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Some fluid-inclusion measurements for geothermal drill holes in California, Nevada, El Salvador, and Russia

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CONTENTS

FIGURES

TABLE

INTRODUCTION

The purpose of this report is to make available fluid-inclusion information from drill holes in five geothermal areas: The Geysers and Long Valley caldera in northern California; Steamboat Springs, Nevada; the Ahuachapán field of El Salvador, Central America; and the Mutnovsky geothermal field, Kamchatka Peninsula, Russia. These data were produced at the request of various individuals to provide needed subsurface-temperature data for their investigations. The fluid-inclusion information presented in this report has not been previously published, and, since the author did not work in these geothermal areas, only a very minimal attempt is made at interpreting the data. Information on the location of the drill holes from which the core specimens originated ranges from very poor in the case of the Russian drill holes to very good for those in the USA.

Mineral specimens from drill-core samples in the five geothermal areas were utilized as cleavage chips, thin sections polished on a single side, or double polished thin sections (polished on both sides). Fluid inclusions from all three USA geothermal areas were found in either hydrothermal or primary quartz crystals. These fluid inclusions firstly were frozen and gradually thawed to determine the final melting-point temperatures (T_m) as the last piece of ice melted and secondly, were heated to the temperature at which the vapor phase disappeared to obtain homogenization temperatures (T_h). For the El Salvador and Russian core specimens the fluid inclusions were hosted in calcite, and the order of the two procedures was reversed because calcite is a much softer mineral than quartz and there is a greater danger of the fluid inclusions decrepitating as the ice expands during freezing.

A Chaixmeca microthermometry apparatus was used during studies of the Steamboat Springs and The Geysers fluid inclusions. For the remaining studies, a Linkam THM 600 heating/freezing stage and TMS 90 temperature control system were employed. Accuracy of the data generated from both instruments is similar, with values of about ±2°C for heating studies and about ±0.2°C for the freezing methods.

FLUID INCLUSION DATA

The Geysers

Union Oil of California's Dillingham & Vought 2 geothermal drill hole, located at 903.7 m altitude in the northwest corner of Section 34, Township 11 north, Range 8 west, Sonoma County, California, was spudded April 11, 1980, and completed June 14, 1980, to a depth of about 2,628 m (Reed, 1982). The single core specimen obtained from the 1,132 to 1,134-m depth interval consisted of a light gray, brecciated igneous rock with quartz and feldspar phenocrysts in a fine-grained matrix. Spaces between breccia fragments are filled by euhedral crystals of early green tourmaline and later colorless quartz. The presence of tourmaline in other Geysers drill holes suggests that temperatures of the circulating hydrothermal fluids very likely exceeded 370°C (Hulen, Walters, and Nielson, 1991).

No fluid inclusions were found in the tourmaline of this core specimen; however, associated quartz crystals contain abundant liquid-rich, secondary fluid inclusions ranging in size from about 10 to 100 µm with the vapor phase comprising about 10 to 30 percent of inclusion cavities. T_h measurements for 55 fluid inclusions in three quartz chips range from 242° to 365°C (Figure 1) and have a mean T_h of 269°C (Table 1). Final melting temperatures for 22 of the fluid

Figure 1 near here

Table 1 near here

inclusions are all 0.0°C indicating that the fluids consist of nearly pure water. Vapor and vapor-rich, secondary fluid inclusions were observed within primary quartz phenocrysts of this specimen; however, no attempt was made to obtain microthermometric data for these inclusions.

Fluid-inclusion studies of six other drill holes in The Geysers steam field reported a similar range of T_h values (223° to 313°C) as those in this report, but T_m measurements were considerably more variable (0.0° to -2.4°C) (Moore and others, 1989). Moore and others (1989) explain the combination of low salinities (T_m of 0.0°C) and high T_h values as suggesting that the inclusions trapped a steam condensate. The same explanation probably is applicable to the fluid-inclusion data of this report.

Several of the fluid inclusions from these quartz chips contain ~1-μm-size moving particles. Similar moving particles have been reported in fluid inclusions of drill core from Yellowstone National Park (Bargar, Fournier, and Theodore, 1985). They speculated that the particles might be bacteria that were trapped during formation of the fluid inclusions. If this explanation is ever proven to be valid, the particles would be very significant because of the high temperatures at which the postulated bacteria would have lived.

