rev 62: 129-142

Upton P, Craw D (2014a) Extension and gold mineralisation in the hanging walls of active convergent continental shear zones. J Struct Geol 64: 135-148

Upton P, Craw D (2014b) Modelling of structural and lithological controls on mobility of fluids and gold in orogenic belts, New Zealand. In: Garofalo PS, Ridley JR (eds) Gold-Transporting Hydrothermal Fluids in the Earth's Crust. Geol Soc London Special Publ 402: 231-253

Wannamaker PE, Jiracek GR, Stodt JA, Caldwell TG, Gonzalez VM, McKnight JD, Porter AD (2002) Fluid generation and pathways beneath an active compressional orogen, the New Zealand Southern Alps, inferred from magnetotelluric data. J Geophys Research 107(B6)

Chapter 10
Mining, Processing and Environment at Macraes

10.1 Macraes Mine System

The Macraes mine includes several open pits along the strike of the Hyde-Macraes Shear Zone, and an underground mine down-dip below Frasers open pit (Chap. 1). Ore from these excavations is trucked to a central processing plant where it is crushed and ground initially to fine sand ($\sim$50 μm). Oxidised ore from the near-surface excavations contains supergene gold that has been naturally liberated from sulphides, so this ore is sent directly from grinding to the cyanidation plant. Oxidised ore constitutes a minor proportion of the overall ore feed. Most of the ore, containing pyrite and arsenopyrite liberated by the initial grinding, is passed through a flotation plant where the sulphide minerals are separated to form a concentrate with $\sim$10 % sulphide minerals (Fig. 10.1).

The sulphide concentrate is reground to $\sim$15 μm, while the sulphide-free flotation tailings are discharged to a tailings impoundment (Fig. 10.1). Before 1999, the sulphide concentrate was sent directly to the cyanidation plant for gold recovery. The concentrate tailings were initially discharged to a separate tailings impoundment, but tailings were mixed into a single impoundment after 1993. In 1999, a pressure oxidation autoclave was introduced, and the sulphide concentrate is passed through this to oxidise sulphides and liberate gold before cyanidation. Additional gold-bearing sulphide concentrate was imported from the Reefton mine, 700 km away, between 2007 and 2015, and this constituted about 10 % of the ore concentrate feed (Fig. 10.1; Chap. 1).

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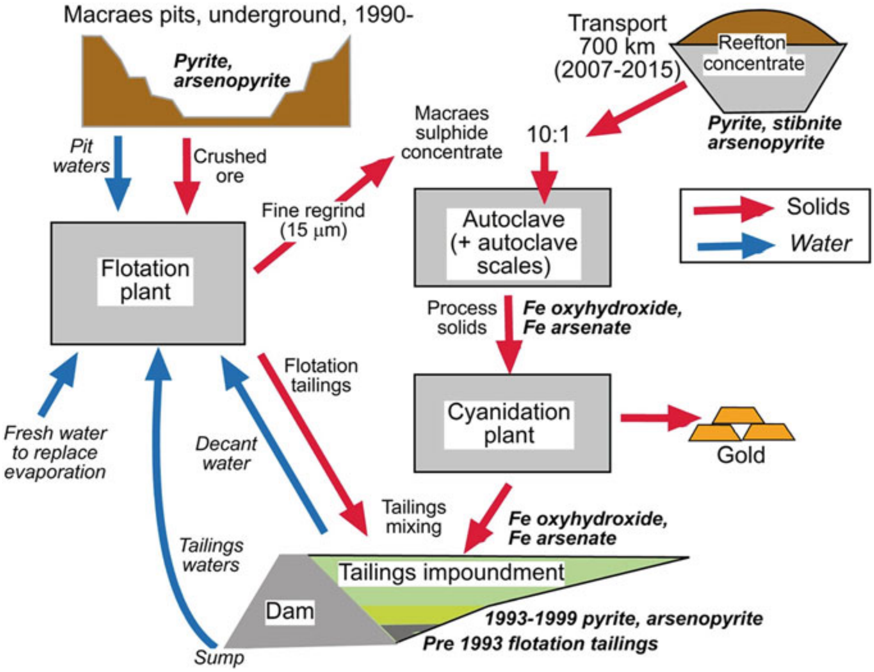

Fig. 10.1 Schematic layout of the Macraes mine, processing system, and tailings disposal (modified from Milham and Craw 2009). Principal water pathways are indicated

10.2 Lithological Controls on Gold Recovery

Lithological variations in the host schists have had important effects on the nature of the mineralisation processes, and these variations have also affected the emplacement of mineralised quartz veins (Chaps. 4–6). The quartz veins and associated mineralised breccias form relatively gold-rich ore (up to 10 g/tonne) from which sulphide minerals are relatively easily separated by flotation. The gold, which is mostly microparticulate (Chap. 5) is readily liberated from the sulphide mineral grains by the fine grinding stage. However, the large volumes of ore that contain disseminated sulphides in variably altered host rock schists have lower gold grades and the gold is not as easily extracted as it is from quartz veins. Gold recovery from these rocks has been strongly affected by the primary lithological variations and their effects on mineralisation style.

Micaceous schists (Chaps. 3, 4) that have been mineralised without strong subsequent deformation typically contain abundant coarse pyrite porphyroblasts and are commonly relatively sulphur-rich as a consequence (Fig. 10.2a, b). These rocks contain relatively little arsenopyrite, and the gold is nanoparticulate and/or solid solution in the pyrite porphyroblasts. That gold is not readily liberated by fine grinding, so cyanidation typically recovers less than 60 % of the gold in this ore

