DISCHARGE OF THERMAL FLUIDS AT TE AROHA (NZ)
(a case history of CO_2-driven geysering wells)

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Abstract

Te Aroha is a small thermal prospect in the North Island of New Zealand where surface manifestations have been monitored over the past 100 years. Its main attraction is the 67 m deep Mokena well which discharges sodium-bicarbonate fluids periodically at a maximum temperature of 83°C, with a long term rate of 0.7 kg/s since 1936. Two other wells have also discharged fluids by geysering, but at lower flow rates of ≤ 0.1 kg/s.

The discharging wells are driven by a periodic CO_2 gaslift. The Mokena well deposits aragonite and requires reaming at half-yearly intervals to maintain production. Discharge characteristics of the wells and fluid chemistry data are presented which allow an estimate of CO_2 concentrations required to maintain the periodic gaslift (about 3 g CO_2 per kg of fluid).

Introduction

Thermal water at Te Aroha has been used for balneology and therapeutics since the 19th century. Surface manifestations were mapped as early as 1884, and spring temperatures have been monitored at intervals since then (Healy, 1956); all thermal springs shown in Fig. 1 were known over 100 years ago. The total natural discharge rate has never been measured but probably did not exceed 0.5 kg/s, as indicated by figures cited in Henderson (1913) and Healy (1956). Spring No. 15 (see Fig 1) always showed the highest temperature (59°C in 1889 and 55°C in 1993 after pumping).

None of the springs showed geysering activity. The thermal waters discharge neutral pH sodium-bicarbonate water with a high amount of dissolved solids (about 12 g/kg); their chemistry was described by Henderson (1913).

To obtain more thermal water, a 70 m deep well was drilled in 1936 which discharged periodically by geysering thermal fluids at 83°C with an equivalent long term flow rate of about 0.7 kg/s.

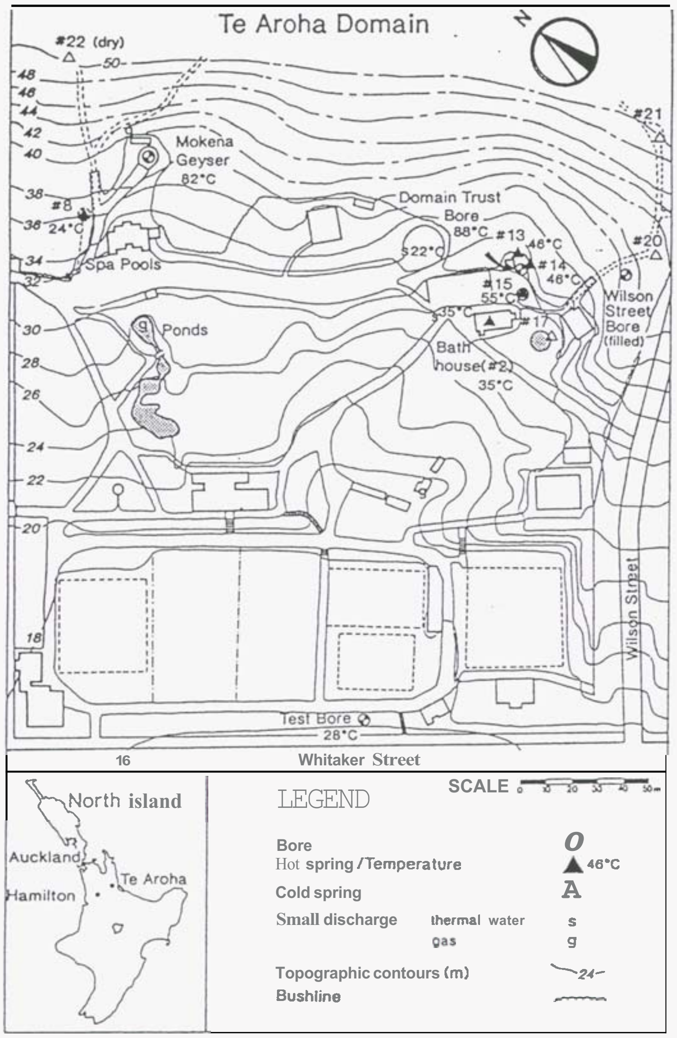

Fig. 1: Map of the Te Aroha Domain showing location of thermal springs and thermal wells.

