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ARTICLE

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Lithological and spatial controls on the distribution of quartz veins in andesite- and rhyolite-hosted epithermal Au–Ag deposits of the Hauraki Goldfield, New Zealand

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Abstract Vein distributions in line samples from four epithermal Au–Ag deposits of the Hauraki Goldfield were logged and quantified by vein spacing, vein density, vein thickness and percentage of vein extension. One deposit is hosted in andesite lavas (Martha Hill), one in andesite lavas and dacite porphyry, dacitic tuffs and pyroclastic breccias (Golden Cross), and two in rhyolite lavas and rhyolitic tuffs with minor andesite lavas or andesite dikes (Ohui and Wharekirauponga). The vein systems in these deposits form fault-controlled arrays of extensional veins. Vein spacing distributions are non-fractal over two to three orders of magnitude (1 mm to 5 m), and therefore fractal dimension statistics are not applicable. The coefficient of variation (C_v) of vein spacing was used as a measure of the degree of vein clustering. Rock type has a marked influence on vein spacing distributions, with veining in rhyolite lava having lower average thickness and percentage extension, but a generally higher degree of vein clustering compared with veining in andesite lava in the same deposit. Vein spacing distributions in well-jointed lithologies, mainly andesite lava, have C_v values (0.8–1.2) that are indicative of anticlustered to weakly clustered patterns, particularly in the vein stockwork of the upper part of the Golden Cross deposit. These C_v values are consistent with field observations that joints are a major control on vein spacing. In the poorly jointed dacitic and rhyolitic rocks, the veins are weakly to strongly clustered as shown by higher C_v values (1.2–2.4), and are commonly associated with normal faults. Overall, andesite lava and dacite porphyry and pyroclastics host thicker and more persistent veins than rhyolite lava and tuff. These larger veins contain significant volumes of high-grade gold mineralisation. The higher chemical reactivity to hydrothermal fluids of andesite and dacite compared with rhyolite may have aided propagation and thickening of the veins in andesite-hosted deposits. Within an individual epithermal deposit, location close to thick veins, representing major fluid conduits, commonly overrides the effect of different lithologies. Sites that are deeper and located within or adjacent to major vein structures have higher average vein thickness, percentage extension and degree of vein clustering. Systematic collection and analysis of vein spacing, thickness and density data can be used to define trends that are useful in the exploration of gold-bearing epithermal vein deposits.

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Introduction

The Hauraki Goldfield, in the North Island of New Zealand, contains epithermal Au–Ag mineralisation in quartz veins associated with tectonically controlled fracture systems in andesite, dacite and rhyolite of Miocene–Pliocene age. Vein spacing, vein density and vein thickness data are used here to determine variations in vein distributions within and among deposits hosted in andesite and dacite (Martha Hill at Waihi and Golden Cross) and predominantly hosted in rhyolite (Ohui and Wharekirauponga). These variations can be related to lithological and structural controls on the distribution of the veins. As reported elsewhere by the present authors (Brathwaite et al. 1994; Cargill et al. 1995a, b), one of the main aims was to determine why the thickest and most persistent veins occur in andesite lavas, whereas rhyolite lavas are characterised by zones of thinner veins.

Waihi and Golden Cross are major Au–Ag deposits, with substantial historic and current production. Ohui and Wharekirauponga have minor historic production and/or recent exploration activity.

Regional geology and mineralisation

The Hauraki Goldfield is associated with a Miocene–Pliocene calc-alkaline volcanic zone (Coromandel Volcanic Zone) related to the

Australian–Pacific convergent plate boundary. A block-faulted basement of Jurassic greywacke is overlain by a thick sequence of andesite and lesser dacite of the Coromandel Group, which largely underlies rhyolite and ignimbrite of the Whitianga Group (Fig. 1). The majority of the regional faults strike NE to NNE and NNW, and are dominantly normal in character and reflect Late Miocene–Early Pliocene rifting of the Coromandel Volcanic Zone. The goldfield contains some 50 epithermal Au–Ag deposits within a zone 200 km long by 40 km wide, and mineralisation is predominantly localised in steeply dipping quartz veins filling extensional fractures (Brathwaite et al. 1989; Brathwaite and Pirajno 1993). Many of the vein systems, including those studied here, form fault-controlled arrays of extensional veins – the fault-fracture meshes of Sibson (1996). The majority of the quartz veins are hosted by andesitic and dacitic rocks of the Coromandel Group; rhyolitic rocks and basement greywacke are lesser hosts. The quartz veins are enclosed by adularia–illite alteration zones that are characteristic of low sulfidation type epithermal deposits. The main ore mineral is electrum, accompanied by ubiquitous pyrite with minor amounts of acanthite. Deeper-level quartz veins contain minor sphalerite, galena and chalcopyrite, as in the deeper part of the Martha Hill deposit. The quartz veins are made up of thin (mm-scale) bands that have formed by incremental filling during multiple episodes of hydraulic fracturing. They are interpreted as products of fluid-driven structural permeability (Sibson 1996), which, by analogy with active geothermal systems, is a manifestation of convective flow of hydrothermal fluid within 2 km of the surface (Henley 1985).

The selected deposits are located in the southern part of the Hauraki Goldfield (Fig. 1). Other deposits at Neavesville, Komata and Karangahake were also studied (Cargill et al. 1995a, b), but as the vein datasets are less complete and the results are similar they are not included here.

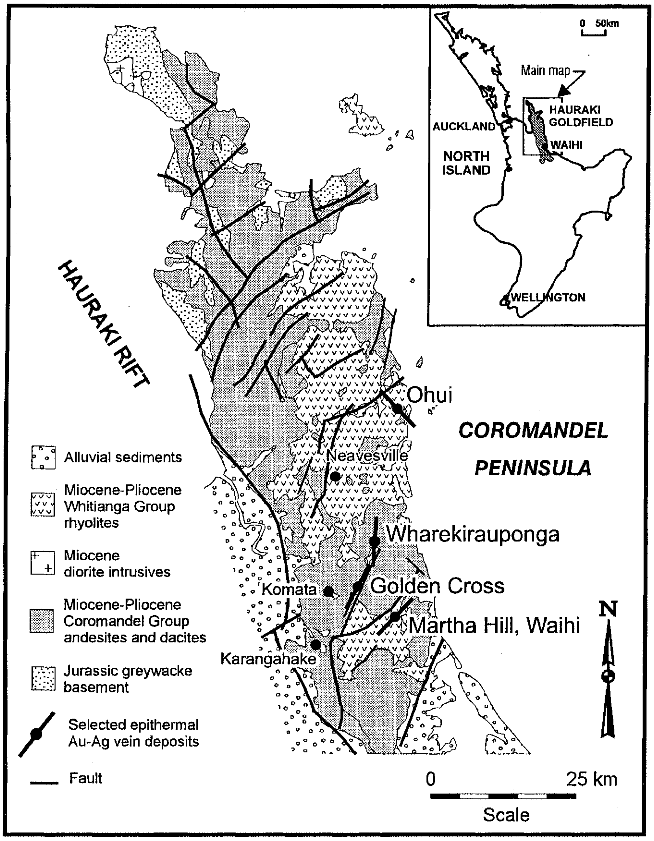


Fig. 1 Regional geology of the Hauraki Goldfield and location of the Ohui, Wharekirauponga, Golden Cross and Martha Hill epithermal Au–Ag deposits

Analysis of vein arrays

Quartz vein data were recorded on line samples, as one-dimensional (1-D) datasets, by logging the position and thickness of the veins, and host lithology from diamond drill core and open pit traverses. Calcite veins at Golden Cross were also logged and their distribution reported previously (Cargill et al. 1995a, b). As they post-date the quartz veins and are not gold-bearing, they effectively reduce the number of quartz veins by dilution. This effect has been compensated for by subtracting the thickness of the calcite veins from the total length of line and recalculating the number of quartz veins per metre (vein density). Drill core was from holes that intersected the dominant vein sets at high angles, and line samples in the open pits at Martha Hill and Golden Cross were near perpendicular to the strike of vein systems. The minimum vein thickness recorded was 1.0 mm. Vein spacings were measured from wall to wall, rather than from vein centre to vein centre, because the latter parameter ignores the wide variation in vein thickness. The sum of vein thickness over the length of the line gives a measure of the extension (percentage extension) along the individual line samples (McCaffrey and Johnston 1996). The parameters of average vein thickness, vein density, percentage extension, average spacing, and coefficient of variation of the spacing were calculated (Table 1) and graphed to define trends. Vein counts ranged from 69 to 959 over line lengths of 12.0 to 134.2 m (Table 1), and exceed the threshold of sample lines containing a minimum of 50 veins that is desirable for stable results (McCaffrey and Johnston 1996).

