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Cretaceous tectonics and gold mineralisation in the Otago Schist, New Zealand

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ABSTRACT

This paper provides a regional-scale background for understanding gold-mineralising processes in the Otago Schist during the Cretaceous. At this time the schist belt was in the latter stages of formation as an accretionary complex with 2000 km strike length on the Pacific margin of Gondwana. The Otago Schist is interpreted as an exhumed accretionary wedge of structurally stacked clastic metasedimentary rocks with minor metabasic rocks. Metamorphic grade reached upper greenschist facies. Gold and other related elements were mobilised from the metasedimentary rocks during metamorphism, and these elements contributed to the high levels of orogenic gold endowment (>18 million ounces in the schist belt. Mesozoic Gold deposits were emplaced in two distinct pulses, one at the beginning of the Early Cretaceous (~140-135 Ma) and the other at the end of the Early Cretaceous (~112-100 Ma). These mineralising pulses were driven by regional tectonic events that may have involved episodic underplating of subducting material, and/or subduction of spreading ridges. The earlier event was most closely associated with metamorphic processes that mobilised gold from the accreted metasediments during convergent tectonics, and appears to have been the more economically significant. The later event took place as accretionary processes ceased and the Zealandia portion of Gondwana began to undergo intracontinental rifting.

Key words: gold, mineralisation, Otago Schist, New Zealand, Cretaceous

INTRODUCTION

The Mesozoic Otago Schist metamorphic belt in southern New Zealand has produced more than 12 million ounces (Moz) of gold from placer and orogenic deposits (Williams, 1974; Moore and Doyle, 2015). Production at the world-class Macraes orogenic mine (Figure 1) has yielded more than 4 Moz since 1990 and remaining resources include at least another 6 Moz of gold (Moore and Doyle, 2015). Hence, the Otago Schist is a well-endowed gold province, and is considered to be prospective, particularly for new orogenic deposits. Recent and on-going gold exploration in the province has targeted the Macraes type of deposit, which is characterised by a shear zone containing large volumes of mineralised rock containing disseminated gold in association with sulphide minerals (Teagle, Norris and Craw, 1990; Craw, 2002; Mitchell *et al*, 2006; Jones, Craw and Norris, 2007).

Results of modern exploration efforts, some of which are reported in this monograph, provide new information on mineralisation in particular areas of the schist belt. An important context in which to conduct exploration activity in the Otago Schist is to understand the regional geological evolution of the host rocks, particularly the stages of evolution that are directly relevant to gold mineralisation. To that end, this paper reports on recent advances in understanding of the geological history of the Otago Schist and the associated processes related to gold mobilisation and deposition. We focus on the Cretaceous history of the schist belt, as that is the time in which most of the orogenic gold was emplaced (Mortensen *et al*, 2010), and when initial stages of exhumation and erosion of these deposits began to concentrate placer gold (Craw 2010). Some more localised gold mineralisation occurred in the Miocene in northwest Otago (Figure 1; Craw *et al*, 2007), but these deposits are outside the scope of this paper.

TECTONIC SETTING

The present day Otago Schist is part of a 2000 km long belt of Mesozoic schist (Haast Schist) that crops out discontinuously from the Chatham Islands to the central North Island. This Mesozoic schist belt lies towards the eastern (Pacific rim) side of the continental margin of Zealandia. In the Cretaceous this continent-ocean margin was a subduction zone along the Gondwanan margin, and current models of the Otago Schist emphasise its origin as an exhumed Mesozoic accretionary wedge (Figure 2).

The accretionary wedge model (e.g. Rahl *et al*, 2011; Mortimer, McLaren and Dunlap, 2012) builds on the recognition of the Otago Schist as a metamorphic overprint on tectonostratigraphic terranes, and of a forearc basin and coeval Cordilleran batholith to the west (Figure 2). In Otago, schist protoliths include the Caples Terrane and Rakaia Terrane, the latter being part of a larger Torlesse Composite Terrane (Figure 2). Outside the schist these greywacke sandstone-dominated terranes retain their sedimentary features including fossils of Permian and Triassic age. Within the schist, there are additional lithotectonic subdivisions (Mortimer, 2004; MacKenzie and Craw, 2005). Recent detrital zircon work (e.g. Jugum, Norris and Palin, 2013; Cooper and Ireland, 2013; Mortimer, Lee and Stockli, 2015) indicates that both older (Carboniferous) and younger (late Early Cretaceous) protoliths are present, and ideas on the terrane makeup of the schist belt will likely continue to evolve in the future.

