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THE TE MIHI STEAM RESERVOIR, WAIRAKEI. AN EXPLOITABLE GEOTHERMAL RESOURCE

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ABSTRACT

Recent drilling in the Te Mihi Field - the western extension of Wairakei - has confirmed the presence of a 300-400 m thick steam reservoir, produced by falling aquifer pressures and trapped below an impermeable cap - the Huka Falls Formation - of lacustrine siltstone and hydrothermal eruption conglomerates. The presence of a shallow vapour-dominated reservoir was initially inferred from precise gravity changes and from direct measurement of steam pressures in the Te Mihi 200 series wells. Investigation of the boundaries of the reservoir by shallow (600 m) wells is proceeding and will be followed by production drilling along known active faults. One 400 m well (WK228) already drilled has an output of 90 t/hr of dry steam (11 MW_e), a substantial and cheap energy supplier to the Power Station.

The strategy for Wairakei development over the next decade is likely to be changed if the Te Mihi Steam reservoir can be successfully exploited. The cost advantage of cheap steam in the west needs to be balanced against the additional expense of extending the steam pipelines a further 1-2 km. However. the provision of extra steam supplies should allow the closing down of the Eastern Borefield - already threatened by cold water invasion - and the utilisation of existing shallow wells for reinjection. This should maintain reservoir pressures and temperatures, control ground subsidence and eliminate wasteful discharge of effluent to the Waikato River. In the long term, deep drilling in the postulated upflow regions at Wairakei, such as Te Mihi, will be necessary to maintain steam supplies to the station.

Introduction

Following the spectacular success of WK228 (11 MW_e) drilled in September 1985 on an active NNE-trending fault near Flash-plant 9 in the Te Mihi extension of Wairakei, it was unanimously decided at a meeting of the "Wairakei Working Party on Steam Supply" held at Wairakei Geothermal Research Centre on 13th November 1985, to investigate and recommend further sites for dry steam production in the Te Mihi Field, thus eliminating the need for other alternative steam supplies (Grant 1985). The first of a series of new wells (WK229) was drilled in July 1986 to identify the eastern boundary of the steam field and further wells will be drilled in late 1986 - early 1987 to identify the northern and western boundaries.

The Resource: Dry steam has been accumulating in the Upper Waiora reservoir below the Huka Falls Formation for at least the last 27 years. This steam cap is produced by flashing of reservoir fluids instigated by pressure drawdown (Studt 1958; Bolton 1970), propagated throughout the reservoir by production. In the sixties and early seventies. a substantial steam cap formed to the southwest of the Wairakei Field, partly by SW migration along active faults, and discharged at Karapiti fumaroles in The Craters of the Moon Thermal area (Allis 1979). WK204 tapped this steam cap in the Karapiti Rhyolite in 1960 at the intersection of the Wairakei Fault. and discharged an estimated 250 t/hr of dry steam until quenched (Grindley 1965). Its subsequent history as the infamous "Rogue Bore" is documented by Thompson (1976). Unfortunately, no attempts were made to exploit this dry steam resource to the southwest and it has since largely vented and wasted to atmosphere except close to the borefield (e.g. WK216).

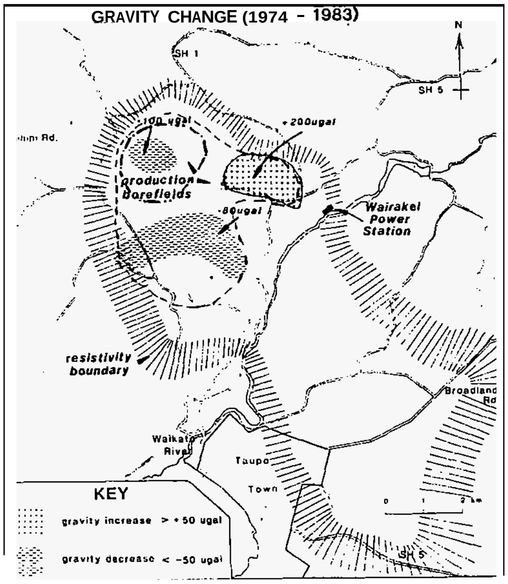

FIGURE 1: Wairakei and Tauhara Fields showing resistivity boundary (Risk et al. 1984) boundaries of high pressure (>20 bars) steam zone at Te Mihi and low-pressure steam zone at Karapiti in the south as outlined by gravity decreases. Area of water invasion into steam zone in Eastern Borefield indicated by gravity increase.

