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# PAST AND PRESENT-DAY THERMAL ACTIVITY BETWEEN THE ORAKEIKORAKO AND TE KOPIA GEOTHERMAL AREAS, NEW ZEALAND

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## ABSTRACT

The Orakeikorako and Te Kopia geothermal fields lie 7 km apart near the southern end of the Paeroa Fault in the Taupo Volcanic Zone of the North Island. Whether or not the two fields are connected hydrologically, and if so how, has been long argued but most maps show them as separate.

Recent mapping in the area between Orakeikorako and Te Kopia shows clear evidence for geothermal activity in the past, including the presence of:

1. Hydrothermally altered rocks exposed over an area of about 30 $km^2$. These contain a wide variety of hydrothermal minerals including assemblages of: a) kaolinite ± alunite ± cristobalite; b)mordenite+ montmorillonite and c) adularia+quartz (± illite).

2. Silica sinter at two locations. One contains laminated stromatalitic-type and well-preserved filamentous microbes.

3. Three hydrothermal eruption breccias older than 26,600 years but younger than 60,000 years. These were locally derived and contain matrix-supported clasts of sinter and other lithologies. Many clasts were hydrothermally altered, before they were ejected. Their alteration assemblages are the same as those present in the surficial rocks.

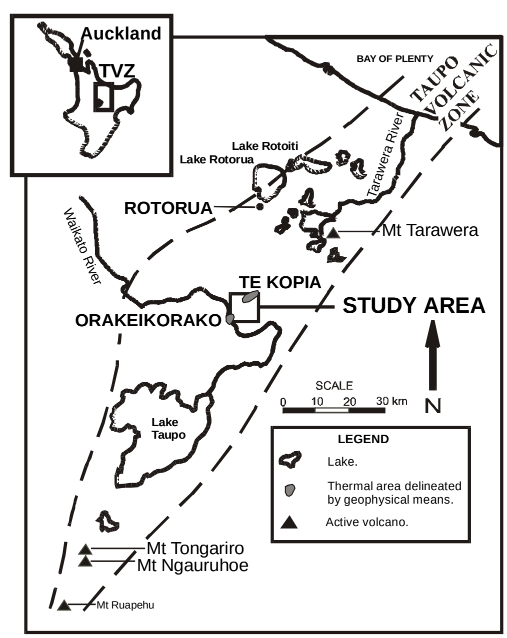
Several previously unreported thermal manifestations also occur. These consist of dilute acid sulfate pools, gently steaming ground and thermally stressed vegetation. Temperatures 15 cm below the ground surface are locally up to 79ºC.

These features show that thermal activity was once both extensive and intense in the area between the Te Kopia and Orakeikorako geothermal fields. Prior to 26,600 years ago alkali chloride springs discharged there, steaming ground was more widespread and at least three hydrothermal eruptions occurred. Subsequently the surficial thermal activity has declined to the present-day rather feeble manifestations. However, a usable geothermal resource may still be present below them.

## INTRODUCTION

The Orakeikorako and Te Kopia geothermal fields lie 7 km apart in the Taupo Volcanic Zone, about 270 km southeast of Auckland and 20 km northeast of Taupo (Figure 1). Both geothermal fields are long lived (Lloyd, 1972; Bignall & Browne, 1994) but are still vigorously active (Hamlin. et. al., 2000; Martin et. al., 2000). The surficial hydrothermal alteration at both fields records previous widespread and intense thermal activity. However, the hydrological relationship (if any) between them has not been established despite their similar geological settings. To address this question the geothermal geology of the area between the two fields was mapped in detail, for the first time, to determine the nature and extent of any hydrothermal activity, both past and present, that occurs there. Former geothermal activity is recorded by the surficial alteration. This was interpreted by comparison with the alteration that occurs in the explored geothermal systems within the Taupo Volcanic Zone.s

**Figure 1.** Locations of the Orakeikorako and Te Kopia geothermal fields and the study area.



## GEOLOGICAL SETTING

The Orakeikorako and Te Kopia geothermal fields occur in an area of mostly Quaternary calc-alkaline rhyolite lavas and pyroclastic deposits including widespread ignimbrites; thin lacustrine sediments and alluvium occur in places. The subsurface stratigraphy was revealed by 4 holes drilled at Orakeikorako and 2 at Te Kopia that penetrate down to 1500 m. The Te Kopia field lies astride the Paeroa Fault, which is the most prominent structural feature in the region. It strikes northeast and has a downthrow to the west of more than 400 m at Te Kopia. This normal fault has played a major role in controlling the hydrology of the Te Kopia field for more than 260,000 years.

