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C.J FAGAN[1]
Masters Student, Department of Geology, The University of Auckland, NZ

C.J.N WILSON[1]
Professor, Department of Geology, The University of Auckland, NZ

K.D SPINKS[2]
Geothermal Geologist, Mighty River Power, Hamilton, NZ

P.R.L BROWNE[1]
Associate Professor, Department of Geology, The University of Auckland, NZ

S.F SIMMONS[1]
Associate Professor, Department of Geology, The University of Auckland, NZ

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[1]Department of Geology, The University of Auckland, Private Bag 92019 Auckland Mail Centre, Auckland 1142, New Zealand
Ph. +64 (09) 373-7599 Fax +64 (09) 373-7435

[2]Mighty River Power, PO Box 445, Hamilton, New Zealand
Ph +64 (07) 857-0165 Fax +64 (09) 857-0249

STRATIGRAPHY, HYDROTHERMAL ALTERATION AND EVOLUTION OF THE MANGAKINO GEOTHERMAL SYSTEM, TAUPO VOLCANIC ZONE, NEW ZEALAND

C.J. FAGAN[1], C.J.N. WILSON[1], K.D. SPINKS[2], P.R.L. BROWNE[1], S.F. SIMMONS[1]

[1] The University of Auckland, Auckland, New Zealand
[2]Mighty River Power, Hamilton, New Zealand

SUMMARY – Four exploration wells at the Mangakino geothermal field reveal a thick sequence of flat-lying ignimbrites and an alteration pattern similar to other active geothermal fields in the Taupo Volcanic Zone (TVZ). Rocks encountered in the deepest well, MA2 (3192m), are interpreted as thick caldera infill with five separate ignimbrites identified, the thickest being >800m thick. Surficial ignimbrites exposed nearby have distinctive mineralogies and crystal contents, which have enabled correlations to be made with down-hole lithologies. The alteration mineralogy of cuttings and core samples is similar to other geothermal fields in TVZ. Ca-silicate minerals (epidote, wairakite) occur in MA2 below 2200m, and adularia replaces, wholly or in part, primary andesine. Other hydrothermal minerals present include chlorite, quartz, calcite, titanite and pyrite. Measured downhole temperatures reach 250°C at 3000m in MA2 and are consistent with the mineralogical assemblages represented in the youngest phase of alteration. Fluid inclusions in secondary calcite show high temperatures (300 & 315°C) while inclusions in primary quartz show ~165°C (the current temperture at the depth of the core), recording current conditions. This evidence for two different temperatures in the fluid inclusion data and two episodes of alteration may indicate a previous thermal event which is possibly related to dike intrusion on the periphery of the Mangakino field.

1. INTRODUCTION

The Mangakino geothermal field and prospect (Fig. 1) are located approximately 40km northwest of Wairakei geothermal field. Cuttings and core obtained from an ongoing exploration programme provide unique insights into the subsurface stratigraphy and associated hydrothermal alteration within the Mangakino caldera complex.

In this paper, we present new data on the occurrence and distribution of common hydrothermal minerals and stratigraphy of the deepest vertical well at Mangakino (MA2). This well was drilled vertically to 3192m depth with a maximum temperature of 254°C. We also discuss the relationship between this well and other nearby wells drilled within the Mangakino caldera complex.

