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The Fluid Inclusion And Mineralogic Record Of The Transition From Liquid- To Vapor-Dominated Conditions In The Geysers Geothermal System, California

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ABSTRACT

Fluid-inclusion measurements and textural relationships demonstrate that coarse-grained quartz and calcite from the upper part of The Geysers thermal system formed during the transition from liquid-dominated conditions to the modern vapor-dominated regime. The most diagnostic characteristics of these transition assemblages are: 1) evidence of quartz dissolution; 2) contemporaneous trapping of high-and low-salinity waters representing liquids dominated by boiled reservoir fluid and condensate respectively; 3) the presence of solid inclusions in quartz of bladed, but commonly corroded, calcite; and 4) the common occurrence of multiple generations of primary, CO_2-bearing vapor-rich inclusions. Corrosion of the quartz and calcite occurred as condensate, generated at the top of the developing heat pipe, percolated downward. These minerals were subsequently precipitated when the descending fluids boiled.

INTRODUCTION

The Geysers is a long-lived hydrothermal system that developed during the emplacement of a hypabyssal granitic intrusion 1 to 1.5 million years ago (Dalyrimple, 1992; Hulen et al., 1997). Although The Geysers is now vapor-dominated, geochemical and petrologic investigations demonstrate that the modern steam reservoir formed from a much larger liquid-dominated system that may have persisted in the central Geysers until 0.28 Ma (Moore and Gunderson, 1995; Shook, 1995; Hulen et al., 1997). This transition may have been triggered by catastrophic boiling and venting that accompanied seismic activity.

In this paper we describe the conditions associated with the transition from a liquid to a vapor-dominated regime. The paper is divided into two parts. In the first part, the occurrence, temperatures, and compositions of fluid inclusions associated with intergrown quartz and bladed calcite are presented. We will demonstrate that this "boiling assemblage", which has been encountered primarily above the modern steam reservoir (Sternfeld and Walters, 1989), formed during the initial development of the vapor-dominated system. The quartz crystals are unusual because they host numerous primary vapor-rich inclusions filled with a low-density CO_2-bearing fluid. To our knowledge, this is the first time the results of microthermetric measurements on such fluid inclusions have been reported. In the second part of the paper, the fluid-inclusion measurements and mineral textures are incorporated into a conceptual model that explains the origin and characteristics of this mineral assemblage.

MINERAL RELATIONSHIPS

General Features and ***Distribution***

The occurrence of large, terminated quartz crystals in highly altered "bleached" metagraywacke containing abundant bladed to rhombohedral calcite, pyrite, pseudohexagonal pyrrhotite, potassium feldspar, and clays was first reported by Sternfeld and Walters (1989). They suggested that this assemblage represented a complex history of boiling and alteration by acidic condensate. Sternfeld and Walters (1989) observed this unique assemblage in 15 of the 19 wells that had been drilled in the northwest by GEO Operator Corporation, and based on publically available drilling records, they concluded that it may

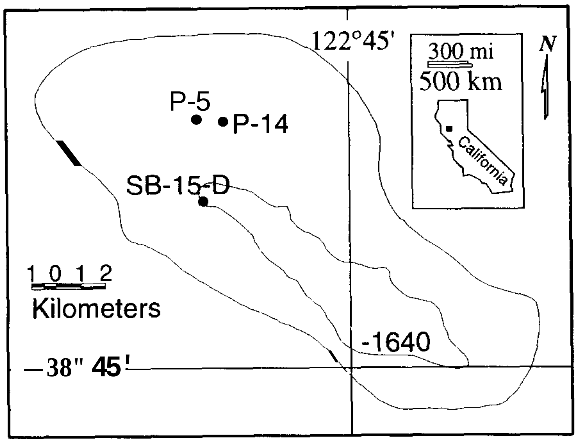

Fig. 1. Location map of The Geysers and the samples studied in this investigation. The top of the steam reservoir at an elevation of - 1640 m (relative to mean sea-level) is shown for reference.

