

## RECENT GEOPHYSICAL AND GEOCHEMICAL STUDIES FROM THE TOKAANU-WAIHI HYDROTHERMAL SYSTEM (TAUPO VOLCANIC ZONE NEW ZEALAND)

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### ABSTRACT

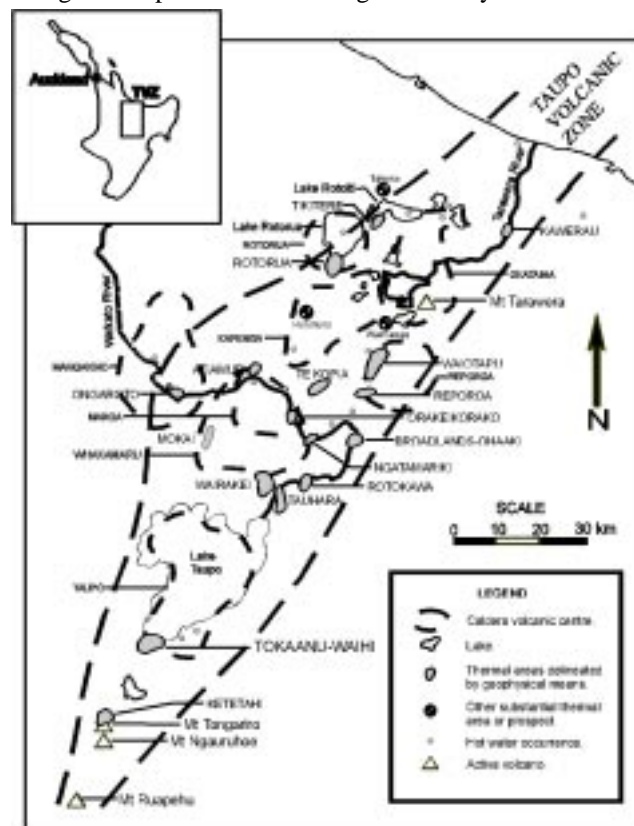
Previous geophysical studies of the Tokaanu-Waihi hydrothermal system combined with recent measurements using new techniques have provided a large database from which a comprehensive resistivity boundary has been constructed. The mapped area with low resistivity coincides with that of demagnetized ground defined from an aeromagnetic survey carried out in 1997. By combining the geophysical information with comprehensive geochemical studies it is possible to map the extent and the hydrological structure of the system including the position of the upflow beneath Hipaua.

### 1 INTRODUCTION

The Tokaanu-Waihi (T-W) hydrothermal system lies on the flanks of the Kakaramea-Tihia andesite massif at the southern end of Lake Taupo within the Taupo Volcanic Zone (TVZ) of New Zealand (Figure 1). The terrain is extreme and limited access has meant that unlike other high temperature fields in the TVZ, its resistivity boundary was not defined until recently.

Discharges from the T-W geothermal areas (shown in Figure 3), originate from a high temperature hydrothermal system which produces neutral pH NaCl waters at Tokaanu, mixed Cl-HCO<sub>3</sub> waters at Waihi Foreshore and steam at Hipaua. The steaming ground area Hipaua is the 3<sup>rd</sup> largest of its kind in the TVZ and covers approx. 1km<sup>2</sup> of steep ground along the Waihi Fault. Because of the separation and discharge characteristics of the surface manifestations, it was thought that Hipaua and Tokaanu might belong to two separate reservoirs (Hegan, 1974). It was also postulated by Giggenbach that this system represented an outflow of deep fluids from the Tongariro hydrothermal system (lying 15km southwest) (Robinson and Sheppard, 1986).

However, there is geochemical evidence showing that the Tongariro and T-W discharges originate from completely separate hydrothermal reservoirs (Giggenbach, 1996). Magmatic input in the T-W thermal waters, is possible since they have the highest Cl (3500ppm) concentration of all NZ hydrothermal prospects. Significant micro-seismic swarm activity has occurred in T-W area; these were thought to represent crustal magma activity beneath



the reservoir (Hochstein et al., 1995).