Long Valley caldera

The Shady Rest geothermal drill hole is located in the southwestern moat of Long Valley caldera, eastern California (Lat. 37°39.4'N; Long. 118°57.2'W) at 2,375-m elevation (Urban, Diment, and Sorey, 1987). The hole was spudded on May 5, 1986, and completed to 715-m depth on June 17, 1986, through a collaborative effort by the U.S. Department of Energy, Mono County, the California Energy Commission, and the U.S. Geological Survey; the maximum measured temperature was 202°C at 335-m depth (Wollenberg and others, 1987).

Two quartz crystals from about 328-m depth in the Shady Rest drill hole were utilized for heating and freezing of ~6 to 200 μm-long, liquid-rich fluid inclusions. T_h measurements for 53 fluid inclusions ranged from about 186° to 265°C (Figure 2) and averaged about 196°C. Sorey

Figure 2 near here

and others (1991) reported calcite fluid-inclusion T_h values of 193° to 206°C for four depths between 328 and 613 m in the Shady Rest drill hole. T_m values for 28 of the quartz fluid inclusions in the present study are -0.3° or -0.4°C indicating that the salinity of the trapped fluid is about 0.5 or 0.7 weight percent NaCl equivalent. The majority of inclusions contain only about 5 percent vapor; however, three vapor-rich fluid inclusions were observed in one of the crystals. Homogenization temperatures were not obtained for these three inclusions, but the T_h values for a few of the liquid-rich fluid inclusions would plot very close to the reference boiling-point-with-depth curve given in Urban, Diment, and Sorey (1987) and it may be possible that the vapor-rich fluid inclusions were produced during previous boiling conditions. In fact, hydrothermal-alteration studies have suggested that past temperatures were at least 65°C higher than at the present time (Flexser, 1991); similarly, oxygen isotope analyses indicate that presently the upper part of the drill hole is slightly cooler than during an earlier, higher-temperature thermal episode (Smith and Suemnicht, 1991).

Two of the fluid inclusions analyzed for this study contain tiny, (1 or 3μm) rod-shaped moving particles. The T_h values for fluid inclusions hosting these bacteria-like particles are 191° and 209°C.

Steamboat Springs

The GS-5 drill hole is one of eight holes drilled by the U.S. Geological Survey at the Steamboat Springs, Nevada thermal area. The drill holes were an early exploration effort to determine if this siliceous, hot-spring area could be exploited for geothermal power (Thompson and White, 1964). GS-5 was spudded on September 24, 1950, at 1,421-m altitude on the Main Terrace and completed on October 19, 1950, to a depth of 175.3 m (White, 1968). A stratigraphic log of the drill hole is given in White, Thompson, and Sandberg (1964) and descriptions of the hydrothermal alteration and chemical analyses of the altered rocks were published by Sigvaldason and White (1962).

For this study, 5 double-polished thin sections of core from depths of 42, 70, 97, 114, and 171 m were prepared. Only sparse, pseudosecondary(?), liquid-rich, fluid inclusions were located in the hydrothermal quartz crystals from the two shallower depths; however, primary quartz crystals in Mesozoic (White, Thompson, and Sandberg, 1964; White, 1968) granodiorite core specimens from the remaining three sample depths contain numerous, liquid-rich, secondary fluid inclusions. T_m data (0.0° or -0.1°C) for 30 fluid inclusions show that these fluids are of very low salinity (≤ 0.2 weight percent NaCl equivalent) and could be similar in composition to surface water at Steamboat Springs reported by White (1957).

In Figure 3, T_h values for fluid inclusions from the five sample depths are compared with a

Figure 3 near here

curve showing measured temperatures at depth in GS-5 and a theoretical boiling-point with depth curve for pure water (White, 1968). The bottom-hole temperatures were measured during drilling and are somewhat lower than temperatures in equilibrium with the rock (Cathy J. Janik, written commun., 1995).

