STRUCTURAL SETTING AND GEOMORPHIC FEATURES OF THE ORAKEIKORAKO GEOTHERMAL FIELD, TAUPO VOLCANIC ZONE: A REMOTE SENSING APPROACH

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SUMMARY - A remote sensing analysis of the geomorphology of the Orakeikorako region using aerial photographs and satellite imagery yields results that are similar to those developed in published accounts. Integration of all available geologic information is required in order to interpret and ground-truth the remotely sensed data. A large elliptical structure east of the Waikato River at Orakeikorako and west-northwest faulting may be products of transtensional stresses present in this area of the Taupo Volcanic Zone. The Orakeikorako geothermal field is migrating eastward and/or is in decline based on remote sensing, geological and geophysical data.

1. INTRODUCTION

The purpose of this paper is to present new information about the tectonic and structural setting of the Orakeikorako geothermal field. Methods used in this study are largely based on remote sensing techniques using aerial photographic and satellite data. To provide a comprehensive interpretation, results of remote sensing analyses have been integrated with previous and new field research.

2. THE STUDY AREA

Orakeikorako is situated in the Taupo-Rotorua segment of the Taupo Volcanic Zone (TVZ) on the eastern margin of Maroa Volcanic Centre (Figure 1). approximately 26 km northeast of Taupo.

Geothermal activity at Orakeikorako is closely associated with a series of northeast trending normal faults which splay from the Paeroa fault (Bignall, 1994). Southwest of Te Kopia, the Paeroa Fault bifurcates into the Whakaheke and Matangiwaikato faults, which form the northern and southern boundaries, respectively, of the Orakeikorako geothermal field. Northeast trending faults between the major splay faults are down-thrown to the northwest and diverge toward the southwest. Hydrothermal activity occurs along the bounding faults, and steeply dipping intermediate Golden Fleece, Rainbow, East Wainui, and Emerald faults, and along numerous minor unnamed faults (Bignall, 1994). Lloyd (1972) suggests that heat escapes at the intersections of north trending cross faults with the northeast trending faults.

3. METHODS

3.1 Remotely sensed data

Remotely sensed data used in this study included black and white aerial photographs, Landsat thematic mapper (TM) and Systeme Probatoire de l'Observation de la Terre (SPOT) multispectral (XS). The 1 : 16 000 aerial photographs were acquired in 1963 and 1 : 50 000 in 1997. The Landsat 4 data was recorded on the 25 December 1990 and the SPOT 1 data was collected on 1 September 1989.

The combination of small scale, high spatial resolution photographs, and multispectral satellite images allowed mapping of lineaments and geomorphic features at regional and local scales. This data combined with field observations and previous studies provided an insight to the structural setting and tectonics of the Orakeikorako geothermal field.

3.2 Data processing and image analysis

Environment for Visualising Images (ENVI) version 3 processing software was used to analyse the digital data. Processing was performed on both Silicon Graphics and Digital Alpha 200 UNIX-based work-stations in the Spatial Analysis Facility of the Department of Geography, University of Auckland.

Preliminary lineament and geomorphic maps were manually constructed using stereoscopic photograph pairs. Aerial photograph SN9584/ B14 was scanned and saved as an image file. The photograph and satellite images were georeferenced in ENVI using ground control points from the 1 : 50 000 topographic map (U17). The Landsat image was used as a large scale base map. The black and white 1 : 50 000 aerial photograph SN9584/B14 was used

