STRUCTURAL SETTING OF NGAWHA GEOTHERMAL SYSTEM, NORTH ISLAND, NEW ZEALAND

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SUMMARY - Drillhole information and inter-pretation of gravity data, aerial photographs and satellite images show that the Ngawha Geothermal Field and the area nearby consists of a series of faulted blocks of different sizes. The locations of the volcanism and a possible intrusion, as well as the hydrology of the Ngawha system, are controlled by the geometry of the fault blocks.

INTRODUCTION

The Ngawha geothermal system is located within the north central area of the virtually aseismic Northland Peninsula (Figure 1) and is the only known, active high temperature system outside the Taupo Volcanic Zone. The geology of Ngawha and its environs comprises about a 500 m thickness of Cretaceous-Tertiary age sedimentary rocks of marine origin which are underlain by Permian-Jurassic metasediments (Kear and Hay, 1961; Thompson, 1961; Skinner, 1981; Isaac and Grieve, 1989). These older metamorphosed rocks (Waipapa Group), primarily greywacke and argillite, form the basement of Northland and outcrop along the east coast. Ngawha is located within a basaltic volcanic field of Quaternary age and the thermal area is itself partly surrounded by lava flows and cinder cones.

Due to its isolation from other active hydrothermal features in New Zealand, the broader geological setting of Ngawha is important not only because of its heat source, but also because of structural features that produced conditions that enabled the system to develop where it has.

GEOLOGICAL CHARACTERISTICS OF NGAWHA

Basement Rocks: The basement Waipapa Group rocks comprise a succession of quartzo-feldspathic greywackes and argillites that have experienced prehnite-pumpellyite grade metamorphism, probably to temperatures of ~350°C (Thompson, 1961; Mayer, 1968; Black, 1989). Drillcores from Ngawha and exposures show gradation between these rock types, and beds range in thickness from tens of centimetres to metres. In appearance the rocks are typically dark grey-green, highly indurated fine-grained rocks, cut by numerous narrow veins containing quartz, calcite, chlorite and pumpellyite. These metasediments are exposed from 15 km east of Ngawha to the coast (Figure 1) and their surface dips gently westward. At Ngawha, the top of the basement has been shown by drilling to be at depths from 220 to 500 below sea level (Bowen and Skinner, 1972; Skinner, 1981; Browne, 1981; Cox, 1985). Deep petroleum drilling in the Waimamaku Valley near the west coast, 45 km from Ngawha, indicates that the basement rocks are here deeper than 3352 m, the maximum depth drilled (Hornibrook et al., 1976).

Overlying Rocks: In the mid-Northland area, late Cretaceous-Tertiary age sedimentary rocks of largely marine origin cover extensive areas of the basement (Figure 1) and unconformably overlie the Waipapa Group rocks. The younger rocks form a chaotic "megabreccia", probably deposited in the Miocene, and their internal disorder suggests this sedimentary mass has experienced tectonically induced slumping and transport (Spörli and Kear, 1989). These sedimentary units have a low bulk

