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BOILING AND THERMAL - PRESSURE CHANGES RECORDED IN CALCITE-HOSTED FLUID INCLUSIONS OF THE NGAWHA GEOTHERMAL FIELD, NEW ZEALAND

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SUMMARY – Calcite-hosted fluid inclusions separated from cuttings and cores of Ngawha wells were studied to understand boiling-mixing processes affecting reservoir fluids and the origins of calcite. Evidence of boiling is represented by co-existing liquid-rich and vapour-rich inclusions at most depths and the common occurrence of platy calcite. Over 1000 fluid inclusions have Th values that range from 160 to 306 °C and Tm values that range from -0.4 to -2.5 °C. Crushing experiments and Tm data suggest that inclusion fluids contain up to 3.7 wt % CO_2, approximately twice as much as in the modem fluid. It thus appears that calcite and the fluid inclusions formed under a wide range of pressures, some of which approached lithostatic. The build up of high partial pressures of CO_2 is likely due to the impermeable nature of the shallow sedimentary host rocks.

1. INTRODUCTION

The Ngawha geothermal system lies in the central axis of the Northland Peninsula, within a region of Quaternary basaltic volcanism; it is the only high temperature geothermal system in Northland (Figure 1). The field is situated within a depression, the Ngawha Lake basin, at an average elevation of 200 m asl. Fluid from two wells (Ng 9 and Ng 12) is used to generate electricity (~10 MWe) through an Ormat plant.

The Ngawha geothermal system is predominantly hosted by sedimentary rocks and is associated with fluids containing high concentrations of CO_2 (Sheppard, 1984). Not surprisingly, calcite is the dominant mineral in veins and fractures (Browne, 1980; Cox and Browne, 1998), providing a partial record of the distribution and movement of CO_2 in geothermal fluids (e.g. Simmons and Christenson, 1994). In this paper, we describe preliminary interpretations from a fluid inclusion study on calcite from the Ngawha geothennal system (Aredriningsih, 2001).

2. GEOLOGY AND THERMAL ACTIVITY

Basement rocks of the Permian-Jurassic Waipapa Group are made up of quartzo-feldspathic greywackes and argillites (Skinner, 1981), and these host the geothermal reservoir. Though their porosity is poor, fractures and interconnected joints provide most of the permeability (Browne, 1980) and confine the extent of the reservoir (e.g. Cox and Browne, 1998). The overlying Cretaceous-Tertiary sedimentary sequence is about 500 m thick and comprises siltstones, mudstones and shales, interleaved with zones of tectonic breccia (Skinner and Grindley, 1980). Their fine grained and ductile nature forms a partial barrier to ascending thermal fluids (e.g. Cox, 1985). The presence of steeply dipping faults (NE and NW trending) with offsets of no more than a few tens of meters (Petty, 1985) provide the main conduits for fluids reaching the surface.

The thermal features include neutral to acid hot pools, gas seeps and cold lakes. They form three linear arrays that trend northeast (Figure 2). The low liquid discharge (1-2 l/s, total) and the seemingly high gas flux are distinctive features of the surface activity (Giggenbach and Lyon, 1977).

The deep reservoir water at Ngawha has a temperature of about 230° C and is generally similar in composition to reservoir waters found in TVZ geothermal systems. It contains about 1200 ppm Cl and 1-2 wt.% CO_2 (Sheppard, 1984). This fluid is slightly over-pressured with respect to a hot hydrostatic boiling point for depth gradient, due to the confining nature of the shallow sedimentary strata (e.g. Browne and Lawless, 2001).

3. SAMPLES AND METHODS

Hydrothermal calcite occurs mainly as fracture and vein fillings (Cox and Browne, 1998). It commonly forms platy crystals. Fluid inclusions were studied in twenty-two samples from six wells (Ng-2, Ng-3, Ng-4, Ng-5, Ng-13, Ng-16) ranging from 328 m to 1200 m depth. Inclusions in one Sample of quartz (Ng-4) were also studied.

