ELSEVIER
Journal of Structural Geology 26 (2004) 995–1005
JOURNAL OF STRUCTURAL GEOLOGY
www.elsevier.com/locate/jsg

Tectonic and structural setting for active mesothermal gold vein systems, Southern Alps, New Zealand

D. Craw*, J.R. Campbell

Geology Department, University of Otago, PO Box 56, Dunedin, New Zealand

Received 24 September 2002; received in revised form 25 April 2003; accepted 5 June 2003

Abstract

The Southern Alps of New Zealand is an active oblique collisional mountain belt with extensive regional tectonically driven fluid flow. There is no evidence for igneous activity, and fluids consist of varying proportions of meteoric water and mid-crustal fluid derived from dehydration reactions. Fluid flow is controlled by fracture porosity, particularly in damage zones along faults and fault intersections. Gold and arsenic bearing veins exposed at the surface indicate two principal zones of gold mineralisation at depth. One of these is in the highest mountains, near to, but not in the region of maximum uplift. Deformation is dominated by reverse faulting, but some normal and strike-slip faults occur as well. The other zone of gold mineralisation is at and near the intersection of regional oblique dextral reverse faults and regional strike-slip faults. Both zones are characterised by small discontinuous vein systems, locally accompanied by ankeritic alteration of host rock. Veins occur in extensional and shear veins, and in dilational jogs with implosion breccias. Gold mineralisation occurred at many structural levels between the brittle–ductile transition and the near-surface region. The Southern Alps hydrothermal system represents an active roof zone to a mesothermal gold deposition system at depth. As such, this is a modern analogue for mesothermal gold terranes elsewhere in New Zealand and around the world. Observations on the regional distribution of fluid flow in active orogens can give insights into fluid flow at depth where gold mineralisation is occurring now. Comparison of these observations with ancient gold-bearing belts allows construction of three-dimensional concepts of orogenic fluid flow and gold mineralisation.

Keywords: Tectonics; Gold; Hydrothermal; Faults

1. Introduction

Mesothermal gold deposits, vein deposits formed at ca. 200–400 °C, are structurally controlled vein systems found in exhumed metamorphic belts, principally in greenschist facies rocks. Individual deposits have their own unique structural features, but in general mesothermal deposits have a distinctive range of structural characteristics. Economic deposits typically occur close to, but not in, major crustal structures such as faults or shear zones (Groves et al., 1989; Vearncombe et al., 1989; Cassidy et al., 1998). Deposits commonly consist of a well-defined set of close-spaced (metre to 10's of metres) subparallel and structurally related veins that are individually discontinuous and have variable width. Veins generally cut metamorphic fabric in the host rocks, but ductile-deformed veins occur also (Barnicoat et al., 1991). Mineralisation was focussed in quartz veins, but host rock alteration on the metre scale is common, dominated by silicification, ankerite replacement, and/or potassium metasomatism (Cassidy et al., 1998). A gold–arsenic association is an important principal metallic signature, but tungsten (as scheelite) and/or antimony (as stibnite) are common accessories. Most economic mesothermal deposits formed near to the brittle–ductile transition (Sibson et al., 1988; Hagemann et al., 1994), but vein systems have formed over a wide range of structural levels to within a few kilometres of the surface (Craw, 1992; Hagemann et al., 1994; Witt and Vanderhor, 1998).

Reconstruction of the tectonic and structural setting of mesothermal deposits is a desirable pursuit, in order to understand the structural framework in which the deposits formed. Such understanding can contribute to predictive models of deposit geometry and extensions to known deposits, and also to exploration models. However, most mesothermal gold deposits occur in ancient metamorphic belts that have been deeply eroded on a regional scale and have had a complex subsequent geological history. This post-mineralisation history results in structural overprinting, obscuring many aspects of formation of the deposits. This is especially true for gold deposits in Archean terranes, which

---

* Corresponding author. Tel.: +64-3-479-7529; fax: 64-3-479-7527.
E-mail address: dave.craw@stonebow.otago.ac.nz (D. Craw).

0191-8141/$ - see front matter © 2004 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jsg.2003.11.012

are economically the most important deposits (Groves et al., 1989).

This study addresses the problem of determination of structural and tectonic setting of mesothermal gold deposits in general by using a modern analogue, the Southern Alps of New Zealand. This analogue has the advantage that many aspects of the structural evolution of the mountain belt, including details of plate tectonic geometry and rates, are well known and can be observed and measured. Like all sets of mesothermal deposits, those of the Southern Alps have unique structural features. Nevertheless, the overall geometry of gold mineralisation in the active orogen can be used as a template with which older metamorphic belts can be compared, and similarities and differences noted and more readily understood. Also, observations and deductions on the nature of processes of mineralisation in the active orogen can contribute to our understanding of processes of mineralisation in ancient orogens. This study aims to be as objective as possible and reports structural and related observations without imposition of structural models. We present an overview of the tectonic setting of the active orogen, describe the currently active hydrothermal systems, and then describe the mineralised zones in the context of that hydrothermal system.

2. Paleotectonic setting and ancient mesothermal gold

The South Island of New Zealand contains two principal host rocks to mesothermal gold deposits: Paleozoic metasediments in the west, and Mesozoic metasediments in the east (Fig. 1). The Paleozoic metasediments and associated gold deposits, including the currently exploited Reefton deposit (Fig. 1), have affinities to the mesothermal deposits and host rocks of the Lachlan Orogen of south-eastern Australia, and were once connected (Goldfarb et al., 1998). These metasediments were intruded by Paleozoic plutons as an important part of the orogenic history. The Mesozoic metasediments and mesothermal deposits of the South Island formed as part of a convergent orogen along the Pacific margin of Gondwana, similar to, but younger than, the Paleozoic–Mesozoic New England Orogen of eastern Australia and its various mesothermal deposits (Goldfarb et al., 1998). Mesozoic orogenesis was characterised by juxtaposition of a wide variety of disparate terranes via collision and margin-parallel strike-slip motion. The New England Orogen was intruded by plutons during Paleozoic–Mesozoic orogenesis, as were some terranes in New Zealand. However, the portion of the New Zealand Mesozoic orogen that hosts mesothermal gold deposits is notably free of synorogenic magmatism. This set of terranes consists of metagreywackes metamorphosed and variably uplifted in the Mesozoic, and is exposed over the eastern part of the South Island (Fig. 1). Mesozoic mesothermal gold deposits occur in greenschist facies rocks (Otago Schist) exposed by late Mesozoic uplift (Fig. 1). The main expanse of these Mesozoic metagreywackes is truncated on the western side by the Alpine Fault, and a small zone of mesothermal gold-bearing Mesozoic metagreywackes has been offset to the northwest by the Alpine Fault to the northern end of the South Island (Fig. 1).