Towards the southwest the displacement of the Paeroa Fault is very much less, so that at Orakeikorako it is represented by three splay northeast striking normal faults with only a few metres displacement on each. Even here, however, these faults affect the shallow hydrology of this field (Lloyd, 1972; Hamlin et. al., 2000). Both geothermal fields have large numbers of thermal manifestations, and surficial alteration is widespread. Geysers, hot pools discharging alkali/chloride water, steaming ground and mud pools occur at Orakeikorako and there are also several hydrothermal eruption breccias and extensive deposits of silica sinter, some of which formed more than 40,000 years ago (Sannazzaro, et. al., 2000). The present-day thermal activity at Te Kopia comprises mainly steaming ground, pools with acid sulfate water, mud pools and several fumaroles, including the two with the highest outputs in New Zealand. On the western margin of the field, dilute chloride-bicarbonate waters discharge at temperatures of about 60ºC. However, the presence of silica sinter, including geyserite, shows that hot alkali chloride waters discharged along the base of the Paeroa Fault about 3,000 years ago (Bignall and Browne, 1994; Martin et. al., in press) although it has not done so as in historic times. Thermal activity at the field has also changed greatly elsewhere during its lifetime even in the past decade individual thermal features have appeared only to become extinct a few years later (MacKenzie, et. al., 1994). Hydrothermal eruption breccias older than 1800 years occur and a crater 400m wide is recognisable although partly filled with landslide debris.

There have been several geological, geochemical and geophysical surveys made of both the Te Kopia and Orakeikorako fields, including those by Mahon (1965 a, b, c), Healy (1974), MacDonald (1965). Bromley (1992), Lloyd (1972), Bignall and Browne (1994), Soengkono (1999) and Sheppard and Klyen (1992). However, none report any hydrothermal alteration or thermal activity occurring between the two fields.

## THERMAL ACTIVITY IN STUDY AREA

Present-day Activity

Field mapping showed thermal features in the study area that had not been reported previously. These include:

(a) isolated pools of perched steam-heated water measuring up to $24m^2$. Temperatures at 15cm depth around the pools are mostly less than 70ºC with no, or very little, overflow.

(b) areas of steaming ground and isolated steam vents mostly surrounded by thermally stressed vegetation and patches of kaolin stained by hematite; the maximum temperature measured at 15 cm depth was 79ºC. The largest manifestations cover areas of about 200 $m^2$ but some have been partly covered by landslide deposits.

(c) areas of warm ground without visible steam discharges. These features are characterised by bare altered ground or thermally stressed vegetation. Ground temperatures reach 60ºC in places.

No springs discharge alkali chloride water but the area is still thermally active.