JURASSIC-CRETACEOUS METAMORPHISM AND DEFORMATION

The Otago Schist host rocks consist predominantly (>95%) of clastic metasedimentary rocks (greywacke and argillite), now transformed to greyschist. The remaining volume of schist comprises horizons of a basalt-chert-limestone association that has been metamorphosed to greenschist, quartzite and marble. Very rare pods of ultramafic schist are locally associated with greenschist bands (Turnbull, 2000). Mapped metamorphic zones in the schist are based on index minerals in greyschist assemblages and metamorphic grade ranges from pumpellyite-actinolite, and lawsonite-albite-chlorite, to greenschist facies. The greenschist facies is divided into a lower grade chlorite zone and a higher grade garnet-biotite-albite zone (Figure 1, 3). The lower metamorphic grade flanks of the Otago Schist (chlorite zone and lower grade) were initially metamorphosed in the Late Jurassic (c. 180-155 Ma) with cooling and recrystallisation persisting into the Early Cretaceous (c. 135 Ma; Mortimer, 1993; Gray and Foster, 2004; Mortimer, McLaren and Dunlap, 2012). In contrast, the higher grade metamorphic core of the belt (garnet-biotite-albite zone) underwent ductile deformation, with associated mica recrystallisation, to the end of the Early Cretaceous (c. 110 Ma; Gray and Foster, 2004; Mortimer, Lee and Stockli, 2015). Metamorphism and ductile deformation resulted in pervasive foliations, large-scale (1-5 km) recumbent folding, and strong quartz rodding lineation (Mortimer, 1993, 2003; Craw, 1998; Turnbull, Mortimer and Craw, 2001). The metamorphic fabric in parts of the belt has been broadly mapped as “platy schist” in which the foliation dominates in highly deformed rocks, and “hingy schist” in which syn- and late-metamorphic ductile folds dominate outcrops, with variable development of a fold axial surface cleavage (Mortimer, 2003; MacKenzie and Craw, 2005).

Folding and shear zone development in the schist continued during late metamorphic uplift, as different parts of the schist belt were uplifted through the brittle-ductile transition (Figure 3, 4; Mortimer, 1993; MacKenzie and Craw, 2005). This occurred in the Late Jurassic and the beginning of the Early Cretaceous in lower metamorphic grade rocks of the schist flanks, and in the latest Early Cretaceous in what is now the higher grade metamorphic core (Figures 1-4). At least some metamorphic boundaries in the schist belt, particularly those on the north side of the schist core, are now mainly tectonic features, involving both late-metamorphic shear zones and post-metamorphic faults (Craw, 1998; Mortimer, 2000; Deckert, Ring and Mortimer, 2002; MacKenzie and Craw, 2005).

REGIONAL EXTENSION AND SCHIST EXHUMATION

There are two well-known examples of low angle mineralised late-metamorphic shear zones that have been cut and truncated by low angle post-metamorphic normal faults in the Otago Schist (Figure 3). One is the Hyde-Macraes Shear Zone (HMSZ) of East Otago, where ductile to semi-brittle shear zone fabrics are developed in chlorite zone schist. The HMSZ is truncated by the Footwall Fault (Figure 3) which forms a structural lower boundary that truncates the shear zone. The other example is the Rise and Shine Shear Zone (RSSZ) of Central Otago in which mineralised shear zone fabrics are developed in garnet-biotite-albite zone schist. In this example, the post-metamorphic Thomsons Gorge Fault truncates the structural top of the RSSZ, rather than being a footwall structure (Figure 3). Other examples of low angle brittle faults include the Cap Burn Fault and faults in the Cromwell Gorge (Figure 1). All these post-metamorphic, post-mineralisation, post-shear zone faults probably have several kilometres of dip-slip displacement on them and are first order features responsible for the Late Cretaceous exhumation of the schist, somewhat analogous to Cordilleran metamorphic core complex exhumation (Deckert, Ring and Mortimer, 2002).

TWO PULSES OF CRETACEOUS GOLD MINERALISATION

Otago orogenic gold deposits are controlled by structures that cut the metamorphic fabric of their immediate host rocks, and are clearly late metamorphic to post-metamorphic in relative timing (Williams, 1974; Craw, 2002; Craw *et al*, 2007; Mackie, MacKenzie and Craw, 2009). At least some of the orogenic deposits were subsequently exhumed to be eroded into Cretaceous sediments (Craw, 2010). Hence, most mineralisation in the Otago Schist was Cretaceous. This timing of mineralisation has been quantified by isotopic dating of a selection of deposits (Mortensen *et al*, 2010). Results of the dating study, combined with lead isotope data, have identified two distinct pulses of gold mineralisation, in earliest Early Cretaceous (~140-135 Ma) and latest Early Cretaceous (~112-100 Ma) (Figure 4; Mortensen *et al*, 2010).

