# Fluid-Inclusion Studies of Hydrothermal Minerals from Geothermal Drill Holes at Medicine Lake Volcano, Northern California

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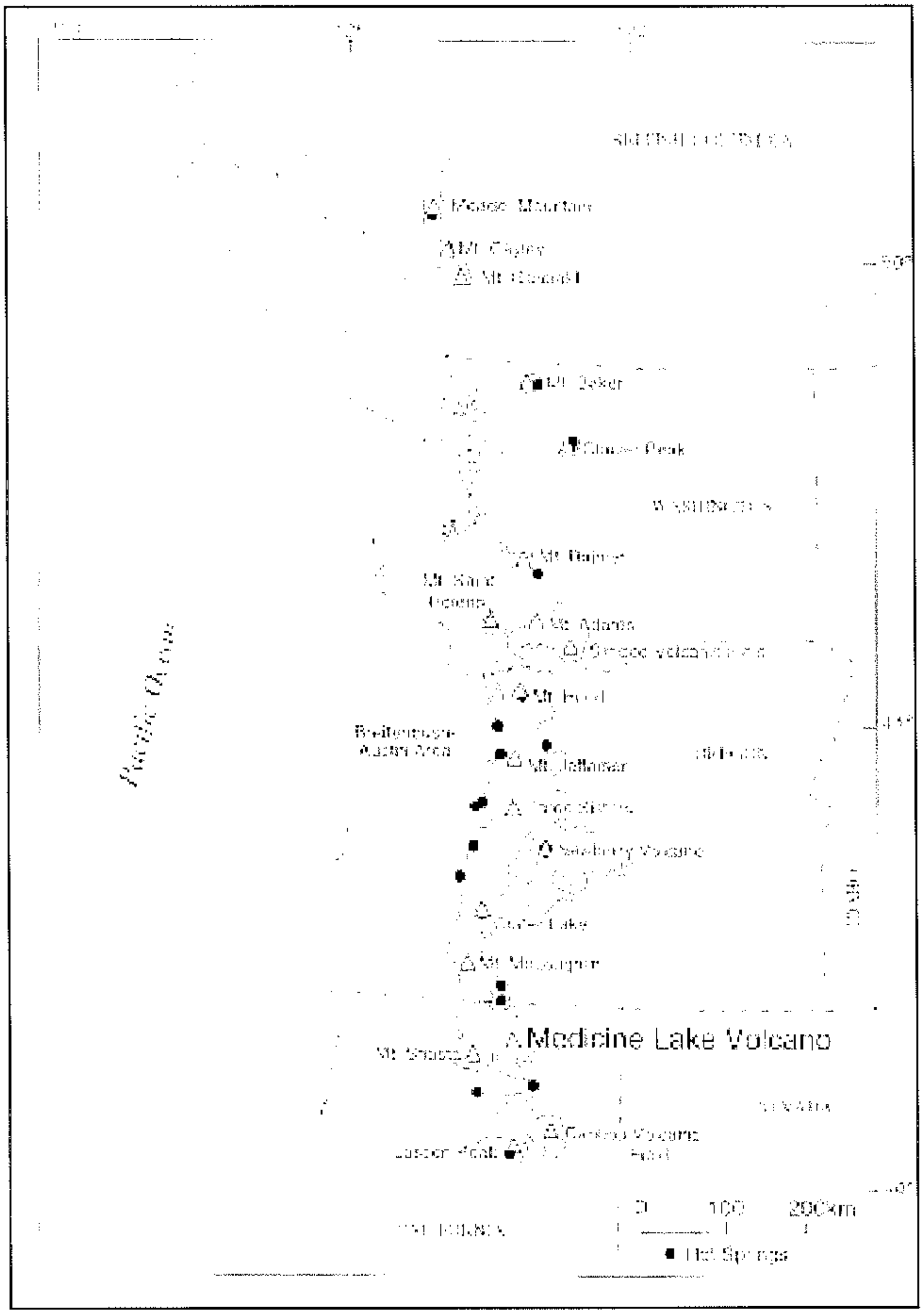

Figure 1. Location map of Medicine Lake volcano, northern California in relation to other volcanoes of the Cascade Mountain Range (shaded areas).

## INTRODUCTION

Medicine Lake volcano is a large (about 2,000 kilometer$^2$ [km]) Pleistocene to Holocene volcano in the Cascade Range of northern California about 50 km east-northeast of Mount Shasta (Figure 1) (Donnelly-Nolan, 1988, 1990). The accumulation of lava flows that comprise this low, broad, shield-shaped volcano probably began erupting about 1 million years ago (Donnelly-Nolan and others, 1990). At least 17 eruptions have occurred at Medicine Lake volcano during the past 12,000 years; composition of these lava flows ranges between basalt (< 52% $SiO_2$) and rhyolite (> 72% $SiO_2$) with only scarce dacite (62-67% $SiO_2$) lavas (Donnelly-Nolan and others, 1990). The most recent volcanic activity (about 900 years ago), at Glass Mountain and Little Glass Mountain, occurred in the vicinity of the 7 x 12 km caldera (depression due to collapse of volcano's summit following an eruption) (Figure 2) (Donnelly-Nolan and others, 1990).

Owing to this recent volcanism, Medicine Lake volcano was viewed as a possible resource for geothermal energy (energy derived from underground hot fluids, commonly associated with active volcanic regions, which are used in driving generators to produce electricity). As such, over the past couple of decades, various private companies have invested considerable effort in trying to determine the geothermal energy potential of the area. Industry evaluation of the volcano included completion of several drill holes. Initially, results of the drilling mostly were proprietary; however, drill-core samples from 12 holes were made available for scientific investigations. In