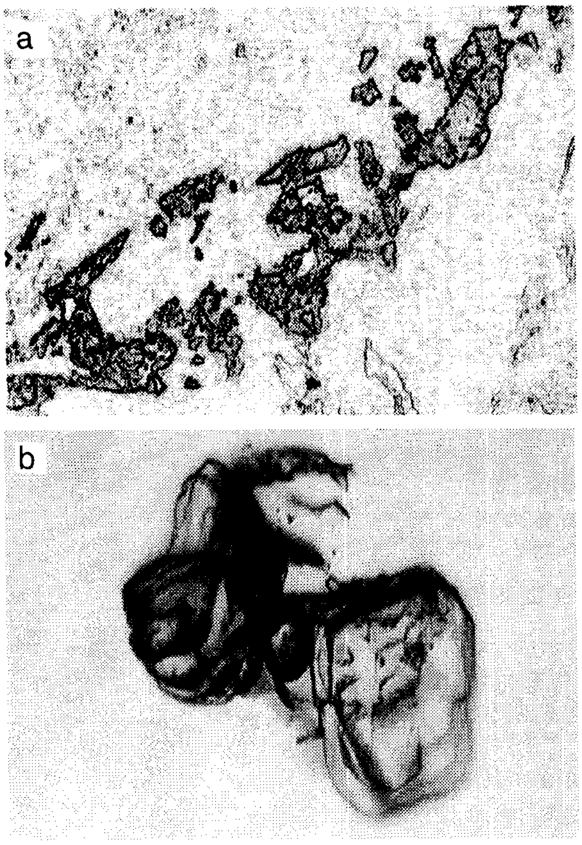

Fig. 2. Solid inclusions in quartz. (a) Bladed and corroded calcite encapsulated in quartz from SB-15-D-315 m. The edges of the calcite have been highlighted for visibility. Field of view is 0.94 mm. (b) Rhombohedral calcite and chlorite in quartz from Prati-14. **A** primary fluid inclusion containing a large vapor bubble can be seen between the two crystals. Field of view is 0.38 mm.

be a common feature of The Geysers. However, no detailed descriptions were available for the occurrences outside of the northwest portion of the field.

In this study, we present fluid inclusion and textural data on quartz from three wells, SB-15-D-289 to 472 m, Prati-5-1271 m, and Prati-14-1537 m (Fig. 1). The crystals contain a variety of solid inclusions. Calcite is the most common, but sheet silicates, and in SB-15-D, actinolite and epidote have been found. Calcite occurs as rhombohedral and bladed crystals within growth zones and as coarse-grained aggregates of bladed crystals (Fig. 2). The occurrence of calcite in the growth zones is particularly significant because it demonstrates that deposition was contemporaneous with quartz. The bladed calcite is commonly corroded (Fig. 2a). Textural relationships suggest that the deposition of chlorite in SB-15-D and in Prati-14 (Fig. 2b) was also contemporaneous with quartz, but that the epidote and actinolite represent earlier periods of mineralization.

Several of the quartz crystals from SB-15-D display distinct growth zoning defined by three. dimensional arrays of fluid inclusions. This zoning is best developed in quartz from 430 m (Fig. 3). Severe scalloping of the crystal face due to corrosion is clearly evident in this photomicrograph. Such corrosion may be a common, but difficult, feature to observe in quartz crystals that do not display obvious growth zoning.

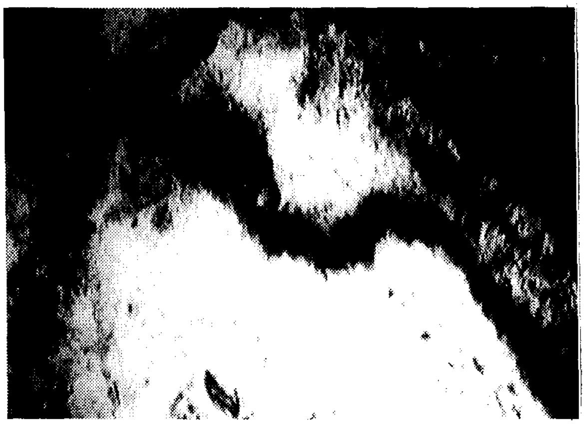

Fig. 3. Corroded growth zone, outlined by fluid inclusions, within the interior of quartz from SB-15-D-430 m. Field of view is 2.2 mm.

