Proceedings World Geothermal Congress 2023
Beijing, China, April 17 – 21, 2023

Characteristics of fluid inclusions in Menengai geothermal field, Kenya from wells MW-35, MW28A & MW-10B.

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Key Words; Fluid inclusions, Geothermal, Fluids, Menengai

ABSTRACT.

The optimal way to use this template is to type (or paste) your text immediately after the ABSTRACT heading, then delete all the words we have entered here already afterwards – this will keep all the formatting intact. Menengai caldera located within the axis of the central segment in the Kenyan Rift is a major Quaternary central volcano. It hosts one of the high temperature geothermal fields located in the central Kenyan rift valley. Local temperature information can be obtained from fluid inclusions trapped in minerals if they contain hydrothermal fluids representative of the recent thermal conditions. Fluid inclusion studies have therefore been carried out with a view to evaluate the evolution of thermal fluids in the Menengai geothermal field using fluid inclusions observed in quartz and calcite hydrothermal minerals. Inclusions were analyzed at varying depths between 1000-2000 m in MW-35, MW-28A (1346-1348 m) and MW-10B(1426-1428m) by micro-thermometry. Fluid inclusions in calcite occur in platy calcite crystals and the quartz crystals are mainly hosted in vesicles in the rock cuttings. Quartz in some occurs instances occurs as prismatic euhedral crystals radiating from the vesicles. The results indicate that we have two types of inclusions Type 1 fluid inclusions two-phase are (Liquid+ vapor) aqueous inclusions. Type 2 inclusions are monophase fluid inclusions (liquid or vapor). Type 1 are common in all samples and are forms either as primary isolated, clusters or randomly distributed inclusions or as secondary inclusions or as trails along annealed fractures in the grain. Type 2 are rare and are observed as isolated inclusions or in a cluster with other types (i.e., Type 1 and 2). The most predominant population throughout the different samples is two phase (Liquid + vapor) aqueous fluid inclusions (i.e., Type 1). Fluid inclusions vary in size from 0.5-5 µm, with inclusions that have less than 40% vapor volume homogenizing faster. The homogenization temperatures and salinities vary from 200-349 ^{o}C and 0.27- 6.16 eq. wt % NaCl.

1. INTRODUCTION

Menengai high temperature geothermal field is hosted within a Menengai caldera, a Quaternary volcano located within the central part of the Kenyan rift valley. It is located 10 km from the fourth largest city in Kenya, Nakuru city. The Menengai caldera has been examined through several workers, with numerous pioneering studies including Leat 1984, Geotermica Italiano 1987, KenGen 2004, GDC 2010, culminating in the drilling of three the Exploration wells in 2011. To-date more than 40 geothermal wells have been drilled in this field in the past decade, with more than 130 MWe of steam being ready for evacuation for power generation. Temperatures above 400^{o}C have been recorded in this field from real time data collected during well logging and from alteration mineralogy. To collaborate this information, complimentary fluid inclusion studies were undertaken given that fluid inclusions have a direct connection with paleo-fluids that have permeated different strata and are the store house of information on the pressure–temperature conditions, density and composition. Homogenization temperatures (Th) can indicate the spatial and temporal evolution of a system, the relation between relief, water table and temperature constraints, thus assisting geological interpretations. Ice melting temperatures (Tm) can indicate salinity (and potentially the gas concentrations), particularly where trends in Tm and Th data for individual inclusions are available; these data may also provide evidence for boiling and mixing in the system (Hedenquist, J.W. et.al., 1992). In this study we contribute more data to previous works on homogenization temperatures; Mibei, 2012, Lopeyok, 2013, Kipchumba,2013, Kahiga,2014, Mutua, 201. Further we discuss the physical characteristics of the fluid inclusions studied.

1.1 Menengai Geothermal system

1.1.1 Summary of Geology

The evolution of the Menengai Caldera started around 200 Ka before present with the formation of a 30km^3 trachytic shield volcano (Leat,1984). Subsequently, eruption of two voluminous ash-flow tuffs (about 29 km^3) occurred, each preceded by major pumice falls. This was followed by two caldera forming eruption events (Syn-caldera activity) at around 29 Ka and 8 Ka respectively, accompanied by eruption of 20-30km^3 of ash flow (Leat 1984, Macdonald,2011) resulting in a 11.5 x 7.5 km Caldera. Post-caldera activity is largely marked by a series of lava flows (at least 70 flows) (Leat, 1984). At the surface Menengai caldera is dominated by trachytic lavas (which exhibit variation in texture and flow), pyroclastic, ignimbrites and basalts. The youngest erupted lava flows are located at the central part of the caldera; their source being traced to the fissures. The preponderance of the pyroclastics deposited to the west was probably due to prevailing easterly winds at the time of the eruption. The most productive wells are within the central caldera area.

