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A BRIEF HISTORY OF CHEMICAL EXPLORATION AT OHAAKI-BROADLANDS

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ABSTRACT

The investigations at Ohaaki illustrates how the chemical knowledge at each stage of exploration was used to predict the then unproved chemical parameters of the system. Initial surface chemistry predicted high gas concentrations at depth. Measurements on fluid inclusions, together with well chemistry was used to deduce the chemical, thermal and hydrological history of Ohaaki-Broadlands. Recent data have shown the importance of the CO_2 rich steam-heated waters in relation to hydrology, mineral deposition, permeability, dilution, and corrosion. It is recommended that more attention be given to these types of water in investigation of any geothermal system.

PRE-DRILLING EXPLORATION

Prior to drilling, Ohaaki was well known for its 'ngawha' or hot spring - Ohaaki Pool - with its crenellated edges and the silica terraces produced by its discharge.

The natural activity was limited to a few hot springs and hot water seepages into the Waikato River and minor areas of mud pools and steaming ground (Mahon and Ellis, 1968). The flows from the springs, other than the Ohaaki Pool and a neighbouring spring, were relatively small and usually less than 1 litre/sec. The two largest pools discharged 12 litres/sec, approximately 1/3 of the total surface flow of 30 to 35 litres/sec. This was very small compared to that from Geyser Valley, Wairakei, which was estimated to be 250 litres/sec in 1951 (Gregg 1958). Gregg and Laing (1951) numbered more than 230 different features in Geyser Valley, of which 22 were active geysers. A detailed list of features at Ohaaki was not compiled but Mahon and Ellis considered only seven springs worth sampling in 1965 only two of which were boiling. The total heat flow was about 100 MW (Nlis 1980) compared to about 500 MW at Wairakei and at Waiotapu.

The hot waters discharged from springs in the Ohaaki-Broadlands area were mainly neutral-chloride-bicarbonate waters. Chloride concentrations ranged from 300 to 1000 mg/kg and the consistency of the Cl/B, Cl/F and Na/Li ratios was used to suggest a common reservoir of hot water. Springs 6 and 7 located in the south area of activity on the east bank of the Waikato River (close to BR7) had Cl/B ratios of 8 and 8.2 compared to features in the north and west with values of 10 to 11. This difference was not seen to be significant (see later) and the generally low Cl/B ratios were interpreted to be due to the presence of andesites (c.f. Kawerau) or sedimentary formations (c.f. Ngawha).

The high bicarbonate concentrations in the flowing pools (eg Ohaaki Pool had $HCO_3 = 680$ mg/kg) were correctly interpreted to indicate high CO_2 pressures at depth. Silica concentrations in the springs of up to 340 mg/kg indicated minimum temperatures of 200°C. The high sulphate and ammonia concentrations in the lower pH spring waters suggested that they were partly steam heated. Calcium concentrations were low in the flowing pools due to the high bicarbonate. It was apparent that the low natural heat and mass flow indicated low permeability and that these flows would be affected rapidly by well discharges.

BR1 to BR10 (Fig 1)

Drilling began in 1965 and BR1 was discharged on 1/2/66 and BR10 on 9/5/68. The waters discharged from the first ten holes showed the existence of a relatively homogenous body of water in the vicinity of Ohaaki

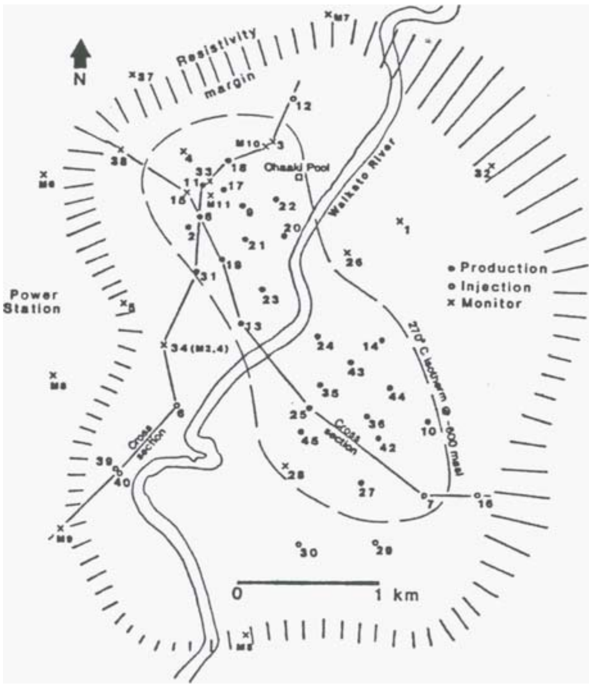

Figure 1: Plan of the Broadlands/Ohaaki system showing the location of production, injection and monitor wells drilled between 1965 and 1984. The resistivity margin (Risk, 1986) and 270°C isotherm at ~900 m depth (-600 m.a.s.l.) are also shown.