The earlier pulse of Cretaceous mineralisation involved the HMSZ and the Glenorchy mineralised vein swarm, hosted in lower grade schists on opposite flanks of the schist belt (Figure 1, 4; Mortensen et al. 2010). Both of these deposits have Au-W enrichment, with Au dominating at Macraes and W dominating at Glenorchy (Williams, 1974). The later mineralisation pulse mainly involved small quartz vein-dominated deposits hosted in normal faults, such as those at Nenthorn and Barewood (Figure 1, 4), which are scattered throughout the schist belt but occur mostly in the higher grade core (Figure 1; Mackie, MacKenzie and Craw, 2009; Mortensen *et al*., 2010). In addition, the compressional shear-hosted, and locally fold-related, RSSZ that has some resemblances to Macraes (Cox *et al*, 2006; Craw *et al*, 2007; MacKenzie and Craw, 2007) is grouped in this later mineralisation pulse (Figure 4; Mortensen *et al*, 2010).

Both pulses of Cretaceous orogenic gold deposition display a similar range of mineralisation styles, which mainly reflect the depth at which mineralisation occurred (Figure 4; Craw, Upton and MacKenzie, 2009). The Macraes deposit formed under chlorite zone greenschist facies conditions in host rock of similar metamorphic grade (Figure 4), so hydrothermal fluids were almost in chemical equilibrium with the host rock. Only subtle mineral alteration reactions occurred during this process (Craw, 2002; Jones, Norris and Craw, 2007; Craw, Upton and MacKenzie, 2009). Alteration at Glenorchy was also subtle and reflects late metamorphic fluid processes (Begbie and Sibson, 2006). At the opposite end of the spectrum of mineralisation styles, shallow-formed deposits that are mainly hosted in normal faults, typical of the second Cretaceous mineralisation pulse, have negligible alteration of host rocks (Craw, Upton and MacKenzie, 2009). This lack of alteration resulted from low volumes of mineralising fluids passing quickly through the open structures, with low host rock permeability limiting water-rock interaction (Craw, Upton and MacKenzie, 2009). Between these formation depth extremes, the most common alteration reactions involved replacement of metamorphic chlorite in host rock by hydrothermal ankerite (Figure 4) and auriferous pyrite (MacKenzie and Craw, 2007; Craw, Upton and MacKenzie, 2009). Ankerite derived from related reactions is also widespread in veins and breccias in these deposits (Craw, Upton and MacKenzie, 2009).

METAMORPHIC GOLD MINERALISATION

Recrystallisation and metamorphic reactions in the Otago Schist during Jurassic-Cretaceous metamorphism and deformation, which led to the first pulse of mineralisation, has resulted in mobilisation of metals and metalloids relevant to orogenic gold deposits, particularly in the greenschist facies (Figure 5; Pitcairn *et al*, 2006, 2010; Pitcairn, Craw and Teagle, 2014, 2015). Importantly, at least half of the gold dispersed through the metasedimentary and metabasite protoliths was mobilised from those rocks during metamorphism. Most of the protolith gold was initially concentrated in diagenetic pyrite (typically 0.5-2.0 ppm Au), and that gold was mobilised when the pyrite recrystallised to metamorphic pyrite and ultimately to pyrrhotite under subgreenschist and/or greenschist facies conditions (Figure 5; Pitcairn *et al*, 2010; Large *et al*, 2011).

This metamorphic gold mobilisation was accompanied by even more substantial mobilisation of As and Sb, such that c. 90% of the protolith contents of these metalloids were extracted from metasedimentary rocks as they passed through the greenschist facies (Figure 5). Metamorphic mobilisation of As from metabasites was less effective than from metasediments, and some As may have been transferred to metabasite layers from enclosing metasediments (Figure 5; Pitcairn, Craw and Teagle, 2015). The generally efficient mobilisation of these metalloids, accompanying gold mobilisation, has ensured that Otago Schist orogenic mineralisation that arose from metamorphic processes is characterised by elevated As and Sb footprints (Figure 5, 6; Craw *et al*, 2007; 2015). Tungsten was also mobilised during metamorphism (Figure 5), starting in the pumpellyite-actinolite facies, where it migrated into syn-metamorphic quartz-albite veins (Pitcairn, Craw and Teagle, 2014). Initial elevated Mo contents of diagenetic pyrite were also mobilised during metamorphism into the metamorphic pile, but there is only minor Mo enrichment at Macraes mine, and the rest of the Mo is dispersed through the host rocks (Pitcairn *et al*, 2010; Large *et al*, 2012; Craw *et al*, 2015).

ROLES OF GRAPHITE IN GOLD MINERALISATION

One of the most distinctive features of the Macraes deposit is the thick (>250 m) graphitic shear zone that hosts much of the gold (Craw, 2002; Pitcairn *et al*, 2005; Jones, Craw and Norris, 2007; Henne and Craw, 2012; Hu *et al*, 2015). Most of the graphite is hydrothermal in origin, and this process has resulted in increase of C content of the rocks from a background of c. 0.1 wt% to 1-3 wt% (Craw, 2002; Henne and Craw, 2012; Hu *et al*, 2015). The background carbonaceous material in metasedimentary protoliths was derived from organic content, which is observed in moderate abundance in nonschistose Torlesse greywacke, and occurs in close association with the diagenetic pyrite from which the metamorphogenic gold was derived (Large *et al*, 2012; Henne and Craw, 2012; Hu *et al*, 2015). This primary sedimentary carbon was progressively mobilised into various structural settings during prograde metamorphism, and the carbonaceous material became progressively mature and graphitised, in parallel with the mobilisation of metals and metalloids (Figure 6; Large *et al*, 2012; Hu *et al*, 2015).

