PROCESSES AFFECTING SPRING DISCHARGE AND CHEMISTRY IN THE NGAWHA GEOTHERMAL SYSTEM

B. W. CHRISTENSON[1] & T. M. SCOTT[2]

[1]Rafter Isotope Laboratory, IGNS, PO Box 31-312, Lower Hutt
[2]NZ Environmental, Puketona Rd R D 3 Kerikeri

SUMMARY - Hotspring discharges at Ngawha show a wide compositional range over a relatively small spatial area. Compositionally, water in the Jubilee Bath most closely corresponds to fluids in the production reservoir, whereas those in the adjacent Domain and Tiger Bath areas are dominated by HCO_3^- and SO_4^{2-} respectively. The spring fluids, which discharge through a 600 m thick aquiclude which has conductive temperature profiles, appear to be advectively transported to the surface by a strong gas flux from the production reservoir. Spring fluid compositions are controlled by processes involving these gases.

1.0 Introduction

The presence of a 600 m thick aquiclude over the Ngawha geothermal production reservoir makes the physical and chemical characteristics of its natural thermal discharges rather unique amongst NZ hydrothermal systems. The undisturbed, large hot water systems in the Taupo Volcanic Zone (TVZ) typically have convective thermal profiles extending to the surface, with boiling point fluids often discharging as hot springs or fumaroles. At Ngawha, however, maximum natural discharge temperatures approach only 50 °C, are typically gas-rich, and show extensive effects of interaction with these decoupled hydrothermal gases derived from depth.

In this paper, we assess the results from ongoing chemical and thermal monitoring of surface features in the Ngawha field in order to ascertain the nature of the processes controlling the discharges, as this is of considerable importance if we are to understand future production-induced changes in the system.

2.0 Previous Work on Ngawha Fluids

Analytical results from earlier studies on the geochemistry of the fluids at Ngawha have been comprehensively summarised in Sheppard & Johnston (1984), which contains data extending back to 1949. A monitoring programme of the springs and baths was undertaken between 1979-1983, corresponding to the main period of exploration drilling of the resource. However, the sampling frequency was not consistent over this period, and the effects of rainfall and pool drainage, etc. were not reported (Sheppard and Johnston, 1984)). Since 1997, results of rather more systematic baseline and production monitoring activities have been summarised 6-monthly by NZ Environmental Ltd. (eg., Scott and Glover, 2000, and references therein).

Interpretive studies of fluid geochemistry of the Ngawha system have been few. Giggenbach and Lyon (1977) presented a model of the field based on results of thorough geochemical and isotopic sampling of the springs/pools, and those from then recently drilled well NG-1. Heavy isotopic ^{18}O signatures from the fluids suggested significant exchange with the reservoir rocks containing them, although the gas-rich nature of the fluids was also identified as a possible explanation. In addition, ^{13}C partitioning between CO_2-CH_4 indicated equilibrium temperatures of ca. 400 °C, which in conjunction with the gas-rich, high enthalpy nature of NG-1, led these authors to view the system as vapour-dominated. This interpretation remained popular through the 1980's (eg., Heinrich et al., 1989).

Subsequent drilling and output testing of the reservoir prior to production in the late 1990's proved the present resource to consist of a gas-rich, but essentially single-phase liquid which resides at boiling point only near the top of the production reservoir. Indeed, enthalpy measurements from currently producing wells (NG-9 and NG-12) suggest very little in the way of even production-induced boiling of reservoir fluids adjacent to the wellbores. However, reservoir modelling by Grant et al., (2002) points to the existence of boiling-point fluids at the base of the caprock in the so-called "permeable reservoir".

3.0 Reservoir Structure and Temperature Distribution

The boundary of the field, as defined by resistivity (AB/2=1000), has an area of ca. 15 km^2, and is roughly triangular in plan. Current models of the reservoir (Grant et al., 2002) suggest that the main upflow for the field is situated in the north, and this flow evidently spreads laterally as it outflows southward.

The reservoir rocks are Permian to Jurassic graywackes and argillites of the Waipapa group, the permeability for which is largely fi-acture-controlled. The reservoir rocks are unconformably overlain by up to 600 m of Cretaceous-Tertiary marine sediments (sandstones, siltstones, limestones, argillaceous limestones and calcareous mudstones). These rocks are collectively impermeable, and form an effective caprock to the hydrothermal system.

