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Thermal and Chemical Evolution of The Geysers Geothermal System, California

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ABSTRACT

Fluid inclusions and mineral assemblages provide a record of the thermal and chemical changes that occurred during the evolution of The Geysers geothermal system. The data document the presence of an extensive liquid-dominated geothermal system that developed in response to felsite intrusion and its evolution to a vapor-dominated regime. Temperatures within the early liquid-dominated system ranged from 175°C at a distance of 7200 feet from the felsite to more than 350°C near the contact while salinities varied from 5 equivalent weight percent NaCl (at a distance of 5500 feet) to more than 26 weight percent NaCl. As temperatures around the felsite declined, the liquid-dominated system collapsed upon itself. Downward migration of the low salinity waters resulted in dilution of the fluids present in regions now occupied by the caprock and normal vapor-dominated reservoir. In contrast, dilution was minor in rocks now hosting the high-temperature vapor-dominated reservoir. This suggests that low permeabilities are the primary reason for the development of the high-temperature reservoir.

Boiling within the caprock produced late-stage veins of calcite and quartz. As the fluid boiled off, condensate was trapped as low salinity fluid inclusions. Within the main body of the reservoir, a liquid phase with salinities of up to 7 equivalent weight percent NaCl persisted to temperatures between 250° and 270°C. However, except for the presence of vapor-rich inclusions, little evidence of boiling within the reservoir rocks was preserved.

INTRODUCTION

Although the pioneering work of White and others (1971) provided the basic framework needed for understanding the origin of The Geysers steam field, many of their hypotheses have remained untested and new questions have been raised as a result of recent field developments. For example, little direct information is available on the composition of the early fluids, the nature of the reservoir boundaries, and the differences between the normal 240°C vapor-dominated reservoir (NVDR) and the underlying high-temperature vapor-dominated reservoir (HTVDR).

Answers to these and other questions require information on the compositional and thermal evolution of the system. Sternfeld (1981) and Moore and others (1989) used fluid inclusions in cuttings to characterize the early hydrothermal system that developed above the present steam reservoir. These studies demonstrated that temperatures had been significantly higher in the past and that the salinities of the fluids were on the order of several weight percent. In this paper we expand significantly on the earlier fluid inclusion investigations. More than a thousand new measurements have been made on core and cuttings samples from 8 Calpine Corp. and 10 Unocal Geothermal Division wells (Fig. 1; Table 1). These new data are combined with the existing information to characterize the conditions within the caprock, the NVDR, and the HTVDR during the evolution of The Geysers geothermal system.

MINERALOGIC RELATIONSHIPS

The rocks at the Geysers show evidence of two distinct periods of alteration (Lambert, 1976; Sternfeld and Elders, 1982; Walters and others, 1988; Moore and others, 1989; Hulen and others, 1991). The oldest event is the result of high-pressure, low-temperature regional metamorphism during Franciscan time (Late Mesozoic). This metamorphism produced, in addition to phases such as lawsonite and pumpellyite, widespread veins of calcite and quartz. The second period of alteration is related to the intrusion of a felsic, composite Plio-Pleistocene pluton beneath The Geysers (Schriener and Suemnicht, 1980; Thompson, 1989). This pluton, which is commonly referred to as the felsite, produced calc-silicate and boron-bearing mineral assemblages. In this investigation, five major vein assemblages were studied. With increasing distance from the pluton, the key vein assemblages are:

1: tourmaline-biotite-actinolite-clinopyroxene-epidote-quartz-potassium feldspar;

2: biotite-actinolite-clinopyroxene-epidote-quartz-potassium feldspar;

3: actinolite-ferroaxinite-epidote-quartz-prehnite-potassium feldspar;

4: epidote-chlorite-quartz-potassium feldspar;

5: quartz-potassium feldspar-calcite.

In addition to these minerals, Hulen and others (1991) have identified prehnite in assemblage 4 and late-stage wairakite that postdates assemblage 5.

