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GEOLOGY AND MINERAL PARAGENESIS STUDY WITHIN THE COSO-EGS PROJECT

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ABSTRACT

The Coso Geothermal Field is a large, high temperature system located in 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 project. The reservoir rocks generally consist of a complex, interfingering sequence of diorite, granodiorite, and granite. The diorites show weak to strong alteration representing multiple hydrothermal events. The work described here was undertaken to evaluate the geology and thermal history of the East Flank, in order to better understand how the rocks will behave during hydrofracturing.

Eight East Flank wells have been studied. The alteration assemblages present indicate that the granites are younger than the diorites. The oldest alteration sequence consists of epidote, pyrite, sphene, chlorite, and calcite; this sequence developed before the granite was emplaced. This alteration appears to be due to fluids of a deep, crustal origin. The granites are less common and more weakly altered than the diorites; the younger alteration assemblage as found in the granites consists of clays, calcite, chlorite, and sericite. Fluid inclusion studies were implemented to separate different thermal events. Fluid inclusions were studied from three wells: 83-16, 38B-9, and core hole 64-16. Inclusions from calcite, quartz, feldspar, and epidote were studied. Quartz- and calcite-hosted inclusions from the upper 256m in 64-16 are characterized by salinities usually less than ~2 weight percent NaCl equivalent and homogenization temperatures that differ by less than ~15^{o}C from the down hole measurements. Minerals in these veins, which typically contain significant open-space, display euhedral forms. These relationships suggest that the inclusions could be related to the modern geothermal system. Inclusions from 83-16 and 38B-9 display a broad range of salinities from ~0 to 7 wt % NaCl equivalent and homogenization temperatures (202.5^{o}C to 325^{o}C) that range from several tens of degrees below to tens of degrees above the present day values. The temperature-salinity relationships suggest that many of these inclusions represent older thermal events. Taken together, the mineral assemblages and fluid-inclusion data suggest a long and complex thermal history for the East Flank.

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. The East Flank of the Coso field is currently under study as a DOE-funded Enhanced Geothermal Systems (EGS) project. The work described here was undertaken to better understand the geologic setting of this portion of the field, and in particular, its thermal and structural history. In this paper, the lithology and mineral parageneses of the East Flank are described, along with data from fluid inclusion studies. Correlations of petrologic and petrographic data with the structural data are explored. These studies and those of Adams et al. (1977) 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. The age of the volcanic rocks and associated volcanics is between 1.0 and 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 approximately 5 to 20 km beneath the field (Duffield et al., 1980; Reasenberg et al., 1980). Three periods of recent geothermal activity were documented by Adams et al (1997); 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-

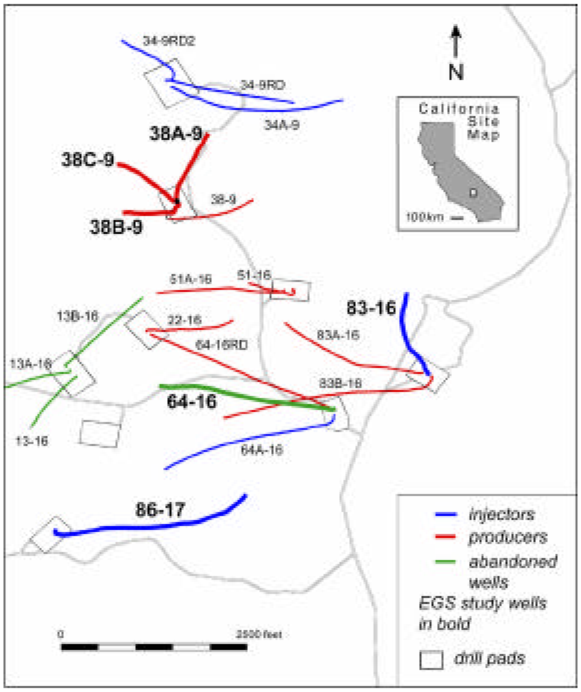

Figure 1. Area map of the East Flank.

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.