A number of normal and reverse faults have been inferred on the basis of Waipapa Group basement offsets between production wells, and through identification of zones of locally intense shearing (Petty, 1985). Temperature profiles within the caprock are largely conductive, although temperatures near known fault zones (eg., NG4, 13 and 2) are higher than in adjacent unfaulted areas (eg., NG9 and NG11).

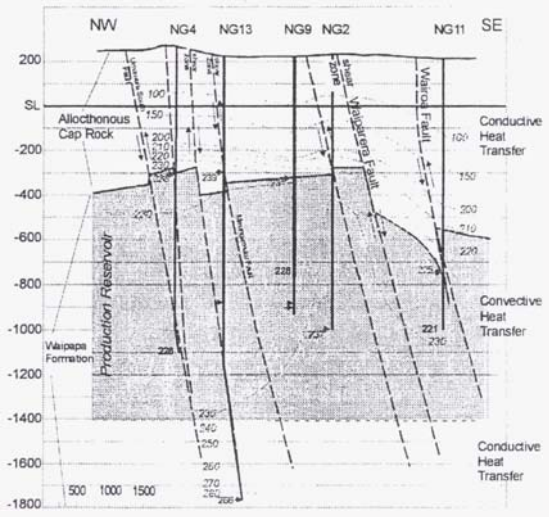

Figure 1. Thermal and geological profile through system.

Temperatures in the production reservoir are interpreted to be convective, although temperatures decrease with depth below the caprock - production reservoir contact to ca. 1600 m depth in the northwest part of the field (Fig. 1). This has been interpreted by Grant et al. (2002) to be the result of southerly outflow beneath the caprock from the source upwelling located near NG5.

Permeability abruptly decreases below ca. 1600 m depth, where corresponding temperature profiles become markedly conductive. Maximum temperatures for the field are found in this conductive zone (286 "C, 2000 m depth in well NG13).

3.1 Geochemical Structure

The production reservoir fluids are essentially dilute NaCl solutions of near-neutral pH. The fluids contain up to ca. 0.5 molal CO_2, and are enriched in both NH_3 and B, which sets these fluids apart from those found in the Taupo Volcanic Zone (TVZ) geothermal systems.

There is surprisingly little variation in enthalpy or chloride contents between production fluids, where the highest Cl^- contents are found in fluids from wells 4, 9, 12 and 13. Interestingly, fluids from NG12 and NG9S show the greatest vapour loss, consistent with their location in the high-temperature, 2-phase zone at the base of the caprock. Conversely, production from NG9D is deeper (>950 m), and shows less vapour loss. Fluids from wells NG 18, 2 and 8 are more dilute than the above, consistent with their positions relatively closer to the inferred lateral inflow of recharge water along the eastern margin of the field (Grant et al., 2002).

Jubilee spring in the Spa area has Cl^- contents higher than any of the deep reservoir fluids, a feature which may be explained by a combination of adiabatic and conductive cooling of the fluids during ascent. Other evidence suggests that this fluid is comprised of close to 100 % of the deep reservoir fluid component. For comparison, springs from the other two main areas (Maori Domain and Tiger) contain between just 10% to 50% of this deep reservoir component. Data from three shallow wells in the area also show this mixing-induced variation in Cl^- contents. Old Well fluids, for example, are similar in composition to those of adjacent springs (eg., Bull Dog).

The Spa Hotel well data of Glover (sampled August 1981; reported in Sheppard & Johnston, 1984) demonstrate shallow mixing processes in the Ngawha Springs. Water from 25 m depth measured 63 °C, was Cl^--deficient and HCO_3^--enriched, whereas that from 11 m depth was 83 °C and had Cl^- concentrations similar to those from Jubilee Bath. The Cl^- fluids here discharge at temperatures higher than those recorded in temperature logs from any of the production wells (approaching

boiling-point), suggesting the existence of relatively sharp thermal gradients close to the fracture channels. HCO_3^--enrichment fluids point to the existence of steam (or gas) - heating of groundwater in this area.

