

Hydrological controls on mineralisation in the active epithermal environment, Taupo Volcanic Zone (TVZ), New Zealand

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Abstract

At Broadlands-Ohaaki geothermal system, TVZ, mineral distribution patterns in geothermal wells are analogous to those in epithermal veins. Fluid flow through geothermal wells is focused over vertical intervals > 500m with discharge at rates up to 90 l/s. Focused flow at similar rates also occurs in natural systems where hydrothermal eruption vents provide enhanced vertical permeability. These vents are commonly aligned with the tectonic fabric, indicating fault control at depth. We suggest that host rock strength and structural context exert significant control on the hydrological regime conducive to epithermal mineralisation.

Keywords: *permeability, rift, hydrothermal eruption, normal fault, geothermal*

Introduction

Epithermal ore bodies develop in zones of high paleo-permeability, often in association with extensional tectonics. Highest grades are generally localised within steeply dipping faults and associated fractures that were clearly channels of strongly focussed flow during hydrothermal mineralisation. In this paper, we examine analogous zones of permeability within the active epithermal environment to better understand structural and lithological controls on permeability and ore formation.

The central TVZ hosts over 20 geothermal systems within a seismically active rift zone (Fig. 1). On the order of 10^8 m³ of 250°C fluid discharges annually due to magma-driven fluid convection, which extends the full depth of the seismogenic zone (6-8 km) (Bibby et al., 1995; Sibson & Rowland, 2003). Fluids percolate through a heterogeneous and rifted crustal rock assemblage comprising Quaternary basins filled with pyroclastic deposits and intercalated flows overlying Mesozoic metasediments and presumably plutonic intrusions. Relationships between geothermal fields, which are delimited by regions of low resistivity, and rift structure are shown in Fig. 1.

Despite the presence of highly mineralised precipitates, up to 6wt% Au and 30wt% Ag in geothermal wells (Brown, 1986), and the natural occurrence of ore-grade gold-silver mineralisation in several TVZ geothermal systems (eg. Hedenquist & Henley, 1985), ore bodies appear absent, raising questions about local (100m < L < 2km) controls on epithermal mineralisation. In this paper, we examine the geological controls on fluid flow in the epithermal environment of four geothermal systems (Table 1) to assess circumstances leading to focussed high-flux flow, a highly desirable attribute for ore formation.