The increased graphite content of the shear zone at Macraes seemingly played an important structural role, by lubricating the microshears and thereby helping to facilitate deformation and deformation-related fluid flow in the shear zone (Craw, 2002; Upton and Craw, 2008; Henne and Craw, 2012). Emplacement of the disseminated gold and associated sulphide minerals at Macraes depended on localised permeability enhancement at the mineral grain scale, over a deformation zone that is up to 250 m thick (Jones *et al*, 2007; Upton and Craw, 2008). Graphite was precipitated from the percolating fluid as a product of reaction between methane and carbon dioxide (Craw, 2002; Upton and Craw, 2008; Henne and Craw, 2012). In addition, many pelitic schists, in particular, have relatively high primary carbon contents, and some of these are also locally enriched in diagenetic and/or metamorphic pyrite (Large *et al*, 2012; Henne and Craw, 2012). Such graphitic pelitic schists may be preferential geochemical hosts for gold and sulphides because of their relatively reducing geochemistry. In contrast, there is only sparse evidence for gold enrichment of metabasites (Bierlein and Craw, 2009; Coote, Henderson and Waterhouse, 2011; Pitcairn, Craw and Teagle, 2015), which are typically more oxidised rocks.

COMPRESSIONAL VS EXTENSIONAL HOST STRUCTURES

The Macraes deposit (the first pulse of mineralisation) formed in a thrust shear zone in the latter stages of metamorphism during regional compression, as the rocks passed through the brittle-ductile transition (Figure 3, 4, 6). However, the Macraes deposit also contains numerous extensional veins that formed at the same time as the dominant compressional structures (Upton, Begbie and Craw, 2008). In contrast, the approximately coeval Glenorchy vein system is dominated by mineralised normal faults in association with a swarm of extensional veins, with no associated compressional structures (Begbie and Sibson, 2006).

The second pulse of mineralisation was mainly associated with normal faults, although the Rise & Shine Shear Zone is an exception as it has upright fold zones associated with shear zone development (Cox *et al*, 2006). Regional normal fault development occurred mainly after the regional plate tectonic geometry had changed to become extensional in southern New Zealand at the end of the Early Cretaceous (Figure 2, 7). Most these younger gold deposits occur in swarms of normal faults that strike northwest across the whole schist belt, reflecting this regional change in tectonic setting. Mineralisation occurred at the same time as extensional normal faults were facilitating unroofing of the schist belt, including erosion of the deposits formed in the first mineralisation pulse (Figure 3, 7). At that time, regional topography was dominated by river systems controlled by normal faults, in which locally-thick sediments were accumulated (Figure 7; Mitchell *et al*, 2009; Craw, 2010).

The driving force(s) that caused the discrete pulses of mineralisation are not known, but they represent key events for initiating focussed hydrothermal activity and mineralisation aaditional to the normal processes of accretionary complex formation (Figure 8a,b). The mineralisation pulses may have been related to subduction of spreading ridges, which could have supplied extra heat beneath the extending orogen (Figure 8b; Tulloch *et al*, 2009; Mortensen *et al*, 2010). Alternatively, underplating of slices of accreted metasediments may have occurred periodically (Figure 8b; Cooper and Ireland, 2013; Mortimer, Lee and Stockli, 2015). The second pulse of mineralisation seemingly lacked the collisionally-driven accretion, thickening, and resultant metamorphism that accompanied the first mineralisation pulse (Figure 4, 6) and drove the mobilisation of gold and associated elements (Figure 6, 8) at the beginning of the Early Cretaceous. These observations favour the first pulse of mineralisation as the more fertile and more economically significant gold producing event.

There is an apparent contradiction in coexisting and coeval compressional and extensional deformational styles that occur to some extent during both pulses of mineralisation, within the overall tectonic evolution from accretionary complex to regional extension (Figure 2, 4). However, coeval compression and extension can arise because of localised reorientation of stress orientations around rock inhomogeneities (outcrop scale; Upton, Begbie and Craw, 2008) or rock trajectory divergences (mountain range scale; Upton and Craw, 2014). The latter feature is common in oblique collisional mountain belts, where the resultant extensional structures host hydrothermal mineral deposits (Upton and Craw, 2014). In addition, regional scale normal faulting can occur in the upper portions of thickened accretionary complexes during on-going convergence (Figure 8b; Platt, 1986; Ring *et al*, 1999). If underplating is the dominant mode of accretion and erosion is not trimming down the increased height of the wedge, then the wedge has to lengthen to regain critical taper and this lengthening is usually expressed by horizontal extension and normal faulting in the upper parts of the wedge. At the same time a subhorizontal foliation forms in the underplated rocks.