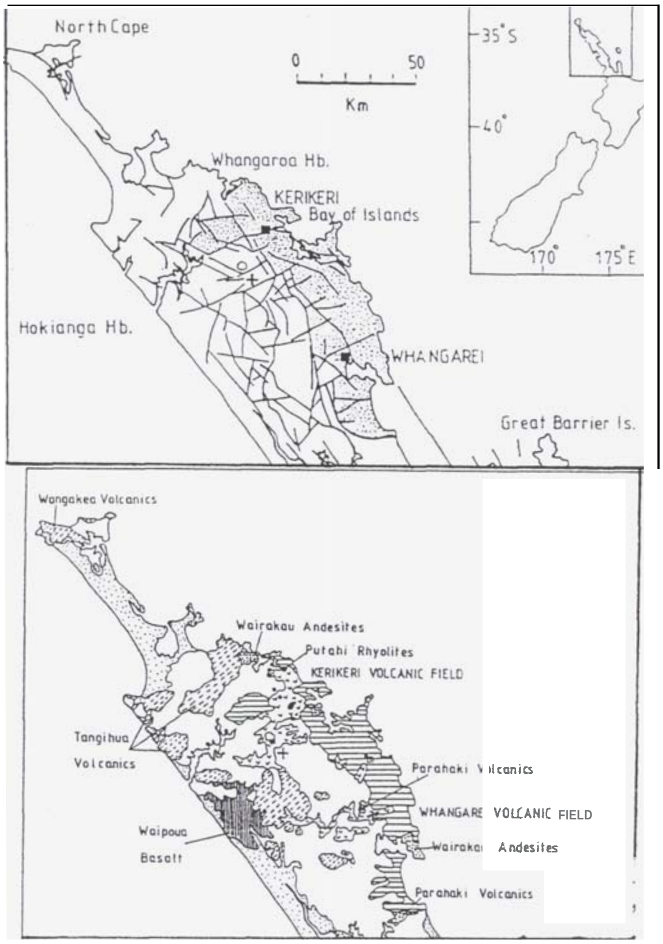


Figure 1. Top: Composite map showing major faults in Northland. Shaded area is relatively uplifted Permian-Jurassic Waipapa Group basement. The location of Ngawha central to the Northland Peninsula is shown by "+". Bottom: Geological summary map of Northland. The white areas are outcrops of the Cretaceous-Tertiary sedimentary rocks; the Quaternary basalts surrounding Ngawha are also shown.