Spatial distribution and thickness of veins

Various techniques have been used to determine the spatial characteristics of fault, fracture and vein sets (Gillespie et al. 1993, 1999). Some fracture systems follow a fractal/power-law (scale independent) pattern and can be characterised by fractal statistics (e.g. Manning 1994). In previous reports (Cargill et al. 1995a, b), we used the interval counting technique to obtain fractal spacing dimensions as a measure of the degree of clustering of veins. However, the data were truly fractal (i.e. scale invariant) only over a spacing range of less than one order of magnitude (0.03–0.2 m). An evaluation of the techniques of fractal analysis by Gillespie et al. (1993) found that the spacing population method provided a better characterisation of entire populations of faults and joints than the interval counting method. Using the spacing population method, the vein spacing data show convex-upwards curves on log–log spacing cumulative frequency graphs (e.g. Fig. 2), rather than the straight-line plots of fractal/power-law distributions. Correcting for the finite range effect (Pickering et al. 1996) does not significantly reduce the curvatures. The curved plots indicate scale dependence over three orders

Table 1 Summary of quartz vein data. *and* andesite, *dac* dacite porphyry, *wx* dacite breccia, *wt* dacitic tuff, *rhy* rhyolite, *tuff* rhyolitic tuff, (*pit*) open pit line sample, (*DDH*) diamond drill core line sample

Location and lithology	Line length (m)	No. of veins	Average spacing (mm)	Spacing C_v	Average thickness (mm)	Extension (%)	Vein density	Vein density[a]
Martha Hill								
MH1090and (pit)	134.2	959	117	1.1	23	16.8	7.1	10.5
MH1045and (pit)	68.7	583	93	1.2	25	21.4	8.5	10.8
Golden Cross								
G370and (pit)	36.0	293	115	0.8	8	6.2	8.1	8.7
G340Edac (pit)	12.0	70	163	1.2	6	3.5	6.0	6.0
G340Wand (pit)	21.0	227	84	1.1	8	9.1	10.8	11.9
GWH00wx (DDH)	22.5	123	164	1.7	24	13.3	5.1	6.3
GWH00dac (DDH)	34.3	277	130	2.0	16	13.1	6.9	9.3
GWI23wt (DDH)	46.5	245	218	2.4	21	8.8	4.7	4.7
GWI23dac (DDH)	19.8	70	283	1.5	7	2.4	3.6	3.6
Ohui								
OH7and (DDH)	59.6	462	124	1.2	5	3.9	7.8	8.1
OH2rhy (DDH)	19.0	69	271	1.3	3	1.2	3.6	3.6
OH2tuff (DDH)	15.6	80	189	1.4	6	2.9	5.1	5.2
OH15Brhy (DDH)	55.1	303	178	1.7	2	1.3	5.5	5.4
Wharekirauponga								
WKP17and (DDH)	46.0	292	151	1.8	7	4.7	6.3	6.3
WKP17rhy (DDH)	35.8	274	124	1.3	7	5.4	7.6	8.1
WKP18and (DDH)	18.1	253	69	1.1	6	11.6	14.0	16.0
WKP18rhy (DDH)	36.9	352	99	1.2	9	8.9	9.5	10.8
WKP16rhy (DDH)	34.8	272	125	1.4	3	2.5	7.6	8.0

[a] Vein density modified for the effect of vein thickness, see text for explanation

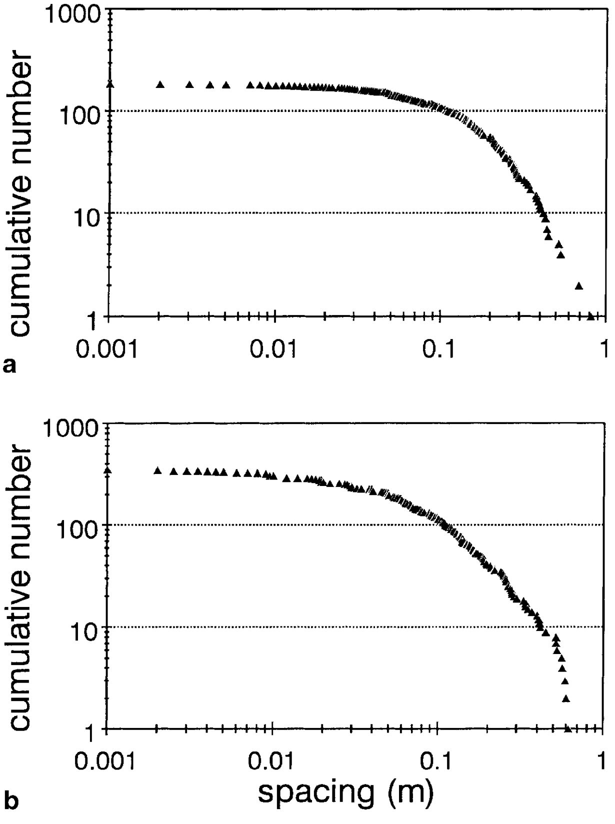


Fig. 2 Log–log cumulative frequency graphs of spacing between individual veins for line samples from **a** Martha Hill open pit andesite at 1045RL, and **b** rhyolite intersection in Wharekirauponga drill hole WKP18

of magnitude, with steep right-hand segments that may reflect an approach to an upper limit of vein spacing in fault-fracture meshes. The convex-upwards curves follow log-normal frequency distributions (cf. Gillespie et al. 1993), which are typical of vein arrays in non-bedded rocks (Gillespie et al. 1999).

Another measure of clustering in 1-D datasets is the coefficient of variation (C_v) of the spacing, defined as the ratio of the standard deviation to the mean of the spacing (McCaffrey and Johnston 1996; Gillespie et al. 1999). If the veins are clustered then $C_v > 1$, and if the veins are anticlustered (i.e. they have a low degree of clustering), $C_v < 1$. For perfectly regular spacing $C_v = 0$. In this study C_v values for the vein spacings measured range from 0.8 to 2.4 (Table 1).

Thick veins are commonly made up of multiple thin bands, and are in effect very tight clusters of thin veins. However, individual bands can only be clearly seen in cut and polished surfaces, which precludes their routine measurement in open pit faces and drill core. Therefore, banded veins are counted as single veins. This approach is reasonable because it is the thick banded veins that carry most of the gold and are therefore of greatest economic interest.

Vein thickness affects the average vein density, i.e. there can only be a limited number of thick veins in a given interval, and the vein density should be standardised for purposes of comparison. This is done by subtracting the total thickness of all veins from the total length of the line sample used, and recalculating the vein density for the reduced length of sample line. Subtraction of vein thickness has the effect of increasing the vein