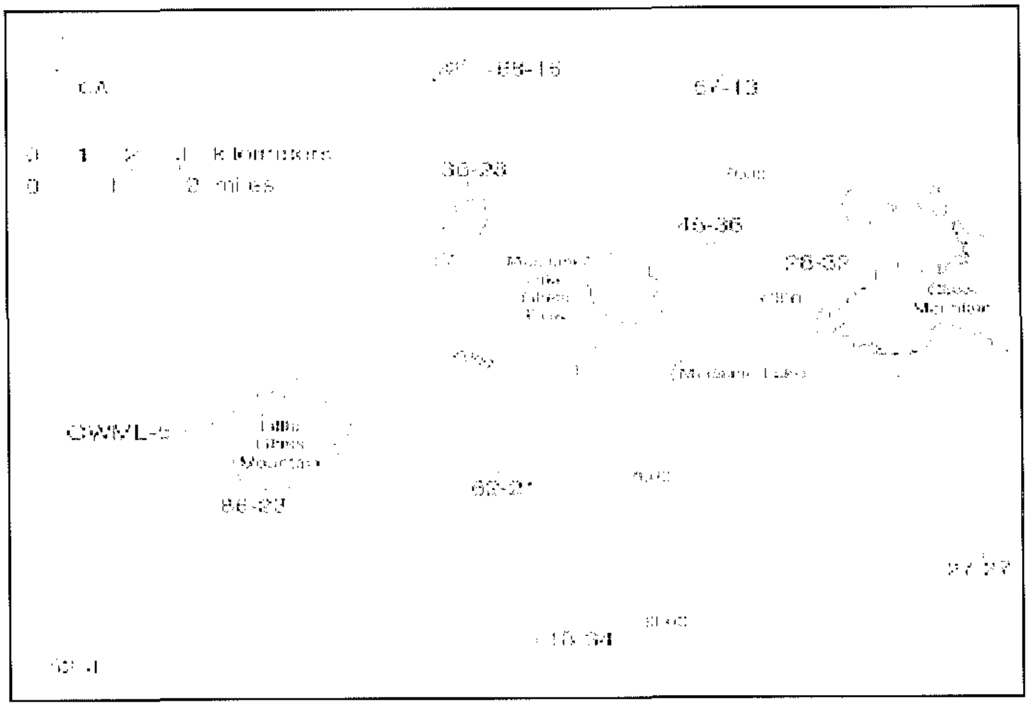

Figure 2. Topographic map of Medicine Lake volcano, northern California showing the location of 11 of the 12 geothermal prospect drill holes (open circles) included in this study. Drill hole ML 88-12 is about 10 km west of the ML 52-4 drill hole. The rim of the caldera lies within the closed 7,000 foot contour lines. Shaded areas are Holocene volcanic deposits.

1992, a group of interested U.S. Geological Survey scientists took advantage of this unique opportunity to examine the extensive collection of drill-core specimens. As a member of this group, my interest was in obtaining information on past and present-day temperatures of the thermal fluids circulating through rocks penetrated by the drill holes.

Prior to this investigation, some general information on the petrology of eight flank drill holes was provided by Donnelly-Nolan (1990). A temperature of 105°C at 1.2 km depth and a geothermal gradient of 100°C/km between depths of 0.5 and 1.2 km were reported for the ML 88-12 drill hole (not shown in Figure 2) located about halfway between Mount Shasta and the Medicine Lake volcano (Blackwell and others, 1990). Also, measured geothermal gradients of 88°C/km, 227°C/km, and 548°C/km were given for three wells sited within the volcano's caldera (Donnelly-Nolan and others, 1990).

## HYDROTHERMAL MINERALOGY

More than 600 representative core specimens from the 12 drill holes, which range in depth from about 340 m to 1,370 m (see Figure 2 for locations of all but the ML 88-12 hole), were collected for this study. Some volcanic glass, and open spaces of many fractures, vesicles, and areas between fragments of breccias in core specimens from all 12 drill holes show alteration effects caused by circulating thermal fluids. This study of drill-hole samples from the Medicine Lake volcano area identified 44 metamorphic minerals (zeolites, carbonates, sheet-silicates, silica minerals, sulfides, sulfates, and other minerals) (Table 1) that formed by hydrothermal (hot water) alteration of preexisting rocks at low (<~200°C) to moderate (~200° to 400°C) temperatures (Bargar and Keith, 1993). Table 1 shows the temperatures at which these minerals have been found in well-studied geothermal systems throughout the world. Many of the hydrothermal minerals identified from the drill holes must have formed at temperatures below 200°C. Only rocks near the bottoms of the two intracaldera drill holes (ML 28-32 and ML 45-36) display more intense alteration reflective of exposure to higher-temperature fluids. The presence of minerals such as garnet, epidote, actinolite, prehnite, and talc indicates that past downhole temperatures have been in the range of 200°C to more than 300°C. A few additional minerals listed in Table 1 could possibly have been deposited at temperatures above 200°C. More specific temperature data for the two intracaldera drill holes can be determined from minerals containing fluid inclusions (microscopic cavities in the crystals filled by water and gas phases that were trapped during or following crystal formation) such as quartz, calcite and possibly wairakite. In addition to providing a probable temperature range over which the minerals formed, fluid inclusions also may be used to determine the salinity of the fluids from which the crystals precipitated.

Table 1. Hydrothermal minerals identified from geothermal drill holes at Medicine Lake volcano and the temperatures at which these minerals are found in studied modern geothermal areas.