Pool eg BR2, BR3, BR4, BR8 and BR9, with chloride concentrations of 1250-1350 mg/kg in the deep water. The chloride concentration was constant with depth to over 500 m. The closeness of these holes to a major upflow zone was indicated by a number of chemical parameters, i.e. the quartz and alkali geothermometer gave values close to the maximum temperatures measured in the wells, and the relatively low CO_2/H_2S and low concentrations of HCO_3, SO„ Ca, and F indicated high temperatures. The silica temperatures were close to those measured just below the Broadlands and Ohaaki Rhyolites indicating those as zones of permeability. The first 3 East Bank wells, BR1, BR7 and BR10 had high Na/K ratios, and much higher HCO_3 concentrations and CO_2/H_2S ratios than the West Bank wells. It was suggested that these did not indicate a flow from the Ohaaki Pool area to these eastern wells but that the chemical differences were due to the impermeability of the rocks into which these wells were drilled. N.B. Temperatures in these three wells showed maxima at 270-280°C compared to 265-290°C in the five high temperature western wells.

The other difference noted was the change in Cl/B ratios from 11 in the West Bank to 6.8 to 7.0 in the East Bank. The low ratios were related to the high elevation of greywacke. The high gas concentrations deduced from the spring chemistry were observed in the wells. The CO_2/H_2S gas ratios ranged from 35 to 130 with CO, and H_2S gas concentrations being 7 to 50 and 35 to 130 times higher than those found at Wairakei. The low enthalpy wells, BR8 and BR9 were used to obtain a best guess of the deep fluid gas concentrations ie CO_2 = 250 millimole/100 moles (0.6 wt %) and H_2S = 5.6 millimole/100 moles (0.011 wt %). Later estimates based on BR19 (see below) are somewhat higher.

Mineral equilibria calculations showed that feldspar-mica controlled the pH and that the water was just undersaturated with respect to calcite.

The other major chemical information was obtained from BR5 and BR6. These wells, drilled in the SW showed that the chloride water became colder and more stagnant and eventually disappeared at BR6, at least between depths of 650 and 1080 m. The chloride content of BR6 was approximately 30 mg/kg whilst the bicarbonate and calcium contents were exceedingly high (2300 and 250 mg/kg respectively). The latter two resulted in a thick build up of travertine at the outlet of the bypass pipe. It was suggested that the near-neutral calcium bicarbonate water discharged from this drill hole was probably heated by steam separating and migrating from the chloride water reservoir further north.

Early temperature decreases were noted with the discharge of UR3 (low permeability) but not in BR2 and BR8 (large producers).

Flow from Ohaaki Pool ceased subsequent to well discharge. This pool was particularly affected by BR3. It was obvious that the flow of hot water to the surface was limited, indicating relatively low permeability in the sub-surface rocks. The chloride content of the pool remained constant at around 1050 mg/kg during the period 1950-1968. This is in contrast to the springs in Wairakei Geyser Valley which showed dilution before flow ceased. This illustrated the effect of permeability, ie high permeability at Wairakei allowed ready access of surface waters once pressures decreased whilst at Ohaaki, low permeability inhibited dilution.

LATER CHEMISTRY

(1) Fluid inclusion thermometry

Several fluid inclusion studies incorporating homogenisation (Th) and ice melting (Tm) measurements have been conducted on Broadlands quartz and calcite. Browne et al (1976) concluded that the fluid inclusions formed at temperatures similar to those now existing. However, closer examination of a larger data set (Hedenquist 1989) showed some systematic trend. If the pre-drilling temperature (inferred from drillhole measurements) is subtracted from the mean fluid inclusion temperature at the same depth, an indication is observed of whether the system has been heating or cooling since fluid inclusion formation. Major cooling (up to 30°C in BR16) is indicated in the eastern part of the East Bank and in the margins of the West Bank (Fig.2). In contrast there is good correlation between fluid inclusion and present temperatures in the production zone, even evidence of heating in some West Bank wells since fluid inclusion formation. In general Th values for secondary inclusions are lower than for primary inclusions and are closer to present temperatures. The cooling cannot be explained by lower hydrostatic head but by incursion of marginal fluids.

(2) . Fluid types and evidence for boiling and mixing

Fig.3 shows aquifer chloride concentrations versus the enthalpy of the aquifer. The effects of "excess enthalpy" are caused by two phase flow into a well or separate liquid and steam feed zones. The varying amount of steam shows a steam gain or loss trend (Hedenquist et al 1988), and if this is eliminated theoretically the basic mixing relationships are seen more clearly.