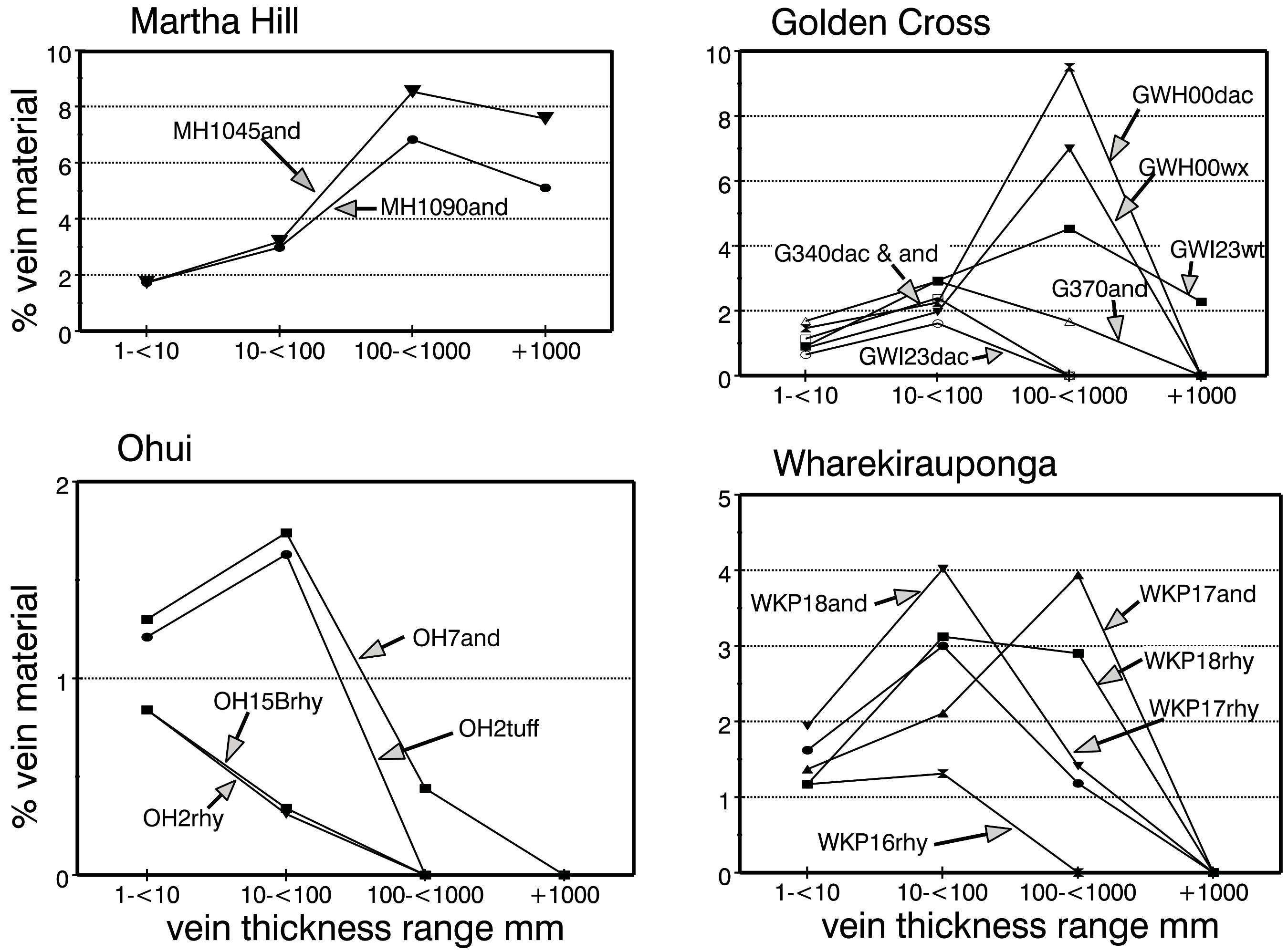


Fig. 3 Variations in vein thickness for different lithologies within the Au–Ag deposits. Plots show selected vein thickness ranges as a proportion of vein material along each line sample. Data from Martha Hill, Golden Cross, Ohui and Wharekirauponga. See Table 1 for explanation of labels

density, with greater increases in line samples having thicker veins. Plots of the modified vein density versus C_v thus enable direct comparison of the degree of vein clustering in line samples with different vein size distributions and/or vein densities.

The proportion of vein material for selected ranges of vein thickness (Fig. 3) is useful in comparing vein thickness variations for different line samples, and highlights the effect of thick veins. Plots of average vein thickness versus vein density were used to compare vein thickness distributions both within and between different deposits (Fig. 4). Line samples with a high average vein thickness relative to vein density have fewer but

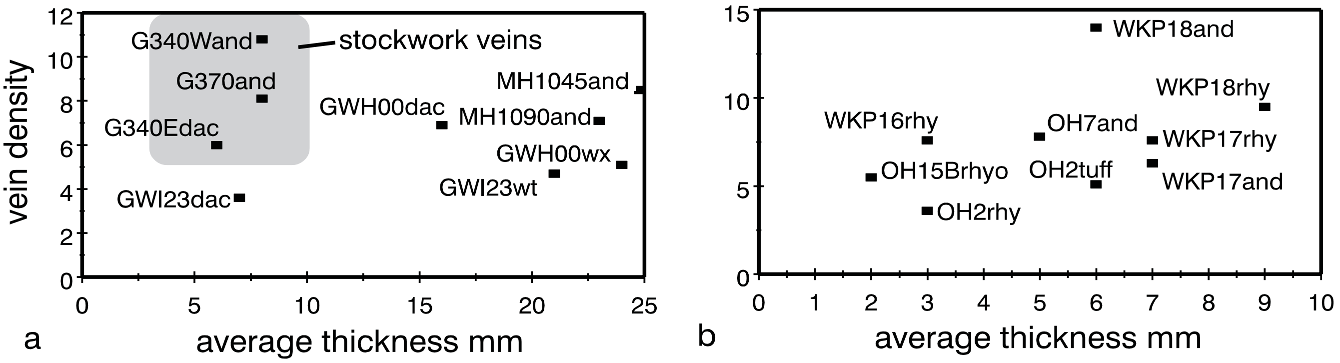


Fig. 4 Average vein thickness versus vein density (number of veins/m) for line samples from **a** Martha Hill (*MH*) and Golden Cross (*G*), and **b** Ohui (*OH*) and Wharekirauponga (*WKP*). Note field of stockwork veins as represented by datasets from the Empire Stockwork at Golden Cross. See Table 1 for explanation of labels

thicker veins, whereas those with lower average vein thickness relative to vein density have many thinner veins, e.g. stockwork-style veining.

Martha Hill, Waihi

The Martha Hill (Waihi) deposit is a large vein system which extends 1.6 km along a NE strike in a zone up to 500 m wide, and was mined underground to depths of over 600 m below surface (Morgan 1924; Brathwaite and McKay 1989). The underground mines produced 1100 tonnes of Au–Ag bullion (Au:Ag of 1:10) between 1883 and 1952. Since 1988, open pit mining of remnants of the Martha and Welcome lodes, and the veined zone between, has produced about 2500 kg of gold and 20,000 kg of silver annually. The quartz veining is hosted by Late Miocene andesite flows and minor interflow tuffs which dip at 30–40°SE. The host andesites are hydrothermally altered with pervasive quartz–adularia–illite–pyrite ± chlorite–calcite alteration surrounding the quartz veins in the open pit. The vein and fault system forms a complex braided pattern in plan and cross section, with two main vein zones (Martha and Welcome) in the open pit (Fig. 5). The multiphase vein filling includes crustiform quartz and quartz pseudomorphs after bladed calcite textures. The veins dominantly strike NE with minor NNE and E–W strikes. The majority of veins are mode I opening fractures (Pollard and Aydin 1988), with little or no lateral movement of vein walls (Cargill 1994). Mutual vein cross-cutting relationships indicate that vein formation on these directions was broadly synchronous, although the NE-striking veins commonly cut the E–W-striking veins. Some thin veins follow local joints, the majority of which are sheeted joints parallel and adjacent to the main veins and faults. In other locations, primary columnar and entablature joints are recognised in andesite flows, but these joints appear to have had little influence on the veins. There are numerous faults both parallel and oblique to the main vein trends, N–S and ENE sets being the most prominent in the open pit (Fig. 5). Most of the faulting pre-dates the main stage of veining, but there is an overlap in time with early formed veins. Kinematic indicators on the faults suggest that normal dip-slip movements dominate, although some faults show evidence for later strike-slip movement (Cargill 1994).

