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ASSESSMENT OF FAULTS AND FRACTURES AT THE MOKAI GEOTHERMAL FIELD, TAUPO VOLCANIC ZONE, NEW ZEALAND

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ABSTRACT

The Mokai geothermal field is located 25 km north-west of the Wairakei field in the Taupo Volcanic Zone, central North Island of New Zealand. Its main reservoir was defined by an area of low electrical resistivity (about 12-16 km^2) which is associated with hydrothermally demagnetised rocks at depths between 500 and 1000 m. Lateral outflow of thermal waters occurs toward the lower topography of the Waikato River valley in the north.

An analysis of detailed digital topography data (25 m grid) by contour and shaded relief plots was made to identify lineaments caused by faults and their fractures in the Mokai area. The result confirms the existence of three dominant structural trends at Mokai striking NE, N, and NW. A map of 'fault and fracture density' (FFD), defined as the total length of lineaments per unit area, was constructed for the area. It shows that the Mokai geothermal reservoir and its thermal outflow are associated with a zone of high FFD, suggesting the significant influence of geological structures on the hydrology of the present geothermal system. The result also suggests that a deep feed zone of thermal waters lies outside the southern resistivity boundary of the field.

1. INTRODUCTION

Geological structures are important controls on high temperature geothermal systems in the Taupo Volcanic Zone (TVZ), a Quaternary volcano-tectonic depression in the central North Island of New Zealand. Geophysical studies (Modriniak and Studt, 1959) and examination of LANDSAT images (Wan and Hedenquist, 1981) showed that the positions of geothermal systems in the TVZ can be interpreted as resulting from the intersection of regional faults trending in NE (parallel to TVZ boundary), NW, and NNW directions. Other studies indicate that faults provide permeable paths for geothermal fluids (through zones of fractured rocks). For example, productive geothermal wells at the Wairakei field are associated with permeable faults at depth (Grindley, 1965). A close relationship also exists between surface faulting and thermal manifestations at Orakeikorako (Lloyd, 1972; Hamlin, 1999) and Te Kopia (Grange, 1937; Healy, 1952; 1974; Bignall and Browne, 1994; Browne *et al.*, 1994). A more recent study (Soengkono, 1999) has shown that the extent of the Te Kopia geothermal reservoir is also significantly influenced by faults and fractures that can be mapped from their surface expressions.

The Mokai geothermal system is located in the western part of the TVZ, south-east of the Maroa Volcanic Centre (Fig. 1). Three main structural trends occur in the Mokai area. One is N-S, as represented by the Hauraki Fault (Grindley, 1960) (see Fig. 2) and other smaller faults along the belt of rhyolite domes west of Mokai (Wilson *et al.*, 1986), and by the general strike of concealed (volcanic) depressions interpreted from magnetic surveys (Soengkono, 1990). Another trend is NE-SW (parallel to the trend of the TVZ), shown up by the lineation of closely clustered rhyolite domes within the Maroa Volcanic Centre and by young fault scarps displacing the domes and surrounding rock formations (Lloyd, 1978). A third structural trend is NW-SE, indicated by a regional fault running through the Wairakei and Mokai geothermal systems (the Mangakino-Ahimanawa fault; see Fig. 1), which was recognised on LANDSAT images (Wan and Hedenquist, 1981). In addition, Lloyd (1978) also mapped some curvilinear faults sub-parallel to the belt of rhyolite domes west of Mokai (Fig. 2).

Lloyd (1978) suggested that a fault system (the Pukemoremore Fault) provides a permeable zone where geothermal waters feed the Mokai system. Study of drillhole cuttings and cores by Dr. C. P. Wood of the NZ Geological Survey (unpublished reports) indicated permeable zones inside the Mokai reservoir comprising fractures and open cracks. In this paper, the relationship between faults and fractures and the Mokai geothermal system is investigated further by analysing detailed digital topographic data of the area.