West Bank wells show similar aquifer enthalpies to those on the East Bank but the latter have slightly lower chloride concentrations. Wells on the margins have compositions between the production fluids and a diluting end member with chloride = zero and aquifer enthalpy = 630.5/g (= 150°C). This is steam heated ground water with a high temperature zero chloride and high dissolved CO_2 (Hedenquist and Stewart 1985). This water was noted previously e.g. BR6 (Mahon and Finlayson 1972) and its genesis from the deep chloride water examined (Mahon et al. 1980). Later when severe corrosion problems were noticed with shallow casing its extent and chemical characteristics were examined in more detail. It is a CO_2 rich fluid rather than a bicarbonate fluid as carbonic acid predominates. Cross sections (Figs 4 and 5) show the prevalence of the CO_2 rich fluid.

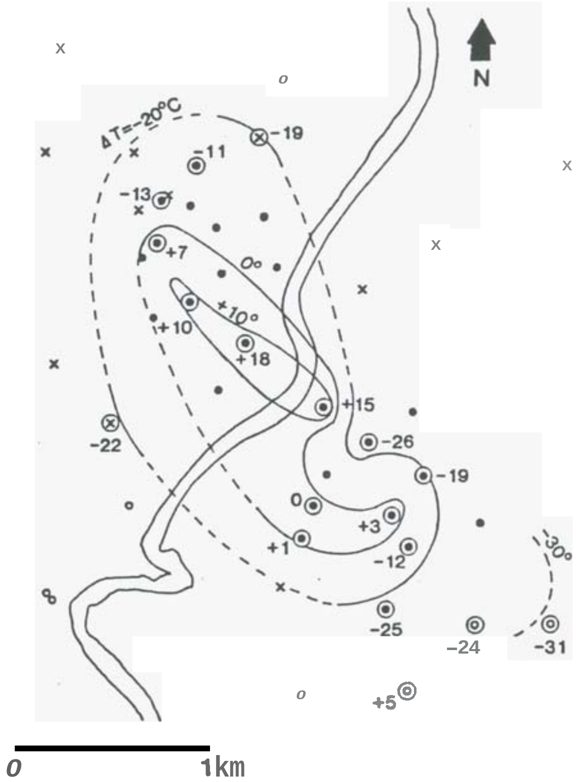

Figure 2: Comparison of past (primary fluid inclusion homogenization) with present (measured) temperatures (AT, Table 2). The eastern portion of the East Bank and the margins of the West Bank have cooled considerably probably due to dilution, since peak thermal conditions.

On average the East Bank wells are diluted 15-25 % by steam heated fluid from the parent fluid (BR15), whilst West Bank production wells are usually boiled equivalents of the parent. The mixing is seen in the diluted waters on the margins and temperature inversions which correlate with the diluted waters.

The excess enthalpy of most of the East Bank wells is due to relative low permeabilities related to the late deposition of illite, which is in turn a factor related to the incursion of and dilution by the marginal waters. It is important to note that the best producer BR25 has no excess enthalpy, the least dilution (Rg.3) and does not have fluid inclusion evidence of cooling (Fig.2).

Ohaaki pool shows that the West Bank fluids are diluted by steam-heated waters at shallow levels and is evidence for the existence of steam heated waters on the western margins. Further evidence for the wide spread existence of steam heated water comes from comparison of initial and recent (post-long discharge) composition (Fig.3 inset). In most cases production wells show a change in chemistry consistent with dilution by steam heated waters, with the dilution having been mused by depressurisation of the system related to the discharge testing (Hedenquist et al 1988) and draw down of the steam heated water.

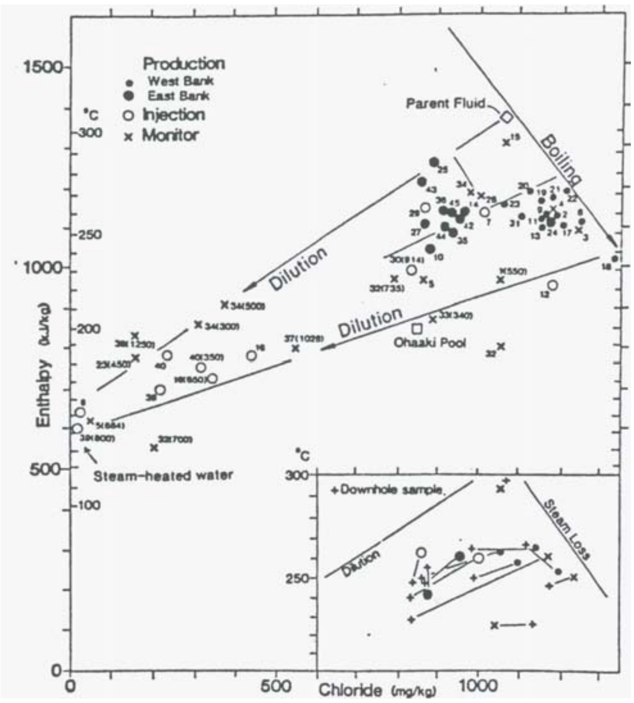

Figure 3 Chloride-enthalpy plot of initial discharge chemistry, corrected for steam loss and excess enthalpy to quartz geothermometer temperatures (or to chalcedony geothermometer values in the case of values ~<180°C). The depth of downhole samples is shown in parentheses (m). Modified from Hedenquist and Stewart (1985) and Hedenquist et al. (1988).