Vein data was from line samples on the western wall of the open pit at 1090RL and 1045RL (Fig. 5). The host rocks in both traverses are moderately to well-

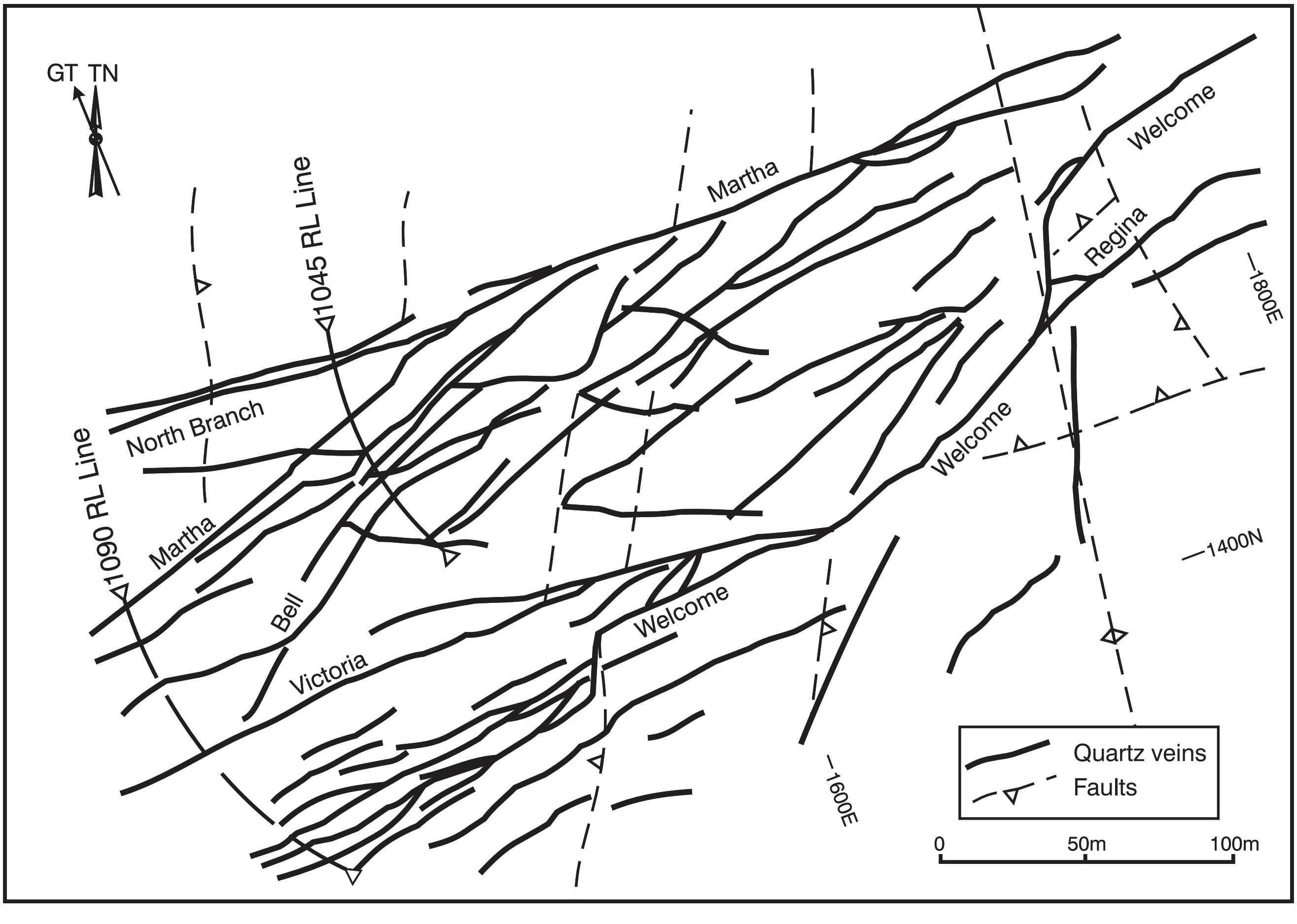


Fig. 5 Plan of major quartz veins (veins thicker than 0.1 m) in the Martha Hill open pit at 1100RL (after Cargill 1994), with location of line samples at 1090RL and 1045RL. Thickness of veins not shown

jointed andesite flows. Vein shapes are generally tabular, showing vertical and lateral continuity, although many are complicated by horsetails, deflections and breakouts (Fig. 6). The two lines have high percentages of vein extension (16.8 and 21.4%, Table 1). Both lines have virtually the same proportion of vein material in the < 100 mm vein size range, but the 1045RL line has a higher proportion of thick veins in the > 100 mm range (Fig. 3).

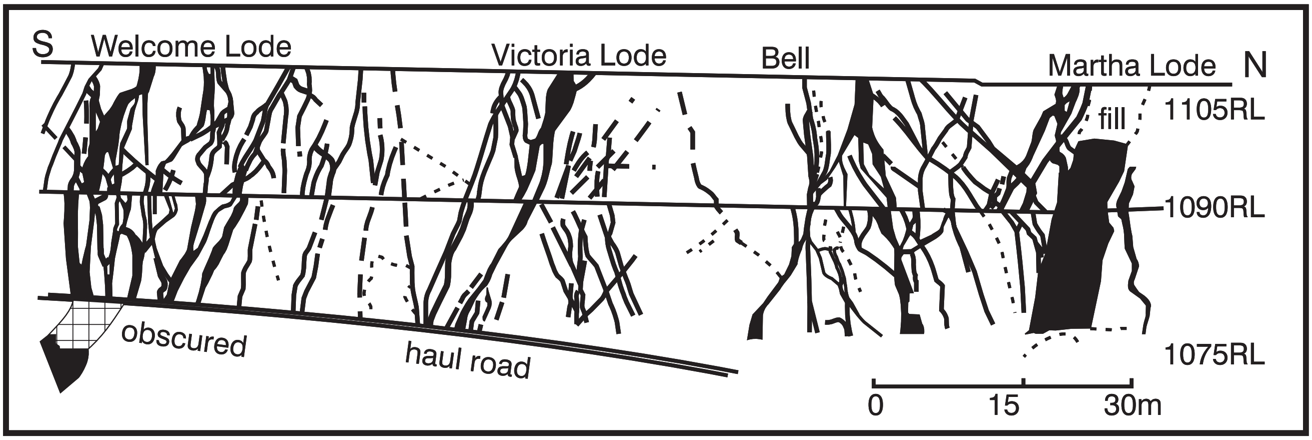
The difference in the vein distributions across the western part of the vein system is a reflection of the upward splaying of the veins and the breaking up of large lodes into smaller veins and stringers towards the west. This is exemplified by the Welcome Lode, which at 1045RL is essentially a single very thick (19 m) vein, whereas at 1090RL it has broken up into several thick veins and numerous veinlets (Fig. 6). The line at 1045RL (approximately 1500E on the mine grid, Fig. 5) is also closer to the centre of the vein system, which at depth is between about 1700E and 1900E (cf. Morgan 1924). Therefore at Martha Hill, variations in vein size and distribution are primarily controlled by position within the vein system. The lithology is essentially the same in the two lines.

Golden Cross

The Golden Cross deposit is hosted in Late Miocene andesite flows, andesitic to rhyodacitic pyroclastic rocks and dacite porphyry (Keall et al. 1993; Caddey et al. 1995; David and Barber 1997; Mauk et al. 1997). In two phases (1885–1917 and 1991–1998) of mining activity, some 23,000 kg of gold was produced from the deposit. Production in 1997 was 3231 kg Au and 10,745 kg Ag. The recent phase of mining was on the Empire Vein Zone, located along strike from the old Golden Cross workings (Hay 1989). An upper stockwork zone of shallow and steep-dipping veins was mined from an open pit (Empire Stockwork), and a deeper moderately to steeply dipping vein structure (Empire Vein Zone) was mined underground (Fig. 7). The Empire Vein Zone and Stockwork are enclosed by quartz–adularia–chlorite–illite–pyrite alteration, with interlayered illite/smectite prominent at shallow levels. The Empire Stockwork is mainly thin cryptocrystalline quartz veins, whereas in the Empire Vein Zone, veins are thicker, with crustiform banding and hydrothermal breccias. Up to eight stages of veining have been identified in the Empire Vein Zone, including two stages of late barren calcite veins (Mauk et al. 1997). Stage four, consisting of multiple episodes of banded quartz veins, makes up the bulk of the Empire Vein Zone and is the main electrum-bearing stage. The Empire Vein Zone consists of a steeply west-dipping main vein with subsidiary footwall splays, and was interpreted as being localised at dip and strike deflections related to strike slip and reverse movements on the coincident Empire Fault (Keall et al. 1993; Caddey et al. 1995; David and Barber 1997). However, by rotating the structure to allow for probable post-mineralisation tilting of about 30° east, the dip of the Empire Fault and the main vein become steeply east-dipping, which suggests normal faulting and a dominantly extensional environment (Mauk et al. 1997).