| Drill hole no. | OWML5 | 18-34 | 27-27 | 28-32 | 36-28 | 45-36 | 52-4 | 57-13 | 62-21 | 68-16 | 86-23 | 88-12 | Temp.[2] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Zeolite minerals | | | | | | | | | | | | | |
| Analcime | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | X | -- | 70—300 |
| Chabazite | X | -- | -- | -- | -- | -- | X | -- | -- | -- | -- | -- | <75 |
| Heulandite | X | -- | -- | X | -- | X | X | -- | X | -- | -- | -- | 60—170 |
| Laumontite | -- | -- | -- | X | -- | X | -- | -- | -- | -- | -- | X | 43—230 |
| Levyne | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | X | -- | <70 |
| Mordenite | -- | -- | -- | X | -- | X | X | -- | X | -- | -- | -- | 85—230 |
| Phillipsite | -- | X | -- | -- | -- | -- | -- | -- | -- | -- | X | -- | 37—85 |
| Scolecite | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | X | -- | 65—100 |
| Stilbite | X | -- | -- | -- | -- | -- | X | -- | -- | -- | X | -- | 70—170 |
| Thomsonite | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | X | -- | 60—110 |
| Wairakite | -- | -- | -- | X | -- | X | -- | -- | -- | -- | -- | -- | 180—300 |
| Carbonate minerals | | | | | | | | | | | | | |
| Aragonite | -- | -- | -- | X | -- | -- | -- | -- | -- | -- | -- | -- | <80 |
| Calcite | X | X | X | X | X | X | X | X | X | -- | X | X | <100—350 |
| Dolomite | X | -- | -- | X | -- | -- | -- | -- | X | -- | -- | -- | <10—250 |
| Kutnohorite | -- | -- | X | X | -- | -- | -- | -- | -- | -- | -- | -- | <10—70 |
| Rhodochrosite | -- | -- | -- | -- | -- | X | -- | -- | -- | -- | -- | -- | 30—130 |
| Siderite | X | X | -- | X | -- | -- | X | -- | -- | -- | -- | -- | <10—160 |
| Sheet-silicate minerals | | | | | | | | | | | | | |
| Kaolinite | -- | -- | -- | X | -- | -- | -- | -- | -- | -- | -- | -- | <50—170 |
| Halloysite | -- | -- | -- | -- | -- | -- | X | -- | -- | -- | -- | -- | <50 |
| Smectite | X | X | X | X | X | X | X | X | X | -- | X | X | <200 |
| Illite-Smectite | -- | -- | X | X | -- | -- | -- | -- | -- | -- | -- | X | 50—270 |
| Illite | -- | -- | -- | X | -- | X | -- | -- | -- | -- | -- | -- | 150—<300 |
| Chlorite-Smectite | -- | -- | -- | X | -- | X | -- | -- | -- | -- | -- | -- | <100—240 |
| Chlorite | -- | -- | -- | X | -- | X | -- | -- | -- | -- | -- | X | <100—350 |
| Apophylite | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | X | -- | 50—70 |
| Prehnite | -- | -- | -- | -- | -- | X | -- | -- | -- | -- | -- | -- | 210—350 |
| Talc | -- | -- | -- | X | -- | -- | -- | -- | -- | -- | -- | -- | 290—320 |
| Silica minerals | | | | | | | | | | | | | |
| Opal | -- | -- | -- | -- | -- | X | -- | -- | -- | -- | -- | -- | <100 |
| Cristobalite | X | -- | -- | X | -- | X | X | -- | X | -- | -- | -- | <100—210 |
| Chalcedony | X | -- | -- | X | -- | X | X | -- | X | -- | -- | -- | <100—240 |
| Quartz | X | -- | -- | X | X | X | -- | -- | X | | -- | X | 100—300+ |
| Sulfide minerals | | | | | | | | | | | | | |
| Marcasite | -- | -- | -- | X | X | -- | -- | -- | -- | -- | -- | -- | 80—170 |
| Pyrite | -- | -- | -- | X | X | X | X | -- | -- | -- | -- | X | <100—350+ |
| Pyrrhotite | -- | -- | -- | X | -- | X | -- | -- | -- | -- | -- | -- | 97—265 |
| Sulfate minerals | | | | | | | | | | | | | |
| Anhydrite | -- | -- | -- | X | -- | X | -- | -- | -- | -- | -- | -- | 60—300 |
| Gypsum | -- | -- | -- | X | X | -- | -- | -- | -- | -- | -- | -- | <70 |
| Natrojarosite | -- | -- | -- | X | X | -- | -- | -- | -- | -- | -- | -- | 50 |
| Other minerals | | | | | | | | | | | | | |
| Iron oxide[1] | X | X | -- | X | -- | X | X | -- | X | X | -- | X | <100—250 |
| Magnetite | -- | -- | -- | X | -- | -- | -- | -- | -- | -- | -- | -- | >200? |
| Gyrolite | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | X | -- | <50—>200 |
| Adularia | -- | -- | -- | X | -- | -- | -- | -- | -- | -- | X | -- | 150—300+ |
| Actinolite | -- | -- | -- | X | -- | X | -- | -- | -- | -- | -- | -- | 260—400 |
| Epidote | -- | -- | -- | X | -- | X | -- | -- | -- | -- | -- | -- | 220—350 |
| Garnet | -- | -- | -- | X | -- | -- | -- | -- | -- | -- | -- | -- | 250—300+ |

[1] Iron oxide includes both amorphous iron oxide and hematite in XRD analyses.

[2] Measured temperatures (in °C) at which minerals occur in modern geothermal areas. Data from Tómasson and Kristmannsdóttir (1972); Kristmannsdóttir (1975); Kristmannsdóttir and Tómasson (1978); Kristmannsdóttir (1979); Jakobsson and Moore (1986); Fridleifsson (1991); Honda and Muffler (1970); Keith, White, and Beeson (1978); Holland and Malinin (1979); Elders and others (1979); Cavarretta, Gianelli, and Puxeddu (1982); Leach, Wood, and Reyes (1983); Aumento and Liguori (1986); Hulen and Nielson (1986); White, Hutchinson, and Keith (1988); Horton (1985); Bargar and Keith (1999); McDowell and Paces (1985).

## Fluid Inclusion Data

Doubly polished (polished on both sides) thin sections of hydrothermal quartz, calcite, and wairakite crystals, along with a few unpolished, thin, calcite cleavage chips were used for fluid-inclusion analyses in this study. Very thin chips of the minerals are heated on a microscope stage to the temperature at which the liquid and gas phases inside the fluid inclusions merge by expansion or contraction to a single phase (either gas or liquid). This is called the homogenization temperature (Th) and is generally presumed to be the minimum formation temperature of the fluid inclusion (Roedder, 1984). The fluid inclusions also are frozen on the microscope stage and then gradually thawed; the temperature at which the last piece of ice melts (Tm) is recorded. This ice-melting temperature can be used to determine the salinity (in weight % NaCl equivalent) of the fluid from which the crystals precipitated (Potter and others, 1978). Successive calibration runs (for the Linkam THM 600 heating/freezing microscope stage and TMS 90 temperature control system), using synthetic fluid inclusions (Bodnar and Sterner, 1984) and chemical compounds with known melting points recommended in Roedder (1984), suggest that the accuracy of the Th measurements is within ± 2.0°C and the Tm values are accurate to at least ± 0.2°C.

Fluid-inclusion data were only obtained for quartz, calcite, and wairakite from the two geothermal drill holes (ML 28-32 and ML 45-36) that were completed within the caldera of Medicine Lake volcano. Hydrothermal quartz crystals occur in open spaces of six drill holes, calcite was found in all but one drill hole, and wairakite was identified only in the two intracaldera holes (Table 1). Calcite and wairakite are colorless to white soft minerals for which leakage of fluid from the inclusions potentially could result in erroneous fluid-inclusion data; on the other hand, quartz is a colorless hard mineral that generally is not believed to leak and is regarded as a very good mineral for fluid inclusion analyses (Roedder, 1984). Most fluid inclusions appear to have formed along healed fractures and are classified as being of secondary origin. Many similar inclusions are referred to as pseudosecondary because later mineral growth on exterior crystal faces sealed off healed fractured zones leaving crystal rims free of fluid inclusions. A few inclusions are very large compared with the size of the host crystal and appear to be isolated from other fluid inclusions; such inclusions are classified as primary because they must have formed during initial crystal growth. Quartz specimens first were frozen and gradually thawed to obtain the Tm values; these specimens were then heated to record the Th data. The order of heating and freezing was reversed for the soft calcite and wairakite minerals because of the possibility that expansion of ice in fluid inclusions of these minerals might cause the inclusions to break.