Insight into the reservoir processes operating in the upper 50 m of the caprock are gained from consideration of the relative Cl^--HCO_3^--SO_4^{2-} concentrations of the respective fluids. Spa area fluids (Jubilee and Tranquility) and those from the deep (production) reservoir are all Cl^--dominant, consistent with the Cl^--H relations described above. Tiger area fluids

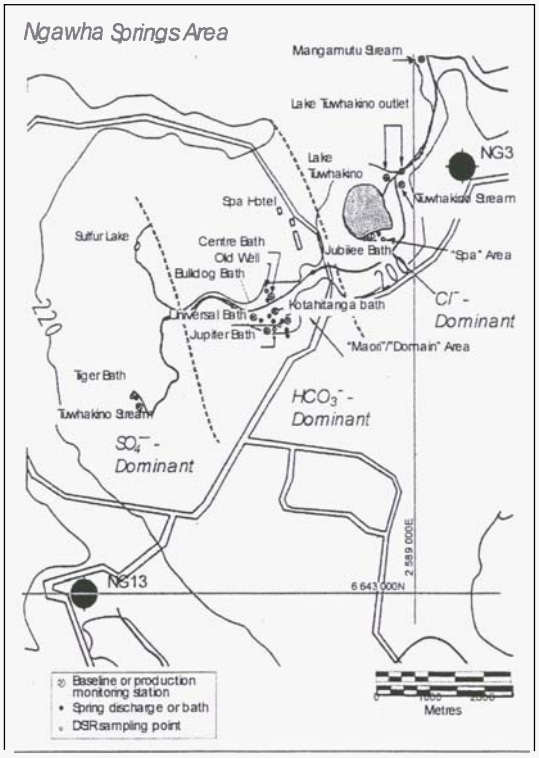

Figure 2. Distribution of spring fluid types.

are dominated by SO_4^{2-}, whereas fluids from Maori Domain are distinctly enriched in HCO_3^- over those in the Spa area. The Spa area discharges, therefore, appear to contain the highest proportion of production reservoir fluids. These fluids also plot close to the "full equilibrium" line in a Na-K-Mg plot, whereas, owing to their higher relative condensate contents, discharges from both Universal and Tiger spring fluids are comparatively more immature.

This transcribes to a spatial distribution of predominant fluid types as portrayed in Fig. 2, where SO_4^{2-} fluids dominate in the west, HCO_3^- fluids dominate in the central area, and the least contaminated upwelling of deep system (i.e., Cl^--dominant) fluids occurs in the Spa area. Note, however, that the treatment used here addresses only the relative compositions of the fluids in terms of these end-members, and does not delineate fluxes of the end-member components through any of the three areas.

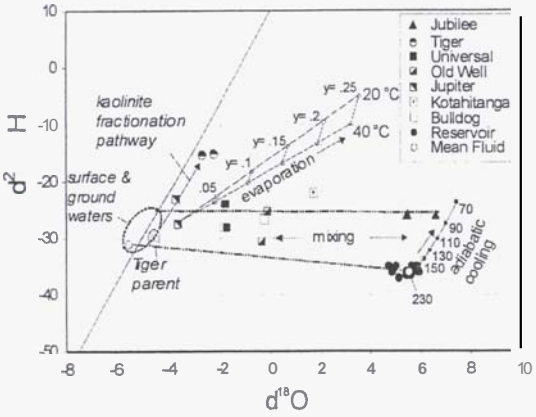

Figure 3. $\delta^{18}O$ and δ^2H compositions of spring and reservoir fluids.

$\delta^{18}O$ and δ^2H signatures for the spring fluids are portrayed in Fig. 3. The production fluids are ca. 5 ‰ lighter in δ^2H than local average meteoric waters (Giggenbach & Lyon, 1977), which is unusual for NZ geothermal systems, and begs the question as to age and source of these fluids. The spring fluids occupy positions uniformly above the tie-line between these two end-member mixing components, consistent with enrichment due to evaporation.

The 8 ‰ enrichment in δ^2H values in Jubilee Spring waters is best explained by adiabatic cooling of the ascending Cl^- fluid. It is of interest to note that the most significant ^2H fractionation occurs at lower temperatures (40 to 100 °C), as the vapour-liquid fractionation factors for ^2H are much larger over this range than at reservoir temperatures (67 to 27 vs 0 at 220 °C). The very strong enrichment in ^2H shown in the Tiger Bath fluids cannot be explained by boiling alone, but are the likely result of preferential fractionation of the light isotope into clay alteration (principally kaolinite) associated with these fluids.

Insights into the relative roles of vapour and liquid transport on spring chemistry are shown in Figs. 4-6, where reservoir fluid compositions are compared to both baseline and production monitoring data. The latter are used in this case because there are minimal uncertainties introduced into the data set by variations in sample location and technique.