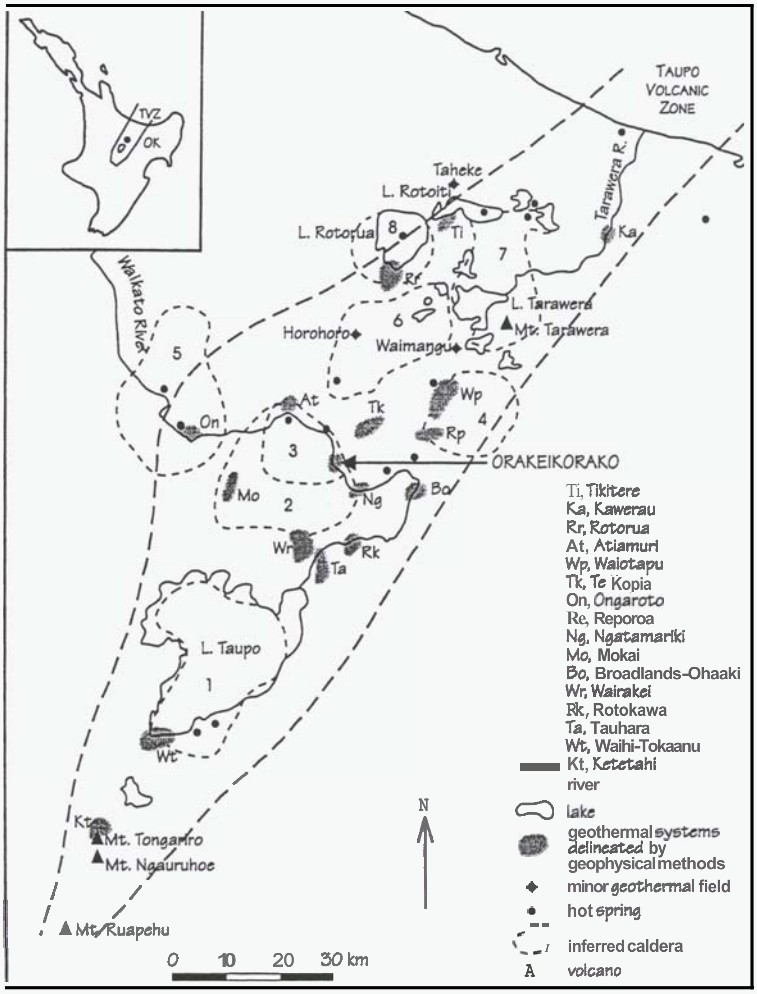


Figure 1. Location map of Orakeikorako geothermal field and other active geothermal areas and volcanic centres within the Taupo Volcanic Zone. Volcanic centres: 1, Taupo; 2, Whakamaru; 3, Maroa; 4, Reporoa; 5, Mangakino; 6, Kapenga; 7, Okataina; 8, Rotorua.

to map geomorphic features at local scale. Lineaments and other topographic structures identified stereoscopically and additional features identified on the image in ENVI (possible due to the very high resolution of the image and the ability to "zoom in" to the photograph) were transferred to a vector overlay covering SN9584/B 14.

Visual analysis and previous studies using Landsat and SPOT images, especially those within the Taupo Volcanic Zone (eg Cochrane et al, 1994), identified Landsat bands 4 and 5 and SPOT band 3 as being useful in lineament analysis. Landsat band 4 in the four principal directions to emphasise more subtle lineaments. Convolution filters are, in effect, directional edge detectors which enhance the visibility of like-digital numbers in the direction of the filter. The decision as to which filter to employ was based on visual result, ease of application and least distortion of original data. Fifty percent of the original image was added back to the filtered image to minimise distortion and ensure that features could still be recognised.

Four maps of predominantly straight lineaments were constructed manually over each of the filtered Landsat band 4 images. These maps were combined to produce a map of total combined lineaments. Cross referencing between convoluted images and maps and/ or aerial photographs is required to ensure features such as roads, fence lines and vegetation boundaries are disregarded.

4. RESULTS AND DISCUSSION

4.1 Geomorphic features

Geomorphic features are the surface expression of a combination of surface processes and/or the underlying geology. For this reason, the geologic origin of such features can rarely be interpreted directly from remotely sensed data. Integration of all available information is required in order to interpret the remotely sensed data. For example, shallow dipping structures, such as thrust faults, are difficult to recognise by the remote sensing methods used in this study. Figures 3 and 4 identify the location of features cited by number in text.

Perceptional problems introduce a bias in interpretation of lineaments. Straight lineaments tend to be more easily recognised than do curved or curvilinear features, yet both m y be geologically important. Straight lineaments are not necessarily faults but may also reflect the geomorphic expression of vertical structures, such as dykes, or fractures or the intersection of straight planar surfaces.