**Figure 1:** Location map of Tokaanu-Waihi hydrothermal system and other active geothermal prospects and volcanic centers within the Taupo Volcanic Zone.

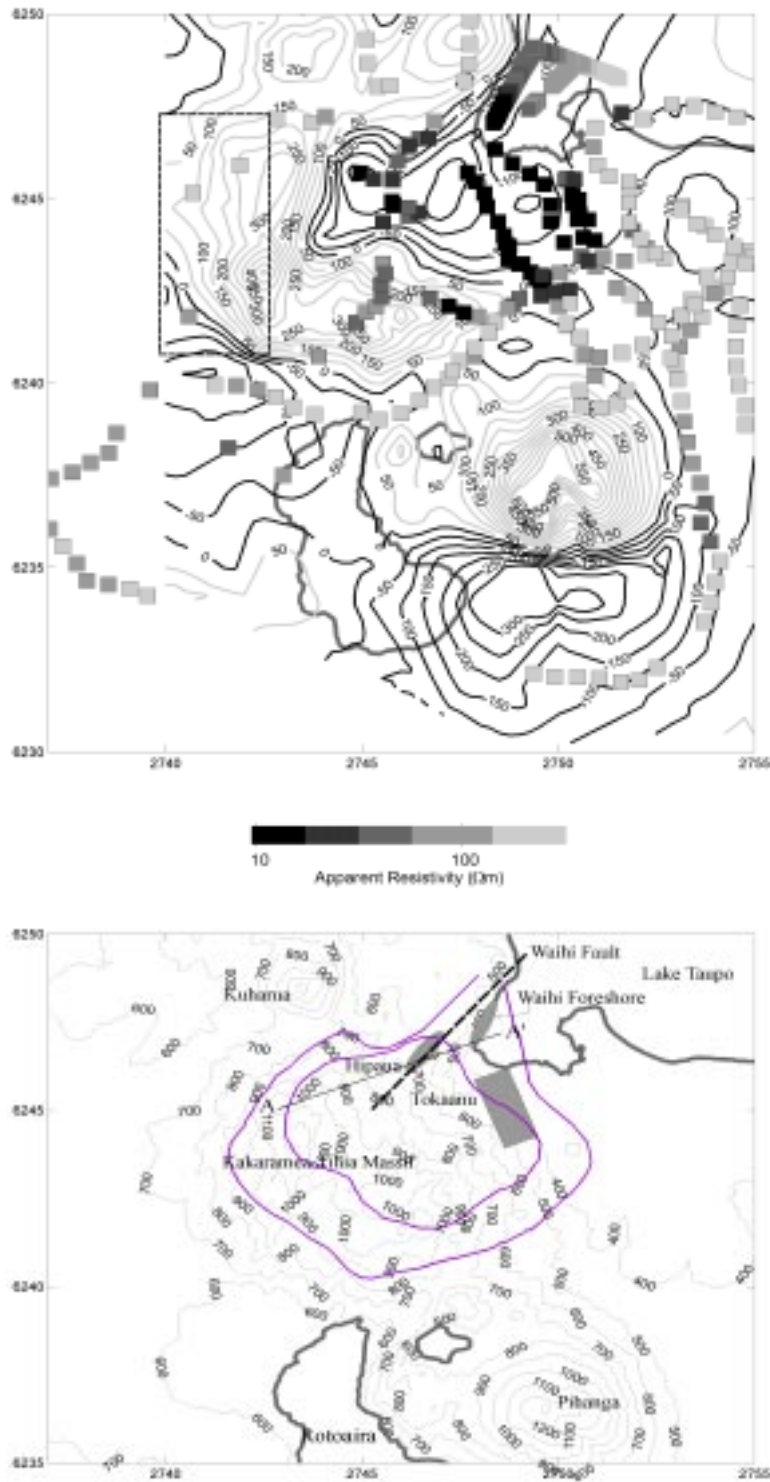


Figure 2: (Top) Results of resistivity surveys taken in the Tokaanu-Waihi area including: Wenner and Schlumberger arrays ( $AB/2=500$ ), waterborne resistivity (equiv. to  $AB/2 \approx 500\text{m}$ ), and 50 Hz MT data. The resistivity pixel overlies the 2<sup>nd</sup> order regional magnetic anomaly of the Tokaanu-Waihi Area (contour interval nT). Area covers 18 km x 20 km. The outlined box represents the area of confidential data used to interpret resistivity contours near the Mt Kakaramaea summit in Figure 3.

