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STRESS-CONTROLLED HYDROTHERMAL FLUID FLOW IN BASEMENT GREYWACKE, KUAOTUNU, COROMANDEL PENINSULA, NEW ZEALAND

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SUMMARY - A hydrothermal fault-fracture system extends into well-exposed basement greywacke at Kuaotunu, the northem-most of the major Hauraki Goldfields. Stress-controlled structural permeability in a predominantly extensional tectonic regime has governed hydrothermal fluid flow in the greywacke. Localised dilatation has occurred as a consequence of two modes of brittle failure: extension fracturing perpendicular to the least principal stress, and extensional-shear fracturing inclined to the directions of principal stress. Changes in the dip of normal faults, linkage structures between closely-spaced parallel faults, and fault reactivation of suitably oriented bedding planes have focussed fluid into remarkably localised conduits.

1. INTRODUCTION

During Late Miocene-Early Pliocene volcanism, Au-quartz veins were deposited by hydrothermal systems active in the Hauraki Goldfields of the Coromandel Peninsula. Generally, these deposits occur within Neogene cover volcanics. However, the most northerly field, Kuaotunu (Figure 1a), is exceptional because gold-bearing quartz veins occur within low-porosity greywacke basement. Excellent exposures of hydrothermal veins occur on the northern slopes of Black Jack Hill which is capped by a siliceous paleosinter. The fault-fracture feeder system beneath the sinter outcrops over a vertical interval of 212m and is particularly well exposed on the adjacent coastal section. This system provides a unique opportunity to investigate the character of the permeability structure within low-porosity basement rock and provides an analogy to some of the active geothermal systems of the Taupo Volcanic Zone. This paper presents the results of reconnaissance fieldwork.

2. GEOLOGY

The greywacke basement comprises well indurated interbedded argillites and sandstones of the Moehau Formation. These strata are folded into a series of isoclinal NNW-trending anticlines and synclines with axial planes dipping 65' west (Skinner 1976). The basement is unconformably overlain by breccias associated with Coromandel Group andesitic volcanism (Parkinson 1980). Towards the end of this phase of volcanism the Kuaotunu hydrothermal system was active and precipitated siliceous sinter in the area of Black Jack Hill. Plant remains occurring at the base of sinter terraces provide good paleosurface constraint.

Faulting has occurred either parallel or perpendicular to the basement fold axes with predominantly dip-slip movement during Cenozoic extension (Skinner 1976). Parkinson (1980) observes that the dominant fault set at Kuaotunu trends N-S and dips to the west, perhaps exploiting a basement weakness produced by the W-dipping greywacke beds. The two major vein systems yielding economic gold deposits, the Try Fluke Reef and Waitaia Reef, also trend N-S but dip predominantly to the east.

3. HYDROTHERMAL FEEDER SYSTEM

The feeder system comprises an anastomosing mixture of predominantly N-NE trending normal faults and subvertical extension fractures (Figure 1b). Hydrothermal alteration is pervasive in the upper section but decreases dramatically with depth corresponding to a change in lithology fiom porous breccia to tight greywacke. Within the lower section, some extension fractures retain drusy apertures gaping up to 20 cm (Figure 2). They are often interconnected by faults with a surface veneer of quartz. These arrays of faults and extension fractures appear mesh-like in the