Relative HCO_3^--NH_3-Cl^- contents are portrayed in Fig. 4. As mentioned previously, Cl^- in these spring fluids derives primarily from the

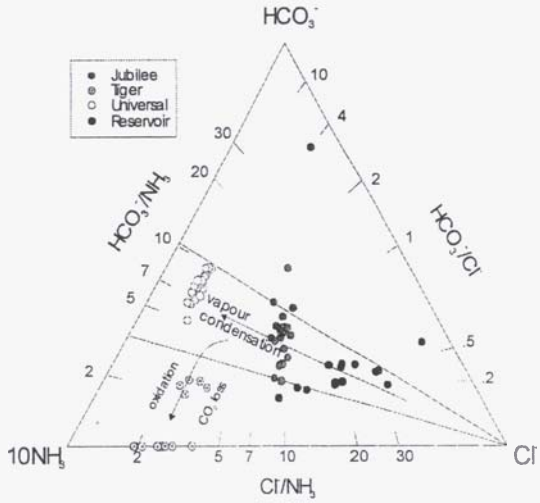

Figure 4. Relative contents of Cl^-, HCO_3^- and NH_3 in spring and production reservoir fluids.

deep reservoir liquid inputs; Cl^- is not carried in the vapour under conditions extant in the Ngawha reservoir. The Cl^- content of the average groundwater (Giggenbach and Lyon, 1977) is 12 mg/l, which therefore is the maximum concentration in mixed condensate-groundwater fluids. From Fig. 4, there is a clear mixing relationship evident between condensate and a deep reservoir liquid in all of the spring fluids. These condensates are bicarbonate-enriched, and have a range of HCO_3^-/NH_3 ratios of ca. 3 to 10. As described above, Jubilee has the highest deep reservoir liquid contents as defined by Cl^-, but it is apparent that even Jubilee waters contain condensate.

Tiger bath fluids are NH_3-enriched (HCO_3^--depleted), but this proves to be an artefact of their chemistry being SO_4^{2-}-dominated. SO_4^{2-} forms through near-surface oxidation of H_2S gas being transported in the vapour phase. This gas reacts with oxygen to form elemental sulfur according to:

$$H_2S_{(aq)} + O_{2(aq)} \leftrightarrow S_e + H_2O.$$

This reaction proceeds very rapidly, but further oxidation of the *S* to sulfate is a slower reaction involving intermediate oxidation state sulfur species, and is typically dependent on bacterial or transition metal catalysis. The *summary* reaction can be presented as:

$$S_e + 2H_2O \leftrightarrow SO_4^{2-} + 2H^+ + H_{2(aq)}$$

Since the reaction products include H^+, solution pH decreases with reaction progress. Other components in the liquid phase (eg., NH_3, H_3BO_3) will, however, exert a buffering influence on solution pH, but once the buffering capacity is exceeded, HCO_3^- will be converted to $H_2CO_3°$ and evolve CO_2 according to

$$H_2CO_3° \leftrightarrow CO_{2(g)} + H_2O,$$

with a net removal of bicarbonate from solution.

Relative variations in B, F^- and Cl^- contents are shown in Fig. 5. The Cl^-/B mass ratios are consistent for all of the discharges ($R_{Cl\text{-}B} \approx 1.5$), which in light of the previous evidence for vapour condensation into all shallow aquifers, suggests that vapour phase B transport, like that of Cl^-, is of little consequence in the system and that both components derive from the deep liquid phase. The Jubilee Bath waters once again have compositions most similar to the deep liquids.

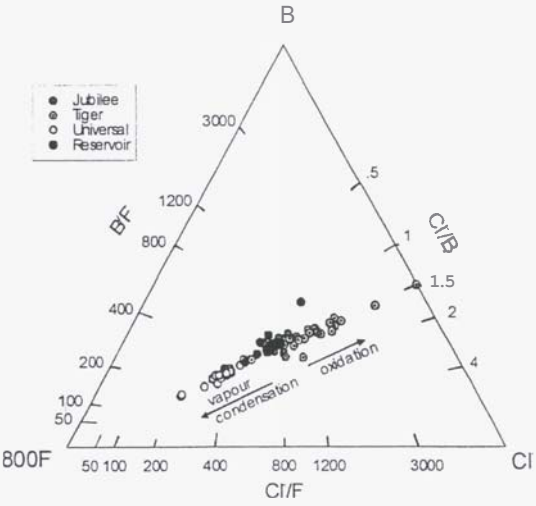

Figure 5. Relative contents of Cl^-, B and F^- in spring and production reservoir fluids.