CONCLUSIONS

The Otago Schist belt was constructed during Jurassic to Cretaceous accumulation of an accretionary complex above a subduction zone on the paleo-Pacific margin of Gondwana. The tectonic zone that includes the schist belt extends for 2000 km, although the Otago Schist forms the widest and best-exposed portion. The Otago Schist is highly endowed with orogenic gold that was emplaced in the above tectonic setting in the Cretaceous. Two Mesozoic gold mineralisation pulses occurred: one at the beginning of the Early Cretaceous (~140-135 Ma), and the other at the end of the Early Cretaceous (~112-100 Ma). The earlier event occurred in the latter stages of metamorphism of the schist belt, during which gold, arsenic and related elements were mobilised as metamorphism proceeded from greenschist facies to amphibolite facies conditions.

The earlier gold mineralising event involved formation of the Hyde-Macraes Shear Zone, which hosts the world-class Macraes gold mine. This shear zone formed as syn-metamorphic ductile folding gave way to more focused ductile thrust deformation. Deformation in the shear zone was enhanced by hydrothermal graphite lubrication. At the same time as the Macraes deposit was forming on what is now the northeastern side of the schist belt, the Glenorchy scheelite (±gold) field was forming on what is now the western side of the belt. Glenorchy deposits are dominated by veins hosted in extensional faults and fractures. The occurrence of coevally-formed extensional and compressional structures is a widespread phenomenon in tectonic belts, and can be related to stress-switching driven by local rock inhomogeneities, or to larger scale divergences in rock trajectories during oblique convergence. Similar coexistence of compressional structures at depth and extensional structures in the upper parts of the wedge can arise in accretionary complexes where underplating is the main mode of accretion and erosion is too slow to compensate the underplating-related thickening of the wedge.

While the Hyde-Macraes Shear Zone was being formed and mineralised in the Early Cretaceous, the rocks that now form the higher-grade core of the Otago Schist belt were still being deformed and metamorphosed under upper greenschist facies conditions. These higher grade rocks were not exhumed until the end of the Early Cretaceous, and this exhumation coincided with the second pulse of orogenic gold mineralisation. Widespread normal faulting occurred across the schist belt, and most of the boundaries between the high grade schist core and lower grade rocks on the flanks of the schist belt are now defined by such normal faults. Some of the steeply dipping normal faults in core and flanks host gold-bearing vein systems, commonly in localised swarms.

The driving force(s) for formation of the two pulses of Cretaceous gold mineralisation are not known, but these driving forces were important for formation of discrete, and locally extensive, mineral deposits, rather than minor background metal mobility that probably occurred throughout the Jurassic-Cretaceous tectonic evolution of the schist belt. Episodes of tectonic underplating of slices of incoming material into the accretionary complex may have played a part in causing the two distinct mineralisation pulses, as may occasional subduction of spreading ridges (Figure 8). Irrespective of the underlying tectonic cause, the earlier gold mineralising event, which was intimately associated with metamorphism of metal-bearing sediments, appears to have been the economically most significant event.