From Figure 3 there appears to be three separate groupings of fluid inclusions. (1) At 70-m depth, the present temperature is about 15°C warmer than the minimum fluid inclusion T_h value, suggesting that past temperatures have been slightly lower at this depth. (2) Several of the liquid-rich fluid inclusions from the remaining four sample depths have T_h measurements that plot very close to the measured temperature curve. However, many of these T_h values also plot above the theoretical boiling-point-with-depth curve where evidence for boiling such as vapor-rich inclusions are not present. These T_h data indicate that the fluid inclusions must have formed at some previous time when both the existing temperatures and theoretical boiling-point-with-depth curve were higher than at present. (3) At the lower three sample depths many of the liquid-rich fluid inclusions along healed fractures in primary quartz crystals have T_h values (shown as separate groupings in Figure 3) that exceed the present-day temperatures by as much as 200°C. Mariner and Janik (1995) indicate that present-day temperatures as high as 243°C may occur at depth in the Steamboat Springs thermal area. Fluid inclusions having substantially higher T_h values must have formed under far different temperature and pressure conditions possibly, as long ago as the Cretaceous Period (age of the host granodiorite).

The possibility that the fluid inclusions formed at different times is reasonable because the Steamboat Springs thermal area is believed to have been intermittently active over the past ~3 million years (Silberman and others, 1979). This time period should be sufficient for many changes to occur such as erosion of a few tens of meters of overburden resulting in liquid-rich fluid inclusions that homogenize at temperatures greater than the present theoretical boiling-point curve. Thompson and White (1964) discuss erosion of this magnitude that has occurred in some parts of the area during the late Tertiary(?) and Quaternary periods.

Ahuachapán, El Salvador

The Ahuachapán geothermal field, located in northwestern El Salvador, has been producing electricity since about 1975 (Dipippo, 1986). One of the production drill holes, AH-6, is situated at an elevation of 783-m near the power plant and was drilled to a depth of 591 m (Dipippo, 1986). Drill core from this hole contained calcite chips from 390-m depth that could be polished on one side for fluid inclusion studies. The fluid inclusions analyzed are all liquid-rich, but the calcite chips are very small and it is uncertain if the inclusions are secondary or pseudosecondary, or even if some are primary. T_h values for 39 fluid inclusions ranged between 226° and 262°C and averaged 236°C (Figure 4). The minimum T_h value is slightly higher than the measured

Figure 4 near here

temperature (~220°C) at the sample depth (Einarsson, Vides, and Cuéllar, 1975) suggesting that the drill-hole fluids may have cooled a few degrees subsequent to the formation of these fluid inclusions in the calcite chips. Only 8 T_m values were obtained for the three calcite sample chips: Five T_m values are -0.5°C and 3 are 0.0°C. The salinity of the trapped fluids may be as much as 0.9 weight percent NaCl equivalent, whereas present Ahuachapán reservoir fluids typically contain about 1.4 weight percent dissolved solids (Einarsson, Vides, and Cuéllar, 1975).

Mutnovsky geothermal field, Russia

One very altered core specimen was obtained from each of three drill holes (designated as the 020, 033, and 048 wells) in the Mutnovsky geothermal area on the Kamchatka Peninsula of Russia. Binocular microscope observations and X-ray diffraction analyses of the three samples showed the presence of hydrothermal quartz-prehnite veins, disseminated pyrite crystals, and chlorite in core from 700-m depth in well 048; chalcedony, wairakite, disseminated pyrite and plagioclase (albitization?) in silicified, brecciated core from 365-m depth in the 033 well; and chalcedony, plagioclase (albitization?), and chlorite, in addition to open space fillings of green, euhedral, epidote crystals associated with later, colorless wairakite or calcite (fracture filling) in the core sample from 1,087-m depth in the 020 well.

A double-polished thin section was obtained for core specimens from each of the three wells. Fluid inclusions were observed in wairakite from the 020 and 033 wells, but variable liquid-to-vapor ratios of coeval inclusions suggest that necking-down occurred and the fluid inclusions were not analyzed. However, several fluid inclusions were observed and analyzed for one unpolished calcite cleavage chip from the 020 core specimen. No T_m values were obtained because melting of the ice could not be seen in the murky chip during two freezing attempts. T_h values ranging between about 258° and 277°C (Figure 5) and averaging about 269°C were

Figure 5 near here

obtained for 15 of the 25 liquid-rich, primary, fluid inclusions that were observed during heating.

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FIGURE CAPTIONS

Figure 1. Histogram of T_h values for the Dillingham & Vought 2 drill hole, The Geysers geothermal area, northern California.