(3) Gas chemistry of the chloride fluids and steam heated waters

Broadlands has one of the highest gas contents of New Zealand geothermal systems (Hedenquist & Henley 1985, Giggenbach 1986). This is related to the magmatic component of the gases and its location along the eastern andesitic arc margin of the Taupo Volcanic 'Zone (Giggenbach 1989). All initial total discharge gas concentrations have been plotted in Fig.6 and model curves calculated for gas fractionation from a boiling liquid and its corresponding vapour phase (Glover 1970). The liquid model curve has been adjusted so that it is consistent with the lower limit of gas concentrations passing just over most of the plotted data. The situation has been modelled assuming a 280°C liquid of composition similar to BR19 with the parent 300°C liquid composition calculated for single step separation; the coexisting vapour composition has also been calculated for 20°C steps. These end member curves envelope most of the gas data, with intermediate points resulting from excess enthalpy mixtures, or from continuous vapour separation From the 300°C parent fluid (modelled by 1°C steps - dashed line). The higher gas contents in total discharge for East Bank wells is due to the common Occurrence of

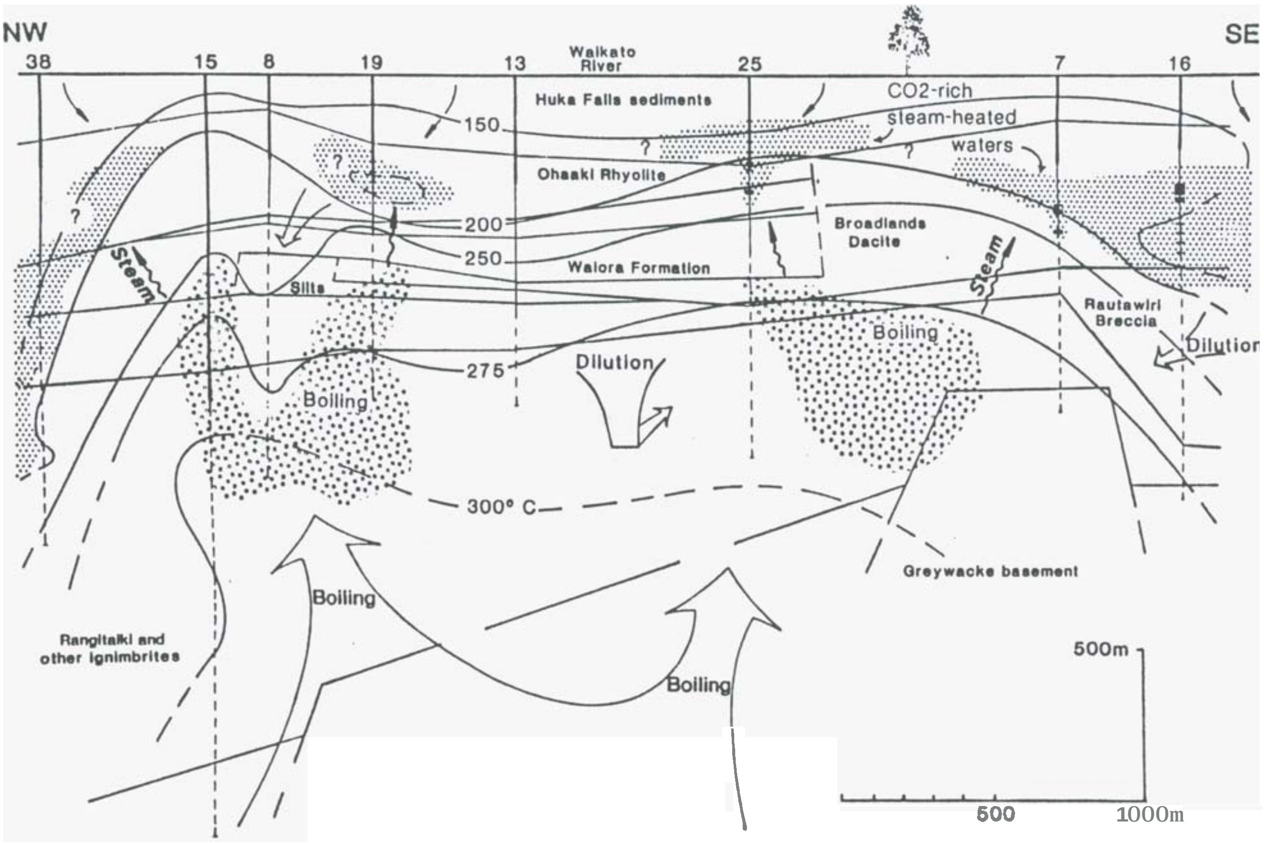

Figure 4 Northwest-southeast cross-section through the Broadlands system showing stratigraphy (Browne, 1971a; Wood, 1983) and isotherms (initial measurements after post-drilling stabilization; Ministry of Works and Development, 1977), and the inferred (schematic) distribution of CO_2-rich, steam-heated waters (stippled) as well as general patterns of boiling and dilution. The pattern denoting boiling is only meant to imply upflow; boiling is not restricted only to these zones. Rather, boiling conditions will prevail across most of the base of the system from at least 300°C, where the isotherm is near horizontal and will continue to the near surface in the two zones of upflow. The steam-heated waters form over the top