Lineaments within resistant rock masses reflect the inherent structure of the unit and episodes of deformation within the unit. In the vicinity of Orakeikorako, primary forms of deformation appear to be faulting and fractures related to dome formation. Generally, lineaments are not preserved well in weak unconsolidated materials, such as the Taupo Pumice Alluvium (TPA), suggesting that any lineaments are either erosion features or, if there is evidence of an offset, recent faulting.

A map of all observed lineaments with a rose diagram of lineament orientation, and regional and local interpretative maps are given as Figures **2, 3** and **4.**

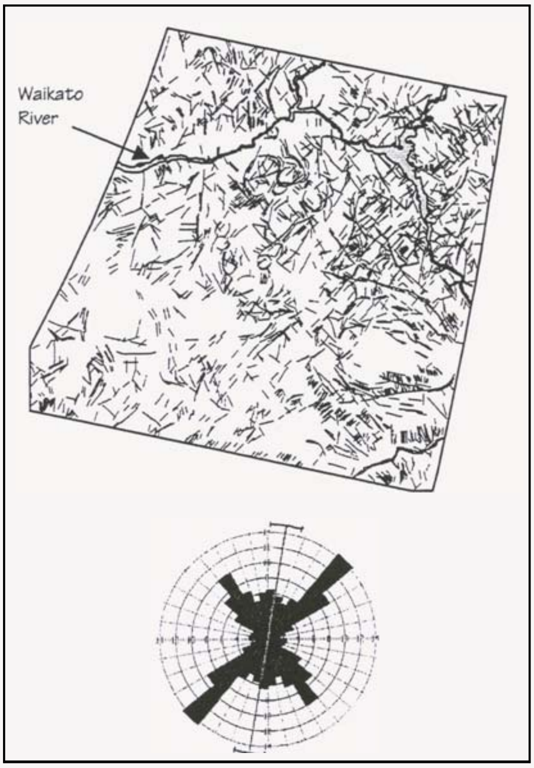


Figure **2.** Map and rose diagram showing location, density and orientation of all lineaments observed in this study by remote methods.

Four geomorphic domains can be recognised based on lineament densities and geomorphic features in Figure **2.** Each domain is related to specific lithologic units and therefore probably reflect their physical properties. ***Domain** 1* consists of a high density orthogonal lineament fabric, and contains Haparangi Rhyolite, Huka Group, Ohakuri Group and Paeroa Ignimbrite. At Orakeikorako, lineaments are also observed in the TPA. ***Domain* 2,** comprises areas with less densely spaced lineaments which mainly coincide with Haparangi Rhyolitic Pumice and Mokai Ignimbrite. *Domain* **3** consists of a cluster of highly elliptical features which coincide with topographic highs and are the surface expression of domes of Haparangi Rhyolite, as mapped by numerous authors, including Grindley **(1960),** and Healy et al **(1964).** Less regular forms are not as easily identified by remote methods. All domes within the Landsat image are cut by at least one set of lineaments and/or faults, indicating fault movement since formation of specific domes. It is assumed that lineaments with no apparent vertical or lateral offset represent fracture patterns within the Haparangi Rhyolite. *Domain 4* is characterised by patches and corridors largely devoid of lineaments and are closely associated with areas of **TPA** as mapped by Grindley **(1960)** and Healy et **al (1964).**

Concentric features **(40)** on the southeastern edge of Tutukau Dome (8) are consistent with flow or pressure ridge features formed when the lava was mobile, or possibly developed during cooling. Paterson et **al (1983)** describe a similar pattern for concentric ribs of indurated Haparangi Rhyolite separated by zones of unconsolidated rhyolitic breccia at Aratiatia. Refer to Figures **3** and **4** for location of numbered features.