## Drill hole ML 28-32

Homogenization temperatures (Th) were obtained for 94 liquid-rich, secondary and pseudosecondary, fluid inclusions in quartz specimens

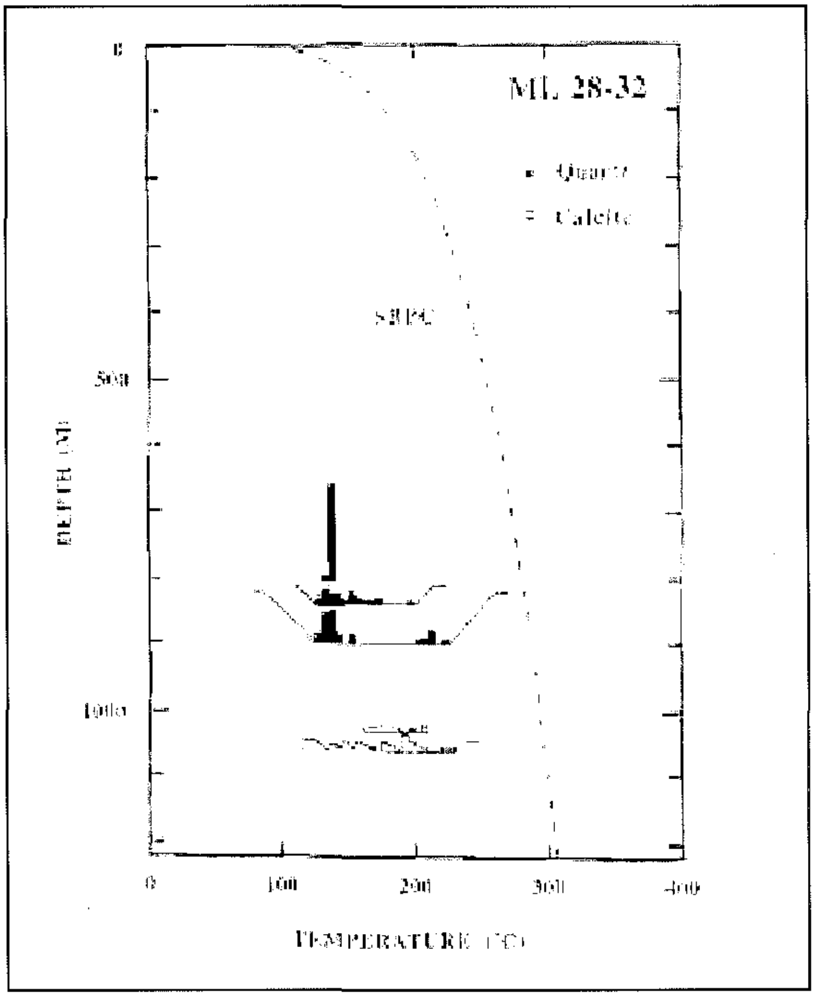

Figure 3. Plot of depth below ground surface vs. fluid-inclusion homogenization temperatures (Th) for fluid inclusions in hydrothermal quartz and calcite minerals in core from the ML 28-32 drill hole (data from Table 2). Dashed curve is a theoretical reference boiling-point curve for pure water originating at the ground surface (after data in Elder, 1981, Table A5).

Table 2. Fluid-inclusion heating/freezing data for hydrothermal minerals in geothermal drill core from Medicine Lake volcano

| Sample depth (m) | Host mineral | Number of melting-point temperature measurements | Melting-point temperatures $T_m$ (°C) | Salinity (wt percent NaCl equivalent) | Number of homogenization temperature measurements | Range of homogenization temperatures $T_h$ (°C) | Mean homogenization temperature $T_h$ (°C) |
|---|---|---|---|---|---|---|---|
| **Drill hole ML 45-36** | | | | | | | |
| 432.5 | quartz | 1 | 0.0 | 0.0 | 1 | 150 | — |
| 753.8 | " | 33 | 0.0, -0.1 | 0.0, 0.2 | 51 | 211 – 324 | 268 |
| 827.2 | " | 15 | 0.0, -0.1 | 0.0, 0.2 | 28 | 198 – 324 | 259 |
| 841.6 | " | 19 | 0.0, -1.7 | 0.0, 2.9 | 27 | 227 – 312 | 254 |
| 854.4 | calcite | 0 | — | — | 25 | 178 – 213 | 188 |
| 855.0 | quartz | 29 | 0.0, -0.1 | 0.0, 0.2 | 53 | 189 – 304 | 268 |
| 856.2 | " | 33 | 0.0, -0.1 | 0.0, 0.2 | 56 | 197 – 373 | 244 |
| 1011.0 | calcite | 30 | 0.0, -1.1 | 0.0, 1.9 | 46 | 202 – 285 | 249 |
| 1184.8 | wairakite | 0 | — | — | 4 | 194 – 263 | 211 |
| **Drill hole ML 28-32** | | | | | | | |
| 804.1 | quartz | 0 | — | — | 31 | 130 – 138 | 136 |
| 811.2 | " | 8 | -0.5, -0.6, +4.1 | | 26 | 125 – 196 | 147 |
| 819.8 | " | 16 | -0.2, -0.4, -0.5<br>-0.9, -1.2, +2.6<br>+3.1, +3.2 | | 37 | 127 – 223 | 154 |
| 1030.2 | calcite | 0 | — | — | 12 | 163 – 207 | 183 |
| 1043.9 | " | 0 | — | — | 32 | 139 – 225 | 177 |

from three depths in the ML 28-32 drill hole; the Th values range between 125° and 223°C (Table 2; Figure 3). Only 24 melting-point temperature (Tm) measurements were obtained for these fluid inclusions. Some of the analyzed specimens were too murky to determine the temperature at which the last piece of ice melted. The vapor bubble for several fluid inclusions disappeared during freezing and did not reappear until +2.6° to +4.1°C. These positive Tm values indicate metastability and the fluid inclusions cannot be used for salinity calculations (Roedder, 1984). Other Tm values range between -0.5° and -1.2°C corresponding to 0.9 to 2.1 weight percent NaCl equivalent. Tm data were not obtained for two calcite cleavage chips; Th values for 44 fluid inclusions in the calcite specimens range between 139° and 225°C.

### Drill hole ML 45-36

Homogenization temperatures were obtained for 216 liquid-rich, secondary, pseudosecondary, and primary fluid inclusions in quartz crystals that line open spaces in drill core from six depths in the ML 45-36 drill hole (Table 2). Three vapor-rich pseudosecondary fluid inclusions from one specimen also were analyzed; these inclusions homogenized to the vapor state but the precise Th values were not observed. Th measurements for quartz specimens from this drill hole range between 150° and 373°C (Figure 4). Tm values of 130 fluid inclusions are mostly 0.0° and -0.1°C corresponding to a salinity of 0.0 to 0.2 weight percent NaCl equivalent. Nine fluid inclusions in one quartz specimen have a Tm value of -1.7°C, which corresponds to a salinity of 2.9 weight percent NaCl equivalent.