By comparison, Universal Bath waters are enriched and Tiger Bath depleted in F respectively relative to the deep waters. This points to vapour phase transport of F as HF gas, with subsequent condensation into near-surface aquifers. The relative depletion of F- in Tiger Bath waters is the result of pH dependence of F speciation on volatility. The pK for HF at 50 °C, is ca. 3.4. At pH's below this value, the solubility becomes increasingly controlled by the volatility of HF gas, in much the same manner as that described for CO_2 above. Therefore, the relative depletion of F^- from Tiger Bath waters can be attributed to the oxidation of H_2S, and evolution of HF gas from the bath waters.

An indication of the relative magnitude of HF mobility in the system is discernable from Fig. 6. Here relative B, F^- and NH3 contents show that the Jubilee fluids, while being most similar to the deep reservoir fluids, also show evidence of vapour condensation, with net addition of NH_3. The condensation pathway

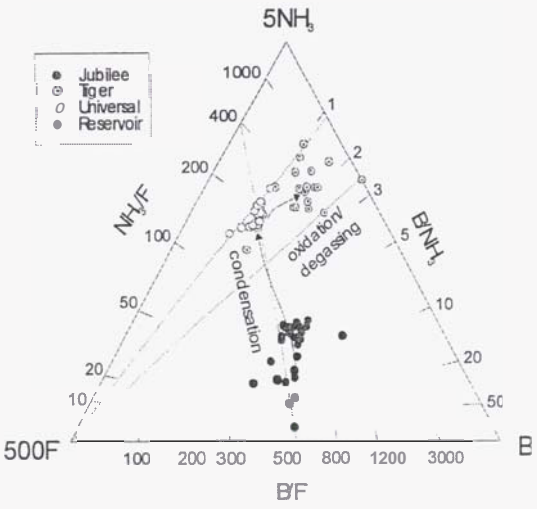

Figure 6. Relative contents of F^-, NH_3 and B in spring and production reservoir fluids.

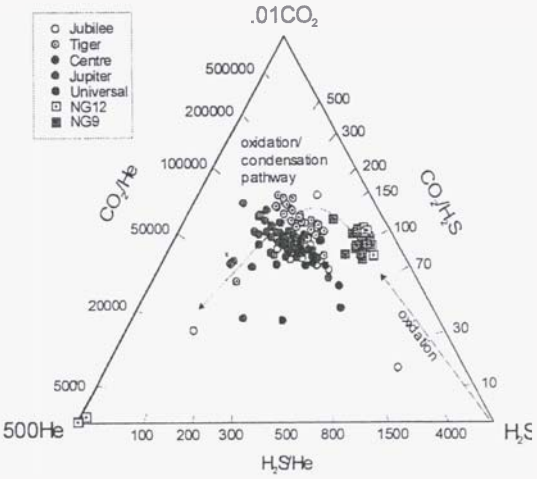

Figure 7. Relative contents of He, CO_2 and H_2S in spring and production reservoir fluids.

suggests that the condensate has a NH_3/F^- mass ratio of ca. 400 (Fig. *6)*. As described above, Tiger Baths are depleted in F^-.

Relative CO_2-He-H_2S contents for baseline and production period fluids from baths and production wells are portrayed in Fig. 7. Gases from the production fluids are relatively enriched in H_2S compared to those discharging through the baths. Two processes may contribute to the observed H_2S depletion in the bath discharges. First, as gases separate from the production reservoir fluids and rise through the caprock environment, they are variably condensed into caprock pore fluids. Following from the above discussion on solubilities of these three gases, it follows that H_2S becomes preferentially absorbed over CO_2 and (especially) He from the ascending vapours. Secondly, as pointed out above, H_2S is very reactive in such environments, reacting with both introduced atmospheric oxygen in groundwater to form SO_4^{2-}, and with Fe-bearing minerals to form iron sulfide. Both processes are likely to contribute to the observed H_2S depletion in the bath discharges. Also apparent from Fig. 7 is the relative enrichment in CO_2 in the Tiger Bath waters over either Jubilee or Universal bath waters. Again, this is the result of the acid pH conditions in the Tiger Bath source fluid environment resulting in relatively less absorption of CO_2 gas into solution.

