

GEOLOGIC FRAMEWORK OF THE EAST FLANK, COSO GEOTHERMAL FIELD: IMPLICATIONS FOR EGS DEVELOPMENT

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ABSTRACT

The Coso Geothermal Field is a large, high temperature system located in eastern California on the western edge of the Basin and Range province. The East Flank of this field is currently under study as a DOE-funded Enhanced Geothermal Systems (EGS) project. This paper summarizes petrologic and geologic investigations on two East Flank wells, 34A-9 and 34-9RD2 conducted as part of a continuing effort to better understand how the rocks will behave during hydraulic and thermal stimulation. Well 34A-9 is the hottest well at depth in the East Flank, reaching nearly 350°C.

The reservoir on the East Flank is dominated by diorite and granodiorite. Specifically, the diorites are several different quartz diorites and diorite. Thick intervals of granite, a minor rock type throughout most of the field, were encountered in 34A-9 and 34-9RD2. The granite tends to be much less altered, veined, and fractured than the other rock types, and thus probably a poor stimulation target.

Late stage vein minerals include calcite, quartz, chlorite, and hematite at shallow depths and rare epidote, chlorite, quartz, adularia, and wairakite in the deepest portions of East Flank wells. The distribution of mineral assemblages suggest well 34A-9 was drilled through the caprock and into the uppermost part of the reservoir rocks of a relict geothermal system.

The temperatures indicated by the clay minerals are much lower than would be predicted from the present day downhole temperatures, but are in good agreement with fluid inclusion temperatures. These relationships imply the system is currently being reheated.

Lost circulation zones tend to correlate with zones of relatively substantial calcite veining. Fluid inclusion measurements indicate some of the calcite was deposited by high salinity fluids not related to the current geothermal system. Other inclusions contain low salinity fluids that could be related to the current geothermal system. These fracture zones have been

episodically reactivated and modified by dissolution and reprecipitation of calcite.

INTRODUCTION

The Coso Geothermal Field is a large, high-temperature system located in California on the western edge of the Basin and Range province (Fig. 1). The system is related to young volcanic activity. The field produces 240 MWe. This study describes mineralogic and petrologic investigations undertaken as part of a DOE-funded Enhanced Geothermal Systems (EGS) project designed to improve permeabilities and injectivities of wells on the East Flank of the field. The objective of this work is to better understand the geologic setting of the East Flank, and in particular, its thermal and structural history. These studies and those of Adams et al. (2000) indicate that the system has undergone multiple thermal events and that the East Flank is currently reheating.

GEOLOGIC SETTING

The Coso geothermal field lies within a major volcanic center, which contains 38 rhyolite domes and almost as much basaltic material in its eastern portion. Two main periods of volcanism have occurred; the first was between 4.0-2.5 Ma, and the younger from 1.0 -0.4 Ma (Duffield et al., 1980). Both the rhyolite and the geothermal system are believed to be related to a partially molten body of magma located 5 to 20 km beneath the field (Duffield et al., 1980; Reasenberget al., 1980). Three periods of recent geothermal activity were documented by Adams et al (2000); the first occurred approximately 307,000 years ago and is associated with travertine deposits on the eastern side of the field. The second event produced a high- temperature geothermal system associated with sinter deposits that formed at ~238 ka on the East Flank. A major upflow center appears to have been located in the southwestern part of the field. The most recent activity has reheated rocks on the East Flank and reactivated the

southwestern upflow center. The present activity may have begun within the last several tens of thousands of years (Kurilovitch et al., 2003).

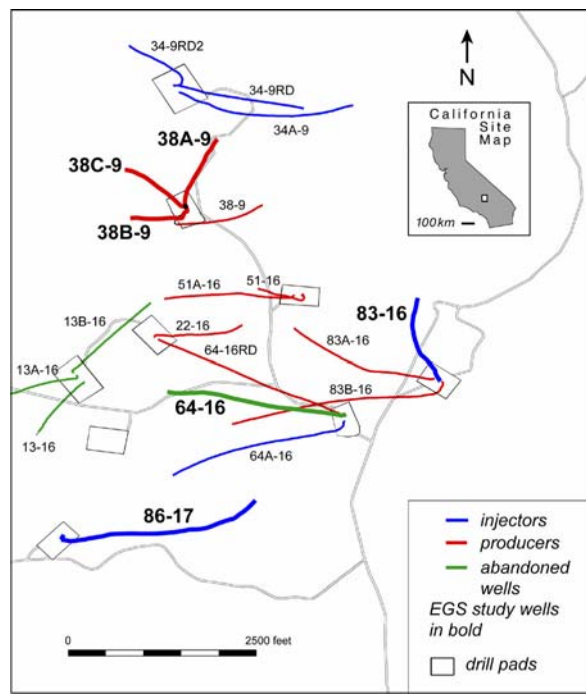


Figure 1. Area map of the East Flank.