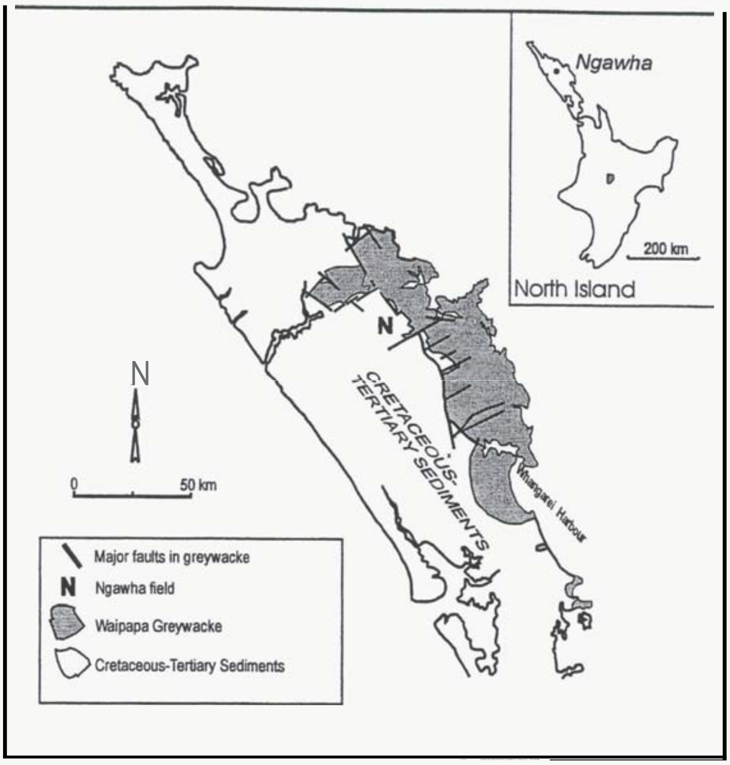

Figure 1. Location of the Ngawha field and regional geology.

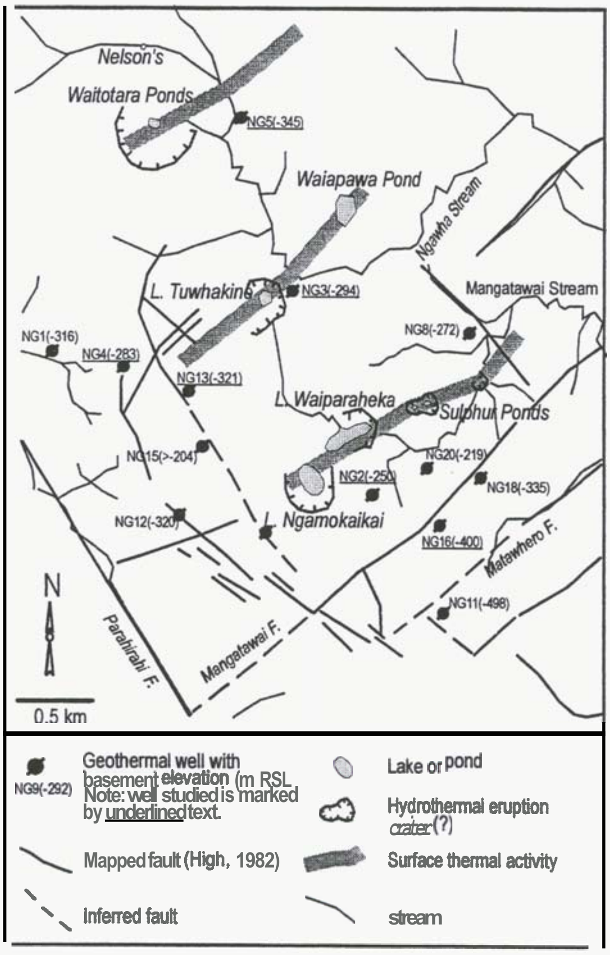

Figure 2. The Ngawha field showing the distribution of the thermal features and wells (modified from Cox, 1985).

Over **70** doubly polished **sections (–100 µm** thick) were made. Primary fluid inclusions were clearly associated with **crystal growth** zones, whereas secondary fluid inclusions occur along healed fractures.

Microthermometric **data** were obtained on a Fluid Inc.–adapted USGS gas heating-freezing system. The thermocouple **was** calibrated using synthetic fluid inclusions. Homogenisation temperatures (Th) are accurate to ± **2°C** and ice melting temperatures (Tm) are accurate to ± 0.1°C.