1.2.2 Menengai Geothermal fluid characteristics

Menengai reservoir fluids belong to the Na-HCO_3 facies. Most of the wells in this field have excess enthalpy, this is attributed to reservoir boiling and preferential steam inflow into the wells. CO_2 is the dominant gas in the Menengai geothermal reservoir accounting for over 80 % of the gases present, Kipngok et.al.,2019. Stable water isotopes ($\delta^{18}O$ and $\delta^{2}D$) indicate a meteoric origin of the recharge water for Menengai geothermal fluids; Mutonga, 2015, Kipngok et.al.,2019, Montcoudiol, et.al.,2019. Geothermal fluids from Menengai wells are characterized by high dissolved mineral content (EC > 3000 μS/cm) and alkaline pH (>8.8) Montcoudiol, et.al.,2019. Measured reservoir temperatures in the deeper feeders of the Menengai reservoir vary between 250-350ºC, Kipngok et.al., 2019.

2.0 WELL INFORMATION

MW-28A is an S-type directional well drilled in the Eastern part of the Menengai caldera, with an Azimuth of 170º. It was spud in Oct 2014, with the aim of further expanding the field to the east. Surface and anchor casing shoes were set at 73m and 452m respectively, the Kick-off point was 470 m. The production casing shoe was set at 1130m. It was drilled to a total depth 2299 m Cellar Top (CT). The well penetrated highly fractured and high temperature zones with differential temperatures in some instances reaching 89˚C during drilling, the formation encountered in this well include Trachyte, Pyroclastics and Tuff.

MW-10B is a J-Type directional well drilled N90ºE to the East of Mlima Punda with the aim of contributing to the 105 Mwe for the power plants. It was drilled to a depth of 2162 m CT in 2017 with a KOP (Kick off Point) at 412 m CT and the production, anchor and surface casing were set at 1110.56 m.

CT m, 345.67 m CT, and 87 m CT respectively. It was drilled to a depth of 2162 m CT. The formations encountered in this well include Pyroclastic, Tuff, Trachyte and Syenite. Syenite in this well is associated with high temperature minerals like actinolite and wollastonite.

MW-35 is a vertical well drilled to depth 1624 m though the target depth was 2500m, drilling was suspended due to a stuck pipe. The well was aimed at further exploring the eastern part of the caldera, as well as provide steam for the 60 MWe power plant. The rock units encountered consist predominantly of trachyte, basalts and syenite. The main hydrothermal minerals observed in the study well include; calcite, pyrite, epidote, wollastonite and clays. The surface, anchor and production casing shoes were set at 58.20 m, 351.88 m and 852 m respectively.

