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BOREHOLE EXPERIMENTS OF SYNTHETIC FLUID INCLUSION LOGGING AT WD-1 IN THE KAKKONDA GEOTHERMAL FIELD, NORTHEASTERN JAPAN

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ABSTRACT

Synthetic fluid inclusion logging is a new method of temperature measurement and direct fluid sampling in high-temperature geothermal wells. The method has been developed by the Geological Survey of Japan and the New Energy and Industrial Technology Development Organization (NEDO). The first borehole experiment was carried out in the fall of 1994 at a deep research hole (WD-1) drilled by NEDO in the Kakkonda geothermal field, northeastern Japan, and several experiments were conducted in 1995 and 1996. In the experiments, cracked crystals (quartz and calcite) soaked in solutions in gold or platinum capsules were mounted on containers for temperature measurement. The containers were placed in the borehole for one hour to three months. Trapping temperatures of fluid inclusions were determined by microthermometric measurement. Within short (one hour, one, two and three days), middle (one month) and long (three months) term experiments, fluid inclusions were synthesized in all quartz crystals soaked in alkaline solution, in some quartz crystals in NaCl solutions, and in all calcite crystals. Homogenization temperatures of the fluid inclusions were mostly concordant with borehole temperatures which were measured by other conventional logging tools. For fluid sampling, cracked quartz crystals without sealing are mounted in containers through which borehole fluid flows. A small number of fluid inclusions were synthesized under the short and middle term experiments, and many inclusions were synthesized enough for chemical analyses under the long term experiment. These results indicate that the synthetic fluid inclusion logging system is available to temperature measurement and fluid sampling in high-temperature geothermal wells.

1. INTRODUCTION

Synthetic fluid inclusion logging can be applied to high-temperature geothermal wells. It was first proposed within the drilling project in Valles caldera, New Mexico, USA (Bethke *et al*., 1990). During the “Deep--Seated Geothermal Resources Survey”, this method has been developed by the Geological Survey of Japan and the New Energy and Industrial Technology Development Organization (NEDO) (Sasada and Sawaki, 1995). The first downhole experiment was conducted in the fall of 1994 at WD-1 (Sawaki *et al*., 1997), which is a deep research hole in the Kakkonda geothermal field, northeastern Japan, drilled by NEDO (Yagi *et al*., 1994). After that, several experiments were carried out. This paper integrates results of the experiments after 1994, and evaluates the synthetic fluid inclusion logging.

2. PRINCIPLES OF THE SYNTHETIC FLUID INCLUSION LOGGING

Temperatures higher than 350 ^{o}C have been determined in a number of geothermal wells drilled in igneous-related geothermal systems. One of the current problems of logging such high-temperature geothermal boreholes is that the conventional temperature logging tool composed of electronics has temperature limitation under high temperatures. Synthetic fluid inclusion is applicable to measure high temperatures as long as host crystals are stable.

Natural fluid inclusions in hydrothermal minerals have been used for temperature measurement in various geothermal systems. Fluids trapped in microcracks of crystals result in fluid inclusions through healing, and the inclusions are called “secondary inclusions”. This process occurs commonly in hydrothermal minerals in natural geothermal systems, and the use of synthetic fluid inclusions is application of natural crack healing. Host minerals of quartz and calcite are available for the method because they commonly occur as hydrothermal minerals in geothermal systems and contains many fluid inclusions. Especially, α-quartz is one of the most suitable host minerals for this method because it is stable up to 573 ^{o}C (Sawaki *et al*., 1997).

For temperature measurement, cracked synthetic crystals which contain no natural fluid inclusion are soaked in silica-saturated solutions sealed in gold or platinum capsules, and they are mounted in containers. The containers are placed in a geothermal borehole for several days to several tens of days to heal fractures in the host crystals (Figure 1). The crystals recovered from the boreholes contain many fluid inclusions, and trapping temperatures of the fluid inclusions, that is, borehole temperatures are determined from homogenization temperatures (*Th*) of the inclusions by microthermometric measurement using a heating stage.

