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CHARACTERISTICS OF BROADLANDS - OHAAKI WATER CHEMISTRY, AND CHANGES SUBSEQUENT TO INITIAL PRODUCTION

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ABSTRACT

The chemistry of initial discharges from wells in Broadlands-Ohaaki geothermal system, New Zealand, indicates two 'separate' deep waters, one typically discharged from wells in the northern portion of the system and the other discharged from southern wells. However, the primary source of these two waters is likely the same, with only processes along separate north and south 'pathways' being different.

Boiling is the dominant process affecting the northern waters, whereas southern waters are diluted considerably before undergoing any boiling. The dilution water is cool (~150°C), dilute chloride water, rich in bicarbonate. It has developed on the margin of the system (and over its top) by the condensation of steam plus CO_2 into meteoric waters. These condensates diluted to some extent northern (Ohaaki) production waters subsequent to initiation of discharge testing. However, this dilution appears to have been caused by a greater contribution from a shallow feed to the wells rather than dilution in the production formation itself.

INTRODUCTION

The Broadlands-Ohaaki geothermal system, located within the Taupo Volcanic Zone of New Zealand, was first drilled in 1966. At present, a 110 MW electrical generation station is scheduled to be commissioned in 1987. The subsurface pattern of temperature at Broadlands is rather simple and well known (M.W.D., 1977); as a result, most wells are 'hot', with a maximum of 304°C measured. However, several 'hot' wells are relatively impermeable and have no potential for steam production. The wells are distributed along the east and west banks of the Waikato River into a northern group near the Ohaaki Pool and a southern group near Broadlands (Fig. 1); other than Ohaaki Pool, natural discharges are minor. To date, 43 wells have been drilled, of which approximately 20 will be used for production.

The purpose of this study is to identify chemical characteristics of initial fluids discharged from Braadlands wells that may assist in a better understanding of the physical characteristics of the wells and of the system itself. Paramount for the siting of any further production and injection wells is the understanding of permeable zones and the paths of fluid movement.

This report is preliminary, in that it only considers 'initial' discharge chemistries (representative of the initial feed zone(s) to the well). Whether or not this 'initial' discharge is characteristic of the extended discharge chemistry, and patterns of chemistry change with discharge (during large scale testing from 1967 to 1971), are only briefly considered.

The geology and alteration of the Broadlands-Ohaaki system has been discussed by Grindley and Brown (1968), Browne and Ellis (1970), Browne (1971, 1973) and Wood (1983). The geochemistry of the waters was investigated by Mahon and Finlayson (1972), and again summarized in a M.W.D. report (1977). The results of the 1967-1971 production testing, and subsequent recovery, were discussed by Hitchcock and Bixley (1976) and further interpreted by Grant (1977).

WATER CHEMISTRY

From the analyses of well dis'charges (Mahon and Finlayson, 1972), it is clear that there are two principle types of subsurface thermal waters. One is a chloride water, typical of the deep upflow of most Taupo Volcanic Zone systems. Chloride is by far the dominant anion, and the concentrations of major cations (Na, K, Ca, Li) as well as silica are controlled by temperature-dependent mineral-water reactions.

The other principle water type has bicarbonate as a major or dominant anion (here arbitrarily defined as $m_{Cl}/m_{HCO3} < 2$ for separated water at analysis temperature), and is exemplified by waters from wells 5, 6, 12, 16, 32, 37, 38, 39, 40 (Fig. 1). In some cases, sulphate is also significant in these waters (e.g. wells 32, 37, 39). These waters are distributed around the margin of the drilled system (Fig. 1), and were first clearly defined and interpreted by Mahon, et al. (1980).