Evidence for Past Geothermal Activity

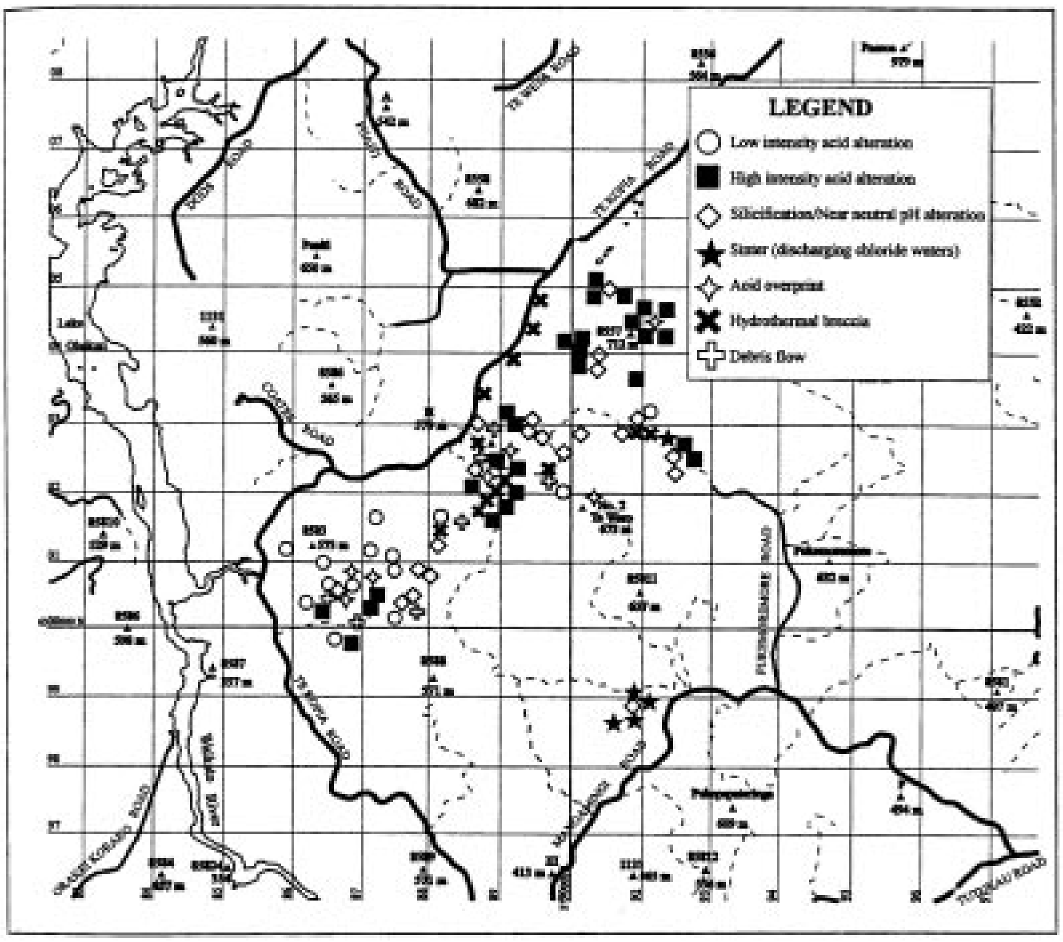
Evidence for former thermal activity in the study area is revealed by the widespread occurrence of hydrothermally altered rocks, including silica sinter, and three distinct hydrothermal eruption breccias.

Field mapping shows that hydrothermally altered rocks are exposed over an area of 30 $km^2$ between the southern margin of the Te Kopia field and the northern margin of Orakeikorako (Figure 2). Several hydrothermal minerals (Table 1) were identified by transmitted and reflected light petrography and by X-Ray Diffractometry.

**Table 1**: Summary list of hydrothermal mineral occurring at the surface in the study area

| |
|---|
| WIDESPREAD |
| kaolinite, hematite, montmorillonite, adularia, quartz |
| MODERATELY COMMON |
| dickite, alunite, albite, illite, mordenite, cristobalite |
| RARE |
| sulfur, sericite, pyrophyllite, pyrite, chlorite |
| SINGLE OCCURRENCE |
| sphalerite, heulandite, clinoptilolite, diaspore |

**Figure 2.** Distribution of hydrothermal mineral assemblages in the area between Orakeikorako and Te Kopia (from Clark and Browne, 1998). Grids are in km.




The minerals (Table 1) may be grouped, according to their associations and hydrological significance, as follows:

1. Kaolinite-Alunite hydrothermal alteration

Kaolinite+alunite±cristobalite±native sulfur±pyrite±hematite is widespread in the study area. In places kaolinite is substituted for by dickite and diaspore occurs at one location. The assemblage grades into rocks containing montmorillonite and mordenite and also overprints earlier formed assemblages (see later). The kaolinite+alunite assemblage is interpreted as having formed by their host rocks reacting with acid sulfate waters derived from steam condensate. The amount of erosion that has occurred since this alteration assemblage formed is unknown but its presence indicates that the rocks were once pervaded by steam or affected by descending steam condensate. Fluid pH's were probably between 2 and about 5 and the temperatures were probably less than about 130ºC but locally exceeded 250ºC, as is indicated by the presence of rare diaspore and dickite. Some rocks with this type of alteration are covered by unaltered Oruanui Ash that deposited 26,600 years ago (CJN Wilson, pers. comm) showing that acid fluids were circulating in the area before then - as they still do today.