Mesothermal gold deposits in the Otago Schist have formed under a wide range of pressure and temperature conditions during uplift of the schist belt (Craw, 1992). The Macraes deposit, the only Mesozoic deposit currently mined, is in a 100-m-wide gently-dipping shear zone formed under greenschist facies conditions (ca. 350 °C, 10 km) at the brittle–ductile transition (Fig. 2; Craw et al., 1999). However, most Otago Mesozoic deposits formed at 5–10 km in steeply dipping brittle normal faults; e.g. Barewood and Glenorchy deposits, both former mines (Fig. 2; Paterson, 1986; McKeag and Craw, 1989). Near-surface deposits (<3 km, ca. 250 °C) occur also, such as the Miocene Shotover deposits (Figs. 1 and 2; Craw, 1989) that are discussed further in a later section.

3. Current tectonic setting

The Alpine Fault is the boundary between the Australian and Pacific tectonic plates in the South Island. The Alpine Fault is an oblique reverse structure, dipping SE beneath the Southern Alps that form the topographic backbone of the South Island (Figs. 1 and 3). The relative plate vector driving fault movement and associated deformation is directed ENE–WSW with relative horizontal motion of ca. 37 mm/year in the NE South Island (Fig. 1; De Mets et al., 1990). The Southern Alps are actively rising on the Alpine Fault and a set of northwest dipping oblique reverse faults near the topographic Main Divide, the Main Divide Fault Zone (Figs. 3 and 4A and B; Cox and Findlay, 1995).

Uplift rates are high (>8 mm/year; Simpson et al., 1994) immediately adjacent to the Alpine Fault in the central Southern Alps, and decrease eastwards to ca. 1 mm/year or less to the east of the Main Divide (Teagle et al., 1998). Rapid uplift has exhumed upper amphibolite facies schists adjacent to the Alpine Fault over the past few million years (Fig. 4B; Cooper, 1980). This rapid exhumation has resulted in a conductive thermal anomaly, as rocks are rising faster than they can cool (Koons, 1987), and thermal gradients of 60–90 °C/km have developed near the surface (Fig. 4B; Holm et al., 1989; Allis and Shi, 1995; Craw, 1997). Metamorphic grade decreases southeastwards as slower uplift rates have resulted in less exhumation (Grapes and Otsuki, 1983). Greenschist facies rocks occur immediately west of the Main Divide, and subgreenschist rocks dominate east of the divide (Fig. 4B).

Uplift rates also decrease northeast and southwest along the Alpine Fault (Wellman, 1979). The northern section of the Southern Alps, near the Alpine Fault/Hope Fault junction (Fig. 1), has upper greenschist facies rocks (garnet zone) exposed adjacent to the Alpine Fault, and

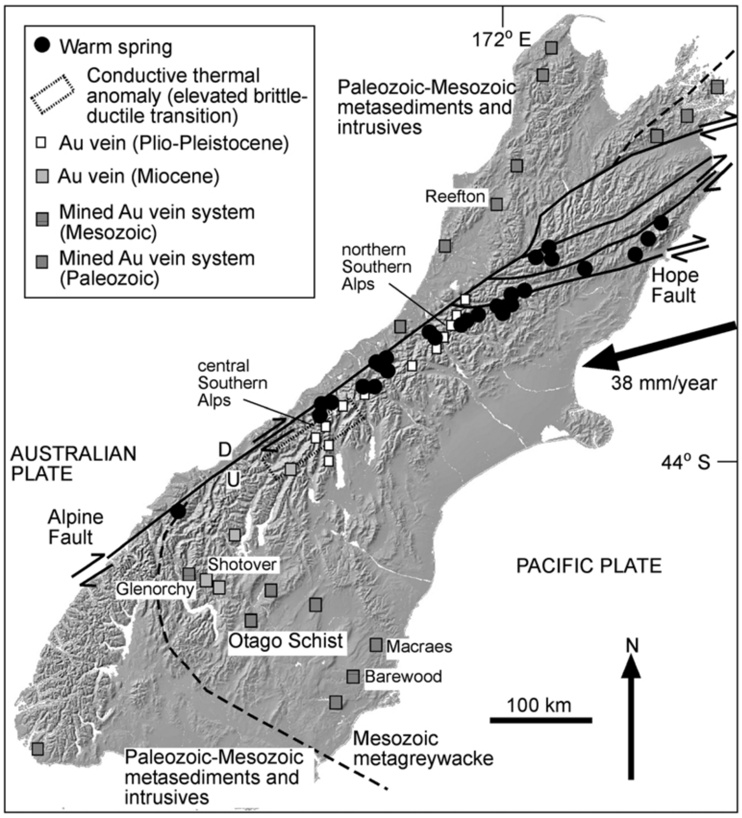

Fig. 1. Topographic map of the South Island of New Zealand, constructed from a digital terrain image (Geographx.co.nz), showing the locations of gold-bearing vein systems of various ages (see text) in a generalised geological context. Also shown are warm springs along the principal faults of the Southern Alps. The approximate extent of raised brittle–ductile transition in a conductive thermal anomaly is shown in the central Southern Alps (after Koons, 1987; Leitner et al., 2001). The plate tectonic setting is shown with the Alpine Fault as the Pacific–Australian plate boundary with relative motion vector (after De Mets et al., 1990).

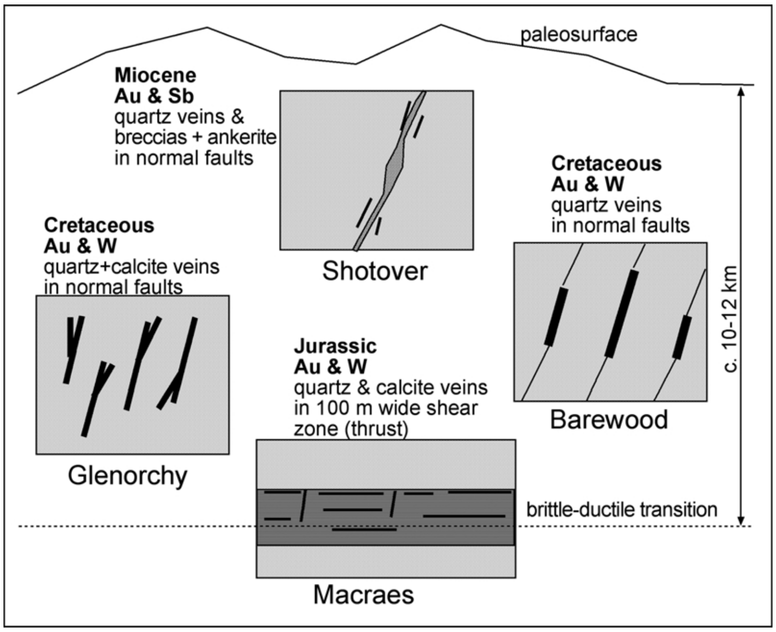

Fig. 2. Cartoon sketch showing the generalised structure, mineralogy and relative depths of formation (after Craw, 1992) of four representative mined mesothermal gold deposits in the Otago Schist (Fig. 1).