Thirty Tm values were obtained for secondary liquid-rich fluid inclusions in one of two calcite specimens analyzed from this drill hole. Tm measurements for 22 fluid inclusions in one crystal from this specimen were 0.0°C (salinity = 0.0 weight percent NaCl equivalent). Eight fluid inclusions in a separate calcite crystal from the same specimen had Tm values of -1.1°C corresponding to a salinity of 1.9 weight percent NaCl equivalent. Th values for 71 analyzed fluid inclusions in the two calcite specimens ranged from 178°C to 285°C. Forty-one liquid-rich fluid inclusions in a wairakite specimen mostly leaked during heating. No Tm values were measured for the wairakite fluid inclusions, and only four Th values between 194° and 263°C were recorded. Reliability of the fluid-inclusion measurements in calcite and wairakite crystals reported here are quite suspect; however, the measured Tm and/or Th values of these inclusions fall within the range of data for the quartz specimens from this drill hole (Figure 4; Table 2) and thus were not eliminated from the data set.

## BACTERIA-LIKE PARTICLES

A 2-mm-long, colorless, euhedral, quartz crystal from a fracture in a rhyolitic lava flow from 856.2-m depth in drill hole ML 45-36 contains dozens of bacteria-like moving particles that were trapped within a 200μm x 130μm, liquid-rich, primary fluid inclusion (Photo 1) (Bargar, 1992). The moving particles, ranging in size from <0.5μm (undefined

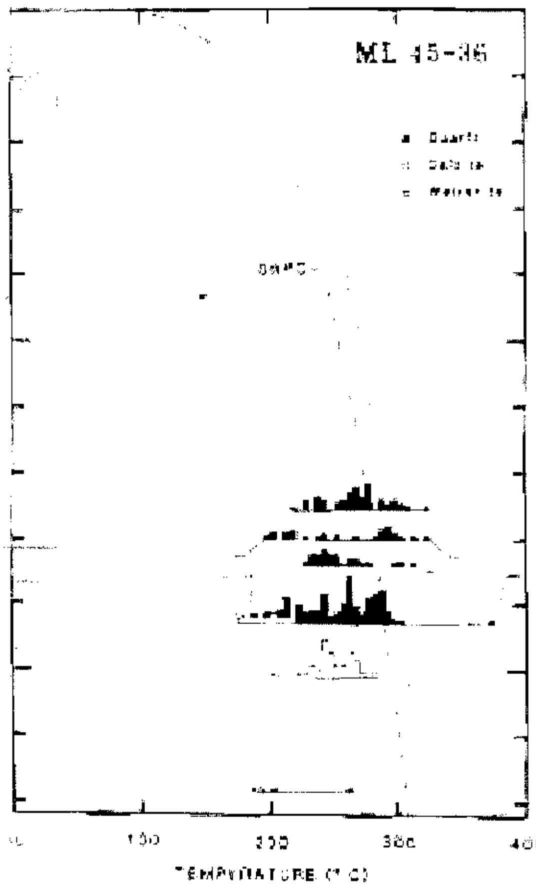

Figure 4. Plot of depth below ground surface vs. fluid-inclusion homogenization temperatures (Th) for fluid inclusions in hydrothermal quartz, calcite, and wairakite minerals from the ML 45-36 drill hole (data from Table 2). Dashed curve is a theoretical reference boiling-point curve for pure water originating at the ground surface (after data in Elder, 1981, Table A5). Dotted curve is a theoretical reference boiling-point curve for pure water originating 150 m above the present-day ground surface assuming the presence of an overburden of this thickness of glacial ice.

shapes) to ~3µm to 5 µm (rodlike) (Photo 2), were first noticed during initial heating of the fluid inclusion. The sub micron-sized particles move very rapidly at ambient temperature while the larger, rod-shaped particles move very sluggishly and are difficult to distinguish among the shadows near the vapor bubble and the outer margins of the fluid inclusion. Around 62°C, a large number of moving particles became apparent near the lower surface of the vapor bubble. Each particle moved in a constant circular mode perpendicular to the length of the vapor bubble; the combined movement of all of the particles defines a cylindrical current (shown in a videotape attachment of Bargar and Keith, 1997). Individual particles appear to bounce off the boundary between water and the vapor bubble, become caught in the continuous current, and then return to the water-vapor interface. The thermal-induced current has a greater velocity at the lower end (right side of Photo 1).Towards the upper end (near center of fluid inclusion) of the short tubular-shaped convective cell, the current velocity appears to gradually decrease, and the particles eventually drift off into the large interior area of the fluid inclusion. Some particles disappear behind the vapor bubble, but they most likely reenter the convective cell because the number of particles within the cell appears to remain nearly constant. As the temperature is reduced, movement of the larger rod-shaped particles decreases until at room temperature only a very slow Brownian-like motion (random movement caused by constant collisions with water molecules) is observed.

Salinity of the water in the fluid inclusion is very low with a Tm value of 0.0°C. No Th measurement was obtained because heating was discontinued at ~130°C in order to insure preservation of the very large fluid inclusion (very large fluid inclusions have a slight tendency to break during heating). Fifty-five other liquid-rich, secondary or pseudosecondary fluid inclusions in quartz crystals from the same fracture have Th values between 197° and 373°C (average of 244°C); Tm values for 33 of these fluid inclusions is 0.0° or -0.1°C (salinity = 0.0 to 0.2 weight percent NaCl equivalent) (Table 2).

Similar moving particles were found in liquid-rich, secondary fluid inclusions in quartz crystals from depths of 753.8 m (Th of 253° to 278°C; Tm of 0.0°C), 841.6 m (Th of 233° to 265°C; Tm of 0.0° and -1.7°C), and 855.0 m (Th of 260° and 289°C; Tm of 0.0°C) in the ML 45-36 drill hole.

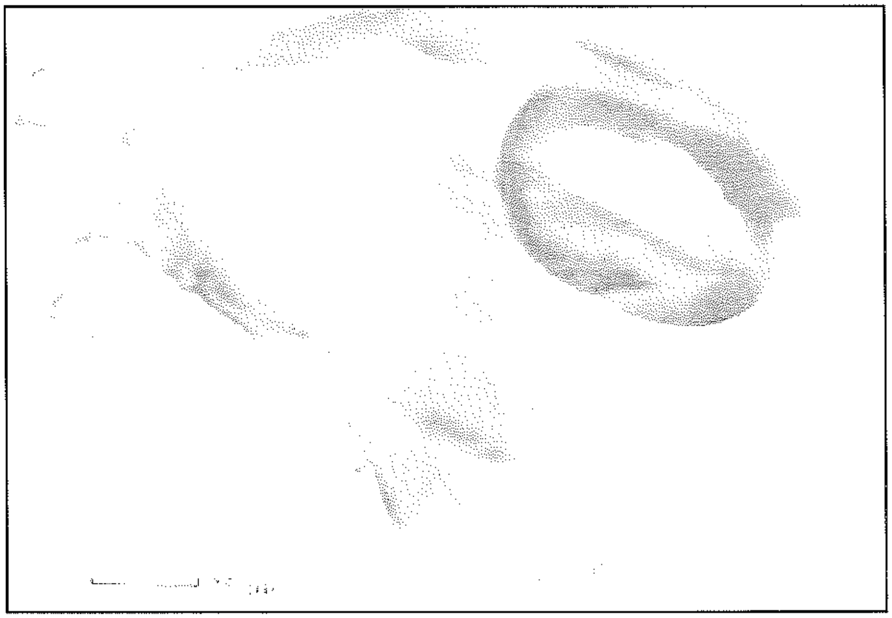

Photo 1. Photomicrograph of a 200 µm x 130 µm liquid-rich, primary fluid inclusion in a 2 mm long colorless quartz crystal from a fracture in a rhyolitic lava flow at 856.2 m depth in the ML 45-36 drill hole. The fluid inclusion contains dozens of tiny moving bacteria-like particles.