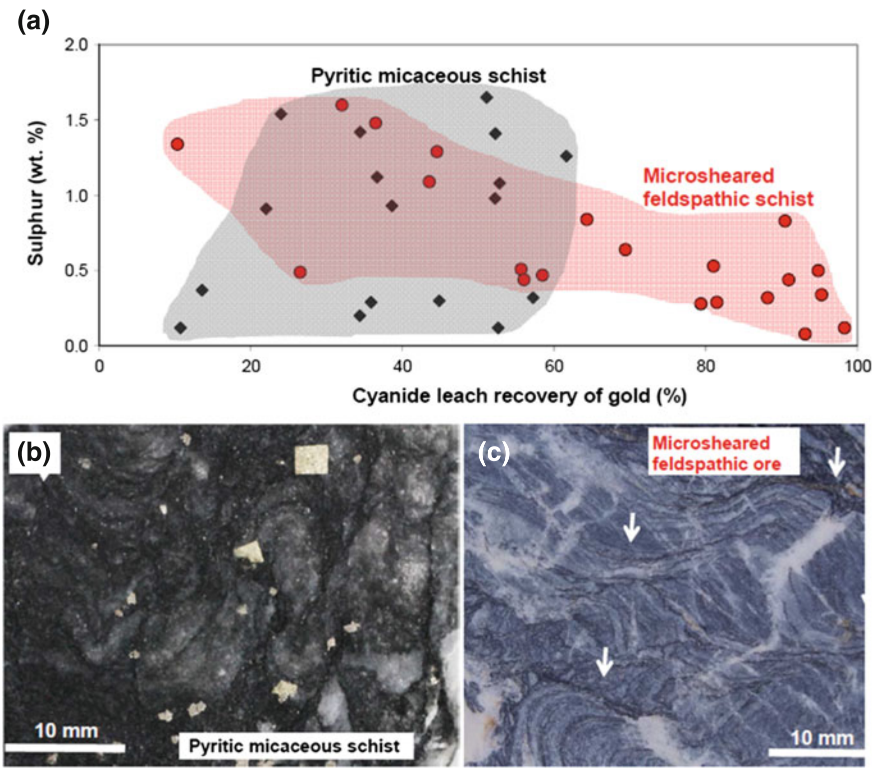

Fig. 10.2 Lithological controls on gold recovery. **a** Comparisons of gold recovery for hand specimens of variably refractory disseminated ore types (modified from Petrie et al. 2005). Typical examples of end-member mineralised rock types; **b** pyritic micaceous schist with coarse pyrite porphyroblasts (*white*) and **c** microsheared and silicified feldspathic schist with scattered sulphides on microshears (*arrowed*)

type (Fig. 10.2a). This ore type was therefore highly refractory in the processing plant (Petrie et al. 2005).

In contrast to micaceous schist, the other principal lithological end-member, feldspathic schist (Chaps. 3, 4) has been mineralised with sulphides along microshears, with accompanying silicification (Fig. 10.2c). This ore type has relatively low sulphur contents, and the sulphide minerals, both pyrite and arsenopyrite, are commonly fractured by post-mineralisation deformation. The gold is microparticulate within the sulphides as grains fully encapsulated, and as gold grains along fractures, in the sulphides. The microparticulate gold is generally readily liberated by fine grinding from the microsheared feldspathic schist, and this results in a high cyanide recovery (Fig. 10.2a).

There are lithological variations between these end-member rock types, as the proportions of feldspathic and micaceous components vary widely from the centimetre to metre scales (Chap. 3). Hence, there can be considerable overlap in refractory nature of intermediate rock types (Fig. 10.2a). In addition, all the variably micaceous rock types were prone to more advanced shearing and addition of graphite during shear zone evolution, to ultimately form black sheared rocks that constitute another end-member mineralised rock type (Chaps. 3–5). Sulphides in the black sheared rocks are finer grained and typically comminuted to some extent, and contain microparticulate gold in sulphide grains and fractures. Hence, this gold is accessible to cyanidation. However, the graphite and fine grained pyrite mineral surfaces adsorb some of the gold dissolved in cyanide solution, a process known as "preg-robbing". Preg-robbing of gold from black sheared ore results in lowered recovery from this ore type, to similar levels (<60 %) to those seen with refractory ores (Petrie et al. 2005).

10.3 Pressure Oxidation

To address the problems of poor gold recovery from the refractory and preg-robbing ore types, a pressure oxidation autoclave was incorporated into the processing system in 1999 (Fig. 10.1; Johnston et al. 2001). The sulphide concentrate is fed as a slurry through the autoclave, which operates with a high oxygen atmosphere (>3000 kPa) at 225 °C. The slurry has a residence time of about 1 h, during which the sulphide minerals are progressively oxidised, a highly acid solution (pH ~ 1–2) evolves, and the contained gold is liberated. The discharge solids are dewatered, acid generated is neutralised, and then the ore passes to the cyanidation plant. Oxidation in the autoclave is equivalent to the natural supergene oxidation processes that affected the near-surface ores that are subjected to direct cyanidation. Concentrate tailings that were stored in a dedicated impoundment before 1993 were fully reprocessed through the pressure oxidation system to extract the gold lost because of the poor recovery issues associated with refractory and preg-robbing ore types.

The pressure oxidation process in the autoclave produces a wide range of minerals as the ore is oxidised, in what is a complex chemical system where silicates and sulphides are degraded (Craw 2006). These minerals form scales on the walls through the autoclave, recording the results of progressive oxidation and alteration reactions (Figs. 10.3 and 10.4). Sulphur is almost immediately fully oxidised, the slurry becomes highly enriched in dissolved sulphate, and numerous sulphate minerals form. Iron is initially oxidised to Fe^{2+} and then to Fe^{3+} (Fig. 10.4a) and the minerals formed reflect these changes. For example, ferrous sulphates form initially, to be replaced by hematite and ferric iron oxyhydroxide. Similarly, arsenic is oxidised through As^{3+} to As^{5+} in parallel with iron oxidation, and a range of As minerals can form (Figs. 10.3, 10.4b). Other minor sulphides are oxidised at the same time (Fig. 10.4c). Decomposition of silicates contributes abundant Al^{3+}, much of which initially remains in solution at the low pH of the slurry, and some Al sulphates and clay minerals form (Figs. 10.3, 10.4e, f).