of the system and then drain to deeper levels on the margins. The position of extreme (external) casing corrosion (Hedenquist and Stewart, 1985), marked on BR7, 16 and 25 casing, and some of the thermal inversions help constrain the distribution of the steam-heated waters. Modified from Hedenquist and Stewart, 1985.

excess enthalpy conditions, which result from lower permeabilities here, possibly due to the abundance of illite deposited into fractures.

The calculated parent fluid at 300°C has a CO_2 concentration of 0.62 molal (2.7 wt %) and H_2S of 0.0044 molal (0.015 wt %) and a CO_2/H_2S ratio of 132 This compares well with a gas content of 0.9 molal deduced by Sutton and McNabb 1977, by modelling the vapour pressure depth relationship (ie the deviation from that of pure water is due to the gas concentration). A model curve based on *0.6* m CO_2 at 300°C closely matches measured temperature profiles in production wells.

The gas concentration of steam heated water is very variable. Downhole samples of these waters show CO_2 concentrations between 0.02 and *0.50* molal and more than 90% present as H_2CO_3. Elevated CO_2/H_2S ratios from 300 to 1600 are observed in the steam heated waters (eg $CO_2/H_2S = 347$ in BR40) probably due to at least 3 processes:

(a) H_2S being more soluble than CO_2 therefore the CO_2/H_2S ratio in the steam is greater than that in the parent fluid.

(b) Partial oxidation of H_2S in the steam heated waters.

(c) Pyrite formation (up to 8 wt % has been observed at shallow levels in BR16; (Ewers and Keays 1977).

The distinction between East Bank and West Bank chloride fluids is also evident in the N_2-Ar-He relationship (Giggenbach 1986, 1989). East Bank fluids appear to have a more "magmatic" signature (ie a higher N_2/Ar ratio) than West Bank fluids. This may be due to a greater age of water-rock interaction in the East than the West. Thus the East Bank rocks may have less capacity to overprint the magmatic signature than the younger West Bank portion of the system.