As the system cooled, the early veins were crosscut by veins typical of greater distances from the felsite. The extent of this cooling is documented in the fluid inclusion data discussed below. Assemblages 1 through 4 occur within highly contorted metamorphosed quartz-calcite veins of Franciscan age and in younger crosscutting fractures. Within the Franciscan veins, the calc-silicate minerals form small, commonly porous aggregates that replace preexisting calcite (Hulen and others, 1991).

Calcite is much more abundant in the caprock than it is in the NVDR (Sternfeld and Elders, 1982; Thompson and Gunderson, 1989; Sternfeld, 1989; Gunderson, 1990; Hulen and others, 1991). Within the caprock, calcite occurs as both a late-stage mineral

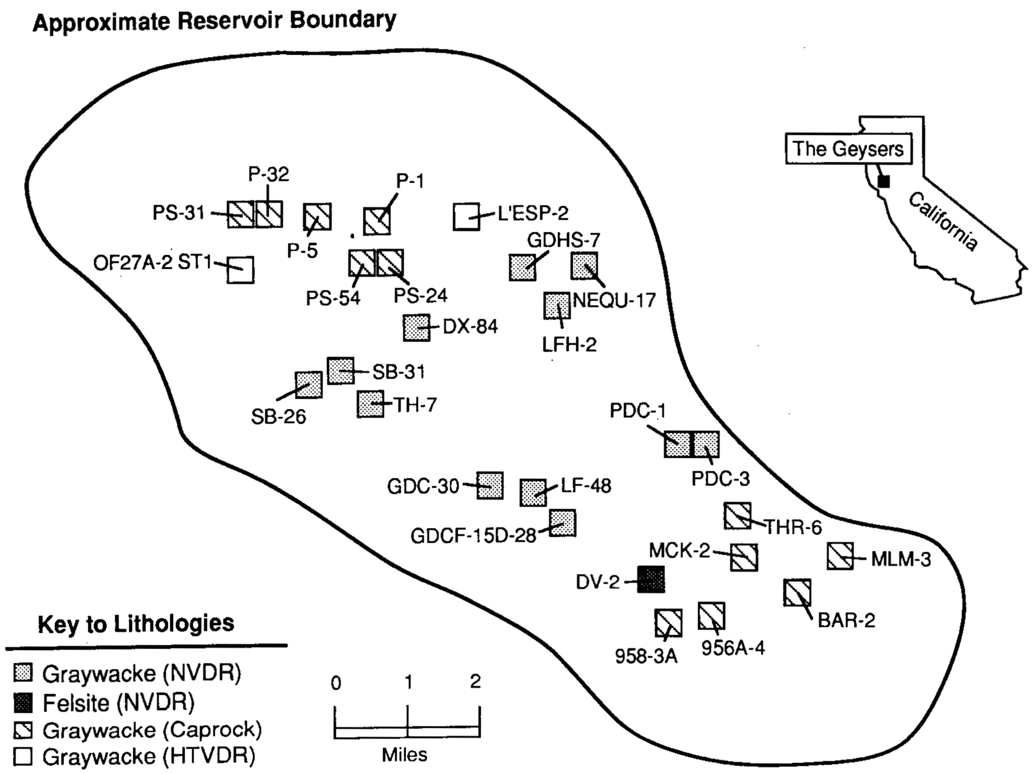

Fig. 1. Locations and lithologies of the samples studied. Data from LFH-2 and SB-26 are from Sternfeld (1981). Abbreviations: NVDR = normal vapor-dominated reservoir; HTVDR = high-temperature vapor dominated reservoir.