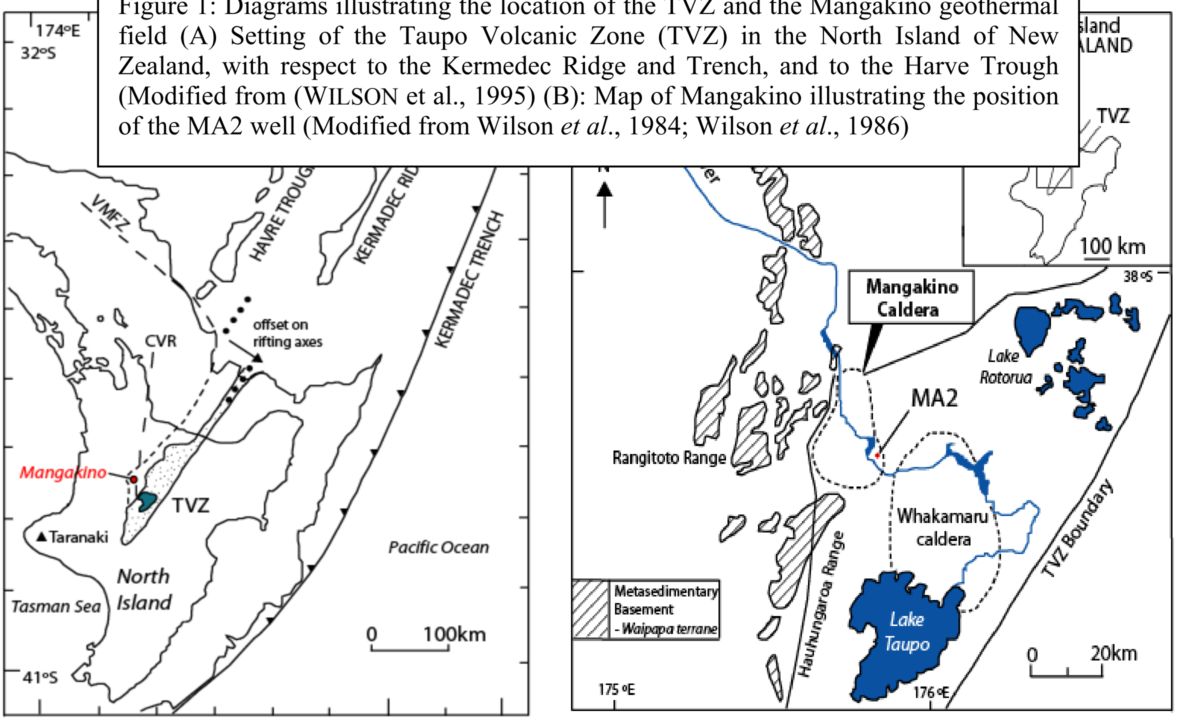

Figure 1: Diagrams illustrating the location of the TVZ and the Mangakino geothermal field (A) Setting of the Taupo Volcanic Zone (TVZ) in the North Island of New Zealand, with respect to the Kermedec Ridge and Trench, and to the Harve Trough (Modified from (WILSON et al., 1995) (B): Map of Mangakino illustrating the position of the MA2 well (Modified from Wilson *et al.*, 1984; Wilson *et al.*, 1986)

2. THE MANGAKINO GEOTHERMAL FIELD

The Mangakino geothermal field is situated in the oldest of the 8 documented TVZ rhyolitic calderas, which was active between 1.6 – 0.93 Ma. At least 5 ignimbrite eruptions are ascribed to this caldera with >500 km^3 of magma erupted (Wilson, 1986). In the Mangakino prospect, four completed wells range in depth from 600-3192 m. Initial exploration of the field carried out by the Crown in the 1980s led to drilling of MA1 (607 m deep). MA1 reached a maximum temperature of 185 °C and encountered bicarbonate-chloride fluids (Na-K equilibration temperatures >240 °C) at 350 m depth, where high permeability was recognized (Spinks *et al.,* 2005) .

The geology of MA1 was described by Peter Wood, who inferred the Whakamaru ignimbrite to be overlying 300m of lacustrine sediments, now labelled as the Reporoa Group by Gravley *et al.* (2006). The Marshall ignimbrite underlies the Reporoa Group at the base of this well (Wood, 1986). These relationships are consistent with the exposed stratigraphy of these units. Along with the local resistivity anomaly, the results from MA1 suggested the existence of a viable geothermal resource. In 2004, Mighty River Power re-examined the Mangakino prospect using updated techniques leading to the drilling of the deepest vertical well MA2 to 3192 m vertical depth.

Other relevant studies associated with this investigation include the examination of the surface geology within and surrounding Mangakino caldera described by Martin (1961), Blank (1965) and Wilson (1986).