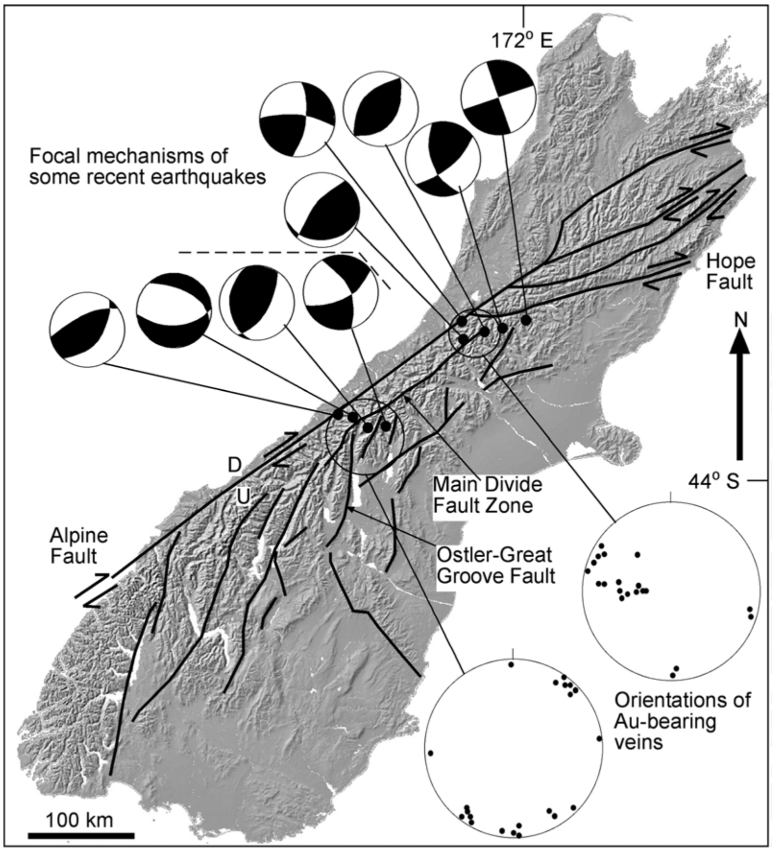

Fig. 3. Structural map of the South Island of New Zealand (based on Fig. 1), showing the principal active faults. Recent focal mechanisms for earthquakes in the central and northern Southern Alps are shown for comparison between the two parts of the orogen (after Anderson and Webb, 1994; Leitner et al., 2001). Lower hemisphere projections of attitudes of gold-bearing veins in the central and northern Southern Alps are shown also.

subgreenschist facies rocks straddle the Main Divide (Fig. 4A). Greenschist facies rocks make up the whole width of the southern Southern Alps to the north of Glenorchy (Fig. 1).

The central and southern parts of the Southern Alps have numerous active faults oriented oblique to the orogen, with NNE, N and NW strikes (Fig. 3). These faults obliquely intersect the NE-trending mountain backbone and associated Main Divide Fault (Fig. 3). This geometry of fault intersections dies out northeastwards as ENE striking strike-slip faults dominate the orogen in the northern part of the South Island (Fig. 3).

The central section of the Southern Alps is seismically relatively quiet, with few earthquakes of $M > 4$ recorded (Anderson et al., 1993; Leitner et al., 2001), apart from large ruptures on the Alpine Fault itself every ca. 250 years (Norris et al., 2001). Examples of minor recent events in the area (Fig. 3) show that normal, reverse and strike-slip events occur with a wide range of orientations. This is in accord with modelling predictions of a dilational zone east of the Alpine Fault (Koons et al., 1998). In contrast, the northern section has had several large ($M > 5.5$) events in the past few years, with strike-slip and reverse motion senses (Fig. 3; Anderson et al., 1993; Leitner et al., 2001), in accord with the geologically well-defined movement senses on the major faults of the area. The base of seismicity is ca. 10–14 km over most of the Southern Alps, but becomes shallower (ca. 8–10 km) in the central Southern Alps (Leitner et al., 2001) where the conductive thermal anomaly has raised the brittle–ductile transition (Koons, 1987; Craw, 1997).

4. Hydrothermal system

4.1. Observed fluid system

The Southern Alps are pervaded by an active tectonically driven hydrothermal system (Koons et al., 1998). The most obvious manifestation of this system is a belt of warm springs that emanate from the Mesozoic metagreywackes near to major faults along the orogen (Fig. 1). The warmest spring, 56 °C, discharges in a valley in the conductive thermal anomaly zone (Fig. 1). The belt of springs lies immediately east of the Alpine Fault for much of the fault's length, then deviates along the strike-slip faults at the north end of the South Island (Fig. 1). The springs are all meteoric water, which has had little chemical interaction with the host metagreywacke along its flow path at temperatures below ca. 150 °C (Barnes et al., 1978; Allis and Shi, 1995). Meteoric water flow (Fig. 4A and B) is topographically