These waters form by the condensation of steam plus gas (largely CO_2 and H_2S) into dilute and cool meteoric water, and form mainly on the margins of the system adjacent to chloride waters. Most of the bicarbonate waters at Broadlands are actually mixtures of the steam-heated bicarbonate

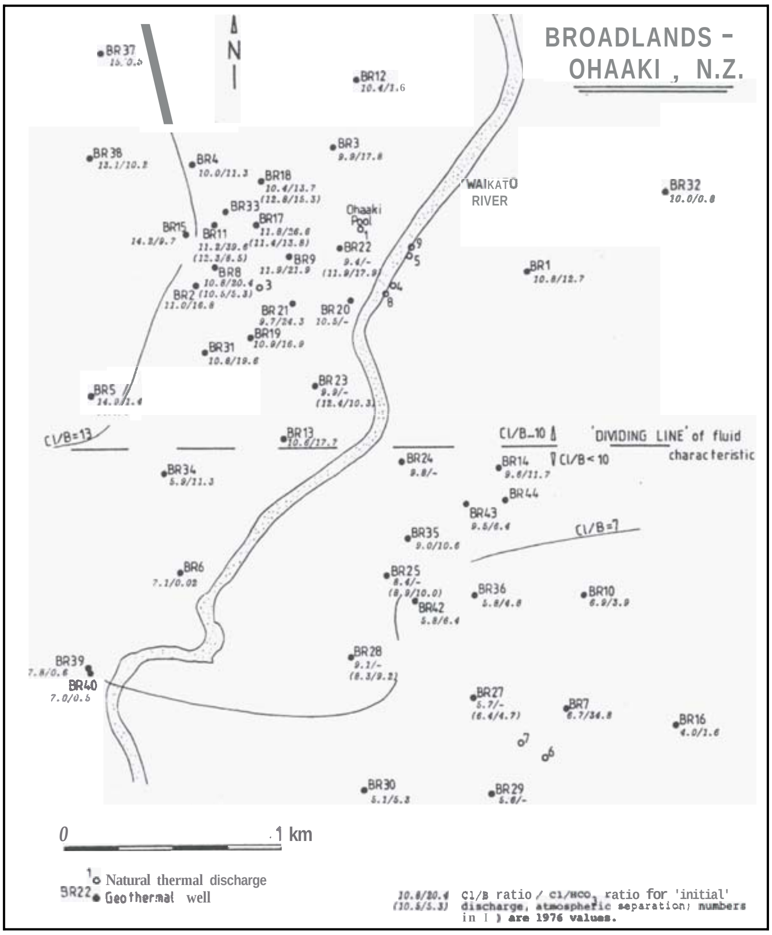

Figure 1: Cl/B and Cl/HCO$_3$ ratios in initial and 1976 well discharge waters, separated at atmospheric pressure (except for the downhole samples, Figure 2). In general water chemistry characteristics separate the wells into northern and southern types, coincident with Cl/B = 10 (see also Figure 2).

water (containing nil chloride) and deep chloride waters, though waters from well **6** are most representative of the unmixed, endmember bicarbonate water.

Mixing Relationships

Mixing relationships may be most simply represented by plotting the conservative quantities of chloride and heat content (i.e. not gained or lost in mineral reactions) (Fig. 2). Heat contents of each water are determined from quartz geothermometers, assuming that they are (relatively, at least) most representative of true feed zone temperatures; chloride concentrations are corrected for steam loss during sampling from the quartz geothermometer temperature and for any excess steam in the formation, i.e. excess enthalpy wells (data summarized from Mahon and Finlayson, 1972, M.W.D., 1977 and D.S.I.R. and M.W.D. files). Some wells (30, 32, 37, 38, 39) were not able to sustain a discharge, and were sampled down the well; where there was a concentration gradient down the well, the analysis plotted is from the highest chloride zone.

Boiling and steam loss by a water in the formation will result in a fluid's composition migrating away from the steam point on the mixing diagram (at zero chloride and ~2800 kJ/kg), i.e. to a higher chloride at a lower temperature. Dilution in the natural system will result in a mixture plotting between the two end members. However, as pointed out by Grant, et al. (1982), dilution by a 'cold sweep', due to exploitation, will result in the chloride decreasing but enthalpy remaining almost constant. This is due to the heat buffering capacity of the rock over geologically short periods of time (a few years), and has been demonstrated to occur at Cerro Prieto by Grant, et al. (in press).