LITHOLOGY AND PARAGENESIS

Eight wells have been studied in detail in order to characterize the lithologies present in the area (refer to Fig. 1). The reservoir rocks generally consist of a complex, interfingering sequence of diorites, granodiorites, and granites (Fig. 2). The diorites are the dominant rock type present. They generally contain: 12-14% quartz, 35-38% plagioclase feldspar, 3-8% potassium feldspar, 15-30% micas, 0-8% hornblende, varying chlorite and 0-2% epidote (Lutz and Moore, 1997). Based on the varying proportions of hornblende, potassium feldspar, biotite, and epidote, the diorites are further subdivided into hornblende-biotite-quartz diorite and biotite-quartz diorite. The hornblende-biotite-quartz diorite tends to be more mafic. It is characterized by more hornblende, epidote, and sphene than the biotite-quartz diorite, and very little potassium feldspar. The biotite-quartz diorite is more felsic in composition, contains more potassium feldspar and biotite, and generally lacks epidote. The diorites generally show at least some foliation. The granodiorite is intermediate in composition between the diorites and the granite. It typically consists of 27% quartz, 31% plagioclase, 31% potassium feldspar, 3% calcite, 7% biotite and 1% chlorite. The granites are generally less common than the other rock types present, and display a large range in grain size. The granites contain approximately: 36% quartz, 22% plagioclase feldspar, 33% potassium feldspar, 3% calcite, <7% biotite and 2% chlorite. The diorites are the dominant rock type present in all but one of the study wells.

A general paragenesis based upon vein minerals observed in thin section and is presented in Figure 3. As shown in the figure, epidote and pyrite are early stage minerals. Chlorite, hematite, calcite and quartz are present throughout much of the thermal history. Dolomite and anhydrite appear to be restricted to a relatively narrow portion of the paragenesis. In the core samples, epidote-containing veins fill low-angle and generally contain no open spaces. Fluid inclusions indicate high temperatures and salinities of formation. Many sealed calcite and/or chlorite veins are present in all rock types. They postdate the epidote veins but predate partially filled veins containing calcite, hematite, and/or quartz. The youngest veins typically consist of quartz and/or calcite, and often contain abundant open-spaces. Euhedral crystals are common. The calcite can be bladed, rhombohedral, or scalenohedral in habit. The calcite sometimes occurs with quartz or hematite. The quartz is usually drusy in habit, and occurs along the vein selvages, indicating that it predates the calcite when both minerals are present. Coexisting calcite and quartz are only rarely found within the wells.

As a rule, the diorites are more altered than either the granodiorite or the granite. The diorites commonly contain vein assemblages consisting of epidote + hematite + calcite + chlorite, and pyrite + epidote whereas the granites contain the assemblages of clays, calcite, chlorite, and sericite. The high temperature alteration of the diorites but not the granites implies that the deposition of the epidote veins predates or is simultaneous with the granite intrusion.

FLUID INCLUSION STUDIES

The paragenetic relationships suggest that calcite, and perhaps other minerals, were deposited at several different times during the evolution of the Coso field. Fluid inclusion studies were implemented to aid in characterizing these thermal events. Fluid inclusions from five wells were studied: 83-16, 38B-9, 38C-9, 64-16RD, and core hole 64-16. Inclusions from calcite, quartz, feldspar, and epidote were investigated. Samples from the core represent euhedral crystals handpicked from the veins. In Figure 4 is shown a sample of a partially filled calcite vein from corehole 64-16. Additional data was obtained on individual chips in doubly polished thin sections. These sections were prepared from the