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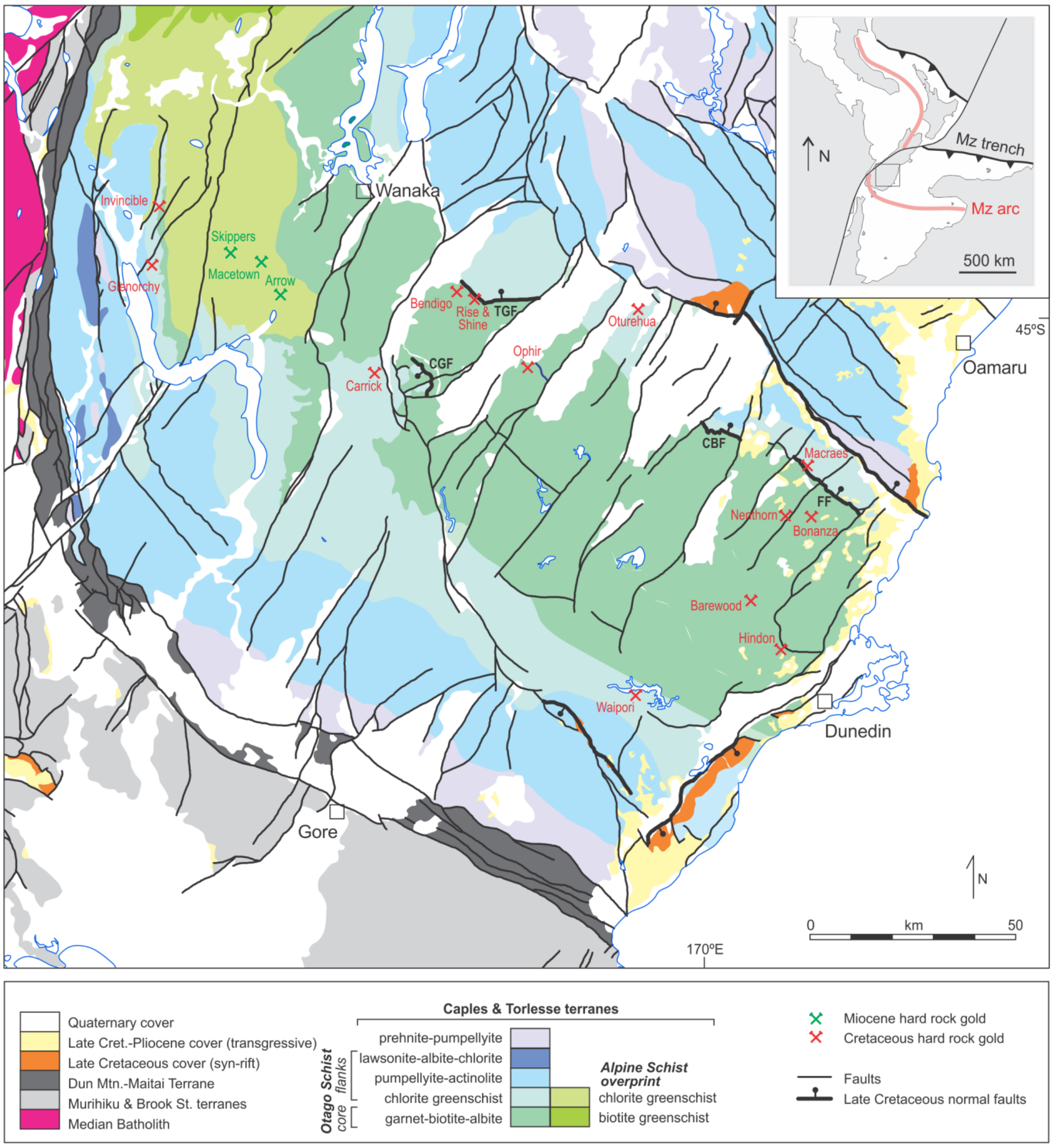

FIG 1 Location map showing the Otago Schist orogenic gold province and its geological framework. Based on Turnbull (2000) and Forysth (2001). Inset shows the locations of the Mesozoic (Mz) trench, subduction boundary, and associated arc, in the context of the modern geography of New Zealand. TGF=Thomsons Gorge Fault, CGF=faults in Cromwell Gorge, CBF=Cap Burn Fault, FF=Footwall Fault.

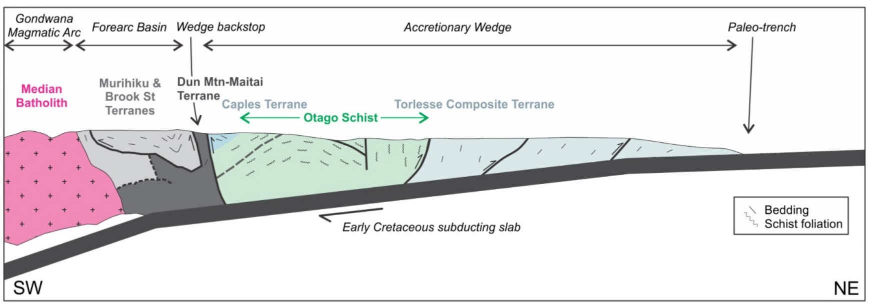

FIG 2 Present day surficial geology across the Otago Schist (plain font) related to components of a Cretaceous subduction margin (italic font). Not to scale; based on figure in Mortimer, McLaren and Dunlap (2012). The low angle NE-dipping fault within the Otago Schist is the approximate projected location of the Hyde-Macraes Shear Zone/Footwall Fault and the Rise and Shine Shear Zone/Thomsons Gorge Fault (Figure 3).

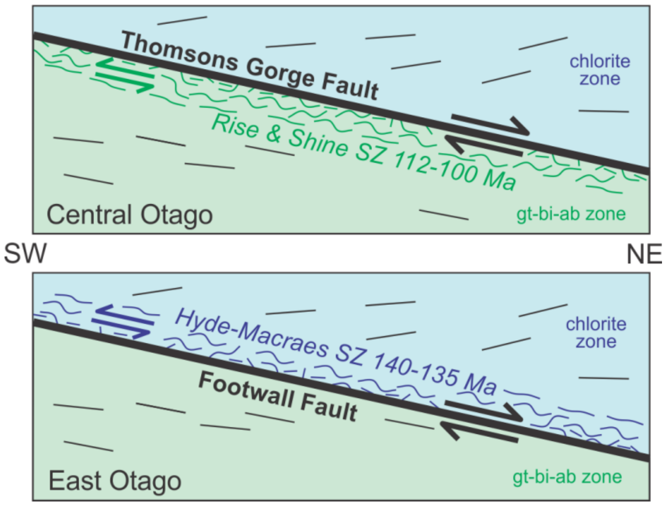

FIG 3 Unmineralised low angle brittle normal faults have reactivated and truncated mineralised semi-brittle compressional shear zones on the northeastern flank of the Otago Schist. Age ranges of movement from Mortensen *et al* (2010) and Mortimer, Lee and Stockli (2015).