2. GEOLOGICAL AND GEOPHYSICAL SETTING

The Mokai geothermal field is situated directly west of the Pukemoremore rhyolite dome (Fig. 2) of the Maroa Volcanic Centre. Other rhyolite domes to the south-west and west (Fig. 2) were probably extruded along a fault system associated with the Whakamaru caldera proposed by Wilson *et al.* (1986). This large caldera structure predates the activity of the Maroa Volcanic Centre (Wilson *et al.*, 1995). Most of the areas between these rhyolite domes are covered by ignimbrite flows that originated from other volcanic centres in the south and the north. Detailed geological mapping (Lloyd, 1978) and drillhole data showed that rhyolitic volcanic activity has been dominant in this area for more than 300 ka.

Although the occurrence of surface thermal manifestations in the Mokai area was reported in 1937 (Grange, 1937), interest in it as a geothermal prospect was revived only in 1977 following the result of a reconnaissance resistivity survey (Bibby, 1977). Since 1979, ten wells have been drilled and at least seven of them are productive. They encountered temperatures greater than 240°C. Locations of the first six wells are shown in Fig. 2.

The Mokai geothermal field was defined by an area of low electrical resistivity (Bibby *et al.*, 1984) that covers about 12-16 km^2. Airborne magnetic surveys (flown 300-400 m above ground) and magnetisation measurements of cores (Soengkono, 1985; Hochstein and Soengkono, 1997) showed that, within this resistivity low, the reservoir rocks at depth between 500 m and 1000 m have also been hydrothermally demagnetised. A hydrological model of the Mokai geothermal system, involving the north-easterly outflow of geothermal waters from the area of low resistivity, was first proposed by Bibby (1977) on the basis of resistivity measurements and the occurrence of warm springs north of the low resistivity area (the North Mokai Springs; see Fig. 2). Results from more extensive resistivity measurements (Bibby et al., 1984), geochemical investigations (Henley and Glover, 1980), and drilling itself, support this model.

The total heat loss through surface manifestations at Mokai is only about 6 MW (Bibby *et al.*, 1984). However, a much greater heat loss (395±120 MW) occurs through concealed outflow of thermal waters from Mokai towards the Waikato River in the north (Stagpoole and Grantham, 1981).

3. ASSESSMENT OF FAULTS AND FRACTURES

In a young volcanic setting such as the TVZ, geological structures often have recognisable topographic expressions. Hence, a careful examination of topography can help assess geological structures, particularly faults and their fractures that are often marked by topographic lineaments. For example, at the Te Kopia field in the eastern part of the TVZ (see Fig. 1), an analysis of digital topographic data revealed the detailed pattern and distribution of faults and fractures influencing the extent of the geothermal reservoir (Soengkono, 1999).

Following the result at Te Kopia, a similar topographic analysis was conducted at Mokai. The detailed digital topography of Mokai (25 m grid) was available from the Land Information NZ. The analysis was targeted to trace topographic lineaments (resolution of about 100 m) that can be interpreted as faults and their fractures. The lineaments were traced from a plot of detailed topographic contours (10 m interval) superimposed upon eight different shaded topographic reliefs created by changing the apparent 'sun' position using a 45° increment of azimuth starting from the N; Fig. 3 shows an example of such topographic reliefs. The lineaments in the Mokai area determined from the detailed topographic analysis are shown in Fig. 4. Prominent lineaments clearly mark the Pukemoremore and Hauraki Faults. Most of the curvilinear faults mapped by Lloyd (1978) across Mokai area (Fig. 2) are shown in Fig. 4 as poorly defined belts of shorter lineaments.

Fig. 5a is a rosette diagram of the lineaments in Fig. 4. A modified rosette diagram was also constructed (Fig. 5b), by plotting the total length (km) of the lineaments (instead of the number of lineaments). Both rosette diagrams (Figs. 5a and 5b) clearly show three peaks, which confirm the existence of the three main structural trends (N-S, NE-SW, and NW-SE) in the Mokai area suggested by the previous studies (Grindley, 1960; Lloyd, 1978; Wan and Hedenquist, 1981; Wilson *et al.*, 1986; Soengkono, 1990).