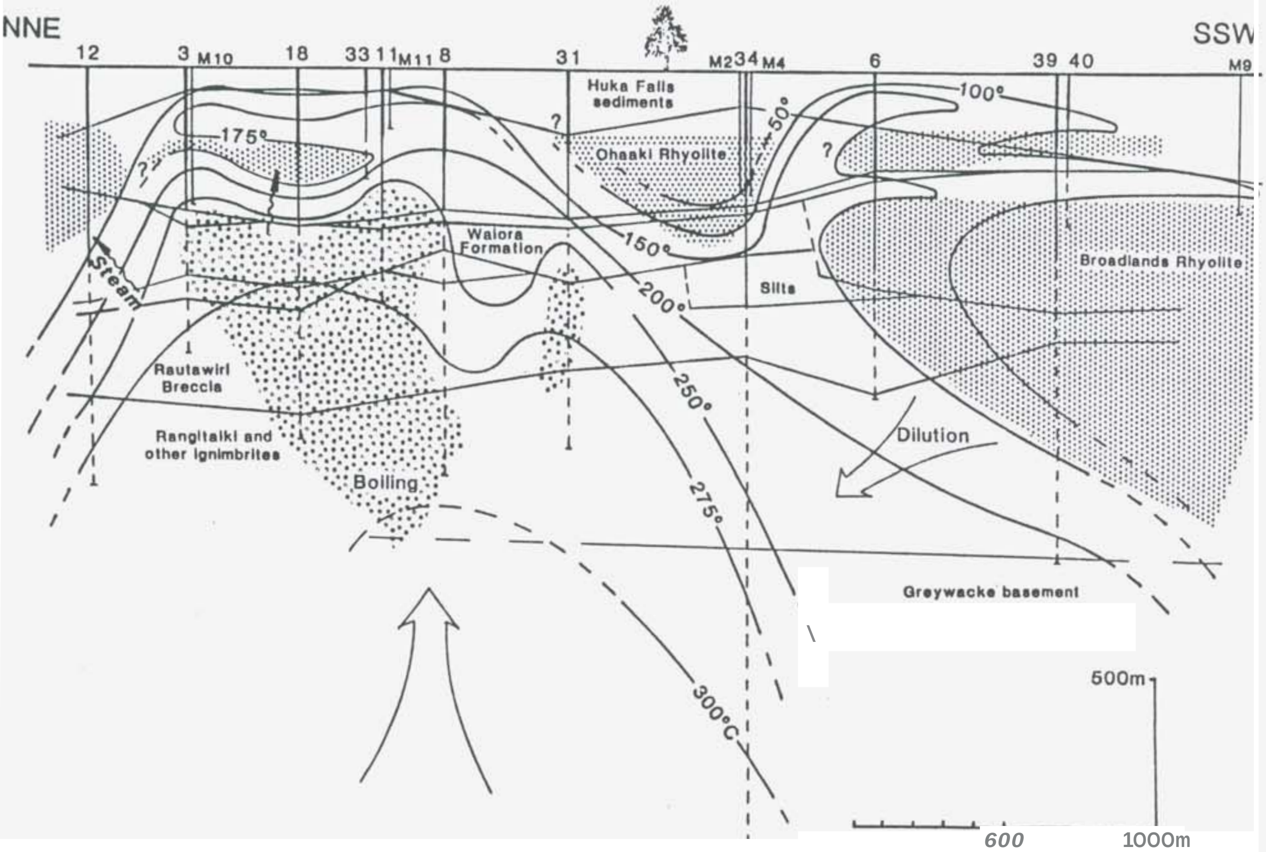

Figure *5:* North northeast-south southwest cross-section through West Bank wells, showing the same information as **Fig.4.** The extensive presence of steam-heated waters on the southwest margin of the system is confirmed by the chemistry of downhole samples of BR6, 39 and 40. This section is essentially parallel to the dominant structural trend (and direction of fracture permeability?) in the Broadlands system.

(4) Variations in Chloride/Boron ratios

The chloride/boron ratios in Ohaaki waters vary from 4 in BR16 to 15 in BR37 (Fig.7). There is a close inverse correlation between depth to basement (local elevation -300 m.a.s.l.) and the Cl/B ratio, with discharges from wells in the vicinity of the horst block (southeast) having the lowest Cl/B values, and the highest Cl/B ratios found in the northwest where the depth to the greywacke or thickness of volcanics is the greatest. This compares with Ngawha, where low Cl/B ratios (< 1) are found probably due to interaction with greywacke sediments, (Ellis and Mahon 1977). If this were the reason for the changed Cl/B ratio it would mean that 1 km of extra greywacke doubles the boron content. Alternatively, boron may be fixed in alteration minerals in volcanics above the basement. If this process occurred higher Cl/B ratios might be expected at shallower levels in a drillhole. Five wells (Table 1) had downhole samples collected from different levels and all five showed a higher Cl/B ratio at shallower levels.

CONCLUSIONS

Meteoric water circulates in the Broadlands system to depths where it is heated by conduction and magmatic input with the magmatic component providing much of its chloride and dissolved gases (Giggenbach 1986, 1989). In the past, the upflow of deep fluids occurred to a greater degree on the eastern portion of the near surface (<2000 m depth) system. Boiling in the upper 1500 m resulted in the formation of marginal steam-heated fluids that subsequently diluted the ascending chloride fluid. With time this dilution occurred at deeper level, particularly in the East Bank. This decreased average permeabilities in the East Bank by deposition of illite and may have shifted the locus of the upflow towards the West Bank. At the West Bank

TABLE 1

Well	Depth	Cl	B	Cl/B
BR12	635	1229	31.6	16.3
BR12	1300	1115	35.9	9.5
BR16	650	333	24.2	4.2
BR16	1200	824	64.8	3.9
BR32	608	50	<1	> 15
BR32	1050	1074	36.6	9.0
BR34	740	35	0.6	18.0
BR34	1250	933	24.8	11.5
BR39	800	28	1.2	7.1
BR39	1470	16	1.0	4.9