PETROLOGY AND PETROGRAPHIC STUDY OF WELLS 34-9-RD2 AND 34A-9

Well 34-9RD2, the target of a DOE-funded EGS project, and well 34A-9, which is a proposed injector well on the same pad are located within the hottest part of the East Flank. Temperatures reaching close to 350°C have been encountered within well 34A-9. Cuttings samples from well 34-9RD2 were studied from 3600 feet to its total depth of 7310 ft and from well 34A-9 from 3600 feet to its total depth at 9735 ft. Observations taken on the chipboards and thin sections included: rock type, mineralogy and relative degree of pervasive alteration, veining types and relative amounts, and presence of euhedral crystal vein fillings. The summary log for well 34-9RD2 is shown in Figure 2.

The dominant rock types in the wells are quartz diorite, granodiorite, and granite. Petrologic and alteration studies by Kovac et al. (2004) indicate the quartz diorite is the oldest of the reservoir rocks. The granodiorite is intermediate in age. Granite is the youngest of the three rock types. The presence of extensive intervals of granite in these two wells is unusual because usually it is a minor rock type within the East Flank reservoir (Kovac et al., 2004). In both wells 34-9RD2 and 34A-9 granite occurs between approximately 5000 and 7000 ft. The granite is generally less altered and less veined than the other rock types and we infer from this observation that the

granite is less fractured. Low fracture permeabilities within the granite are supported by drilling results. Many different vein minerals can be identified in the wells. As in other East Flank study wells, calcite and chlorite are the most abundant. However, quartz veins are more abundant in wells 34-9RD2 and 34A-9 than in other study wells.

HYDROTHERMAL ALTERATION AND MINERAL PARAGENESIS

Paragenetic relationships among the vein and alteration minerals were established to develop a conceptual model of the thermal history of the East Flank. Minerals were studied under a binocular microscope and in thin section. Select samples were also studied using X-ray diffraction techniques. The mineralogic relationships were corroborated by detailed studies of core samples from another East Flank well, well 64-16, which was cored to a depth of 2025 ft (Kovac, unpub. data). Figure 3 summarizes the paragenetic sequence of East Flank vein minerals based on these observations. The initial thermal event recorded by the reservoir rocks is represented by greenschist facies metamorphism of quartz diorites. This event is labeled Stage 0. This regional event produced chlorite, epidote, and sphene in the groundmass of the rocks. Locally the rocks are foliated and display poikilitic textures. The oldest recognized veins consist of massive pyrite, magnetite, epidote, and quartz followed by calcite. This event, referred to as stage 1 (Fig. 3) may have been related to the granite's emplacement. Stage 2 is represented by sealed veins of calcite + hematite + chlorite. Fluid inclusions in calcite from this stage often have higher salinities of up to a few weight percent NaCl equivalent than later stages of calcite. The next event, Stage 3, is divided into two substages. At shallow depths this stage (Stage 3A) is represented by hydrothermal breccias cemented by drusy quartz. Intergrown euhedral quartz crystals and calcite, which in places is bladed, formed during this stage. The presence of intergrown quartz and calcite are indicative of boiling. In the deepest part of well 34A-9 at 9710 ft, vein assemblages we interpret to be related to this thermal event consist of epidote (Fe-poor) + sericite + quartz +/- chlorite and adularia are present. This assemblage (Stage 3B) implies temperatures in excess of ~250°C (Browne, 1984; Henley and Ellis, 1983). The last major stage, Stage 4, is broken up into two substages. Calcite dominates the vein assemblages. The calcite exhibits several distinct morphologies. The earlier calcite (Stage 4.1) is represented by scalenohedral crystals. These crystals were encapsulated by later blocky calcite (Stage 4.2) which is often associated with hematite. Sometimes, several generations of calcite are present in the same sample, and the crosscutting relationships are evident. In the deepest parts of the