Figure 2 illustrates a relatively simple pattern of water chemistry at Broadlands. A majority of wells in the Ohaaki Pool vicinity have quartz temperatures from 250° to 270°C, and deep chloride concentrations of about 1100-1200 mg/kg. Waters from west bank wells on the margin of the system (37, 38, 39, **40**) all plot close to a dilution line between the high temperature, high chloride waters (A$_1$) and the nil chloride, bicarbonate-rich water in well **6** (B). This bicarbonate endmember has a chalcedony geothermometer temperature of 150°C (it is usually observed that waters cooler than 170° to 180°C are usually in equilibrium with chalcedony rather than quartz).

In many cases, the high chloride, northern (west bank) wells lie above the dilution trend, A$_1$-B. This is due to boiling of a water (either before or after dilution) and steam loss in the formation before it reaches the well (in the system prior to any significant exploitation, i.e. 'initial' discharge). The greatly diluted natural spring waters also plot above (though parallel to) this line. This may be caused by silica precipitation as the waters slowly rise to the surface (in the case of warm springs) and/or boiling (in the case of Ohaaki Pool). Most springs have a low Cl/HCO$_3$ ratio, consistent with their being a result of dilution of deep chloride waters by carbonate-rich waters.

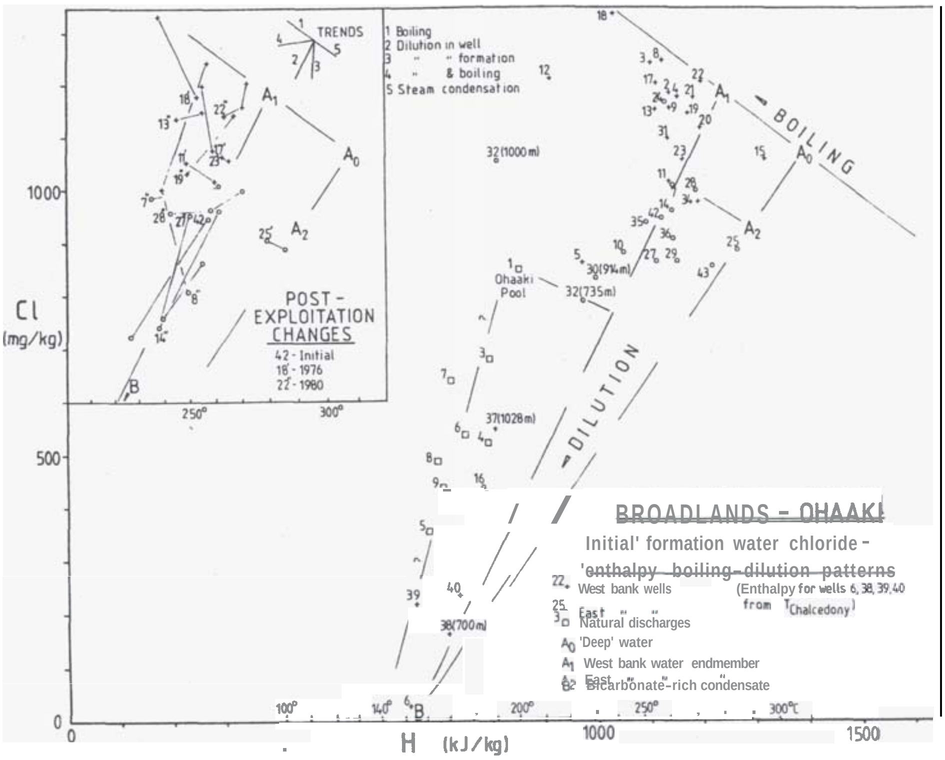

Figure 2: Chloride-enthalpy boiling dilution diagram for Broadlands-Ohaaki waters. West bank deep waters have apparently undergone a greater amount of boiling prior to dilution than have east bank waters. Post-exploitation dilution trends for several wells (inset) indicate a greater contribution in the well by a more dilute water than initially produced (trend 2). If the dilution was in the fornation, it would be expected that the rock would buffer the temperature (and reset the Quartz geothermometer in the diluted water) thus resulting in trend 3.

Several of the southern (mainly east bank) wells plot on or near to the dilution line A -B (e.g. wells 7, 10, 14, 30, 35, 42). However! several others plot below the dilution line A_1-B (e.g. wells 25, 27, 28, 29, 36, 43 as well as west bank 34). Although this could be caused by condensation of steam into diluted water, the more realistic possibility is that they have resulted from boiling of a water plotting near A_2 and dilution with B (or vice versa).