Figure 3: (Bottom) Topographic map of Tokaanu-Waihi area with resistivity boundary from data presented in Figure 2 and Risk et al. (1998) (contour (elevation) interval in m). Areas with thermal discharge are shown in stippled shading.

Until 10 years ago the Tokaanu-Waihi hydrothermal system was one of the least studied prospects in the TVZ; also it is one of the few without deep investigation wells. As a consequence it has been necessary to apply a combination of traditional and alternative geophysical and geochemical methods to understand the overall structure and extent of this prospect. A summary of more recent surveys undertaken in this area are presented here and provide the information needed to construct a hydrological model of system.

## **2 GEOPHYSICAL STUDIES**

### **2.1 Electrical Resistivity Surveys**

The first resistivity measurements in the Tokaanu-Waihi area were made in 1966 using the Wenner array with electrode spacing of approx. 550m. Measurements were made along easy access routes. Later additional measurements were made using the Schlumberger array with spacing (AB/2) of 500m and 1,000m, repeating measurements of previous sites and along new tracks cleared for forestry and for the construction of the Tokaanu Hydroelectric Power Station. Reeves and Ingham (1991) tested the magnetotelluric (MT) method over the flat land close to the Tongariro River Delta. In the late 1980's Geothermal Consultants NZ Ltd. carried out a comprehensive survey around the Tokaanu-Waihi, this data remains confidential, although restricted use of this data has been permitted to interpret the western boundary in this study.

Further resistivity measurements were made along roads and tracks by the Institute of Geological Nuclear Sciences (IGNS) between 1996 and 1998. Gaps still existed over the high elevation ground of the Kakaramea-Tihia andesite massif and in the Lake Taupo Waihi Bay area. The recently developed 50 Hz MT method was used in the high terrain to gather more data because the equipment is portable and at each measurement site the array could be adjusted to suit the terrain conditions. The method, equipment and results from the 1997-1998 survey have set out by Risk et al. (1997 and 1998). In the Waihi Bay waterborne resistivity measurements were also taken. Caldwell and Bibby (1992) describe the measurement method and Risk et al (1998) present the results from that survey.

### **2.2 Magnetic Surveys**

Healy (1942) made a series of measurements of the shallow vertical magnetic intensity at the Tokaanu and Waihi thermal areas and found that the areas of

thermal activity were characterized by low magnetic values presumably due to hydrothermal alteration. An aeromagnetic survey was flown in 1950-1951 at a height of 1500 m above sea level (Gerard and Lawrie 1955), and indicates a more extensive magnetic low covering the Tokaanu-Waihi corner of Lake Taupo. This suggested that hydrothermal activity was not just limited to the shore. Unfortunately this survey when flown only had 2 lines crossing the area of interest at a spacing of 5 km.

A recent survey was flown by the author and Dr Soengkono of the Geothermal Institute (University of Auckland) in December 1997 to determine in more detail the short wavelength magnetic anomalies over the wider Tokaanu-Waihi area. The survey was flown at low level (700 m  $\pm$  100 a.s.l., approx. 300m above ground) at a line spacing of approximately 1km. The lines were initially flown from the west to east and then north and south tie lines covering a 20 x 18km grid. Total magnetic force was observed and reduced for first and second order residual anomalies (Soengkono et al., 1991). The second order regional anomaly have been plotted below the apparent resistivity values in Figure 2.