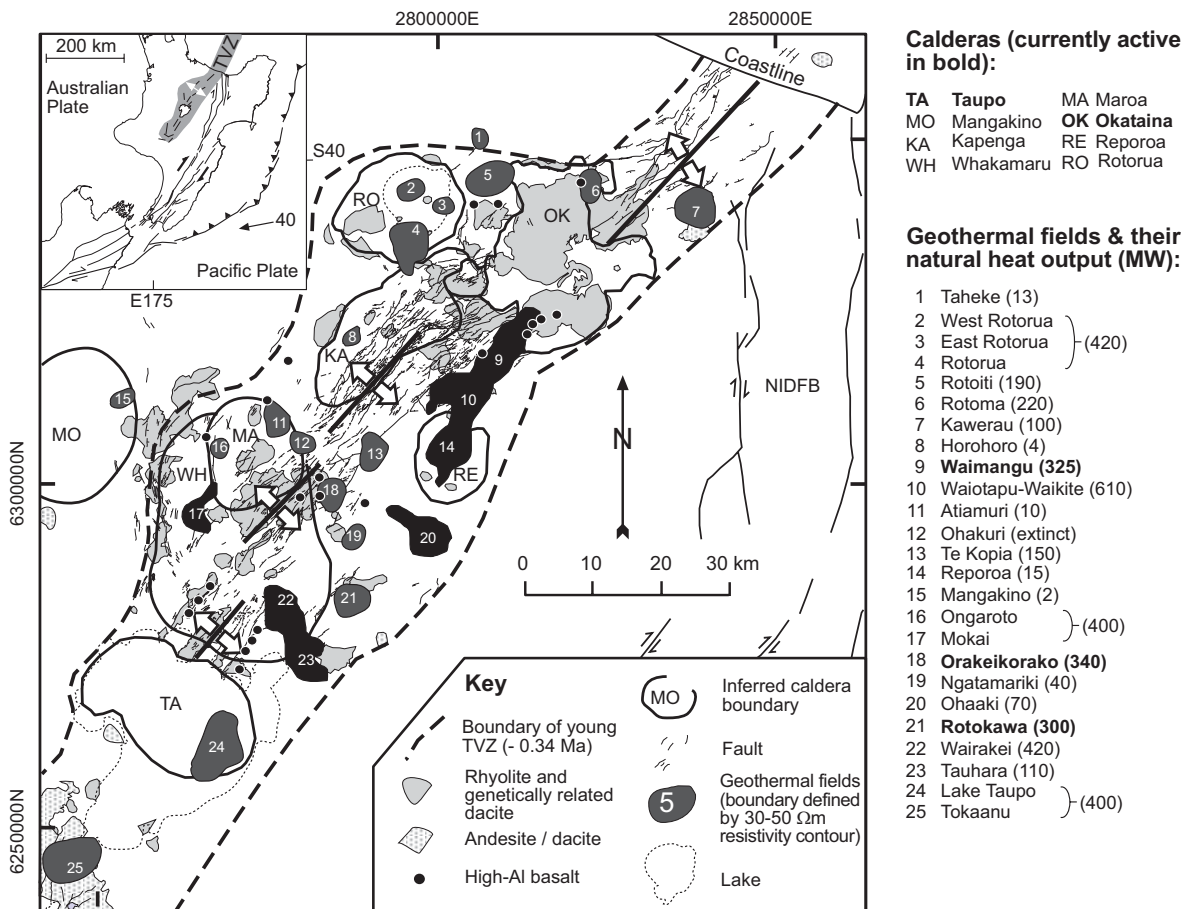


Figure 1. Map of the Taupo Volcanic Zone showing the distribution of geothermal systems, defined by the presence of low-resistivity zones ($< 50 \Omega$ m) (after Bibby et al., 1995), in relation to rift architecture, major volcanic rock types and caldera boundaries (after Rowland & Sibson, 2001). Natural heat outputs are from Bibby et al. (1995). NIDFB, North Island Dextral Fault Belt. Inset shows tectonic context.

Table 1. Character of the epithermal environment in selected geothermal systems of the TVZ

Geothermal system	Discharge rates (highest example)	Discharge location	Character of permeability	Stratigraphy in epithermal environment	Structural context in epithermal environment	Mineralisation
Broadlands-Ohaaki	30 - 90 l/s	Geothermal well	Anisotropic focused high-flux vertical flow over depth intervals > 500 m	Mostly high porosity weak pyroclastics & reworked equivalents	Unknown	Mineralogy & textures analogous to bonanza Au-Ag veins
Waimangu	100 - 120 l/s	Hydrothermal eruption vent, superimposed on a volcanic vent	Anisotropic focused high-flux vertical flow to depths > 100 m?	Mostly high porosity weak pyroclastics & reworked equivalents	Basalt fissure at caldera-rift intersection	Unknown
Rotokawa	< 10 l/s	Hydrothermal eruption vent	Anisotropic focused vertical flow to depths > 400 m?	Mostly high porosity weak pyroclastics & reworked equivalents	Hydrothermal vents aligned on NE-SW trend	Sulphur, gold @ 50 ppb
Orakeikorako	< 15 l/s (combined spring discharge)	Distributed within fault blocks	Distributed	Mostly high porosity weak pyroclastics & reworked equivalents	Fault blocks bounded by 2 nd order normal faults, which act as flow barriers to depths > 50 m	Unknown

Case studies

Broadlands-Ohaaki (Fig. 2A)

In its natural state, Broadlands-Ohaaki does not appear to have been an ore-forming environment, as indicated by sparse concentrations of gold and silver found in hydrothermally altered rocks. However, drilling of geothermal wells changed the permeability structure by creating high-flux vertical flow paths over depth intervals > 500 m. Spectacular bonanza gold, platy calcite and colloform banded silica deposit downstream of the fluid feed point (Brown, 1986; Simmons & Browne, 2000). These mineral distribution patterns reflect conditions of boiling upflow by chloride waters in focused conduits, with discharge rates up to 90 l/s. The flow regimes of geothermal wells therefore appear analogous to flow regimes producing epithermal veins. This raises the question as to how high-flux flow is focused in naturally discharging geothermal systems.