2. Mordenite-Montmorillonite hydrothermal alteration

This assemblage is quite pervasive and both minerals mainly occur in the groundmass of their host rocks. In places this assemblage is accompanied by three other zeolites-heulandite, clinoptilolite or stilbite. This is a low temperature assemblage that readily forms at temperatures below 120ºC from waters of near neutral pH. We interpret the mordenite-montmorillonite assemblage as being mainly a product of reactions between glass present in the volcanic rocks and descending conductively heated groundwaters, as suggested by Henneberger and Browne (1980) to explain the genesis of the same assemblage at Ohakuri where similar rocks occur. This implies that these waters were not derived from the geothermal reservoir itself although some may have contained traces of cooled thermal water. Little mass transfer is involved in forming the mordenite-montmorillonite assemblage as all the necessary constituents can be readily extracted from the glass in the volcanics with the (OH) and n.$H_2O$ components being obviously provided by the circulating groundwaters.

3. Adularia-Quartz hydrothermal alteration

Adularia and quartz are common in the study area and occur as both replacement and vein minerals. However, they are overprinted in places by either the kaolinite + alunite or montmorillonite + mordenite assemblages. Illite also overprints some adularia crystals and minor pyrite is associated with the assemblage. However, calcite, wairakite and epidote were not seen although they all occur in drillcores from the Orakeikorako and Te Kopia systems.

Rocks containing quartz-adularia reacted with alkali chloride waters of near neutral pH and these minerals also precipitated directly from water of this type to form veins. Such processes occurred in the subsurface although their products are now exposed at the ground surface due to faulting and erosion along the Paeroa Fault.

Hydrothermal quartz crystals sampled at three locations contain fluid inclusions whose homogenisation ($T_h$) and ice melting temperatures (Tm) could be measured. The Tm values of 85 inclusions were between 0.0 and -0.1ºC showing that the trapped waters are very dilute (apparent salinities are between zero and 0.2 wt% NaCl equivalent) and also showing that little, if any, $CO_2$ was trapped.

The quartz crystals hosting the inclusions are euhedral to subhedral although some have been partly corroded by steam condensate. Those in the central part of the study area (elevation 650 masl.) occur in veins (elevation 560 masl.) but crystals in the north litter the ground surface where they have been eroded from their host rocks. However, crystals in the southern part were collected from a vein in a block from a debris flow (elevation > 480 m) displaced from the Paeroa Fault. Inclusions are of both primary and secondary origins and all homogenised into the liquid phase. The $T_h$ values of the inclusions (n = 18) in the southern area are between 220 and 245ºC and those (n= 63) in the central part between 190ºC and 250ºC with modes at 235ºC and 195ºC respectively. The fluid inclusions (n = 173) present in quartz at the north margin of the study area (strictly the southern part of the Te Kopia field) mostly homogenised between 210 and 250ºC. A 6mm long euhedral crystal from the central area recorded progressive cooling that occurred during its formation; from 238ºC (crystal core) to 192ºC (margin). This suggests that the Th values of inclusions in the other crystals also yielded true records of the temperatures prevailing at the times their trapping occurred.

4. Overprint Alteration Assemblages

Overprinting of one alteration assemblage by another occurs in many places and is also obvious in thin sections although we suspect that the initial alteration assemblage may have been completely destroyed in some instances. Kaolinite-alunite overprints both adularia+quartz and mordenite+montmorillonite alteration throughout the study area, but mainly in the south; mordenite+montmorillonite also overprints the adularia-quartz assemblage. An example of the former is a vein where adularia rhombs are preserved although this mineral has entirely altered to kaolinite. Dyke-like structures, possibly veins, up to 1 m wide, also in the southwest now consist of a non-equilibrium assemblage comprising kaolinite, cristobalite, adularia and montmorillonite. The features are overlain by 26,600 years old ash which is unaltered showing that all hydrothermal activity here had ceased by the time it deposited.

The overprint textures and mineralogies record changing conditions in the hydrology of the area and the interplay of neutral pH alkali chloride, acid sulfate and heated groundwaters. The kaolinite-alunite overprinting of adularia-quartz, for example, indicates that the piezometric surface descended so that rocks that were once saturated with alkali chloride water become exposed to acidic steam condensate.