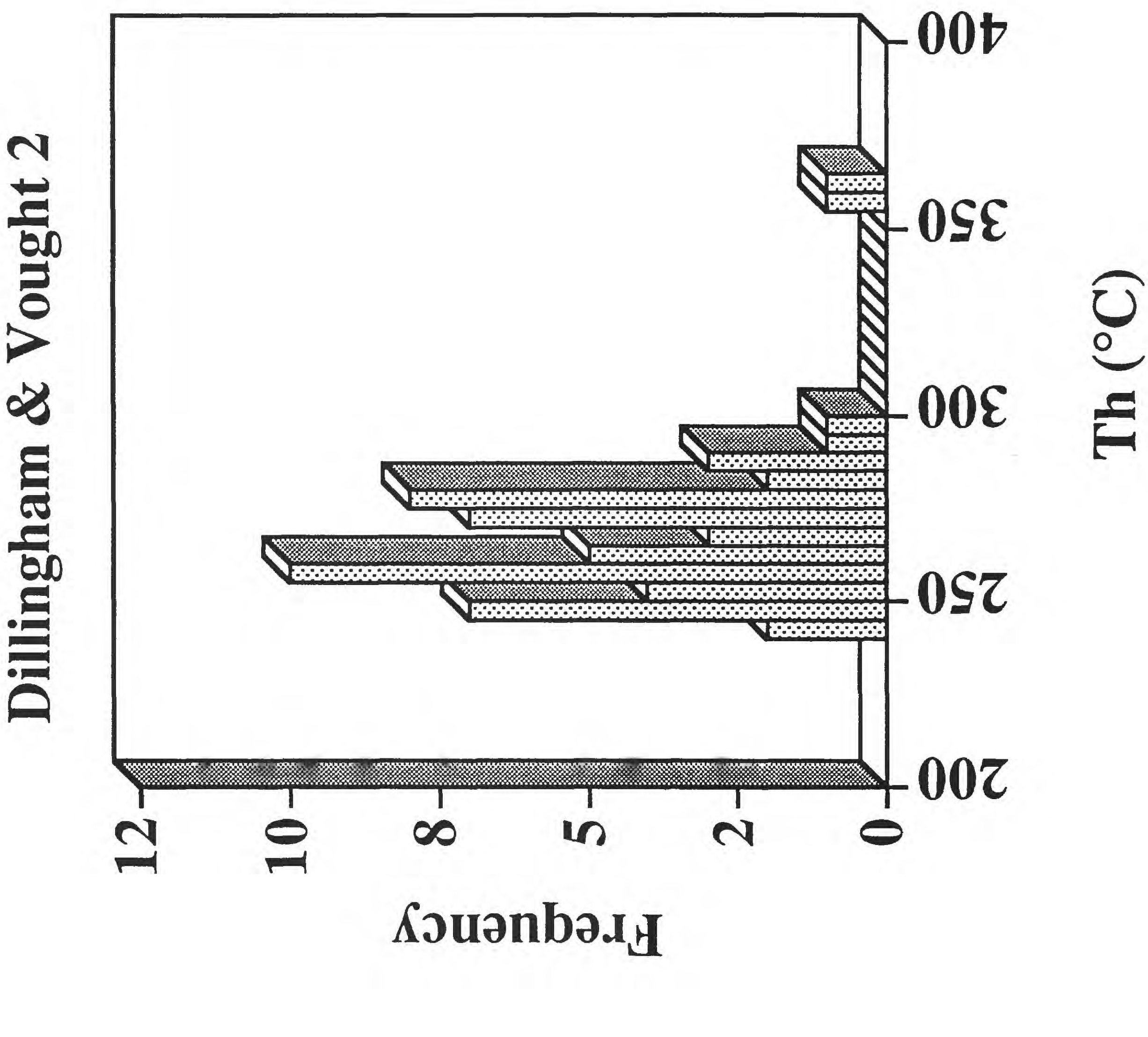
Figure 2. Histogram of T_h values for the Shady Rest drill hole, Long Valley caldera geothermal area, California.

Figure 3. Plot of fluid-inclusion T_h values vs. depth within the GS-5 drill hole, Steamboat Springs, Nevada. Solid curve shows the downhole measured temperatures; dashed curve shows a theoretical boiling-point-with-depth curve for pure water (White, 1968). T_h measurements are shown by histograms with sample depth beneath the ground surface as the baseline.

Figure 4. Histogram of T_h values for the AH-6 drill hole, Ahuachapán geothermal area, El Salvador, Central America.

Figure 5. Histogram of T_h values for the 020 well, Mutnovsky geothermal area, Kamchatka, Russia.