3. METHODS AND TECHNIQUES

Descriptions of the minerals and rocks of >60 samples are based on a combination of thin section, X-ray diffraction (XRD) analysis and binocular microscopy. Cuttings were sampled and described at 50 m intervals to delineate the stratigraphy and hydrothermal alteration. As the majority of this work is based on study of cuttings, the stratigraphic interpretations are provisional; however, the lithological units are presumably thick and homogenous as deduced from observations of units on the surface. Other effects such as down-hole mixing are thought to be minimal. Mineral abundances and alteration intensities reported here were visually estimated from thin sections and may have errors of ±5 to 10 percent. Because of their utility as mineral geothermometers, clays were studied in detail using XRD analysis.

Surface lithologies from within and surrounding the Mangakino caldera were also sampled, and studied in thin section. These samples permit comparison between the surface and subsurface samples and were important in estimating the lithic and crystal abundance and content of specific lithological units.

4. STRATIGRAPHY OF MA2 WELL

The boundaries between units in Figure 2 are based on both stratigraphic and petrographic correlations with rocks exposed on the surface from within or surrounding the Mangakino caldera complex. The stratigraphy of ignimbrites in the Mangakino area (Wilson, 1986) is based on both field relationships and K/Ar, Ar/Ar and fission track dating (Blank, 1965; Houghton *et al*., 1995; Martin, 1961; Wilson, 1986).

Ignimbrite	Crystal abundance	Crystal content					Distinguishing Features
		plg	qtz	bio	opx	hb	
Whakamaru	35-40%	✓	✓ X	✓	✓	✓	Vitraclasitic, partly welded, abundant in quartz
Waiotapu	10%	✓ X	✓	-	✓	-	Crystal poor, hard dense lenticulite
Marshall	8%	✓ X	✓	-	✓	-	Large pumice clasts, crystal poor, non welded
Rocky Hill	20%	✓ X	✓	✓	✓	✓	Large amphibole crystals, greywacke common, densely welded
Ahuroa	10-12%	✓ X	✓	-	✓	-	Lacks andesite lithics, flattened pumice, lithics mainly rhyolite and basalt
Ongatiti	40%	✓ X	✓	-	✓	✓	Ongatiti like welded ignimbrite inclusions, variable lithic content
Unit C	30-40%	✓ X	-	-	✓	-	Absence of qtz, lithic clasts dominated by andesite lava

Table 1: Summary of ignimbrite petrographic characteristics. Crystal abundance and presence based on Martin (1961) and distinguishing features based on Wilson (1986). ✓ = present, X = abundant. Crystal abbreviations: plg = plagioclase, qtz = quartz, bio = biotite, opx = orthopyroxene and hb = hornblende.

Wood (1986) indicated that the 0.32 Ma Whakamaru ignimbrite, which underlies most of the exposed Mangakino landscape, overlies a thick sequence of lacustrine sediments and volcaniclastic units (now termed the Reporoa Group: Gravely *et al*., 2006) related to the post-collapse infill of the Mangakino caldera. Predating these deposits are at least 7 ignimbrites associated volcanism at Mangakino that were identified by Wilson (1986)

The petrographic observations of the exposed ignimbrites indicate an alternating sequence of crystal poor to crystal rich units. The same pattern is seen in the cuttings, and variations in crystal contents were used to distinguish ignimbrite units (Table 1). In detail, the presence or absence of pseudomorphs after amphibole were used a guide to identify the Rocky Hill and Ongatiti ignimbrites.