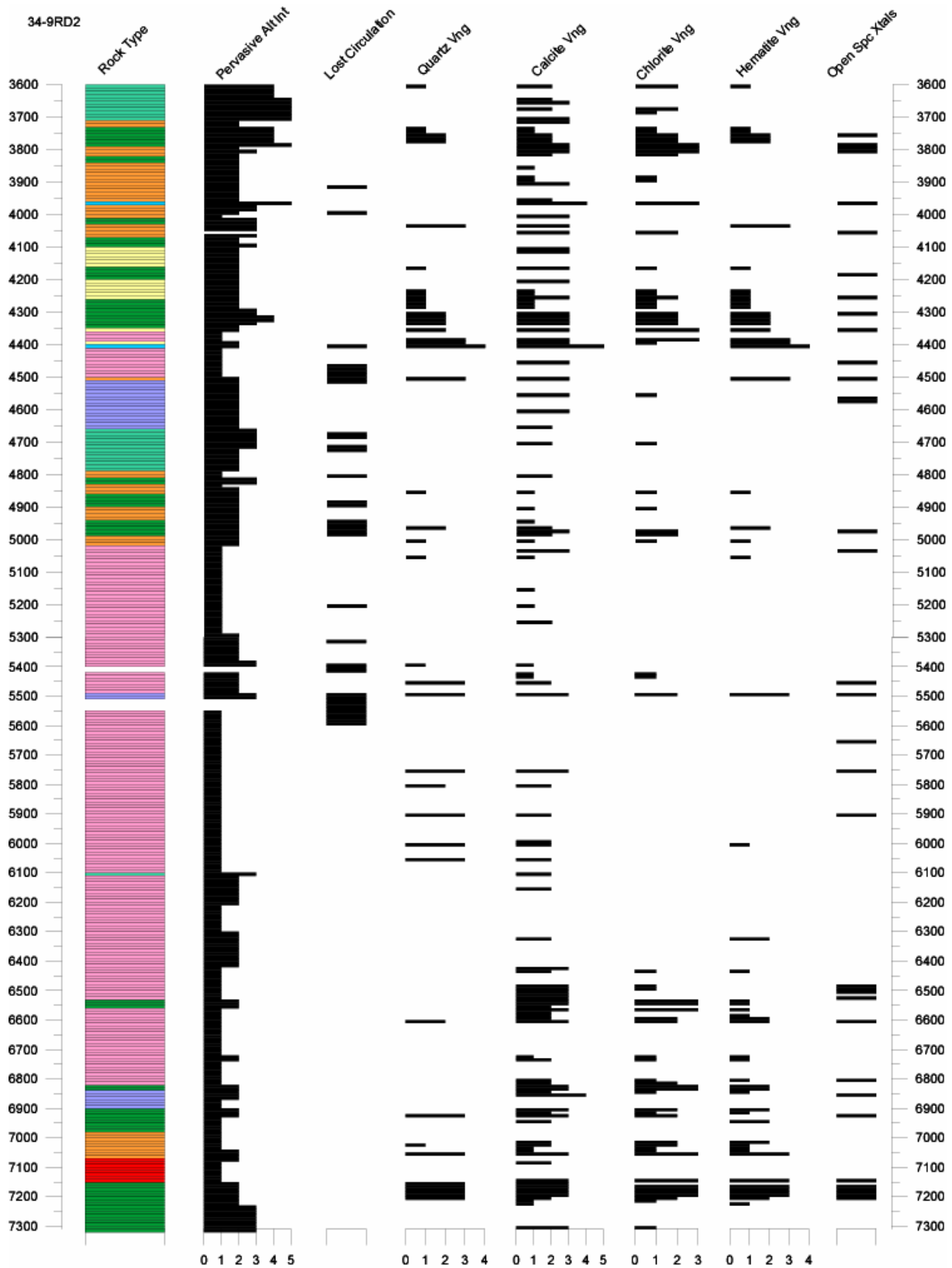


Figure. 2. Summary log of data recorded on well 34-9RD2. Depth is shown in feet. Rock types are coded as follows: greens/yellow- diorites, orange- granodiorite, pink- granite, red- microgranite, purple- metasediments, and blue- massive veining.