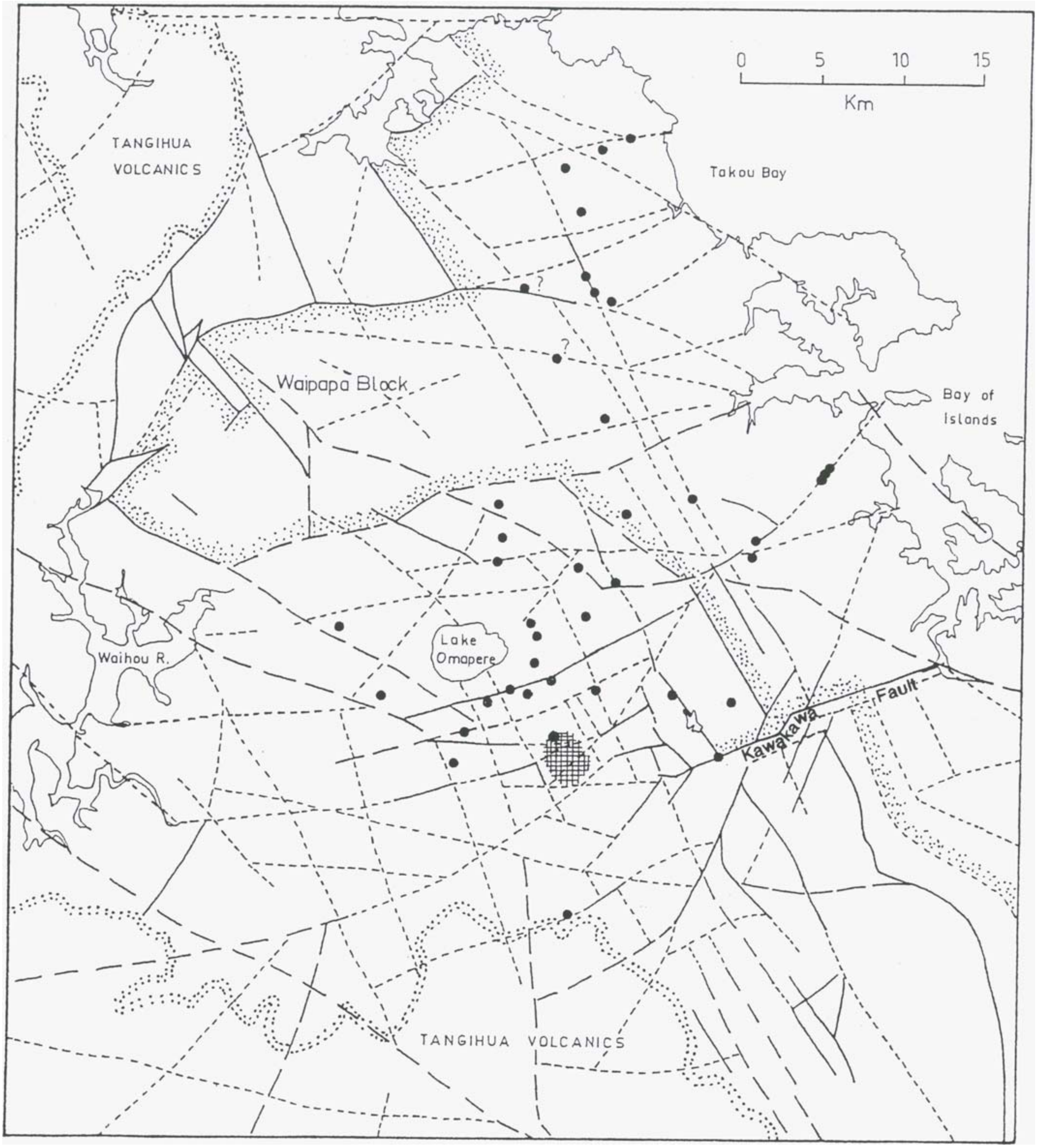


Figure 2. Fault-lineament map of the area around Ngawha. Solid lines are mapped faults (Kear and Hay, 1961; Thompson, 1961; Skinner, 1981), heavy broken lines are Landsat lineaments (Skinner and Grindley, 1980), fine broken lines are lineaments derived from air photographs and drainage-topography patterns. Solid circles represent volcanic centres; Ngawha is shaded and dotted outlines show outcropping Waipapa Group rocks and Tangihua Volcanics.

permeability due to their fine-grained nature and high clay contents. They therefore act as an aquitard to the geothermal system, which is largely hosted within the basement rocks. There is some low level horizontal permeability within the overlying rocks (Cox, 1985), and their vertical permeability is also low except along faults. Faults and other lineaments occur in the area, including Ngawha itself, but any permeability they initially possessed has been short-lived due to deposition of secondary minerals. There are NE-alignments to the zones of surface thermal activity (Fleming, 1945), which primarily reflect aquitard permeability. However, zones of higher permeability extend into the basement, as is indicated in the central thermal zone where deep waters leak to the surface in diluted form (Figure 2).

The surficial basalt lava flows at Ngawha and in the surrounding region (Kerikeri Volcanic Field) are discussed elsewhere (e.g. Heming, 1980; Cox, 1984) but their petrochemistry and age relations also indicate that the

Ngawha system and the youngest volcanism are located within a large fault-bound structural block. Basaltic eruption centres and flows surround the geothermal area on three sides and in the north may mask areas of gas discharge. Five kilometres north west of Ngawha is the Te Pua andesite and the Putahi rhyolite dome, with basalt flows both east and west of them.

Regional structure of Northland

In the Northland area, large scale faults are, in many places, associated with geomorphological features (Figures 1 and 2), for example, on the margins of uplifted basement blocks and some coastal features. Also important are sets of transverse faults, mainly striking ENE and NNW, but also NW. Faults at different magnitudes are important, not only with respect to surface morphology, but also in their relationship to the location of volcanic centres, small intrusive bodies and hydrothermal systems.

A composite fault map of Northland (Figure 2) demonstrates the apparent spatial association of the volcanic centres with the intersections of major regional structures, especially those on which significant vertical movement has taken place. Although the high susceptibility of the Cretaceous-Tertiary sediments to weathering makes structural interpretation difficult, fault crush zones influence drainage and physiography and show as well-defined lineaments on satellite images and aerial photographs (Skinner and Grindley, 1980). Further, in most cases the patterns of the drainage are controlled by the locations of faults.

INTERPRETATION AND COMMENTS

Fault-Lineament map of the region surrounding Ngawha

The apparent association of volcanism with patterns of major faulting indicates control on the location of volcanoes by preexisting faults (?late Oligocene-Miocene) that penetrate deep within the basement metasediments. It is postulated that sets of such structures form a tensional environment and have produced zones of crustal weakness allowing magma to ascend to form centres of Quaternary volcanism. In Northland, Quaternary volcanism is generally associated with areas of uplifted basement (Thompson, 1961).

Broad scale structural trends can be identified (Figure 2); however, some limitations on recognising lineaments and interpreting them as faults are:

(a) lineaments within the Cretaceous-Tertiary sediments may be surficial (e.g. due to folds, slumps or shear) and therefore not reflect basement faults. Some basement faults in the Ngawha area are, however, active and penetrate this overlying cover (High, 1982), notably at the boundaries of the geothermal system.

(b) lineaments in basalt flows may be unrelated to deep faults, or may reflect structures present in the sedimentary cover. In some cases the form of a flow reflects pre-older structures, but some faults do cut the basalt flows.

(c) lineaments within the adjacent Tangihua volcanic masses (Cretaceous-(?)Tertiary, and largely basaltic) are unlikely to be produced by basement faults (Spörli and Kear, 1989).

(d) contacts between different sedimentary lithologies are not necessarily faults.