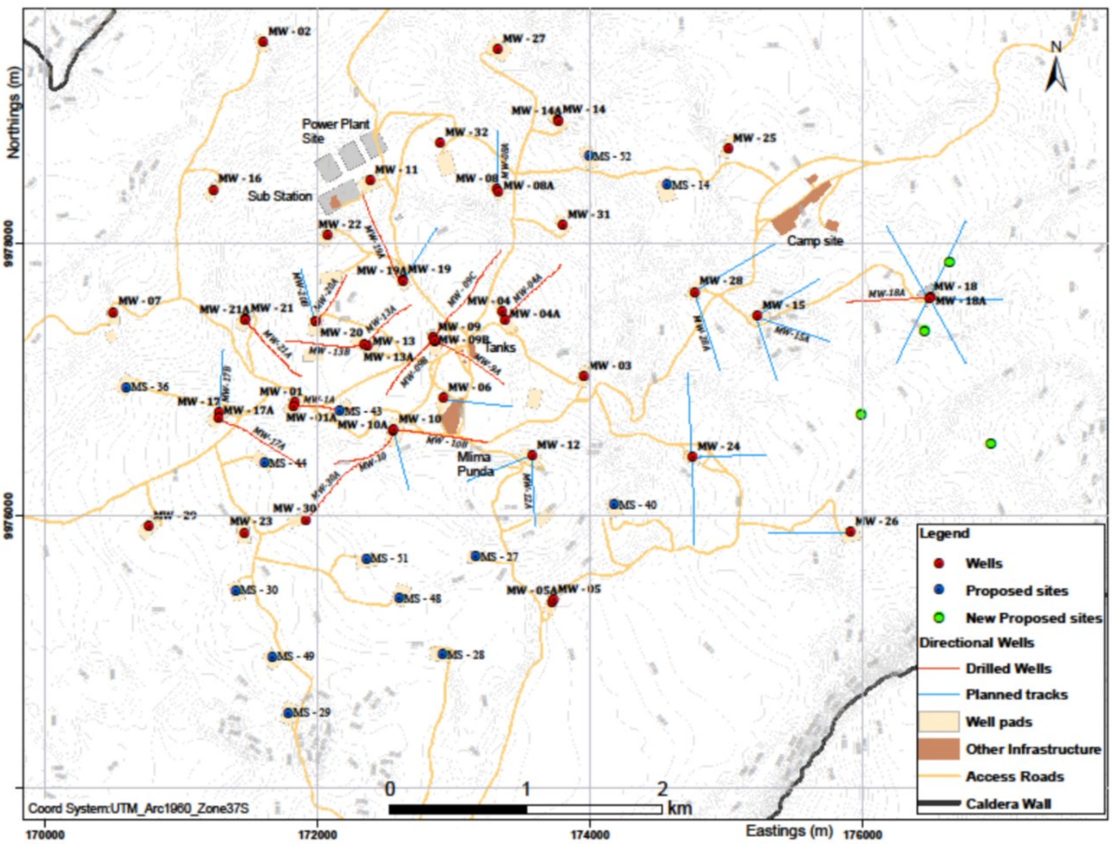


Figure 1: The well location of MW-28A, MW-35 and MW-10B with the Menengai Caldera.

2.1 Mineral alteration zones

In the Geothermal wells drilled in Menengai Caldera, calcite, pyrite, smectite, zeolites, chalcedony, quartz, chlorite, albite, epidote, wollastonite, illite and actinolite occur as the main alteration minerals Mbia, 2014. Five different mineral alteration zones have been identified in this field, Mibei et al 2012 , that include;

Unaltered zone (0-400 m) This zone represents the shallow depth of the study wells. It extends from 0-400 m, 0-408 m and from 0-386 m depth in wells, MW-28A, MW-10B and MW-35 respectively. This zone represents the fresh young post-caldera lava. This zone is characterized by fractured fresh and mildly oxidized lava with some minor tuff intercalations.

Smectite-Zeolite zone (400-800 m) This zone forms the lowest grade alteration zone and is mainly represented by Zeolites (cowlescite and mesolite) as index minerals. In almost all wells this zone is characterized with abundant calcite and appearance of some pyrite. Zeolites appear as rounded massive minerals and are noted in this well from 215-234 m and 408-420 m in MW-10B. Zeolite declines in abundance with depth.

Quartz-Illite zone (750-1150 m) This zone corresponds with the upper zone of the geothermal reservoir in Menengai. The zone is characterized by the occurrence of secondary quartz which occurs as replacement of chalcedony and illite clays. Quartz indicates temperatures over 180^{o}C (Reyes, 2000). The depth and thickness of this zone is variable from well to well. Secondary quartz appears as colorless to white hexagonal, euhedral to subhedral crystals infilling the vesicles. In the cuttings, quartz is differentiated from zeolites by its higher refractive index. In MW-10B it's noted at 1424-1450 m, 1506-1508 m.

Illite-Epidote zone (1000-2300 m) The appearance of epidote indicates formation temperature of above 250^{o}C. It's a byproduct of the replacement of plagioclase and pyroxenes during hydrothermal alteration at high temperatures and is normally associated with actinolite and chlorite. It appears as a pale green colorless mineral in MW-10B encountered from 1426-1542 m,1480-1482 m,1506-1508 m 1664-1666 m, 2140-2142 m, In MW-28A it was first encountered at 1012-1080m. In MW-28A chlorite was noted at 1700m.

Wollastonite-actinolite zone (1400-2300 m) This zone is normally characterized by the presence of either Wollastonite and/or actinolite. In MW-10B the mineral was identified from 2088-2162 m using a binocular microscope. In thin section at 1426-1428 m, 1480-1482 m, 1506-1508 m, 1664-1666 m. Wollastonite appears as green fibrous minerals and is normally associated with epidote, actinolite and prehnite. Its first appearance indicates temperatures above 270^{o}C.

Calcite is abundant and occurs within almost all lithologies in all wells below 200 m but diminishes at temperatures above 280^{o}C. This mineral is related to boiling, dilution and condensation of carbon dioxide in geothermal systems. It is worth noting that calcite may be formed by heating up of fresh groundwater and, hence, is not related to geothermal activity all the time. This explains the reason for the appearance of calcite in nearly the entire well column for the wells however platy calcite is mostly found within the reservoir mostly from 800 m and above.