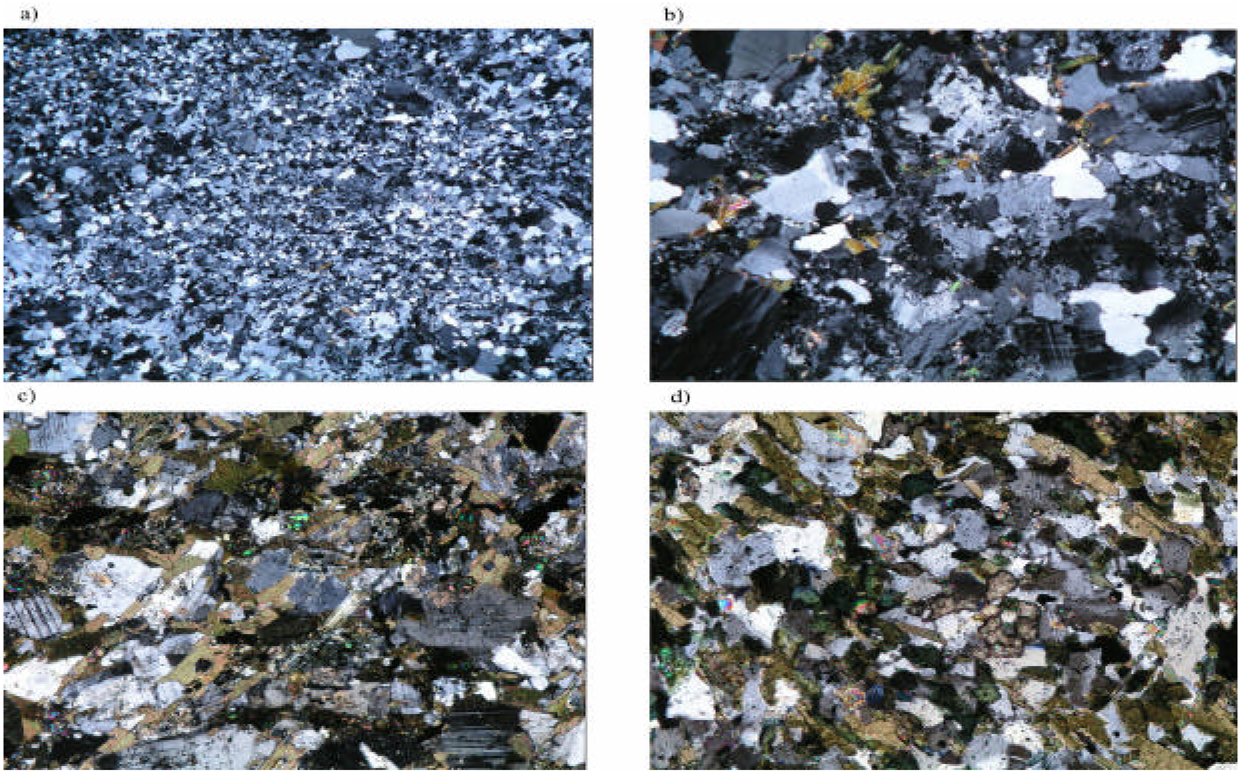

Figure 2. Rock types found in the East Flank wells; a) granite, b) granodiorite, c) biotite quartz diorite, d) hornblende biotite quartz diorite.

cuttings samples. A great variety in both homogenization temperatures and salinities is observed in the East Flank inclusions. Temperatures ranged between 117- 327°C. The salinities of these inclusions varied between 0 - 14 weight percent NaCl equivalent.

Figure 5 shows a plot of depth in meters versus homogenization temperature for fluid inclusions from the 64-16 pad. For comparison, the measured downhole temperatures and boiling point to depth curve for a 0% salinity, gas-free fluid are also shown. Several trends stand out in the inclusion data that provide insight into the thermal behavior of this system. Most of the inclusions that have much higher homogenization temperatures than the present values also have higher salinities; some greater than the present boiling point curve. These inclusions are not likely related to the present geothermal system, but are vestiges of prior events. Secondly, many of the low-salinity inclusions have homogenization temperatures close to, or below the present temperatures. These inclusions were trapped in the euhedral crystals representing the youngest identified hydrothermal event. This indicates that the temperatures are higher now than they were during vein deposition. This data will be combined with stable isotope analyses of the calcite to better define the origins of the fluids.

DATA CORRELATIONS

One of the ultimate goals of this investigation is to predict which fractures will open during hydrofracturing. Figure 6 shows a summary of the fracture, lithologic, mineral and drilling data from a lower third of well 38B-9. Only cuttings are available from this well. The fracture frequency and

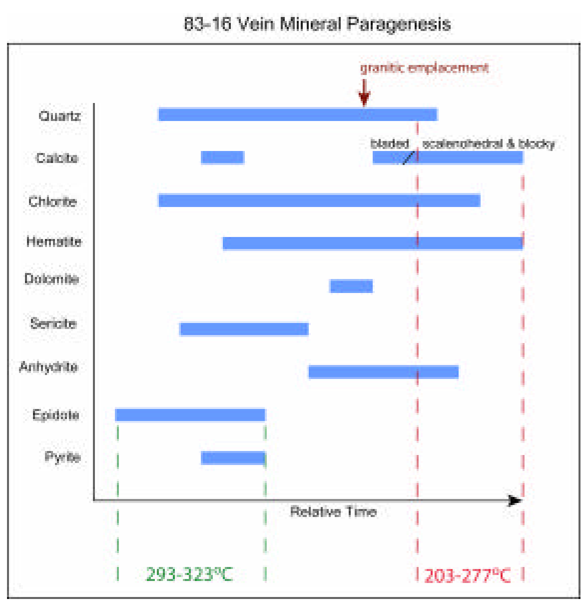

Figure 3. Vein mineral paragenesis for Coso well 83-16.