Waimangu (Fig. 2B)

The closest natural spring discharge of comparable flow rates (100 – 120 l/s) is Frying Pan Lake, Waimangu. Vents that feed the thermal discharge formed 1st April 1917 due to a hydrothermal eruption that lasted 3 days. Frying Pan Lake occupies the western part of Echo Crater, which formed during the 1886 eruption of Tarawera (Keam, 1981; Simmons et al., 1993). Fluid conduits are thus related to both hydrothermal and volcanic explosive activity and may be expected to extend over a vertical interval at least > 100m. Geothermal wells have not been drilled here, so subsurface conditions are interpreted from eruption deposits. There is no evidence for mineralisation or metal transport (Sheppard, 1986). Thus, apart from the visible discharge, it is difficult to assess the ore forming potential in terms of fluid chemistry. Fluid throughput is significant and focused, so the ore forming potential from a hydrological perspective seems comparable to that of the geothermal well.

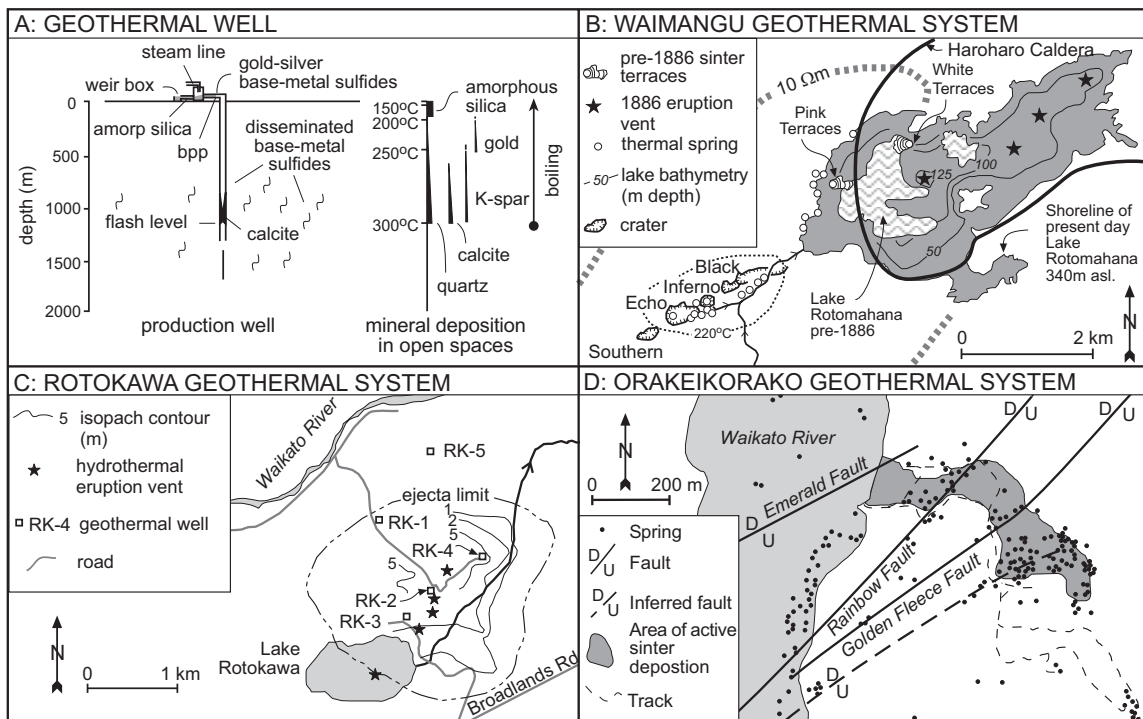


Figure 2. (A) Schematic diagram showing environments of precious- and base-metal mineralisation at Broadlands-Ohaaki (from Simmons & Browne, 2000). The distribution of minerals that deposit from boiling and mixing, as determined by numerical modelling, are shown on the right against boiling point for depth temperatures. (B) Location of thermal springs within Waimangu in relation to volcanic vents and hydrothermal eruption craters (after Simmons et al., 1993). Dashed line represents 10Ωm resistivity boundary delimiting the subsurface region occupied by chloride waters. (C) Alignment of hydrothermal eruption vents at Rotokawa (after Collar, 1985). Vent positions are inferred from distribution and isopachs (thickness m) of vent breccia. (D) Distribution of hot springs in relation to normal faults at Orakeikorako geothermal system (after Lloyd, 1972).

