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INTEGRATED ALTERATION MINERALOGY AND FLUID-INCLUSION STUDY AT THE DIXIE VALLEY GEOTHERMAL FIELD. NEVADA

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ABSTRACT

Cuttings from geothermal wells in Dixie Valley, Nevada document the complex history of the Jurassic reservoir rocks now contained within the hanging wall of the Stillwater normal fault. Six stages of post-Oligocene alteration can be recognized on the basis of mineral paragenesis, rock associations, fluid-inclusion temperatures and apparent salinities. The paragenetic sequence from oldest to youngest consists of: Stage I) epidote-chlorite-calcite veins; Stage 11) illite; Stage III) wairakite-quartz-calcite-potassium feldspar-epidote veins; Stage IV) mixed-layer illite-smectite and quartz-calcite veins; Stage V) chalcedonic quartz-dolomite-calcite-chlorite/smectite-barite-hematite veins; and Stage VI) quartz-calcite veins. Fluid-inclusion data yield the following temperatures and apparent salinities in weight percent NaCl equivalent: Stage I) 270" to 325°C and 1.4 to 1.6%; Stage 11) 220" to 270°C and 1.6 to 1.9%; Stage 111) 230" to 240°C and 1.2%; Stage IV) 180" to 220°C and 0.4 to 0.5%; Stage V) <160°C and 0.0%; and Stage VI) 200" to 270°C and 0.0 to 0.5%. Present-day fluid inclusions deposited in wellbore scale yield homogenization temperatures of about 200°C and salinities of 0.0 to 0.4 weight percent NaCl equivalent. Moderately saline fluids of the Stage I through III assemblages appear to be associated with hydrothermal systems that developed during initial Basin and Range extension. Low salinity and low temperature Stage IV and V inclusions suggest the presence of cool fluids at shallow depths along the Stillwater fault. Stage VI quartz and calcite veins were deposited by the modern geothermal system (Tmax = 248°C, salinity = 0.1-0.2 wt %) along this still-active fault.

INTRODUCTION

Dixie Valley is a fracture-dominated geothermal system located on the east side of the northern Stillwater Range in west-central Nevada. With a 62 megawatt power plant (operated by Oxbow Power Corp.), Dixie Valley is the largest non-volcanic geothermal system in the Basin and Range province. Although the circulation of geothermal fluids within the field is dominantly controlled by fracture permeability along the still-active rangefront fault (the Stillwater normal fault), most wells produce from a zone of fractured Jurassic-age rock located above the trace of the main fault. These Jurassic rocks have undergone a long and complicated structural history that includes both Mesozoic compressional and Cenozoic extensional events (Plank, 1996). Our studies have focussed on the post-Oligocene alteration of these rocks, and the relationship and cumulative effect of these alteration events upon the permeability of the current geothermal reservoir (Lutz et al., 1996; 1997). From our petrographic and fluid inclusion work, we now recognize six major mineral assemblages that represent alteration events associated with the early stages of Basin and Range extension and the evolution of the Dixie Valley geothermal system.

The purpose of this paper is to refine our model of the alteration history of reservoir rocks in the Dixie Valley geothermal field based on new information obtained from fluid-inclusion analyses and petrographic observations from wells located outside of the main producing area. The objective is to understand the history of fluid flow along faults and the alteration events that have affected the permeability of the present geothermal reservoir.

METHODS

Cutting samples from six Dixie Valley geothermal wells were studied in thin-section to determine rock type and the distribution and paragenetic relationships among the secondary minerals. X-ray diffraction techniques were used to characterize the clay minerals and to determine the percentages of mineral phases in the rock. Fluid-inclusion analyses of vein material yielded the homogenization temperatures and apparent salinities of the fluids that produced the alteration minerals. Mineral geothermometers are compared with the inclusion temperatures and downhole thermal measurements to assess the evolutionary changes that have occurred since the secondary minerals were formed.

Fluid-inclusion analyses were made on polished thin-sections of well cutting samples from production wells 45-33, 82-5, 73B-7, and 52-18, and from wells 62-21 and 66-21 located to the southeast and southwest, respectively, of the field (Fig. 1). Most of the thermometric measurements were made on calcite vein fragments collected from the well cuttings. In addition, fluid inclusions in scale deposits from geothermal well 76-7 were studied. Preliminary fluid inclusion analyses were also performed on vein samples from the Dixie Comstock mine and Mirrors outcrop localities. A total of 550 fluid inclusions were measured.