Some calcite-hosted fluid inclusions were crushed to assess the gas contents of the inclusion fluids (Roedder, **1984).** Vapour-bubble expansion (Figure **3)** indicates the presence of gas (e.g. CO_2) while vapour bubble collapse indicates the presence of pure water vapour (Roedder, **1984).**

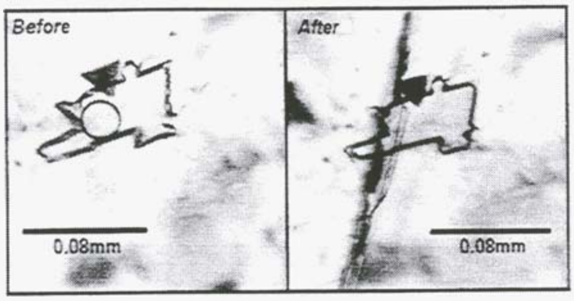

Figure 3. **Left:** Photomicrograph showing **a** calcite-hosted primary liquid-rich inclusion (Ng5 -**1020** m) before crushing. Right: Photomicrograph of the same inclusion after crushing. The fracture crossing the inclusion cavity formed from crushing and allowed the internal pressure to equalise with atmospheric pressure, resulting in bubble expansion that completely filled the cavity

4. RESULTS

Primary and **secondary** inclusions **(10** to **100µm)** containing two-phases, liquid and vapour, were observed in **all** calcite and quartz samples. **They** ranged in **shape from** flat and **thin** to equant and irregular to negative crystal. Liquid-rich inclusions containing ***–85%*** liquid were abundant and commonly found with vapour-rich inclusions containing **>95%** vapour. Their coexistence in many samples and the platy nature of many calcite **crystals** indicates vapour-saturated conditions at the time of inclusion entrapment and calcite deposition (Browne, **1978;** Roedder, **1984).** **This** means that Th **data** *can* **be** used directly to infer the fluid temperature and pressure during calcite precipitation (Roedder and Bodnar, **1980).**

Microthermometric data were obtained on **mnore** than **1000** fluid inclusions. Th **data** range from **160"** to **306°C,** with mean values clustering **between** 200 and 260 °C (Figure **4).** Primary and **secondary** inclusions appear to have formed under **similar** conditions on the basis of overlapping Th data. Comparison of the Th values and down-hole temperatures show: **1)** cooling of more than **50** °C at shallow level (300-**500** m) in Ng **4** and Ng **13;** and 2) heating of about 20 **°C** at deep level **(>800 m)** in Ng **5** and Ng **13.** The **bulk of** the **data,** however, have **similar** homogenisation and down-hole temperatures, suggesting that there **has been** little change in the temperature gradient since the fluid inclusions **formed.**

Ice melting temperatures range from **-0.4°** to **-2.5°C** with median values clustering between **-0.6** and **-2.0** °C (Figure **4).** These correspond to salinities ranging **from** 0.7 **to 4.2 eq wt %** NaCl. For comparison, the calculated ice melting temperature of the parent geothermal fluid **from** Ng **13** is **-0.9** °C.

Fluid inclusions in twelve calcite **crystals** were crushed while observing them under the microscope. In most **cases,** the vapour bubble of liquid-rich inclusions expanded and completely filled the inclusion volume, signifying the presence of CO_2 and minimum concentrations of **0.35** to **0.40** wt% CO_2 **(Sasada** et al, **1986).** These estimates **are** well within the range observed in the modern reservoir fluids. The maximum concentration could be **as** high **as 3.7 wt** % CO_2 given the **absence** of clathrates and ice melting temperatures of less than **-1.5** °C (e.g. Hedenquist and Henley, **1985)**

5. DISCUSSION

While the Th **data** suggest that thermal conditions have remained more or less the same, the Tm **data** indicate that the modem fluids are more dilute than in **the** past. **This** difference may result from a change in the concentration of dissolved **salts (i.e. from** >2.0 to 0.2 **wt** % NaCl), or **a** change in the concentration of dissolved gas (i.e. ftom **3.5** to **1-2 wt%** CO_2), or a change in both. Of the **three** possibilities, we believe that the compositional differences mostly reflect changes in the CO_2 concentration, **as** interpreted for other New Zealand geothermal **system** (Hedenquist and Henley, **1985). This** requires **a** smaller change in **concentration** than for dissolved **salts** (a factor of **2** difference versus a factor of **10** difference). **This** change in CO_2 concentration is also sensitive to overall pressure gradient and of **gas** loss resulting ftom boiling.