A similar steam cap appeared to the northwest of Wairakei at least as early as 1958 when WK201 encountered dry steam below the Huka Falls Formation. Unfortunately, because the anchor casing was set too shallow, well WK201 blew out to the surface and was abandoned as the first Wairakei Rogue Bore (Grindley 1965).

The thickness. size and pressure of the steam cap has fluctuated subsequently but still constitutes a significant resource (Grant 1982) occupying an interval from 300 to 400 m thick over an area of at least 3 km^2, at a mean pressure of 24 bars. Although some discharge of steam occurs naturally to the north in the active fumarolic area north of Te Rau-Te-Huia Stream, there is little steam discharge to the south apart from a line of weak fumaroles north of WK201 and near WK215, so that the reservoir may be relatively intact. Steam pressures in the Waiora reservoir decrease eastwards towards the Western Production borefield. and southward towards the Karapiti Thermal area from about 24 bars to about 12 bars (Grant 1982. p. 35. fig. 3).

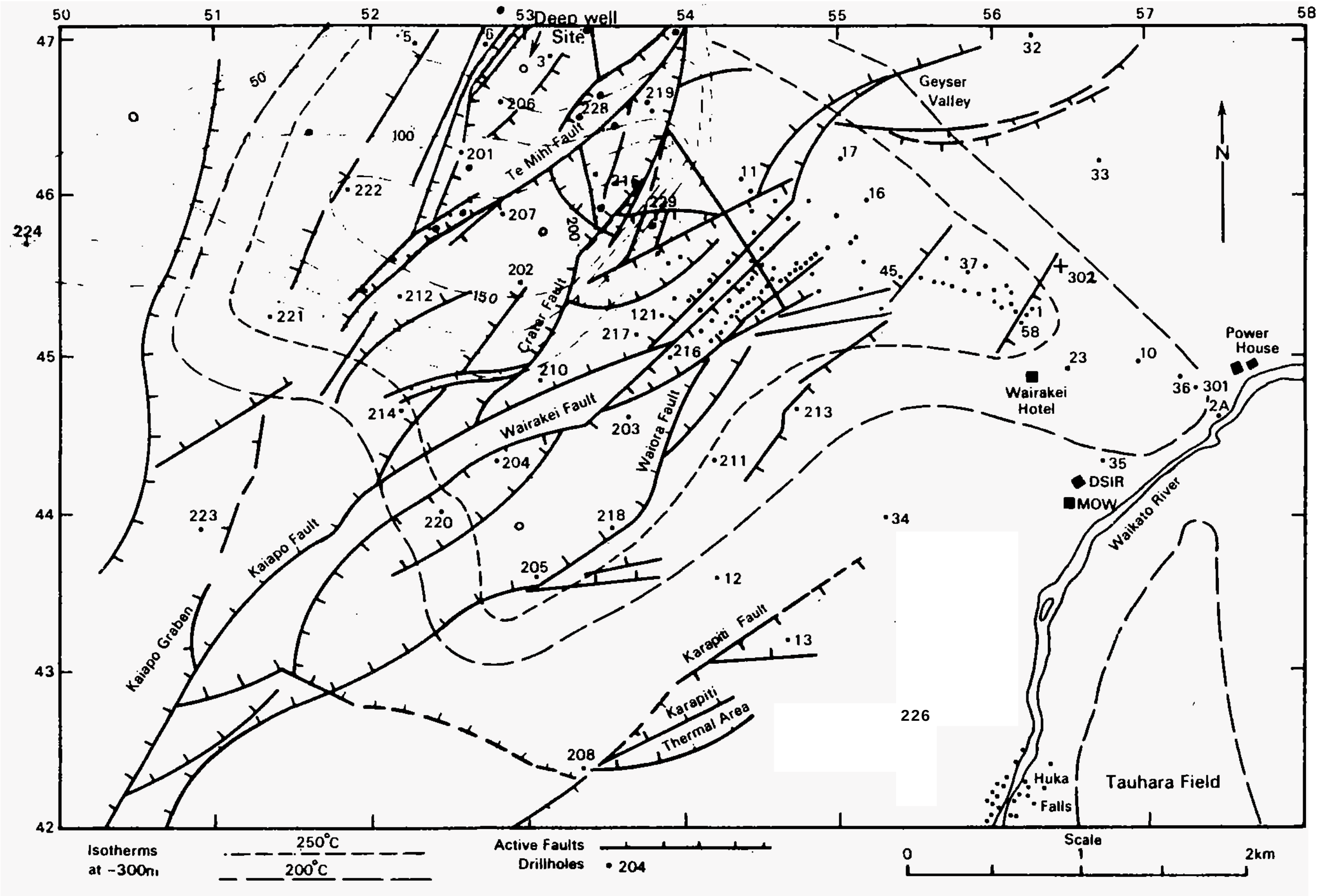

FIGURE 2: Active fault map of Wairakei Geothermal Field showing isotherms (-300 m), isopachs on hydrothermal eruption breccias, and sites for dry steam producers (solid circles), deep investigation wells (open circles), and new reinjection well (WK302) (after Grindley 1974. 1982. modified).