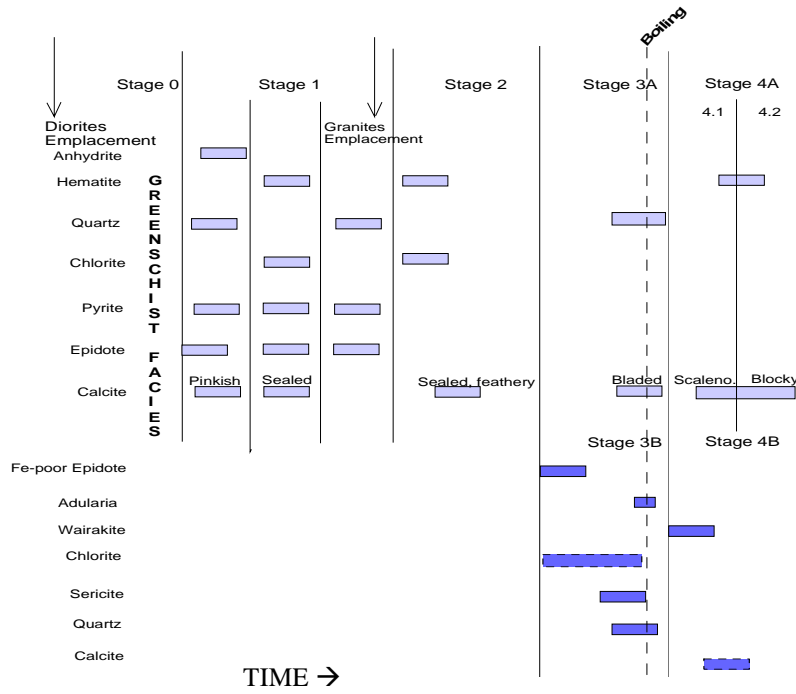


Figure 3. Generalized paragenetic sequence of East Flank vein minerals. The designations -A and -B refer to shallow and deep assemblages, respectively.