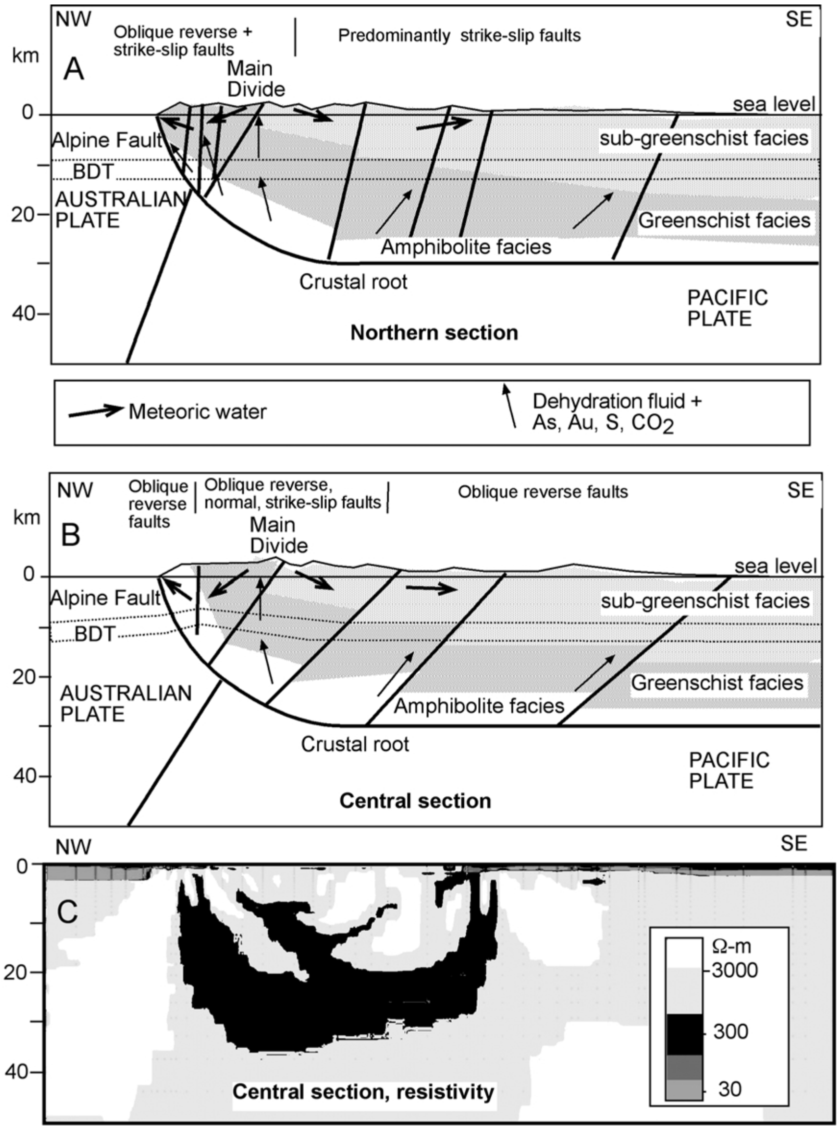

Fig. 4. Cross-sections through the Southern Alps at the scale of the crustal thickness with inferred hydrothermal fluid distribution, derived in part from Norris et al. (1990) and Koons et al. (1998). (A) Northern section of the Southern Alps, near the intersection of Alpine and Hope Faults (Figs. 1 and 3). (B) Central section of the Southern Alps, through the area with conductive thermal anomaly (Figs. 1 and 3). (C) Crustal scale resistivity section for the central Southern Alps, presented at the same scale as (B). The section is derived from magnetotelluric data (Wannamaker et al., 2002), and shows low resistivity zones inferred to contain connected fluid.

driven, and enhanced by the voluminous rainfall recharge (up to 12 m/year precipitation) west of the Main Divide. Some meteoric water also penetrates to the brittle–ductile transition and possibly further but water–rock interaction at the elevated temperatures of such flow paths (>200 °C) progressively obscures the original isotopic signature (Jenkin et al., 1994; Upton et al., 1995).

Buoyancy-driven mid-crustal fluids, derived from metamorphic dehydration reactions, rise through the active orogen and locally mix with meteoric water (Figs. 4A and B and 5A and B; Koons et al., 1998; Vry et al., 2001). The distribution of this fluid in the central Southern Alps is probably indicated by crustal scale low resistivity anomalies that extend down to ca. 35 km beneath the mountains (Fig. 4C; Wannamaker et al., 2002). Zones of inferred connected fluids reach up towards the Main Divide, to the conductive thermal anomaly to the west, and to the eastern edge of the mountains (Fig. 4C). The relationships, if any, between inferred connected fluid zones (Fig. 4C) and faults in the Southern Alps (e.g. Fig. 4B) are not clear as yet (Upton et al., 2002).

4.2. Fluid flow inferred from rock interaction

Rocks along the Alpine Fault in the central section (Fig 4B) have been extensively clay-altered by low temperature (30–100 °C) meteoric water, and commonly cemented with calcite (Fig. 5C; Johnstone et al., 1990). These amphibolite facies rocks have been variably retrogressed under greenschist facies conditions along fractures and foliation surfaces,

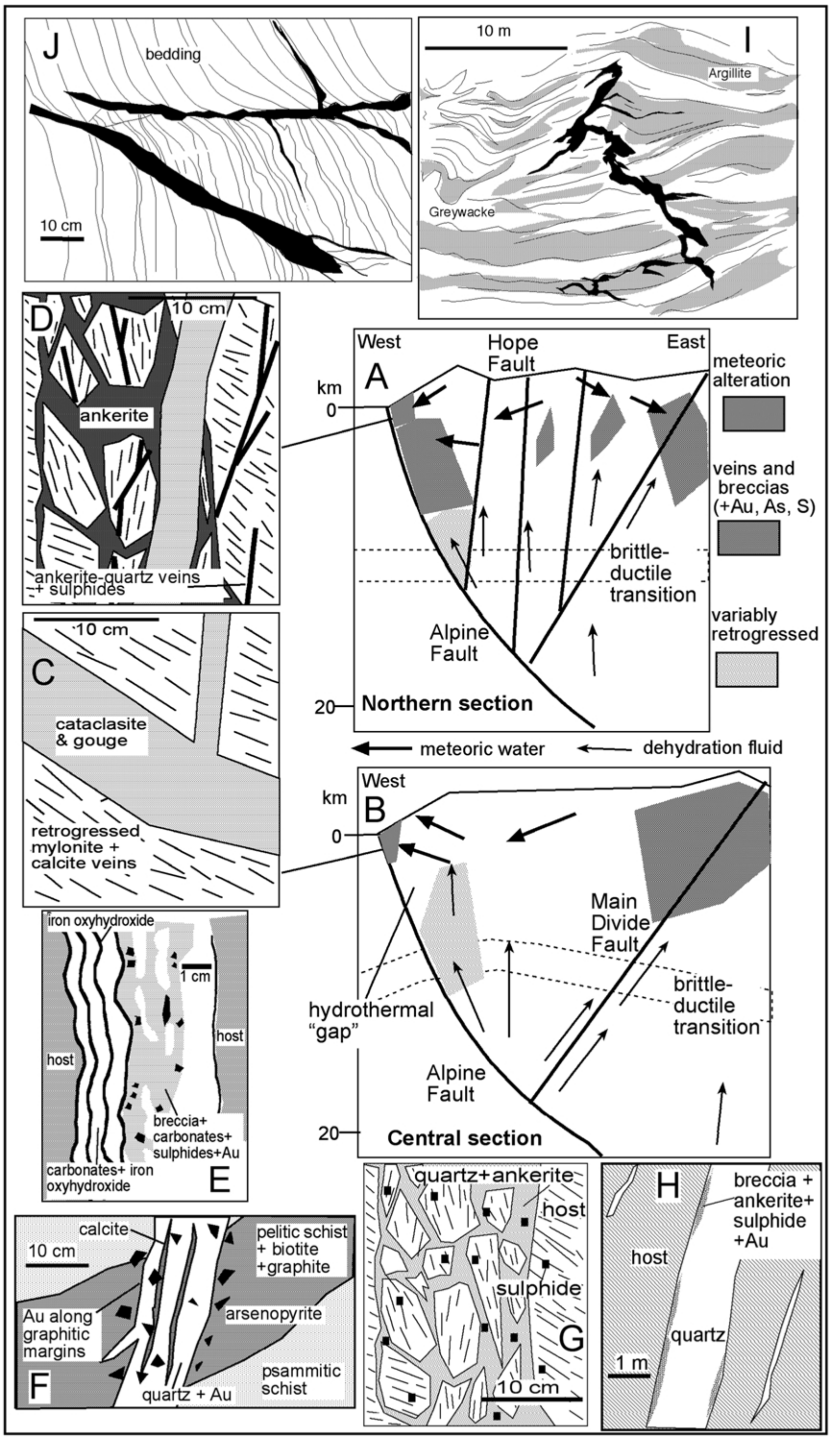

Fig. 5. Cross-sections through hydrothermal vein deposits in the Southern Alps. (A) and (B) are enlarged views of the western ends of sections (A) and (B) in Fig. 4, showing the general areal distribution of different types of fluid-rock interaction zones as indicated in the key (to the right of (A)). (C) and (D) are typical outcrop sketches of vein systems in the Alpine Fault zone in the central and northern sections ((B) and (A)), respectively. (E)–(H) are typical outcrop sketches for a range of vein types in the Main Divide region of the central section ((B); see text). (I) and (J) are outcrop sketches from the Main Divide region of the northern section ((A); see text).

yielding albite–epidote–chlorite–actinolite alteration. However, there is little evidence for hydrothermal activity in these rocks between the brittle–ductile transition and the near-surface calcite alteration zone, apart from widely spaced fractures that contain quartz and calcite crystals deposited by mainly meteoric water (Jenkin et al., 1994). Hence, there is a gap in hydrothermal activity during uplift of these rocks, inferred to be between ca. 2 and 8 km depth (Fig. 5B).