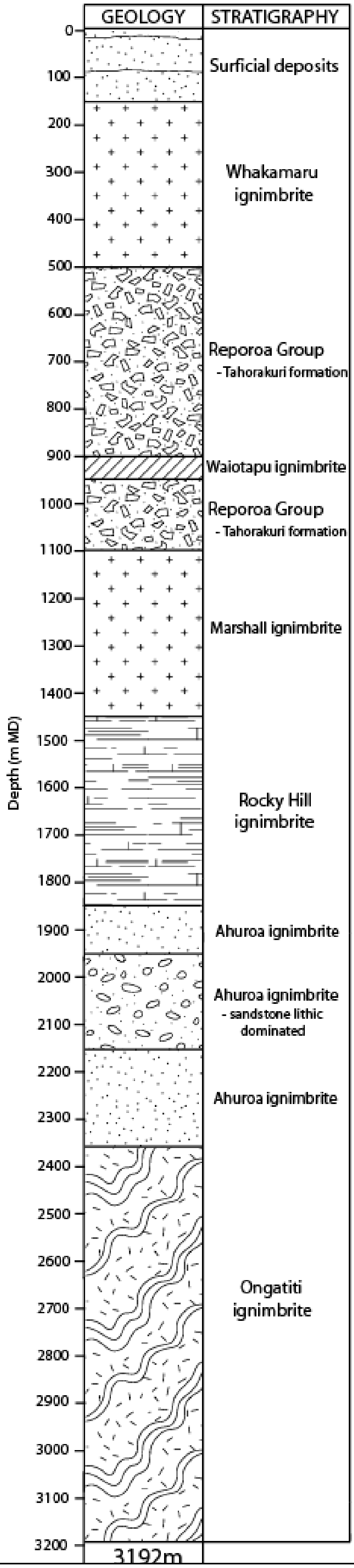

Figure 2: Stratigraphic column of MA2

The Whakamaru ignimbrite is distinctive due to its stratigraphic position, high crystal content and presence of plagioclase, sanidine, quartz, orthopyroxene, amphibole and biotite. It overlies the Reporoa Group which comprises sandstone, mudstone and conglomerate, which are low in crystal content. A crystal-poor, lithic-poor ignimbrite occurs within the Reporoa group sediments at around 900 m depth and is inferred to be the 0.71 Ma Waiotapu ignimbrite from these characteristics and ages of the bracketing units.

The Marshall ignimbrite (1100 to 1450 m) is crystal-poor ignimbrite, with crystals of plagioclase and quartz, with clasts of pumice and rhyolite lava. The boundary between the Marshall and the underlying Rocky Hill ignimbrites is characterised by a distinct change in both the mineralogy and crystal abundance. The Rocky Hill (1450 to 1850 m) is a densely welded crystal-rich ignimbrite containing plagioclase, quartz, orthopyroxene, distinctively large hornblende, and rare biotite, with lithic clasts of andesite and rhyolite lavas.

The Ahuroa (1850 to 2360 m) is a crystal-poor ignimbrite with plagioclase and rare quartz phenocrysts. The lithic composition of this ignimbrite is heterogenous with basalt and rhyolite, while the lack of andesite lithics distinguishes if from the overlying Rocky Hill and underlying Ongatiti ignimbrites. The Ongatiti ignimbrite (2360 to 3192 m) also contains greywacke lithics, and phenocrysts comprising plagioclase, quartz, orthopyroxene and apatite.

The Unit C ignimbrite, which underlies Ongatiti in surface exposures, is the only deposit in the Mangakino area known to be quartz-free. The pumice composition is andesitic (CJNW, unpubl. data), and the composition of the lithic clasts is also dominated by andesite lava. Other ignimbrites illustrate considerable heterogeneity in their lithic content (mixtures of rhyolite lavas, obsidian, greywacke, pumice).

Based on the characteristics of the deepest well cuttings, we infer that MA2 bottoms out in the Ongatiti ignimbrite, and did not reach Ignimbrite C. Other, non-welded deposits (Unit D, Kidnappers) recorded from surficial exposures are absent or are thin enough that a 50 m sampling interval does not record their presence.

5. OCCURRENCE AND DISTRUBUTION OF COMMON HYDROTHERMAL MINERALS OF MA2

Hydrothermal minerals recorded in MA2 include: quartz, chlorite, illite, albite, K-feldspar, calcite, titanite, epidote, wairakite and pyrite.

Silica:

Quartz: Quartz is the most common hydrothermal mineral and is the first replacement mineral present in MA2 from 200 m-3192 m. It occurs both as a cavity-filling and a replacement mineral, with its abundance varying between 2 and 30 percent with higher values corresponding with higher temperatures at greater depths. Replacement quartz occurs as small interlocking anhedral crystals, which commonly replaces ignimbrite groundmass and associated lithic fragments. The replacement quartz itself often shows secondary replacement by calcite indicating two episodes of alteration. Clear euhedral crystals up to 2 mm long fill thin veins and are indicative of direct deposition. Quartz (replacement and veining) frequently shares grain boundaries with illite, calcite and chlorite.