Delineating the Resource: The approximate location of the Te Mihi Steam Reservoir is apparent from the map (Fig. 1) showing gravity changes (1974-1983) circulated by R.G. Allis (after Hunt 1983) at the Wairakei meeting. The gravity decrease of 100 ugal at Te Mihi and 80 ugal at Karapiti is considered to mark replacement of water by steam in the Waiora Reservoir. The corresponding gravity increase of 200 ugal in the Eastern Borefield is considered to mark collapse of the steam reservoir and replacement by water.

The updated resistivity boundary (Risk et al. 1984) (Fig. 1) provides an approximate indication of the northern and western boundaries of the Te Mihi Steam Reservoir. The northern boundary lies almost 1 km north of the map edge (Fig. 2) where steaming ground and fumaroles are visible almost as far north as Link Road.

The southern boundary of the Te Mihi Steam Reservoir lies between WK212 (20 bars) and WK214 (12 bars) and is probably fairly sharp, perhaps a permeability barrier. The eastern boundary has been explored by WK229, drilled in the rough, thermally-active upper Waiora Valley between the western borefield and Alum Lake. Drilling problems due to the high permeability and fractured reservoir rocks required that the potential steam zone be cased off. Preliminary indications are that steam pressures are between 15 and 20 bars, similar to those presently encountered in the Borefield to the east. The eastern boundary of the exploitable steam zone is probably close to the line of the Crater Fault (Fig. 2).

Drilling of the northeastern, northern and western boundaries of the Te Mihi Field is presently being undertaken by shallow (600 m) failing wells.

Exploiting the Resource: The success of WK228 shows that fault-controlled permeability is the key to exploiting the steam in the Te Mihi Field. Because steam moves through the reservoir less readily than liquid water, due to the low porosity of the reservoir rocks and the higher viscosity of steam relative to hot water, horizontal flow is slower in a single-phase steam reservoir than in a 2-phase or liquid-filled reservoir. Precise siting of steam production wells is, therefore, demanded for optimum production. Figure 2 is an updated active fault map of Wairakei while Figure 3 shows the faulted structures controlling the high permeability and production of WK228, WK229 and earlier deep investigations wells in the western (Te Mihi) extension of the Wairakei Field.

Because of steep topography in the Te Mihi Field and the deployment of steam pipe lines and power lines along valleys and across easier topography, drillhole sites are quite difficult to find, especially when they are required to be located adjacent to active fault scarps. Of the eight sites chosen (Fig. 2) Site SE may be difficult to drill due to the proximity of the main pipelines from the Te Mihi Field. Site SB is also in close proximity to an 11 Kva power line and may need to be moved southwest towards Site SA, or northeast towards WK207 (unless the line is shifted). Site SD, the stepout from WK228, is close to thermally-altered ground and may be difficult to construct. Site SF is between Alum Lake and the Wairakei Mud Crater and will require road access. The remaining sites (SG, SH along Te Rau-Te-Huia Stream) should present no problems.

Life of the Steam Reservoir: The shallow steam reservoir in the Te Mihi Field is currently decaying at the rate of 0.5 bar/year and this has undoubtedly accelerated since Wk228 was opened for production. Interference tests are planned once WK228 is connected and producing to measure pressure drawdown in neighbouring wells (WK215, 219, 206, 207, 222) believed to be open in the steam zone. This should provide vital information on the size of the resource and the optimum rate of production. Estimates of the potential life of the steam reservoir until pressures are reduced below pipeline requirements (6 bars) may also be possible.' A lifetime of 5-10 years was estimated by those attending the recent Working Party meeting.