Farther north, in the northern section (Figs. 4A and 5A) near the Alpine Fault/Hope Fault intersection, rocks near the Alpine Fault are more extensively fractured and faulted than in the central section. Extensive greenschist facies retrogression (albite–epidote–chlorite) has occurred near the brittle–ductile transition (Vry et al., 2001), and associated veins have been deformed in a ductile manner and locally mylonitised. Low temperature calcite cementation and clay alteration are common, as in the central section (Fig. 5A). However, this northern section is notable for the more extensive hydrothermal alteration and vein formation that occurred between the retrogression and near-surface alteration. This intermediate level alteration is dominated by ankeritic carbonate with associated quartz, in veins and host rock alteration on the centimetre to metre scale (Fig. 5D).

5. Au bearing veins

Gold occurs in a wide variety of late-stage veins throughout the Southern Alps. The veins are most abundant near to the Main Divide in the central and northern sections (Fig. 1). Veins typically occur in subparallel swarms that crosscut the host rock foliation or bedding. Most veins are less than 10 cm wide and continuous for <1 m but some larger veins occur, with ca. 1 m width and 10's of metres in length. Vein margins are irregular and branching, and contain zones of brecciated host rock. Some veins fill minor faults in association with fault gouge, and breccia zones up to 1 m wide occur in dilational sites along some such faults. These mineralised zones are most commonly found in fractured rocks in intersection zones between strands of the Main Divide Fault zone and oblique structures striking from the south (Fig. 3; Craw et al., 2002).

Quartz is the most common vein mineral to host gold, but albite is common in some veins in the northern section (Becker et al., 2000). Ankeritic carbonate is a common accessory mineral in many veins, locally dominating veins at some localities (Templeton et al., 1999). Ankerite pervades adjacent host rocks along fractures and grain boundaries. Gold is generally associated with sulphide minerals, mainly pyrite or pyrrhotite and arsenopyrite, with rare scheelite.

5.1. Central section

In the central section, gold-bearing veins are restricted to the Main Divide region, and no gold is found near the Alpine Fault (Fig. 5B). Veins have a northwesterly to northeasterly strike and steep dip (Fig. 3), and are generally not parallel to nearby principal faults. Instead, the veins fill extensional sites that developed near to fault zones, commonly at a high angle to the fault. The shallowest-formed veins (Fig. 5E), inferred to have formed within <1 km of the surface east of the Main Divide (Templeton et al., 1999), fill thin (centimetre scale) fractures locally almost perpendicular to a major fault, in the immediate wall rock to the fault. These veins have no quartz, and are dominated by ankerite, calcite and iron oxyhydroxide, with scattered sulphides in brecciated host rocks. The deepest formed veins (Fig. 5F; Craw et al., 1987), in upper greenschist facies rocks west of the Main Divide, are made of quartz and calcite with accessory biotite and chlorite and formed under greenschist facies conditions. Gold is coarse grained (up to 3 mm) and associated with arsenopyrite and rare scheelite in veins and immediate host rock where the host rock is graphitic (Fig. 5F). These veins crosscut regional folds associated with the rise of the Southern Alps, and are clearly late Tertiary in age (Craw et al., 1987).

Most deposits in the Main Divide region of the central section are well-defined features cutting across almost all structures associated with the rise of the mountains. The deposits are commonly dominated by centimetre scale breccias in fault zones, cemented with quartz and ankerite, with scattered arsenopyrite and pyrite (Fig. 5G). The largest deposits are made up of massive quartz veins on the centimetre to metre scale, with minor brecciation and ankerite impregnation on the vein margins (Fig. 5H). Sulphides and gold are almost invariably associated with the marginal breccias.

5.2. Northern section

Veins near the Main Divide in the northern section are larger and more continuous than those in the central section, and have a general northerly strike with variable dips (Fig 3). These veins are hosted by subgreenschist rocks near the Main Divide Fault Zone (Fig. 6). A swarm of similar veins continues northward, hosted in progressively higher-grade rocks up to garnet zone near the Alpine Fault (Fig. 6). Veins consist mainly of massive quartz and albite, with narrow marginal breccias containing pyrite, arsenopyrite and minor chalcopyrite. The veins cut steeply across competent layers such as greywacke (sandstone) and locally penetrate parallel to bedding in less competent layers such as argillite (mudstone) (Fig. 5I). This results in highly irregular vein structures (Fig. 5I), which are not due to post-mineralisation deformation. Deformation of veins is minor, and results in prominent internal fracture arrays but no obvious changes in vein shapes. The example in Fig. 5I is cutting across a low-grade metagreywacke sequence that had been deformed by the Main Divide Fault before mineralisation (Becker et al., 2000). On a smaller scale, mineralised veins have formed in minor structures in thrust faults associated with the Main Divide Fault (Fig. 5J).

The distribution of gold-bearing veins in the northern section is distinctly different from that in the central section, and the gold-bearing veins merge with the more extensive vein systems along the Alpine Fault in the northern section. Clearly, the zone of intersection of the Alpine Fault and the Hope Fault and related structures (Fig. 6) is an important zone for fluid migration and mineralisation.

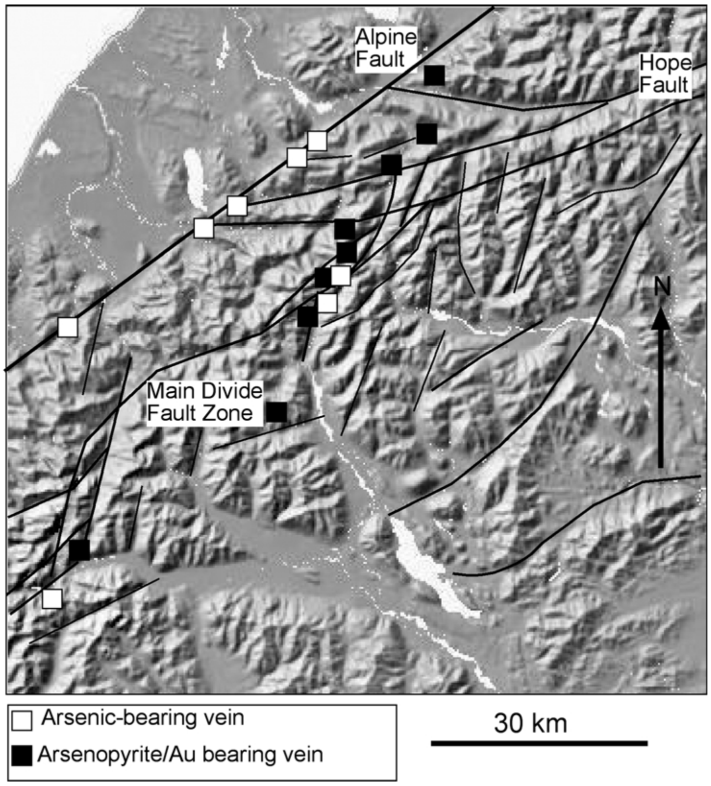

Fig. 6. Topographic and geological map of the intersection zone between the Alpine Fault and Hope Fault (Fig. 1) and the Main Divide region to the south of the intersection zone. The topographic map (derived from digital elevation image: Geographx.co.nz) shows the strong topographic control exerted by the underlying structure, particularly active faults, in this region. Gold-bearing veins (black squares) and late stage arsenic-rich veins (open squares) are shown along the Main Divide, Alpine Fault, and in the region of the fault intersection zone. Warm springs (open circles) are common in the fault intersection zone.