### **2.4 Qualitative interpretation of geophysical data:**

Apparent resistivity values from measurements listed in section 2.1 have been plotted in Figure 2. The darker shading highlights the resistivity low area, the areas with high resistivities are shown by correspondingly lighter shading. Apparent resistivities of less than 20  $\Omega$ m measured over the central Tokaanu-Waihi field indicate the presence of intense thermal alteration and the presence of geothermal fluids, values greater than 100  $\Omega$ m suggest colder and unaltered ground. The resistivity pixels overlay the 2<sup>nd</sup> order residual magnetic anomaly over the field. The diagram shows that the area with low apparent resistivity corresponds with the area of demagnetized rock indicated by the negative magnetic anomaly. The patterns of magnetic anomalies and associated thermally altered and demagnetized rocks in many geothermal prospects in the TVZ have been discussed in Hochstein and Soengkono (1996).

The newly interpreted resistivity boundary in Figure 3 was constructed using only the resistivity measurements. However, the magnetic pattern did assist in the interpretation of the structure over the high terrain in the west close to the summit of Kakaramea.

The resistivity and magnetic low anomalies on the northern side of the Waihi Bay, close to the Waihi

Fault as it enters the Lake, show an elongated pattern following the trace of this fault in the Lake. Thermal fluids still discharge close to the shore. The anomaly further out suggests that there was or still is alteration occurring due to thermal fluids moving through the fault and discharging in the deeper regions of the Bay.

### 3 GEOCHEMICAL STUDIES

#### 3.1 Water and Gas Chemistry

The main thermal areas within the Tokaanu Waihi field occur at the Tokaanu, Waihi Foreshore and a 1km<sup>2</sup> area of steaming ground called Hipaua (Figure 3). Waters were collected from these features and analysed for the normal major constituents, separate samples were collected for isotope analyses. Steam samples were also collected and analyzed for major and minor gas constituents and condensate samples for stable isotopes. The chemical composition of water and steam discharges from Tokaanu, Waihi Foreshore and Hipaua are listed in Severne (1998).

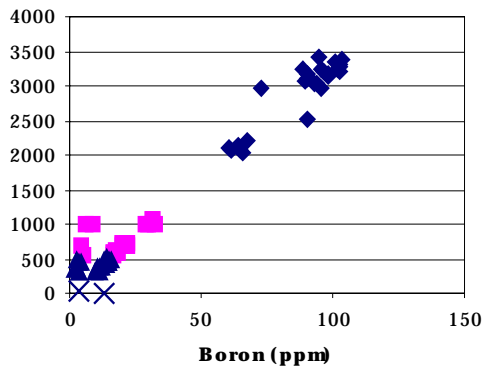


Figure 4: Diagram showing the boron and chloride in thermal waters found in springs and shallow bores at Tokaanu, Waihi Foreshore springs and Hipaua condensate pools (symbols explained Figure 5).

In Figure 4 the concentration of the conservative tracers Cl and B are shown. This diagram indicates that there is a linear relationship between the two in the fluids. This trend indicates that the liquids from these locations have common origin within the system.

The fluids at Tokaanu are characterized by high Cl and Na contents of up to 3500 mg/kg and 1400 mg/kg respectively, these values were recorded in the

Tokaanu Domain. The nearby shallow bores have increasingly higher HCO<sub>3</sub>, Mg and Ca concentrations, however the maximum value of these is found in the Waihi foreshore springs. Increases in Mg, Ca and HCO<sub>3</sub> concentrations are typical of waters that have been diluted by shallow groundwater. The Hipaua pools are acid condensates formed by steam H<sub>2</sub>S condensing into the shallow water table. Relative Cl, SO<sub>4</sub> and HCO<sub>3</sub> contents of fluids from the Tokaanu-Waihi field have been plotted in Figure 5. Unmixed Tokaanu samples lie at the Cl apex of the plot. Fluids found discharging at the Waihi Foreshore form an intermediate cluster of points midway along the Cl-HCO<sub>3</sub> axis; these are the 'mixed chloride-bicarbonate fluids, they also occur in several boreholes at Tokaanu. The composition of these fluids is characterized by higher HCO<sub>3</sub> (mg/kg) values and correspondingly lower Cl (mg/kg) values.