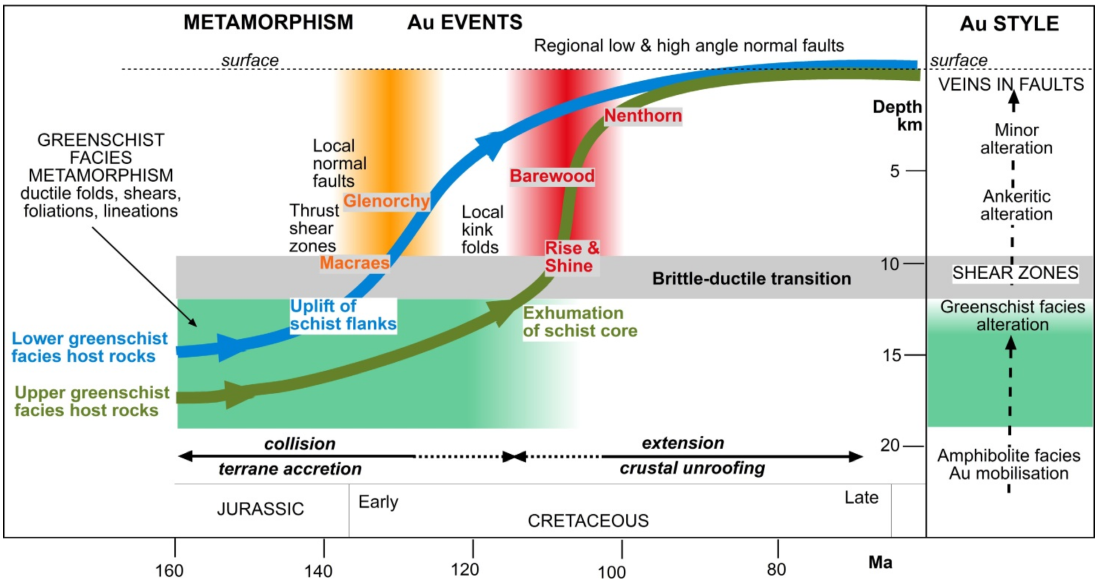

FIG 4. Tectonic evolution of Otago Schist in relation to the two Cretaceous pulses of gold mineralisation (after Mortensen *et al*, 2010), showing differential uplift trajectories of lower greenschist facies rocks (blue) and upper greenschist facies rocks (green). Typical styles of gold mineralisation at different crustal levels on these uplift trajectories are indicated at right.

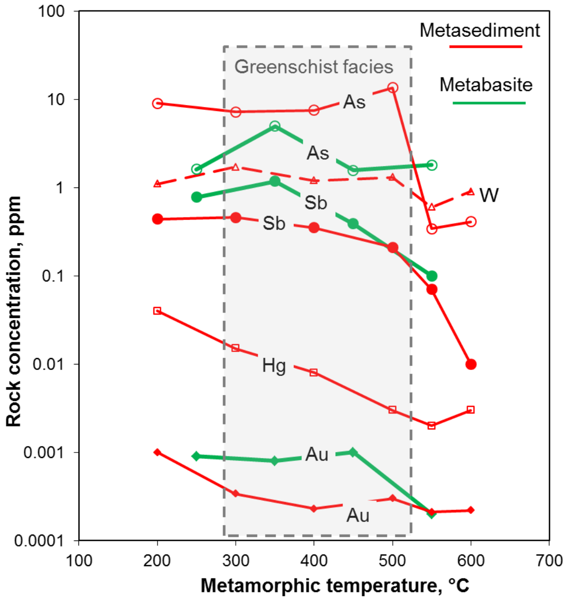

FIG 5 Changes in metal and metalloid contents of Otago Schist with increasing metamorphic grade, quantifying the mobilisation of these elements in greenschist facies (after Pitcairn, Craw and Teagle, 2014, 2015).