Secondary quartz occurs as replacement of chalcedony at depth and was found deposited mainly in vesicles. It´s presence in a geothermal system indicates temperatures of above 180^{o}C (Franzson, 1998).

3.0 FLUID INCLUSION MICRO THERMOMETRY

3.1 Methodology

The trapped fluids, dubbed as fluid inclusions, give an estimated temperature from the time when the fluid was trapped in the mineral grain. In this study, calcite, and quartz grains from different depths in wells MW-35, MW-28 and MW-10B amenable to fluid inclusion studies were identified and hand-picked for fluid inclusion geothermometric analysis. Platy calcite crystals have obvious cleavage. In the Menengai, calcite occurs as a replacement of rock forming mineral and volcanic glass and as platy crystals infilling vesicles. Secondary quartz crystals were identified in cuttings by its typical euhedral shape. The crystals were then set in resin for easy handling.

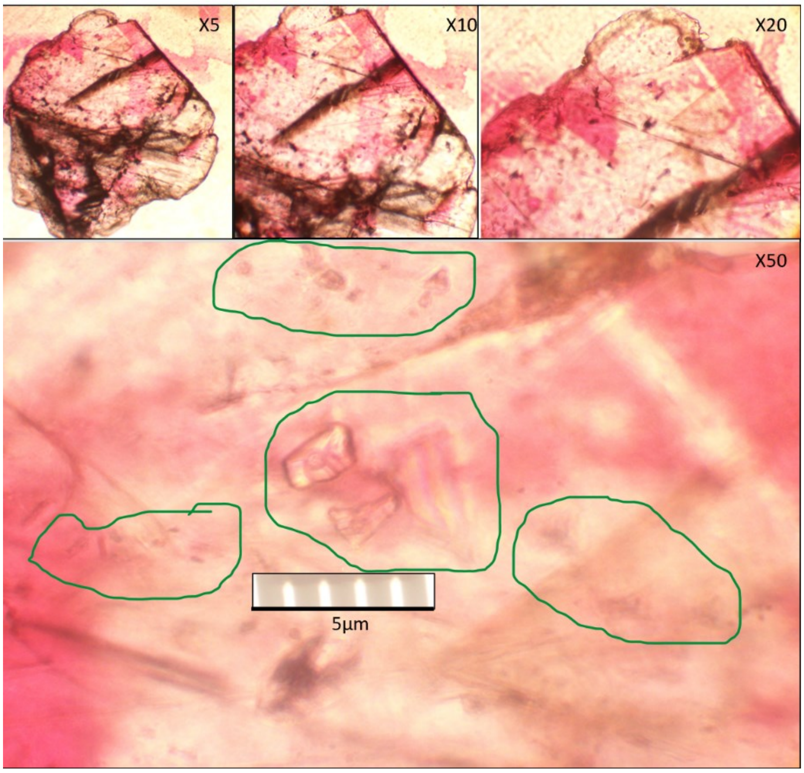


Figure 2: Micrograph of fluid inclusion observed under various objective lenses, notice how large the inclusions appear in clusters of various sizes according to size.

Since the crystals were not clear enough, they were polished at various stages to enhance their transparency.

In general, the fluid inclusions were many in volume but were quite small so less ≤3µm. All inclusions measured inclusions appear to be primary. Primary inclusions are formed during primary crystal growth, often concentrated along the first order of growth discontinuity, or occur as isolated inclusions distributed within the crystal (Roedder, 1984)