4.2 Slope Movement

Evidence of slope movement include arcuate to semi-circular scarps, hummocky ground, sink holes and dry channels. Arcuate to circular scarps may have been formed by either slope failure or hydrothermal eruption. Lagoon (44), River **(45)** and Matangiwaikato **(46)** hydrothermal eruption craters (Figure **4)** were mapped by Lloyd **(1972).** Further field investigation is required to confirm the origin of similar features, such as arcuate features and a deposit **(43)** on the western side of the field. There is. little evidence of pre-TPA slope movement.

Lobes of debris commonly associated with mass movement are not prominent at Orakeikorako as any debris would be rapidly eroded **and** removed by the river.

Pipe, tunnel and gully erosion are responsible for the development of the hummocky nature of surfaces mantled by the TPA, rather than mass movement. Sink holes and a scarp above the head of a minor stream west of, and adjacent to the Umukuri fault are the result of pipe erosion in the TPA. Immediately east of the Umukuri Fault, dry channels in the TPA indicate a changed base level, perhaps from faulting, with the dry channels positioned on the upthrown side. Due to the nature of the TPA these channels may well have been formed by rapid erosion. Similarly, **2** m to **3** m deep gullies formed in the **TPA** on farmland near the intersection of Whakapapa and Tutukau roads probably formed during storm events.