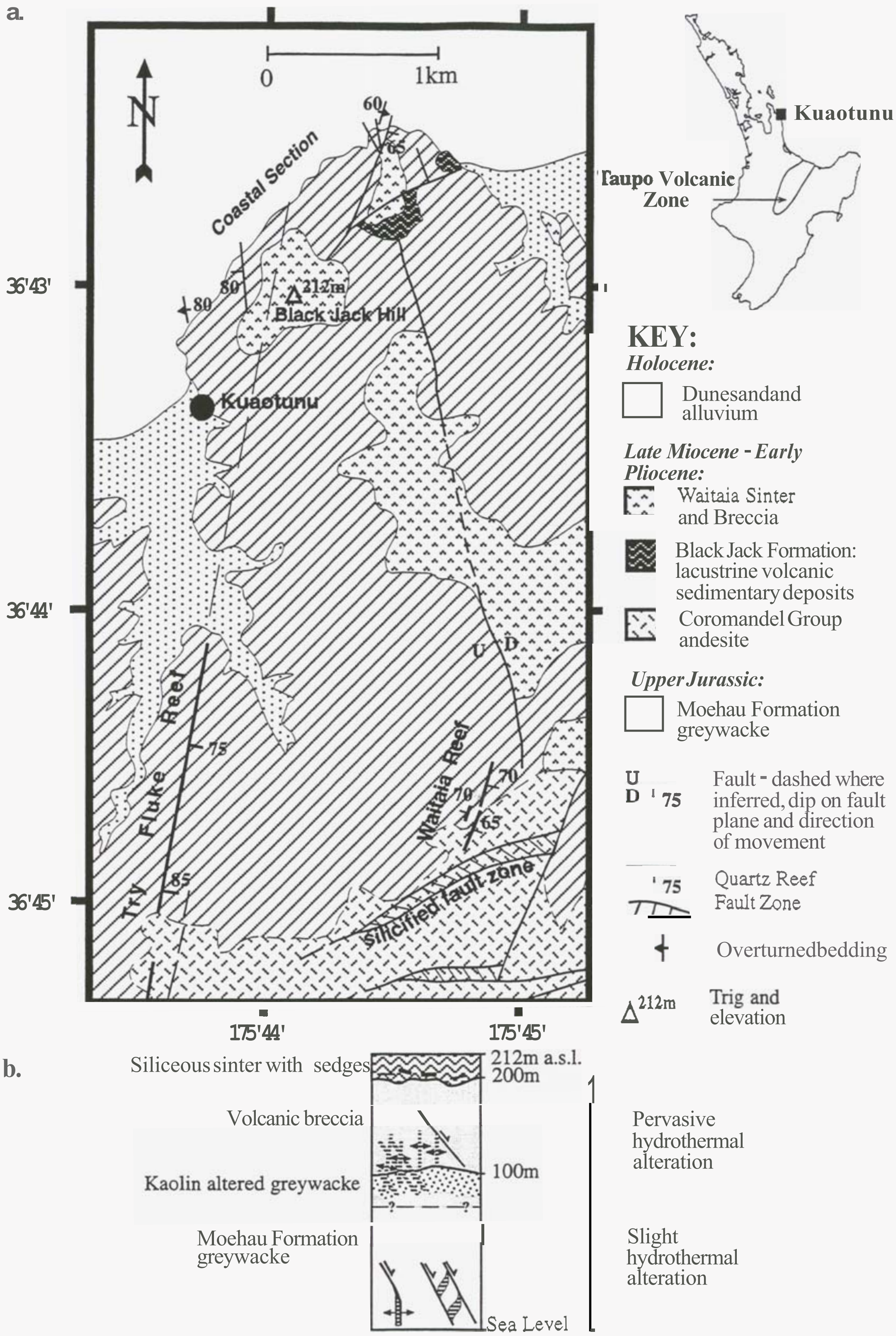


Figure 1. a) Geological map of Kuaotunu region after Skinner (1976) and Parkinson (1980). Inset shows locations of Kuaotunu and Taupo Volcanic Zone within the North Island of New Zealand. b) Schematic section through Black Jack Hill showing the main hydrothermal and structural features of the feeder system.

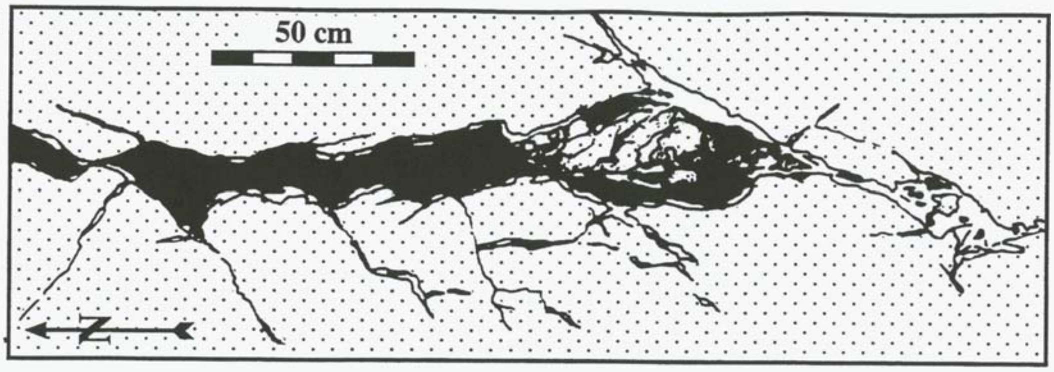


Figure 2. Plan drawing of a drusy gaping fracture in basement greywacke (black = gaping cavity)

manner described by Hill (1977) and Sibson (1994). Wallrock alteration is slight and it is clear that these fracture systems have served as remarkably localised conduits for flow of hydrothemal fluids within the basement greywacke.