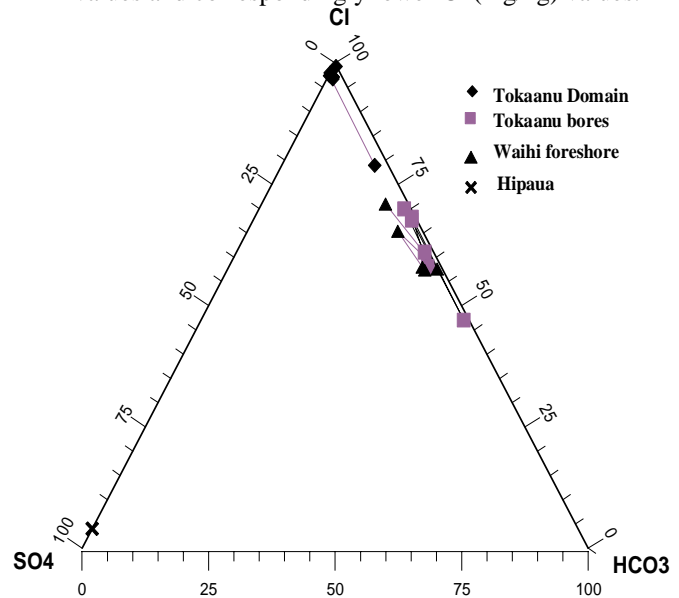


Figure 5: Plot of relative Cl, SO<sub>4</sub> and HCO<sub>3</sub> contents of thermal waters of the Tokaanu-Waihi system (after Giggenbach, 1988).

The initial thermodynamic evaluation of the discharges using the Na, K, and Mg contents of waters show that Tokaanu the samples fall on the full equilibrium line at 240-260°C. The constituents in Tokaanu shallow bores and Waihi Foreshore waters are shifted toward the Mg corner away from the full equilibrium line reflecting cooling shallower conditions. The chemical composition of steam discharges from Tokaanu and Hipaua are listed in Severne (1998). Gas-geoindicators based on concentration ratios of CO<sub>2</sub>, CH<sub>4</sub>, H<sub>2</sub> and Ar devised by Giggenbach (1991) indicate that deep equilibration temperatures lie between 200-300°C

### 3.2 Isotopic Composition of Waters and Condensates

The stable isotope data were examined to assess the effects of boiling and mixing of the deep fluid during its ascent to the surface. Data used to illustrate these processes in Figures 6 & 7 are listed in Severne (1998). Robinson and Sheppard (1986) and Giggenbach (1996) discussed the isotopic compositions of waters discharged from the Tokaanu-Waihi area. Their interpretation was based almost entirely on samples from discharged waters, as they had only 3 steam condensate samples. In Figure 6, cold meteoric waters in the area plot close to the average meteoric line for the area:  $\delta D = 8 \times \delta^{18}O + 12$ . Most of the samples except the Tokaanu steam condensate samples are enriched in  $\delta D$  and  $\delta^{18}O$  which indicates that there is enrichment by either evaporation, steam loss or oxygen isotope exchange of the hot water with the rocks or a combination of these. The data in Figure 6 suggests that fluids discharging at Tokaanu derive from high chloride waters, supplied from a deep parent water, which has a chloride content of close to 2400mg/kg and an initial isotopic composition P (Figure 6). The discharge fluid at Tokaanu may be obtained by assuming maximum vapour loss with boiling at 260°C. The Tokaanu fumarole samples have variable composition showing the greatest depletion in  $\delta D$  and  $\delta^{18}O$ . These data lie to the left of the line formed from the steam derived from single stage boiling. As found by Giggenbach and Stewart (1982), data points of secondary steam generally lie to the left of the primary steam data in Figure 7. This effect is probably due to partial condensation loss of the liquid phase or the steam being, in part, derived from heated ground water. This pattern was also observed for the Tongariro Central Crater fumarole (Lyon & Stewart, 1985). The Hipaua fumarole samples therefore represent steam derived from single step steam separation. These discharges have had little interaction with shallow environments and may have risen directly to the discharge points. The samples with the most positive  $\delta^{18}O$  values are Taumatapuhipuhi geyser and the pools 2 and 3, these samples also have exceptionally high chloride contents at Tokaanu. This situation confirms Sheppard and Robinson's (1986) suggestions that evaporation or loss of steam has increased both Cl and stable isotope values by boiling (Figure 7). Waters affected by surface evaporation lie along a line on a slope of approximately 3 (Giggenbach and Stewart, 1982). This type of non-equilibrium evaporation is evident in some of the Tokaanu springs.