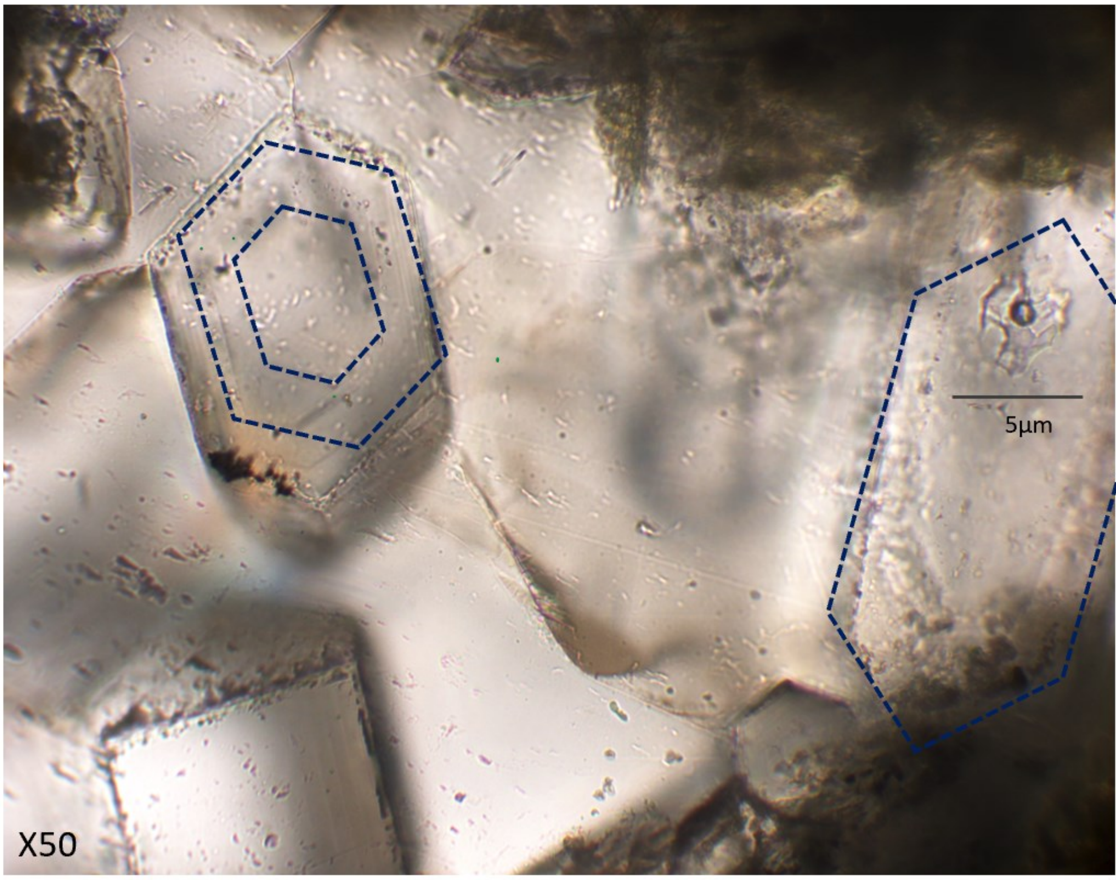


Figure 3: Quartz crystals hosting various generations of fluid inclusions forming hexagonal traces at various levels within the quartz crystals.

Upon confirmation by use of the petrographic microscope of the presence of clear fluid inclusions we proceeded with micro-thermometry the inclusions were cooled to get the freezing temperatures of the inclusions, then slowly heated, to get the melting point temperature, on a Linkam THSMG 94 heating and freezing stage until the fluid homogenized in a single phase (i.e., bubbles disappeared) and the temperature of homogenization (Th) was measured. The temperature measurements were taken with heating at a rate of 20°C/min.

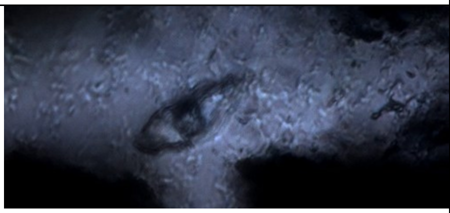
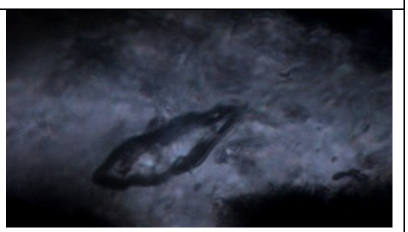
Sample no. 26	Well.ID MW-28A	Depth 1622-1624m
26°C	150°C	295°C
		

Figure 4: Micrograph shows the homogenization process for the fluid for one the fluid inclusions hosted in quartz, sample 26 (1346-1348) MW-28A from room temperature to homogenization at around 300°C. Note the position of the vapor

vacuole a) when the sample is cooled to room temp at 26°C, b) when heated at 150°C & c) When the sample is homogenizing (disappears) at 295°C.