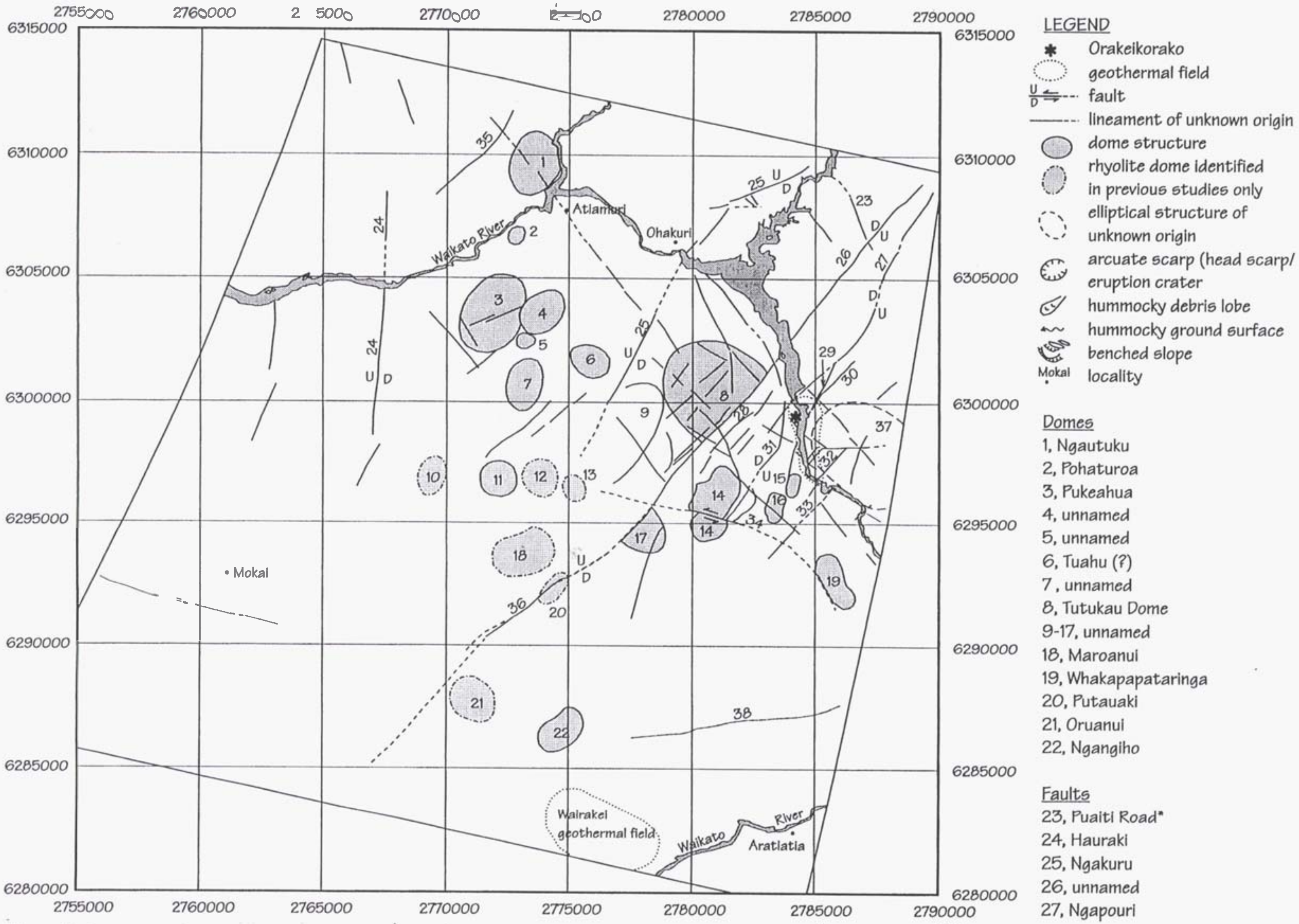
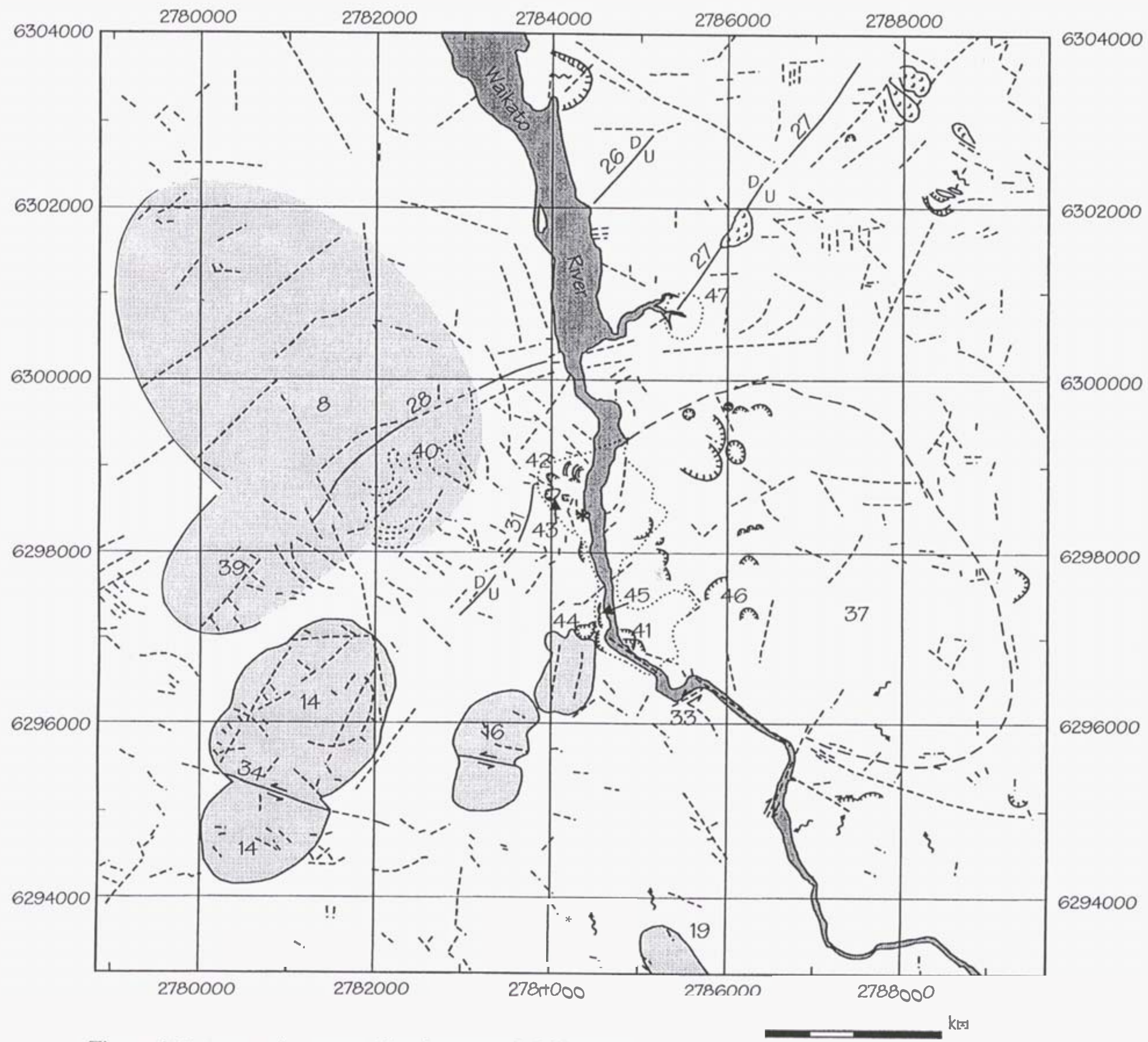