## DISCUSSION

This study of core samples from 12 geothermal prospect drill holes in the Medicine Lake volcano area identified 44 minerals that must have formed by hydrothermal alteration at low to moderate temperatures. The identified mineral assemblages (zeolites, carbonates, sheet-silicates, silica minerals, sulfides, sulfates, and other minerals) from the drill holes sited outside the caldera of Medicine Lake volcano (Table 1) characterize conditions attributed to zeolite-facies metamorphism (metamorphism occurring under low temperature and pressure conditions). The minerals identified from the upper parts of the two intra-caldera drill holes (Table 1) also appear to reflect the same low-temperature (<200°C) conditions. It is only near the bottoms of the ML 28-32 and ML 45-36 drill holes that several of the identified minerals (garnet, epidote, actinolite, prehnite, and talc) undoubtedly formed under somewhat higher-temperature (200° to 400°C) subgreenschist- to greenschist-facies (containing green minerals such as chlorite, epidote and actinolite that formed under low to moderate temperatures and pressures) conditions (Liou, Maruyama, and Cho, 1987).

No fluid inclusions were found in hydrothermal minerals from the drill holes outside the Medicine Lake caldera. Studies of fluid inclusions within quartz and calcite deposits from the ML 28-32 drill hole produced homogenization temperatures (Th) that are mostly characteristic of zeolite-facies metamorphism (Table 2; Figure 3). It is only the presence of the metamorphic minerals garnet, epidote, actinolite, and talc (Table 1) that indicates the existence of past higher temperatures in this drill hole. However, in the ML 45-36 drill hole the Th values for calcite and quartz fluid inclusions predominantly fall in the 200° to >300°C range (Table 2; Figure 4) characteristic of subgreenschist- to greenschist-facies conditions. The presence of epidote, actinolite, and prehnite (Table 1) provides additional support for higher-temperature metamorphism.

Fluid inclusion studies of several geothermal drill holes in Japan indicate that at a given depth minimum Th values are generally the same or slightly warmer than the present measured temperatures (Taguchi and Hayashi, 1982; Taguchi and others, 1984). These workers indicate that minimum Th values can be used to estimate present-day temperatures where drill-hole temperature-data were not obtained or are unavailable for proprietary reasons. Minimum Th measurements for fluid inclusions in the lower half of the ML 45-36 drill hole (Figure 4) suggest that present-day temperatures in the lower few hundred meters may be near 200°C. The majority of Th measurements is much higher than 200°C reflecting much hotter conditions that occurred in the past. In fact, numerous Th values plot above the theoretical reference boiling point curve (dashed line in Figure 4). Fluids trapped within inclusions at any given depth would be liquid-rich at temperatures below the boiling-point curve. Fluid inclusions forming at temperatures hotter than the boiling-point curve at any depth would be expected to be vapor-rich or at least there should be coexisting liquid-rich and vapor-rich fluid inclusions. The fluid inclusions whose Th measurements plot above the boiling-point curve in Figure 4 are only liquid-rich and could not have formed under boiling conditions as would be suggested by this diagram.

Photo 2. Photograph (using a laser scanning microscope) of tiny, rodlike particles trapped inside the fluid inclusion shown in Photo 1.

A study of fluid inclusions in hydrothermal minerals recovered from drill holes in Yellowstone National Park by Bargar and Fournier (1988a) yielded data similar to the Medicine Lake fluid-inclusion study. That is, Th measurements for liquid-rich fluid inclusions plot above a theoretical reference boiling-point curve. During the late Pleistocene Era (about 45,000-14,000 years ago), the Yellowstone area was covered by hundreds of meters of glacial ice. Because of the additional weight of the ice, any fluid inclusions that formed those many thousands of years ago did so under very different temperature and pressure conditions than exist at the present time. Consequently, a theoretical reference boiling-point curve reflecting the maximum temperature that can be attained in a hot-water system at a given depth in the Pleistocene Era had to have been elevated by several hundred meters above the present-day Yellowstone ground surface. For example, a liquid-rich fluid inclusion in a quartz crystal lining a fracture could have formed at 300°C under the tremendous overburden of ice. After all the ice melted, that same fluid inclusion with a Th of 300°C would remain where the present-day temperature of the hot water circulating through the fracture was only 200°C.

Anderson (1941) and Donnelly-Nolan and Nolan (1986) discussed evidence for about 150 m thickness of Holocene glacial ice in the Medicine Lake volcano area. An additional ground cover of 150 m of glacial ice would require that pore-fluid pressures in the underlying rock be increased in proportion to the weight of the overlying column of ice. According to the above field studies, a theoretical reference boiling-point curve would have to originate approximately 150 m above the present ground surface of 0 m depth (dotted curve in Figure 4) at the time the Medicine Lake area was covered by glaciers. This adjusted boiling-point curve can account for a majority of the anomalous fluid inclusion Th measurements for the ML 45-36 drill hole. A somewhat thicker ice cover would be necessary to account for all of the anomalous Th values. In any event, the fluid-inclusion studies of the ML 45-36 drill core samples appear to support the concept of late Pleistocene glaciation in the Medicine Lake volcano area.

A second aspect of the fluid-inclusion study worth emphasizing are the dozens of tiny (<0.5 to ~ 3 to 5 µm) rod-shaped (Photo 2) and undetermined shaped moving particles that were observed within fluid inclusions in quartz from four depths (753.8, 841.6, 855.0, and 856.2 m) in the ML 45-36 drill hole. These particles apparently were trapped over a period of time during growth of the quartz crystals because the particles occur within primary, pseudosecondary, and secondary liquid-rich fluid inclusions.