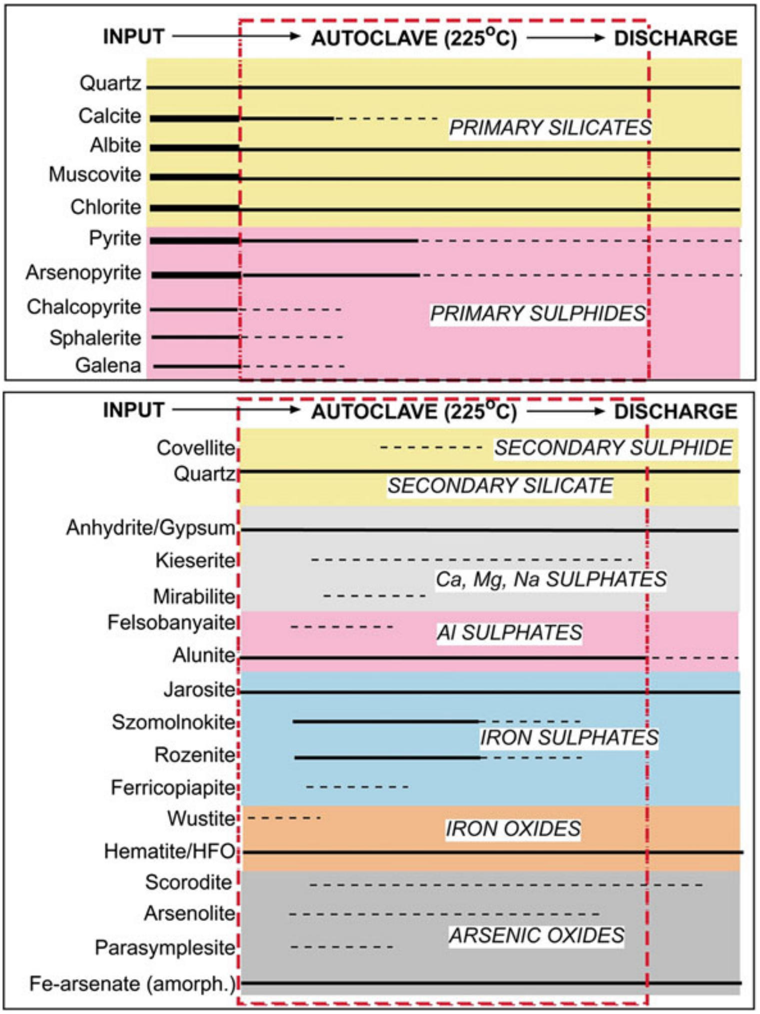

Fig. 10.3 Summary of minerals that form as scales during pressure oxidation of Macraes ore, arranged according to occurrences as the ore passes through the autoclave from *left* to *right* (modified from Craw 2006)

The end results of the oxidation processes are fine grained solids that are dominated by ferric iron oxyhydroxides, jarosite (K–Fe^{3+} sulphate), and ferric arsenate material that is poorly crystalline and variable in composition but has some affinities to scorodite. The most crystalline equivalent of this material forms on the walls of the autoclave near to the discharge point (Fig. 10.5). The jarosite is zoned, with significant Al in solid solution towards alunite which also commonly forms in the autoclave (Figs. 10.3 and 10.4d; Kerr et al. 2015a). Some substitution of Na for

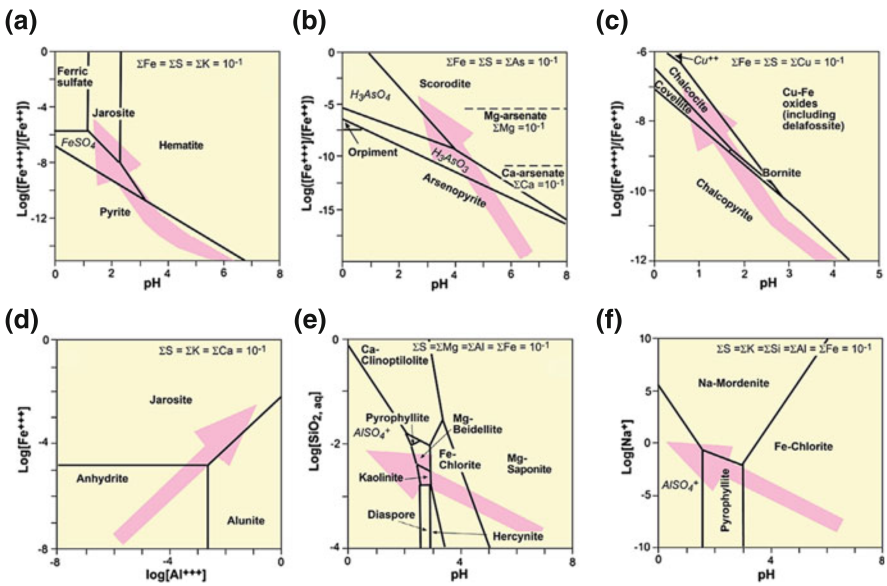

Fig. 10.4 Calculated phase diagrams (Geochemists Workbench) for mineral transformations in the Macraes autoclave, showing the chemical evolution pathway of the oxidising ore slurry (modified from Craw 2006)

K occurs as well. However, the jarosite contains negligible As in solid solution, and the As is confined to a separate ferric arsenate phase (Fig. 10.5).

10.4 Mine Tailings

The tailings impoundments are some of the key structures at the mine because of the large volumes of low Au grade ore that is processed (Fig. 10.6). The different processing strategies have yielded slightly different tailings compositions through the mine life, but the tailings are dominated by fine sand from the flotation plant (Fig. 10.1). Each tailings impoundment has a lake (decant pond) on its surface, where processing water accumulates as the solids settle. This water is recycled back to the processing plant because the mine site has a net water shortage. Significant amounts of water are lost via evaporation from the decant ponds, because evaporation exceeds precipitation in the area. Abundant UV light from sunshine decomposes any cyanide residues in the decant pond waters all year round. Some tailings water passes through the tailings and the dams, and is collected at the dam toes to be recycled as well (Figs. 10.1 and 10.7).

Tailings water chemistry undergoes changes as it moves through the impoundment, and compositions have evolved with time as the processing systems

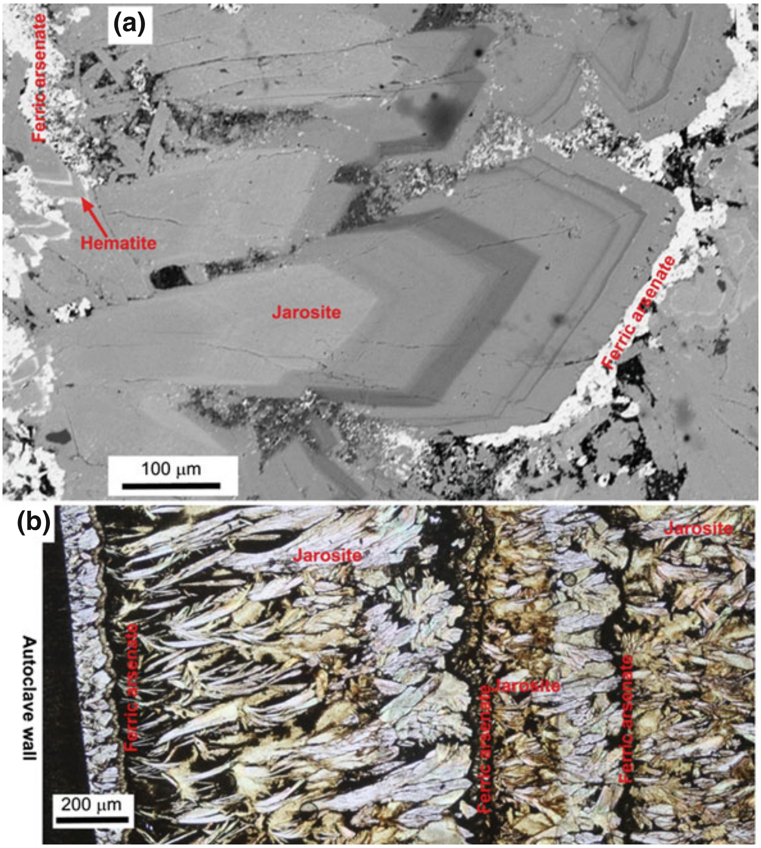

Fig. 10.5 Images of the principal end-products of the pressure oxidation process, as preserved in scales on the autoclave wall (modified from Kerr et al. 2015a). **a** SEM backscatter image of zoned jarosite crystals, with finely intergrown ferric arsenate. **b** Thin section image (*plain light*) of the same material in a, showing larger scale intergrowths of jarosite (*pale yellow*) and ferric arsenate (*black*)