This composite map shows several features. Dominant trends are the ENE and NNW faults bounding the exposed basement blocks, and various sets of lineaments parallel to them. These trends appear to be those of older fault systems within the basement. Secondary trends imposed on them strike NW and NE, and are probably younger.

Structural Patterns in the Basement Rocks

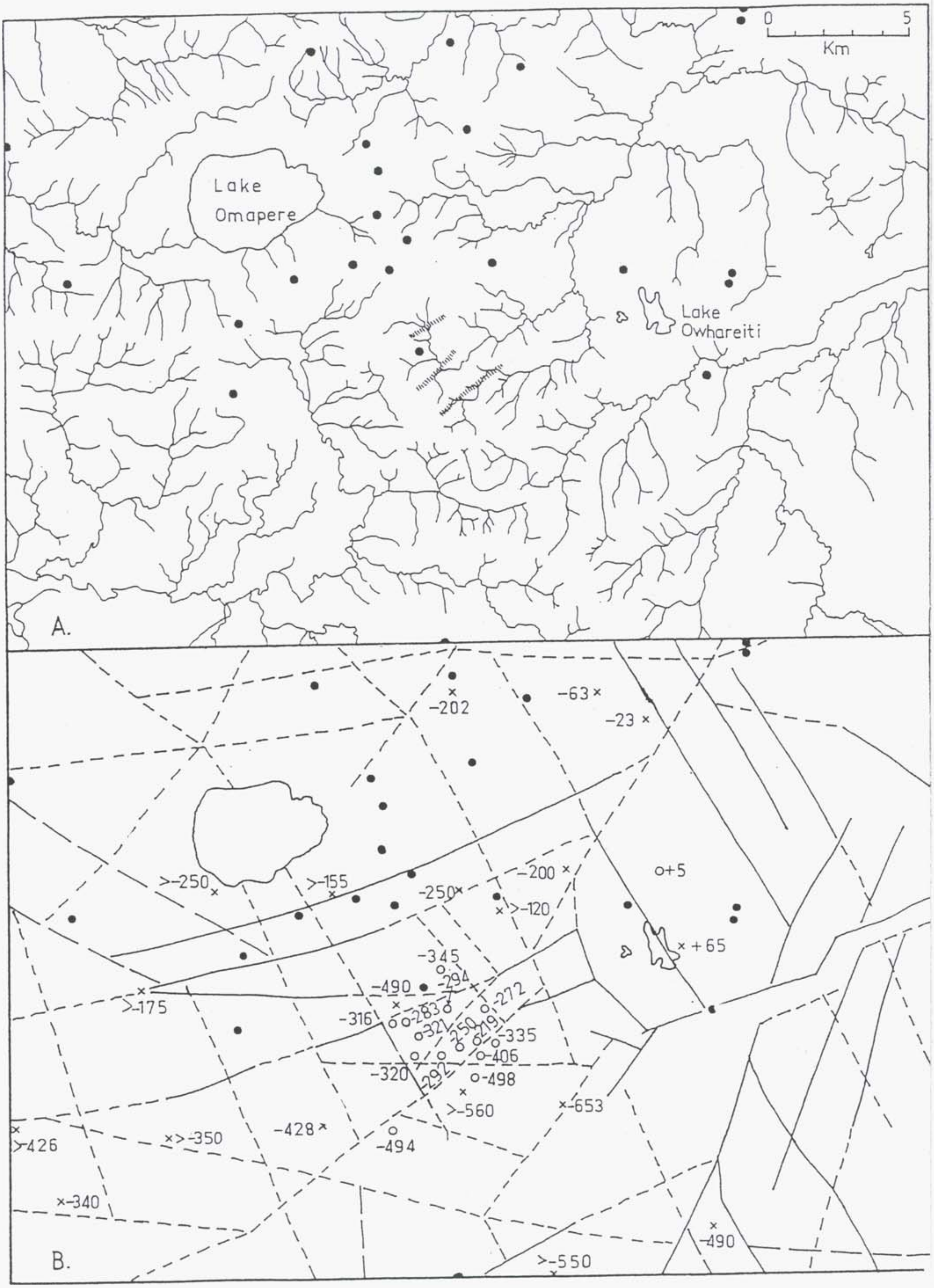
One of the major structural features in this part of Northland is the ENE-trending Kawakawa Fault system which passes 2 km south of the Ngawha thermal area itself, and which has an observed downthrow on its southern side of at least 200 m (Ferrar, 1925). This system appears to have a component of right lateral slip (Hay, 1960) and forms an obvious scarp. The location of the western end of the ENE-trending faults belonging to the Kawakawa Fault system is not known; however, it does extend further west than Ngawha

An outcome of this study is the recognition of a structure comprised of a fault block 20 km wide (N-S) and bounded by parallel ENE-trending faults. The Kawakawa Fault defines the southern boundary, and its northern boundary is the southern edge of the uplifted basement of the Waipapa Block (Figures 1 and 2). This fault block extends eastward to the coast and probably offshore for at least 10 km. Not only does the Ngawha geothermal system occur within this large block but so also does virtually all the Quaternary volcanism.