FLUID-INCLUSION PETROGRAPHY

Vapor-rich inclusions are common in all samples, and in some are the dominant fluid-inclusion type. Most are secondary in origin and too small to

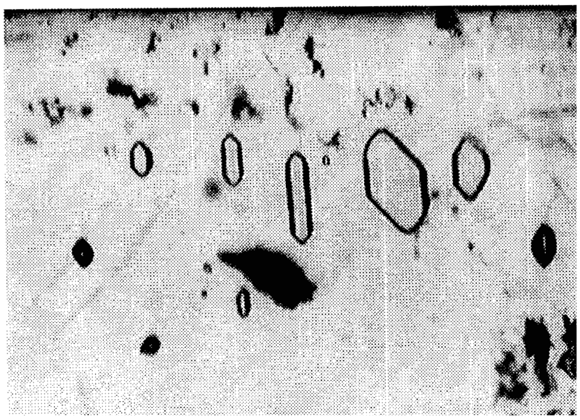

Fig. 4. Primary vapor-rich inclusions in quartz from Prati-14.

allow measurement of phase changes during heating and cooling. The larger vapor-rich inclusions, with maximum dimensions of more than several tens of microns, can be divided into two types on the basis of their compositions and habit. Fourier Transform Infrared (FTIR) spectroscopy indicates that type I vapor-rich inclusions are water-rich. These inclusions were found at a depth of 315 m in SB-15-D. All of the type I inclusions that were identified were secondary in origin, irregular in shape, and necked. Although no liquid-rich inclusions are associated with them, the larger vapor-rich inclusions contain small amounts of a moderate-salinity liquid that was accidentally trapped as the fluid boiled.

Type II vapor-rich inclusions contain appreciable CO_2 and were identified optically and by FTIR spectroscopy in samples from depths below 430 m in SB-15-D and in Prati-5 and Prati-14 (Fig. 4). Large, primary type II inclusions are distinguished from type I inclusions by their tendency to develop negative crystal shapes. A spindle stage was utilized to confirm the origin of these inclusions and determine their dimensions and orientations (Anderson et al., 1993). Although these measurements demonstrate that the inclusions formed primarily on the rhombohedral faces of the quartz crystals some were also trapped on the prism faces. The majority of the vapor-rich inclusions are tabular in shape and elongated perpendicular to the "C" axis of the crystal. Less commonly, the inclusions have a distinct triangular shape due to trapping on rhombohedral faces of skeletal crystals. Although inclusions with maximum dimensions of up to 850 microns have been observed, lengths ranging from several tens to several hundreds of microns are more common.

Liquid-rich inclusions recording a wide range of salinities and temperatures were found in the samples. The majority are secondary or pseudosecondary in origin, occurring along short, curved, healed fractures. Spindle stage studies of secondary planes in SB-15-D-459 m, which appear typical, indicate a preference for fracturing parallel to the "C" axis. Most primary inclusions define growth zones or occur at the interface between the quartz and solid inclusions of calcite or chlorite. Rarely, they occur as large isolated cavities.

FLUID-INCLUSION SYSTEMATICS

SB-15-D

More than 575 quartz-hosted liquid-rich inclusions from 9 depth intervals were studied. Homogenization temperatures and salinities ranged from 188" to 304°C and from 0.0 to 3.7 weight percent NaCl equivalent. The results of these heating and freezing measurements are summarized in Figure 5.

Primary liquid-rich fluid inclusions were observed in all quartz crystals containing primary type II vapor-rich inclusions. The homogenization temperatures of these liquid-rich inclusions ranged from 271" to 287°C at 430 m; 244° to 249°C at 459 m, and 241" to 289°C at 472 m. Because the data suggest these inclusions were trapped in a boiling environment, the homogenization temperatures also represent the trapping temperatures. With the exception of one inclusion from 472 m, which yielded a salinity of 0.5 weight percent NaCl equivalent, all of the primary liquid-rich inclusions yielded salinities of 0.0 weight percent NaCl equivalent.

Few primary liquid or vapor-rich inclusions were found in quartz crystals from depths shallower than 430 m. However measurements on secondary inclusions suggest that the quartz crystals formed at similar or slightly higher temperatures than those at deeper depths. Samples from 289 and 378 m indicate minimum formation temperatures of 304°C, whereas those from other intervals suggest trapping temperatures of at least 248" to 278°C.