Rotokawa (Fig. 2C)

The origins of hydrothermal eruptions are poorly understood. However, throughout the TVZ there seems to be a common relationship between hydrothermal eruption vents and the location of faults, as suggested by the alignment of volcanic vents at Waimangu. More compelling evidence is seen at Rotokawa, where a number of hydrothermal eruption deposits (15) have centres that align along a NE-SW trend (Collar, 1985; Browne & Lawless, 2001). The natural discharge at Rotokawa is < 10 l/s and the fluids are known to be transporting gold and silver at similar concentration to Broadlands-Ohaaki (Brown, 1986). This may point to the transient nature of permeability around hydrothermal eruption vents; higher discharge may have occurred in the past.

Orakeikorako (Fig. 2D)

Steeply dipping structures are common hosts to epithermal veins and the occurrence of these in geothermal areas would seem likely analogues. Orakeikorako is one of the best examples where we may examine the relationship between faulting and fluid flow. Here, a number of small offset faults trend northeast and cross-cut the geothermal field; although there is a close correlation between thermal activity and structures, few hot springs occur along faults (Lloyd, 1972). In fact, vertical differences (~ 5 m) in the water table occur across fault blocks, indicating that the faults behave as barriers to cross-fault flow, compartmentalising at least the shallow hydrology (Rowland & Sibson 2004).

Structural prospectivity

Hydrothermal eruption vents are the most common TVZ conduit for large volumes of focused vertical flow and their alignment may indicate fault control at depth. This is of importance because epithermal mineralisation is linked in many cases to hydrothermal breccias and related structural control (eg. Hedenquist & Henley, 1985; Sillitoe, 1993). We can assess development of suitable structural control if we know the strength of the host rocks and their location in the context of the extensional system.

For a structure to be analogous to a geothermal well, it must maintain open space over suitable depth intervals (> 1000 m). Of the three possible macroscopic modes of brittle failure, extension fractures and extensional shears may be considered prospective hosts for mineralisation. Faults, on the other hand, may be highly permeable during a seismic event, but not at other times. The tendency for faults to behave as barriers to flow during inter-seismic periods is enhanced by the presence of gouge, which is likely in weak rocks and where faults have accrued significant displacement (i.e. first order structures).

We can construct a brittle failure mode plot for extensional tectonic regimes by plotting the differential stress ($s_1 - s_3$) required for the gaping fractures against effective vertical stress, $s_v \phi = s_v (1 - I_v)$, where I_v is the pore fluid factor ($I_v = 1$ \bar{P} lithostatic fluid pressure; $I_v = 0.4$ \bar{P} hydrostatic fluid pressure). Failure curves for intact rock of tensile strength, T , are constructed assuming a representative coefficient of internal friction, $m_i = 0.75$ (Sibson 1998, 2000) (Fig. 3A). The differential stress required for reshear of an optimally oriented cohesionless fault with a static coefficient of friction $m_s = 0.6$ is shown for comparison. Each failure curve defines the transition from gaping fractures in the near surface to faulting with increasing effective overburden (Sibson 2000). Using this transition, we can define two permeability fields: a field of structural conduits and a field of likely structural barriers. This plot illustrates several important points: (1) rocks with high tensile strength can sustain gaping fractures to greater depth than less competent rocks, (2) within the epithermal environment, the mode of brittle failure is extremely sensitive to variations in tensile strength, (3) pore fluid pressure increases the depth extent of the field of structural conduits, and (4) the presence of a through-going cohesionless fault well-oriented for reactivation precludes all other forms of brittle failure in intact rock (Sibson 1998).