Because of its intermittent discharge, the well is known as the 'Mokena Geyser' (see Fig. 1). Although deposition of aragonite in the well affects the flow rate, periodic reaming at half-yearly intervals has maintained production during the past 56 years. The Mokena well is probably the oldest producing geothermal well in New Zealand.

Table 1: Chemistry of selected Te Aroha waters (ranked on bicarbonate)

	HCO3	Na	Cl	SO4	B	Si02	K	Ca	Mg	Li	F	pH	Temp	Code
DTB	7700	3159	631	348	158	108	74	5.6	3.5	2.10	1.29	7.9	67.0	10
DTB	7700	3200	550	390	159	133	66	11.2	4.0				67.0	11*
MOKENA	7500	3200	550	390	162	135	66	6.9	3.9				85.0	2*
MOKENA	7500	3385	574	312	156	116	70	8.2	3.6	2.13	1.72	7.9	85.0	1
SP-15	6700	2911	611	335	145	106	69	6.8	3.4	0.48	1.53	7.3	55.0	7
SP-13	6600	2825	609	330	145	102	67	13.6	5.0	1.84	1.18	7.2	46.0	5
SP-14	6600	3071	524	279	155	107	73	11.2	4.0	1.99	1.51	7.3	46.5	6
SP-8	4900	2176	433	273	99	84	53	31	7.8	1.38	1.01	7.0	24.0	4
SP-21	2100	663	111	81	28	63.4	20	141	27.5	0.26	0.25	6.3	17.5	9
SP-20	320	110	31	35	3	44	3.4	24.5	13.1	0.03	0.38	5.8	15.5	8

* 2,11 analyzed by RJ Hill Laboratories, others by Univ. of Auckland

Three other wells have been drilled in the Te Aroha Domain since 1936 (to depths between 65 and 105 m). The recently infilled Wilson Street Bore **(WSB)** was drilled in 1937/8; it also discharged periodically although with a lower flow rate (equivalent to about 0.1 kg/s long term flow) at temperatures up to 75°C. The non-producing Test Bore' near Whitaker Street was drilled in 1956 and encountered temperatures of 62°C at 65 m depth. Another bore, the Domain Trust Bore (DTB) was drilled more recently, in 1986; it also discharges water periodically, with temperature of up to 88°C and flow rates similar to those of the Wilson Street Bore.

Neither the WSB nor the DTB have produced thermal water for longer periods, which might explain why the temperature of springs around both bores has not changed significantly over the last 100 years whereas, of the 6 warm springs mapped in 1889 in the vicinity of the Mokena bore, only one spring (No. 8 in Fig. 1) has survived; its temperature, however, declined from 43°C in 1889 to 24°C in 1993.

Hydrological setting and fluid chemistry

Te Aroha is one of several thermal spring systems associated with the eastern boundary fault of the Hauraki Rift (Hochstein and Nixon, 1979). Little is known about the likely extent of the Te Aroha reservoir. The small extent of the surface manifestations, small discharge rates, and the low productivity of the wells indicate that any reservoir beneath is of small extent. Even with the naturally-producing Mokena well, the total heat output of the prospect is less than 0.5 MW.

The constituents of Te Aroha waters are listed in Table 1 (all samples were taken in April 1993). Analyses from the wells show the highest bicarbonate values. Colder springs (Nos. 8, 21) contain a mixture of thermal water and groundwater. Hot springs Nos. 13 and 14 discharge at a level close to 32 m (a.s.l.) which appears to be close to the mean piezometric level between cycles in the Mokena well.

The waters probably originate from a distant source (Coromandel/Kaimai Range?). Significant ^{18}O shifts (Lyon and Giggenbach, 1992) of Mokena water and rather low (<150°C) cation equilibrium temperatures (T(Na-K) of Giggenbach) can be interpreted in terms of partial re-equilibration along flow paths since oxygen shifts require host rocks with temperatures >150°C. If this interpretation were correct, the Te Aroha reservoir could be the endpoint of a long outflow path. The K-Mg temperatures (about 110°C) and the Si02 (chalcedony) equilibrium temperatures (115 to 130°C) could represent likely minimum and maximum temperatures of the local Te Aroha reservoir.