Lineament patterns also suggest that Ngawha is located at the loci of the main sets of different structural trends. Fault interpretation from air photographs covering the Ngawha basin (Grindley, 1981) additionally suggests that the Ngawha block has been the centre of more intense tectonism than has the surrounding area. Kear (1964) suggested that regional volcanic alignments in Northland implied a relation between volcanism and structure, with major fractures parallel to the main structural trends, acting as conduits for magma that ascends into shallower, subordinate fault systems. The plumbing patterns of the latter systems then determine the observed volcanic centre alignments. The conclusion here is that although faults determine the locations of volcanic centres, the dominant control is by deep faulted blocks, formed by sets of transverse faults.

Depth to Basement Model

Several models representing or showing the depths to the Waipapa basement rocks at Ngawha and in the surrounding region have been produced (e.g. Skinner, 1981; Suprijadi, 1981; Isaac and Grieve, 1989). The approach in our study is summarised in Figure 3,B. The locations of faults (strictly lineaments) and depths to basement relative to sea level are given. Basement depth information is data from geothermal wells (Figure 4), and interpretation of resistivity soundings (Macdonald, 1981; Senor, 1981; W.J.P. Macdonald, pers. comm., 1984).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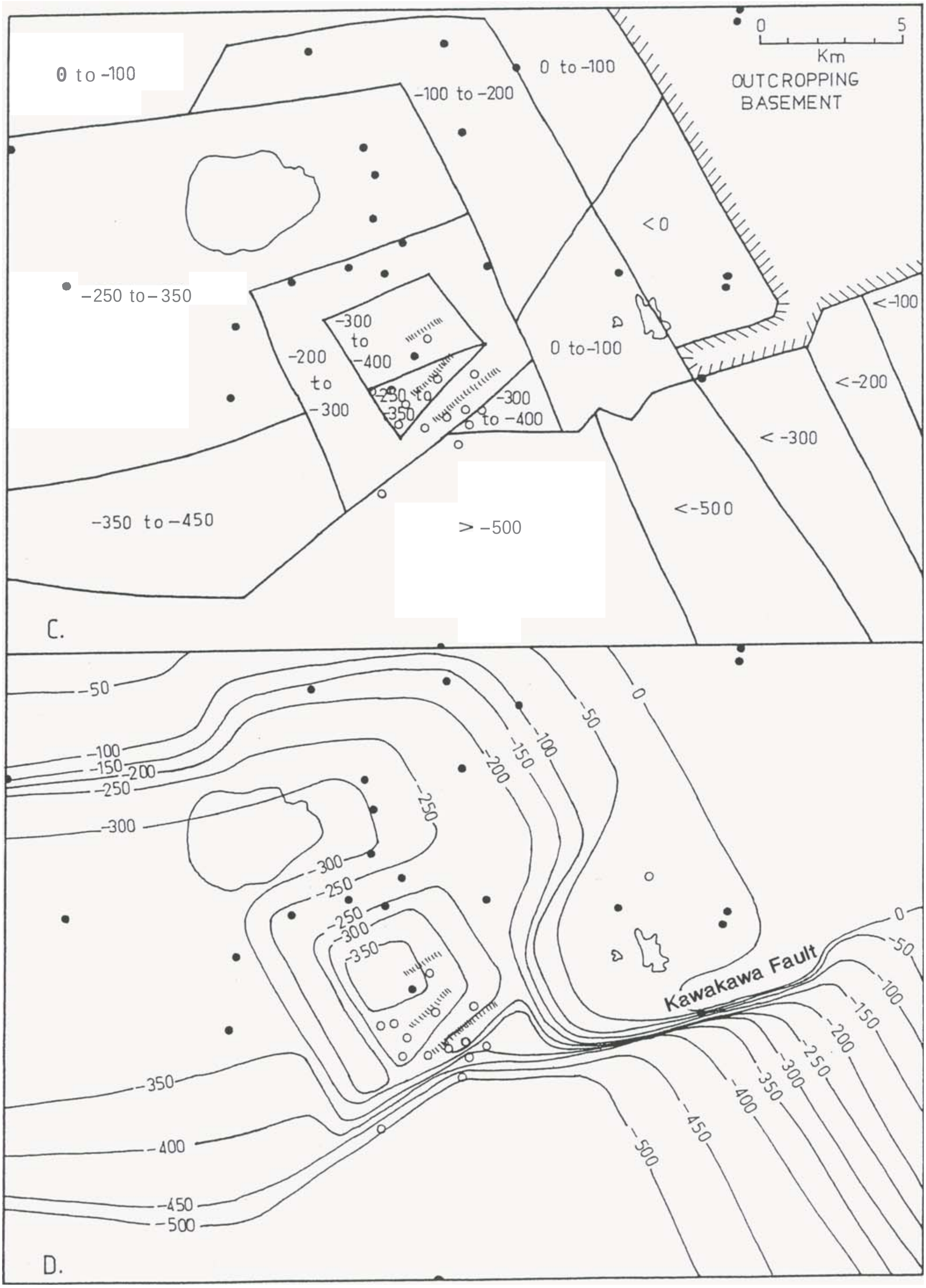
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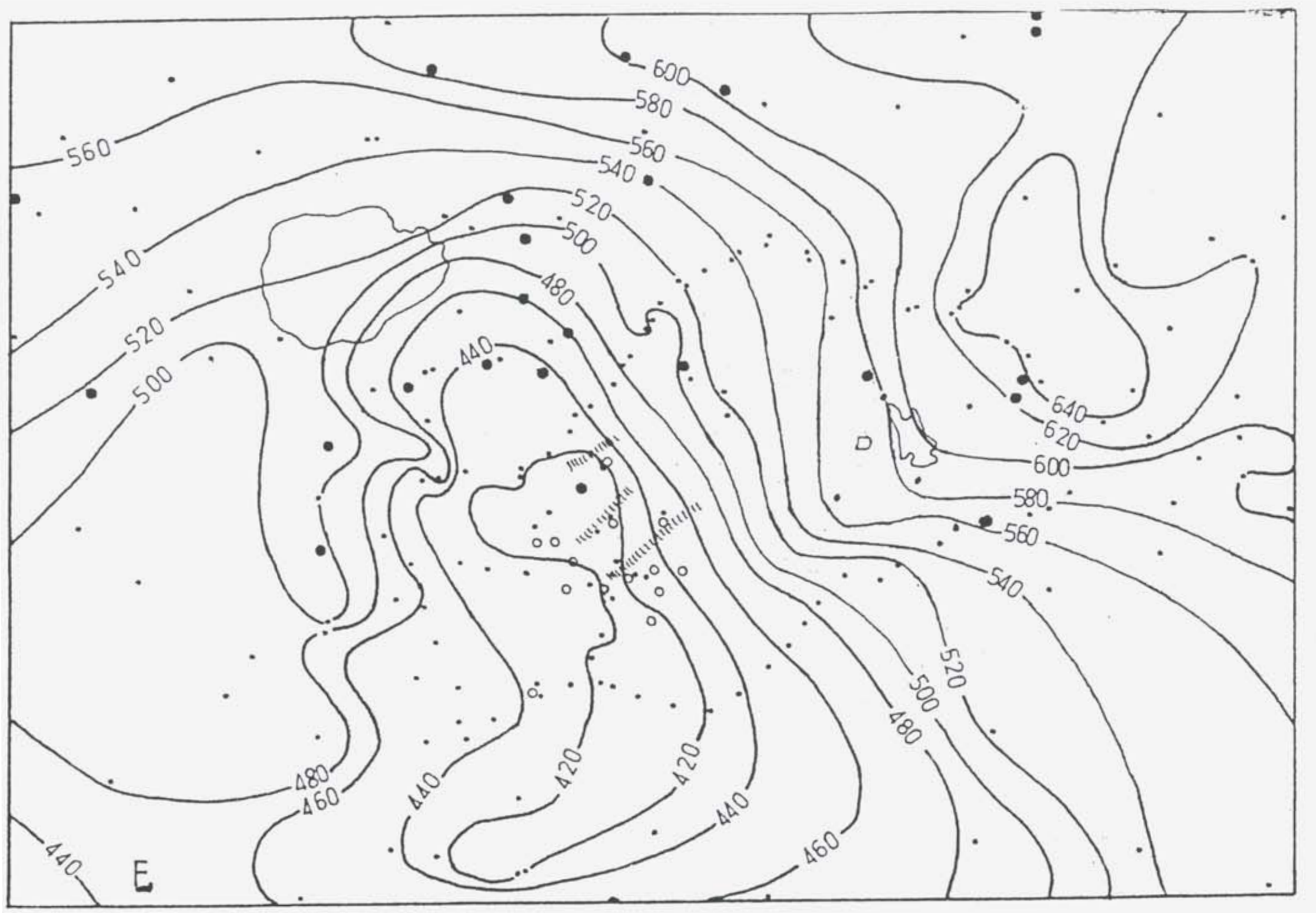