Name	Sample from	Drilled Depth	Elev. MSL	Distance from Felsite
956A-4	Caprock	2070	1233	4733
958-3A	Caprock	2440	536	3036
BAR-2	Caprock	2500	-273	5227
DV-2	NVDR	3713	-665	-365
DX-84	NVDR	7736	-4180	2020
GDC-30	NVDR	5022	-2920	1080
GDCF-15D-28	NVDR	5032	-2015	485
GDHS-7	NVDR	8075	-4825	3175
L'ESP-2	HTVDR	11059	-8075	925
LFH-2	Caprock	3100	495	7995
LFH-2	Caprock	3800	-205	7295
LFH-2	Caprock	4800	-1198	6302
LFH-2	Caprock	5200	-1592	5908
LFH-2	Caprock	5600	-1985	5515
LFH-2	Caprock	5800	-2182	5318
LFH-2	Caprock	6000	-2379	5121
MCK-2	Caprock	2170	312	5512
MLM-3	Caprock	4330	-2216	4284
NEGU-17	NVDR	8531	-5245	3755
OF27A-2 ST1	HTVDR	10377	-7225	775
PDC-1	NVDR	5140	-2326	4174
PDC-3	NVDR	5990	-3140	3360
P-1	Caprock	5160	-2032	4968
P-1	Caprock	5170	-2042	4958
P-1	Caprock	5190	-2062	4938
P-5	Caprock	4170	-1572	5428
P-32	Caprock	5960	-3793	3207

Name	Sample from	Drilled Depth	Elev. MSL	Distance from Felsite
PS-24	Caprock	4080	-1426	5574
PS-31	Caprock	4650	-2480	4520
PS-31	Caprock	5090	-2904	4096
PS-54	Caprock	4140	-1477	5523
SB-26	Caprock	360	1752	6752
SB-26	Caprock	820	1292	6292
SB-26	Caprock	1100	1012	6012
SB-26	Caprock	1360	753	5753
SB-26	Caprock	1400	713	5713
SB-26	Caprock	1700	418	5418
SB-26	Caprock	2000	130	5130
SB-26	Caprock	2340	-192	4808
SB-26	Caprock	2500	-345	4655
SB-26	Caprock	2540	-384	4616
SB-26	Caprock	2700	-537	4463
SB-26	Caprock	2740	-575	4425
SB31	NVDR	3740	-1565	3135
TH-7	NVDR	1000	740	5240
THR-6	Caprock	3490	-1121	5379
THR-6	Caprock	4020	-1601	4834
THR-6	Caprock	4110	-1692	4808
THR-6	Caprock	5430	-2902	3598

Table 1. Depths and distance from the felsite of the samples studied. All depths are in feet. Elev. MSL = elevation relative to mean sea level. Other abbreviations as in Fig 1. LHF-2 and SB-26 data are from Sternfeld (1981).

intergrown with quartz or as bladed crystals (assemblage 5), and as a relict phase in the Franciscan veins associated with actinolite and epidote. These late-stage textures indicate deposition from boiling fluids. Except for the shallow reservoir represented by TH-7 (Gunderson, 1989), calcite is not common as a late-stage mineral in the NVDR and little carbonate remains in the Franciscan veins. The loss of calcite has been ascribed to the formation of the calc-silicate minerals and to dissolution (Gunderson, 1989; Hulen and others, 1991).

Most of the quartz within the Franciscan veins contains abundant small fluid inclusions that gives it a turbid appearance. In contrast, quartz that is intergrown with the calc-silicate aggregates is often clear. This quartz appears to have formed during the metamorphism that accompanied emplacement of the felsite. Most of the fluid inclusion data described in the following sections was obtained on grains of this clear quartz.

FLUID-INCLUSION SYSTEMATICS

Fluid inclusions are common in the veins. They can be classified into several types on the basis of their compositions and phase relationships. These include: two-phase liquid-rich inclusions whose final phase to melt is ice; two-phase vapor-rich inclusions; two-phase liquid-rich inclusions whose final phase to melt is CO_2 clathrate; three-phase liquid-rich inclusions containing daughter crystals of halite; and four-phase liquid-rich inclusions containing daughter crystals of halite and sylvite.