Clays: Illite and chlorite are the most abundant clay minerals present, comprising up to 55 percent of altered volcanic rocks. Illite remains relatively abundant as the temperatures increase, but chlorite becomes increasingly scarce with depth. Illite is a common replacement phase which first appears in the Reporoa Group lake sediments and typically comprises 20 percent of the altered rocks. It shares grain contacts with quartz, calcite and chlorite and is commonly found on the rims of most grains. It may also occur in fractures, indicating direct deposition from solutions. Replacement illite is fine grained, patchy and frequently replaces calcite, secondary feldspar rims of phenocrysts, and tuff and lithic grains. Replacement illite often shows secondary replacement by chlorite, suggesting two episodes of alteration. Chlorite is a common replacement mineral of illite, calcic plagioclase, quartz, tuff grains and lithic fragments in the Reporoa Group sediments but becomes negligible (<5 %) where it is present in the felsic dominated ignimbrite host rocks.

Feldspars: Albite and K-feldspar (adularia) are the only hydrothermal feldspars present and together make up 10-15 percent of the altered rocks. The first appearance of feldspar (albite) in MA2 is in the Marshall ignimbrite. K-feldspar replaces primary andesine in the ignimbrites, occurs as crystals in groundmass and shows secondary replacement by illite, once more suggesting two episodes of alteration. The unaltered adularia is clear in thin section and inclusion free, while the albite is chalky in colour and commonly occurs only as pseudomorphs of andesine.

Carbonates: Calcite is a widespread hydrothermal mineral and commonly makes up more than 20 percent of the altered rocks. Both replacement and direct-deposition calcite is recognized, with replacement calcite being the most abundant. Calcite typically pseudomorphs quartz and plagioclase phenocrysts and shares grain boundaries with primary quartz and plagioclase, volcanic glass, hydrothermal feldspars, clays and calc-silicates. The first appearance of calcite is observed at 250 m within the Whakamaru ignimbrite. Direct-deposition calcite is observed at 800 m where calcite infills thin veins within sandstone and tuff fragments.

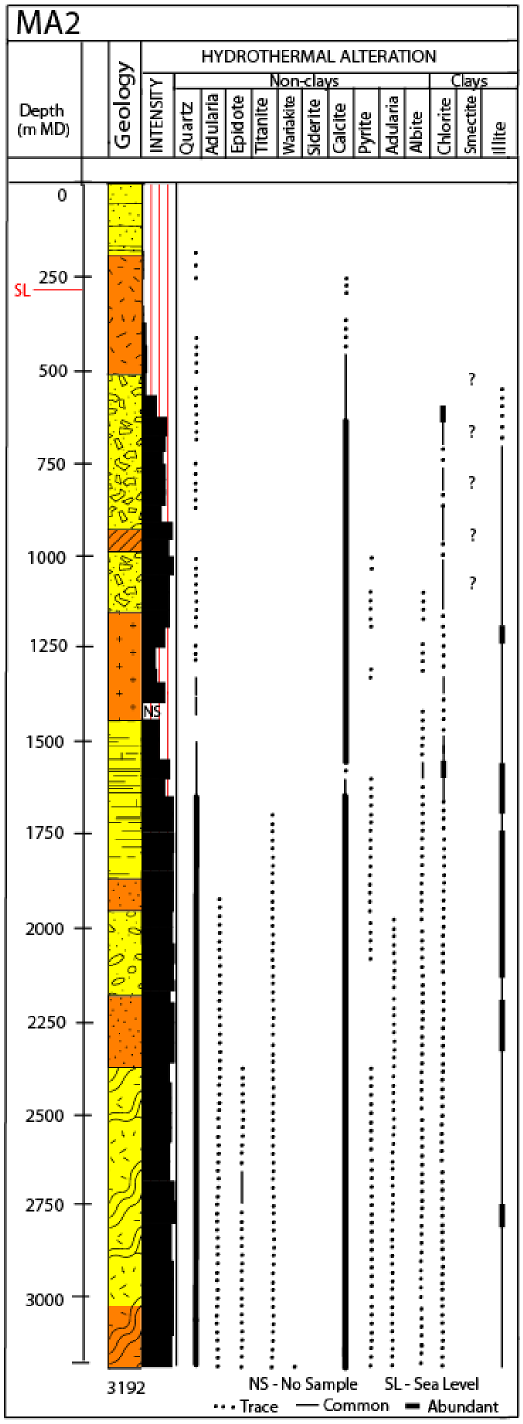

Figure 3: Distribution and occurrence of hydrothermal minerals in MA2. Mineral abundance is denoted above as: Trace (<10 %), Common (10-25 %) and Abundant (>25 %).