Figure 1



Dillingham & Vought 2
Frequency
0
2
5
8
10
12
200
250
300
350
400
Th (°C)

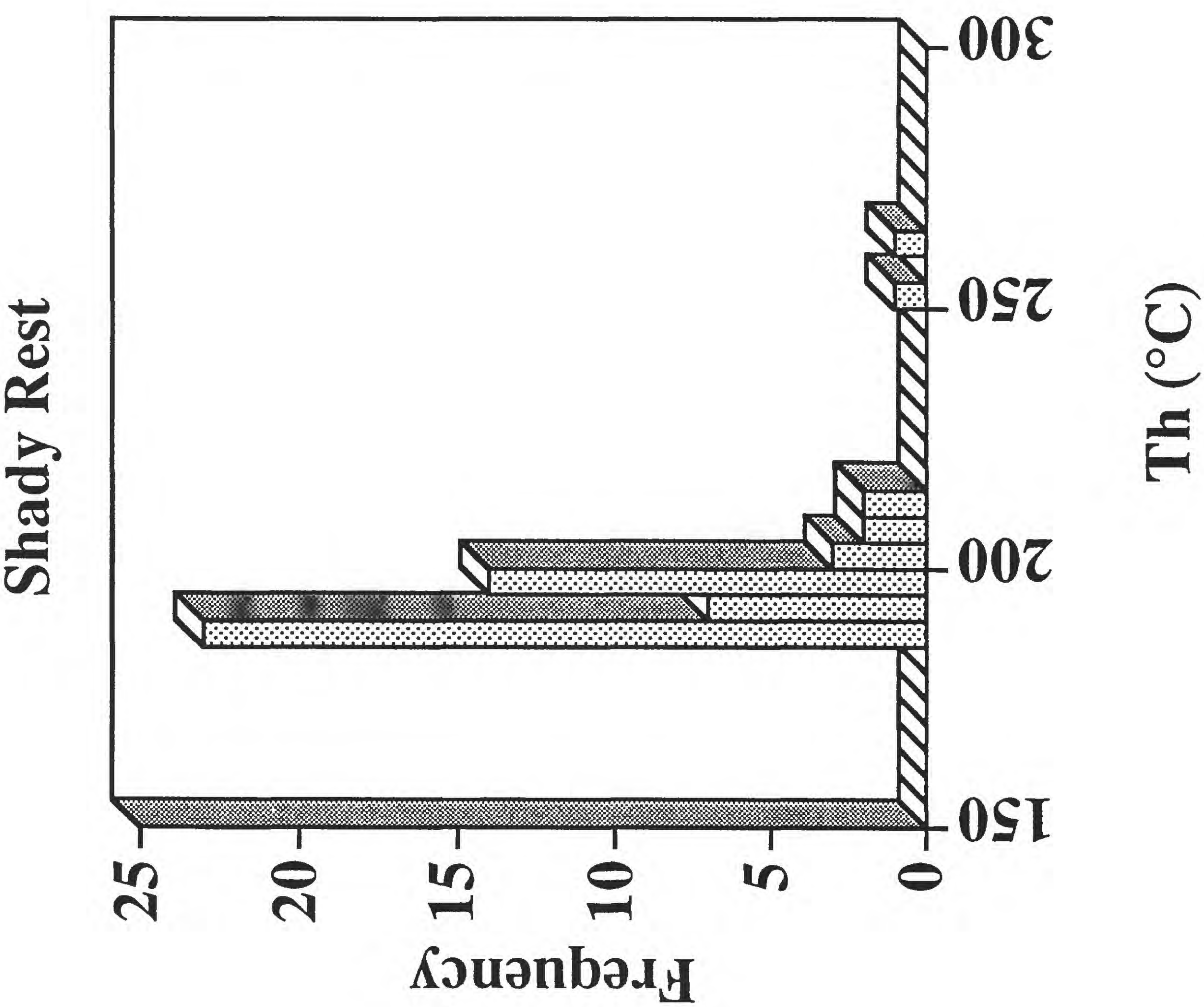
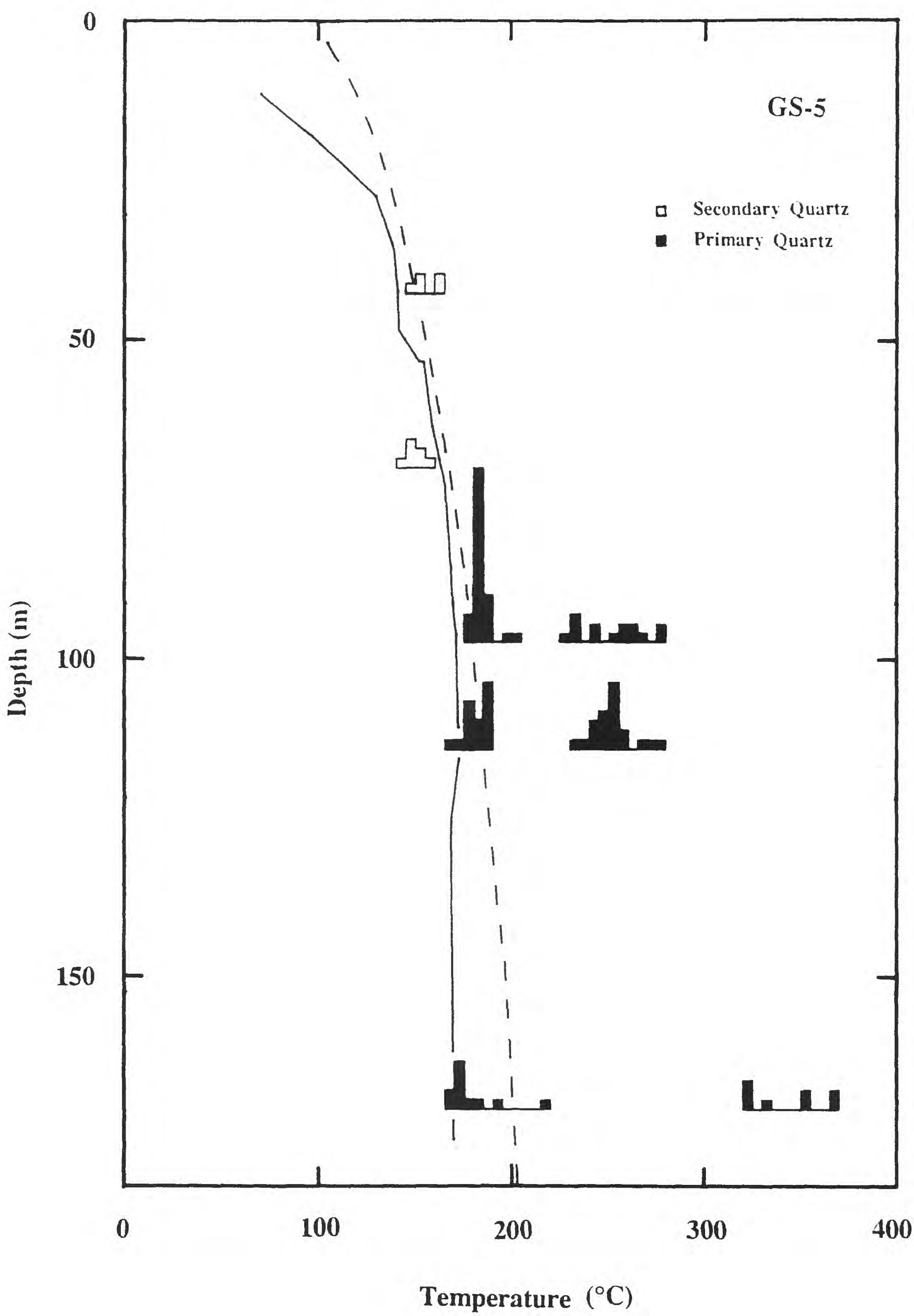