Figure 3. Interpretative map of regional geomorphic features



FAULTS CONTINUED
28, Whakaheke
29, Rainbow
30, Golden Fleece
31, Umukuri
32, Matangiwaikato
33, unnamed
34, Tutukau *
35, unnamed
36, Whangamata

Miscellaneous
37, elliptical structure
38, contact between Haparangi Rhyolite Pumice and Orakonui Formation
39, lobate structure (lava flow?)
40, lava flow structures?
41, Red Hill
42, western springs and mud pots
43, breccia number eleven?
44, Lagoon Crater
45, River Crater
46, Matangiwaikato Crater
47, Waihunuhunu hot springs
(* new name)

Figure 4. Interpretative map of local geomorphic features

4.3 Present structural and tectonic setting

The results show that the structure of the region is dominated by an orthogonal fabric with a strong north-northwest to northwest component that is not shown on existing maps. In some areas the regional pattern appears dissected by lesser cross-cutting faults of varying orientation.
Most lineaments are short; no lineament could be traced continuously for the length of faults shown on published maps, such as Grindley **(1960)** and Healy et al **(1964),** including the Paeroa and Umukuri **(31)** faults. This could be in part due to the local scale of this study compared with the regional scale and interpretation of published maps or because evidence of faulting in the field may not be readily identified in the remotely sensed data. However, it is likely that the faults are segmented, possibly ***en echelon*** and far more complex than indicated on published maps.

Faulting along the course of the Waikato River has not been addressed in previous studies. The river does not appear to be controlled by the strength of the varying lithologies that it cuts through. Northwest to west-northwest faults may control the course of the river directly south of Orakeikorako.

The Hauraki Fault **(26),** where it crosses the Waikato River, has been mapped as a concealed fault by Healy et al **(1964).** However, the fault is quite evident on the Landsat image and its status as a concealed fault needs re-assessment. The strong lineament **38** can be identified as the boundary between Haparangi Rhyolite and Orakonui Formation. Very short lineaments at the bottom right comer of Figure **2** appear related to fall-line erosion, such as gully or incipient gully, overland flow or through-flow features, controlled by the dip-slope direction rather than fractures. These features exemplify the need for the integration of remote sensing methods with field work.

Cross-cutting relationships between faults and between domes and faults indicate the timing of events. Sinistral and/or vertical movement on the Tutukau Fault **(34)** has occurred since the formation of dome **14.** However, Whakaheke Fault **(28)** which intersects Tutukau Fault, shows no evidence of lateral offset. The duration of movement on the Tutukau Fault is therefore constrained to post-dating the formation of the dome and before movement on the Whakaheke Fault.