The thermal springs and the geysering wells at Te Aroha also discharge a significant amount of gas. The dominant gas is CO_2, which made up about 94 to 96 mole % of gases sampled from natural springs (Henderson, 1913), similar to the CO_2 proportion of the Mokena bore gas discharges, namely 98.8% in 1936 as reported by Henderson (1938) and 94% according to more recent analyses by Lyon and Giggenbach (1992). Since the bottom temperatures in the geysering wells at Te Aroha are below boiling point for depth temperatures, Henderson (1938) and Healy (1956) suggested that the driving mechanism for the intermittent well discharges was not deeper flashing of steam but a periodic build-up of CO_2.

Geysering wells driven by C02 are a rare phenomenon. A summary of such wells has been given by Rinehart (1980); most of the wells cited discharge cold fluids like those at Saratoga Springs (New York, USA) referred to recently by Lund (1993).

Discharge characteristics of the Mokena bore

Discharge rates and cycling periods of this bore were measured in detail between November 1936 and June 1937 (Henderson, 1938). The period between successive eruptions varied at that time between 0.25 and *0.6* hr. In September 1956 the period was 0.3 to **0.4** hr (Healy, **1956),** and in April **1993** it varied between 0.5 and 0.8 hr; the **period** appeared to be bi-modal. There is a tendency for the period to increase with time (i.e. with increasing scaling in the well); the volume discharged per cycle also increases with the period (see Fig. **2).** After cleanouts (by reaming), the cycle period decreases, but the total volume discharged, say, per hour, increases again. Few reliable discharge data have been reported since 1937. In June 1993 (5 months after a cleanout) about 2 m^3 of fluids were discharged per cycle (period of 0.77 hr); this value plots at the right hand margin of Fig. **2.**

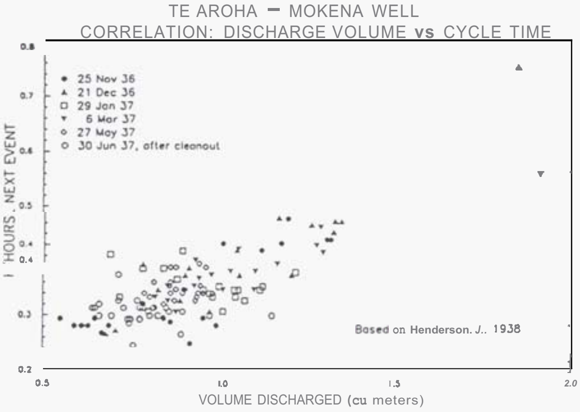

Fig. **2:** Mokena Well: discharge volume per eruption versus cycle time.

Temperatures observed in 1993 at various depths in the well during successive cycles are shown in Fig. 3a. The data indicate significant temperature changes during each cycle and show that a temperature versus depth profile cannot be defined for this well down to 60 m depth. More meaningful are the two enveloping curves. The temperature changes for constant depths are plotted in Fig. 3b, indicating that the largest change occurs just below the bottom of the **(4** inch) casing at 28 m depth, whereas the temperature remained constant at the bottom (67 **m)** of the well during cycles. The diameter of the well is 3 inches below 28 m depth. **A** temperature pattern similar to that in Fig. 3a was also observed by Healy except that his enveloping curves enclosed smaller amplitudes. The data in Fig. 3a indicate that negligible discharge derives from below 60 m and that some cooler water enters the well (at the end of the eruption) at **28** m depth.