have changed (Craw and Nelson 2000; Craw 2000, 2003). The most significant changes in water chemistry occurred after the introduction to pressure oxidation in 1999 (Fig. 10.7). Before this change, the decant waters had low to moderate sulphate concentrations and calcite dissolution/precipitation equilibria dominated the water chemistry. Pressure oxidation discharge waters have very high dissolved sulphate concentrations, which caused the decant waters to become saturated with respect to gypsum. At the same time, lower pH caused a significant decrease in saturation with respect to calcite. The lowered pH in the decant waters was partly a result of some discharge of low-pH autoclave solutions, and partly a result of in situ oxidation of relict Fe^{2+} remaining in those solutions, which occurs on a time scale of months (Fig. 10.7; Craw 2003). Since the initial change to pressure oxidation,

Fig. 10.6 Aerial view in 2014 of the two principal tailings impoundments at Macraes mine (from GoogleEarth). *Brown* waters in the impoundment to right result from autoclave discharge of iron oxyhydroxide, jarosite and ferric arsenate. A third impoundment (not shown) was also in use in 2014 (Chap. 1)

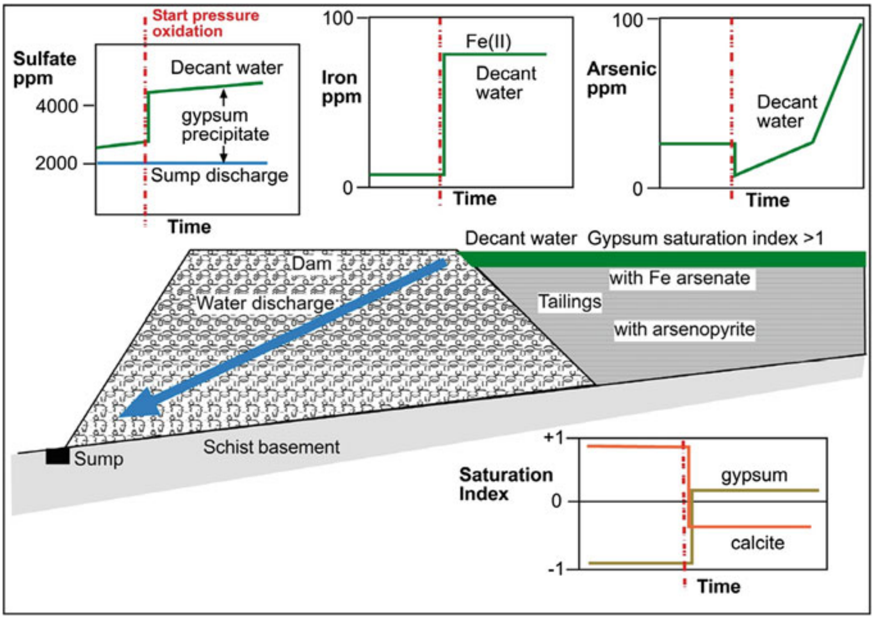

Fig. 10.7 Schematic cross section of the tailings impoundment after introduction of pressure oxidation, and principal changes to water compositions that occurred immediately after that introduction (modified from Craw 2003)

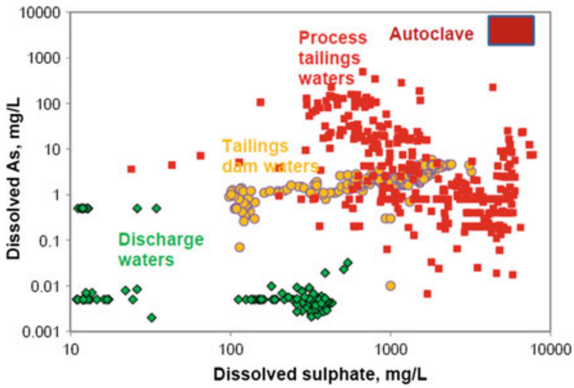

Fig. 10.8 Changes in dissolved sulphate and dissolved arsenic through the pathway of discharge waters from the processing system at Macraes mine, from autoclave (*top right*) to tailings dam seepages (*bottom left*) that are recycled back through the processing plant

more complete oxidation in the autoclave normally minimises the relict Fe^{2+} in discharge waters.

Dissolved As in decant waters is highly variable, depending mainly on the amount of adsorption of As^{5+} that has occurred to suspended ferric iron oxyhydroxide particles and colloids (Fig. 10.6). This adsorption, and localised precipitation of scorodite in the tailings (Craw et al. 2002; Craw and Bowell 2014), causes a steep decrease in the As concentrations through the tailings dam complex, from nearly 10000 ppm in autoclave waters to ~1 ppm in waters seeping through the dams (Fig. 10.8). This decrease in As concentrations is also facilitated by some dilution by groundwater near the base of the dams. Groundwater seeping from the site in the vicinity of the dams has even lower As concentrations, typically <0.01 ppm. Sulphate concentrations decrease in parallel with As, partly as a result of precipitation of gypsum within the impoundment system, and partly as a result of dilution (Fig. 10.8).

10.5 Environmental Context of Orogenic Gold Mines

Orogenic gold deposits form at a wide range of crustal levels, and the Macraes deposit formed at the deeper end of the spectrum (Chap. 9). Despite the wide range in styles of mineralisation associated with this spectrum of mineralisation systems, orogenic gold deposits have some broadly predictable features that can impact on the environment during exploration, mining, and mineral processing (Fig. 10.9; Craw and Bowell 2014). A notable feature of the deposits is that abundant calcite in host rocks and mineralised rocks, and comparitively small amounts of sulphides, ensures that associated waters typically have neutral or slightly alkaline pH (Craw et al. 2002). Acid rock drainage is either completely absent or occurs only locally on open pit walls and sulphidic outcrops (Kerr et al. 2015b). Localised acidification such as that associated with the Macraes autoclave are readily neutralised on site by the abundant surrounding neutralisation capacity.