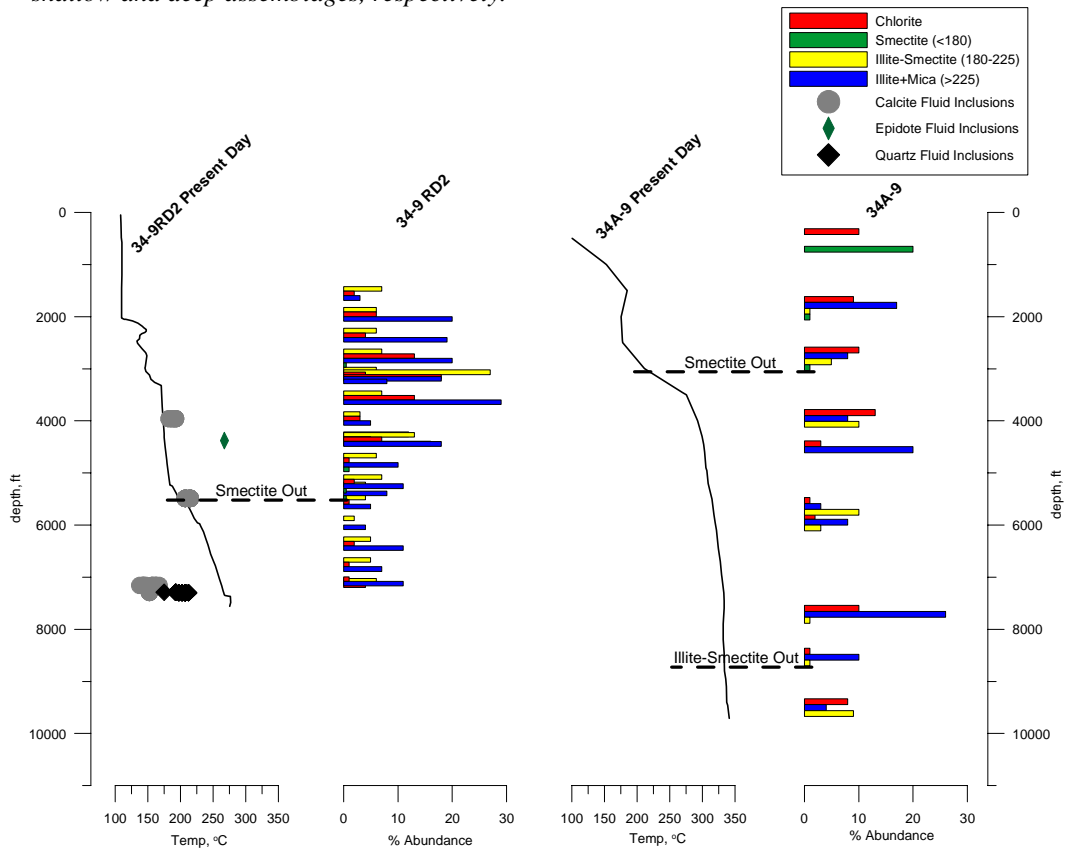


Figure 4. A summary of temperature, fluid inclusion, and clay mineral data for both wells. The dashed lines indicate the interpreted disappearance of smectite and illite-smectite.

reservoir, the silicate minerals were followed by wairakite (e.g. at 9710 ft in well 34A-9). In well 72-19, drilled within the upflow zone beneath the southwest portion of the field, wairakite postdates the assemblage quartz + epidote + calcite + pyrite + chlorite. Wairakite is a common late-stage mineral in geothermal systems, forming during the waning stages of activity (Moore et al., 2002). Additionally, calcite is still often found to be the last veining present even at great depth. Thus, Stage 4B, wairakite + calcite, is established. As noted below, calcite deposited during Stage 4 typically hosts fluid inclusions with the lowest homogenization temperatures and salinities. Simmons et al. (2000) assert that late, pure, massive calcite veins can be deposited from downward-moving, CO₂-rich, steam-heated waters.

The distribution of clay minerals can provide an independent estimate of temperature. Figure 4 shows the percentages of clay minerals, smectite, interlayered illite-smectite, illite and chlorite in the groundmass of the reservoir rocks encountered in wells 34-9RD2 and 34A-9. In general, smectite is stable up to temperatures of ~180°C, interlayered illite-smectite to ~225 °C and illite and chlorite at greater temperatures (Henley and Ellis, 1983; Browne, 1984).

Clay minerals are uncommon in the veins and thus they cannot be uniquely assigned to one of the paragenetic stages. However, the distribution of clay minerals shown in Figure 4 implies that at least several thermal events are represented. Despite the complexity of the clay distributions the abundances of both smectite and interlayered illite-smectite appear to vary with depth. The base of the smectite zone occurs at depths of ~5500 in 34-9RD2 and ~3000 in 34A-9. A temperature of ~180°C at about 5500 ft, implied by the disappearance of smectite, appears to be fairly consistent with both the measured downhole temperatures and with the homogenization temperatures of calcite fluid inclusions in well 34-9RD2. In contrast, interlayered illite-smectite persists in rocks where downhole measured temperatures exceed its typical stability range, suggesting this mineral formed during an earlier, lower temperature thermal event. These relationships suggest recent heating of the field, which has not yet been recorded by the rocks.

FLUID INCLUSION STUDIES

Samples of euhedral calcite and quartz crystals and one epidote crystal were chosen from the cuttings for fluid inclusion analysis. All of the inclusions found in these samples were two-phase (liquid and vapor) at room temperature. Homogenization temperatures and salinities of the inclusion fluids calculated as weight percent NaCl equivalent (Bodnar, 1993) were determined. Figure 6 summarizes relationships between depth, homogenization temperature, and

salinity for inclusions from well 34-9RD2. The measured downhole temperatures and boiling point to depth curve for a 0% salinity, gas-free fluid are also shown for comparison. Salinities are coded by symbol size. Inclusions in calcite had the lowest temperatures and salinities. Temperatures of homogenization in calcite varied between 150 and 215°C, and salinity varied between 0.9 to 2.7 weight % NaCl equivalent, which is generally the higher end of calcite salinities as measured in other wells. Quartz varied in homogenization temperatures between 175 and 213°C, and salinities varied between 1 and 4 wt. % NaCl equivalent. The primary inclusions in quartz had higher salinities than the secondary inclusions in quartz. The inclusions in epidote had by far the highest measured temperatures and salinities. Homogenization temperature was approximately 268°C while salinity was approximately 11 wt. % NaCl equivalent.