Most of the fluid inclusions occurring in the samples are vapor-rich. These inclusions are found randomly distributed throughout the grains and as planar arrays that define healed fractures. The presence of secondary planes that lack liquid-rich inclusions provides evidence of boiling throughout the system.

The majority of the fluid inclusions examined in this study were of secondary or undefined origin. Primary fluid inclusions are uncommon, occurring primarily within the caprock.

Heating and freezing measurements were made on liquid-rich fluid inclusions using a Fluid Inc. adapted U.S.G.S.-type heating/freezing stage calibrated with synthetic fluid inclusions. The accuracy of the microthermometric measurements, based on repeated measurements of the synthetic fluid inclusion samples, is estimated to be ± 0.1°C at temperatures below 0.0°C and ± 3°C at 374°C.

The fluid-inclusion measurements define strong gradients in the compositions and temperatures of the fluids that have circulated through the geothermal system. Homogenization temperatures (Th) of the inclusions ranged from 120° to 470°C, whereas NaCl contents varied from less than .18 to 42 weight percent. The data are plotted with respect to their vertical distance from the felsite in Figures 2 and 3. These distances were taken from Gunderson (1989) for samples provided by Unocal Geothermal Division or estimated from the data presented by Thompson (1989).

The apparent salinities of the two-phase inclusions were calculated from their ice-melting temperatures using the equation of Potter and others (1978). NaCl contents of halite-bearing inclusions were determined from the dissolution temperature of the salt using data summarized by Sourirajan and Kennedy (1962). If the dissolution temperature could not be measured, a minimum value of 26 weight percent NaCl was assigned to the inclusions. No quantitative compositional data was obtained on inclusions containing halite and sylvite was because of their small size.

A few of the fluid inclusions from the caprock and NVDR contained enough CO_2 to produce CO_2 clathrate on cooling below 0°C. Low CO_2 clathrate dissociation temperatures of up to 1.7°C indicate that their CO_2 contents were on the order of 5 weight percent.

DISCUSSION

The Caprock and Normal Vapor-Dominated Reservoir

Fluid inclusions from the caprock were studied in samples from the northwest and southeast parts of The Geysers while those from the NVDR come primarily from the central portions of the field (Fig. 1). Despite the spatial separation of the samples, comparison of the data shows that similar temperature and salinity relationships existed throughout the field.

Fluid-inclusion data were obtained on calcite and quartz from the caprock and on quartz, epidote, actinolite, and ferroaxinite from the NVDR (Figs. 2 and 3). Figure 2 shows that the maximum homogenization temperatures of the samples increase with decreasing distance to the felsite. The minimum homogenization temperatures of the NVDR samples range from 250° at distances of less than 4000 feet from the felsite to 240°C at greater distances.

The maximum salinities of the inclusion fluids also increase as the felsite is approached (Fig. 3). The highest values are found in tourmaline-bearing veins. Fluid inclusions in these veins frequently contain halite, indicating NaCl contents of at least 26 weight percent, and less commonly halite and sylvite.

As the geothermal system evolved, both fluid temperatures and salinities decreased. A good example of this relationship is provided by data from DV-2, which was taken from the felsite. This sample is characterized by early tourmaline-bearing veins. High-salinity fluid inclusions in the tourmaline-bearing veins contain halite or halite and sylvite and have average homogenization temperatures of 328°C. The younger quartz veins are characterized by inclusion fluids with salinities of 3 to 6 equivalent weight percent NaCl and average homogenization temperatures of 271°C. Similar, moderate salinity fluids are found throughout the caprock and NVDR (Fig. 3).

Fluid inclusions with very low salinities, between 0.0 and 0.4 equivalent weight percent NaCl, are common within the caprock but only occur sporadically within the NVDR. The combination of high homogenization temperatures (>200°C) and low salinities suggests that the fluids consist of condensate or mixtures of condensate and saline fluid.