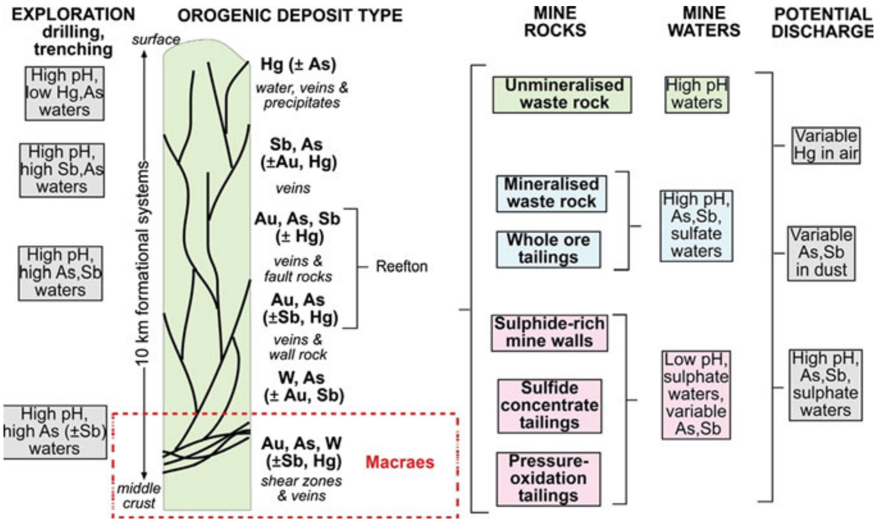

Fig. 10.9 Overview of environmental issues related to exploration and mining in orogenic gold deposits formed at different crustal levels (Chap. 9), showing the Macraes deposit characteristics in this context (modified from Craw et al. 2015)

Arsenopyrite is almost ubiquitous in orogenic gold deposits, and the close relationship between this mineral and gold ensures that arsenopyrite is a key target for crushing, grinding and processing of ore. Hence, dissolved arsenic is the principal potential environmental issue at all orogenic mine sites, as amply demonstrated by the Macraes deposit (Fig. 10.9). Arsenic mobilisation in mine waters is enhanced by the high pH of most mine waters, and lowered by adsorption to iron oxyhydroxide at Macraes and other similar mines (Roddick-Lanzilotta et al. 2002; Craw et al. 2002). Addition of artificial chemicals, such as ferric chloride, to mine waters can produce additional ferric iron oxyhydroxide to increase the adsorption capacity (Milham and Craw 2009).

Antimony is also mobile under similar conditions to As, and can contribute to environmental issues in the same settings (Milham and Craw 2009; Druzbicka and Craw 2013; Kerr et al. 2015b). Antimony concentrations in Macraes mine ores are generally low (Chaps. 5, 6). However, orogenic deposits formed at shallower crustal levels commonly contain higher Sb contents, and some of the Reefton deposits in the NW South Island contain abundant stibnite (Fig. 10.9). This stibnite formed a significant part of the Reefton sulphide concentrate that was transported to Macraes for pressure oxidation processing (Fig. 10.1; Milham and Craw 2009). Dissolved Sb adsorbs to iron oxyhydroxides in a similar manner to As, although As preferentially adsorbs to displace Sb when both As and Sb are present (McComb et al. 2007; Muller et al. 2015). At Macraes mine, the low proportion of the processed Reefton concentrate and the abundant ferric iron oxyhydroxide has ensured that Sb levels in mine wastes and mine waters have remained very low and of no environmental significance (Milham and Craw 2009).

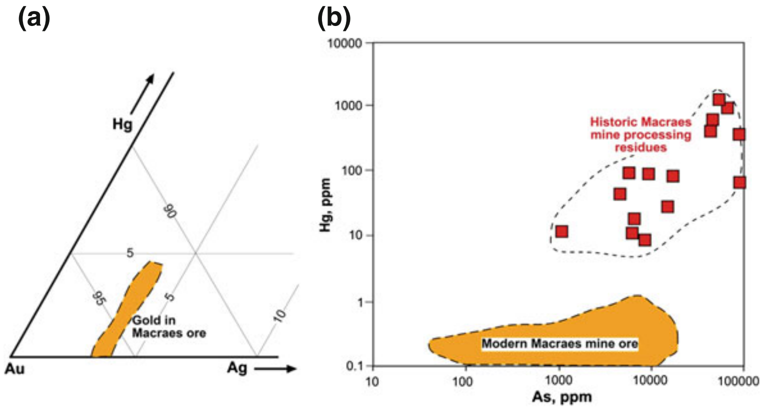

Fig. 10.10 Mercury at Macraes mine. **a** Compositions of gold in primary ore (wt% data from MacKenzie and Craw 2005). **b** Comparison of Hg contents of ore in the modern mine with some historic processing wastes that have residues from mercury amalgamation (modified from Mains and Craw 2005)

Mercury is a small but potentially environmentally significant component of some orogenic gold deposits, especially those formed at shallow levels (Fig. 10.9). However, even Macraes deposit has minor Hg in the ore, mostly occurring in the gold (up to 4 wt%; Fig. 10.10a). The low Hg contents in the ore can be concentrated during gold extraction, and can become a problem in the final stages of gold purification, where liquid mercury accumulations can occur. However, most mercury associated with mine wastes around orogenic gold deposits is derived from historic mining activity, where mercury amalgamation was an important part of the gold extraction process. This occurred in historic processing sites around the Macraes mine (Fig. 10.10b; Holley et al. 2010).

References

Craw D (2000) Water-rock interaction and acid neutralization in a large schist debris dam, Otago, New Zealand. Chem Geol 171: 17-32

Craw D (2003) Geochemical changes in mine tailings during a transition to pressure–oxidation process discharge, Macraes Mine, New Zealand. J Geochem Explor 80: 81-94

Craw D (2006) Pressure-oxidation autoclave as an analogue for acid-sulphate alteration in epithermal systems. Mineral Deposita 41: 357-368

Craw D, Nelson M (2000) Geochemical signatures of discharge waters, Macraes mine flotation tailings, east Otago, New Zealand. NZ J Marine Freshwater Res 34: 597-613

Craw D, Bowell RJ (2014) Chapter 10. The characterisation of arsenic in mine waste. In: Bowell RJ, Alpers C, Jamieson H, Nordstrom DK, Majzlan J (eds) Arsenic. Mineralogical Society of America Reviews in Mineralogy 79: 473-506

Craw D, Koons PO, Chappell DA (2002) Arsenic distribution during formation and capping of an oxidized sulphidic minesoil, Macraes mine, New Zealand. J Geochem Explor 76: 13-29

Craw D, Cavanagh J, Druzbicka J, Harding J, Kerr G, Pope J, Trumm D (2015) A geoenvironmental model for orogenic gold deposits to predict potential environmental effects. Mine Water Environ 34: 388-403

Druzbicka J, Craw D (2013) Evolving metalloid signatures in waters draining from a mined orogenic gold deposit, New Zealand. *Appl Geochem 31*: 251-264

Holley EA, Craw D, Kim J (2010) Natural and mine-related mercury in an orogenic greywacke terrane, South Island, New Zealand. NZ J Geol Geophys 53: 103-114

Johnstone Q, LaBrooy S, Craw D (2001) Formation and remediation of scales, pressure oxidation plant, Macraes Mine, New Zealand. Proceedings, Aus Inst Min Metall NZ Branch Ann Conf, pp 275-280

Kerr G, Druzbicka J, Lilly K, Craw D (2015a) Jarosite solid solution associated with arsenic-rich mine waters, Macraes mine, New Zealand. Mine Water Environ 34: 363-374

Kerr G, Pope J, Trumm D, Craw D (2015b) Experimental metalloid mobilisation from an orogenic gold deposit, New Zealand. Mine Water Environ 34: 404-414

McComb KA, Craw D, McQuillan AJ (2007) ATR-IR spectroscopic study of antimonate adsorption to iron oxide. Langmuir 23: 12125-12130

MacKenzie DJ, Craw D (2005) The mercury and silver contents of gold in quartz vein deposits, Otago Schist, New Zealand. NZ J Geol Geophys 48: 265-278

Mains D, Craw D (2005) Composition and mineralogy of historic gold processing residues, east Otago, New Zealand. NZ J Geol Geophys 48: 641-647.