Deep Drilling at Te Hihi

The Te Mihi Field is currently considered the most likely upflow region at Wairakei. a suggestion first made by Studt (1959) on the basis of low magnetic values and later reinforced by the results of three separate resistivity surveys of the Wairakei Field (Risk et al. 1984) which showed lowest resistivities in the northwestern Te Mini area, between Link Road and Te Rau-Te-Huia Stream). Much of this area is actively steaming ground and not suitable for drilling. From temperature and pressure trends, Grant (1982) has presented a case for Te Mihi as the main upflow zone of Wairakei, although the maintenance of pressures and temperatures there may merely reflect absence of sustained local production. These trends will also be masked by formation of a steam cap as happened in the sixties in the Eastern Borefield and in the seventies in the Western Borefield. A multiple heat-source model for Wairakei is likely (Grindley 1982) and the true upflow zones will only become apparent as exploitation proceeds. The Waiora Fault area still claims the largest producers in the Western Borefield despite 25 years of intense production, and must still be considered an important heat source at least down to 2.2 km, where the highest temperature of 275°C was recorded in WK121 (Fig. 4).

Stratigraphic and structural arguments for a caldera margin in the north of the Wairakei Field were first advanced by Grindley (1982) and supported by Healy (1984) with modifications. The Rau-Te-Huia Stream follows an arcuate course which may be the surface expression of such a caldera margin, although the significant stratigraphic displacements of 900 m on the top of the Ohakuri Group (between WK219 and WK121, Fig. 4) are only found below 1 km. The postulated formation of the caldera as a result of subsidence and back-filling by thick Wairakei (= Whakamaru?) Ignimbrites is also a potent argument for a major heat source in this area. Eruption of resurgent rhyolite domes further to the south at Wairakei (Karapiti and Te Mihi Rhyolites) has depressed the Wairakei Ignimbrites at least by 1 km in this area, making it a less atcractiwe proposition for deep drilling, especially since the Wairakei Ignimbrites are thick (1.1 km) and impermeable. However, the positive thermal gradients down to 1 km and the presence of major active faulting warrants a deep well in this area. A site has, therefore, been selected (Fig. 2).

All the facts and theoretical arguments strongly support the case for the first deep well being sited at Te Mihi and close to the presumed site of the buried caldera margin (WK206, 219, 215 triangle). Since discovery of the steam zone, parts of this area will be needed for shallow steam production. This applies to the area between WK215 and WK219. where the original deep well site was located.

Accordingly, a new site is proposed in a relatively upfaulted block 250 m north of WK206, on the high ground overlooking the Rau-te-Huia Stream (Site DH1). An alternate site for a deep well at Te Mihi (Site DH2) has also been selected in the area between WK207, WK215 and WK202 on the western boundary (Crater Fault?) of the upfaulted Wairakei Block. This site is also interesting because of the thick hydrothermal eruption breccias (> 200 m, Fig. 2) intercalated in the lower part of the Huka Falls Formation. suggesting proximity to a heat source.

Because the life of the shallow stream reservoir is limited and will give only a few years respite before steam supplies to the Wairakei Station again became critical, it is strongly recommended that the first deep well (DH1) be programmed for drilling in 1987.

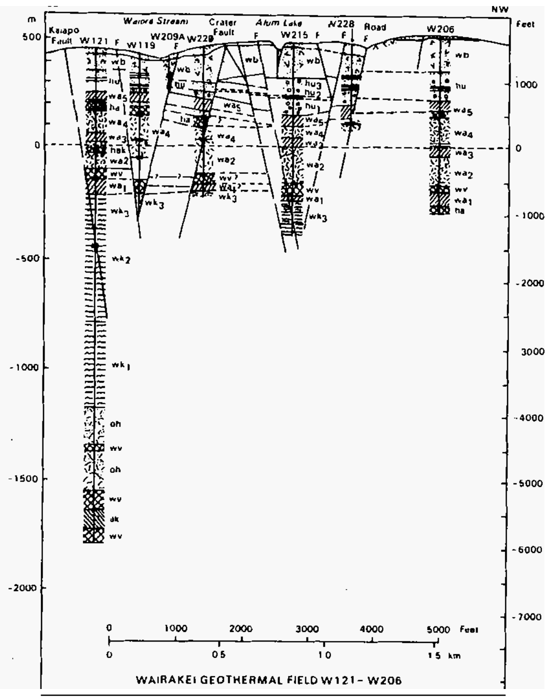

FIGURE 3: Cross section from WK121 to WK215 to WK206 showing structure of Te Mihi Steam Reservoir in relation to Western Borefield and new steam well WK228.

Effects on Reinjection Program

The discovery of substantial and exploitable reserves of dry steam in the Waiora Reservoir of the Te Mihi Field should allow reconsideration of the Reinjection Policy for Wairakei. The substitution of dry steam for two-phase fluid at the flash plants will automatically lower the quantities of separated water discharged to the Waikato River (currently about 4000 t/hr).