Bacteria-like moving particles were trapped within fluid inclusions in hydrothermal quartz crystals that formed on fractures of a 150,000 year old rhyolite lava flow penetrated by a U.S. Geological Survey research drill hole in Lower Geyser Basin, Yellowstone National Park, Wyoming (Bargar, Fournier, and Theodore, 1985) (Th of 190° to 280°C; Tm of 0.0°C) In addition to this report, bacteria-like particles in fluid inclusions also have been observed by this author during fluid-inclusion studies of drill-hole specimens from other geothermal areas. Rod-shaped moving particles are present within several liquid-rich fluid inclusions (Th of 249° to 286°C; Tm of 0.0°C) in hydrothermal quartz crystals from 1,133-m depth in drill core from The Geysers geothermal area of northern California (Bargar, 1995). A few liquid-rich fluid inclusions (Tm of -0.9°C; Th of 215° and 241°C) in hydrothermal quartz crystals from the Miravalles geothermal area, Costa Rica, contain three irregular or rodlike, micrometer-size moving particles (Bargar and Fournier, 1988b). A hydrothermal quartz crystal in one drillhole sample from the Long Valley, California, geothermal area has two liquid-rich fluid inclusions (Th of 191° and 209°C; Tm of -0.3°C) that contain one and two rodlike moving particles, respectively (Bargar, 1995). Also, tiny threadlike and rodlike moving particles were observed in liquid-rich fluid inclusions (Th of 250° and 258°C; Tm of 0.0°C) from a fossil geothermal area near Mount Hood, Oregon (Bargar, Keith, and Beeson, 1993).

At the present time, the possibility that the moving particles within these fluid inclusions might be bacteria is highly speculative. The size and shapes of the particles are consistent with that of bacteria, however, attempts to determine by Raman (R.C. Burruss, U.S. Geological Survey, written communication, 1990) and infrared spectroscopy methods if organic material might be present within one of the Yellowstone particle-bearing fluid inclusions were inconclusive. Nonetheless, an inorganic origin for the particles is difficult to envision from a chemical viewpoint. First, a high degree of supersaturation would be required for the simultaneous nucleation of large numbers of particles, and thereafter some special circumstance would have to prevail that prevented growth of large crystals at the expense of the smaller particles. The fluid inclusions studied all have very low salinities which would tend to negate any supersaturation hypothesis. Also, moving particles were trapped in relatively few fluid inclusions; the vast majority of nearby contemporary inclusions do not contain the moving particles. Thus, it seems highly probable that the moving particles (whatever their origin-organic or inorganic) were carried by the fluids from which the quartz crystals precipitated. These particle-bearing fluids flowed through fractures in the rocks, and subsequently, were trapped within fluid inclusions of the precipitating quartz crystals.

If the moving particles within fluid inclusions in quartz crystals from Medicine Lake volcano, Yellowstone National Park, and elsewhere eventually are proven to be bacteria, they somehow must have become adapted to survival at temperatures above 200°C. The upper temperature limit for life to exist is not presently known but is believed to be between 110°C (hottest temperature at which bacteria have been conclusively identified) and about 200° or 250°C (Brock, 1985). On the other hand, thermophilic bacteria are reported to have been collected from a 350°C "black smoker" hot spring on the East Pacific Rise and grown in the laboratory at 250°C and elevated pressures (Baross and Deming, 1983). The results from this study were disputed

(Trent, Chastain, and Yayanos, 1984); however, Baross, Deming, and Becker (1984) provided additional amino acid analyses and other data in support of their contention that extreme thermophilic microorganisms do exist.

## AUTHOR

Keith Bargar received BA and MS degrees in Geology from San Jose State University. Prior to retiring from the U.S. Geological Survey at Menlo Park in 1995, he spent nearly 25 years studying hydrothermal alteration in geothermal areas of Wyoming, Oregon, California, Hawaii, and Central America. Fluid inclusion analyses were a very valuable tool in these investigations. Presently, he reads novels, swims, rides horses and is continually at his wife's beck and call.

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## REFERENCES

Anderson, C.A., 1941, Volcanoes of the Medicine Lake Highland, California: University of California Publications Bulletin of the Department of Geological Sciences, v. 25, no. 7, p. 347-422.

Aumento, F. and Liguori, P.E., 1986, Conceptual reservoir models through geoscientific investigations: Geothermics, v. 15, p. 799-806.

Bargar, K.E., 1992, Video-tape of bacteria-like moving particles in fluid inclusions from Medicine Lake volcano, northern California (abstract.): EOS, Transactions, American Geophysical Union, v. 73, no. 43, p. 640.

Bargar, K.E., 1995, Some fluid-inclusion measurements for geothermal drill holes in California, Nevada, El Salvador, and Russia: U.S. Geological Survey Open-File Report 95-826, 14 p.

Bargar, K.E. and Fournier, R.O., 1988a, Effects of glacial ice on subsurface temperatures of hydrothermal systems in Yellowstone National Park, Wyoming: Fluid-inclusion evidence: Geology, v. 16, p. 1,077-1,080.

Bargar, K.E. and Fournier, R.O., 1988b, Fluid-inclusion evidence for previous higher temperatures in the Miravalles geothermal field, Costa Rica: Geothermics, v. 17, no. 5/6, p. 681-693.

Bargar, K.E., Fournier, R.O. and Theodore, T.G., 1985, Particles in fluid inclusions from Yellowstone National Park-bacteria?: Geology, v. 13, p. 483-486.

Bargar, K.E. and Keith, T.E.C., 1993, Hydrothermal alteration in cores from geothermal drill holes at Medicine Lake volcano, northeastern California (abstract.): EOS, Transactions, American Geophysical Union, v. 74, no. 43, p. 688.

Bargar, K.E. and Keith, T.E.C., 1997, Estimated temperatures for geothermal drill holes at Medicine Lake Volcano, northeastern California, based on fluid inclusion and hydrothermal mineralogy studies: U.S. Geological Survey Open-File Report 97-716,116 p.

Bargar, K.E. and Keith, T.E.C., 1999, Hydrothermal mineralogy of core from geothermal drill holes at Newberry volcano, Oregon: U.S. Geological Survey Professional Paper 1578, 92 p.

Bargar, K.E., Keith, T.E.C. and Beeson, M.H., 1993, Hydrothermal alteration in the Mount Hood area, Oregon: U.S. Geological Survey Bulletin 2054, 70 p.

Baross, J .A. and Deming, J.W., 1983, Growth of 'black smoker' bacteria at temperatures of at least 250°C: Nature, v. 303, p. 423-426.

Baross, J.A., Deming, J.W., and Becker, R.R., 1984, Evidence for microbial growth in high-pressure, high-temperature environments *in* Klug, M. and Reddy, C.A., editors, Current Perspectives in Microbial Ecology: American Society for Microbiology, Washington D.C., p. 186-195.