ALTERATION MINERALOGY

In our previous studies, we described four major stages of alteration related to the Stillwater fault system (Lutz et al., 1996; 1997). However, based on our more recent fluid inclusion and petrographic work, we now recognize at least six post-Oligocene alteration assemblages in the Jurassic reservoir rocks at Dixie Valley. From oldest to youngest they are: Stage I) epidote-chlorite-calcite veins; Stage 11) illite; Stage III) wairakite-quartz-calcite-potassium feldspar-epidote veins; Stage IV) mixed-layer illite-smectite and quartz-calcite veins; Stage V) chalcedonic quartz-dolomite-calcite-chlorite/smectite-barite-hematite veins; and Stage VI) quartz-calcite veins.

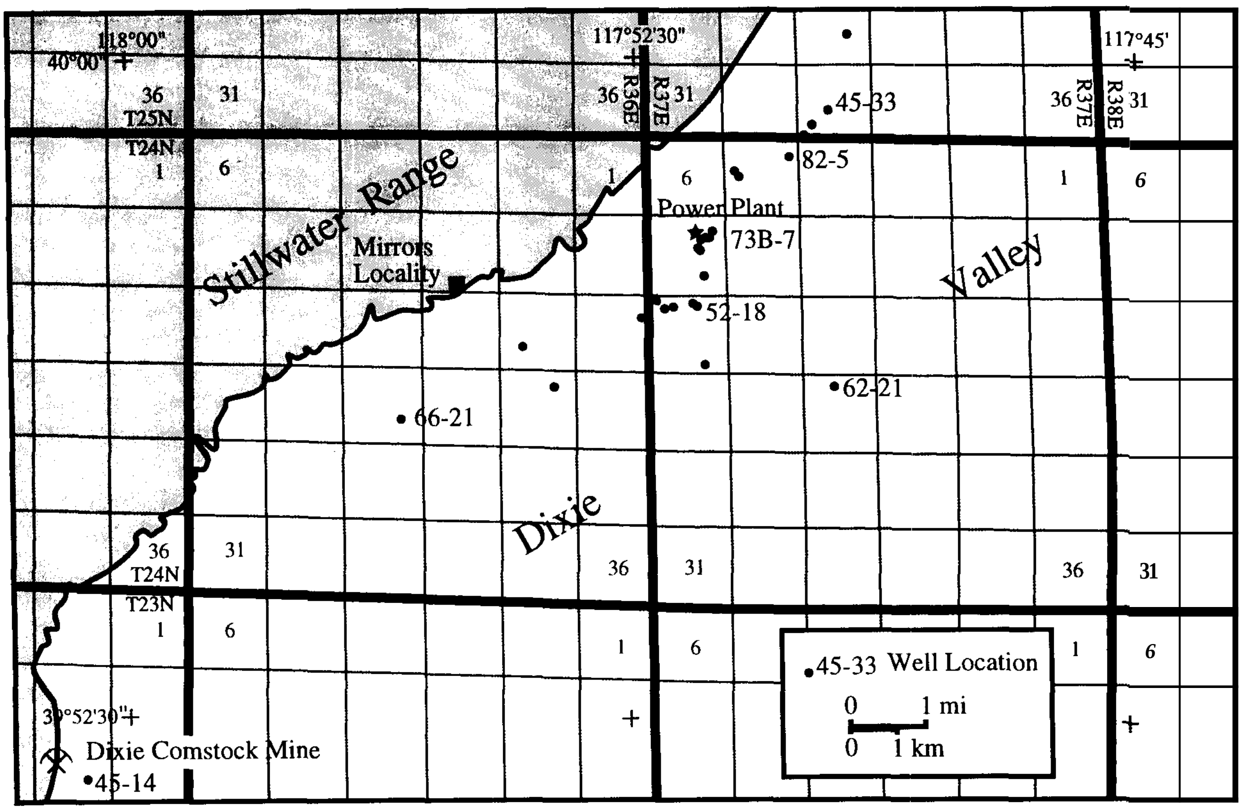


Fig. 1. Map showing locations of study wells in the Dixie Valley geothermal field, F'ershing and Churchill counties, north-central Nevada. Wells 62-21 and 66-21 lie outside of the productive limits of the geothermal field. The Mirrors outcrop locality and the Dixie Comstock hot spring-type gold mine are located along the eastern side of the Stillwater Range where fault zone rocks are exposed in the footwall of the Stillwater fault.