Two phase changes were measured in the vapor-rich inclusions. Secondary type I inclusions from 315 m yielded homogenization temperatures (to the vapor phase) of 220" and 230°C and a single salinity measurement of 1.9 weight percent NaCl equivalent. Temperatures of CO_2 sublimation and ice-melting temperatures were determined on primary type II

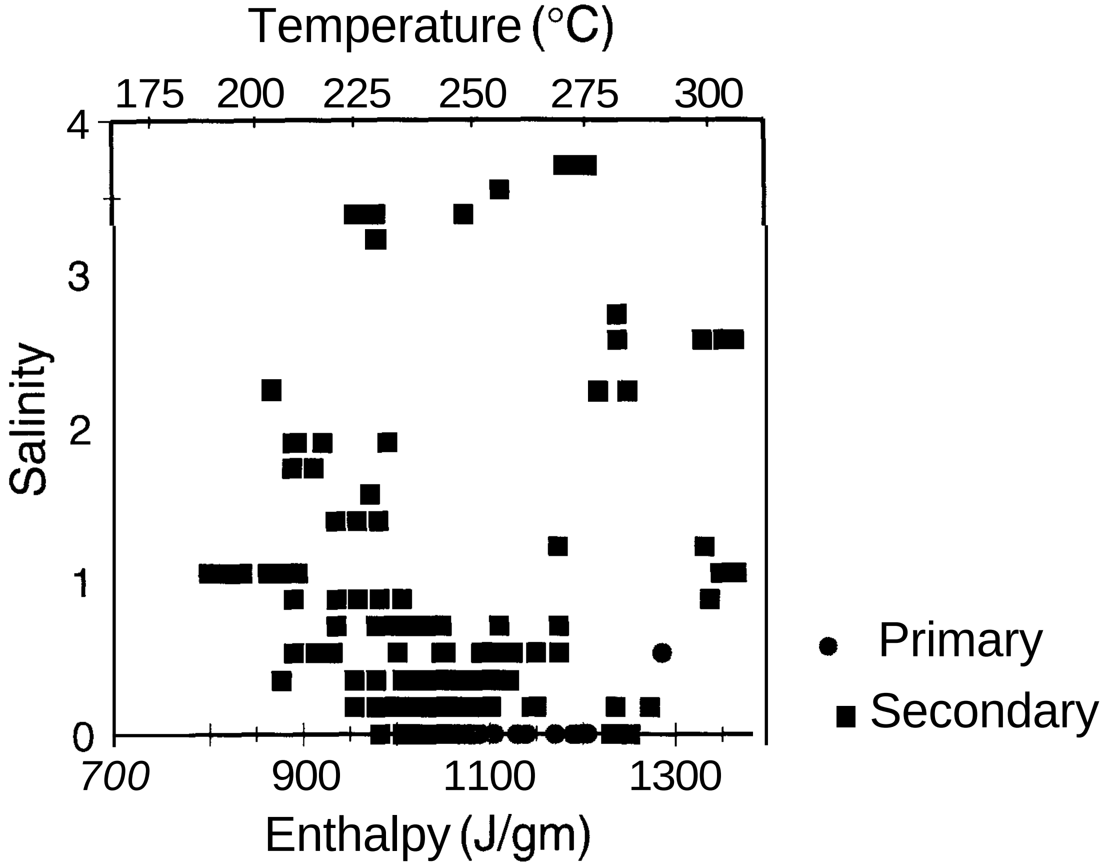

Fig. 5. Enthalpy-salinity relationships for inclusions in SB-I5-D. Salinities are in weight percent NaCl equivalent.

inclusions (Fig. 6). Sublimation temperatures ranged from -92.9" to -87.0°C whereas salinities varied from 0.0 to 0.4 weight percent NaCl equivalent.

Pruti-5 and 14

Quartz from Prati-14 appears to have formed under conditions that were similar to those in SB-15-D. Homogenization temperatures and salinities of liquid-rich fluid inclusions in a single quartz crystal ranged from 223" to 285°C and 0.0 to 2.4 weight percent NaCl equivalent (Fig. 7). Primary fluid inclusions, which are associated with calcite or flakes of chlorite, formed relatively late. These inclusions record temperatures between 243" and 254°C and salinities of 0.0 *to* 0.4 weight percent NaCl equivalent.