the distribution of potentially producing fractures were determined by Sheridan et al. (2003)., based on detailed analyses of the image (FMS logs) and PTS logs. Rate of penetration is based on drilling logs. Open-space crystals refer to the presence of euhedral calcite and/or quartz crystals. The presence of these crystals is indicative of partially filled veins and

Figure 4. An example of calcite crystals containing much abundant space in the core.

based on the paragenetic relationships, represent the locations of the most recently active fractures. The rate of penetration, fracture frequency, and open-space crystal locations all correlate at least moderately well with each other. There are approximately 17 different depth zones where euhedral crystals have been identified. At 12 of the depths, there is a noticeable 'kick' in the rate of penetration. Increases in the rate of penetration frequently correlate with higher permeability zones. In contrast, no correlation was observed between lithology and fracture frequency, potentially producing fractures, weight on bit, vein abundance or vein mineralogy, and for that reason these relationships are not shown.

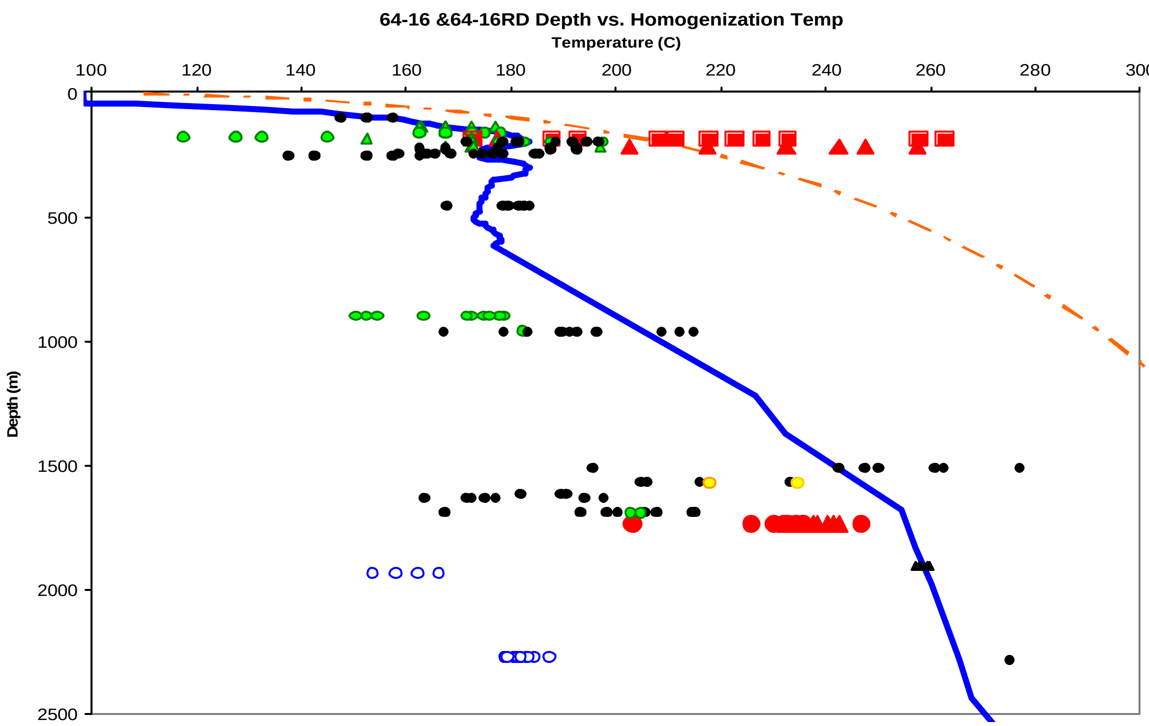

Figure 5. Circles represent inclusions from calcite and triangles inclusions from quartz. Salinity of the inclusion is represented by its general size and color, where black is 0-1%, green 1-2%, yellow 2-3%, and red 3+%. The blue line is present temperature and the dashed line is the boiling pt. curve for pure water.