Parson and Wright **(1996)** state that "pervasive extensional tectonism within the TVZ is largely accommodated by laterally discontinuous northeast trending normal faults with an ***en echelon*** fabric", forming the Taupo Fault Belt and Whakatane Graben. Northeast of Taupo, Cole **(1990)** reported shear strain measurements of $1.1 \pm 0.02 \times 10^{-6}$ rad/yr with extension at an azimuth of **167° ± 10"** and right lateral shear at **034" ± 10°,** indicating both extension dextral shear in an area that would include Orakeikorako. An ***en echelon*** fabric in this study area would account for the segmented nature of major faults in the area, as well as the presence of orthogonal faults. Figure 5 (a) and (b) schematically indicates structures and their orientation which may form as a result of the tectonic environment as described by Cole **(1990).**

The large elliptical structure **(37)** does not figure on existing maps of the area. It is apparent in band **2** of the SPOT image. The origin of the structure and the orientation of the Tutukau Fault may be explained by stresses outlined by Cole **(1990)** and indicated in Figure **5.** It is proposed here that the elliptical structure **(37)** is a basin in which Huka Group materials have ponded; the Huka Group unit increases in thickness in drill holes OK **2** to **OK 4,** in the south (Bignall, **1994).** If this interpretation is correct, the basin may be either a pull-apart basin formed by ***en echelon*** dextral fault overlap (Figure 5a), or a compressional basin (Figure 5b).

Alternatively, the elliptical structure may be a dome that has either been buried by younger volcaniclastic deposits, or is ascending and hence may be providing heat for the Orakeikorako field. To date, little field evidence exists to confii either theory. Resistivity and aeromagnetic data were collected over the Orakeikorako geothermal field by DSIR (in Bignall, **1994)** and Soengkono **(1993).** Active or extinct geothermal fields are usually associated with a negative magnetic anomaly and low resistivity anomaly. The Orakeikorako geothermal field shows both anomalies, but lowest resistivity **(10 Ω-m)** is located toward the centre of the ellipse, while the area of lowest magnetism occurs at the northern boundary of the ellipse. This variation may be the result of different depths of penetration by the methods used or due to uncertainty in the contouring of the geophysical data.

4.4 Geobotany

Geobotanical characteristics of the Orakeikorako field can be identified on the satellite data and are confirmed in the field. Geothermally stressed plant assemblages and habits have been well documented within the TVZ, such as at Waiotapu (Merton, **1992)** and Craters of the Moon (Deroin et al **(1995).** Plant communities become stratified around geothermally affected ground with only tolerant species surviving in the less than hospitable substrate. Characteristics of thermally stressed vegetation include zonation, prostrate habit (especially evident in kanuka), and greatly reduced biodiversity. Examples at Orakeikorako are found around Kurapai and Ellan Vannin, Red Hill, and a hillside just north **of** the tourist area. All the areas of stressed vegetation occur on the eastern side of the field. These areas are also

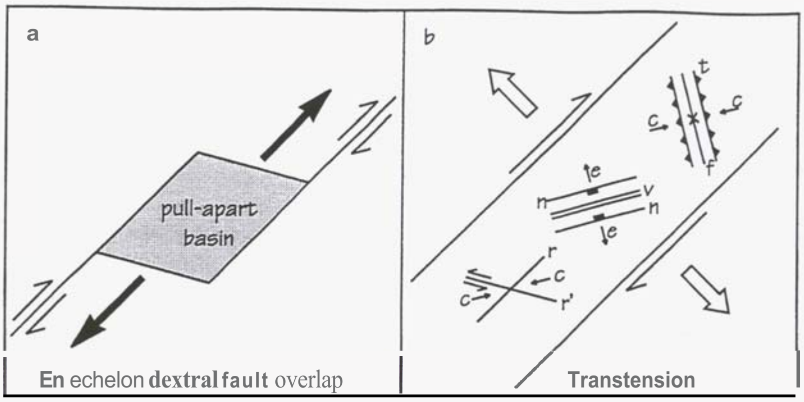


Figure 5a. Schematic representation of a pull-apart depressionformed by offset along en *echelon* strike-slip faults. 5b. Diagrammatic representation of orientation patterns of fault and fold axes during transtension. c, compression axis; e, extension *axis;* **f, fold** axis; **n, normal faults; r, Riedel shears or strike-slip faults; t, thrust faults; v, veins, dikes or extensional features. (modified from Cole, 1990)**

affected by slope movement and are at higher elevations than features surrounded by non-stressed vegetation.