Type II vapor-rich inclusions in Prati-14 quartz displayed the same phase changes as those in SB-15-D. Sublimation temperatures ranged from -56.7° to -58.4°C. However, the final ice-melting temperatures of these inclusions document two distinct groups of salinities; one at 0.0 weight percent NaCl equivalent and a second with salinities between 1.6 and 2.4 weight percent NaCl equivalent. There is no apparent correlation between the sublimation temperatures and salinities of the inclusions.

No primary liquid-rich fluid inclusions were observed in quartz from Prati-5. Secondary inclusions yielded homogenization temperatures that ranged from 192" to 233°C and salinites that varied from 0.2 to 1.6 weight percent NaCl equivalent. Slightly more saline fluids were trapped in the associated calcite. These inclusions recorded homogenization temperatures that ranged from 188" to 221°C and salinities of 0.9 to 2.7 weight percent NaCl equivalent.

Phase changes in a single primary type II inclusion from Prati-5 suggest higher partial pressures of CO_2 than in the other samples. In contrast to inclusions from Prati-14 and SB-15-D, the final phase to dissociate was C02 clathrate at a temperature of +1.8°C. This inclusion yielded a CO_2 sublimation temperature of -57.6°C. Because some of the of CO_2 is incorporated into clathrate during the initial freezing of the inclusion, this sublimation temperature

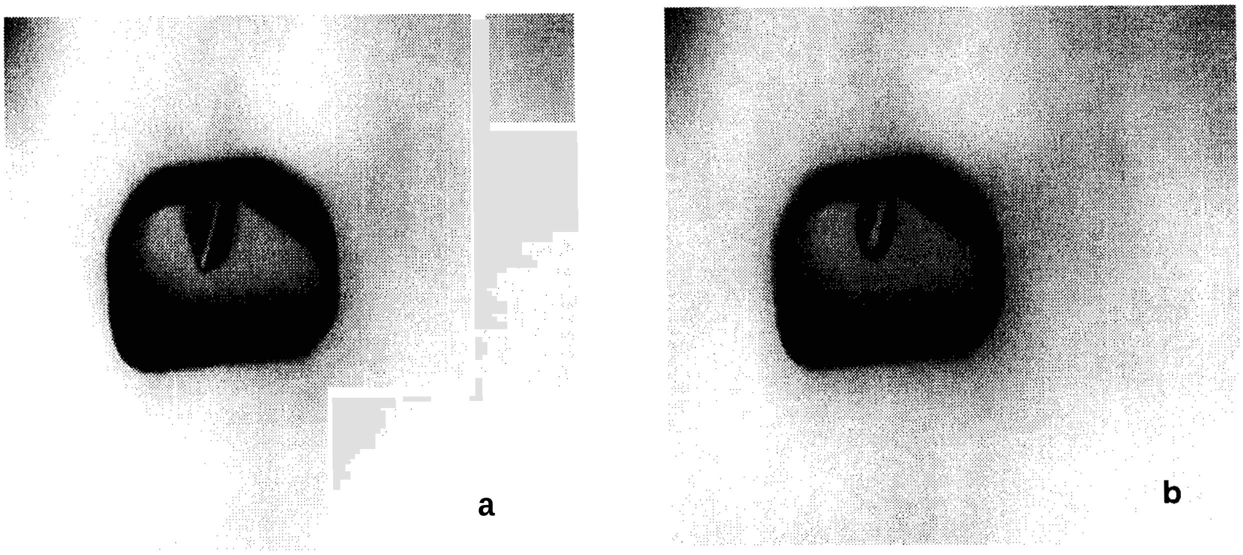

Fig. 6. Photomicrographs of a vapor-rich inclusion from Prati-5 showing the sublimation of solid CO_2. The inclusion is 115 microns across. (a) **A** single crystal of CO_2 at -93°C. The inclusion was initially cooled to nucleate solid CO_2, warmed until a single crystal remained, and then cooled to grow the crystal shown here. (b) Remnants of the crystal shown in 6a after warming to -70°C. Sublimation was complete at -57°C. No liquid CO_2 formed during this process.