Vein data were collected from the open pit on line samples at 370RL and 340RL, and from two underground diamond drill holes (GWI23 and GWH00) at about 200RL in the southern part of the Empire Vein Zone (Fig. 7). At Golden Cross, lithological control on vein distribution is closely related to jointing characteristics. The well-jointed andesite lavas in the open pit contain many veins which are mainly thin (Fig. 3), in contrast to some of the underground sections. These thin veins also tend to be uniformly spaced and hence are only weakly clustered or even anticlustered (G370and in Fig. 8a). The weakly jointed dacite porphyry, in the open pit and underground, is locally well veined near major fault structures, with a high proportion of vein material from thick, rather than thin, veins (e.g. GWH00dac in Fig. 3). Underground, dacitic tuff is generally less veined, but with a slightly higher proportion of thicker veins (GWI23wt in Fig. 3). Veins in

Fig. 6 Quartz veins in western wall of the Martha Hill open pit at 1090RL, showing the major lodes. (After Cargill 1994)



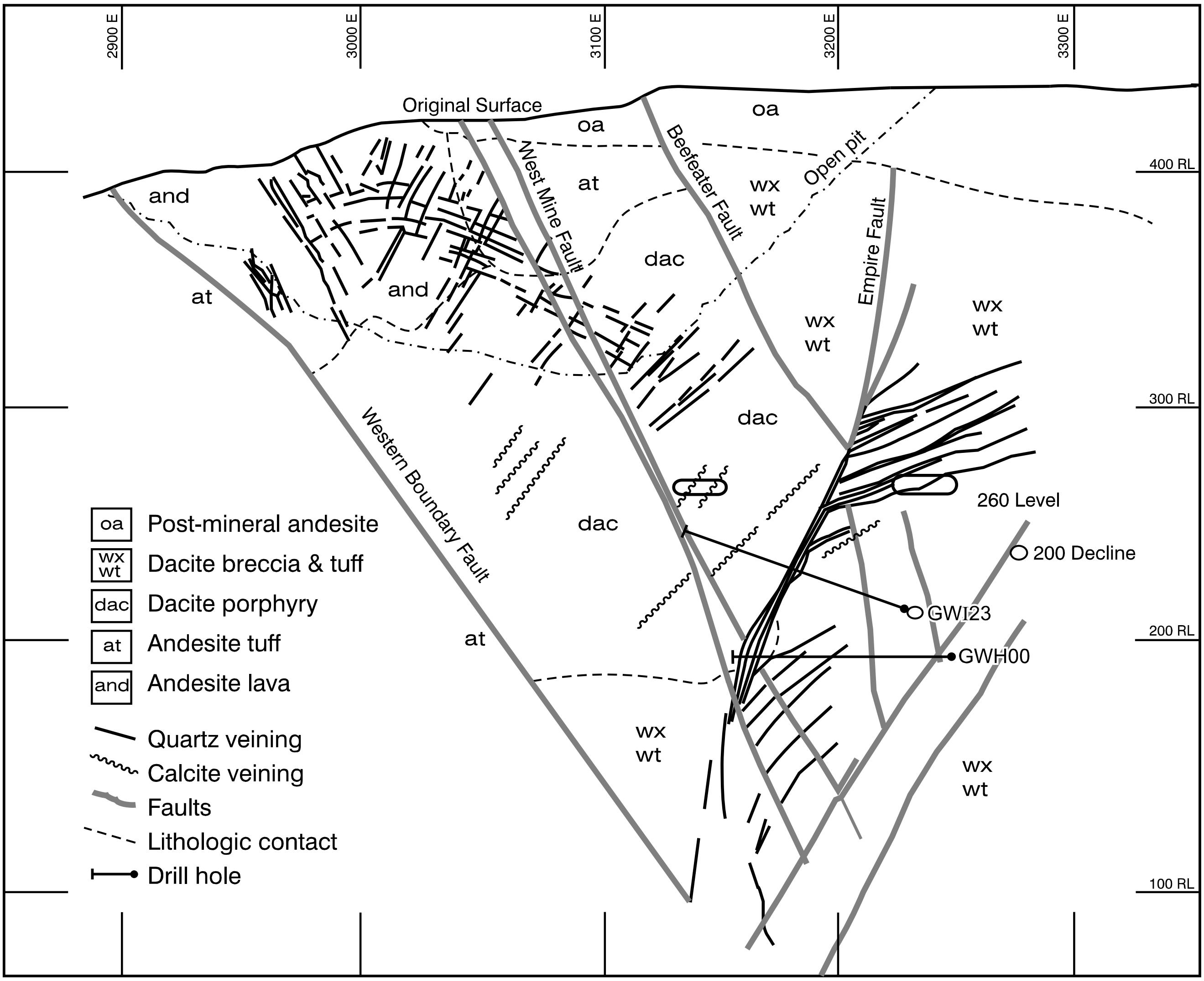
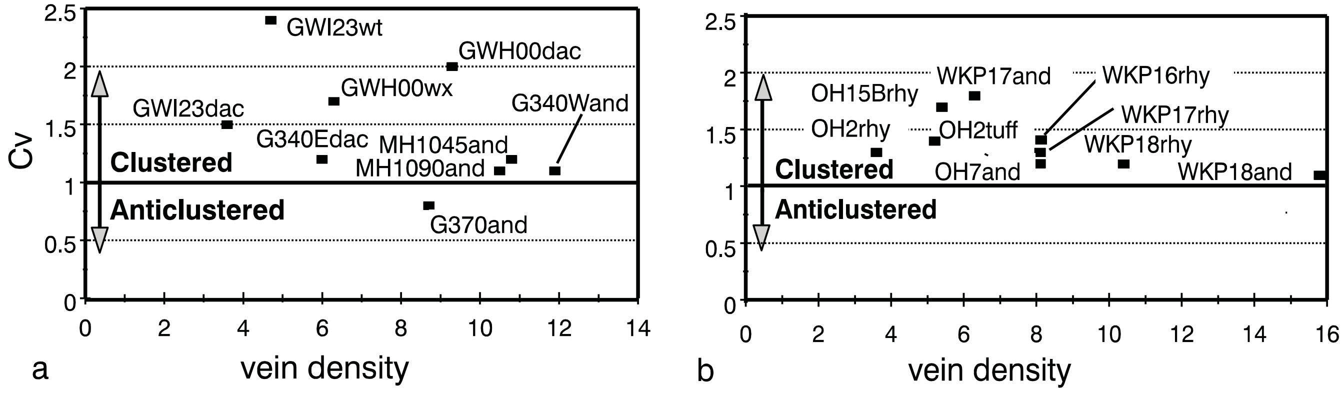


Fig. 7 Generalised cross section of the Golden Cross vein system at 4850N. Line samples in the open pit are located on 370RL and 340RL at around 3000E. Line samples from underground drill holes are from GWI23 at 211RL and GWH00 at 200RL as shown. (After Keall et al. 1993; Mauk et al. 1997)

dacitic rocks (porphyry, tuff and breccia) generally have higher degrees of clustering, with C_v values of up to 2.4 (GWI23wt), than andesite.

Vein distributions are also related to location within the deposit. Dacite porphyry, dacitic breccia and dacitic tuff generally have lower vein densities than andesite,

Fig. 8 Coefficient of variation (C_v) of vein spacing versus vein density (modified for vein thickness) for line samples from **a** Martha Hill (*MH*) and Golden Cross (*G*), and **b** Ohui (*OH*) and Wharekirauponga (*WKP*). Line separates field of clustering ($C_v > 1$) from anticlustering ($C_v < 1$). See Table 1 for explanation of labels



but host thick veins in favourable locations, such as near the Empire Vein Zone, which also coincides with a major lithological boundary between dacite porphyry and dacitic tuff. The inclusion of the thick veins of the Empire Vein Zone accounts for the high vein extension values of around 13% in dacitic breccia (GWH00wx) and dacite porphyry (GWH00dac). Andesite in the open pit shows an increase in vein density and vein clustering with depth. Vein clustering in dacite porphyry increases with depth from a C_v of 1.2 at 340RL (G340Edac) to 2.0 at 200RL (GWH00dac). Also as a function of depth, vein thickness to vein density ratios increase as a result of thicker veins, whereas in the open pit there are many more smaller veins due to stockwork-style veining.