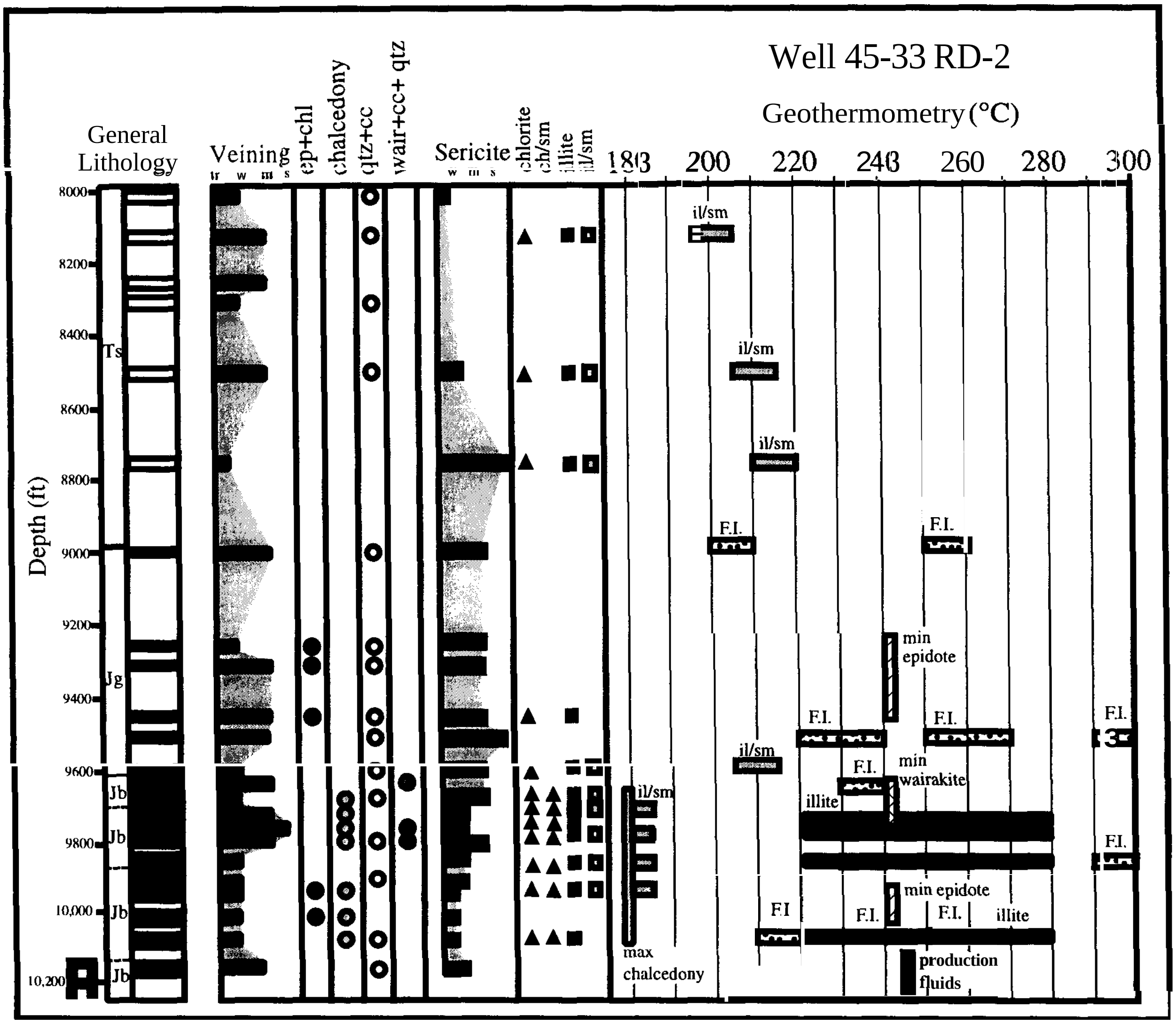
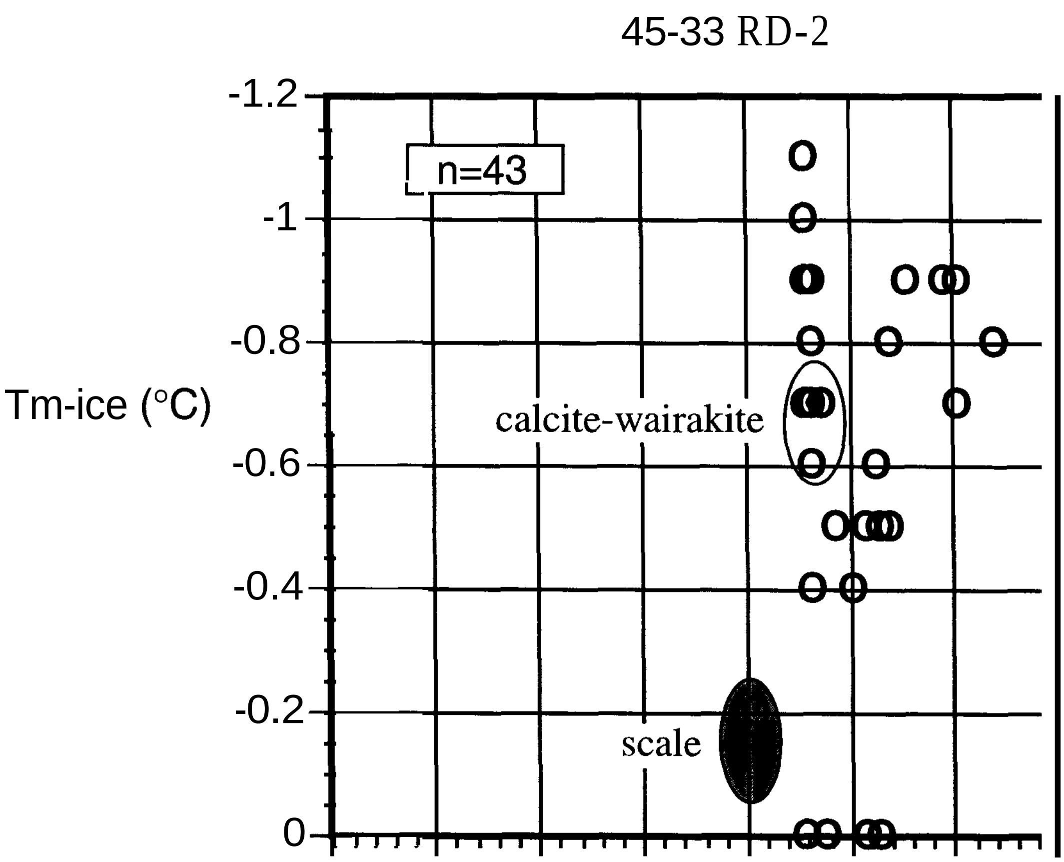