Milham L, Craw D (2009) Two-stage structural development of a Paleozoic auriferous shear zone at the Globe-Progress deposit, Reefton, New Zealand. NZ J Geol Geophys 52: 247-259

Muller T, Craw D, McQuillan AJ (2015) Arsenate and antimonate adsorption competition on 6-line ferrihydrite monitored by infrared spectroscopy. Appl Geochem 61: 224-232

Petrie BS, Craw D, Ryan CG (2005) Geological controls on refractory ore in an orogenic gold deposit, Macraes mine, New Zealand. Mineral Deposita 40: 45-58

Roddick-Lanzilotta AJ, McQuillan AJ, Craw D (2002) Infrared spectroscopic characterisation of arsenate(V) ion adsorption from mine waters, Macraes Mine, New Zealand. Appl Geochem 17: 445-454

Chapter 11
Conclusions: Key Controls on Making of a World Class Deposit

11.1 A World Class Orogenic Gold Deposit at Macraes

The Macraes deposit has many similarities to typical orogenic gold deposits around the world, and some important differences. The main characteristics of the Macraes deposit, as part of the broad spectrum of orogenic deposits, are summarized in Table 11.1 and some of the most important of these characteristics are emphasized in following sections. One of the key differences, as summarized in Table 11.1 and outlined in earlier chapters, is the large volume of rock that has been mineralized at Macraes, with remarkable continuity along 30 km of strike length. In contrast, most orogenic deposits around the world are relatively small and discontinuous.

The economic resources of Macraes deposit have grown progressively since the initial stages of modern exploration to exceed 10 million ounces of gold (Chap. 1). Tungsten, in the form of scheelite, is an additional, potentially economic component of this ore. These resources are vastly greater than anything envisaged by historic miners who first worked the discontinuous quartz veins, and substantially greater than envisaged at the opening of the modern mine in 1990. Further gold resources that are currently sub-economic are known to exist in mineralised rocks along the strike length of the Hyde-Macraes Shear Zone. From a geological, rather than economic perspective, the shear zone was truncated below by a post-mineralisation fault, so the original configuration of the shear zone had significantly more gold than has been defined in the currently-exposed portion. Erosion of shear zone gold has contributed an unknown, but probably large, amount of the 8 million ounces of placer gold that has been mined from sediments resting on the Otago Schist belt (Chap. 2). Hence, the original gold endowment of the shear zone was substantially greater, possibly more than double, the currently defined economic resources.

D. Craw and D. MacKenzie, *Macraes Orogenic Gold Deposit (New Zealand)*,
SpringerBriefs in World Mineral Deposits, DOI 10.1007/978-3-319-35158-2_11

Table 11.1 Summary of the characteristics of the Macraes deposit, in the context of the key parameters that unite and distinguish orogenic gold deposits world-wide (as outlined in Chap. 1)

Key features of orogenic Au deposits	Macraes deposit characteristics
Tectonic setting	Accretionary complex
Host rocks	Metasedimentary schist
Host rock age	Mesozoic (Triassic-Jurassic)
Age of host metamorphism	Mesozoic (Jurassic-early Cretaceous)
Age of mineralisation	Mesozoic (Early Cretaceous; 140–135 Ma)
Host rock metamorphic grade	Lower greenschist facies
Mineralisation relationship to metamorphism	Syn- to late metamorphic
Associated magmatism	None
Mineralisation temperature	300–400 °C
Mineralisation depth	~10 km (brittle-ductile transition)
Hydrothermal alteration	Lower greenschist facies mineralogy; graphite
Mineralising fluid	H_2O; very minor CO_2, CH_4; low salinity
Mineralising fluid source	Metamorphic dehydration; some meteoric
Hosting structure	Ductile-brittle thrust shear zone (dip 15°–20°)
Structural continuity	30 km strike, up to 250 m thick, >1 km down dip
Principal metal suite	Au, W, As; minor Sb, Mo
Base metal enrichment	None; minor sulphidation of host Cu, Pb, Zn
Mineralisation style	Wall rock alteration and replacement; minor veins
Principal metallic minerals	Pyrite, arsenopyrite, scheelite
Gold texture and paragenesis	Encapsulated in polyphase sulphides; rare free Au
Resource size	>300 tonnes Au (>10 Moz Au in 2016)

11.2 Disseminated Gold Ensured Continuity of Mineralised Rock for Mining

The economic success of the Macraes mine has been facilitated by the continuity of mineralised rocks in the shear zone to enable a large tonnage operation, albeit with low average gold grades (Chap. 6). This continuity has arisen because of the nature of the mineralisation processes, which emplaced disseminated gold throughout large volumes of rock in and adjacent to the hosting structures, including some zones with no quartz veins (Fig. 11.1). This style of mineralisation is distinctly different from that which occurred, for example, during middle Cretaceous orogenic gold emplacement in the Otago Schist belt (Fig. 11.1). In that latter example, shallow-level mineralisation was controlled by normal faults, and gold occurs in well-defined quartz veins with no wall rock alteration. The low volume of

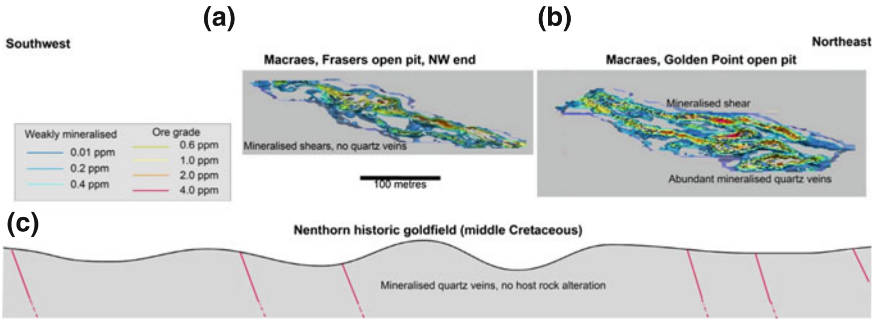

Fig. 11.1 Comparison of extents of mineralised rocks between Macraes and nearby middle Cretaceous orogenic quartz vein deposit at Nenthorn (Chap. 2). All cross sections are the same scale and drawn perpendicular to strike of hosting structure. **a** Mineralised shears at Macraes. **b** Mineralised shears and quartz veins at Macraes. **c** Mineralised quartz veins at Nenthorn. Continuity of gold grades at Nenthorn is speculative

mineralised rock and the large amounts of completely barren rock between mineralised zones at Nenthorn makes this a less attractive mining proposition than the Macraes operation (Fig. 11.1).