Ohui

At Ohui, rhyolite flows and pyroclastic rocks of the Whitianga Group overlie Late Miocene Coromandel Group andesite which is exposed in up-faulted blocks bounded by NNE-striking faults (Fig. 9). Colloform banded quartz and quartz–carbonate veins are hosted in andesite and rhyolite. Vein sets at the different prospects (Fig. 9) have either NNE or NW strikes (Bell and Fraser 1912), and these strikes may be related to interaction of the NNE-striking faults with NW-striking cross faults (Merchant et al. 1988; Irvine and Smith 1990). Hydrothermal alteration in andesite is weakly to moderately developed with a chlorite–calcite-interlayered chlorite/smectite–pyrite assemblage. Rhyolite lava and rhyolitic tuff are generally pervasively silicified by hydrothermal quartz, accompanied by minor adularia, chlorite, illite and pyrite. The presence of sinter in outcrop and relatively low-temperature (∼150 °C) smectite-bearing alteration mineralogy, is indicative of a shallow epithermal system. Historic production from the Ohui field was only 7 kg of Au/Ag bullion, but various prospects within the field have been delineated and tested by recent exploration (Merchant et al. 1988; Irvine and Smith 1990; Smith 1996).

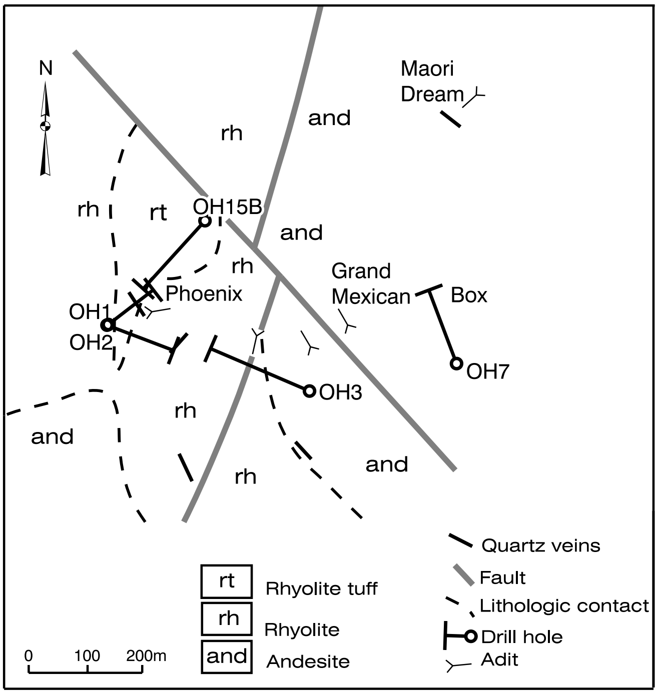


Fig. 9 Geological map of the Ohui field, showing location of prospects and selected diamond drill holes. (Modified from Bell and Fraser 1912; Merchant et al. 1988)

Three drill holes were selected as representative of veining in the different lithologies. Drill hole OH2 intersected a NNE-striking vein set in rhyolite lava and tuff, and OH7 (andesite) and OH15B (rhyolite lava) intersected predominantly NW-striking vein sets (Fig. 9). Flow-banded rhyolite (OH2 and 15B) is characterised by a low proportion of vein material, dominated by thin veins (Fig. 3), and a moderate degree of vein clustering (Fig. 8b). In contrast, andesite lava (OH7) has a higher proportion of vein material coming partly from thicker veins (Fig. 3). Rhyolitic tuff (OH2), with few thick veins, has a similar vein thickness distribution to the andesite lava in OH7.

Wharekirauponga

Gold–silver quartz veins at Wharekirauponga are hosted by Late Miocene flow-banded rhyolite, rhyolitic tuff and minor andesite within a graben bounded by NE-striking faults (Rabone et al. 1989). Steeply dipping veins occur in a zone over a length of at least 800 m and a width of about 150 m (Fig. 10). Historic production from the Wharekirauponga deposit was only 1 kg of Au–Ag bullion, because the grade was too low for underground mining. In outcrop, the quartz veins show a mesh pattern (Fig. 11), with vein intersection lines being sub-vertical and indicative of a vertical intermediate stress axis (s_2). This pattern is characteristic of an extensional-shear fault mesh (Sibson 1996). Hydrothermal alteration is characterised by strong silicification with a quartz–adularia–pyrite ± illite assemblage. Vein fill is dominantly banded chalcedonic quartz with minor vuggy quartz. Many veins appear to be purely opening mode fractures, with flow-banding not offset across the veins (Cargill et al. 1995a). Thin veins commonly pass into unfilled joints. Thicker veins split into thin veins that branch off and rejoin the main vein (Fig. 11), and often terminate in horsetails. The anisotropic effect of flow-banding within rhyolite has only a minor influence on vein orientations, with some veins sub-parallel, and others oblique, to flow-banding. Strong silicification has homogenised the rock, largely neutralising any anisotropy.

Data are from drill holes in rhyolite lava (WKP16) and rhyolite lava and andesite dike (WKP 17 and WKP18). These drill holes all intersect the vein system over a similar depth range and are separated by 100 to 200 m along strike. With the exception of WKP18,

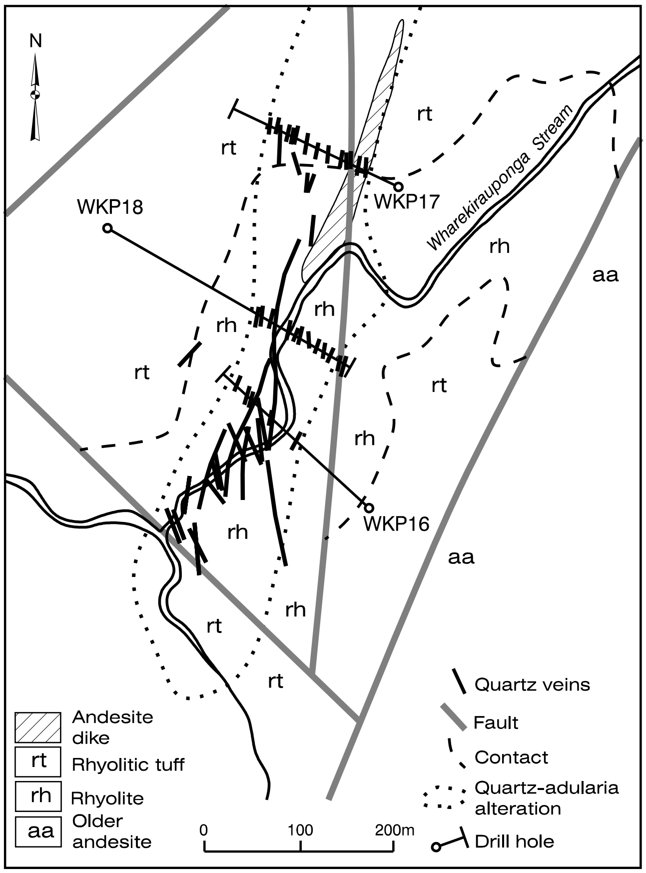


Fig. 10 Geological map of the Wharekirauponga area, showing location of selected diamond drill holes. (Modified from Rabone et al. 1989; Rabone 1991)

rhyolite tends to have a high proportion of the vein material in thinner veins than andesite (Fig. 3). The high percentage extension and vein density in WKP18 may be explained by it intersecting a major fracture zone of hydraulic quartz-cemented breccia.