4.0 RESULTS/ OBSERVATIONS

Primary inclusions are formed during primary crystal growth, often concentrated along the first order of growth discontinuity, or occur as isolated inclusions distributed within the crystal (Roedder, 1984). Secondary inclusions are formed after primary growth, often along healed micro-structures. The inclusions trapped in minerals during crystallization or recrystallization were analyzed to determine the temperature at which the inclusions/vacuoles were formed. Majority of fluid inclusion encountered in both the calcite and quartz crystals are primary fluid inclusions, however they appear to have different generations; the largest ones (between > 5 µm) appear older, the youngest generations are much smaller and < 0.5 µm in size. In some instances, they appear to follow different growth structures in the crystals and other instance appear/occur as discrete swarms. (Figure 2). The inclusions are also two phase and mostly liquid rich with 20-30% vapor for MW-10B (1622-1624 m), MW-35 (1200-1202 m, 1590-1592 m and 1530-1532 m). In MW-35 and MW-10B (1622-1624) we worked on mainly platy calcites because the fluid inclusions were easily identifiable**.** In Sample 26 from MW-28A 1346-1348 m (Figure 3 & Figure 6) inclusions are hosted in euhedral to subhedral quartz crystals. Two-phase vapor-rich inclusions in these wells were quite commonplace but difficult to homogenize even at temperatures above 320°C their presence strongly suggesting trapping of boiling fluids because of the difficult in homogenizing.

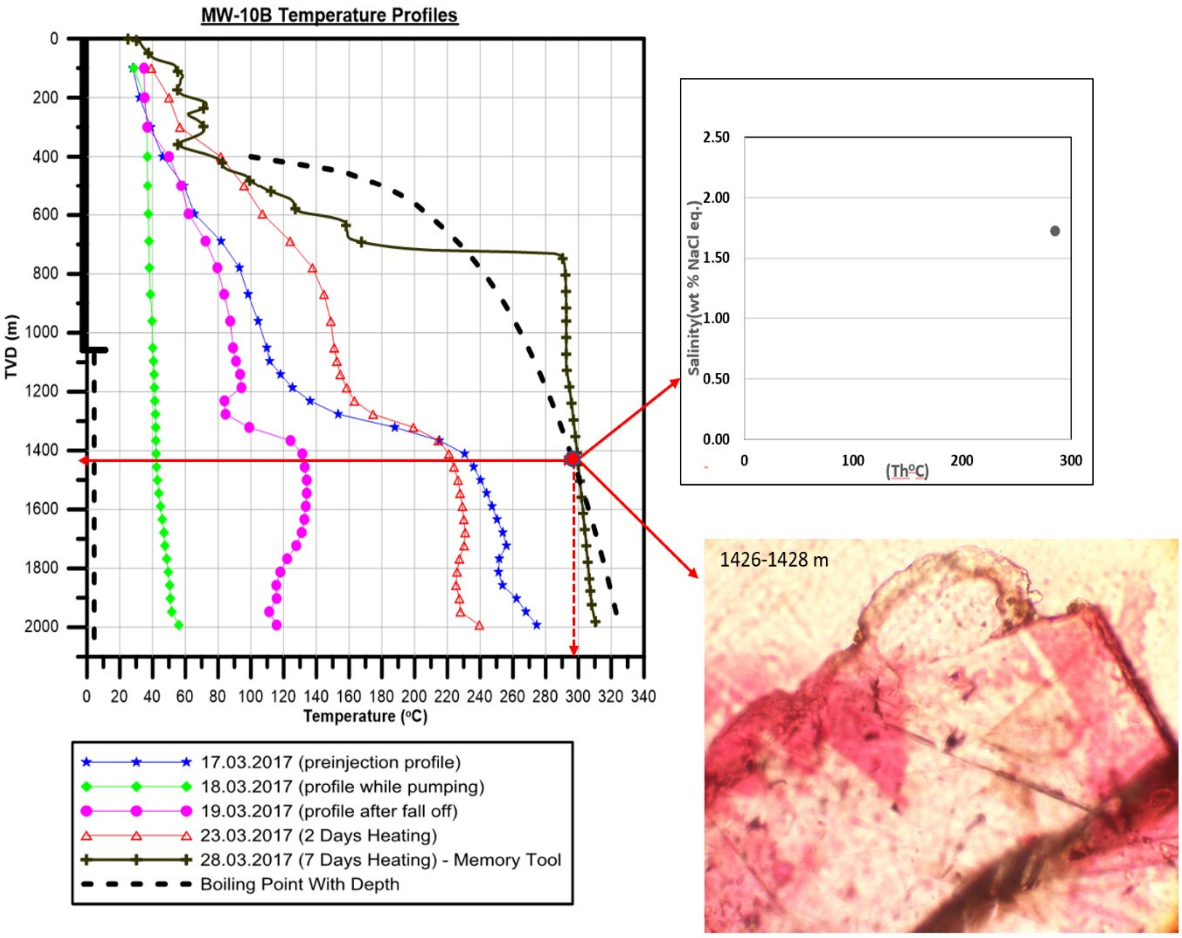


Figure 5: MW-10B Showing Temperature profiles during the well tesing and the Fluid inclusion temperature of homogenisation**, Salinity inset is the fluid inclusion micro-graph for MW-10B (1426-1428 m).**

The fluid incluisonsin MW-10B (1426-1428) are hosted platy calcite which are indicative of boiling and flashing which is most likely related to the formation of the steam-heated aquifer at the top of the system. The (Th°C) tempertaure in this inclusions corresponds to the boiling curve and the temperature measurements after 7 days of heating at a depth 0f 1426-1428 m i.e. the present day temperatures, (Figure 5) also the Salinity is around wt 2 % NaCl eq.indicating low salinity levels.