Blackwell, D.D., Steele, J.L., Frohme, M.K., Murphey, C.F., Priest, G.R. and Black, G.L., 1990, Heat flow in the Oregon Cascade Range and its correlation with regional gravity, Curie point depths, and geology: Journal of Geophysical Research, v. 95, no. B12, p. 19,475-19,493.

Bodnar, R.J. and Sterner, S.M., 1984, Synthetic fluid inclusions in natural quartz I; compositional types synthesized and applications to experimental geochemistry: Geochimica et Cosmochimica Acta, v. 48, p. 2,659-2,668.

Brock, T.D., 1985, Life at high temperatures: Science, v. 230, p. 132-138.

Cavarretta, G., Gianelli, G. and Puxeddu, M., 1982, Formation of authigenic minerals and their use as indicators of the physicochemical parameters of the fluid in the Larderello-Travale geothermal field: Economic Geology, v. 77, p. 1,071-1,084.

Donnelly-Nolan, J.M., 1988, A magmatic model of Medicine Lake volcano, California: Journal of Geophysical Research, v. 93, no. B5, p. 4,412-4,420.

Donnelly-Nolan, J.M., 1990, Geology of Medicine Lake volcano, northern California Cascade Range: Geothermal Resources Council Transactions, v. 14, pt. II, p. 1,395-1,396.

Donnelly-Nolan, J.M., Champion, D.E., Miller, C.D., Grove, T.L., and Trimble, D.A.,1990, Post-11,000-year volcanism at Medicine Lake volcano, Cascade Range, northern California: Journal of Geophysical Research, v. 95, no. B12, p. 19,693-19,704.

Donnelly-Nolan, J.M., and Nolan, K.M., 1986, Catastrophic flooding and eruption of ash-flow tuff at Medicine Lake volcano, California: Geology, v. 14, p. 875-878.

Elder, J., 1981, Geothermal Systems: London, Academic Press, 508 p.

Elders, W.A., Hoagland, J.R., McDowell, S.D. and Cobo, J. M., 1979, Hydrothermal mineral zones in the geothermal reservoir of Cerro Prieto: Geothermics, v. 8, p. 201-209.

Fridleifsson, G.O., 1991, Hydrothermal systems and associated alteration in Iceland: Geological Survey of Japan Report 277, p. 83-90.

Holland, H.D. and Malinin, S.D., 1979, The solubility and occurrence of non-ore minerals *in* Barnes, H.L., editor, Geochemistry of Hydrothermal Ore Deposits, New York, John Wiley, p. 461-508.

Honda, S. and Muffler, L.J.P., 1970, Hydrothermal alteration in core from research drill hole Y-1, Upper Geyser Basin, Yellowstone National Park, Wyoming: American Mineralogist, v. 55, p. 1,714-1,737.

Horton, D.G., 1985, Mixed-layer illite/smectite as a paleotemperature indicator in the Amethyst vein system, Creed district, Colorado, USA: Contributions to Mineralogy and Petrology, v. 91, p. 171-179.

Hulen, J.B and Nielson, D.L., 1986, Hydrothermal alteration in the Baca Geothermal System, Redondo Dome, Valles Caldera, NM: Journal of Geophysical Research, v. 91, p. 1,867-1,886.

Jakobsson, S. P. and Moore, J.G., 1986, Hydrothermal minerals and alteration rates at Surtsey Volcano, Iceland: Geological Society of America Bulletin, v. 97, p. 648-659.

Keith, T.E.C., White, D.E. and Beeson, M.H., 1978, Hydrothermal alteration and self-sealing in Y-7 and Y-8 drill holes in northern part of Upper Geyser Basin, Yellowstone National Park, Wyoming: U.S. Geological Survey Professional Paper 1054-A, 26 p.

Kristmannsdóttir, Hrefna, 1975, Types of clay minerals in hydrothermally altered basaltic rocks, Reykjanes, Iceland: Jökull, v. 26, p. 30-39.

Kristmannsdóttir, Hrefna, 1979, Alteration of basaltic rocks by hydrothermal activity at 100-300°C *in* Mortland, M.M. and Farmer, V.C., editors, International Clay Conference 1978, Amsterdam, Elsevier, p. 359-367.

Kristmannsdóttir, Hrefna, and Tómasson, Jens, 1978, Zeolite zones in geothermal areas of Iceland *in* Sand, L.B. and Mumpton, F.A., editors, Natural Zeolites, Occurrence, Properties, Use: New York, Pergamon, p. 277-284.

Leach, T.M., Wood, C.P. and Reyes, A G., 1983, Geology and hydrothermal alteration of the Tongonan geothermal field, Leyte, Republic of the Philippines (abstract): Fourth International Symposium on Water-Rock Interaction, Misasa, Japan, 29 August-3 September, 1983, p. 275-278.

Liou, J.G., Maruyama, Shigenori and Cho, Moonsup, 1987, Very low-grade metamorphism of volcanic and volcaniclastic rocks-mineral assemblages and mineral facies *in* Frey, Martin, editor, Low temperature metamorphism: New York, Chapman and Hall, p. 59-113.

McDowell, S.D. and Paces, J.B., 1985, Carbonate alteration minerals in the Salton Sea geothermal system, California, USA: Mineralogical Magazine, v. 49, p. 469-479.

Potter, R.W., II, Clynne, M.A. and Brown, D.L., 1978, Freezing point depression of aqueous sodium chloride solutions: Economic Geology, v. 73, p. 284-285.

Roedder, Edwin, 1984, Fluid inclusions *in* Ribbe, P.H., editor, Reviews in Mineralogy, v.12: Washington, D.C., Mineralogical Society of America, 644 p.

Taguchi, S. and Hyashi, M., 1982, Application of the fluid inclusion thermometer to some geothermal fields in Japan: Geothermal Resources Council Transactions, v. 6, p. 59-62.

Taguchi, S., Hayashi, M., Mimura, T., Kinoshita, Y., Gokou, K. and Abe, I., 1984, Fluid inclusion temperature of hydrothermal minerals from the Kirishima geothermal area, Kyushu, Japan: Journal of the Japan Geothermal Energy Association, v. 21, no. 2, p. 119-129.

Tómasson, Jens and Kristmannsdöttir, Hrefna, 1972, High-temperature alteration minerals and thermal brines, Reykjanes, Iceland: Contributions to Mineralogy and Petrology, v. 36, p. 123-137.

Trent, J.D., Chastain, R.A. and Yayanos, A.A., 1984, Possible artifactual basis for apparent bacterial growth at 250°C: Nature, v. 307, p. 737-740.

White, D.E., Hutchinson, R.A. and Keith, T.E.C., 1988, The geology and remarkable thermal activity of Norris Geyser Basin, Yellowstone National Park, Wyoming: U.S. Geological Survey Professional Paper 1456, 84 p.