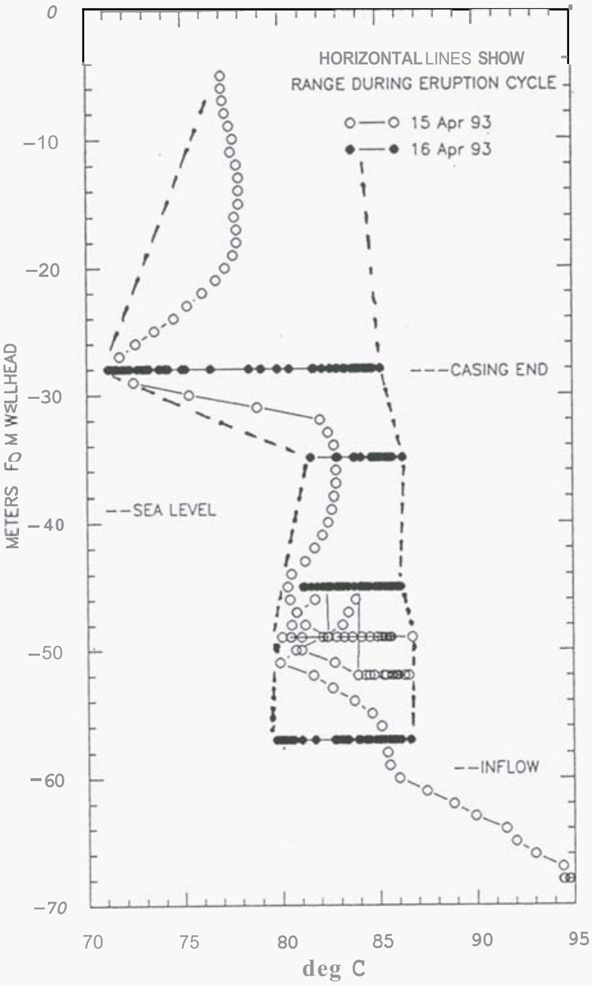

Fig. 3a: Mokena Well: temperature variations at various depths during eruption cycle.

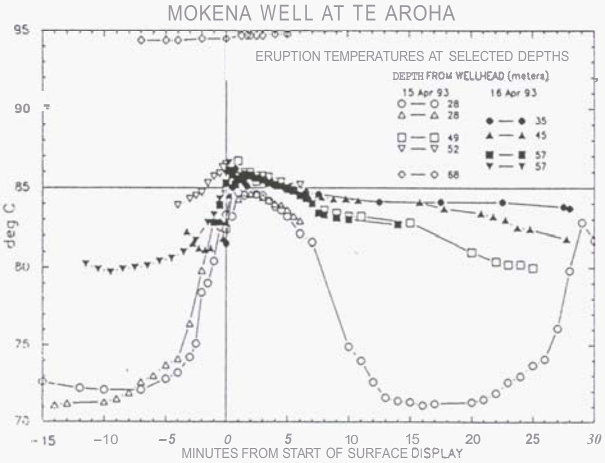

Fig. 3b: Mokena Well: temperature variations with time for constant depths.

A discharge mechanism which at some stage involves two feed points is also indicated by the observation of Henderson (1938) that smaller secondary peaks could be observed in about 30% of his discharge plots. Healy (1956) also occasionally observed smaller secondary peaks.

Discharge characteristics of other Te Aroha wells

Discharge characteristics of the Wilson Street Bore (WSB) have been described by Henderson (1938). During drilling, geysering action was observed when a depth of 35 m was reached and a 34 m deep casing set. The bore was deepened to 95 m but caved in at 59 m depth; periodic discharges began from an inflow at that depth. The long term flow rate was small (0.45 m^3/hr), the cycle period being 0.66 hr including a discharge period of about 10 min. In 1956 the cycle period was 0.37 hr; temperature variations at given depths during the cycle were less than those in the Mokena well. Bottom temperatures were 85°C (Healy, 1956). This well is no longer open.

The third well with geysering characteristics is the Domain Trust Bore (DTB), drilled in 1986 to 105 m depth. Cased down to 40 m (4 inch), this well also caved in at 57 m. On re-opening in April 1993, it discharged periodically with characteristics similar to those of the WSB. Long-term discharge was about 0.45 m^3/hr, the cycle period being between 0.25 and 0.35 hr. Temperatures observed during several cycles are shown in Figs. 4a and 4b. The envelope in Fig. 4a shows no inversion. At intermediate levels slightly cooler temperatures were observed after the eruption (see T at 30 m in Fig. 4b), indicating that cooler, probably gas-depleted, liquid displaces hotter gas-charged fluids; the same occurs in the Mokena well. Minor scaling was observed at the well head but we do not know whether significant scaling has occurred in this well.