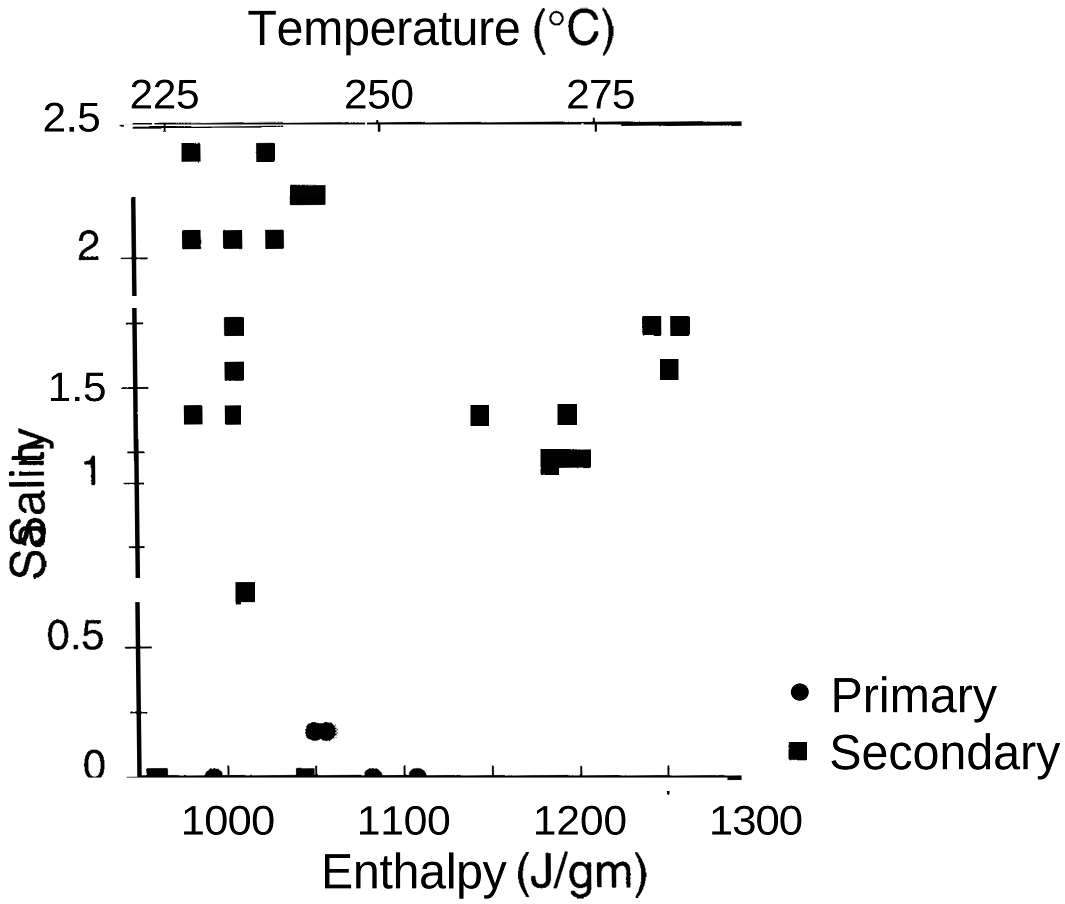

Fig. 7. Enthalpy-salinity relationships for inclusions in Prati-14. Salinities are in weight percent NaCl equivalent.

must reflect a minimum CO_2 pressure. A gas analysis of quartz from the same depth yielded 50.6 mole percent CO_2, 8.3 mole percent CH_4, 37.0 mole percent H_2O, and minor amounts of other gases (Moore et al., 1997).

DISCUSSION

Quartz is the most common hydrothermal mineral in the secondary assemblages at The Geysers. Fluid-inclusion trapping temperatures indicate that it was deposited at temperatures ranging from >440° to approximately 245°C (Moore and Gunderson, 1995; this study).

Our observations suggest that the quartz crystals from Prati-5, Prati-14, and SB-15-D display textures and features that are not found within the main portion of the modern steam reservoir. Quartz crystals from these wells are distinguished by: 1) their size; 2) multiple generations of primary CO_2-bearing vapor-rich inclusions; 3) primary low-salinity liquid-rich inclusions; 4) evidence of dissolution during mineralization; and 5) contemporaneous deposition of calcite, which is often bladed and corroded. The host rocks are commonly bleached and contain late-stage clays and dissolution textures produced by acidic condensate (Sternfeld and Walters. 1989; Moore and Gunderson, 1995).