The availability of dry steam in the west may also allow the eventual closing down of the Eastern Production Borefield, currently contributing about 800 t/hr of the total mass production of 5200 t/hour. These wells should then become available for reinjection wells at a considerable saving in capital costs through not requiring an estimated 10-15 new reinjection wells around the south and east field margins as had been planned.

As a first step towards reinjection in the Eastern Production Borefield, it is planned to pipe the separated water from Flash Plant 7 down WK58. If these tests are successful, the whole of the Circle area could become a "Reinjection Park" in the next decade.

As a further field test of reinjection in the east, a new reinjection well WK302 has been planned for some time. Possible sites were chosen to the east of Wairakei Stream but these require a 2 km pipeline from the Flash plants in the western Production Borefield.

To reduce costs a new site for WK302 has, therefore, been chosen closer to the Eastern Borefield and to the "Subsidence Bowl" in lower Wairakei Stream. Completion of this well should provide valuable information on the lithology and physical properties of the Huka Falls and Waiora breccias to the north of the Eastern Borefield and enable reinjection tests to be carried out prior to the eventual demise of the Circle wells.

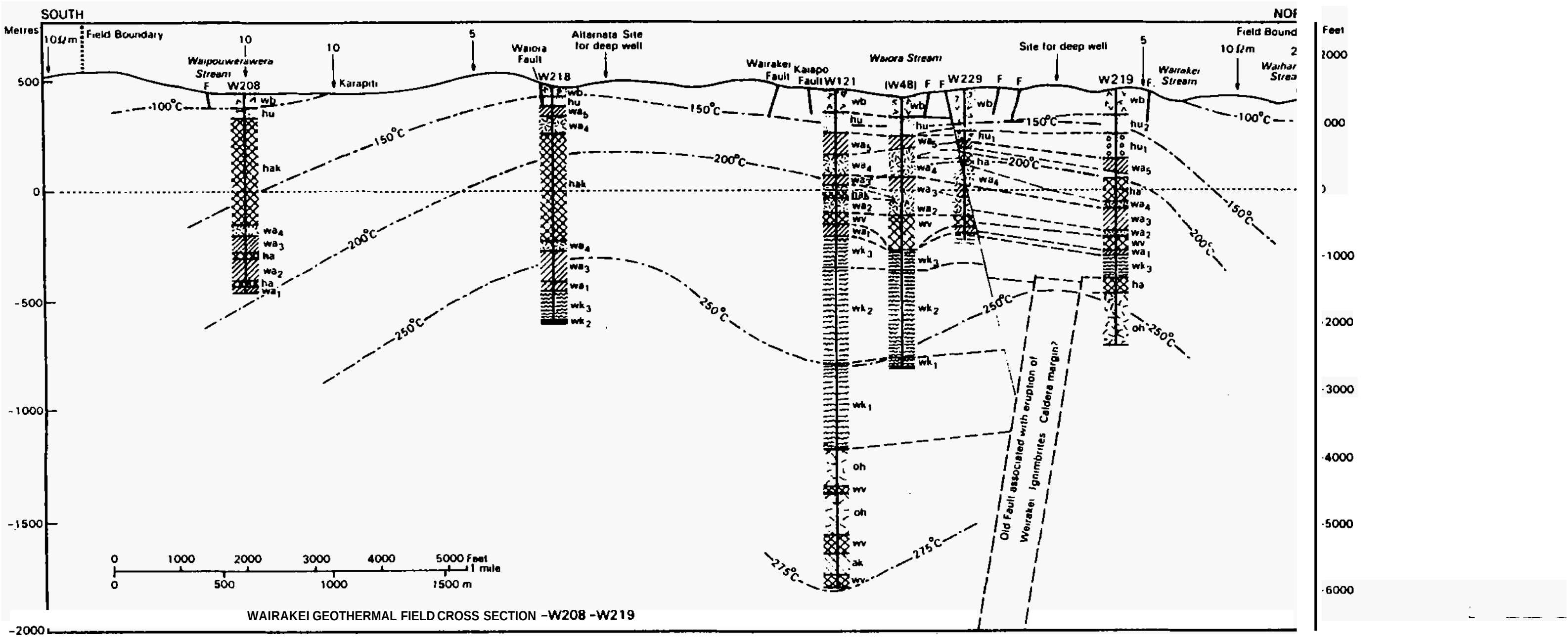

Figure 4. Cross section of Wairakei Geothermal Field between investigation wells WK208, WK218, WK121 and WK219 showing correlation of geological formations, isothermal surfaces and potential deep well sites (Grindley 1982).