Hydrological model

Using the observations presented, a tentative hydrological model can be developed which describes the geysering activity at Te Aroha. Since the fluid volume in the DTB is about 0.4 m^3, each cycle discharges about $^1/_4$ to $^1/_3$ of this volume. The fluid volume in the Mokena well is about 0.3 m^3; here, each cycle discharges about 5 to 10 times more fluids than are present in the well at any time. The temperature data indicate that significant inflow occurs not only at about 60 m depth (deep surge zone) but also at 28 m depth (shallow surge zone). The Mokena well therefore has two feed points, and the DTB only one.

Henderson (1938) observed that the liquid level in the bores after an eruption is not static. In the Mokena well in 1993, a liquid level about 5 m below the well head corresponded to a time approximately mid way between eruptions. In the DTB well, this level was about 1.5 m below the well head but showed large variations. In 1936, continuous level recordings of the Mokena well showed that significant oscillations occurred between cycles. One of us (DEM) suspects these oscillations are due to compression and rarefaction of gas bubbles in a frothy fluid (i.e. no oscillations of bottomhole pressures are envisaged).

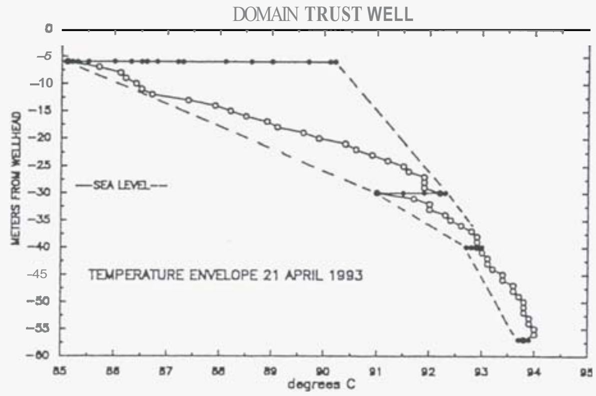

Fig. 4a: DTB: temperature variations at various depths during eruption cycle.

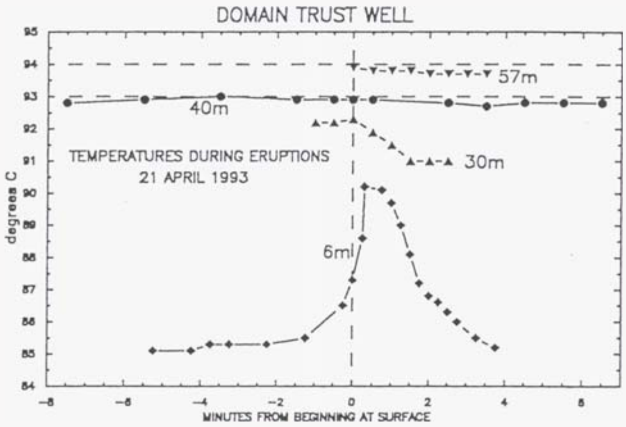

Fig. 4b: DTB: temperature variations with time for constant depths.

During each cycle, fluid flow probably changes direction between the bore and the 'surge zone'. The time when flow direction reverses identifies a natural trigger representing initiation and cessation of a geyser cycle. At present we believe that such a cycle starts in the Mokena well with an inflow from the deep surge zone, thus raising the liquid level towards the well head. Some of this flow also enters the shallow surge zone. The liquid of the initial flow is largely gas-depleted. Eventually, fully gas-charged fluids move into the well from the deep surge zone. At some level in the bore, CO_2 bubbles form and increase fluid speed. Since the maximum height during the spouting discharge is reached early (see Fig. 5), we suspect that a significant amount of the gas-depleted liquid rushing from the lower part of the bore enters the shallow surge zone.

Flow reversal between the bore and the shallow surge zone at Mokena initiates a second (semi-) cycle which begins about mid way during the geyser display. Discharge at the well head is then supported by two feed points but their flow rates decrease with time. The second cycle is absent at the DTB. At present we do not know how much gas is liberated during each eruptive cycle although the likely amount necessary to drive the geyser display can be estimated as shown in the following.