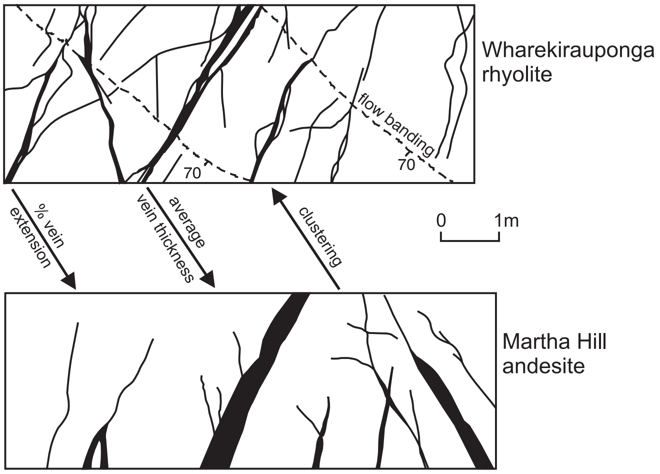


Fig. 11 Differences between rhyolite- and andesite-hosted vein patterns, based on mapped veining at Wharekirauponga (*plan view*) for rhyolite and Martha Hill (*cross section*) for andesite. Flow banding (*dashed lines*) in rhyolite at Wharekirauponga dips 70° south

Lithological controls

The distribution of quartz veining is strongly influenced by lithology, as both bulk competency and competency contrasts between the different lithologies in the volcanic sequences are major controls for permeability to hydrothermal fluids, either through fracture-induced permeability in competent lava flows or intergranular fluid movement in relatively incompetent, porous tuffs and pyroclastic breccias.

The generally well-jointed and competent nature of andesite sequences may aid in the development, continuity and interconnection of the fluid pathways, whereas poorly jointed and/or less competent rock types produce diffuse, poorly interconnected fracture systems. Veins, particularly small veins, preferentially follow pre-existing joints and fractures, as noted at Martha Hill, Golden Cross and Wharekirauponga. Well-jointed rocks contain a greater number of veins, with more regular vein spacings (i.e. less clustering) than poorly jointed lithologies. Andesite lava is commonly well jointed, whereas dacite porphyry, rhyolite lava and pyroclastic rocks are less well jointed and commonly more silicified. The relatively high primary porosity of lapilli tuff and pyroclastic breccia results in less focused fluid flow and more dispersed alteration and vein patterns. Lithology also affects reactivity with hydrothermal fluids, impacting on both mineral deposition and fracture propagation. Under the near-neutral pH fluid conditions of low-sulfidation epithermal gold mineralisation, andesite and dacite are chemically more reactive than the relatively siliceous rhyolite. Chemical reactions at joint tips are likely to aid in the propagation of fractures (cf. Atkinson and Meredith 1987), so, theoretically, andesite and dacite should have longer (and consequently thicker) veins than rhyolite. This difference appears to hold true and is evident in the vein size distributions, where andesite and dacitic rocks tend to host thicker veins than rhyolite (Figs. 4, 11) and rhyolitic tuff. The major vein structures at Martha Hill and Golden Cross also have much greater strike and depth extents than any of the veins hosted in rhyolitic rocks at Wharekirauponga. The rhyolite lava and rhyolitic tuff at Ohui and Wharekirauponga are generally characterised by lower vein thickness and vein density than andesite lava (Fig. 4b). Rhyolite lavas in WKP17 and WKP18 are exceptions.

The coefficient of variation of the spacing (C_v) shows a good correlation with the intensity of jointing, with lower C_v values (0.8–1.2) in well-jointed andesite (Martha Hill and Golden Cross) and higher C_v values (1.5–2.4) in weakly jointed dacite porphyry and breccia (Golden Cross). At Ohui and Wharekirauponga, veins in rhyolite lava and rhyolitic tuff tend to be more clustered than in andesite lava or dike (Fig. 11). WKP17 andesite dike is an exception because it is influenced by strong clustering near its contact with rhyolite. Field studies in sedimentary rocks have found that joint systems are anticlustered ($C_v < 1$) where the systems are saturated, i.e. they have developed to the stage where any further strain is accommodated entirely by increase in aperture on the joints, without the formation of new joints (Gillespie et al. 1997). Published data for veins in sedimentary and metasedimentary rocks have $C_v > 1$ up to 2.2 (McCaffrey and Johnston 1996; Gillespie et al. 1997), and normal fault distributions are in the range of 1.5 to 2.5 (P.A. Gillespie, personal communication, 1998). Application of these ranges to the epithermal vein data, suggests that the veins are controlled by a mixture of joints and faults, with joints having a stronger influence than faults in well-jointed andesite lava at Martha Hill and Golden Cross. This is supported by field observations in the open pits at both of these mines, where thin veins commonly follow joints. The C_v values of 1.5 to 2.4 for veins in dacitic rocks (porphyry, tuff and breccia) at Golden Cross are consistent with faults as the dominant control, as a result of the close spatial association of the veins with the Empire Fault. The C_v values of 1.2 to 1.7 for veins in rhyolite lava and tuff at Ohui and Wharekirauponga are consistent with the poorly jointed nature of these rocks and the presence of fault-fracture meshes in these deposits.

Spatial controls within deposits

At a deposit scale, location relative to thick veins as major fluid conduits may override local lithological differences. For example, at Golden Cross the generally weakly jointed lapilli tuff and dacite porphyry tend to contain few veins, but when adjacent to the Empire Fault the veining occurs in clusters dominated by a few relatively thick veins (i.e. they have a high thickness to density ratio). At Martha Hill, a deeper line sample shows a closer average vein spacing, higher average vein thickness and higher percentage extension, than a line which is 45 m higher and 100 m further from the centre of the vein system. At Golden Cross, a trend with depth of higher average vein thickness, higher percentage extension and greater degree of vein clustering was observed. These trends are illustrated schematically in Fig. 12.

There is a direct relationship between average vein thickness and total extension, with higher percentages of extension reflecting the influence of a few thicker veins, especially in underground drill holes at Golden Cross (e.g. GWH00wx). Comparison between gold grades and percentage of vein material over 1-m intervals for selected drill holes indicates a positive correlation, with higher grades generally associated with higher vein percentages (Cargill et al. 1995a).

In some situations, differences in the proportion of vein material are due to the greater influence of thick veins, e.g. at Martha Hill both the 1090RL and 1045RL lines have virtually the same proportion of veins in the < 100 mm vein size range, but the 1045RL section has a higher proportion in the >100 mm range (Fig. 3). By contrast, the vein thickness distribution in the Golden Cross open pit line samples is relatively uniform across the whole spectrum of vein thicknesses (Fig. 3), reflecting stockwork-style veining at a relatively high level in the epithermal system.

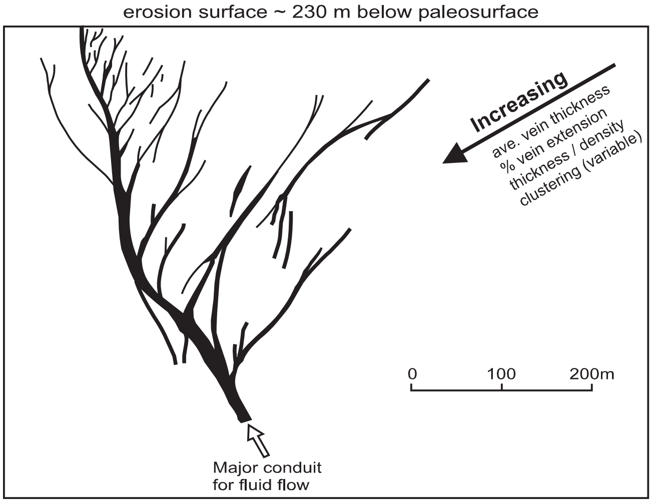


Fig. 12 Schematic representation of spatial variation of veining with depth and relative to major conduits of fluid flow, based on cross sections in the Martha Hill andesite-hosted deposit. The paleosurface is estimated to have been about 230 m above the present erosion surface. (Brathwaite 1999)

Vein distributions may change with time, especially in deposits having protracted veining sequences. However, in discontinuous mine exposures and unoriented drill core it is difficult to consistently distinguish variations in time.

Conclusions

General patterns indicate that vein clustering and vein size distributions are related to host lithology and depth within individual deposits. The physical properties of the rock type, particularly jointing characteristics, have a marked control on the distribution of veining. Well-jointed lithologies, such as andesite lavas, have vein spacing distributions that are anticlustered or have low degrees of clustering (C_v 0.8–1.2). They also show higher percentages of vein extension and vein densities, and a greater proportion of thick veins compared to poorly jointed lithologies. The anticlustered or poorly clustered veining in andesite is consistent with joints as primary permeability surfaces being a major control on the initiation of vein filling. At Golden Cross, veins in poorly jointed dacitic rocks (porphyry, tuff and breccia) generally have higher degrees of clustering (C_v values of up to 2.4), which is consistent with their close proximity to a major fault zone (Empire Fault Zone) as an initiator of structural permeability. Within deposits hosted in both rhyolite lava and andesite lava or dike, rhyolite is characterised by lower vein thickness and percentage of vein extension, but stronger vein clustering. These differences are partly related to the different jointing characteristics of andesite and rhyolite. A second factor is the greater chemical reactivity of andesite and dacite to neutral pH hydrothermal fluids compared to rhyolite. This may have facilitated vein filling of fractures in andesite and dacite, resulting in thicker more continuous veins.