The High-Temperature Vapor-Dominated Reservoir

Two samples from the HTVDR were studied. OF27A-2 ST1 is characterized by tourmaline-bearing veins (assemblage 1) that show little evidence of retrograde metamorphism or secondary alteration. Veins in L'ESP-2 contain assemblage 2 in which biotite has been chloritized or chlorite and pyrite (assemblage 4).

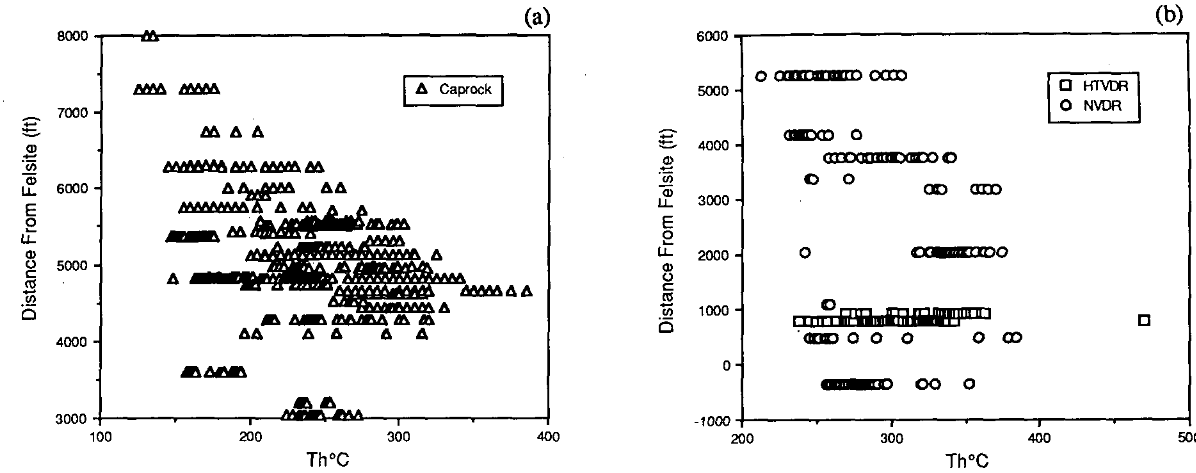

Fig. 2. Homogenization temperatures (Th) of fluid inclusions from the (a) caprock and (b) NVDR and HTVDR. The data are plotted with respect to their vertical distance from the felsite. Abbreviations as in Fig. 1.