A_1 and A_2 could be separate waters, to the extent that their origins are relatively distinct, with the more dilute southern area water derived from greywacke basement (its proximity is noted in well logs). However, the preferred model is for both A_1 and A_2 being derived from a single parent, A_o; A_1 undergoes boiling as it ascends before being diluted, whereas A_2 follows another path involving some dilution before any boiling takes place. Water from well 15 is most similar to A_o, and may be a deep hybrid between A_1 and A_2; it is interesting to note that this is the deepest well at Broadlands and probably discharged from a zone greater than 2000 m deep (M.W.D., 1977).

Exactly where this differentiation (branching of the two paths) takes place (location and depth) is not certain; the estimated minimum temperature of A_o (≥310°C) is only slightly higher than the maximum measured temperature (~304°C). This simple model suggests two distinct 'pathways' for waters up to depths where they feed individual wells, with dilution in the southern wells playing a greater role than in the northern wells.

Grant (1977) points out temperature inversions (a 'cold river') in wells 3, 9, 13, 17, 18, 23 at about 300 m. The temperature drops to ~160°C, consistent with the temperature for the bicarbonate-rich endmember. If A_o water is indeed being diluted by B, this would indicate a very deep penetration of the bicarbonate-rich water, probably along the margin of the system.

Well 24 possesses west bank characteristics, whereas well 34 possesses east bank characteristics. This suggests that the 'dividing line' between the two different domains runs more closely east-west than east bank-west bank (Fig. 1). This separation is also clear in terms of Cl/B ratios, with well waters north of the 'dividing line' (Fig. 1) having Cl/B ≥ 10, whereas those south have a Cl/B <10, and down to 4 (well 16).

DISCHARGE CHEMISTRIES - TRENDS WITH TIME

Fig. 2 (inset) shows the changes from 'initial' discharge to October 1976 for wells 8, 11, 17, 18, 22, 23, 24, 27 and 28. The initial discharges for wells 22 and 23 are in 1971, the year of shutdown, and the initial discharges for wells 27 and 28 are in 1974, after shutdown. Also plotted are compositions for wells 7, 8, 13, 14, 19, 22, 27 and 28, discharged in 1980.

Dilution by a 'cold sweep' (Grant, et al. (1982) of bicarbonate-rich water in the formation due to depressurization following exploitation will not result in movement along the dilution line. Rather, the heat stored in the formation will tend to buffer the heat content of the water (and steam) and will presumably reset the diluted silica content to that for the formation temperature. This should result in an apparent trend towards a hypothetical dilute but hot water.

However, dilution trends which follow the A -B line, subsequent to exploitation suggest that they are due to deep waters being diluted in the well. This would be caused by a greater contribution of a shallow, dilute feed to the well following depressurisation in the deep, principle feed zone.

For the period 'initial' discharge to 1976, wells 11, 23 and 25 show a simple boiling trend, with well 11 (the longest discharged) having the greatest amount of apparent boiling. wells 8 and 22 show trends almost parallel with dilution trend. Based on the previous argument, this would suggest a greater contribution by a dilute feed zone due to depressurisation. Wells 17 and 18 show dilution with a slight increase in temperature This trend may indicate dilution within the formation, with the heat content buffered by the rock, as well as sane degree of condensation. Finally, the trends in wells 27 and 28, whose initial discharges were after shutdown in 1971, suggest a dilution in the well, with possibly some boiling in the vicinity of well 28.

Trends up to 1980 suggest boiling and steam loss was continuing at a greater rate than during pre-exploitation, due to the depressurised state, in wells 7, 13, 19, 22, 28; variable amounts of dilution are also indicated in these wells. The trend for well 8 suggests dilution within the formation, while that for well 14 suggests dilution within the well. Well 27 actually shows a marked increase in a deep component from the 1976 discharge, possibly due to the 1976 dilute component (from a dilute feed zone) decreasing its contribution to the total discharge.