Line samples that are deeper and closer to the core of the vein systems studied here have higher average vein thickness and percentage of vein extension, and in some deposits a greater degree of vein clustering. These features are indicators of the presence of major fluid conduits which may have a greater effect on vein distribution characteristics than rock type alone. In epithermal systems, location within the hydrothermal plume which drives fluid flow will exert a significant spatial control on vein distributions, especially because of the presence of marked vertical and lateral hydraulic gradients.

In exploration, this type of vein analysis can be used to quantify the distribution of veining in different lithologies, with particular reference to potential for stockwork veining. It can also help characterise how vein distributions vary within a prospect, and may indicate changes in vein distributions that would otherwise be difficult to detect. Trends of increasing percentage of extension and vein clustering may be used as vectors to locate the core of the vein system. The collection and analysis of vein distribution data from new prospects can help in their characterisation, and may be used for comparison with other better known deposits. Further work could link the vein analysis to the structural development of the epithermal systems.

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References

Atkinson BK, Meredith PG (1987) The theory of subcritical crack growth with application to minerals and rocks. In: Atkinson BK (ed) Fracture mechanics of rock. Academic Press, London, pp 111–166

Bell JM, Fraser C (1912) The geology of the Waihi–Tairua subdivision. NZ Geol Surv Bull 15, Wellington

Brathwaite RL (1999) Hydrothermal fluid mixing and boiling in the Waihi gold–silver deposit, New Zealand. In: Stanley CJ, Rankin AH, Bodnar RJ, et al (eds) Mineral deposits: processes to processing. Balkema, Rotterdam, pp 25–28

Brathwaite RL, McKay DF (1989) Geology and exploration of the Martha Hill gold–silver deposit, Waihi. In: Kear D (ed) Mineral deposits of New Zealand. Australasian Inst Min Metall Monogr 13, pp 83–88

Brathwaite RL, Pirajno F (1993) Metallogenic map of New Zealand. Inst Geol Nucl Sci Monogr 3, Lower Hutt

Brathwaite RL, Christie AB, Skinner DNB (1989) The Hauraki Goldfield: regional setting, mineralisation and recent exploration. In: Kear D (ed) Mineral deposits of New Zealand. Australasian Inst Min Metall Monogr 13, pp 45–56

Brathwaite RL, Swain A, Christie AB (1994) Patterns of quartz veining in rhyolitic and andesitic host rocks at the Wharekirauponga, Neavesville and Ohui epithermal gold deposits, Hauraki Goldfield. NZ Branch Australasian Inst Min Metall 28th Annu Conf, pp 175–188

Caddey SW, McOnie AW, Rutherford PG (1995) Volcanic stratigraphy, structure and controls on mineralization, Golden Cross Mine, New Zealand. In: Mauk JL, St George JD (eds) Proc 1995 PACRIM Congress. Australasian Inst Min Metall Publ Ser 9/95, pp 93–98

Cargill HJ (1994) Aspects of the structural geology of the Martha Hill epithermal Au–Ag deposit, Waihi, New Zealand. MSc Thesis, Univ Auckland

Cargill HJ, Christie AB, Brathwaite RL, Swain A (1995a) Comparison of vein styles and vein distributions between rhyolite- and andesite-hosted gold/silver epithermal deposits of the Hauraki Goldfield. Inst Geol Nucl Sci, Sci Rep 95/28, Lower Hutt

Cargill HJ, Christie AB, Brathwaite RL, Swain A (1995b) Comparison of vein styles and vein distributions between rhyolite- and andesite-hosted gold/silver epithermal deposits of the Hauraki Goldfield, New Zealand. In: Mauk JL, St George JD (eds) Proc 1995 PACRIM Congress. Australasian Inst Min Metall Publ Ser 9/95, pp 101–106

David V, Barber S (1997) An integrated underground mining approach to the structural complexity of the Empire vein system, Golden Cross mine, New Zealand. Australasian Inst Min Metall 1997 Annu Conf Proc, pp 153–163

Gillespie PA, Howard CB, Walsh JJ, Watterson J (1993) Measurement and characterisation of spatial distributions of fractures. Tectonophysics 226: 113–141

Gillespie PA, Walsh JJ, Watterson J, Eeles M (1997) A1 fracture datasets: A1.1 Vertical persistence and scaling of fractures at Cappanawalla, the Burren. In: Aarseth ES, Bourgine B, Castaing C, et al (eds) Interim guide to fracture interpretation and flow modelling in fractured reservoirs: Joule II, Contract No CT93–0334. European Commission, Brussels, pp 55–80

Gillespie PA, Johnston JD, Loriga MA, McCaffrey KJW, Walsh JJ, Watterson J (1999) Influence of layering on vein systematics in line samples. In: McCaffrey KJW, Lonergan L, Wilkinson JJ (eds) Fractures, fluid flow and mineralization. Geol Soc Lond, Spec Publ 155, pp 35–56

Hay KR (1989) Exploration case history of the Golden Cross project Waihi, New Zealand. In: Kear D (ed) Mineral deposits of New Zealand. Australasian Inst Min Metall Monogr 13, pp 67–72

Henley RW (1985) The geothermal framework of epithermal deposits. In: Berger BR, Bethke PM (eds) Geology and geochemistry of epithermal systems. Soc Econ Geol Rev Econ Geol 2: 1–24

Irvine RJ, Smith MJ (1990) Geophysical prospecting for epithermal gold deposits. J Geochem Explor 36: 394–399

Keall PC, Cook WC, Mathews SJ, Purvis AH (1993) The geology of the Golden Cross orebody. NZ Branch Australasian Inst Min Metall 27th Annu Conf Proc, pp 143–160

Manning CE (1994) Fractal clustering of metamorphic veins. Geol 22: 335–338

Mauk JL, Simpson M, Begbie MJ, Keall PC (1997) Styles and conditions of hydrothermal alteration and vein mineralization at Golden Cross. 1997 NZ Miner Min Conf Proc, Wellington, pp 119–124

McCaffrey KJW, Johnston JD (1996) Fractal analysis of a mineralised vein deposit: Curraghinalt gold deposit, County Tyrone. Miner Deposita 31: 52–58

Merchant RJ, Corbett GJ, Smith MJ (1988) The Ohui Prospect PL 31874, Coromandel Peninsula, status report 1988 by Austpac Gold Exploration (NZ) Ltd. Ministry of Commerce New Zealand, unpublished minerals report M0574

Morgan PG (1924) The geology and mines of the Waihi district, Hauraki Goldfield, New Zealand. NZ Geol Surv Bull 26, Wellington

Pickering G, Bull JM, Sanderson DJ (1996) Scaling of fault displacements and implications for estimation of sub-seismic strain. In: Buchanan PG, Nieuwland DA (eds) Modern developments in structural interpretation, validation and modelling. Geological Society, London, pp 11–26

Pollard DD, Aydin A (1988) Progress in understanding jointing over the past century. Geol Soc Am Bull 100: 1181–1204

Rabone SDC (1991) Review report Wharekirauponga diamond drilling programme 1990, PL 311833, Coromandel Region, New Zealand, for ACM (NZ) Ltd. Ministry of Commerce New Zealand, unpublished minerals report M3021

Rabone SDC, Moore DH, Barker RG (1989) Geology of the Wharekirauponga Epithermal Gold Deposit, Coromandel Region. In: Kear D (ed) Mineral deposits of New Zealand. Australasian Inst Min Metall Monogr 13, pp 93–97

Sibson RH (1996) Structural permeability of fluid-driven fault-fracture meshes. J Struct Geol 18: 1031–1042

Smith MJ (1996) Prospecting Licence 31 2422, Ohui. Report on work completed from July 1993 to July 1996 by Austpac Gold Exploration (NZ) Ltd. Ministry of Commerce New Zealand, unpublished minerals report M3463