Figure 3. Modelling of basement structure, Ngawha region (depth in metres). **A.** Drainage system with main lakes. Volcanic centres are solid circles, and the three NE-trending surface thermal zones at Ngawha are also shown. **B.** Fault-lineament map: unbroken lines are faults (Skinner, 1981); heavy broken lines are Landsat lineaments (Skinner and Grindley, 1980); fine broken lines are lineaments based on drainage-topography patterns. Open circles are drillholes, with depth to basement (relative to m RSL); crosses are electrical soundings with depth to basement. **C.** Depth to basement surface based on simplified model of main fault blocks. Open circles are geothermal wells. **D.** Contour map of basement surface, from fault block model and drillhole data; contour interval is 50 m. **E.** Contour map showing composite gravity measurements (μN/kg); stations are shown as small dots. Contour interval is 20 μN/kg.

The drillholes are restricted to an area of only ~4 x 5 km in the drilled field and one coal exploration hole (Isaac and Grieve, 1989) 8 km to the east. The geothermal drillhole data show that the basement surface (Figure 4) is shallowest near Ng20 (–219 m). North east of this it dips at about 5°, being at an elevation of –345 m at Ng5. However, the surface dips more steeply (~10°) to the south and was reached at -498 m in drillhole Ng11. The resistivity sounding data cover a much wider area (Figure 3,B). Utilising the fault interpretations, depth to basement and outcrop information available (Figure 3,B) the basement surface can be interpreted as a series of fault blocks (Figure 3,C). A smoother representation of the basement surface, produced by contouring the fault block model, is also shown (Figure 3,D).

The features of the model (Figures 3,C and D) are:

(a) basement outcrops in the north east;

(b) downthrown basement south of the Kawakawa Fault with its surface tilted to the south west;

(c) fault block segments within the main Ngawha structural block are progressively deeper to the west;

(d) the Ngawha geothermal system is associated with smaller, downthrown blocks, with minor displacements whose southern margin is the Kawakawa Fault:

(e) a NE-trending fault system, on which vertical displacement has occurred, intersects the geothermal system;

(f) relatively uplifted basement occurs below, and to the west of Lake Owhareiti;

(g) there is an indication of a NNW-trending fault west of Ngawha. This probably forms the western boundary to the geothermal system.

Gravity Survey of Area Around Ngawha

Bouguer gravity data available from previous surveys were combined and replotted to produce a revised gravity map (Fig. 3,E) of the area to compare with the basement models. These surveys consist of regional (Reilly, 1965) and local gravity mapping (Cordon and Hochstein, 1979; Suprijadi, 1981). The spacings of the gravity measurements (Figure 3,E) are typically between 1 and 2 km, but are as close as 200-500 m in some places.

The most obvious feature of the gravity is the central low decreasing westward, from around 620 to 480 μN/kg. This corresponds to a regional gradient of approximately -5 μN/kg per kilometre. Various interpretations have been placed on the results of the different gravity surveys noted above, one of particular interest being that of Suprijadi (1981), who produced a 2-dimensional model of a low density silicic intrusion at a depth of –2 km and a 3-dimensional model with an intrusion at a depth of –1 km. Using the 3-dimensional treatment he also made a residual gravity map (with the effect of the caprock removed) in which the gravity low is displaced –3 km to the NW. This intrusion, which is most likely rhyolitic, is considered important as a possible heat source for the geothermal system. (Heming, 1979; Cox, 1984).

