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# Mineralogy, geochemistry, and structural controls of a disseminated gold-bearing alteration halo around the schist-hosted Bullendale orogenic gold deposit, New Zealand

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**Abstract**

Orogenic gold-bearing quartz veins in the middle Tertiary Bullendale Fault Zone, New Zealand were mined historically for coarse gold in a narrow zone (ca. 5 m thick). However, recent drilling has revealed a broad hydrothermal alteration zone extending into the host schist, in which disseminated sulphide and gold mineralisation has occurred. The evidence of alteration is first seen over 150 m across strike from the fault zone, and the best-developed alteration halo is about 50 m wide. The extent and intensity of alteration is strongly controlled by local structures that developed during regional Tertiary kink folding of the pervasively foliated and fissile metasedimentary schist host. The earliest structures are foliation-parallel microshears (micron to millimeter scale) formed during flexural-slip folding. Later, but related, structures are predominantly normal faults and associated shear zones that have formed extensional sites during the regional folding event. All these structures facilitated hydrothermal fluid penetration and rock alteration, with localised vein formation and brecciation. Where fluid has followed structures, metamorphic chlorite, phengite, and titanite have been altered to hydrothermal ankerite, rutile, and muscovite or kaolinite. Ankerite with $Fe/(Fe+Mg) < 0.4$ formed in host rocks with $Fe/(Fe+Mg)$ of 0.6, and iron released by ankerite alteration possibly formed pyrite and arsenopyrite that host disseminated gold. Fault zones were extensively silicified and veined with quartz, albite, sulphides, and gold. Host rocks have wide compositional variations because of centimeter-scale metamorphic segregation. However, the alteration halo is characterised by elevated $CO_2$ and S, as measured by loss-on-ignition (doubled to ca. 6 wt.%), elevated As (100–10,000 ppm), and weakly elevated Sb (up to 14 ppm). Strontium is elevated and Ba depleted in many altered rocks, so Sr/Ba ratio increases from $<1$ (host rocks) to $>3$ in the most altered and silicified rocks. Many altered and mineralised rocks have low Sr/Ba ($<0.5$) as well. The subtle geochemical signature is not useful as a vector to ore because of the strong microstructural control on alteration. Likewise, there is no evidence for spatial mineralogical zonation across the alteration halo, although the most intense alteration is centred on the main fault zone, and intensity of alteration is controlled by microstructures at all scales. As documented in previous studies, hydrothermal alteration haloes enlarge the exploration target for some orogenic gold deposits, and may include disseminated gold, as in this Bullendale example.
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*Keywords:* Hydrothermal; Mesothermal; Ankerite; Sulphide; Geochemistry; Fault; Shear; Fold

## 1. Introduction

Turbidite-hosted mesothermal (orogenic) vein-hosted gold deposits have traditionally been assumed to have negligible wall rock alteration zones, but

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research in the past 20 years has shown that these deposits typically have hydrothermal alteration haloes (e.g., Böhlke, 1988; Eilu and Mikucki, 1998; Bierlein and Crowe, 2000; Bierlein et al., 2000). Recognition of the existence of alteration zones is important, as this increases the size of the target mineralised zone during mineral exploration (Bierlein and Crowe, 2000). Also, some of the altered host rocks contain anomalous (ppm scale) concentrations of gold, far-removed (metres to tens of metres) from the main vein zones (Böhlke, 1988; Eilu and Mikucki, 1998; Craw et al., 1999). Thus, the volume of potential ore may be greater when alteration zones can be identified (Craw et al., 1999). This has led to the development of the concept of large tonnage, low-grade mesothermal gold deposits that include mineralised host rock as well as the narrow mineralised quartz veins that have traditionally been the focus of mining (Bierlein and Maher, 2001; Christie and Brathwaite, 2003; Goldfarb et al., 2005; Mitchell et al., 2006).

Mesothermal gold deposits typically form during compressional or transpressional tectonics (Kontak et al., 1990; Cox et al., 1991; Bierlein and Crowe, 2000; Goldfarb et al., 2005). Mineralisation in these deposits commonly occurs while the host rocks were being folded and/or reverse-faulted (Sibson et al., 1988; Cox et al., 1991; Goldfarb et al., 2005). Veins form in local extensional sites centred on well-defined fractures in host rocks (Sibson et al., 1988; Cox et al., 1991). Most host rocks are competent and massive on the metre to ten metre scale during mineralisation, so fluid flow was controlled by well-defined fractures in these competent rocks, with minor leakage of fluid into host rocks along, for example, grain boundaries and micro-fractures (Cox et al., 1991; Witt and Vanderhor, 1998). The competent, relatively impermeable host rocks generally resist development of alteration zones, and ensure that the alteration zones are subtle (Gray et al., 1991; Phillips and Powell, 1993). The structures that controlled fluid flow were sporadically developed and were commonly obscured by alteration reactions. Hence, detailed structural control on hydrothermal alteration of host rocks in mesothermal gold deposits has been little-described previously.

This study reports on the nature of the structural control, and the resulting mineralogical and geochemical alteration, of hydrothermal fluid penetration into host rocks adjacent to the Bullendale mesothermal gold deposit in southern New Zealand (Craw et al., 2006). Unlike most mesothermal gold deposits, the deposit we describe is geologically young (middle Tertiary), and was formed relatively close (<5 km) to the palaeosurface. This deposit has had negligible structural over-printing, and the details of hydrothermal fluid flow and alteration are still preserved. Further, the deposit is unusual in that it is hosted in highly fissile rocks that are layered on the millimetre to centimetre scale. This extreme fissility has resulted in locally near-pervasive formation of structurally-controlled fluid pathways through the rock. These provide graphic examples of development of enhanced fluid flow zones during compressional deformation, at a much smaller scale than is normally observed in mesothermal deposits. Despite the well-developed alteration zones associated with this mesothermal gold deposit, there has been little change in bulk rock composition, and hydrothermal alteration reactions were primarily controlled by mineralogical changes. We document the structural and mineralogical changes during mineralisation as an example of an enlarged exploration target and potential ore zone, features that are relevant to all exploration programmes targeting mesothermal gold-bearing vein and/or disseminated systems.

## 2. General geology

### 2.1. Structure of host rocks

The mesothermal system that is the focus of this study, the Bullendale deposit, is hosted in Mesozoic Otago Schist metasedimentary rocks of southern New Zealand (Mortimer, 1993) (Fig. 1). The host rock is pervasively deformed and recrystallised metagreywacke and meta-argillite, with no sedimentary features preserved. The rocks were subjected to at least two phases of isoclinal folding during greenschist facies metamorphism (Craw, 1985). Associated development of pervasive foliations was accompanied by progressive recrystallisation of coarse grained (>100 μm) muscovite and chlorite (Turnbull et al., 2001). This penetrative fabric is a composite feature, defined by convergence of at least two synmetamorphic foliations (Craw, 1985). Foliation development was accompanied by metamorphic segregation and formation of synmetamorphic quartz-albite veins that have been rotated into parallelism with the micaceous fabric, resulting in highly fissile rock with alternating (milllimetre to centimetre scale) micaceous and quartzofeldspathic layers (Fig. 2A and B). Metamorphic calcite, epidote and titanite occur throughout the rocks, particularly in the micaceous layers (Fig. 2A and B). Minor (1–10 m scale) metabasites are intercalated with the metasedimentary rocks, and have similar fabric development, with less quartz. The pervasive metamorphic fabric in the schist was formed subhorizontally during Jurassic orogenesis, and this

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