Histograms of salinities determined on calcite- and quartz- hosted inclusions suggest that several (three or more) distinct populations of fluids were trapped (Figures 6 and 7). Data from all studied East Flank wells were employed. More than half of the inclusions trapped in calcite recorded salinities between 0.5 and 1% NaCl equivalent; furthermore, over 70% of all calcite inclusions have salinities less than 1 weight percent equivalent. Salinities in quartz-hosted inclusions also define several populations with salinities tending to be higher than in the calcite. Less than 25% of the inclusions have salinities of 1 weight percent NaCl equivalent or less; in the calcite, the majority of inclusions had salinities less than 1 wt. percent. Significantly, almost 20% of the quartz inclusions had salinities of 5 wt. % NaCl equivalent and higher. Thus the fluid inclusion data provide a record of water-rock interactions that involved fluids with a wide range of compositions. The earliest fluids trapped in quartz and calcite deposited during Stage 1 had the highest salinities of about 8-10 weight percent NaCl equivalent. The youngest thermal event is represented by the lowest salinity fluids, which are usually equal to or less than 1 weight percent NaCl equivalent.

LOST CIRCULATION ZONES

Zones of lost circulation were encountered mainly between 3900-5500 ft in well 34-9RD2, and between 3600-4500 ft, 7600-8000 ft, and 9300-9700 ft in well 34A-9. Kovac et al. (2004) demonstrated that many of the lost circulation zones were associated with calcite veins, as indicated by the presence of euhedral calcite crystals. Fluid inclusions analyzed for these locations indicate however, that this veining is not necessarily related to the most recent fluids. Some of the inclusions have salinities of about 4 weight percent equivalent or more and temperatures in the mid 200's Celsius, which can be correlated with the oldest stages of the mineral paragenesis. In other