Boiling and the Timing of Mineralization

The occurrence of primary vapor-rich inclusions and textures demonstrating contemporaneous deposition of quartz and calcite at all three localities studied provide unequivocal evidence of mineralization in a boiling environment. The fluid-inclusion data from SB-15-D suggest that mineralization may have occurred over a relatively large temperature interval, from >304°C to at least 241°C (the minimum primary inclusion temperatures). The present temperature at the top of the steam reservoir in SB-15-D is about 230°C (Hulen et al., 1997).

The timing of this mineralization was deduced from $^{40}Ar/^{39}Ar$ age spectra obtained on hydrothermal adularia from SB-15-D-472 m by Hulen et al. (1997). They proposed three time-temperature models, with the most likely suggesting that temperatures declined rapidly from about 330" to 245°C between 0.28 and 0.25 Ma. Based on the correspondence between this temperature range and the temperatures recorded by the fluid inclusions, Hulen et al. (1997) concluded that the precipitous cooling must have occurred in response to boiling during the onset of vapor-dominated conditions in the central Geysers.

A Generalized Model of Mineralization in a Developing Vapor-Dominated Heat Pipe

Boiling is a ubiquitous process in hydrothermal systems and is the dominant control on fluid temperatures and pressures in epithermal environments (Henley et al., 1985). During the boiling of a liquid-filled fracture, the loss of gases from the liquid and the increase in the concentration of dissolved silica due to separation of steam can result in the precipitation of various minerals, including both quartz and calcite. Under closed-system (adiabatic) boiling, increases in the salinity of the residual fluid will be relatively minor. For example, the salinity of a fluid that starts boiling at depth at 300°C and discharges at the surface at a temperature of 100°C will increase by 25 to 30 percent (Simmons and Browne, 1997). In contrast, separation of steam under open-system boiling can produce large increases in the salinity of the fluid, and it has been suggested that this is the mechanism responsible for locally generating saline fluids trapped in inclusions in the Valles Caldera and Ohaaki-Broadlands geothermal systems (Sasada and Goff, 1995; Simmons and Browne, 1997). However, at temperatures below 300°C, neither open-or closed-system boiling will produce a residual fluid undersaturated in silica (Fournier, 1985) and thus, these processes alone will not account for the corrosion of quartz observed at The Geysers.

In contrast to liquid-dominated hydrothermal systems, vapor-dominated systems represent an ideal environment for trapping vapor-rich inclusions and generating fluids that are undersaturated in quartz. The behavior and origins of vapor-dominated systems, which can be modeled as heat pipes (Pruess, 1985; Shook, 1995), were described by White et al. (1971) and Truesdell and White (1973). They showed that vapor-dominated systems develop when discharge exceeds recharge.

The initial response of the reservoir to venting is a drop in pressure and a subsequent drop in the water level as the liquid boils down. As the vapor-dominated reservoir is developing, the rock is left with a considerable amount of heat and may remain above the saturation temperature for a period of time. The difference between the rock temperature and the saturation temperature will increase downward because the temperature-depth gradient in a vapor-dominated system is much less than that of a liquid-dominated system. Liquid that results from steam condensation at the reservoir-cap interface, which functions as a heat sink, will flow downward until the rock temperature becomes higher than the saturation temperature and the liquid boils. This process removes heat and cools the rock to the saturation temperature. **As** the heat pipe approaches steady-state conditions, the salinity of the reservoir liquid will increase with time as a result of steam loss.

The condensate that forms at the top of the developing heat pipe will be a low salinity (essentially nil), slightly acidic water containing variable concentrations of dissolved gases. These fluids will be strongly undersaturated in silica and carbonate. Thus, the downward percolation of the condensate will result in corrosion of calcite and quartz and the formation of clay minerals as the fluids approach equilibrium with the surrounding wall rocks. Within actively convecting hydrothermal systems, fluids will equilibrate with quartz within days to weeks (Rimstidt and Barnes, 1980). Because quartz saturation is readily achieved, it follows that the circulation paths of the undersaturated fluids must be relatively short and that dissolution of quartz will occur close to the site of condensate formation.