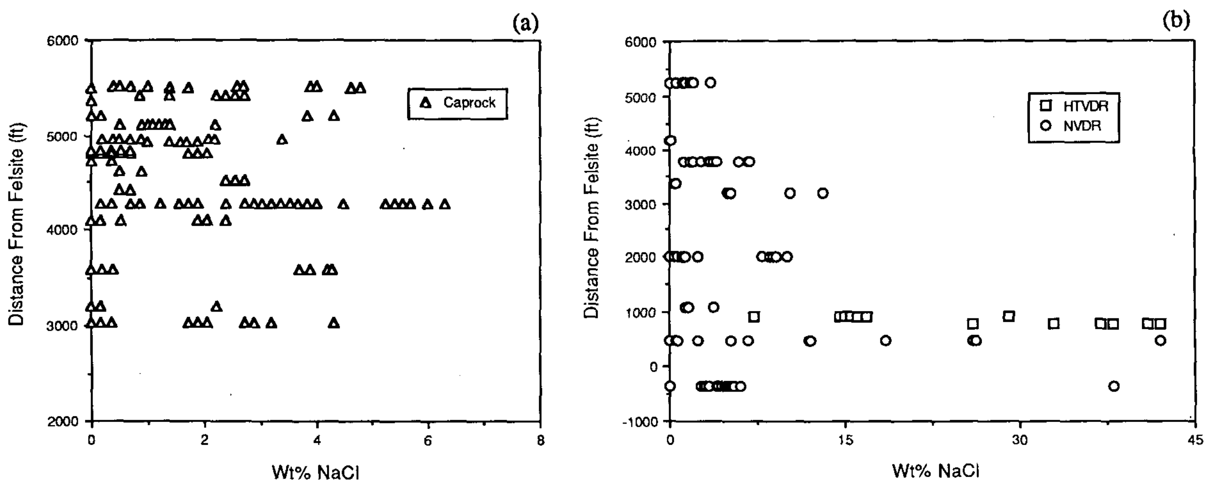

Fig. 3. NaCl contents in weight % (Wt%) of fluid inclusions from the (a) caprock and (b) NVDR and HTVDR. Abbreviations as in Fig. 1. The data are plotted with respect to their vertical distance from the felsite. See text for determination of NaCl contents.

Both samples of the HTVDR contained secondary inclusions in quartz that were suitable for study. With the exception of a single allanite(?)-bearing inclusion from OF27A-2 ST1 (Th≈470°C), the samples had generally similar homogenization temperatures. These temperatures ranged from 237° to 342°C in OF27A-2 ST1 and from 269° to 363°C in L'ESP-2. The highest temperatures are comparable to those samples from the NVDR that contain assemblage 1.

It was more difficult to estimate the salinities of these inclusions because of their small size. In OF27A-2 ST1, only inclusions containing halite could be accurately measured. The NaCl contents of these inclusions ranged up to 42 weight percent. The salinities of the fluid inclusions in LÉSP-2 were lower, ranging generally from 7 to 17 equivalent weight percent NaCl. Although the number of salinity measurements on samples from the high-temperature reservoir is small, it is significant that no evidence was found for the low salinity fluids that were preserved in vein assemblage 1 in the reservoir rocks (0 to 5 equivalent weight percent NaCl).

Origin of the Temperature and Salinity Variations

The data discussed above demonstrate that the gradients in the temperatures and salinities of the inclusion fluids can be related to both time and distance from the felsite. Figure 4 illustrates the salinities and homogenization temperatures for individual inclusions. The overall trend of fluid inclusions from the caprock and NVDR is one of decreasing salinity with decreasing temperature. This relationship suggests that dilution was the primary cause of the variations in fluid chemistry and temperature. However, the vein relationships discussed above indicate that temperatures and salinities also declined as the system evolved. These changes could have resulted from the collapse of