Comparison of the fault block models (Figure 3,C and D) with the revised gravity map (Figure 3,E) indicates that much of the gravity anomaly can be related to basement structure, in particular to its depth. The following basement features are considered to be reflected on the gravity map:

(a) a NE-trending fault system which partly intersects the drillfield;

(b) the Kawakawa Fault system extends through the entire area covered by the map. Its correlation with a "neck" in the central gravity low is believed to be significant, as is the extension of the gravity low to the SW and parallel to the fault system;

(c) the wedge of (relatively) uplifted basement, west of Lake Owhareiti is bounded in the north by a NE-striking fault and to the south by the Kawakawa Fault itself;

(d) the NNW orientation of contours around the gravity low and associated with the downthrown block containing the Ngawha geothermal system.

However, modelling of the gravity data using the contoured basement surface (Figure 3,E) shows that a residual anomaly of -40 to -60 μN/kg remains which cannot be accounted for by variations in basement topography. A tentative interpretation of the overall gravity low is twofold: (1) the greater part of the anomaly south of the Kawakawa Fault system, and extending to the SW, is likely due to differences in basement topography (i.e. the basement is deeper here); (2) the extension of the anomaly north of the Kawakawa Fault system, is likely to be due to both a small block of depressed basement, plus a silicic intrusion below this block. The possible offset of the intrusion by several kilometers to the NW is likely. It is also probable that there is a zone of intense fracturing and hydrothermal alteration around such an intrusion. Other interpretations to explain the anomaly are also possible; for example, it may be due to intense hydrothermal alteration accompanied by fracturing. The deepest hole at Ngawha (Ng13) extended to 2255 m with a true vertical depth of -2025 m RSL but did not encounter any intrusive rocks. It is probable that the intrusion is not located below the most active thermal area but more likely to the north west where the subsurface temperatures are hotter.

CONCLUSIONS

A feature of the Ngawha hydrothermal system is that it is largely confined within the basement rocks. An approach using regional and local scale fault-lineament interpretations has enabled the development of a structural model that explains the system's location. This model is of a simple fault block type. Combining drillhole and geopohysical data on depth to basement has enabled the construction of a structural contour map of the basement surface. Regional faulting of the basement has produced zones in which the youngest intrusive and extrusive activity has preferentially occurred. Smaller scale and local secondary fracturing events have produced the permeability that has enabled a geothermal system to develop at Ngawha.

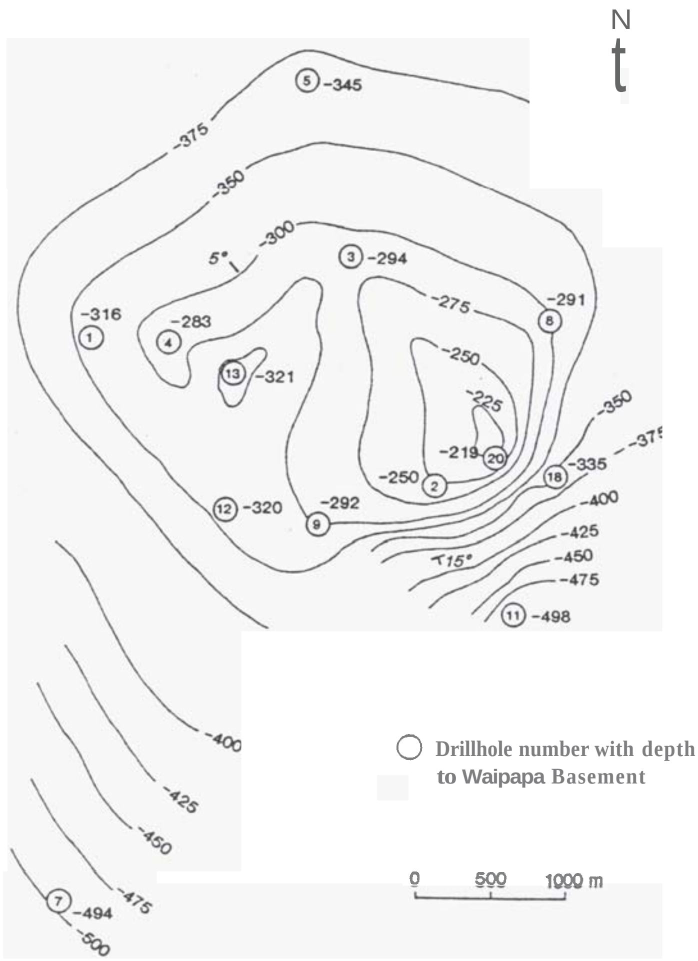

Figure 4. Map showing locations of drillholes in the Ngawha thermal area (depth in m relative to sea level).

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