DISCUSSION

These trends should be treated with caution, as they are each based on only two (and in three cases, three) samples; further compilation of chemical and physical data will allow more conclusive trends to be determined for each well throughout their production history. Although in some instances the observed differences in discharge chemistry may simply be related to variation in wellhead pressure and a variable contribution by two feed zones, no pattern was discerned when wellhead pressure was considered (i.e. it may be expected that a low wellhead pressure may allow a greater contribution from a more shallow, dilute feed zone). The probability that these trends are real (i.e. due to variations in feed zone chemistry or variable contributions from multiple feeds) must be considered, as they would have major implications on the performance of a well with continued discharge.

Trends suggestive of a 'cold sweep' by a shallow, diluting water are not conclusively apparent. There are trends indicating increased boiling and steam loss in the production formation, likely due to the decrease in formation pressure subsequent to exploitation. However, if this pressure decrease is largely due to loss of the CO_2 partial pressure, then it is perplexing why boiling would increase, since loss of gas would cause the boiling temperature at a given depth to increase. Therefore, CO_2 loss should be a self limiting process, with less boiling due to an increase in the boiling temperature resulting in less CO_2 loss.

The most conclusive trend is one of dilution, with the dilute water likely bicarbonate-rich, as evidenced by the projection of the trend and the decrease of the Cl/HCO_3 ratio with dilution (Fig. 1). However, it appears that this dilution may be occurring mainly in the wells, due to a greater contribution by a dilute feed following depressurisation. Although not as serious as dilution of the production formation, this must still be identified in order that these dilute feed zones may be sealed.

CORRELATION OF WATER CHEMISTRY, ALTERATION AND WELL PRODUCTIVITY

Besides chloride and boron, other constituents such as rubidium, caesium and lithium have often been considered as conservative elements, i.e. they are not affected by alteration minerals to a significant degree. However, Goguel (1983) has shown that Rb, Cs and Li are selectively concentrated in alteration minerals at Wairakei and Broadlands (e.g. Rb in illite, Li in chlorite and quartz, and Cs in wairakite).

Browne (1978) has discussed mineralogical indicators of permeability at Broadlands (e.g. abundant adularia in permeable zones). If it is possible to relate trends of trace element content of waters to alteration mineralogy, it may therefore be possible to use these trends to relate to permeability characteristics of a given well or area.

Figure 3 shows a trilinear plot of Cl-Rb-Cs contents of Broadlands waters. If the marginal,