Shady Rest
Frequency
25
20
15
10
5
0
150
200
250
300
Th (°C)

Figure 3


GS-5
Secondary Quartz
Primary Quartz
Depth (m)
0
50
100
150
0
100
200
300
400
Temperature (°C)

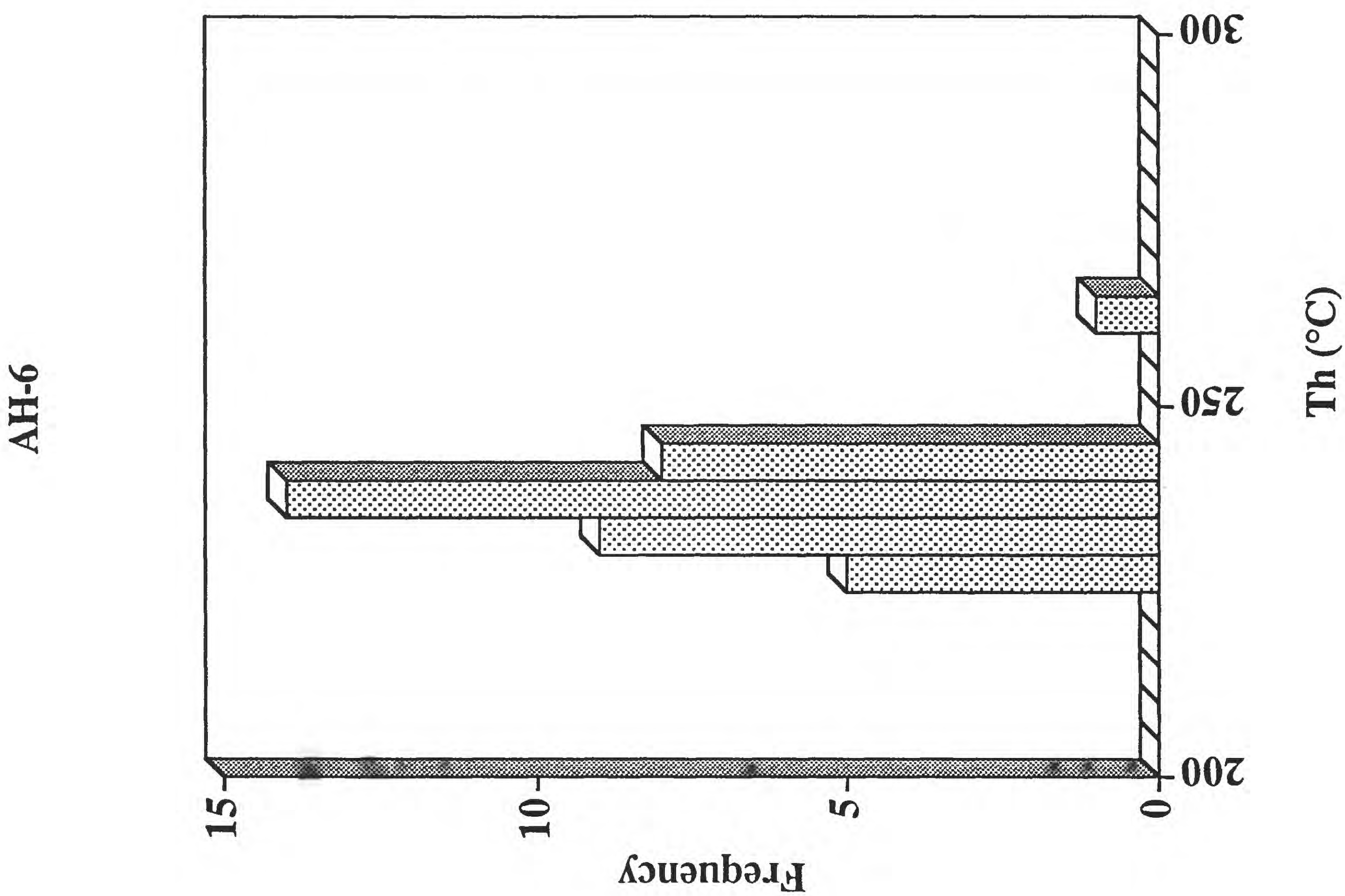

AH-6
Frequency
15
10
5
0
200
250
300
Th (°C)