For fluid sampling, cracked crystals not sealed in capsules are placed in containers into which geothermal fluid flows. Recovered crystals are chemically analyzed by various equipment. α-quartz is the most suitable as a host mineral because it is chemically stable, compared with other minerals.

3. DOWNHOLE EXPERIMENTS AT WD-1

The first borehole experiment was conducted at WD-1 from September to October 1994 (24 days), when the depth of the borehole was 1,500 m (Sawaki *et al*., 1997). After that, several experiments were conducted at other levels.

In July 1995, the depth of WD-1 was 3,729 m. For temperature measurement, some conventional logging tools were used. Synthetic fluid inclusion logging system was also applied at the time. Within the logging, following types of capsules were prepared for temperature measurement: cracked quartz crystals with silica-saturated NaOH solutions (pH 10 and 13) sealed in gold capsules, those with silica-saturated NaCl solutions (3 and 20 wt.%) in platinum capsules, and cracked calcite crystals with $CaCO_3$-saturated solution in gold capsules. Cracked quartz crystals unsealed in gold tubes for fluid sampling were also prepared. The samples were placed at the bottom of WD-1. A temperature at the bottom of WD-1 was estimated over 500 ^oC, using calibrated melting tablets (Ikeuchi *et al*., 1998). Duration of the synthetic fluid inclusion logging was only one hour, but a small number of fluid inclusions were formed in the crystals. *Th* of the fluid inclusions of pH 13 NaOH solution range mainly from 370 to 376 ^oC, which are near the critical point of water. This indicates that the fluid inclusions were formed in critical state of the solution, because the temperature at the bottom of WD-1 exceeded 500 ^oC and the pressure might be lower than hydrostatic pressures.

After WD-1 reached 3,729 m in depth, the deeper part of the well was plugged because of discharge of hazardous hydrogen sulfide gas (Sasada *et al*., 1998). The depth of WD-1 was 2,400 m in the winter of 1995-1996, and the borehole fluid was replaced with meteoric water. Short (one, two and three days) and long (three months) term experiments were carried out at the time (Sasada *et al*., 1996). For temperature measurement, capsules with cracked quartz and calcite crystals and solutions (pH 13 NaOH, and 3 and 20 wt.% NaCl) were used, and they were placed at five levels between 1,485 and 2,390 m in depth. Within the short term experiments, fluid inclusions were formed in quartz soaked in the NaOH solution and in calcite. No or a small number of fluid inclusions were formed in quartz soaked in NaCl solutions at the levels where borehole temperatures were below 250 ^oC. Within the long term experiment, fluid inclusions were formed in all the crystals. *Th* of the fluid inclusions were nearly consistent with borehole temperatures measured by a conventional logging tool, but the three months run was probably affected by recovery of temperature increment at WD-1 during the experiment. *Th* ranges of fluid inclusions in the run are distributed between the temperature profiles determined before and after the run (Figure 2A), and two types of fluid inclusions are observed in the sample from 2,390 m in depth. One is a healed-crack type inclusions, as in other samples, and the other is primary inclusions in overgrowth rims of host quartz (Sasada *et al*., 1996). *Th* of the primary inclusions (345-352 ^oC) are clearly higher than those of healed-crack type inclusions (316-338 ^oC), indicating that the formation stage of the inclusions in the rims were later than that of the healed-crack type inclusions. For fluid sampling, cracked quartz crystals in containers with rupture disks which would break at the required sampling depths were placed at the bottom of WD-1 (2,390 m). Within the short term experiments, a small number of fluid inclusions were formed. On the other hand, many and large fluid inclusions were formed within the long term experiment. This indicates that it takes relatively long time to sample fluid enough for chemical analysis.