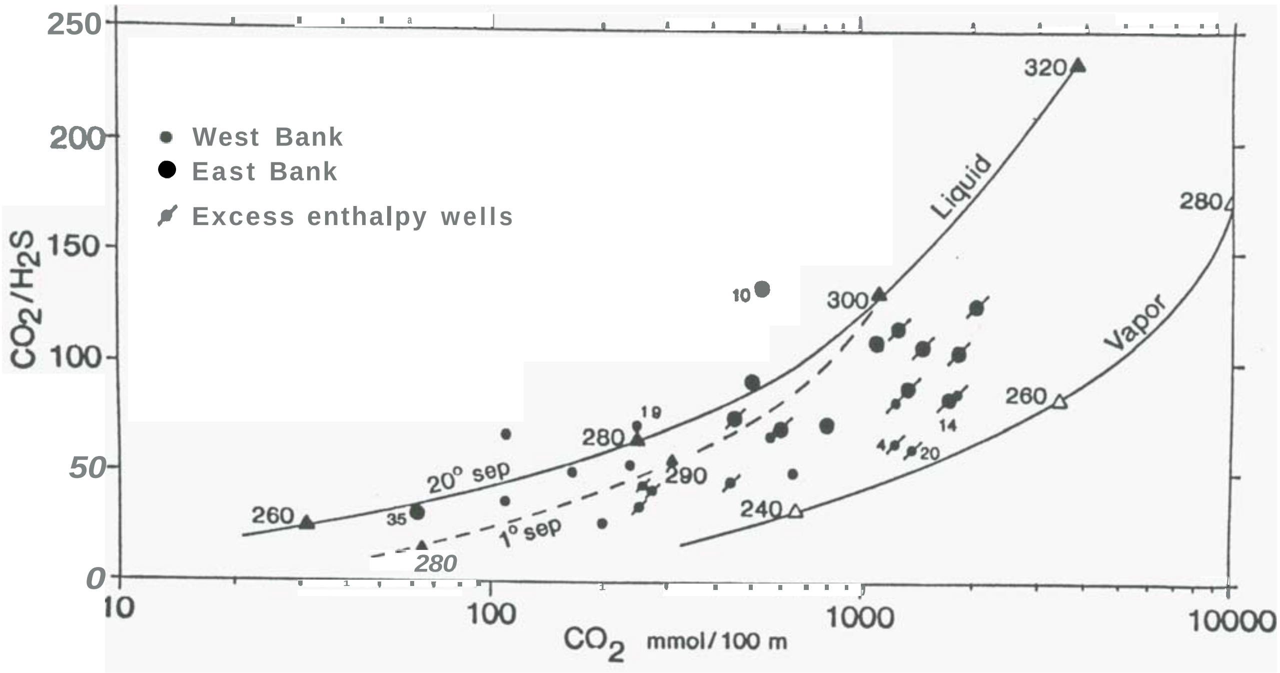

Figure 6: CO_2 (mmol/100 mol) - CO_2/H_2S ratio for total discharge compositions. The 20x variation in total CO, between wells, as well as the variation in CO_2/H_2S ratio, can be accounted for by gas loss from a boiling liquid, and/or a two-phase mixture of liquid plus vapour (ie excess enthalpy discharge).

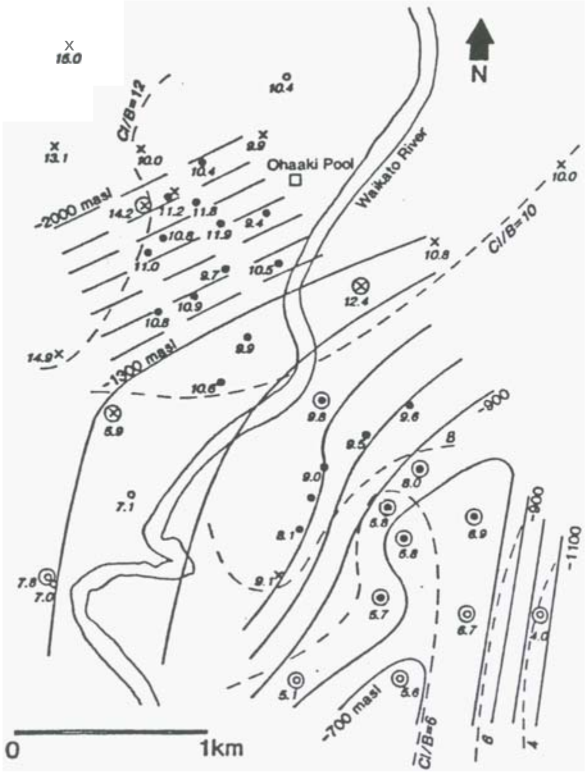

Figure 7 Map showing the elevation (in m.a.s.l.) of the top of the Mesozoic greywacke basement (data from Browne, 1971a; Wood, 1983); wells which penetrate basement are circled.

fluids until they reach shallow levels (500-1000 m depths) and the margins of the system.