Fig. 2. Bottom portion of well 45-33 RD-2 with the clay and alteration mineral geothermometers plotted for comparison with fluid inclusion homogenization temperatures (F.I.) and present fluid temperatures. The Jurassic rocks (Jg = Humboldt igneous complex, Jb = Boyer Ranch Fm) in the production zone contain a variety of alteration minerals including quartz, chalcedony, calcite, dolomite, wairakite, illite and mixed-layer illite-smectite. The Stage IV illite-smectites and Stage V chalcedony assemblages are out of thermal equilibrium with the present measured temperature of 248°C. The wide range of fluid inclusion temperatures represents the different fluids associated with the Stage I-VI alteration events.

In central portions of the geothermal field, wairakite veins are present in the Jurassic reservoir rocks of the deep production wells. In thin-section, the wairakite-quartz-calcite veins appear fresh and occur in sericitized rock. Figure 2 graphically displays the relationships between the mineral and fluid-inclusion thermometry and the location of lost circulation zones in well 45-33 RD-2. Because wairakite commonly forms at temperatures above 240°C and present production fluids in this well are about 248°C, we concluded in our previous study that the wairakite veins probably were deposited by the modern geothermal system.

Our recent petrographic studies indicate that wairakite veins are also found in wells 62-21 and 66-21, located in cool areas outside of the main productive area. In well 62-21 with maximum measured temperatures of about 180°C, traces of wairakite are present in Jurassic rocks at 8300 ft. In well 66-21, wairakite



veins are common from 5600 ft to 6600 ft in the Jurassic igneous complex. The wairakite occurs with prehnite, quartz and calcite in veins that appear to be associated with the presence of andesitic dikes and epidote alteration in the Jurassic section. Also present in this interval are laumontite-calcite veins that record deposition by much cooler fluids (Browne, 1993). These laumontite veins are more likely related to the current thermal regime as maximum measured temperatures are about 150°C in this well. Thus, the wairakite probably formed as a result of an older, hotter hydrothermal event.

In all the wells where wairakite is present, it occurs as veins within sericitized rock, and in most places, it is spatially related to the presence of andesitic dikes that are texturally and mineralogically similar to dikes of Miocene age described from the Stillwater Range (Dilek and Moores, 1995). If the illite in the Dixie Valley drillholes is the same age as sericite from the nearby Dixie Comstock mine (K-Ar dates of 11 to 15 Ma; Vikre, 1994), then it is likely that both the Stage II illite and the Stage III wairakite assemblages in the drillholes are related to Miocene alteration events, The presence of mixed-layer illite-smectite of the Stage IV assemblage, and the chalcedony and dolomite of the Stage V assemblage suggests cooler alteration events that post-date Miocene faulting, basaltic volcanism and dike intrusion.