11.3 Regional Scale Source of Metals and Fluids in Host Schist Belt

11.3.1 Mobilisation of Metals During Prograde Metamorphism

The large metal endowment of the Hyde-Macraes Shear Zone was derived from the hosting Otago Schist belt. Small amounts of metals were derived from large volumes of typical metasedimentary protoliths, not from any specific metal-enriched rock type such as metabasic schists. Gold was initially slightly enriched in diagenetic pyrite, and this gold was mobilised during prograde metamorphism, especially as the pyrite transformed to pyrrhotite in the transition from upper greenschist facies to amphibolite facies (Chap. 9). Arsenic accompanied gold in that diagenetic pyrite and was mobilised in a similar manner. This metal mobilisation was facilitated by generation of a metamorphic fluid from dehydration reactions at the same time. Tungsten was mobilised from detrital rutile, initially into metamorphic veins and then into the mineralising fluid in the greenschist facies.

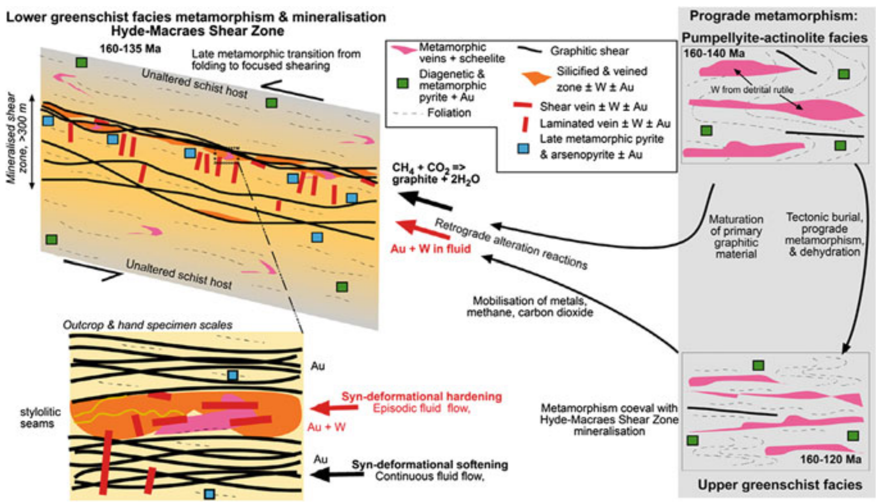

Fig. 11.2 Summary of the key processes that have resulted in mineralisation of the Hyde-Macraes Shear Zone (*left*) from metamorphic processes in the Otago Schist belt (*right*)

11.3.2 Synchroneity of Metamorphism and Mineralisation

The Hyde-Macraes Shear Zone was formed and mineralised under lower greenschist facies conditions as the lower greenschist facies host rocks were being uplifted through the brittle-ductile transition. Prograde metamorphism and associated generation of metal-bearing fluids were still occurring in upper greenschist facies and amphibolite facies rocks immediately below the evolving shear zone (Chaps. 2, 9). This synchroneity of prograde metamorphism at depth and late metamorphic shear zone development ensured that the mineralising fluids were efficiently channeled from source to sink (Fig. 11.2).

11.4 Regional Scale Structural Focusing of Hydrothermal Fluid Flow

11.4.1 Development of a Focused Shear Zone from More Pervasive Ductile Folding

The regional scale mobilisation of the metals from background metasedimentary schists during metamorphism ensured that there was excess of source materials to form large gold deposits. However, these source materials were initially widely dispersed through the host rocks. A key step in the chain of ore formation processes was development of a regional scale shear zone to focus the metamorphogenic fluid flow into a smaller volume of rock (Fig. 11.2). The Hyde-Macraes Shear Zone evolved into a through-going focused thrust structure as shears developed in micaceous schists during ductile folding. Compressive strain became progressively more localised on these shears and folding waned between those shears as a consequence. This focusing of strain was encouraged by progressive change in deformation mechanisms from ductile to brittle, ending with highly localised cataclasis within the shear zone.

11.4.2 Enhancement of the Shear Zone by Hydrothermal Graphite

Shear development was enhanced by introduction of hydrothermal graphite, which acted as a lubricant and focused strain into narrower shears (Chap. 8). Increasing strain enhanced dynamic permeability in these shears, allowing further localising of fluid flow and more hydrothermal graphite deposition, leading to a feedback effect that further enhanced shear development. The graphite formed from mixed methane and carbon dioxide in the fluid as it cooled through greenschist facies conditions (Fig. 11.2). These volatiles, especially methane, were derived during metamorphic maturation of primary graphitic material in the host rocks.

11.5 Late Metamorphic Fluid Flow Caused Replacement Reactions

11.5.1 Grain Boundary Fluid Flow Facilitated Retrogressive Alteration

Fluid flow in the shear zone was controlled by permeability along grain boundaries and microshears, and was essentially metamorphic in style. This fluid flow was almost pervasive through large volumes of rocks in and adjacent to shears, on a scale of hundreds of metres perpendicular to the shear zone structure (Fig. 11.2). Fluid-rock interaction led to lower greenschist facies retrogressive reactions throughout this large volume of rock. The principal reactions that occurred on a large scale were transformation of titanite to rutile, and decomposition of epidote (Chap. 5).

11.5.2 Continuous Fluid Flow in Micaceous Schists

Micaceous schists host the best-developed shears, some of which are graphitic, and these micaceous shears were the principal fluid conduits. Fluid flow was continuous along these shear conduits, albeit slowly (metamorphic rates), and was enhanced by on-going shear deformation. As a consequence, micaceous schists are an important host to ore grade mineralised rocks, and some parts of the deposit have ore of this type only (Chaps. 4, 5).

11.5.3 Episodic Fluid Flow in Fractured Competent Rocks

Flat quartz veins formed within shears, and fill fractures that developed in more competent rocks such as quartzofeldspathic layers. Fractures and subsequent veins commonly nucleated on quartz-rich metamorphic fold hinges. Later brecciation and further vein filling, accompanied by silicification of adjacent rocks, led to formation of masses of competent quartz-rich mineralised rocks on the 1–10 m scale (Fig. 11.2). Individual veins are generally discontinuous on the 1–10 m scale. The fluid flow that formed these veins was episodic, as fractures opened and breccias formed in short-lived discrete deformation events, with fluid derived from the reservoir of micaceous schist conduits.