To illustrate **this point,** we have calculated two model boiling curves (Figure **4)** following the method of Hedenquist and Henley **(1985)** and **Simmons** and **Christenson (1994). Multi-step**

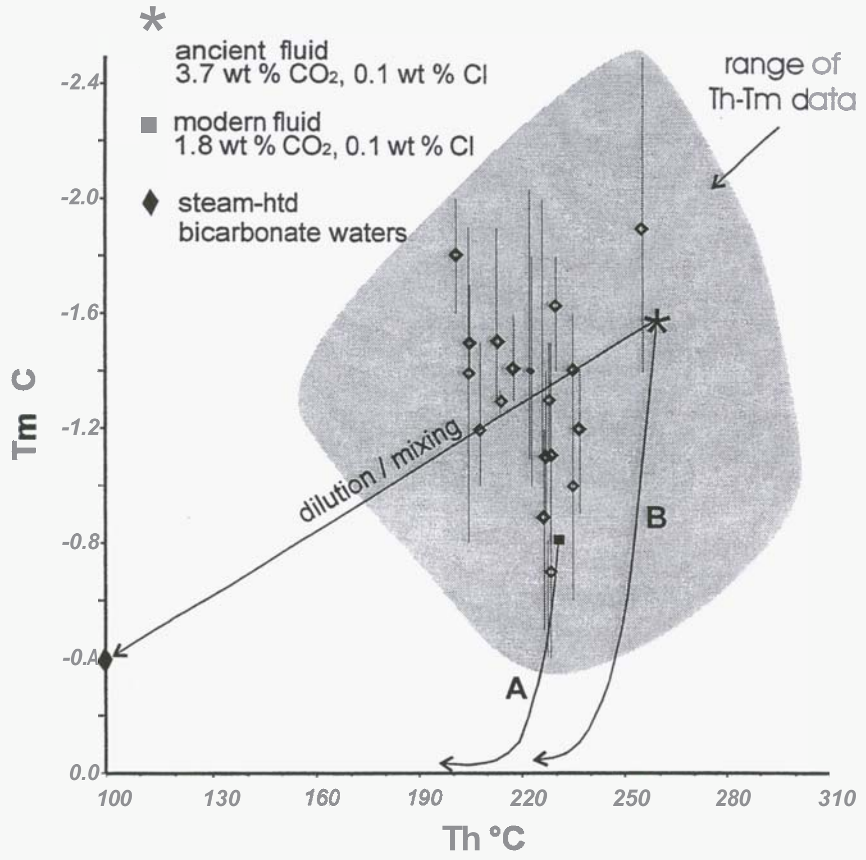

Figure 4. Plot of the Th (average) and Tm (median and range) data and model boiling curves. The shaded area indicates the full Th-Tm range of the fluid inclusion data.