Calc-silicates: Epidote, wairakite and titanite are the dominate calc-silicate minerals present in the cuttings, replacing andesine, tuff fragments and possibly calcite, or otherwise occurring as open-space fillings (vugs). All minerals only occur as trace amounts (<5%). Titanite is the first calc-silicate observed at 1700 m and is a fine, well crystallised phase which is disseminated throughout the thin section. It is commonly associated with calcite and comprises of <5 percent of altered rocks. Epidote is restricted to the deepest part of the well where temperatures exceed >220 °C at around 2370-3192 m, whereas wairakite was only observed in a few samples.

Iron sulfides: Pyrite is the most common sulphide and is widespread throughout the system in minor abundances (<5 %). It is first observed at 1000 m within the Reporoa Group sediments and is present throughout the groundmass as fine grained, euhedral crystals.

6. HYDROTHERMAL ALTERATION IN NEARBY WELLS

The ignimbrite stratigraphy is the same in all wells, and there is no indication of fault offset. MA3 intersects two rhyolite intrusions at 1190 m and 1850 m that are thought to be feeder dikes to surface rhyolite domes of the Northwest Dome Complex to the east of Mangakino (Wilson et al., 1986). The other wells also tend to show the same assemblage of hydrothermal minerals and replacement features observed in MA2, although epidote and wairakite are absent from MA3 which only reaches 2059 m depth. The abundance of illite in MA3 appears greater than in MA2, with at least 30-40 percent of the altered rock composed of illite, suggesting relatively cooler temperatures.

Static formation tests done on both MA2 and MA3 indicate temperatures of 254 °C and 150 °C respectively and maybe the cause for the variations in hydrothermal alteration seen. The presence of a secondary carbonate (siderite) is also noted in MA3. The intensity of alteration within the rhyolite intrusions is low, however the ignimbrites surrounding them are intensely altered which may reflect a thermal aureole effect from the time of dike emplacement around 200-320 ka (Houghton et al., 1991).

7. CHANGES WITH TIME

Fluid inclusion data and alteration mineralogies indicate that flow patterns or temperatures have evolved over time. This is thought to largely be due to the emplacement of rhyolite domes to the east of Mangakino after the Whakamaru ignimbrite and prior to ca. 200 ka (Houghton et al., 1991). The most significant changes appear to have occurred in the deeper parts of MA2 and MA3 where illite replaces adularia which is replacing calcic plagioclase, which may suggest two episodes of alteration. Fluid inclusion data obtained from core material in MA2a (a well drilled in the same position as MA2 but deviated) between vertical depths of 2086 to 2091 m also indicate evidence for a change of temperature. Fluid inclusions in secondary calcite show high temperatures (300 and 315 °C) while inclusions in primary quartz show ~165 °C (the current temperature of the core), recording current conditions. This evidence for two different temperatures in the fluid inclusion data and two episodes of alteration may indicate a previous thermal event which is possibly related to the dike intrusion at the margin of the Mangakino geothermal field.

8. CONCLUSIONS

In this paper we have shown how petrographic characteristics of deposits exposed within and around Mangakino caldera could be used to propose correlations with the downhole lithologies and define the lithological boundaries. The occurrence and distribution of hydrothermal minerals within MA2 mimics these of other TVZ geothermal fields. The plagioclase>adularia>illite relationship observed in petrographical work implies that there are possibly two episodes of alteration. Other secondary replacement relationships are also observed. Fluid inclusion data reflects two temperatures, with secondary calcite temperatures at 300 and 315 °C, while inclusions in primary quartz show temperatures ~165 °C and represents the current temperature of the field. From this evidence, we suggest that an earlier thermal event occurred, associated with the emplacement of rhyolite domes to the east. This early event resulted in the deposition of high temperature minerals (epidote, wariakite) which have since been replaced again by lower temperature minerals such as clays.

9. ACKNOWLEDGMENTS

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