The well site is located on a road from the drop structure on the Main Drain back up Wairakei Stream. It is approximately 150 m west of the Drop Structure and 50 m due north of the Main Drain at c. 50 m west of the junction with the drain from Flash Plant 7. The well should be drilled to c. 450 m depth, cased to 150 m and cored at 50 m intervals for determination of lithology and physical properties. According to Allis & Barker (1982. fig. 3) the subsidence rate at this site is c. 300 mm/year. Since it is close to the north-south axis of the "Subsidence Bowl". horizontal movement is only about 50 mm/year directed on a bearing of 340°T.

Reinjection of separated water (150°C) into the Huka Falls and Waiora aquifers at this site should in the long term contribute to the repressuring of the reservoir and by delaying the collapse of the steam cap might allow subsidence rates to be brought under control if not curtailed (see discussion, pp. 5-6 in Grindley 1983). The cores from this well might also allow some informed discussion on the underlying reason for rapid subsidence at this particular locality. Several geological models and a variety of physical causes of subsidence have been advanced but only the drilling of a well will enable these to be tested. WK302 will also be a valuable reinjection well for the future provided permeability is relatively high. Its location close to the extension of the Karapiti Fault through the Eastern Borefield (Grindley 1965) may provide access to permeable fissured country.

Field Management Options

The successful discharge of the first dry steam well in the Te Mihi Field to the northwest of the present Production Area at Wairakei has made it imperative to retnink the strategy for maintaining steam supplies to the Wairakei Station and disposing of separated water by reinjection into the reservoir. By drilling shallow wells (300-500 m) into the 3 km^2. 300 m thick, vapour-dominated Waiora reservoir at Te Mihi, it may be possible to augment the steam supply to the Power Station sufficiently to allow highly-productive but severely depleted sections of the field to be withdrawn from production, either temporarily or permanently. Field management problems that could be assisted by a reliable steam supply in the west are:

1. Dry steam production on a sufficiently large scale could drastically reduce the total amount of separated water discharged via the main drain to the Waikato River.

2. By progressively closing the Eastern Borefield over the next 5-10 years. these production wells could be utilised for reinjection of separated water from higher up the valley.

3. Steam pressures in the Te Mihi Field will be reduced avoiding potential steam eruptions and decreasing the intensity of fumarolic activity in the thermal areas north of Te Rau-Te-Huia Stream.

4. Reinjection of 150°C water into the Eastern Borefield should repressure the Waiora aquifer and assist in the maintenance of the output of wells from the Western Borefield, by replacing cold recharge with hot recharge.

5. Subsidence in the lower Wairakei Stream area could be controlled by reinjection into the Huka Falls aquifer in the Eastern Borefield.

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APPENDIX 1 RESULTS OF NEW DRILLING

TABLE 1. Stratigraphic sequence in WK228 (DD 485 m)

Depth	Lithology	Formation
0- 45 m	Pumice tephra, rhyolite lapilli	TAUPO PUMICE (tp)
45-140 m	Pumice/rhyolite lapilli tuff/breccia Chalazoidite tuff, tephra	WAIRAKEI BRECCIA (wb)
140-170 m	Pumice siltstone and sandstone (hu$_3$)	
170-185 m	Quartzose crystal tuff (hu$_2$)	HUKA FALLS FORMATION (hu)
185-220 m	Grey siltstone and fine sandstone (hu$_1$)	
220-275 m	Hydrothermal eruption conglomerate (hu$_1$)	
275-355 m	Crystal-vitric tuff (ignimbrite)	WAIORA (wa$_5$)
355-400 m	No cuttings	FORMATION
400-402 m	Lithic-vitric tuff (water laid)	(wa$_4$)

Interpretation of Downhole Data

Circulation was lost at the base of the Huka Falls Formation (270 m), at 315 m where a core of ignimbrite was taken, and at 355 m where the bit dropped 2 m. Maximum temperatures after 5 days were 226°C between 315 and 355 m, falling to 140°C at the well bottom and 150°C at 280 m. The well is cased to 315 m and produced both from here and from a major fissure at 355 m, considered to mark the intersection of the fault dipping east at 80' from the surface trace.

The base of the Huka Falls Formation was 30 m higher than anticipated due to the conglomerate unit thinning rather rapidly north and northwest from WK215 (Fig. 2). The Wairakei Breccia outcrops in the scarp behind WK228 and was not encountered in WK228 until a depth of 45 m, possibly an indication of the total throw on the active fault. Adularia, wairakice and albite are present in both cores (Wood 1986a) indicative of high permeability, normally associated with fissures along active faults (Grindley & Browne 1976).