Figure 5

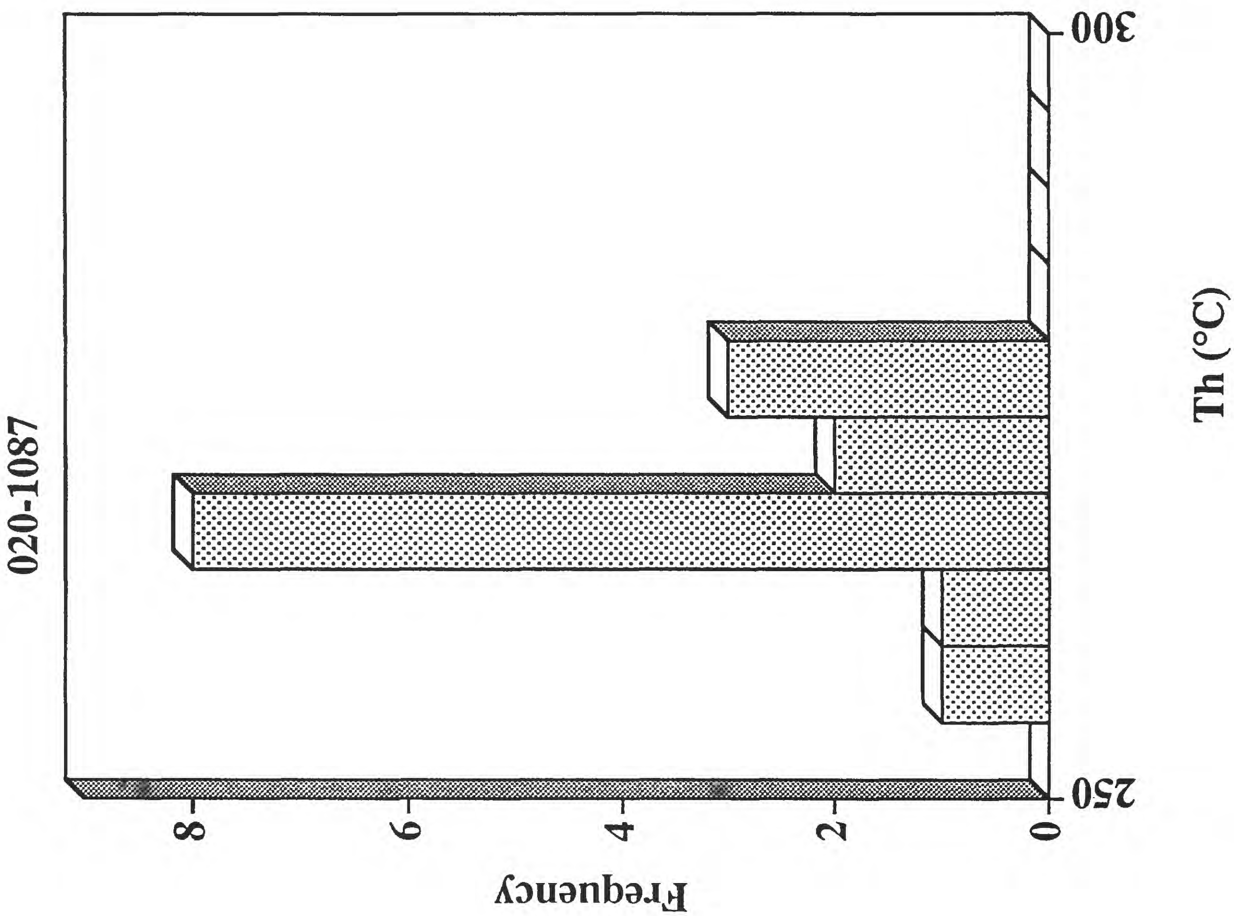


Table 1. Fluid-inclusion heating and freezing data for minerals from a few geothermal drill holes in California, Nevada, El Salvador, and Russia

[—, data not known or not determined; do, ditto; host minerals are hydrothermal crystals except where designated by (P) for primary]

Drill hole	Sample depth below ground surface (m)	Host mineral	Number of T_m measurements	T_m (°C)	Salinity (weight percent NaCl equivalent)	Number of T_h measurements	Range of T_h values (°C)	Mean T_h value (°C)	Measured drill hole temperature (°C)
The Geysers, California									
D & V-2	1,133	quartz	22	0.0	0.0	55	242 – 365	269	—
Long Valley, California									
Shady Rest	328	do	28	-0.3, -0.4	0.5, 0.7	53	186 – 265	196	202
Steamboat Springs, Nevada									
GS-5	42	do	0	—	—	5	149 – 165	155	141
do	70	do	1	0.0	0.0	7	147 – 158	150	165
do	97	quartz (P)	9	0.0	0.0	29	177 – 201	184	171
do	do	do	0	—	—	14	230 – 279	252	171
do	114	do	9	0.0	0.0	17	168 – 189	181	172
do	do	do	6	-0.1	0.2	21	233 – 279	251	172
do	171	do	4	0.0	0.0	11	167 – 216	178	172
do	do	do	1	0.0	0.0	8	321 – 379	342	172
Ahuachapán, El Salvador									
AH-6	390	calcite	8	0.0, -0.5	0.0, 0.9	40	226 – 262	236	220
Mutnovsky, Russia									
020	1,087	do	0	—	—	15	258 – 277	269	—