The parameter 'fault and fracture density' (FFD), defined as the total length of lineaments per unit area (Soengkono, 1999), was computed for the Mokai area. For this computation, the area in Fig. 4 was divided into a 1 km grid system. The total length of lineaments inside each grid (in km) was measured and the result was used to compute a representative value of FFD (in km/km^2, or km^{-1}) at the centre of the grid. A contour map (Fig. 6) was constructed using the values of FFD computed for the whole grid system. Contour values in such a map represent the intensity of faulting and fracturing which can influence the extent of a geothermal system. At Te Kopia, for example, the geothermal reservoir is associated with FFD ≥ 3 km^{-1} (Soengkono, 1999). Fig. 6 shows that zones of FFD ≥ 3 km^{-1} occur inside as well as outside of the Mokai geothermal field.

4. DISCUSSION

In Fig. 7, the results from analysis of FFD in the Mokai area are combined with resistivity survey from Bibby *et al.* (1984). A coherent zone of high FFD (≥ 3 km^{-1}) which is similar to the zone of Schlumberger apparent resistivity ≤60 Ω-m (AB/2=1200 m) is shown in Fig. 7 encompassing the Mokai field and its zone of thermal outflow to the north. This result is a clear indication of the influence of geological structures on the hydrology of the Mokai geothermal system. It also shows that a zone of high FFD, mapped from the surface expressions of faults and their fractures, is associated with a permeable zone at deeper level that allows vertical and lateral movements of thermal waters. The result in Fig. 7 also suggests that a thermal outflow occurs to the west of the Paerata Road north of Mokai, undetected by the resistivity survey because of the relatively high topography.

The zone of high FFD extends about 1.5 km beyond the resistivity boundary to the south of Mokai field. This southern extension is also marked by higher values of FFD (>4 km^{-1}; see Fig. 6). It is possible that this southern high FFD zone represents a deep (>600m) zone of thermal waters feeding the Mokai system. The hydraulic gradient would cause the thermal waters to move northwards before they reach the shallow (≤600 m) depths penetrated by the resistivity surveys.

The Pukemoremore rhyolite dome directly to the east of the Mokai field (outside the resistivity boundary) is covered by an eastern extension of the high FFD zone associated with the Mokai system. A previous magnetic survey (Soengkono, 1985; Hochstein and Soengkono, 1997) indicated that the Pukemoremore dome may have been affected in the past by a hydrothermal demagnetisation event. Results of Schlumberger dc-resistivity traversing (Bibby *et al.*, 1984) show apparent resistivity values of about 700 Ω-m for AB/2=600 m and about 150 Ω-m for AB/2=1200 m in the Pukemoremore area, suggesting a decrease of electrical resistivity with depth. However, there are no other indications to suggest that the Pukemoremore area is part of the Mokai system.

Separate zones of high FFD also occur to the southwest and northwest of the Mokai field (Fig. 7). These zones are not associated with any resistivity or magnetic anomalies that indicate a hydrothermal system. Although rocks with high permeability may occur at depth associated with these zones of high FFD, no geothermal system can develop if there is no heat source.

5. CONCLUSIONS

1. An analysis of detailed digital topographic data (25 m grid) has revealed the pattern and distribution of faults and fractures in the Mokai area. The result confirms the existence of three dominant structural trends at Mokai striking NE, N, and NW.

2. A contour map of 'fault and fracture density' (FFD), constructed from a detailed topographic analysis of the Mokai area, suggests a close spatial relationship between geological structures and the high temperature geothermal system at Mokai. The result shows that the Mokai reservoir, and its zone of thermal outflow towards the Waikato River in the north, are associated with a coherent zone of high FFD (≥ 3 km^{-1}). The result also suggests the possibility of a deep feeding zone of thermal waters outside the southern resistivity boundary of the Mokai field.

3. This study demonstrates that simple analysis of detailed digital topography data is an additional tool to explore and assess a geothermal system.