4. STRUCTURAL CONTROLS ON PERMEABILITY

Hydrothemal permeability at Kuaotunu is largely controlled by structures that were active during Cenozoic extension. Although normal faulting predominates, there are minor components of strike-slip at Kuaotunu. The following analysis assumes purely extensional conditions.

For homogenous isotropic rock with internal pore-fluid pressure, p_f, a stress-field can be described in terms of three principal effective stresses:

$\sigma'_1 = (\sigma_1 - p_f) > \sigma'_2 = (\sigma_2 - p_f) > \sigma'_3 = (\sigma_3 - p_f)$.

In an extensional tectonic regime, σ'_1 is vertical (Anderson, 1951). This configuration of the principal effective stresses may result in three macroscopic modes of brittle failure (Figure 3): 1) vertical pure extension fractures perpendicular to σ'_3; 2) shear fractures (faults) developing in planes containing σ'_2 and dipping typically 60°-70"; and 3) extensional-shear fractures also developing in planes containing σ'_2 but dipping more steeply than shear fractures (Secor, 1965; Anderson, 1951; Hancock, 1985). Material heterogeneity may cause local departures from the far-field stress resulting in varying modes of brittle failure (Sibson, 1996).

Permeability at Kuaotunu has developed in several ways according to the heterogeneity of the greywacke and the geometry of the faults (Figure 4).

Irregularities in dip and strike control permeability along N-NNE trending normal fault planes. Where fault dip steepens, 10 cm thick gapes commonly extend down dip >2m. Connectivity along strike of variably gaping fractures extends in some instances for 10's of meters. Variation in gape is partly due to minor components of strike-slip movement.

Major fluid conduits occur where parallel faults are closely spaced (<2m). A range of linkage structures in the zone between parallel faults can

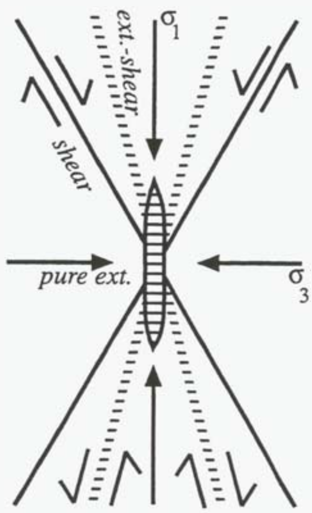
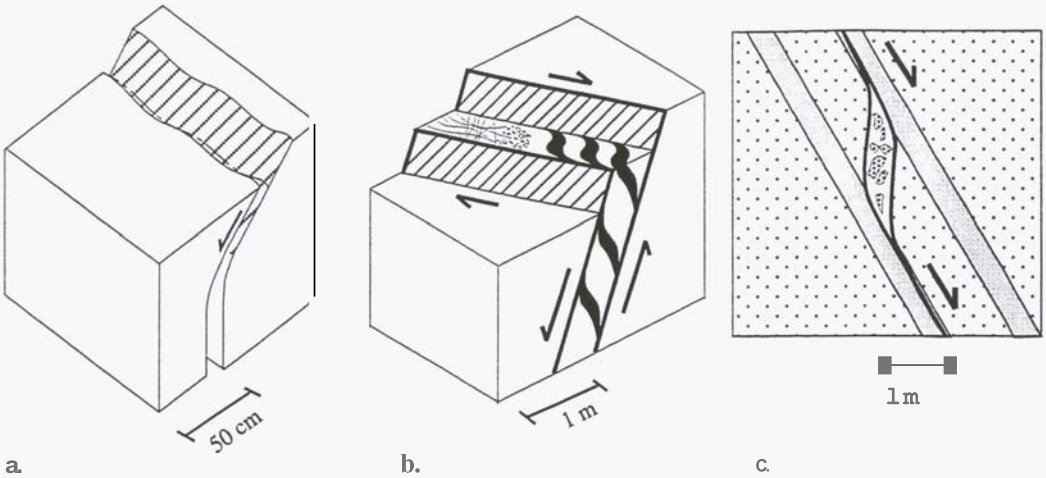


Figure 3. Orientations of brittle failure modes with respect to the stress field for an extensional tectonic regime in homogenous rock. Note that bedding anisotropy may determine which of the conjugate fracture sets predominates.



a. b. c.