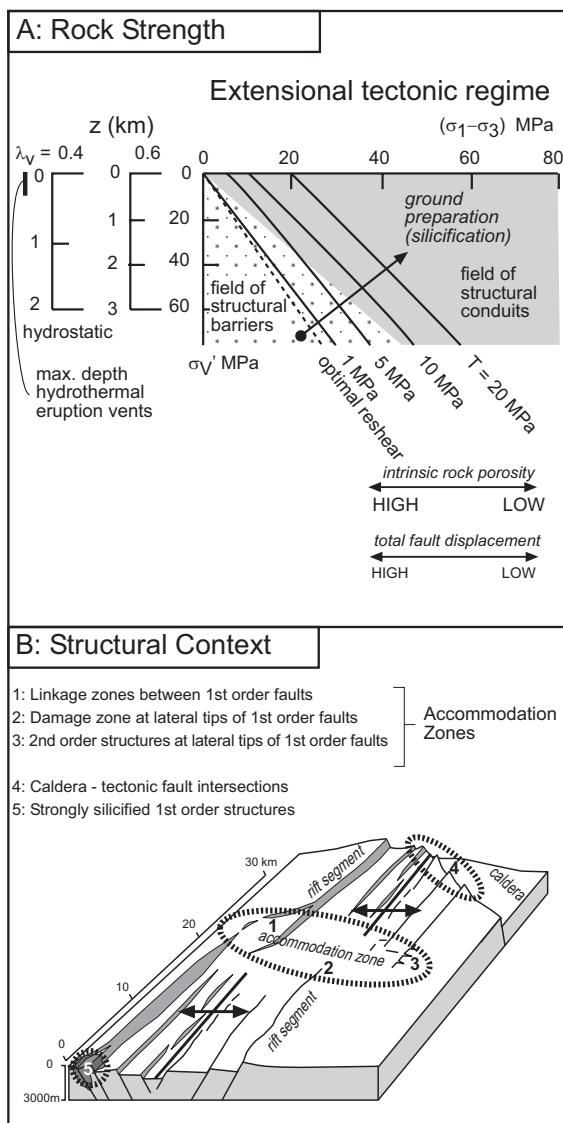


Figure 3. Structural controls on epithermal environments in a rift setting. (A) Rock Strength: Brittle failure mode plot of differential stress ($\sigma_1 - \sigma_3$) versus effective overburden σ_v' in an extensional tectonic regime with $\sigma_v = \sigma_1$ (after Sibson, 2000). Effective vertical stress can be equated to depth for different values of the pore fluid factor, λ_v . Failure curves are plotted for intact rock (coeff. of internal friction = 0.75) with $T = 1, 5, 10$ and 20 MPa and the reshear condition of an optimally oriented cohesionless normal fault (coeff. static friction = 0.6). Fields of structural conduits versus structural barriers are constructed using the transition from gaping fractures to faults with σ_v' . Weak rocks favour development of structural barriers to fluid flow. High intrinsic rock porosity and increasing amounts of displacement on large structures may drive brittle failure into the field of structural barriers. (B) Favourable structural contexts for enhanced vertical permeability in a structurally segmented rift system (after Rowland & Sibson 2004).

Although tensile strengths of rocks in the TVZ are poorly known, most rocks within the pyroclastic and sedimentary basins are weak (< 5 MPa), but moderately-welded ignimbrites and rhyolite domes may range in strength up to ~ 10 MPa with intact greywacke perhaps reaching 15 MPa. This may explain the lack of obvious tectonic focusing of fluids in the near surface; brittle structures formed in low strength rocks tend to impede flow. Major faults with significant displacement are likely to behave similarly. In contrast, second order structures, if in strong rock, are less likely to have significant gouge development and more likely to regain cohesive strength post-seismically through mineral deposition, permitting subsequent development of gaping fractures along fault irregularities. Structural context therefore is of critical importance.

Full analysis of the regional controls on localisation of geothermal systems is beyond the scope of this paper, but it is a topic addressed recently for the TVZ (Rowland & Sibson 2004) and is open to further investigation. Based on the distribution of TVZ geothermal systems, the regions most suited to focussed flow of hydrothermal fluids within a rift system are shown in Fig. 3B.

Summary

TVZ geothermal systems are mostly hosted within high-porosity, low-cohesion pyroclastic rocks, with high rates of natural discharge focused through hydrothermal eruption vents. Focused high-flux flow does not appear to discharge through tectonic faults or fractures, though the alignment of hydrothermal eruption vents suggests fault control at depth. Whether such a structure will host epithermal mineralisation depends on the tensile strength of the host rocks and the structural context; large faults and faults in weak rock likely impede flow.

Acknowledgements

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