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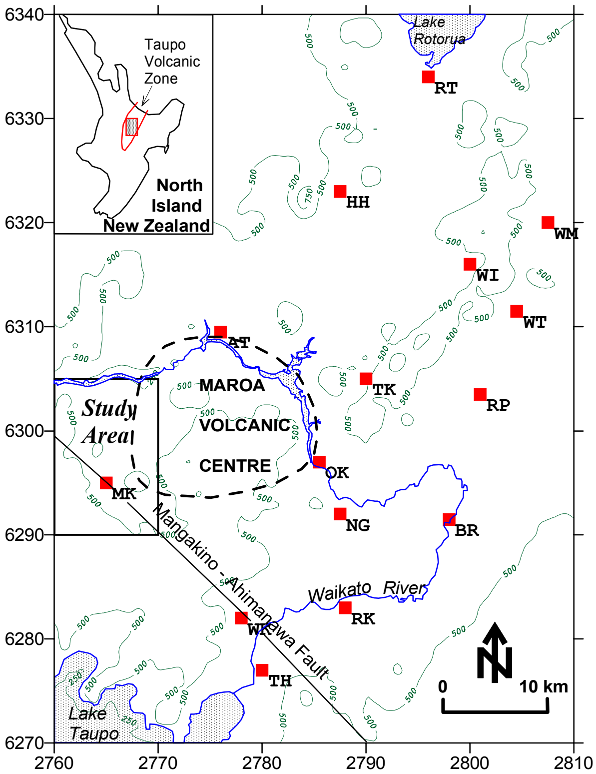

Figure 1. Location map of the study area in the Taupo Volcanic Zone of New Zealand. Geothermal fields are indicated by boxes: TH=Tauhara, WK=Wairakei, MK=Mokai, RK=Rotokawa, BR=Ohaaki-Broadlands, NG=Ngatamariki, OK=Orakeikorako, RP=Reporoa, TK=Te Kopia, AT=Atiamuri, WT=Waiotapu, WI=Waikite, HH=Horohoro, WM=Waimangu, RT=Rotorua. The thin contour lines represent topography (contours-interval = 250 m). The coordinates along the edges of the map are the NZ Map Grid (km).

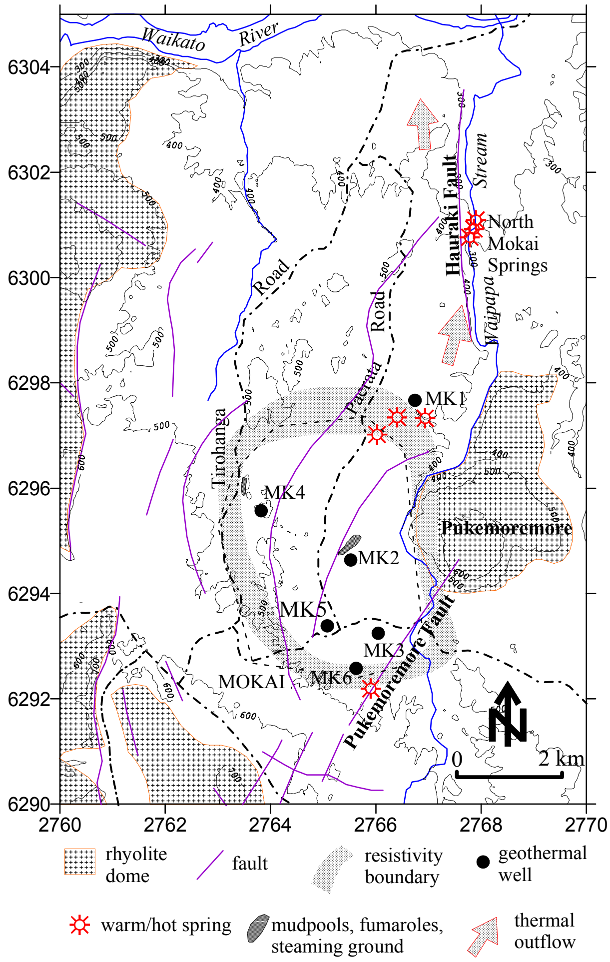

Figure 2. A map of the Mokai area showing its thermal manifestations, geology (simplified from Lloyd, 1978), resistivity boundary (Bibby et al., 1984), and wells MK1-MK6. A model of hydrothermally demagnetised rocks (between 500 m and 1000 m depths) is also shown (broken lined polygon). The thin contour lines represent topography (contours-interval =100 m).