Figure 4. Styles of structurally controlled permeability in greywacke basement. a) Irregularities in the strike and dip of the fault plane control permeability. Extensive gapes occur where the fault plane steepens. b) Zone of high permeability where slip transfer has occurred between closely spaced parallel normal faults. Tension gashes, veining and breccia occur in these zones. Brecciation increases with increasing vein intensity. c) Reactivation of favourably oriented bedding horizons in lower competency lithological units and creation of space in the more competent units.

be observed from dilatational jogs and tension gashes to complete brecciation of the rock mass, indicating a continuum of deformation styles. In a single inter-fault zone, the degree of brecciation can vary along strike from none to intense within the space of 30m consistent with an increase in vein intensity. The along-strike dimension (>50m) of inter-fault dilatant zones raises questions about their ability to focus fluid flow parallel to strike.

Wherebedding planes are favourably oriented for fault reactivation, variation in competency within the greywacke beds appears to exert control over permeability. Quartz mineralisation occurs as a fault plane veneer in the argillite and as infilling interlinked shears and dilatational jogs in the sandstone.

5. MECHANICS OF FRACTURING

Within the basement greywacke, significant dilatation is produced by two modes of brittle failure: pure extension fracturing perpendicular to the least principal effective stress; and extensional-shear fracturing inclined to the directions of effective principal stress. This analysis assumes a purely extensional tectonic regime with $\sigma_v = \sigma_1$. A failure envelope for intact isotropic rock (Figure 5a) normalised to tensile strength **T** can be plotted on a Mohr diagram with shear stress, τ, versus effective normal stress σ'_n, using the Griffith failure criterion:

$$\tau^2 - 4\sigma'_n T - 4T^2 = 0 \qquad (1)$$

The maximum depth (Secor, 1965), at which extension fracturing and extension-shear fracturing can occur depends upon the rock properties of the greywacke, the effective vertical stress, σ'_v, and the pore fluid factor, λ_v (Hubbert and Rubey, 1959):

$$\lambda_v = \frac{P_f}{\sigma_v} = \frac{P_f}{\rho g z} \qquad (2)$$

where z = depth, ρ = density of greywacke, and g = acceleration due to gravity.

For an extensional tectonic regime in the upper crust, the vertical stress equals the greatest principal stress (Anderson, 1951), thus:

$$\sigma'_v = \sigma'_1 = \sigma_1 - P_f = \rho g z(1 - \lambda_v) \qquad (3)$$

Therefore:

$$z = \frac{\sigma'_1}{\rho g(1 - \lambda_v)} \qquad (4)$$

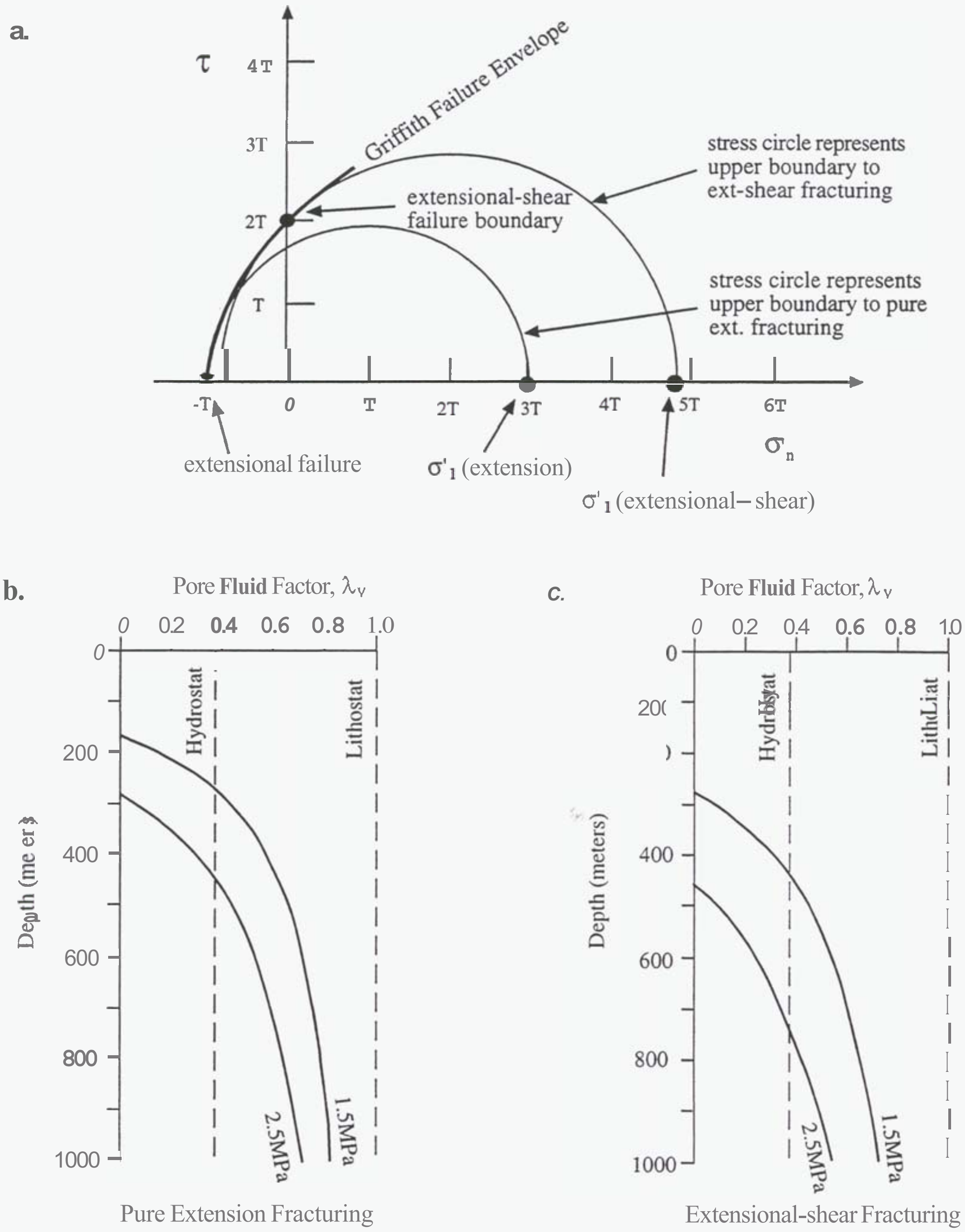


Figure 5. a) Mohr diagram showing the Griffith failure envelope for intact rock normalised to tensile strength, T. Critical stress circles are shown representing maximum $(\sigma'_1 - \sigma'_3)$ allowing pure extension and extensional-shear failure modes. Maximum possible σ'_1 values satisfying each failure mode are indicated. b) and c) Maximum depth curves for pure extension fracturing (a) and extensional-shear fracturing (b) in greywacke with tensile strength ranging from 1.5 - 2.5 MPa and average density = 2650 kg/m^3 (after Secor, 1965).

The geometrical properties of the failure envelope dictate the maximum values of σ'_1 that satisfy each brittle failure mode. Thus, for pure extensional fracturing $(\sigma'_1 - \sigma'_3) < 4T$, so that $\sigma'_1 < 3T$, and for extensional-shear fracturing $3T < \sigma'_1 < 4.831'$.

Maximum depth curves (Figure 5b and c) for each mode of brittle failure have been determined assuming an average density of 2650 kg/m^3, and an appropriate range of tensile strengths from 1.5 MPa to 2.5 MPa (pers. comm. J. St George). Observations of the high-permeability mesh at Kuaotunu are consistent with these depth curves. At hydrostatic fluid pressure, high-permeability in extension fractures and extensional-shear fractures could extend down to ~800m below the paleosurface. Increasing tensile strength by silicification, stress heterogeneity or overpressuring of hydrothermal fluids above hydrostatic, could increase this depth still further.

6. CONCLUSION

Structural control has focussed hydrothermal fluids into extremely localised channels in the basement greywacke. It is significant that the structures controlling fluid flow are those that were actively responding to the state of stress at that time. Creation of permeability due to movement along an irregular fault plane is well recognised (Newhouse, 1940; Wodzicki and Weissberg, 1969) and is significant at Kuaotunu. This preliminary study suggests that much may be learned from a more detailed investigation of the interplay of closely-spaced faults, and of faults and bedding planes, to evaluate their importance with respect to permeability in basement greywacke assemblages.

7. ACKNOWLEDGMENTS

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