6. Discussion

6.1. Metals other than gold

Arsenic is closely associated with gold throughout the world (Boyle, 1979), and almost all Southern Alps gold veins are arsenic-rich. Hence, the occurrence of anomalous arsenic concentrations in veins in the Southern Alps is indicative of a close association of such veins and the gold mineralising system. In particular, anomalous As concentrations have been detected in many late stage fault zones cemented with carbonate (Horton et al., 2001), and these are inferred to represent shallow-level portions of as-yet unexhumed gold-bearing vein systems in the Southern Alps. These As bearing veins are most common in the northern section, near the Main Divide (Fig. 6; Horton et al., 2001). Arsenic anomalies also occur in the zone of fractured rocks adjacent to the Alpine Fault (Fig. 6), principally in ankerite-rich rocks containing pyrite (Fig. 5D). Similar As anomalies occur in late stage carbonates near the Main Divide in the central section (Fig. 6; Horton et al., 2001), but not along the Alpine Fault. In contrast, widespread but minor copper mobilisation has been noted along the Alpine Fault in the central section (Johnstone et al., 1990), and significant copper mobility appears to be largely restricted to this part of the orogen.

No Au or As anomalies have been detected along the strike-slip faults in the northern South Island (Figs. 1 and 3), despite the abundant evidence for hydrothermal processes associated with these faults (Fig. 1). Mercury mineralisation, in the form of cinnabar, has been detected in one of these spring sites (Barnes et al., 1978). Mercury is one of the most soluble metals in hydrothermal settings, and can persist in fluids beyond precipitation sites for other metals. Hence, it is possible that other metals have been mobilised at depth along the strike-slip faults, but this remains speculative.

6.2. Timing of Au/As vein formation

No gold-bearing veins have been radiometrically dated because there are no dateable minerals. Veins have been formed at different structural levels and have undergone different amounts of exhumation through the orogen, so they may have widely different ages of formation within the context of the development of the orogen. The following geological points provide only general constraints on mineralisation ages. A structurally related but relatively young set of veins west of the Main Divide contains adularia crystals but no gold. Ar–Ar dating of adularia suggests vein formation was less than 800,000 years BP (Teagle et al., 1998). Au-bearing veins cut across schist foliation and bedding that have been folded during the rise of the Southern Alps in the Pliocene (Craw et al., 1987; Norris et al., 1990). Near-surface veins cut host rocks on both sides of the Ostler–Great Groove Fault (Fig. 3), which cuts Pliocene sediments east of the Main Divide, and are structurally related to that fault (Templeton et al., 1999). Gold-bearing veins that are largely undeformed (only minor fracturing) cut crushed and fractured rocks associated with the northern end of the Main Divide Fault (Fig. 5I), a Pliocene–Pleistocene structure (Cox and Findlay, 1995; Becker et al., 2000). Similar gold-bearing veins cut progressively higher-grade rocks towards the Alpine Fault (Fig. 6), and were emplaced after the uplift of these higher-grade rocks by post-Pliocene Alpine Fault movement (Norris et al., 1990). These geological constraints imply that vein formation was Pliocene–Pleistocene, and no better resolution is possible as yet.

The Southern Alps as a mountain range were initiated in the Miocene at their southern end, near Glenorchy (Fig. 1; Craw, 1995), and have since evolved northwards. Gold mineralisation similar in style to some of the central section veins (e.g. Fig. 5G and H) occurred in the Miocene in this southern area, e.g. Shotover deposit (Figs. 1 and 2) that have been mined historically (Williams, 1974). These vein systems were formed near-surface (<3 km) and some have associated shallow-level stibnite mineralisation (Craw, 1989). Similar vein systems occur farther northeast along the Southern Alps (Fig. 1). Apparently, gold mineralisation has been occurring in a similar range of structural settings throughout the life of the orogen, from the earliest stages in the Miocene to the mineralisation inferred to be occurring today associated with the active hydrothermal system and shallow-level As-bearing veins.

6.3. Structural controls on gold mineralisation

Mechanical modelling of the central Southern Alps oblique collision zone combined with regional observations (Koons and Henderson, 1995; Koons et al., 1998) show that strain is unevenly distributed across the orogen. Contraction and rotation are concentrated along the Alpine Fault and at the eastern edge of the mountains, where oblique thrusting dominates. In the core of the orogen, near the Main Divide, there are zones of extension parallel and perpendicular to the orogen axis, with some rotation (Koons and Henderson, 1995; Koons et al., 1998). The locally extensional setting of the Main Divide, in an otherwise generally contractional orogen, facilitates fluid migration from depth (Figs. 4B and C and 5B; Koons et al., 1998). Fluid flow is enhanced adjacent to faults by local extensional sites opening due to relative rotation of relatively rigid blocks of host rock (metre to kilometre scale) associated with oblique thrusting (Craw et al., 2002). Rock damage zones along faults have only minor control on mineralisation.

Rock damage zones are more important in controlling mineralisation in the northern section (Figs. 4A and 5I and J). Rock damage zones are especially common near the Main Divide and along the Alpine Fault, but minor faults in between these structures also have been locally important. Rock damage zones are most pronounced in the Main Divide area at the intersection of oblique faults with the Main Divide Fault Zone (Craw et al., 2002), and along the Alpine Fault at the intersection with the Hope Fault and related structures. Hence, permeability for mineralisation in the northern section is related primarily to variable physical disruption of the rocks on a crustal scale at fault intersection zones, rather than by overall orogen geometry and crustal mechanics as in the central zone (above). The transition between the two regimes is abrupt, near the Main Divide south of the Hope Fault (Fig. 6).