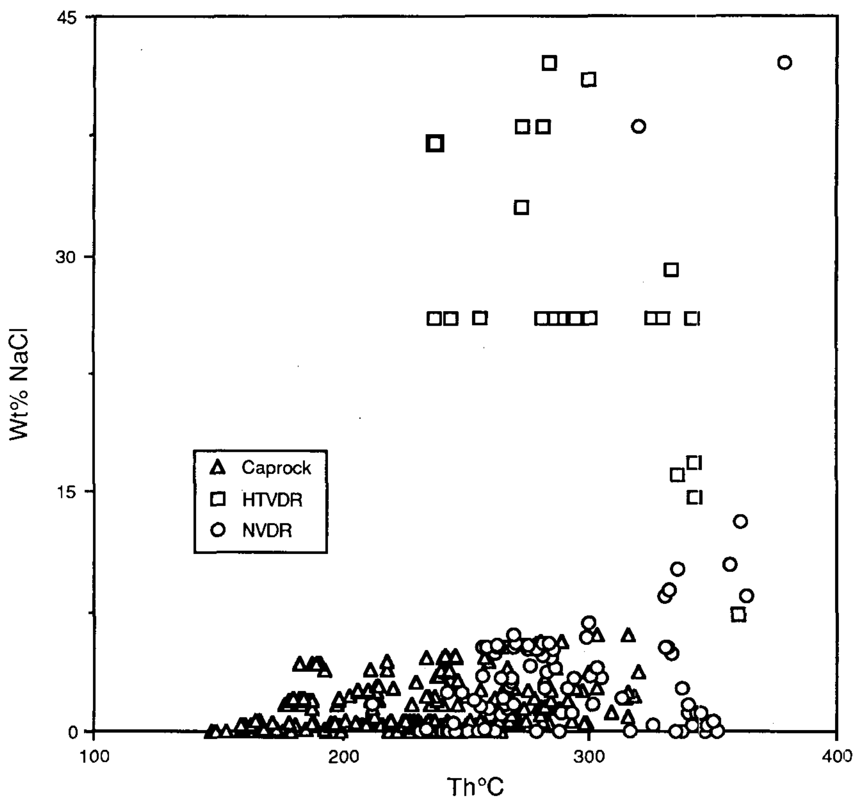

Fig. 4. Crossplot of homogenization temperatures (Th) and NaCl contents of individual fluid inclusions. Abbreviations as in Fig. 1.

the early liquid-dominated hydrothermal system as the felsite cooled, allowing the shallow, dilute fluids to migrate downward into the region now occupied by the NVDR.

Highly saline fluids, some of which were saturated with respect to halite, characterize the HTVDR and the tourmaline-bearing assemblages from the reservoir. Although the halite saturated fluids from the HTVDR display a broad range of homogenization temperatures from 235° to 350°C, they display no obvious dilution trends (refer to Fig. 4). Thus, cooling may have largely conductive.

The compositions of fluid inclusions with homogenization temperatures near 350°C and salinities between 0 and 17 equivalent weight percent NaCl may reflect the effects of boiling. The high-temperatures of the lowest salinity fluids suggest that they represent steam condensate. Thus, the salinity variations of these inclusion fluids may be due to mixing between condensate and paleoreservoir fluids as well as to salinity increases due to boiling. Similar processes may have contributed to the salinity variations observed in the caprock and upper part of the reservoir.

CONCLUSIONS

Fluid inclusion and mineralogic data show, as was proposed by Sternfeld and Elders (1982), that a large scale liquid-dominated geothermal system developed in response to the intrusion of the felsite. During the initial development of this hydrothermal system, temperatures and salinities appear to varied continuously between what is now the caprock, the normal vapor-dominated reservoir (NVDR) and the high-temperature vapor-dominated reservoir (HTVDR). Fluids in the vicinity of the felsite locally reached temperatures exceeding 350°C and NaCl contents in excess of 26 weight percent. The initial salinities and temperatures decreased with increasing distance from the felsite. As the felsite cooled, the hydrothermal system within the caprock and NVDR collapsed downward, progressively diluting the initial high-salinity fluids.

Two samples of the HTVDR were studied. Although fluid inclusions in samples from the HTVDR have homogenization temperatures similar to those in the NVDR, inclusions from the HTVDR typically record much higher salinities. In one sample of the HTVDR containing abundant fresh biotite, fluid inclusions saturated with halite (>26 weight percent NaCl) displayed homogenization temperatures ranging from 237° to 305°C. This suggests that the incursion of low salinity fluids was severely limited by low permeabilities and that temperature changes may have been due largely to conductive cooling. The conclusion that permeabilities were low in the HTVDR is further supported by the lack of retrograde alteration of biotite to chlorite in one of the samples.

The caprock is distinguished from the reservoir rocks by the abundance of calcite. Within the caprock, late-stage calcite was deposited by boiling fluids. As boiling proceeded, acidic condensates, preserved as low salinity fluid inclusions, formed and reacted with the host rocks to produce illite, mixed-layer clays and locally kaolin (Moore and others, 1989; Hulen and others, 1991). These minerals further reduced the permeabilities of the caprock.

Homogenization temperatures indicate that saline water persisted to temperatures between 250° and 270°C within the main part of the reservoir and to slightly lower temperatures in its upper part where calcite locally remained stable. Low CO_2 contents of the late-stage boiling fluids, caused by the upward migration of gas and steam, may have been the primary reason for the absence of late-stage calcite in the developing vapor-dominated reservoir.

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