Well WK228 on first opening (29.10.1985 - Fig. 5) gave a prolific dry steam discharge measured at 180 t/hr when fully open at 6 bg - the pressure of the nearby steam main at Flash Plant 9. The steam pressure in the resecvoir (shut in pressure) is 25 bg (Fig. 6). Since connection to the steam line and the Power Station, the output has dropped to about 90 t/hr - still equivalent to about 11 MW(e) sufficient to fully load the steam line and enable the closing down of three high-output liquid-fed wells (WK206, 207, 215).

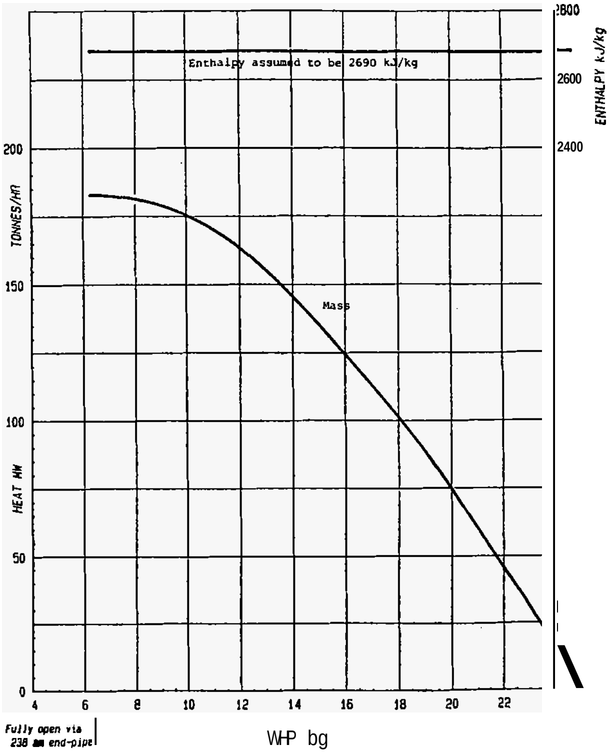

Figure 5. Output Test of Well WK228. Maximum output (180 t/hour)

TABLE 2. Stratigraphic sequence in WK229 (DD 472 m)

Depth	Lithology	Formation
0-45 m	Pumice tephra, rhyolitic sand and gravel	TAUPO PUMICE (tp)
45-140 m	Pumice/rhyolite lapilli tuff Chalazoidite tuff, tephra	WAIRAKEI BRECCIA (wb)
140-182 m	Sandstone, siltstone (hu_3) Vitric tuff (hu_2)	HUKA FALLS FORMATION (hu)
182-227 m	Siltstone conglomerate/ breccia, sandstone (hu_1)	
227-277 m	Pumiceous ignimbrite quartz-plagioclase (wa_5)	WAIORA FORMATION (wa)
277-310 m	Lithic-crystal-tuff rhyolite/dacite lithics	
310-360 m	Flow-banded Rhyolite plagioclase-quartz (ha)	HAPARANGI RHYOLITE
360-460 m	Pumice breccia. tuff	WAIORA FORMATION (wa)
460-560 m	No data	
560-570 m?	Thin-bedded grey siltstone, green sandstone (wa_2)	
?570-647 m	Hard formation, probably Andesite ± Ignimbrite (wk?)	WAIORA VALLEY ANDESITE (wv)

Interpretation of Downhole Data

Circulation was lost at the base of the Waiora ignimbrite unit (Wa5) at 278 m where a core of hydrothermal explosion conglomerate and quartzose sandstone was taken. This breccia is similar to thicker conglomerates found higher in the sequence in the lower Huka Falls Formation (hu_1), and at the same stratigraphic level in WK206.

Hard formation encountered between 310 m and 360 m proved to be intensely altered flow-banded rhyolite with corroded quartz, plagioclase and altered pyroxene and hornblende phenocrysts. Rare lithic clasts are present. This rhyolite is similar to the Te Mihi Rhyolites drilled in the western part of the Te Mihi Field (Grindley 1965; Steiner 1977) and may also be linked With quartz-bearing flow-banded rhyolite drilled in WK219 700 m to the north (Fig. 4). The well was cased into the base of these rhyolite flows (360 m).

Circulation was lost again in the Waiora tuffs and breccias below the rhyolite and not regained below 425 m. Caving of friable altered rocks in the Waiora Formation could not be satisfactorily controlled and -a further casing string was inserted to 524 m Circulation-continued to be lost on resumption of drilling and a drilling break between 590 and 597 m indicated substantial fissures in the underlying hard formation, believed to be the Waiora Valley Andesite (Fig. 3). Further circulation losses were recorded at the final depth (647 m) where Wairakei Ignimbrite was predicted, but no core was taken to confirm this.