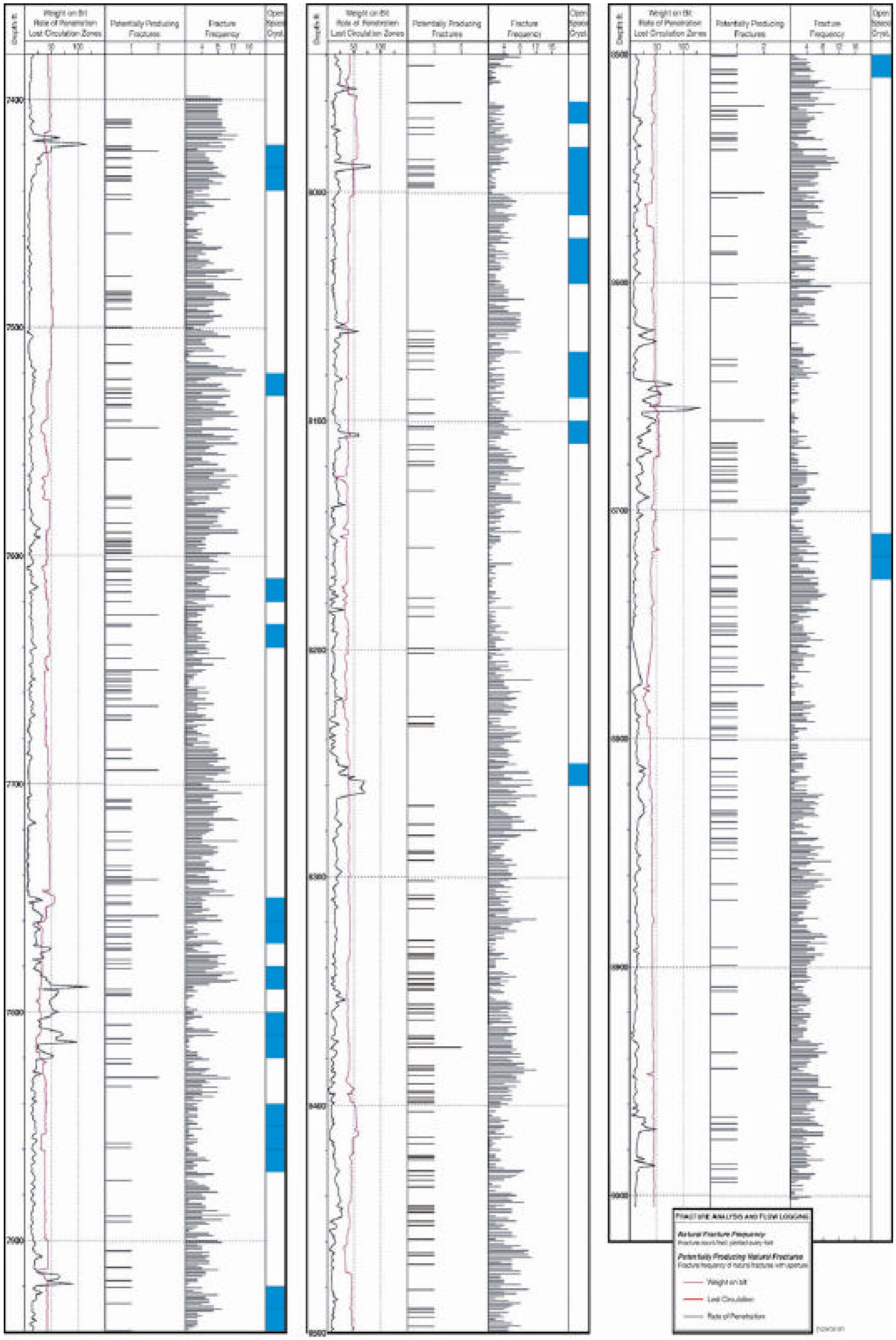

Figure 6. Chart correlating rate of penetration, potentially producing fractures, fracture frequency, and open-space crystal locations for the bottom third of well 38B-9.

CONCLUSIONS

The following conclusions can be drawn from petrologic investigations of East Flank wells:

1. Diorites, granodiorites and granites are the most common rock types on the East Flank. Diorites are the most abundant and most extensively altered.
2. Hydrothermal alteration has produced high temperature veins of epidote-chlorite-pyrite-quartz in the diorite but not granodiorite and granite. The epidote is interpreted as forming prior to or during granitic intrusion.
3. Crosscutting relationships indicate that the youngest veins are only partially filled and contain an early episode of quartz and later calcite and hematite.
4. Fluid inclusions trapped in late-stage quartz and calcite have low salinities. These minerals are considered to represent recent geothermal activity.
5. The distribution of euhedral crystals in well 38B-9 correlates most closely with increased rates of drilling penetration and possibly zones of increased permeability.
6. Depth zones that display a correlation between euhedral crystals, increased rate of penetration and potentially producing fractures may be appropriate targets for hydrofracturing.

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