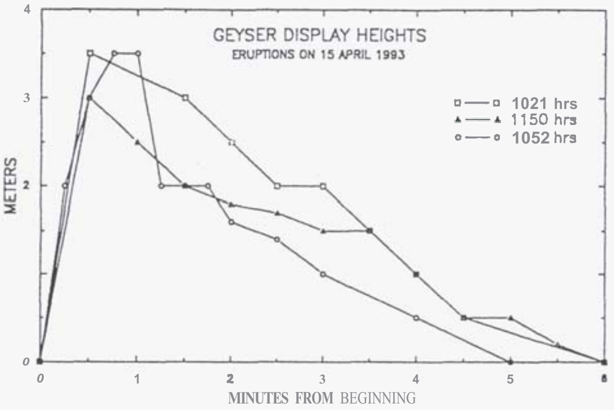

Fig. 5: Mokena Well: Changes in geyser height with time during eruptions.

Estimates of C02 content of fluids in the Mokena well

The frothy nature of the fluid at the well head of the Mokena and DTB wells indicates that gas is the driving force for the geyser display - an inference already made by Henderson (1938). Gas analyses referred to earlier have shown that C02 is dominant (between 94 and 99 mole %). The effect of other gases will be neglected in the following.

Several methods can be used to estimate the likely amount of C02 required to explain the periodic discharge. These are only order of magnitude estimates but they provide an understanding of how the gas-driven discharge mechanism is brought about. Each estimate applies to a different depth or depth interval.

1. CO_2 required to support the observed $\Delta T/\Delta z$ gradient (bottom)

Starting at the bottom, we assume that the observed temperature gradient between 60 and 68 m depth (see Fig. 3a) continues further downwards until boiling point temperatures are reached. In this case the CO_2 content of a liquid H_2O-CO_2 mixture can be assessed from the $\Delta T/\Delta z$ value since:

$$dz/dT = (dz/dP)[(dP/dT)_{H2O} + (CO_2)(dP/dT)_{CO2}]. \quad (1)$$

The observed $\Delta z/\Delta T$ value for the depth interval is 0.903 m/°C.

Since, for a liquid at 91°C:

$dz/dP = 10.57$ m/bar,

$(dP/dT)_{H2O} = 0.0267$ bar/°C,

$(dP/dT)_{CO2} = 0.0189$ (bar/°C)/(g/kg),

the observed $\Delta z/\Delta T$ value indicates: C02 = 3.1 g/kg.

2. CO_2 required to lift a 60 m liquid column

For processes which initiate cycling at the level of the lower surge zone, we assume that at the beginning of the cycle the CO_2 concentration at 60 m depth is just sufficient to provide bubble expansion when the column above is filled with bubble-free liquid. Using known gas solubilities and appropriate liquid densities, the C02 concentration at 60 m depth can be assessed.

The density of a $NaHCO_3$ solution with TDS of, say, 10g/kg is about the same as that of pure water (CRC, 1986). The average temperature of the liquid column prior to eruption is about 80°C. The pressure at 60 m depth is therefore about 5.7 bar at that time. Vapour (H_2O) pressure, however, provides part of the bubble support. Since, for a bottom temperature of 87°C

$P_{H2O} = 0.63$ bar,

it follows that $P_{CO2} = 5.07$ bar.

Using results from Ellis and Golding (1963), and taking appropriate values for C02 solubility (CRC, 1952), it can be inferred that $P(CO_2)$ of 5.07 bar requires 2.5 $g(CO_2)$ per kg liquid at 60 m depth.

3. CO_2 required to stabilize $CaCO_3$

Deposits of almost pure aragonite occur in the upper part of the well (i.e. between 0 and 27 m depth) and have to be reamed at half-yearly intervals to maintain production. Scaling at greater depths apparently does not occur since it would have stopped long-term discharge. We assumed initially that deposition occurs under equilibrium conditions, which allows an estimate of the C02 concentration using the observed HCO_3^- and Ca^{2+} data of the discharged water (see Table 1), allowing for a correction since the true concentrations of both constituents at depth are affected by scaling. Any CO_2 estimate is also affected by uncertainties with respect to the assumption of a representative temperature for the process, the effect of $CaHCO_3^+$ formation (which is poorly defined for temperatures of interest), and partial dissolution of calcite from **rocks** below 28 m depth (as has been reported by Henderson (1938)).

The theoretical Ca concentration at saturation with calcite **and** aragonite *can* **be** defined by combining several chemical equilibria commonly used in **carbonate** chemistry and which takes the form of:

$$Ca_{(theor.)} = [(CO_2)_{aqu.}/(HCO_3^-)^2] \times A \qquad (2a)$$

where $A = [K_1 K_S/(K_S\gamma + 2(\gamma - 1)^2)]$ and using appropriate values of K_S for calcite and aragonite respectively.