5. Silica Sinter

Two previously unreported silica sinters outcrop in the study area (Figure 2). Both occur below Oruanui Ash indicating that they are at least 26,600 years old. At one location (near Mangamingi Road) the sinters, up to 1 m thick, have a vitreous texture and are hard whereas sinter at the other location (north of Pukemoremore Road) is only about 50 cm thick and highly porous. Both sinters contain casts of plant stems and now consist of quartz, opal A and opal CT. Biogenetic forms, including phormidium, are evident under the Scanning Electron Microscope and stromatalitic mats are well preserved in places (Figure 3).

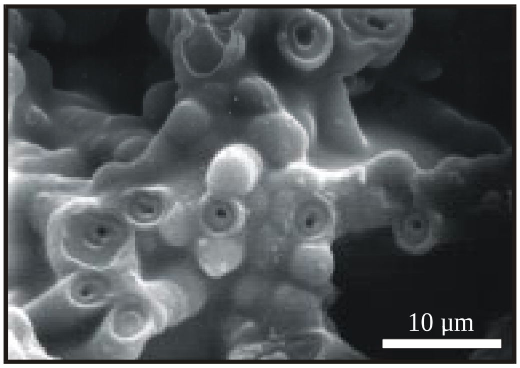



**Figure 3**. Scanning Electron Microscope image of microfilaments coated by silica and occurring in silica sinter in the study area.

No geyserite or silica terrace forms were seen but the presence of the sinter shows that alkali chloride waters once discharged in the study area and that temperatures in the reservoir from which they derived exceeded 180ºC.

6. Hydrothermal Eruptions

At least three hydrothermal eruptions occurred in the study area. This is revealed by the presence of hydrothermal eruption breccias although the locations of their craters are not known with certainty. All the breccias are older than 26,600 years. They are poorly sorted, matrix-supported and without obvious bedding. The ejected clasts are up to 50 cm diameter and mostly angular; they include mainly lacustrine sediments, pumice breccias, lithic tuffs, ignimbrites, silica sinter and one clast of silicified wood. Many of the clasts were hydrothermally altered, before they were ejected, to assemblages of kaolinite+alunite, mordenite+montmorillonite and adularia+quartz. The focal depths of the hydrothermal eruptions that ejected the breccias are unknown but such events are a typical geothermal phenomenon and they have occurred at both the Orakeikorako and Te Kopia fields (Lloyd, 1972; Bignall and Browne, 1994). They are believed to be triggered by slight pressure changes that cause water near boiling temperature in the host rocks to suddenly flash to steam (Browne and Lawless, 2000) and thus to fracture and eject the rocks.

## CHANGES IN GEOTHERMAL ACTIVITY

Mapping, tephrochronology and petrography shows that the area between Orakeikorako and Te Kopia has probably been thermally active for 26,600 years. Indeed, thermal activity still occurs in the area. The evidence for former geothermal activity includes the widespread hydrothermal alteration and the occurrence of hydrothermal eruption breccias. Temporal changes in geothermal activity are clearly evident from the textural relationships of the hydrothermal mineral assemblages, especially the widespread overprinting, and the occurrence of hydrothermal minerals now at the surface that formed within a geothermal reservoir. Fluid inclusion geothermometry results are consistent with interpretations made from the observed alteration mineralogy.

The Paeroa Fault has been active for longer than 140,000 years and episodic movements on it have undoubtedly affected the hydrology of the Orakeikorako and, more obviously, the Te Kopia geothermal fields (Bignall and Browne, 1994). In the area between them geothermal activity was once also more extensive and intensive but now only vestiges of it remain. The reason for the decline in activity is not obvious. Perhaps subordinate faults striking northwest have allowed activity to persist at the Te Kopia and Orakeikorako fields but not in the study area or else mineral deposition permanently sealed the fluid flow channels. Other possible explanations are that cooling in the reservoir below the area occurred as a result of fast inflow of rain water.