6.4. Regional geometry of gold mineralisation

At the present level of erosion, there is a belt of Plio-Pleistocene gold-bearing veins exposed ca. 20–30 km east of the principal fault, the Alpine Fault. The Alpine Fault zone is barren of mineralised veins at this latitude. The zone of veins straddles a major, but subsidiary, fault zone, the Main Divide Fault Zone, which forms the boundary between greenschist facies and lower grade rocks. Veins are most common in extensional sites and local scale fault intersection zones along this belt. The mineralised belt diverges from the Alpine Fault towards the south and veins are older (Miocene) in the southern part of the orogen. Near the intersection between the Alpine and Hope Faults, the belt of gold-bearing veins deviates from the Main Divide and converges on the fault intersection zone. In contrast, a belt of hot springs occurs near to the Alpine Fault in the central Southern Alps, and this belt diverges from the Alpine Fault into the region of strike-slip faults, crossing the belt of mineralised veins near the Alpine Fault/Hope Fault intersection zone. Rock damage zones in this regional scale fault intersection zone have focussed fluid flow and encouraged mineralisation more effectively than structures farther south, and mineralised veins are found from east of the Main Divide right through to the Alpine Fault. The possibility of mineralisation at depth in the zone of strike-slip faults is speculative but plausible. If so, the belt of gold-bearing veins will diverge from the main structure (Alpine Fault) to the northeast.

The present distribution of gold-bearing veins gives some indication of likely positions of more extensive mineralisation at depth, which will eventually be exhumed. These observations give a tectonic basis for the common occurrence of mesothermal Au veins near to, but not in, major faults in ancient orogenic belts. The most prospective part of the orogen at depth will be the major regional fault intersection zone. There is also a likelihood of gently-dipping vein systems at depth beneath the Main Divide, hosted in a ductile shear zone in the low-resistivity anomaly (Fig. 4C), perhaps similar in style to the Macraes deposit (Fig. 2). Fluid flow in this region may be facilitated by hydraulic fracturing as dehydration fluid escapes from the source rock mass (Norris and Henley, 1976).

7. Conclusions

Plio-Pleistocene gold mineralisation in the Southern Alps of New Zealand is localised in the region of the main topographic divide in a belt that runs parallel to the principal regional structure, the Alpine Fault, but ca. 20 km to the east of that fault. Mineralising fluids consist mainly of dehydration fluids emanating from below the brittle–ductile transition in the root of the orogen, and these fluids make their way to shallow levels via a wide range of minor structures. A component of topographically driven meteoric water may be involved as well. Gold-bearing veins occur in extensional sites in minor structures associated with the rise of the mountains. Gold mineralisation is absent from most of the Alpine Fault zone despite shallow and deep hydrothermal activity near the fault. The intersection zone between the oblique reverse Alpine Fault and a set of strike-slip faults is the most pronounced fluid flow zone in the orogen, and gold bearing veins occur sporadically between the Alpine Fault and the topographic divide. Late stage arsenic-rich veins are most common throughout this fault intersection area including along the Alpine Fault zone, indicating further gold mineralisation at depth. Additional gold mineralisation may be occurring at depth along the active strike-slip faults, and near the brittle–ductile transition beneath the main mountain range. Gold mineralisation also occurred in the earliest stages of the development of the Southern Alps in the Miocene.

The Southern Alps is a modern analogue for mesothermal gold mineralisation processes in ancient orogenic belts, and gives some insight into the nature of structural and tectonic controls on this mineralisation. Gold mineralisation occurs throughout the life of an orogen, at many structural levels from the brittle–ductile transition to near surface, and is a normal consequence of collisional tectonics involving mainly greenschist facies rocks. Fluid flow and mineralisation are focussed into a wide variety of extensional sites that are offset from the main regional structure, but hydrothermal activity is enhanced by rock damage zones especially at fault intersection zones within the orogen.

Acknowledgements

Research in the Southern Alps was funded by the NZ Public Good Science Fund and University of Otago. Discussions with J. Becker, S.C. Cox, P.O. Koons and R.J. Norris helped to develop many of the ideas expressed herein. Constructive reviews by Steve Cox and G.J.H. Oliver improved the manuscript.

References

Allis, R.G., Shi, Y., 1995. New insights to temperature and pressure beneath the central Southern Alps, New Zealand. New Zealand Journal of Geology and Geophysics 38, 585–592.

Anderson, H., Webb, T., 1994. New Zealand seismicity patterns revealed by the upgraded National Seismic Network. New Zealand Journal of Geology and Geophysics 37, 477–493.

Anderson, H., Webb, T., Jackson, J., 1993. Focal mechanisms of large earthquakes in the South Island of New Zealand: Implications for the accommodation of Pacific-Australia plate motion. Geophysical Journal International 115, 1032–1054.

Barnes, I., Downes, C.J., Hulston, J.A., 1978. Warm springs, South Island, New Zealand, and their potential to yield laumontite. American Journal of Science 278, 1412–1427.

Barnicoat, A.C., Fare, R.J., Groves, D.I., McNaughton, N.J., 1991. Synmetamorphic lode-gold deposits in high grade Archean settings. Geology 19, 921–924.

Becker, J., Craw, D., Horton, T., Chamberlain, C.P., 2000. Gold mineralisation near the Main Divide, upper Wilberforce valley, Southern Alps, New Zealand. New Zealand Journal of Geology and Geophysics 43, 199–215.

Boyle, R.W., 1979. The geochemistry of gold and its deposits. Geological Survey of Canada Bulletin 280.

Cassidy, K.F., Groves, D.I., McNaughton, N.J., 1998. Late Archean granitoid hosted lode gold deposits, Yilgarn Craton, Western Australia: deposit characteristics, crustal architecture and implications for ore genesis. Ore Geology Reviews 13, 65–102.

Cooper, A.F., 1980. Retrograde alteration of chromian kyanite in metachert and amphibolite whiteschist from the Southern Alps, New Zealand, with implications for uplift on the Alpine Fault. Contributions to Mineralogy and Petrology 75, 153–164.

Cox, S.C., Findlay, R.H., 1995. The Main Divide Fault Zone and its role in formation of the Southern Alps, New Zealand. New Zealand Journal of Geology and Geophysics 38, 489–499.

Craw, D., 1989. Shallow-level, late-stage gold mineralisation in Sawyers Creek, Shotover valley, North West Otago, New Zealand. New Zealand Journal of Geology and Geophysics 32, 375–384.

Craw, D., 1992. Fluid evolution, fluid immiscibility and gold deposition during Cretaceous–Recent tectonics and uplift of the Otago and Alpine Schist, New Zealand. Chemical Geology 98, 221–236.

Craw, D., 1995. Reinterpretation of the erosion profile across the southern portion of the Southern Alps, Mt Aspiring area, Otago, New Zealand. New Zealand Journal of Geology and Geophysics 38, 501–507.

Craw, D., 1997. Fluid inclusion evidence for geothermal structure beneath the Southern Alps, New Zealand. New Zealand Journal of Geology and Geophysics 40, 43–52.

Craw, D., Rattenbury, M.S., Johnstone, R.D., 1987. Structural geology and vein mineralisation in the Callery River headwaters, Southern Alps, New Zealand. New Zealand Journal of Geology and Geophysics 30, 273–286.

Craw, D., Windle, S.J., Angus, P.V., 1999. Gold mineralization without quartz veins in a ductile–brittle shear zone, Macraes Mine, Otago Schist, New Zealand. Mineralium Deposita 34, 382–394.

Craw, D., Koons, P.O., Horton, T., Chamberlain, C.P., 2002. Tectonically driven fluid flow and gold mineralisation in active collisional orogenic belts: comparison between New Zealand and western Himalaya. Tectonophysics 348, 135–153.