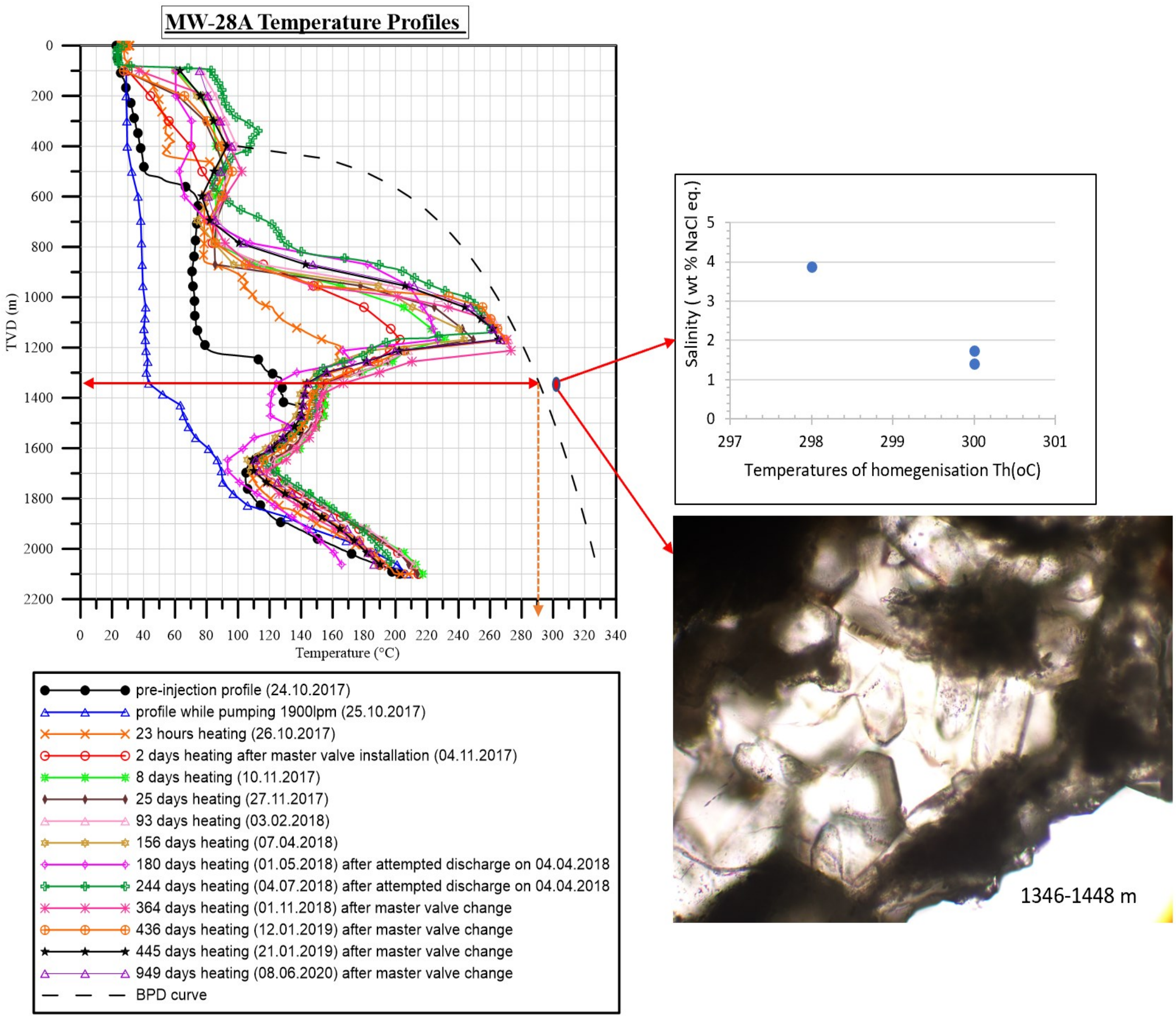


Figure 6: MW-28A Showing Temperature profiles during the well tesing and the Fluid inclusion Temperature of homogenisation,Salinity inset is the fluid inclusion micro-graph for MW-28A (1346-1348 m).