*Evolution **of** the Hydrothermal **Fluids***

Essentially all of the mineralogic and geochemical features outlined in the proceeding section can be recognized in the mineral textures and fluid-inclusion record contained in Prati-14 and SB-15-D. The evolution of the fluids in the single crystal studied from Prati-14 is illustrated in Figure 7. The data suggest that the quartz was deposited by a fluid with a salinity of approximately 1.5 weight percent NaCl equivalent and a temperature of at least 285°C. Subsequent changes in temperature without a significant change in the composition of the fluids implies that the fluids cooled conductively to 260°C. Condensate, which is distinguished by its high homogenization temperature and low salinity (Moore and Gunderson, 1995), first appears in the inclusions between 255" and 260°C. Thus, boiling must have been initiated at somewhat higher temperatures. Although high-salinity waters representing the boiled reservoir fluids are not found in the fluid-inclusion record at these temperatures, they were trapped between 240" and 245°C. These fluids had salinities of about 2.5 weight percent NaCl equivalent.

As the temperatures declined to approximately 235°C, fluids with intermediate compositions were trapped in the secondary liquid-rich inclusions. Fluids with similar compositions were trapped in the primary vapor-rich inclusions, but the trapping temperatures of these inclusions could not be determined. The broad range of compositions (0.7 to 2.4 and weight percent NaCl equivalent in the liquid-rich inclusions; 1.6 to 2.4, and 0.0 weight percent in the vapor-rich inclusions), suggests that the fluids represent mixtures of the boiled liquids and condensate, with the boiled fluids dominating in most inclusions. One possible mechanism for the formation of fluids with similar temperatures but variable compositions is the imbibition of condensate into small, largely isolated fractures that also contained reservoir water. Depending on conditions, these high-salinity fluids could have been accidentally trapped in vapor-rich inclusions after they reentered the heat pipe and boiled, or they could have been trapped in liquid-rich inclusions in portions of the heat pipe that were not superheated.

Significantly, enthalpy-salinity relationships from SB-15-D display a similar geometry, suggesting that similar processes affected the evolution of the fluids in both parts of the field. The variations in the compositions of the highest temperature fluids, which were trapped in secondary inclusions, indicate that boiling was already occurring at 304°C. The differences in the apparent salinities of these high-temperature fluids may reflect both increasing salinity due to formation of steam and the loss of dissolved gases. In this well, the initial development of the heat pipe appears to have occurred at much higher temperatures than it did in the northwest, as indicated by the trapping of condensate at about 290°C in primary inclusions at 472 m and at 280" to 285°C at 430 m. Dissolution of quartz at 430 m, followed by the trapping of fluid inclusions recording temperatures of 271° to 283°C provides unambiguous evidence of this environment. The boiled, residual fluids, which were trapped at slightly lower temperatures, record salinities of 3.7 weight percent NaCl equivalent. Although small amounts of the boiled fluids apparently mixed with the condensate throughout the mineralization process, as indicated by the variable salinities of the inclusions, extensive mixing did not occur until temperatures had declined to 230°C.

SUMMARY

The results of this study demonstrate that the transition from liquid to vapor-dominated conditions at The Geysers is clearly recorded by fluid inclusions and mineral textures found in Prati-5, -14, and SB-15-D. $^{40}Ar/^{39}Ar$ spectra obtained on adularia from the central Geysers indicates that this transition occurred at about 0.28 Ma, more than 0.8 million years after the initial development of the thermal system (Hulen et al., 1997). **As** a heat pipe developed in response to venting and boiling, slightly acidic condensate formed at the base of the cap rock and drained downward, dissolving quartz, calcite, and other minerals present along the vein walls. Deposition of coarse-grained quartz and bladed calcite occurred when the condensate or mixtures of condensate and brine encountered regions of the fracture zones that were still superheated and boiled. Growth of the quartz was episodic, with periods of rapid growth resulting in the formation of skeletal crystals that trapped primary vapor-rich inclusions. The formation of late-stage clays, which is commonly associated with this quartz-calcite assemblage (Sternfeld and Walters, 1989), are the result of continued downward percolation of the acid condensate.

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