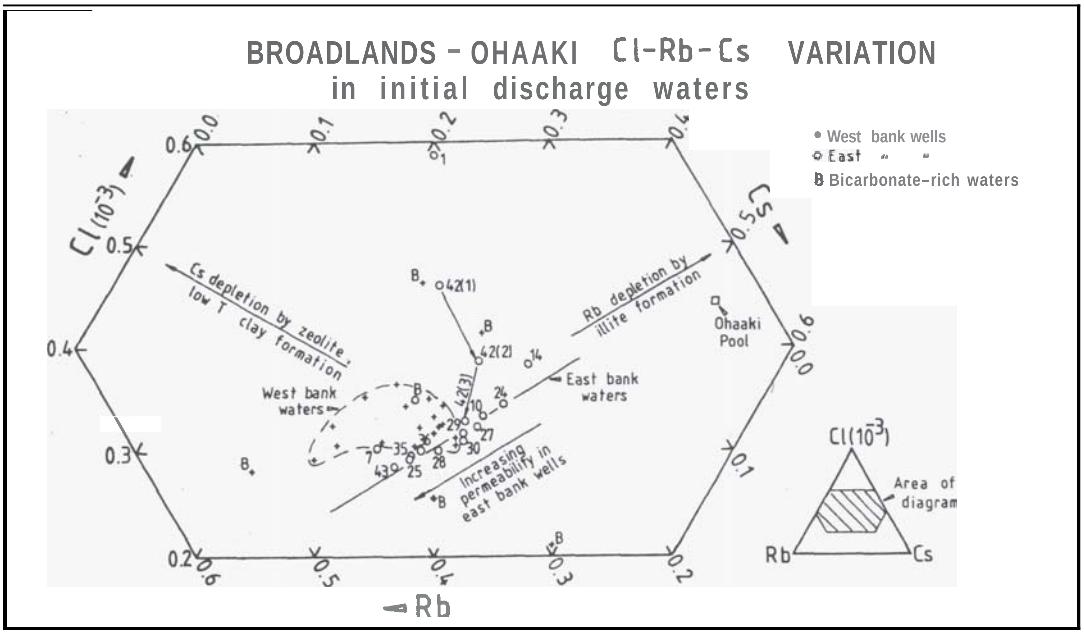

Figure 3: ***Variation** of **chloride-rubidium-caesium in initial discharge waters** of **Broadlands-Ohaaki. There does not appear to be any relationship** for **west bank waters, whereas most east bank waters fall on a trend parallel to rubidium depletion, with the most depleted waters coming from wells with Lowest permeability. This may be due to the formation** of **illite in these wells, which concentrates rubidium in its structure.***

high bicarbonate well waters are eliminated, it may be seen that all of the northern (mainly west bank) well waters plot in a small field that is almost exclusive of southern (mainly east bank) well waters. Also interesting is the fact that the southern, east bank waters define a linear trend almost coincident with a simple Rb depletion trend. This trend towards Rb depletion may be explained by increasing amounts of illite forming in the formation, which will selectively concentrate Rb in its structure (Goguel, 1983).

To test this, quantitative petrologic logs by Browne (1973) were reviewed for the wells on this trend. Only logs for wells 10, 14, 24 and 25 are available; wells past 25 have not been logged quantitatively. Illite is a common alteration mineral at Broadlands (a high temperature type of clay). Browne's logs show illite and other clays often comprising between 10 and 50% of the total mineralogy. However, the mineralogy of the feed zone, and not the whole well, will most accurately reflect water composition.

Based on loss zones (M.W.D. 1977), the dominant feed zones have been identified for east bank wells which have been quantitatively logged. For wells 10, 14, and 24, the feed zones all have between 15 and 40% illite, whereas the feed zone for well 25 has no illite but abundant adularia. Since 10, 14 and 24 plot on the Cl-Rb-Cs diagram in the direction predicted for illite formation, whereas 25 plots at the opposite end of the trend, this pattern empirically supports Goguel's work.

The interesting aspect of this observation becomes apparent when the productivity (i.e. permeability) of the wells is considered.

Well Characteristics

A large portion of the northern, west bank wells are productive (wells 3, 8, 9, 11, 13 and 17 to 23); wells 5, 6, 12, 32, 37, 39 and 40 are on the margin of the system, with bicarbonate-rich waters. The characteristics of southern, east bank wells may be summarised as follows: wells 25 and 35, good producers; wells 27, 28 and 36, moderate to poor producers; wells 7, 10 and 14, nil producers, but hot with a moderate injectivity; wells 24, 29 and 30, nil producers, hot but poor injectivity (M.W.D., 1977 and files). Comparing this summary for southern wells with Figure 3, it appears that the producers, aside from well 27, have relatively Rb-rich waters (i.e. no illite formation), whereas the waters from all the nil producers (except well 1 and 7, which both have nontypical discharge characteristics) plot along the Rb depletion trend (i.e. illite formation).

Given the 'clay-like' properties of illite, it is very likely that its abundant crystallisation will decrease formation permeability. This appears to be the situation when considering the quantitative petrologic logs of wells 10, 14, 24 and 25 in conjunction with identified production zones (i.e. loss zones) and overall well permeability. It also appears, for Broadlands southern (east bank) wells at least, that the trend of a water on a Cl-Rb-Cs plot is indicative of the degree of illite formation in a feed zone, and therefore its permeability. The position of Ohaaki Pool surface water on Figure 3 is extremely Rb depleted. This is consistent with abundant illite formation in the upper levels of the Broadlands system, which has removed Rb from the water on its way to the surface.

The absence of any trend in west Bank waters on Figure 3 may be due to the very minor occurrences of illite in permeable horizons in these wells (Browne, 1973) as well as the absence of zeolites (which would result in Cs depletion); this is particularly the case in the well 17 to 23 series at depths below 800 m, where adularia is the dominant K-silicate alteration mineral. In this situation, Browne (1978) has used adularia as an indicator of relatively good permeability.