In the summer of 1996, middle term (one month) experiment was performed at the same levels as in the winter of 1995-1996. At the time, borehole temperatures of WD-1 might be nearly in natural state because much time had passed after drilling. For temperature measurement, the following samples were prepared, as at the experiment in 1995: cracked quartz crystals with solutions (H_2O, pH 13 NaOH, and 3 and 20 wt.% NaCl) in gold and platinum capsules, and cracked calcite crystals with $CaCO_3$-saturated solution in gold capsules. For fluid sampling, two types of samples were prepared: one was cracked quartz crystals as used in the former experiments, and the other was pairs of quartz plates with pits. The pairs of quartz plates faced each other with pits between them, and they were set in metallic holders. If quartz is newly precipitated between the plates, large fluid inclusions are formed in the pits. After the experiment, many fluid inclusions were formed in the recovered crystals in NaOH and NaCl solutions for temperature measurement. A small number of inclusions were formed in the crystals in H_2O and those for fluid sampling, but no fluid inclusion was in the pairs of the quartz plates. Width between the plates were probably too wide to heal the contact planes by precipitation of quartz. *Th* of the fluid inclusion were concordant with the borehole temperatures, and variation of *Th* became small at each level, compared with those of the experiments in the winter of 1995-1996 (Figure 2B). The small variation may be attributed to stabilization of circumstance of the borehole.

In 1998 to 1999, a one-year experiment was conducted. For the experiment, two types of samples were prepared: one was cracked quartz, as used in the previous experiments, and the other was decrepitated quartz which had contained synthetic fluid inclusions of water. Decrepitation produces minute cracks around fluid inclusions, and the cracks may easily heal in high temperature boreholes. The re-formation of fluid inclusions after their decrepitation would be a potential means of sampling fluids. Both types of crystals in containers through which geothermal fluid could flow were suspended at the bottom, of WD-1, where geothermal fluid discharged. The recovered samples are being analyzed by various techniques.

4. SUMMARY

In 1995 to 1999, several downhole experiments were carried out. Fluid inclusions were formed in samples for temperature measurement in a short time; for example, in one hour over 500 ºC. *Th* of the fluid inclusions were concordant with borehole temperatures measured by conventional logging tools except the measurement at 3,729 m. The results suggest that the synthetic fluid inclusion logging technique is available to measurement of borehole temperatures, at least, up to the critical point of water (374 ºC). Quartz crystals for fluid sampling, fluid inclusions trapping borehole fluid were formed in short-term experiments above 350 ºC, but relatively long time was necessary to sample fluid enough for chemical analysis. This suggests that the sampling method may be applicable to direct fluid sampling in high-temperature geothermal wells.

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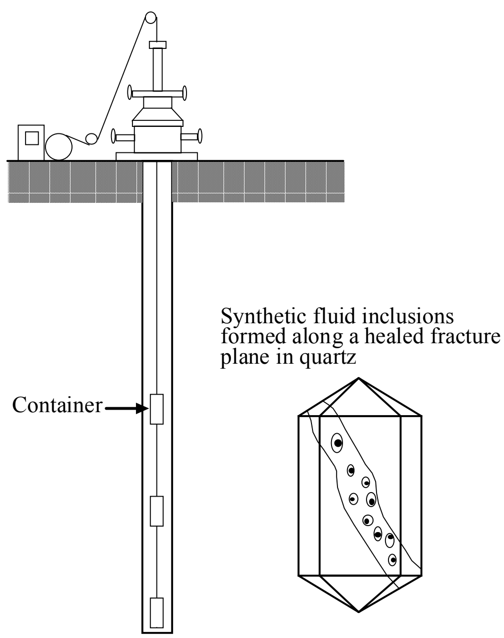

Figure 1. Schematic diagram of the synthetic fluid inclusion logging system.