### 4 CONCLUSIONS

A combination of boiling and mixing of the deep reservoir fluids best explains the variation of the fluids discharging at different locations within the Tokaanu-Waihi Geothermal Field. Previous interpretations of chemical data in Severne (1995) and Sheppard and Robinson (1986) reach similar conclusions. The parent fluid at Tokaanu has a chloride content of approx. 2400mg/kg, and an isotopic composition of  $\delta^{18}O = -3.6\text{‰}$  and  $\delta D = -42\text{‰}$ . Relative concentrations of conservative components of the water and gas discharges clearly indicate that the shallower parts of this system are occupied by at least 3 distinct fluids. These are the fluids discharging in the Tokaanu Domain (which are undiluted, chloride waters concentrated by boiling), mixed bicarbonate chloride waters discharging from shallow bores at Tokaanu and along the Waihi foreshore, and acid condensates occurring at Hipaua. The agreement of the geosensors based on the Na-K; K-Mg and gas-geothermometers indicate that deep equilibration temperatures lie between 200-300°C.

The gas and isotope data combined show that the primary upflow of parent fluids beneath Hipaua. The deep fluids undergo boiling at approximately 190°C. The Tokaanu steam originates from an excessively degassed secondary fluid. The isotopic composition of the less mineralised fluids at the Waihi foreshore and Tokaanu bores is explained by simple mixing between the two end members; this also explains their lower chloride concentrations.

The apparent resistivity data shows that the resistivity boundary of the T-W hydrothermal system closes towards the west behind Kakaramea. The eastern boundary is well defined; further measurements need to be taken further out in the Waihi Bay following the Waihi Fault trace to find unaltered formations with high resistivities. Both the magnetic and resistivity data show low anomalies over the central area of the field including Tokaanu, Waihi and Hipaua geothermal areas. The low anomaly is surrounded by cooler unaltered ground with significantly higher apparent resistivity values. All of the geophysical data agree with the evidence presented by Giggenbach (1996) suggesting that there is no link between the T-W and Tongariro Hydrothermal Systems. When combining the chemical and geophysical data a simple hydrological model of the system can be drawn (see Figure 8), showing the resistivity boundary, the upflow and outflow areas.