CONCLUSIONS

There is no evidence at present to indicate that northern and southern waters have completely separate deep (>2 to 3 km) sources; however, the water chemistry does suggest two rather different pathways of water flow from an initial branching point, whose temperature is $\geq$310°C. Boiling, with 'relatively little dilution, predominates along the northern (west bank) path, whereas dilution (with shallow, bicarbonate-rich marginal condensates) is much more common along the southern (east bank) path; boiling also occurs to varying degrees in the south, serving to modify the intermediate (production zone) level water composition. .

Some of the wells on the margin of the system are greatly diluted by bicarbonate-rich water, formed by the condensation of CO_2-rich steam into cool, meteoric waters. This condensate has also diluted waters discharging from springs (hence its position over as well as adjacent to the system) and appears to have diluted production zone waters during early periods of discharge. This dilution appears to have occurred mainly in the well, due to depressurisation and a concomittant increase of the shallow, dilute contribution; however, some dilution waters may also have entered the deep production formation itself. Further data compilation and interpretation to test these possibilities are necessary.

Preliminary evidence suggests that illite (clay) alteration is much more abundant in the feed zone formation of southern rather than northern wells, particularly in wells with nil production and poor permeability. This suggests that illite formation is contributing to a decrease in permeability. The presence of illite, and therefore poor permeability, appears to be indicated from the position of discharge waters on a Cl-Rb-Cs plot; illite concentrates Rb in its structure, so will tend to deplete the waters in Rb as it is forming.

Given that waters in the north have undergone more boiling than those in the south, it may be inferred that the northern wells are further along the deep water flow path (i.e. the deep upflow is closer to the southern, east bank than the northern, west bank wells). Since dilution is greater in southern wells than northern wells, it could be inferred that the diluting waters are penetrating deeper into the system in the south. .

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REFERENCES

Browne, P.R.L. 1971: 'Petrological logs of drillholes BR 1 to BR 25: Broadlands geothermal field', NZGS Report 52, 86 pg.

Browne, P.R.L. 1973: 'The geology, mineralogy and geothermometry of the Broadlands geothermal field, Taupo Volcanic Zone, New Zealand, Ph.D. Thesis, Victoria University.

Browne, P.R.L. 1978: 'Hydrothermal alteration in geothermal systems', Ann. Review Earth Plan. Sci., p 229-250.

Browne, P.R.L. and Ellis, A.J., 1970: 'The Ohaki-Broadlands hydrothermal Area, New Zealand: mineralogy and related geochemistry' Amer Jour Sci. vol 269, pg 97-131.

Goguel, R.L. 1983: 'The rare alkalies in hydrothermal alteration at Wairakei and Broadlands geothermal fields, New Zealand', Geochim. Cosmochim. Acta., vol. 47, p 429-438.

Grant, M.A. 1977: 'Broadlands - A gas dominated geothermal field', Geothermics, vol. 6, p 9-29.

Grant, M.A., Donaldson, I.G. and Bixley, P.F. 1982: 'Geothermal reservoir engineering', Academic Press, 369 p.

Grant, M.A., Truesdell, A.H. and M., A., 1983: 'Production induced boiling and cold water entry in the Cerro Prieto geothermal reservoir indicated by chemical and physical measurements', Geothermics, in press.

Grindley, G.W. and Browne, P.R.L., 1968: 'The subsurface geology of the Broadlands geothermal field', NZGS Report 34.

Mahon, W.A.J. and Finlayson J.B., 1972: 'The chemistry of the Broadlands geothermal area, New Zealand', Amer Jour Sci, vol 272, pg 48-68.

Mahon, W.A.J., Klyen, L.E. and Rhode, M. 1980: 'Neutral sodium/bicarbonate/sulphate hot waters in geothermal systems', Journal of the Japan Geothermal Energy Association, vol. 17, p 11-24.

Ministry of Works and Development, 1977: 'Broadlands investigation report', June 1977, 236 pg.

Wood, C.P., 1983: 'Petrological logs of drillholes BR 26 to BR 40: Broadlands geothermal field', NZGS Report 108, 49 pg.