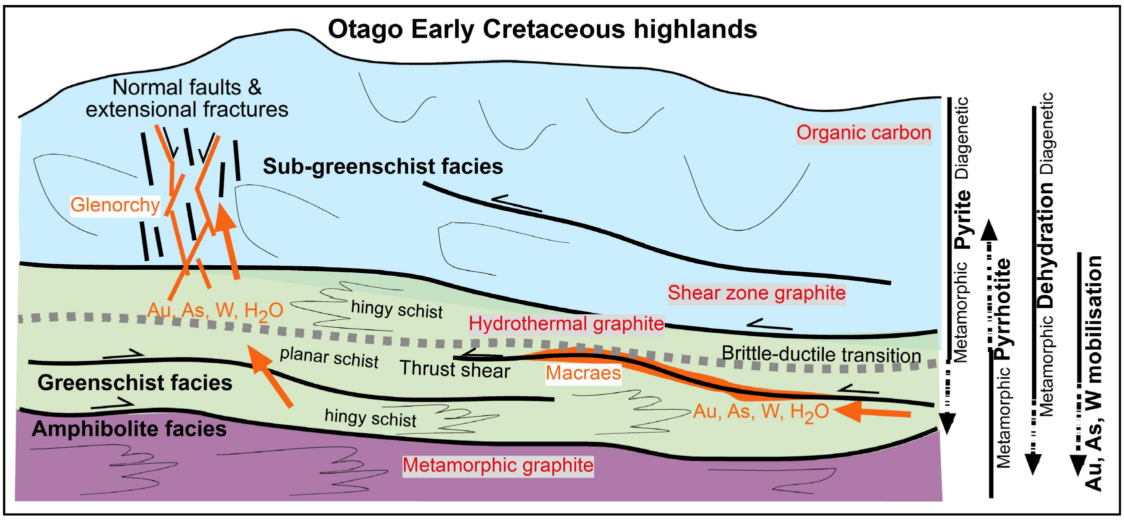

FIG 6 Cartoon cross section (not to scale) across the Otago Schist in the Early Cretaceous (~135 Ma), showing principal pre-exhumation structural and mineralogical features related to metamorphism, fluid flow, and orogenic gold mineralisation.

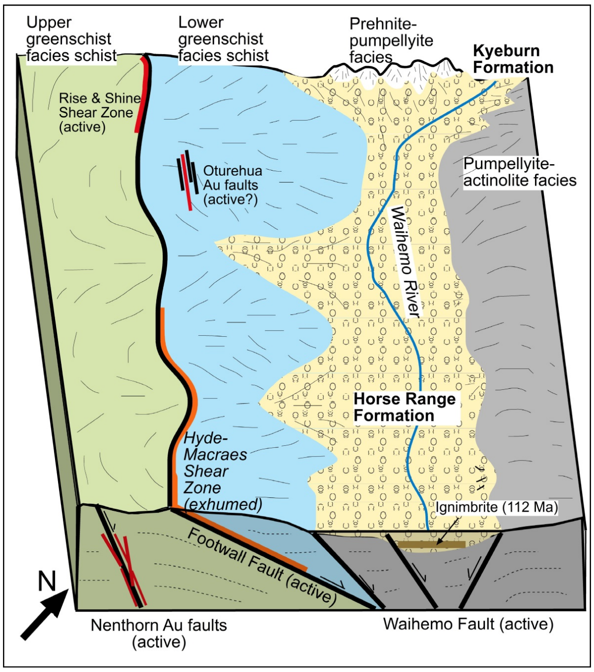

FIG 7 Cartoon block diagram (after Mitchell *et al*, 2009) showing principal paleogeographic and geological features related to orogenic gold mineralisation on the northeast margin of the Otago Schist at the end of the Early Cretaceous, as the higher grade core of the schist belt is being exhumed and exposed at the surface. The second pulse of gold mineralisation is occurring, mainly controlled by normal faults, while gold from the earlier mineralisation pulse is being eroded.

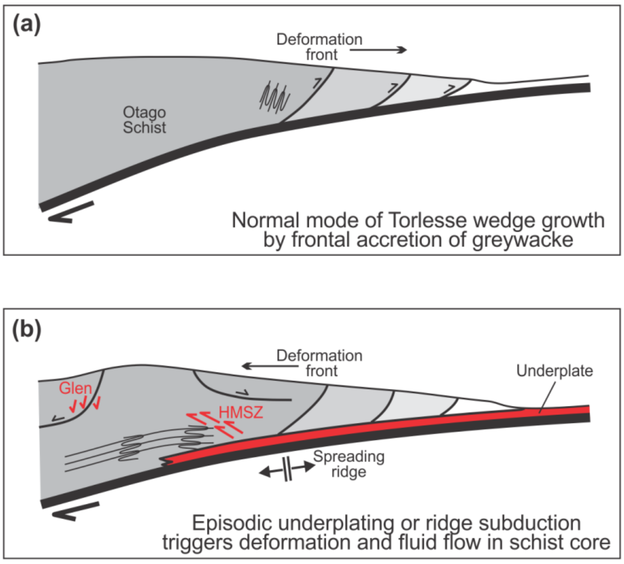

FIG 8 Cartoon cross sections of the Otago Schist accretionary complex: (a) during its normal long-term evolution in the Jurassic and Early Cretaceous; and (b) during episodic abnormal tectonic events at ~135 Ma and ~110 Ma that led to gold mineralisation. Glen = Glenorchy scheelite field; HMSZ = Hyde-Macraes Shear Zone that hosts Macraes mine. Subduction of spreading ridge is speculative.