The presence of steam-heated waters along with cold ground water act as a diluent of the deep upflow and can markedly affect the hydrology of the system (both in its natural and exploited states). Conversely, identification of the distribution (and chemistry) of steam heated waters will assist in the defining the zone of deep upflow. It will also allow their potential for corrosion and dilution to be assessed.

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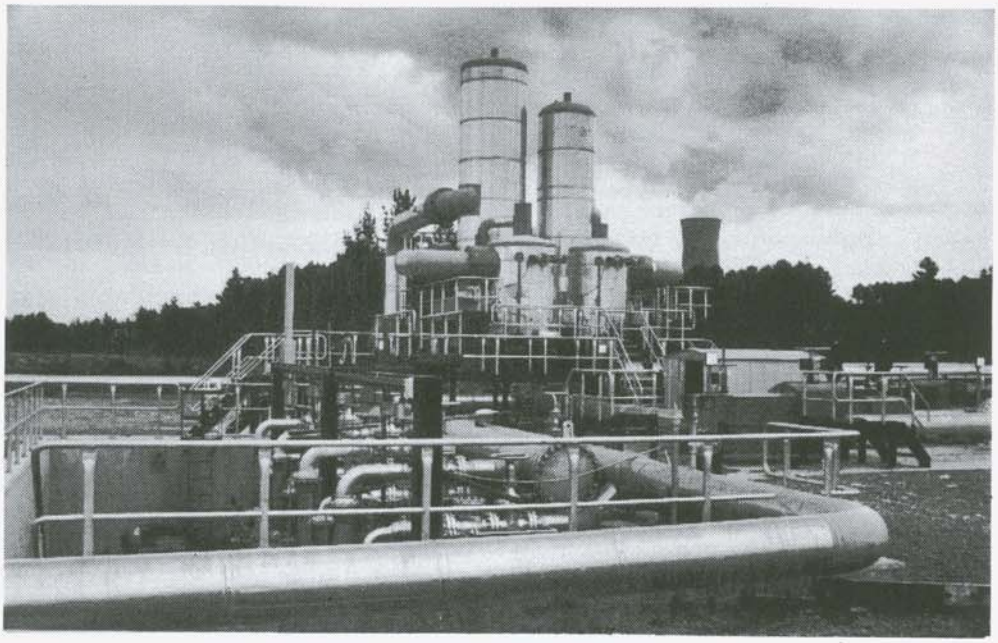

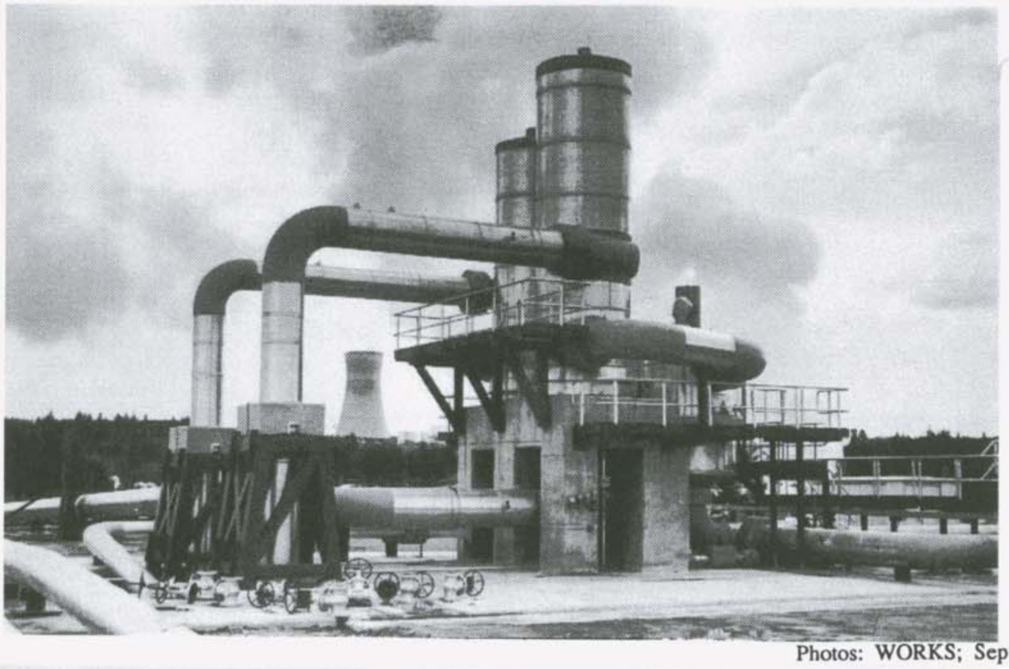

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