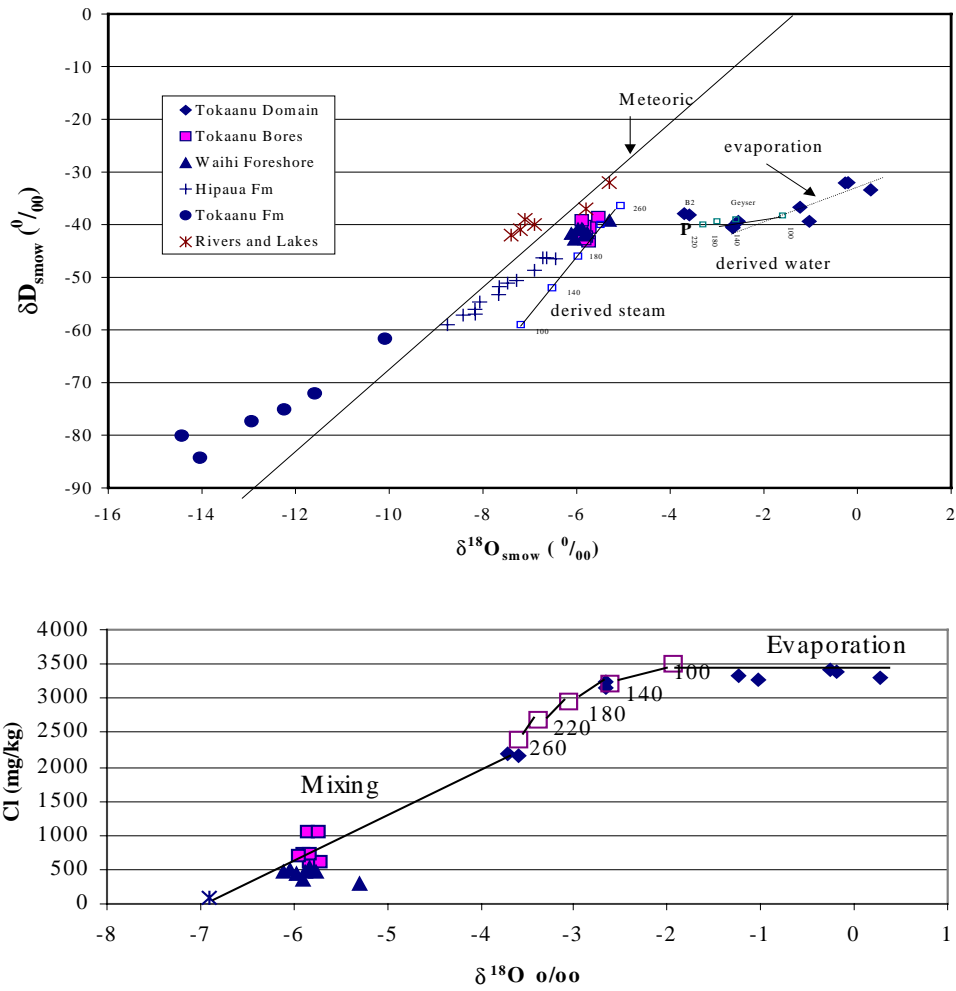


Figure 6 & 7: The isotopic compositions of water and steam discharges from Severne (1998); (6) top  $\delta\text{O}^{18}$  vs  $\delta\text{D}$  and (7) lower Cl vs  $\delta\text{O}^{18}$ .

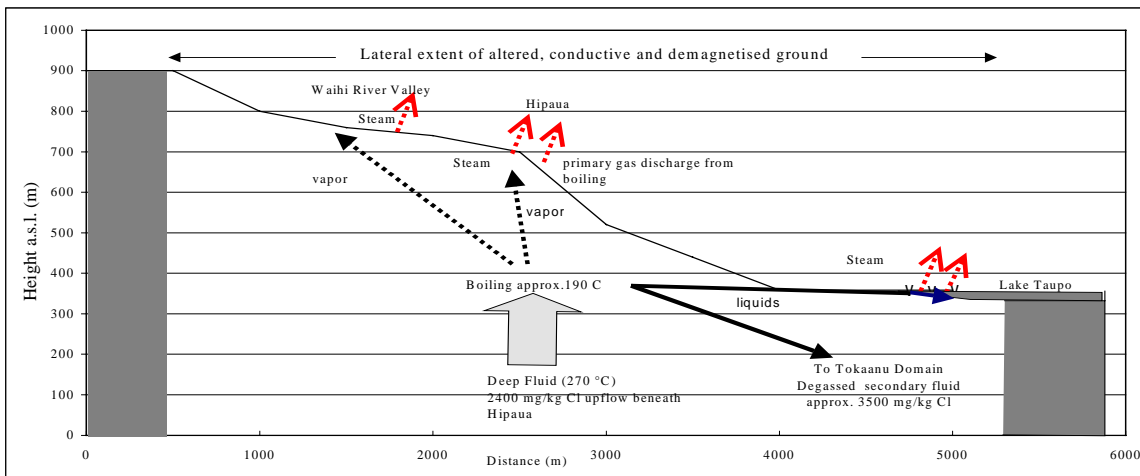


Figure 8: Schematic cross-section of the Tokaanu-Waihi System (A-A' Figure 3), showing the postulated hydrological model modified from Severne (1995).

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