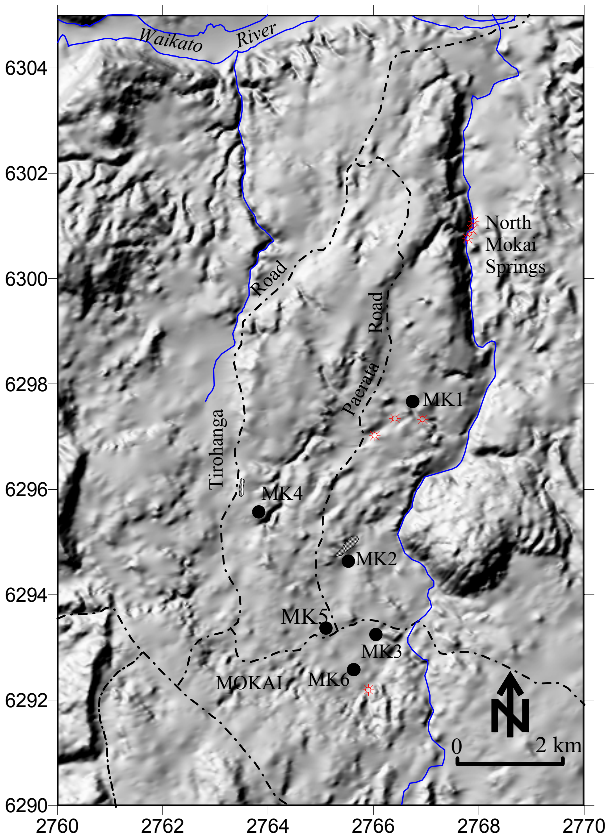

Figure 3. A shaded relief plot of the Mokai area constructed from 25 m grid digital topography data. The apparent 'sun' position is 315° (N45°W) at 45° vertical angle.

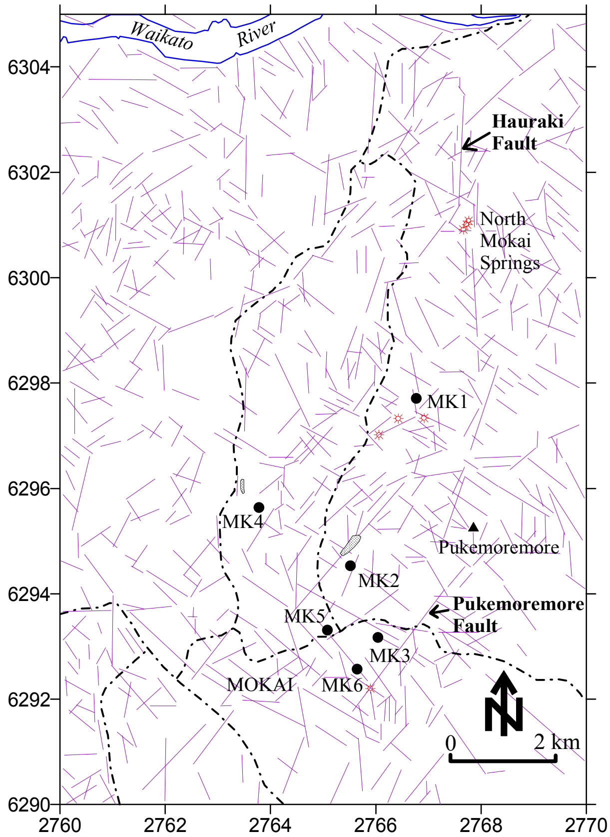

Figure 4. Topographic lineaments in the Mokai area traced from detailed analysis of digital topography.

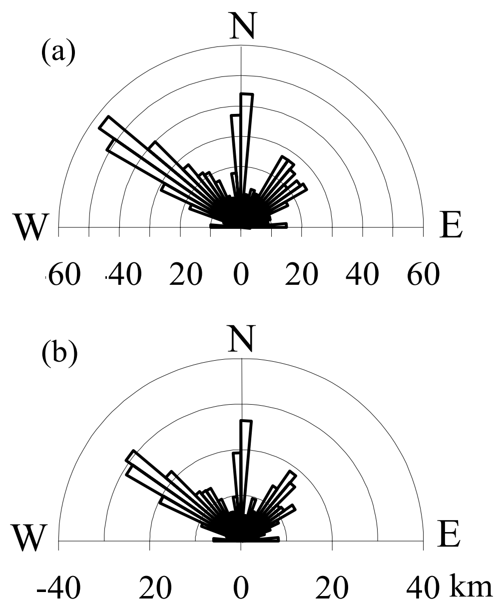

Figure 5. (a) Rosette diagram of the lineaments shown in Fig. 4. (b) Modified rosette diagram of the same lineaments, obtained by plotting total length (km) of lineaments (instead of the number of lineaments).