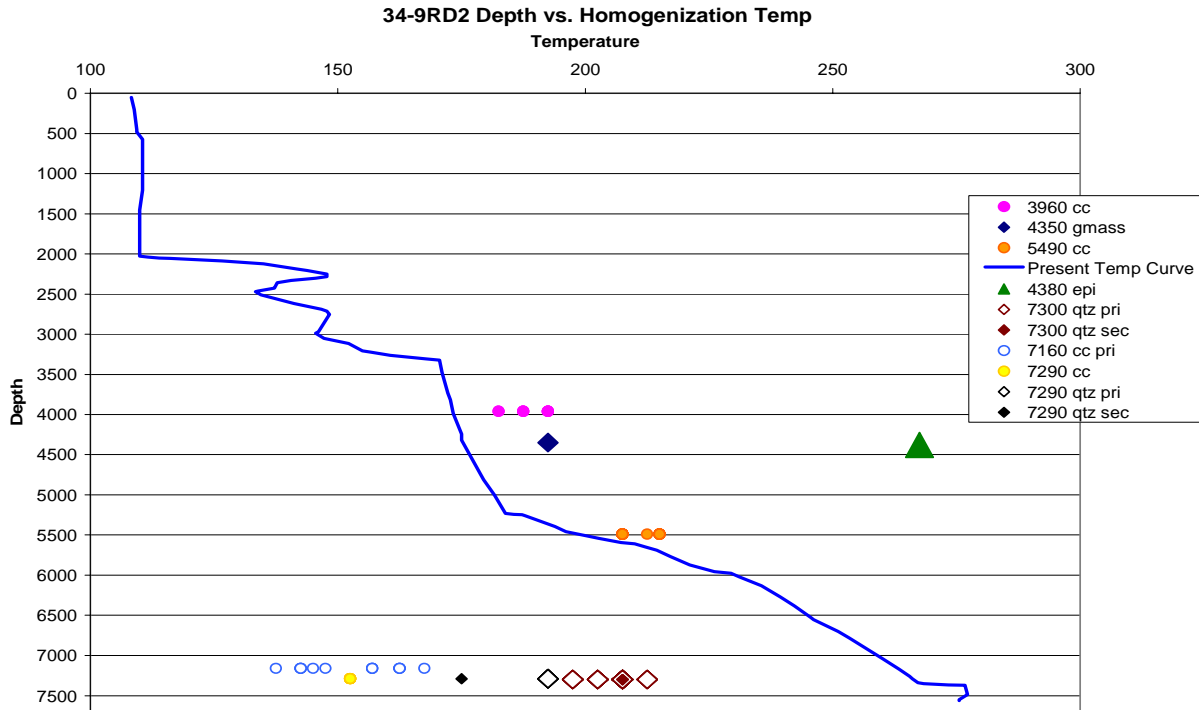


Figure 5. Depth vs. homogenization temperature for fluid inclusions from well 34-9RD2. Symbol size correlates positively with general salinity of the inclusion where the smallest are approximately 1 wt% NaCl equivalent and the largest are about 10 wt. % NaCl equivalent.

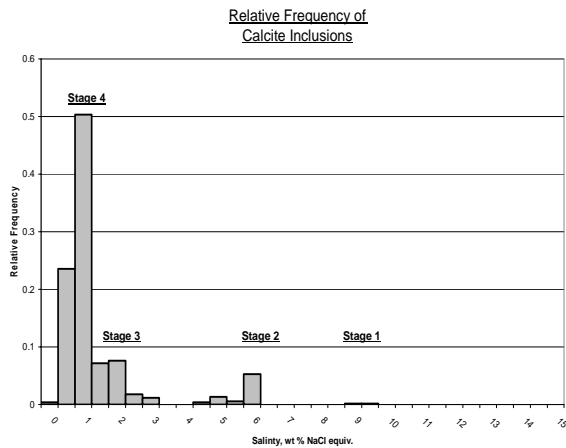


Figure 6. Relative Frequency of salinity in calcite hosted inclusions.

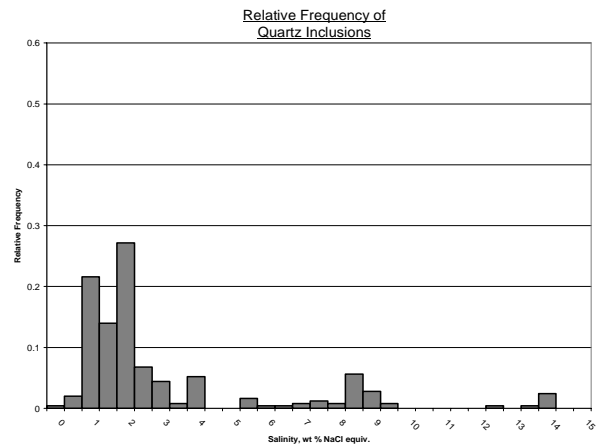


Figure 7. Relative frequency of salinity in quartz hosted inclusions.

cases, low salinities of about 1 weight percent equivalent or less suggest younger fluids were responsible for calcite deposition. Thus the data suggest that the fractures that are currently permeable may have formed at different times and during different hydrothermal events. Also, many of them have been reactivated by younger events over time. Therefore, these locations may be good stimulation targets.

CONCLUSIONS

- Diorites, granodiorites, and granites are the dominant rock types present in the East Flank wells.
- Generally, the granites are the slightest altered, and least veined and least fractured of the dominant rock types. These relationships suggest the granites generally have low permeabilities and have not been

strongly affected by geothermal events. They appear to be the poorest of the potential stimulation targets.

- Zones of lost circulation often correlate with zones of abundant veining. However, fluid inclusion and paragenetic studies show that this mineralization is not necessarily recent, and that some fractures developed during previous thermal events.

- Epidote and pyrite are the oldest vein minerals. At shallow depths, the recent veining assemblage is dominated by euhedral quartz and younger calcite. Furthermore, as indicated by the fluid inclusion studies, several generations of calcite and quartz are present.

- The clay minerals smectite and interlayered illite-smectite occur within the groundmass of the rocks. This assemblage is typical of the caprock sections of modern geothermal systems. In the deepest portions of the East Flank wells, the youngest vein assemblage consists of adularia, quartz, chlorite, Fe-poor epidote and younger wairakite. These minerals are typical of the reservoir sections of modern geothermal systems where temperatures exceed ~250°C.

- Fluid inclusion homogenization temperatures and the distribution of clay and silicate minerals indicate that the modern geothermal system is superimposed on rocks altered in an older, lower temperature thermal regime.

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