The mineralogical evidence records some of the changes in thermal activity that the area has undergone. Using the mineralogy and fluid inclusion geothermometry results we interpret the hydrological conditions summarised in Table 2. However, these conditions changed spatially and temporally during the long life of the system. Faulting brought to the surface rocks that were once 300 m or so below ground surface, as indicated by the homogenisation temperatures of fluid inclusions, where they had been altered by weakly saline, neutral pH waters. The piezometric surface dropped in response to movements on the Paeroa Fault, as also occurred further north at Te Kopia (Bignall & Browne, 1994). Based upon our observations we interpret the geothermal history of the study area as follows:

**Table 2.** Summary of fluid properties deduced from alteration mineralogy and fluid inclusion geothermometry

| **Alteration Type** | **Fluid Origin** | **Temperature (ºC)** | **pH** |
|---|---|---|---|
| Adularia-quartz (±illite) | Deeply derived upflowing alkali-chloride water. Salinity <0.2 wt% NaCl equiv. | 190-245 | Neutral |
| Mordenite-montmorillonite (± other zeolites) | Heated groundwater or groundwater mixed with chloride water | <120 | ~ 7 |
| Kaolin-alunite | Steam condensate | < 140 - ~ 250 | Low 2 to 5 |
| Silica Sinter | Chloride waters discharging at the surface | < 100 (at surface) > 180 at depth | 6 -7 |

Early-Stage Activity (Figure 4A)

During the first recorded stage of thermal activity, from say 260,000 to 120,000 years ago, dilute near neutral pH, alkali chloride waters descended deeply penetrating fractures generated along an incipient Paeroa Fault.

These waters were hotter than 260ºC meaning that a geothermal system had already become well established. The alteration product of these fluids is represented by the quartz+adularia assemblage + their associated minerals formed within the then geothermal reservoir. Concurrently, on the margins of the reservoir, descending rainwater became heated by conduction and reacted with glass in the host ignimbrites to produce the montmorillonite+ mordenite ±other zeolites assemblage. We speculate that the alkali chloride waters discharged at the ground surface as hot pools and geysers and that there were also patches of steaming ground where kaolinite and alunite formed. Thermal manifestations then probably resembled those now visible at Orakeikorako.

Mid-Stage Activity (Figure 4B)