Well WK229 was extremely permeable. consistent with its location between active faults (Fig. 2), and confirmed by medium rank intense hydrothermal alteration, with locally abundant adularia (Wood 1986b). Temperatures peaked at 220°C in the Waiora Formation and remained constant for 300 m to 550 m, decreasing sharply near the hole bottom, below the inferred top of the Wairakei Ignimbrite. On first opening (17 August) WK229 gave a very clean mass discharge of almost 300 t/hr. Measured steam output is 50 t/hr. a power potential of between 6 and 7 MW.

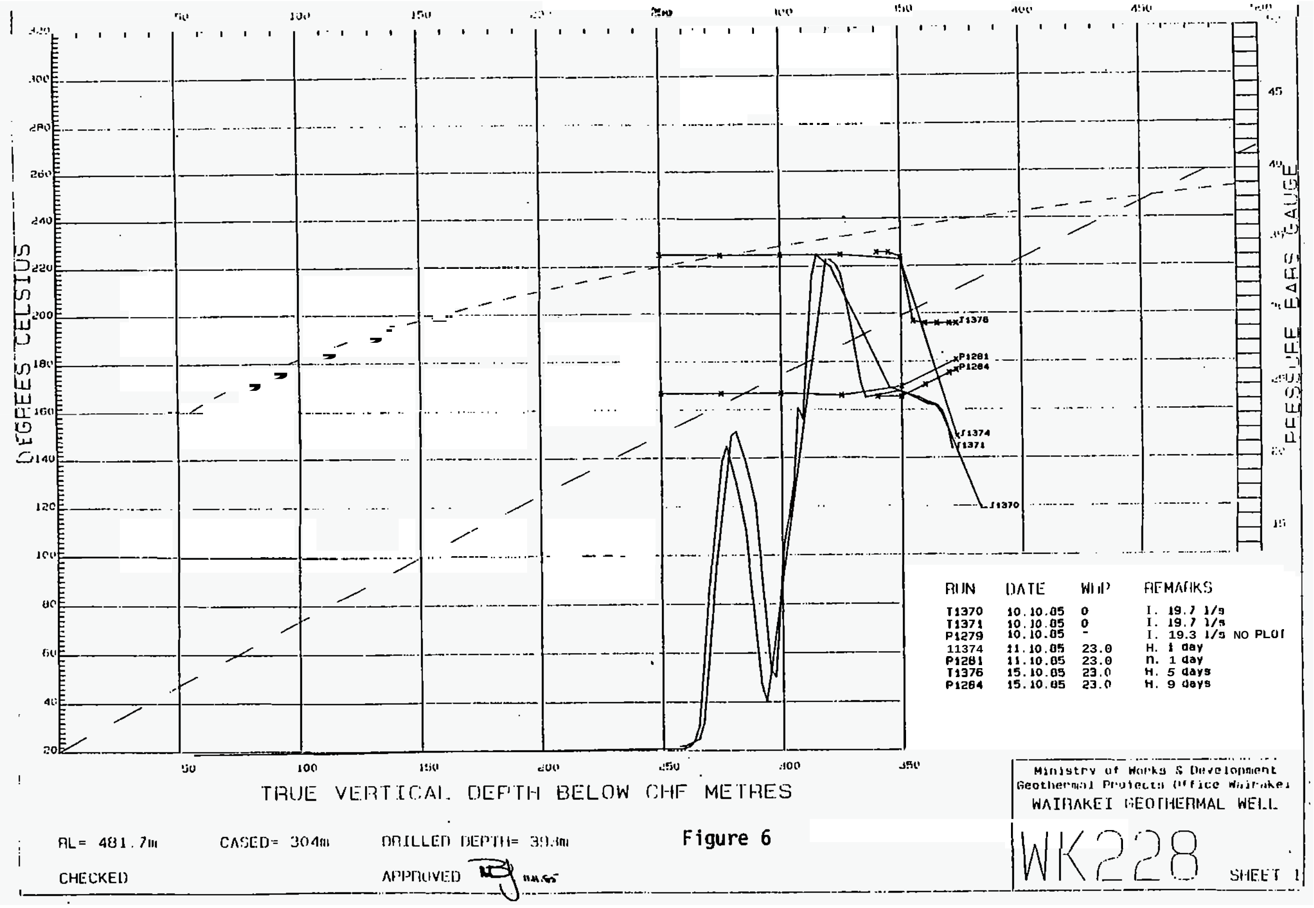

Figure 6