11.5.4 Mineralisation Was Dominated by Replacement Reactions

Hydrothermal alteration and mineralisation in the micaceous shears involved chemical replacement of silicate minerals by sulphide minerals, and the gold accompanied these sulphide minerals. These replacement reactions were largely isochemical, apart from addition of Au, As, Sb, S, and graphitic carbon. Recrystallisation of micas during the replacement reactions caused redistribution and localised enrichment of Cr. Quartz vein formation involved some filling of fractures in the rock, but most early-formed veins of this type were partially replaced by finer grained quartz with sulphides and gold. Breccias were formed in fractured rocks, but these were largely replaced by quartz and sulphides, with some addition of scheelite. Addition of sulphides and gold along microshears was facilitated by replacement reactions, including silicification, along microshear margins.

11.6 Subtle Lithological Variations Enhanced Mineralisation Locally

11.6.1 Anastomosing Micaceous Shears Host Most Gold

The host schist rock mass is broadly mineralogically and geochemically uniform, but minor lithological variations have had major effects on the style of mineralisation at the 1–500 m scales. Micaceous shears that host most of the gold anastomose around pods of more competent feldspathic rocks, many of which are essentially barren of gold. The most economically important shear, the Hangingwall Shear, is dominated by graphitic micaceous schists, with discontinuous complex quartz vein bodies that have been deformed into parallelism with the shear.

11.6.2 Enhancement of Competency Contrasts by Hydrothermal Alteration

Contrasts in rheological competency of the deforming rock mass in the shear zone were enhanced by on-going hydrothermal activity. Precipitation of graphite in microshears and alteration of albite to muscovite caused softening of some rocks and allowed micaceous shears to increase in width (Fig. 11.2). In contrast, silicification and quartz vein emplacement caused rheological hardening and increases in extents of massive bodies between shears.

11.6.3 Local Stress Switching Facilitated Emplacement of Laminated Veins

Lithological and structural inhomogeneities along the strike of the shear zone have caused formation of lateral ramps within the thrust structure, as shears anastomosed around more competent rock masses and stepped between structural levels in the shear zone. Localised stress switching occurred, so that minimum and intermediate principal stresses became interchangeable. This led to widespread development of extensional laminated veins with strikes sub-parallel to the thrusting direction and extensional directions sub-parallel to the strike of the shear zone. These laminated veins were formed with the same minerals at the same time as the flat veins, but with strongly contrasting orientations and textures. Rocks with abundant laminated veins between shears constitute an important part of the resource inventory of some parts of the shear zone.

11.7 Footprint of the Shear Zone Extends to >500 m

11.7.1 Geochemical Footprint Is Dominated by Arsenic

The readily-detectable geochemical footprint of the Hyde-Macraes Shear Zone is largely confined to proximal parts of the mineralised structures (Fig. 11.3). Gold, W, As, Sb and Cr are all enriched to some extent in these proximal rocks (Chap. 6). Arsenic is the most prominent and widespread indicator of mineralisation, and is

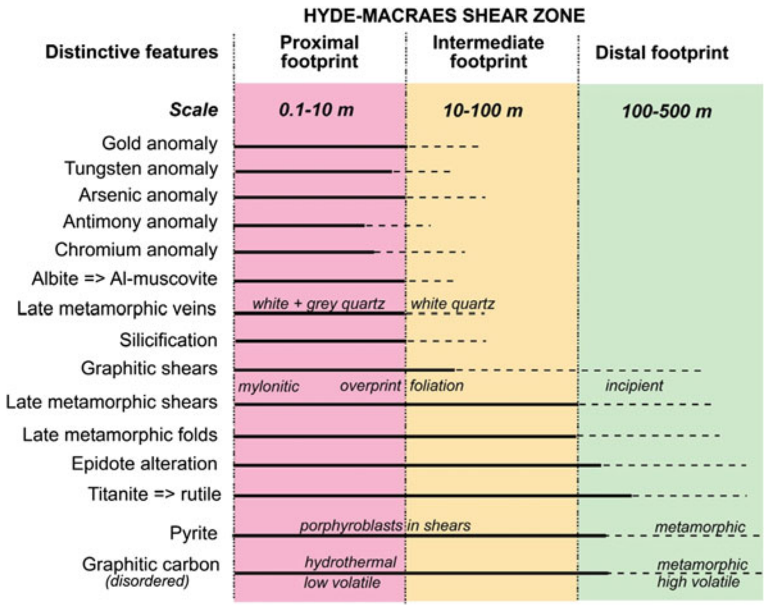

Fig. 11.3 Distinctive features that contribute to the spatial footprint of the Hyde-Macraes Shear Zone at various scales

closely linked to gold anomalism. Geochemical anomalies are most apparent in micaceous shears, as silicified zones and quartz veins are commonly diluted by silica. Sulphur is enriched in mineralised rocks, but some unmineralised rocks contain significant metamorphic pyrite.

11.7.2 Structural Footprint Is Dominated by Late Metamorphic Shears

The shear zone is characterised by late metamorphic shears that crosscut, but are subparallel to, the metamorphic foliation. More deformed shear zone rocks are dominated by the shear fabric, and the metamorphic foliation has been overprinted (Chap. 4). Shearing was accompanied by folding of the metamorphic foliation in less-sheared rocks. In contrast, schists above the main shear zone have flat-lying and planar foliation with localised disruptions by syn-metamorphic rootless fold hinges (Fig. 11.2).

11.7.3 Subtle Mineralogical Alteration Forms the Largest Footprint

Proximal mineralogical changes associated with the geochemical anomalies include arsenopyrite and pyrite replacement of silicates and addition to veins (with scheelite). Minor mineralisation-related white quartz veins, silicification, and pyrite porphyroblasts extend beyond the proximal zone, where they merge with similar metamorphic features (Fig. 11.3). Likewise, graphitic shears are abundant in the shear zone, but occur elsewhere in the schist belt as well (Chap. 8). The most distal mineralogical footprint is the subtle alteration of accessory minerals titanite and epidote (Fig. 11.3).

11.7.4 Principal Geophysical Footprint Is Electrical Resistivity (Conductivity)

The Hyde-Macraes Shear Zone is dominated by rocks that are geochemically and mineralogically little different from the host schist, so the potential for a geophysical footprint is limited. The principal feature of the shear zone that does have a geophysical effect is the enhanced conductivity of the rocks as a result of connected graphitic shears that also contain sulphide minerals (Chap. 8). These features result in a detectable conductivity footprint at a regional scale. That geophysical footprint is partly obscured by wet clay-rich cross-faults.