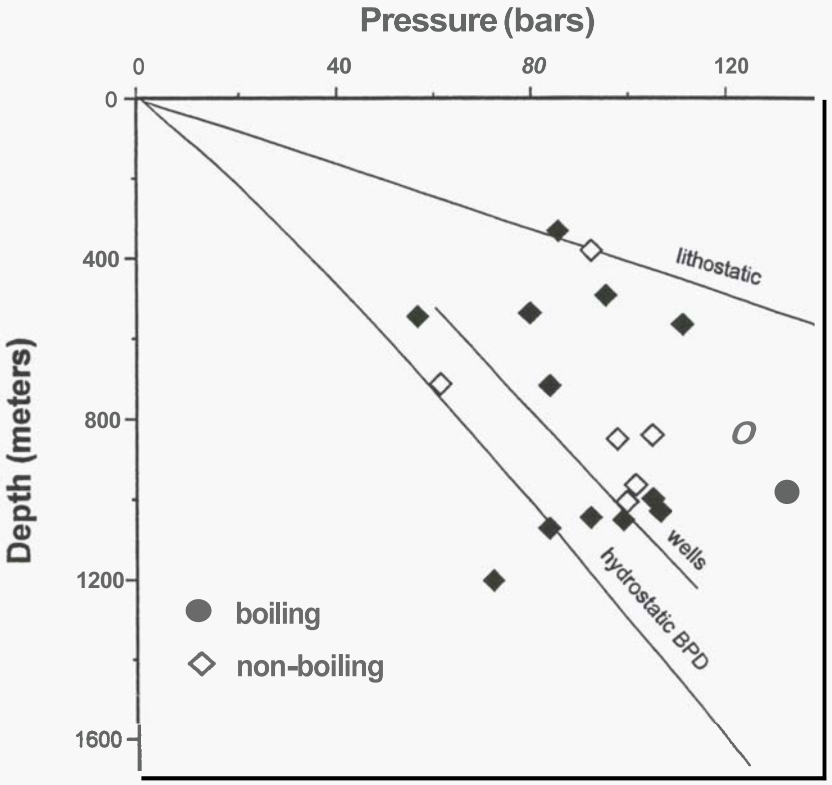

Figure 5. Plot of estimated fluid pressures versus depth. Samples with evidence of boiling are distinguished. Hydrostatic, lithostatic and measured well pressure gradients are shown.

vapour separation is assumed and the fluid compositions (CO_2 and NaCl) are specified to match the Th and Tm data.

Curve A represents the boiling path for the modem parent fluid containing **1.75 wt %** CO_2 and **0.1 wt %** Cl that begins to boil **at 230°C.** Curve **B** represents the boiling path for the ancient parent fluid containing **3.7 wt % CO_2** and **0.1 wt %** Cl that begins to boil at 260°C. A mixing line between ancient parent fluid and a shallow steam-heated bicarbonate water is also shown. Figure 3 shows that the relatively wide range of Tm values at near dorm Th values reflects the effects of boiling and gas loss of the gas-rich parent fluid. Moreover, a significant portion of the Th-Tm data is bracketed by curve B and the mixing line; this is considerably more than can be explained by the modem parent fluid composition and gas loss effects represented by curve A.

Accepting that dissolved CO_2 accounts for much of the Tm data (Figure 4), we estimated fluid pressures assuming a simple H_2O-CO_2 system. The CO_2 partial pressure was calculated from median Tm values and appropriate Henrys Law constants while the partial pressure of water vapour was determined from average Th values and *steam* tables. The total pressures of fluid inclusion populations range plus or minus about 15% (reflecting the range in Th) and are plotted as a function of depth in Figure *5.* They range from *55* to 132 bars, with $p CO_2$ comprising well over 50% of the total pressure. The Ngwaha reservoir pressure gradient (Grant and McGuinness, **1985),** the pure water boiling point for depth hydrostatic gradient (Haas, 1971) and the lithostatic gradient are shown for comparison.

In over half of the samples, the estimated pressures exceed modern values by **50 to 100%** and approach lithostatic loads at shallow depths (<400 m). Despite these extreme pressures, two-phase conditions apparently existed (as indicated by fluid inclusion evidence and the occurrence of platy calcite), possibly in response to local pressure drops (induced by seismicity?) in confined spaces, which sealed through calcite deposition. Pressure estimates for the rest of the samples fall close to the modem pressure gradient, indicating substantially reduced pressures, possibly resulting from hydrothermal eruptions to the surface. It seems that the relatively impermeable Cretaceous-Tertiary sedimentary host rocks confined fluid volumes that allowed pressures and aqueous CO_2 to build up. Eventually these were partially relieved presumably through fracturing and seismicity though over pressured conditions still exist.

6. CONCLUSIONS

Fluid inclusion data indicate that calcite deposited from 170° *to* 310°C. These data show cooling of about 50° in places within the *cap* rock. The central part of the reservoir has not changed, while the northern and western parts of the reservoir have heated about **20° C** since the inclusions formed.

Carbon dioxide is the dominant solute in inclusion fluids. Boiling has affected their CO_2 concentrations and the reservoir fluids, as reflected in the Tm data. The ancient fluid contained more gas and, in some cases, was greatly over-pressured relative to the modern fluid.