De Mets, C., Gordon, R.G., Argus, D.F., Stein, S., 1990. Current plate motions. Geophysics Journal 101, 425–478.

Goldfarb, R.J., Phillips, G.N., Nokleberg, W.J., 1998. Tectonic setting of synorogenic gold deposits of the Pacific Rim. Ore Geology Reviews 13, 185–218.

Grapes, R., Otsuki, M., 1983. Peristerite compositions in quartzofeldspathic schists, Franz Josef–Fox Glacier area, New Zealand. Journal of Metamorphic Geology 1, 47–61.

Groves, D.I., Barley, M.E., Ho, S.E., 1989. Nature, genesis and tectonic setting of mesothermal gold mineralization in the Yilgarn block, Western Australia. In: Keays, R., Ramsay, R., Groves, D. (Eds.), The Geology of Gold Deposits. Economic Geology Monograph 6, pp. 71–85.

Hagemann, S.G., Gebre-Mariam, G., Groves, D.I., 1994. Surface-water influx in shallow-level Archean lode-gold deposits in Western Australia. Geology 22, 1067–1070.

Holm, D., Norris, R.J., Craw, D., 1989. Brittle and ductile deformation in a zone of rapid uplift: Central Southern Alps, New Zealand. Tectonics 8, 153–168.

Horton, T.W., Becker, J.A., Craw, D., Koons, P.O., Chamberlain, C.P., 2001. Hydrothermal arsenic enrichment in an active mountain belt: Southern Alps, New Zealand. Chemical Geology 177, 323–339.

Jenkin, G.R.T., Craw, D., Fallick, A.E., 1994. Stable isotopic and fluid inclusion evidence for meteoric fluid penetration into an active mountain belt, Alpine Schist, New Zealand. Journal of Metamorphic Geology 12, 429–444.

Johnstone, R.D., Craw, D., Rattenbury, M.S., 1990. Southern Alps Cu–Au hydrothermal system, Westland, New Zealand. Mineralium Deposita 25, 118–125.

Koons, P.O., 1987. Some thermal and mechanical consequences of rapid uplift: an example from the Southern Alps, New Zealand. Earth and Planetary Science Letters 86, 307–319.

Koons, P.O., Henderson, C.M., 1995. Geodetic analysis of model oblique collision and comparison to the Southern Alps of New Zealand. New Zealand Journal of Geology and Geophysics 38, 545–552.

Koons, P.O., Craw, D., Cox, S., Upton, P., Templeton, A., Chamberlain, C.P., 1998. Fluid flow during active oblique convergence: a Southern Alps model from mechanical and geochemical observations. Geology 26, 159–162.

Leitner, B., Eberhart-Phillips, D., Anderson, H., Nabalek, J., 2001. A focused look at the Alpine Fault, New Zealand: seismicity, focal mechanisms, and stress observations. Journal of Geophysical Research 106, 2193–2220.

McKeag, S.A., Craw, D., 1989. Contrasting fluids in gold–quartz vein systems formed progressively in a rising metamorphic belt: Otago Schist, New Zealand. Economic Geology 84, 22–33.

Norris, R.J., Henley, R.W., 1976. Dewatering of a metamorphic pile. Geology 4, 333–336.

Norris, R.J., Koons, P.O., Cooper, A.F., 1990. The obliquely convergent plate boundary in the South Island of New Zealand: implications for ancient collision zones. Journal of Structural Geology 12, 715–726.

Norris, R.J., Cooper, A.F., Wright, C., Berryman, K., 2001. Dating of past Alpine Fault ruptures in south Westland, New Zealand. EQC Research Report 99/341. Earthquake Commission, Wellington, New Zealand.

Paterson, C.J., 1986. Controls on gold and tungsten mineralization in metamorphic–hydrothermal systems, Otago, New Zealand. Geological Association of Canada Special Paper 32, 25–39.

Sibson, R.H., Robert, F., Poulsen, K.H., 1988. High-angle reverse faults, fluid-pressure cycling, and mesothermal gold–quartz deposits. Geology 16, 551–555.

Simpson, G.D., Cooper, A.F., Norris, R.J., 1994. Late Quaternary evolution of the Alpine Fault Zone at Paringa, South Westland, New Zealand. New Zealand Journal of Geology and Geophysics 37, 49–58.

Teagle, D.A.H., Hall, C.M., Cox, S.C., Craw, D., 1998. Ar/Ar dating and uplift rate of hydrothermal minerals in the Southern Alps, New Zealand. In: Arehart, G.B., Hulston, J.R. (Eds.), Proceedings of the 9th International Symposium on Water–Rock Interaction, A.A. Balkema, Rotterdam, pp. 801–804.

Templeton, A.S., Craw, D., Koons, P.O., Chamberlain, C.P., 1999. Near-surface expression of a young mesothermal gold mineralising system, Sealy Range, Southern Alps, New Zealand. Mineralium Deposita 34, 163–172.

Upton, P., Koons, P.O., Chamberlain, C.P., 1995. Penetration of deformation-driven meteoric water into ductile rocks: isotopic and model observations from the Southern Alps, New Zealand. New Zealand Journal of Geology and Geophysics 38, 535–543.

Upton, P., Craw, D., Caldwell, T.G., Koons, P.O., James, Z., Wannamaker, P.E., Jiracek, G.J., Chamberlain, C.P., 2002. Upper crustal fluid flow in the outboard region of the Southern Alps, New Zealand. Geofluids 3, 1–12.

Vearncombe, J.R., Barley, M.E., Eisenlohr, B.N., Groves, D.I., Houstoun, S.M., Skwarnecki, M.S., Grigson, M.W., Partington, G.A., 1989. Structural controls on mesothermal gold mineralization: examples from the Archean terranes of southern Africa and Western Australia. In: Keays, R., Ramsay, R., Groves, D. (Eds.), The Geology of Gold Deposits. Economic Geology Monograph 6, pp. 124–134.

Vry, J.K., Storkey, A.C., Harris, C., 2001. Role of fluids in the metamorphism of the Alpine fault zone, New Zealand. Journal of Metamorphic Geology 19, 21–31.

Wannamaker, P.E., Jiracek, G.R., Stodt, J.A., Caldwell, T.G., Gonzalez, V.M., McKnight, J.D., Porter, A.D., 2002. Fluid generation and pathways beneath an active compressional orogen, the New Zealand Southern Alps, inferred from magnetotelluric data. Journal of Geophysical Research 107 (B6).

Wellman, H., 1979. An uplift map for the South Island of New Zealand, and a model for uplift of the Souhern Alps. In: Walcott, R.I., Cresswell, M.M. (Eds.), The Origin of the Southern Alps. Royal Society of New Zealand Bulletin 18, pp. 13–20.

Williams, G.J., 1974. Economic geology of New Zealand. Australian Institute of Mining and Metallogy Monograph 4.

Witt, W.K., Vanderhor, F., 1998. Diversity within a unified model for Archean gold mineralization in the Yilgarn Craton of Western Australia: an overview of the late-orogenic structurally controlled gold deposits. Ore Geology Reviews 13, 29–64.