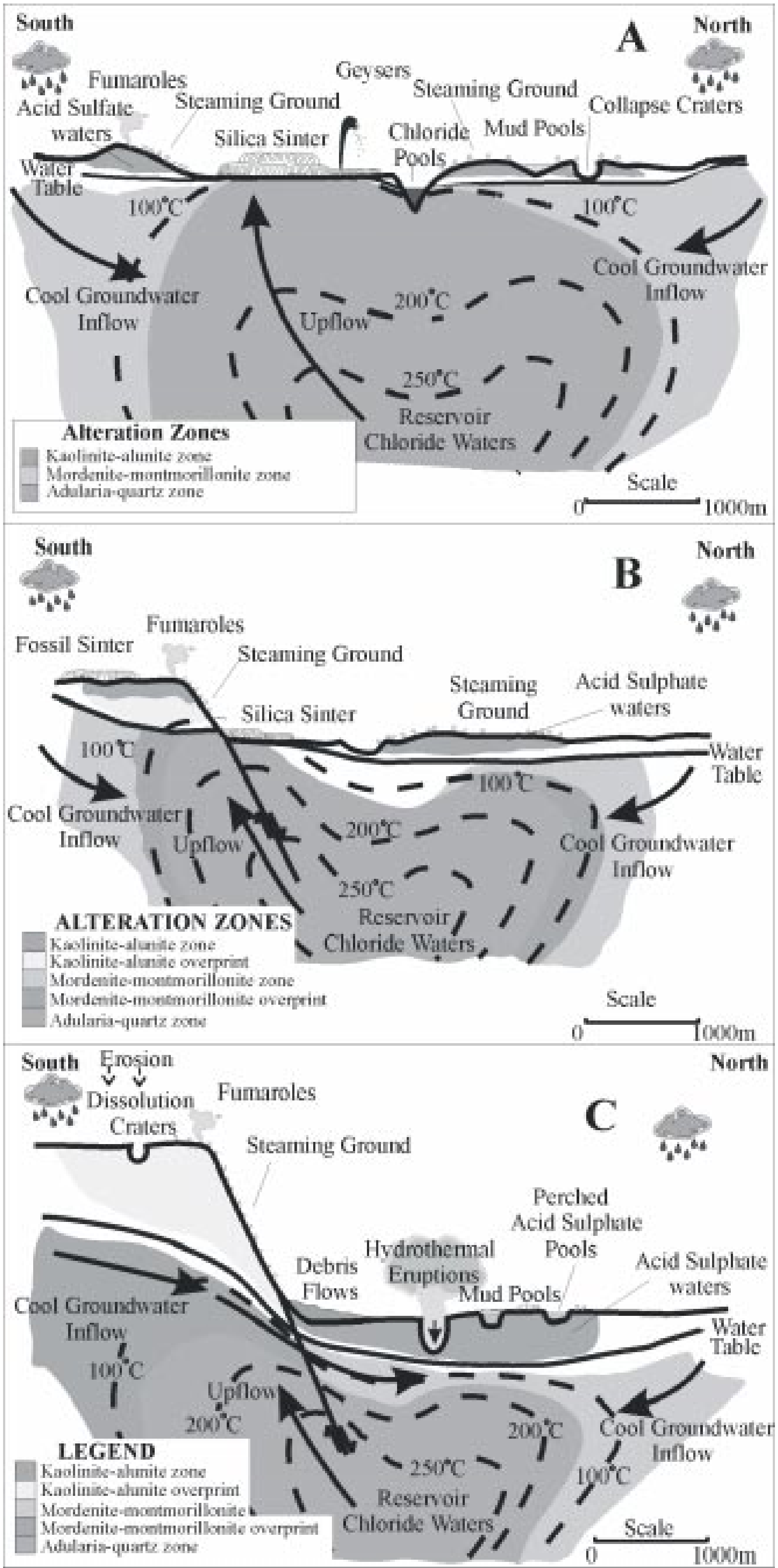
Near vertical displacements of the Paeroa Fault affected the hydrology of the geothermal systems along its strike. Although the movements were episodic their cumulative effect was to progressively lower the then piezometric surface on the eastern part of the field, relative to the new ground surface, thus allowing steam to occupy parts of the reservoir earlier filled by the dilute alkali chloride waters. This stage of activity occurred between 120,000 and say 30,000 year ago. The quartz+adularia and the montmorillonite+mordenite assemblages were partly, or completely, overprinted by the kaolinite+alunite assemblage as a result. West of the Paeroa Fault alkali chloride waters continued to discharge and other manifestations occurred. Faulting triggered hydrothermal eruptions, debris slides and landslides, as hydrostatic pressures declined in the footwall of the fault. Erosion of the eastern block was rapid but did not exceed its rate of relative uplift. This allowed quartz+adularia+illite assemblages, formed perhaps 300 m below the piezometric surface prevailing then, to be exposed earlier than 26,600 years ago.

Late-Stage Activity (Figure 4C)

Movements on the Paeroa Fault continued to affect the geothermal activity, which declined in intensity. There is no evidence that alkali chloride waters discharged during this stage i.e., the past 30,000 years, and the main manifestations were probably steaming ground, fumaroles and perhaps occasional hydrothermal eruptions. Erosion of the steam-altered rocks of the eastern block was rapid and the thermal manifestations there were probably similar to those now discharging at Te Kopia.

A vestige of thermal activity survives to the present day but it is now a faint shadow of the spectacular activity of the past.

Figure 4. Summary of hydrological changes that have occurred in the study area. A. 120,000 to 280,000 years ago. B. 30,000 to 120,000 years ago. C. Post 30,000 years. The Paeroa Fault is the prominent fault.



## CONCLUSIONS

Thermal activity was once widespread in the area between the Te Kopia and Orakeikorako fields and it was probably once contiguous between them. There were frequent changes in the hydrology of the entire area, mainly in response to movements on the Paeroa Fault, but also, perhaps, due to variations in rainfall. Sometime prior to 26,600 years ago thermal activity in the study area started to decline and this has continued until today when there are now only a few feeble surface manifestations. This does not mean that there is not still a usable resource at depths of a few hundred meters. Drillholes at both Te Kopia and Orakeikorako encountered temperatures in excess of 230ºC at depths of about 1000 m.

We are unsure, however, of the relationships between Orakeikorako and Te Kopia or if the manifestations in the study area should be assigned to the northern or southern margins of either. Alternatively, perhaps it was a separate field? There seems to be little lateral flow of thermal fluids along the strike of the Paeroa Fault, at least at shallow depths, and the flow direction at all three places is mainly to the northwest ie. normal to the fault.

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