The fluid incluisons in MW-28A(1346-1348 m) are hosted in secondary quartz. The (Th^{o}C) temperature in this inclusions is slightly higher by approximately ~10^{o}C than the BPWC(Boiling point water curve) and the measured temperatures for this well over a period of time(Figure 6). The salinity values lie between 2-4%(wt% NaCl eq.) which is relatively high.

5.0 DISCUSSIONS

The inclusions vary in size from <0.5->5 µm, we two main types of inclusions Type 1. Two phase (Liquid and Vapor) and type 2 (Mono-phase) which are quite rare. In general, most of the fluid inclusions were quite small making it very difficult to study the inclusions under the optical microscope, especially on a heating/freezing stage. Therefore, we didn't have much choice we relied on the larger inclusions to determine Tm^{o}C, Th^{o}C. Type.1 Fluid inclusions with the vapor phase below 40% were easier to handle because they easily homogenized while the once with higher vapor phase greater than 60% were difficult because even at higher temperatures than 340^{o}C they still had not homogenized the samples got burnt making it had to see the end point.

Interpreted alteration mineral temperatures and fluid homogenization temperatures (Th) that are above their stability and measured temperatures respectively indicate that the geothermal system has undergone some heating whereas those that are below indicate that geothermal system has undergone some cooling (Lagat,2004)

For MW-10B the (Boiling point curve of water) BPCW match or are very close to the maximum Th values of inclusions (Figure 5), indicating that the system was at or close to boiling conditions during the trapping of high- (Th^o C) inclusions, indicating that the geothermal system may have undergone some boiling and nothing much has changed since the time of entrapment.

The (Th^{o}C) temperature in this inclusions of MW-28A is slightly higher by ~10^{o}C than the BPWC, the measured temperatures for this well over a period of time(Figure 5) are also lower than the Th^{o}C. This could be an indication that the reservoiur around this well has undergine some marginal cooling.

Total salinity values deduced from Tm-ice indicate for MW-10B 1-2% (wt% NaCl eq) that most fluids trapped in the inclusions are dilute aqueous fluids, mostly approaching meteoric water while the salinity values for MW-28A lie between 2-4%(wt% NaCl eq) indicating moderately saline fluids which could be related to some magmatic imput to the geothermal fluids.

c) Interpretation

Some of the Th measurements may not be exert probably due to decrepitation, re-equilibration after trapping or due to human error in measuring, thus may lead to erroneous geochemical process interpretation. After searching for inclusions, sometimes they are not useful for micro-thermometry, making it very tedious and time-consuming, hence a lot of patience and a little bit of luck are needed.

6.0 CONCLUSIONS AND RECOMMENDATIONS

Because fluid inclusions deal with temperature and salinity, past thermal and chemical characteristics of a geothermal system are recorded, which maybe compared to the present conditions. Fluids trapped as inclusions during hydrothermal mineral growth are the only samples available of the fluid present during formation of mineral deposits.

Fluid inclusion technique has proved to be a valuable tool together with alteration mineralogy in strengthening geological and geochemical interpretations in Menengai geothermal fields, the fluid inclusion homogenization temperatures are in conformity with the actual measured temperature in the wells, this supports that this is indeed the actual state of the reservoir currently. For MW-28A its slightly higher than the BPWC by 10ºC indicating in the past temperatures may have been slightly higher than currently and the reservoir may have slightly cooled. For MW-10B the Th^{o} indicates that the reservoir conditions may not have changed over time. It has provided information on the thermal evolution of the geothermal reservoir system, the information will be useful in updating; conceptual model, the drilling strategy and help in predicting geological and geochemical processes such as boiling, cooling, etc.

Its recommended that in future the fluid and gas chemistry of the fluid inclusions be studied, this will provide data on the composition of gases and fluids which are important for predicting scaling, corrosion tendencies from the reservoir fluid which will aid in mitigation at an earlier stage. Also its recommend that the GDC(Geothermal Development Company) acquires this equipment since it's very useful while drilling and will provide real time data to mitigate against the challenges metioned.

7.0 ACKNOWLEDGEMENTS

I would like to express my gratitude to my colleagues in GDC who were very helpful during the samples selections and identifying crystals suitable for fluid inclusion studies. Kyushu university economic geology laboratory for allowing access to the Fluid Inclusion equipment and for providing a conducive working environment. I also appreciate Tindell sensei for taking me through the entire process of fluid inclusion studies.

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