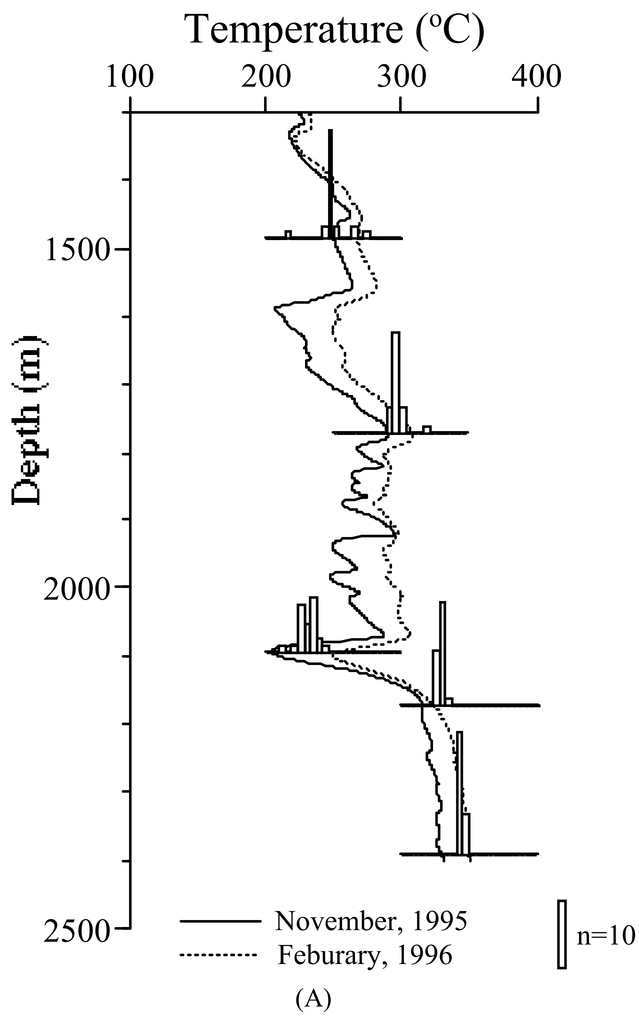

Figure 2. Depth-temperature diagram for WD-1. A; three months, 1995-1996; B: one month, 1996
The histograms show distribution of homogenization temperatures of synthetic fluid inclusions. Solid and dashed curves indicate borehole temperatures measured by conventional logging tools.

Table 1. Results of 1995-1996 experiments.
Borehole temperatures were measured by a conventional logging tool.

Solution	Crystal	Depth(m)	1995					1996	
			Borehole temp.(^oC)	1 day	2 days	3 days	3 months	Borehole temp.(^oC)	1 month
pH13 NaOH	Quartz	1485	251	++	++	++	++	273	++
		1770	290	++	++	++	++	318	++
		2093	203	+	++	++	++	284	++
		2170	315	++	++	++	++	338	++
		2350						351	++
		2390	329	++	++	++	++		
3% NaCl	Quartz	1485	251	-	-	-	++	273	++
		1770	290	-	+	+	++	318	++
		2093	203	-	-	-	?	284	++
		2170	315	+	+	++	++	338	++
		2350						351	++
		2390	329	+	++	++	++		
20% NaCl	Quartz	1485	251	-	+	+	++	273	++
		1770	290	++	++	++	++	318	++
		2093	203	-	-	-	++	284	++
		2170	315	+	++	++	++	338	++
		2350						351	++
		2390	329	++	++	++	++		
pH1 HCl	Calcite	1485	251	++	+	++	++	273	++
		1770	290	++	+	+	++	318	++
		2093	203	+	+	+	++	284	++
		2170	315	+	++	+	++	338	++
		2350						351	++
		2390	329	++	++	++	++		
H2O	Quartz	1485						273	+
		1770						318	-
		2093						284	-
		2170						338	+
		2350						351	+
(for fluid sampling)	Quartz	2390 2350	329	+	+	+	++	351	+

++: many fluid inclusions
+: a small number of fluid inclusions
-: no fluid inclusion