The effect of the $CaHCO_3^+$ complex can be incorporated by introducing:

$$Ca_{true} = Ca_{(theor.)} + CaHCO_3^+.$$

With this term, equation (2a) can be recast in the form:

$$Ca_{true} = Ca_{(theor.)}\ [1 + \gamma + 2(\gamma - 1)^2 * B], \qquad (2b)$$

where $B = K_{CaHCO3}\,(HCO_3^-)$.

The dissociation constant in B has been described by Plummer and Busenberg (1982); it is poorly defined for the temperature range of fluids in the Mokena well although a value of 1.9 would be consistent with the Plummer and Busenberg data.

Using equation (2a), T = 83°C, and Ca^{2+} = 8.2 mg/kg yields a value of: C02 = 2.8 g/kg fluid for aragonite stability. With equation (2b), the value decreases to 1.5 g CO_2/kg fluid.

Assuming that in 6 months a 20 mm scale (0.2 porosity) builds up in the cased section of the well between 7 and 27 m depth, this points to a long term Ca^{2+} loss of about 7 mg/kg fluid. A Ca value of 15 mg/kg in equation (2a) yields 5.3 g CO_2/kg fluids (for aragonite stability), and 2.8 g/kg if equation (2b) is used.

The estimates given above assume equilibrium conditions for C02 exsolution and scale deposition; such deposition can also occur under non-equilibrium conditions as they have been observed by Michels (1991) in a hot well involving calcite deposition. If the actual amount of scaling were known, together with *in situ* chemistry data, the possibility of non-equilibrium conditions could be investigated.

4. CO_2 required to lift fluids above *the well head*

One can assume that the work required to lift fluid to a given height above the well head during geysering derives from expanding CO_2 gas which imparts the necessary velocity at the orifice. Ignoring friction and air resistance, it can be shown that a liquid jetting to 3.5 m (see Fig. *5)* requires an energy of 68.6 J/kg. The work of exsolution can be estimated fiom the reverse process, namely compression **of** a given amount of CO_2 into a unit mass of water. In the upper part of the Mokena bore, compression of 1 g C02 over a pressure range of 1 to 2.9 bar requires 63.7 J/kg (at T = 83°C). Hence, expansion of about 1.1 g of CO_2 per kg of liquid is required for the jet to reach a height of 3.5 m. Residual dissolved CO_2 at atmospheric pressure is still about 0.5 g/kg, pointing to a CO_2 concentration of at least 1.6 g/kg fluid at the orifice. Residual C02 is probably greater, since one cannot expect a representative equilibrium residual value for an accelerating fluid.

Further work

None of the estimates in the previous paragraph can be strongly defended, but it is no coincidence that all values lie within the range of about 1.5 to 5 g CO_2/kg fluid, with a mean of about **3 ±0.5** g/kg. The whole process of cyclic discharge would be better understood **if** in future liquid and gas were sampled at various depths in the well during a whole cycle. Together with additional monitoring of fluid pressure at given depths and monitoring of scaling (downhole logging), important data would become available which would allow a detailed analysis of Mokena well activity, which has delivered gas-rich fluids for more than 56 years. The additional work would also contribute significantly to a better understanding of carbonate chemistry for temperatures that prevail in this unique well.

Acknowledgements

We would like to acknowledge the help of members of the local Council and staff of Te Aroha Domain who allowed us to undertake the studies reported here. The senior author was the recipient of the 1992 Mitsubishi Fellowship (Univ. of Auckland) when this study was undertaken. David Jenkinson undertook all the physical and chemical measurements summarized here while sponsored by Woodward-Clyde (NZ). The data form part of his MSc thesis which on completion will be deposited in the Library, University of Auckland. We would also like to thank the staff of Woodward-Clyde, especially Mr Ian Fraser, for discussion and permission to refer to data in their recently completed Te Aroha report.

Note: Recent temperature logs of the Mokena well (September 1993) have shown that temperatures are in general about **4 to** 5°C higher than those shown in this paper (i.e. bottom temperature was close to 99°C). It is not known yet whether the difference is caused by calibration errors.

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