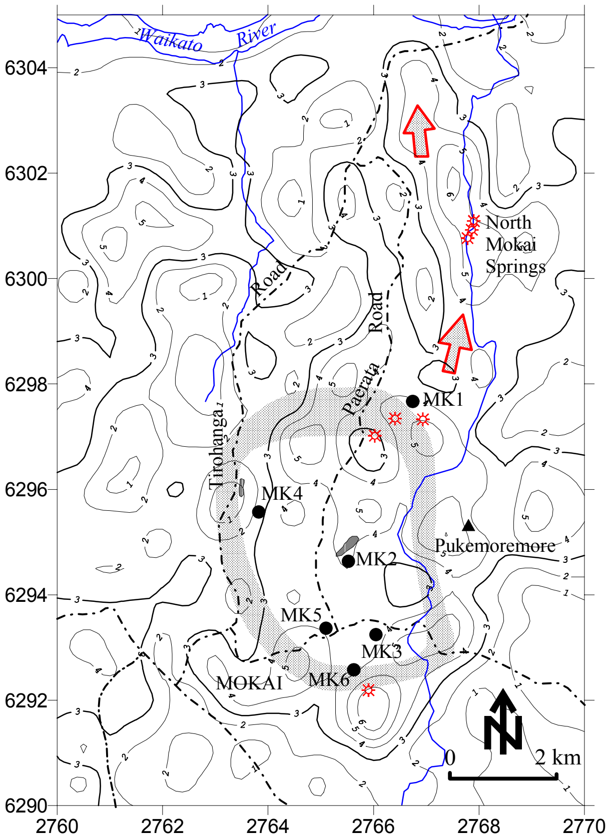

Figure 6. Contours of fault and fracture density (FFD) of the Mokai area. Contour values are in km^{-1} (= km total length of lineaments per km^2 area).

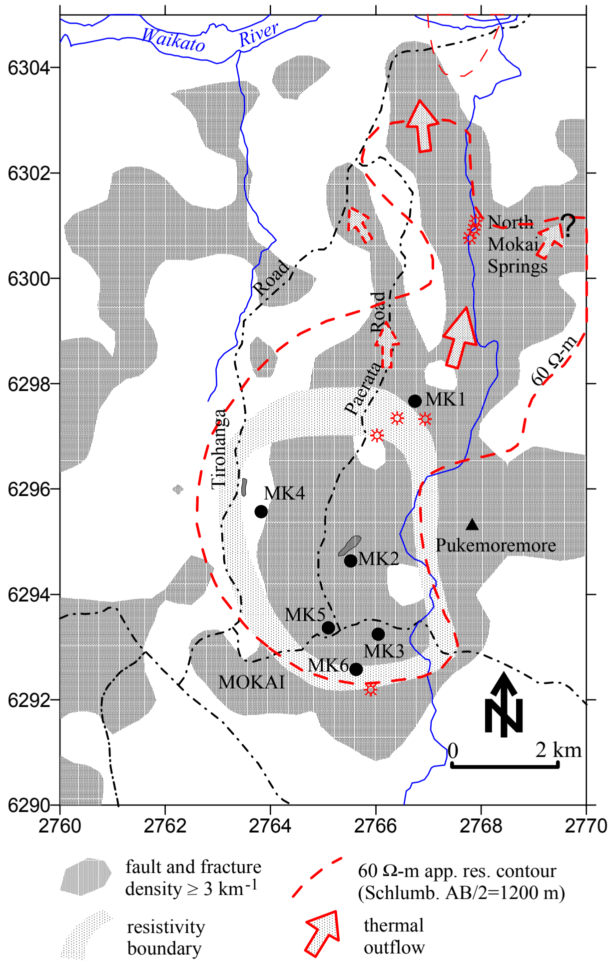

Figure 7. Map of the Mokai area showing the zones of high fault and fracture density, the resistivity boundary, and 60 Ω-m apparent resistivity contour. See text for discussion.