4.0 Discussion and Conclusions

A conceptual model which accounts for the observed characteristics of the Ngawha Springs is shown in Fig. 8. There are three main upwellings portrayed here, coinciding with the three general areas of surface manifestation. Flow through the caprock takes place through fracture conduits most likely related to the Mangamutu fault structure (or more likely along intersections between this fault and unspecified cross-faults). Cl^- liquid and CO_2-rich vapour from the production reservoir rise through these channel ways, with buoyancy derived not from thermal density differences, but through low bulk densities attributed to their bubble contents relative to adjacent pore fluids. Temperature logs from the production wells suggest that temperatures within the conduits are higher than the adjacent country rock through which these gas-rich fluids flow. We refer to this flow regime herein as advective rather than convective.

It is obvious from the amount of gas being discharged through the baths at the three areas (and adjacent grounds, apparent during rainy periods), that there is de-coupling of gas and water flows in the permeable conduits and adjacent reservoir. The flux of Cl^- reservoir fluid appears to be greatest in the Spa area, and evidence points to a uniform decrease of Cl^- discharge across the Domain to relatively low Cl- fluxes in the Tiger Bath area.

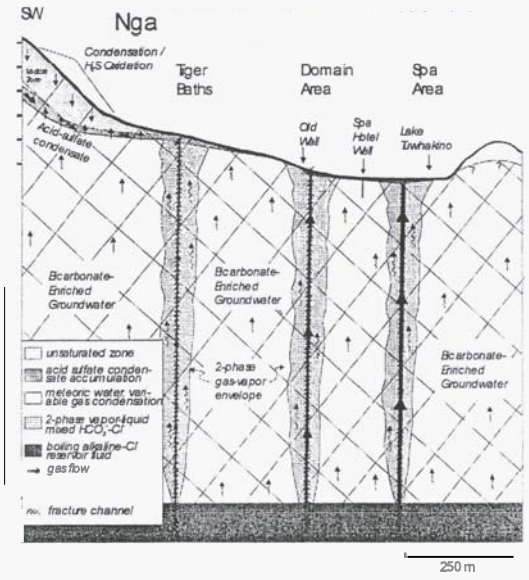

Figure 8. Conceptual model for spring system.

The 2-phase fluid in the caprock originates from adiabatic cooling of gas-charged reservoir fluid at its base. As the fluid moves upward, and temperatures in the caprock fall below boiling point, there will be a corresponding (temperature dependent) increase in gas solubilities, all of which will work to suppress 2-phase conditions. However, confining pressures also decrease along the flow-path, which serves to increase vapour saturation, so it is possible that there will be little change in steady state vapour saturation with decreasing depth, but this needs further study.

The flow of liquid and vapour, then, will be influenced by the vapour/liquid ratios entering the conduits at the base of the caprock, and by changes affecting gas-liquid partitioning along the flow path. Lateral diffusion **of** gas into adjacent groundwater leads to gas saturated pore fluids, which will be quite reactive. Consequent water-rock interaction lead to formation of HCO_3^- enriched waters, which in Fig. 8 are portrayed as envelopes of mixed Cl^--HCO_3^- waters enclosing the main conduits.

The flow behavior of fluid through the caprock is critical to understanding and predicting the longer term impact of production on the springs. The total amount of heat transported by liquid and gas phases is presently unknown. However, with just **2** l/s total flux of deep reservoir fluid discharged at the surface, and noting that water vapour is far more efficient at transporting heat than liquid water, it can be safely assumed that vapour phase transport of heat probably predominates in these features.

As discussed previously, acid-sulfate fluids predominate in the Tiger Baths area. Their mechanism of formation is portrayed here wherein oxygen infiltrates into the unsaturated (ie. vadose) zone environment in the hills above the Tiger Baths area, leading to condensation and oxidation of H_2S to SO_4^{2-}. We suggest that downward percolating condensate coalesces along the groundwater surface, and ultimately flows down-gradient toward the springs area, where it mixes with upwelling Cl^--HCO_3^- fluids at the bath site. It is in this mixing zone where pH reduction (to below ca. 4) leads to release of CO_2 gas by the previously described mechanism.

5.0 References

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