Impermeable sedimentary rocks at shallow depth, a high influx of CO_2, opening and *sealing* of fractures, and the distribution and movement of liquid and vapour, all influenced the development of pressures between hydrostatic and lithostatic and their change over time.

Boiling and some fluid mixing account for most of the microthermometric data. Boiling seems *to* have had the largest influence in lowering the dissolved CO_2 in the parent liquid as indicated by increasing Tm trend.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

Arediningsih, Y. (2001). Fluid Inclusion and Stable Isotope Studies of the Ngawha Geothermal Field, Northland, New Zealand: Evidence for Boiling and Temperature-Pressure Changes. Unpub. MSc Thesis. Auckland University. 108p.

Browne, **P.R.L. (1980)** Joint channels in reservoir rocks of the Ngawha geothermal field, Northland, New Zealand. Proc. 2nd New Zealand Geothermal Workshop, Auckland, p. **81-84.**

Cox, M. E. **(1985).** Geochemical Examination of the Active Hydrothermal System at Ngawha, Northland, New Zealand: Hydrochemical Model, Element Distribution and Geological Setting. Unpub. PhD thesis, Auckland University, **385** p.

Cox, M. E., and Browne, P. R L. **(1998)** Hydrothermal alteration mineralogy as an indicator of hydrology at the Ngawha geothermal field, New Zealand. Geothermics, v. **27,** p. **259-270.**

Giggenbach, W. F., and Lyon, G. L. **(1977)** The chemical and isotopic composition of water and gas discharges **from** the Ngawha geothermal field, Northland. Wellington, Unpub. Report DSIR Chemistry Division.

Grant, M.A. and McGuinness, M. **(1985)** Hydrology : Reservoir Pressure and Temperature Interpretations (Part **1).** The Ngawha Geothermal Field: A New and Updated Scientific Investigations:. Wellington, DSIR Geothermal Report No. **8,** p. **179-187.**

Haas, J. L., Jr. **(1971)** The effect **of** salinity on the maximum thermal gradient of a hydrothermal system **at** hydrostatic pressure: Economic geology, **v. 66,** p. **940-946.**

Hedenquist, J. W., and Henley, R W. **(1985)** The importance **of** CO_2 on freezing point measurements of fluid inclusions; evidence **from** active geothermal **systems** and implications for epithermal ore deposition. Economic Geology, v. 80, p. **1379-1406.**

Petty, D. R **(1985) A** geological reappraisal of the Ngawha geothermal field. The Ngawha Geothermal Field: A New and Updated Scientific Investigations: Wellington, **DSIR** Geothermal Report No. **8,** p. **17-32.**

Roedder, E. **(1984)** Fluid Inclusions. Reviews in Mineralogy. **12,** Mineralogical Society **of** America. **644** pp.

Roedder, E and **Bodnar,** R J. **(1980)** Geological pressure determinations **from** fluid inclusion studies. Annual Reviews Earth Planetary Sciences, v. **8,** p. **263-301.**

Sasada, M., Roedder, E., **and** Belkin, H. E. **(1986).** Fluid inclusions from drill hole **DW-5, Hohi** geothed **area,** Japan: Evidence of boiling and procedure for estimating CO_2 **content:** Journal of Volcanology and Geothermal Research, v. **30, p. 231-251.**

Sheppard, D. S. **(1984)** Fluid Chemistry **of** the Ngawha Reservoir. Proc. **6th** New Zealand Geothermal Workshop, Auckland, p. **151-154.**

Simmons, S.F., and **Christenson,** B.W. **(1994),** ***Origins*** of calcite in a boiling geothermal **system.** American Journal of Science, v. **294,** p. **361-400**

Skinner, D.N.B. **(1981)** Geological setting and subsurface geology of Ngawha. **DSIR** Geothermal Report No. **7,** p. **14-35.**

Skinner, **D.N.B., and Grindley,** G.W. **(1980). Structural** control **of** the reservoir rocks at the Ngawha geothed field, **Northland,** New Zealand. Proc. 2nd New Zealand Geothermal Workshop, Auckland, p. **85-89.**