However, non-stressed vegetation is evident throughout the geothermal field and has been observed overhanging hot pools, mud pots and near boiling, acidic springs. The close proximity of non-stressed vegetation to geothermally affected ground requires steep lateral temperature and/ or chemical gradients. These gradients could be caused by a low permeability substrate which acts as insulator around the fluid conduit. There does not appear to be a direct correlation between lithology and the proximity and type of vegetation at Orakeikorako. Although, variable permeability may be caused by discrete imperrneable lenses within lithological units.

The stability of specific geysers, mud pots and springs also affects the proximity of non-stressed vegetation. In areas of non-stressed vegetation, there is little evidence that overhanging vegetation is affected by intermittent eruption of a mud pot or geysering of a spring, although most of the springs and mud pots in question have been active for several decades. Therefore, it is suggested that these features are either stable or in slow decline and that the presence and absence of characteristic plant communities in different areas within the Orakeikorako geothermal field may be directly related to the stability of specific features.

Fumaroles, mud pools, acid springs and alkali pools associated with non-stressed vegetation are produced by fluid ascending in relatively large conduits resulting in more stable features (less likely to be closed by precipitation of silica, for example). Pressure and temperature, fluid velocity and size of the feature remain relatively constant, and vegetation can establish. Conversely, features associated with stressed vegetation are less stable. In this case fluid would ascend through smaller conduits which are more rapidly obstructed, causing some features to become dormant. This may ultimately lead to the formation of new thermal features andor, in extreme circumstances, a hydrothermal eruption. Possible examples of this process could be the area around Kurapai and Ellan Vannin, and the steaming hillside to the north of the tourist area. Progressive sealing of smaller fault zones may be causing east to northeast migration of the active field Figure *6).*

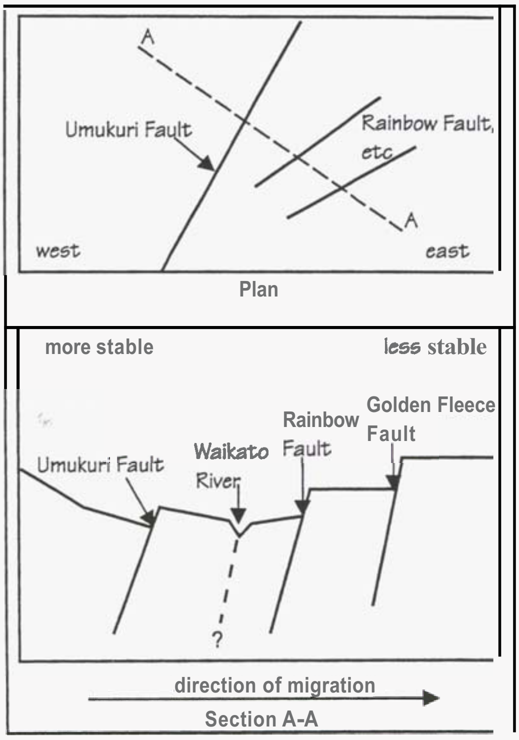


Figure **6.** Schematic representation **of migration of** the Orakeikorako **geothermal** field.

4.5 Migration and/or decline of Orakeikorako

Cold sinter outcrops along the Umukuri Fault west of current activity suggest that the focus of thermal activity at Orakeikorako is either migrating or in decline. The hypothesis that the field is migrating is supported by the distribution of thermally stressed vegetation and lack of volatile features in the western side of the field. The orientation of the magnetic anomaly associated with Orakeikorako is also consistent with an east to northeast migration of geothemal activity.

5. CONCLUSIONS

1. Remote sensing analysis is invaluable in studying a large geothemal area but needs to be interpreted in the light of field studies.
2. Several of the geomorphic structures identified in this study are consistent with, and may have arisen from, the transtensional tectonic setting described by Cole **(1990);**
3. The landscape around Orakeikorako can be segregated into four geomorphic domains that are closely related to the underlying geology;
4. Several lines of evidence indicate that the Orakeikorako geothermal field is migrating northeastward and/or is in decline.

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