FLUID-INCLUSION DATA

Most of the fluid-inclusion data comes trom calcite vein fragments from the deep production wells, Figure 3 is a plot of homogenization temperatures (Th) versus the temperature of ice melting (Tm-ice) in vein samples from well 45-33 RD-2. The data suggest the presence of two distinct populations of fluid inclusions in the Jurassic section. One group has ice melting temperatures of less than -0.4°C (greater than 0.7 wt % NaCl equivalent) and homogenization temperatures of 235" to 300°C. The second group has lower apparent salinities, up to 0.5 wt % NaCl equivalent (Tm-ice of -0.3°C) and homogenization temperatures of 200" to 270°C.

Scale from geothermal well 76-7 was deposited by present-day boiling fluids in the wellbore. Inclusions in the scale yielded homogenization temperatures of 200°C and apparent salinities of 0.18 to 0.4 wt % NaCl equivalent (Tm-ice of -0.1 to -0.2 °C). Part of the lower salinity population of vein inclusions from well 45-33 formed under similar conditions as the calcite scale (Fig. 3). This suggests that some of the calcite in the reservoir rocks was deposited by modern geothermal fluids.

Although fluid-inclusion temperatures for wairakite veins from well 45-33 (Fig. 3, Th = 235°C) are similar to the temperature of the production fluids in this well (Tmax = 248°C), the salinity data indicate that the inclusion fluids are too saline (up to 1.2 wt % NaCl equivalent) to have been produced by the modern geothermal system (fluids with 0.1 to 0.2 wt % NaCl).

Fluid inclusions from calcite veins in the marginal 66-21 and 62-21 wells, and from calcite in quartz breccia samples collected at the Mirrors and Dixie Comstock mine outcrops yielded limited data. The calcite samples contained few fluid inclusions and many of these were stretched or necked. The inclusions homogenized at low temperatures (less than 180°C) and although no salinity measurements were obtained, they generally appear to be of low salinity. Vikre (1994) studied similar fluid inclusions in vein calcite from the Dixie Comstock mine and concluded that these late-stage veins formed at low temperatures (160" to 180°C) from essentially meteoric fluids.

In general, it is not possible to assign a particular calcite vein fragment to a specific alteration assemblage because the individual well cuttings are small and usually do not contain the complete vein assemblage, and the vein assemblages are not mineralogically distinctive. Calcite and quartz are very common vein minerals and occur in most of the alteration assemblages described in this study. Using known thermal stabilities of the alteration minerals as a guide (Browne, 1993), we can predict which groups of fluid-inclusion data may be associated with the individual alteration events. For example, using X-ray diffraction data from 8100 ft in well 73B-7, mixed-layer illite-smectite (Stage IV alteration) appears to have formed between 180" and 220°C (Lutz et al., 1996). Fluid-inclusion study of this sample reveals that inclusions with homogenization temperatures of 180" to 220°C generally have apparent salinities of 0.4 to 0.5% NaCl. Following this integrated approach for other samples, the fluid-inclusion data yield the following temperatures and apparent salinities in weight percent NaCl equivalent for each of the alteration assemblages: Stage I) epidote-chlorite-calcite veins, 270" to 325°C and 1.4 to 1.6%; Stage 11) illite, 220" to 270°C and 1.6 to 1.9%; Stage 111) wairakite-**quartz-calcite-potassium** feldspar-epidote veins, 230" to 240°C and 1.2%; Stage IV) mixed-layer illite-smectite and quartz-calcite veins, 180" to 220°C and 0.4 to 0.5%; Stage **V)** chalcedonic quartz-dolomite-calcite-chlorite/smectite-barite-hematite veins, <160°C and 0.0%; and Stage VI) quartz-calcite veins, 200° to 270°C and 0.0 to 0.5%.

DISCUSSION

Compared with fluid-inclusion studies conducted on samples from the southern Stillwater Range (Parry et al., 1991; Hedderly-Smith, 1997), the fluid inclusions in the Dixie Valley geothermal reservoir generally appear to be less saline, contain less CO_2, and have lower homogenization temperatures. Parry et al. record homogenization temperatures of up to 400°C, salinities up to 39 weight percent NaCl in halite-bearing inclusions, and substantial C02 in clathrate-bearing inclusions. They also record the presence of an early biotite-potassium feldspar assemblage and late Oligocene-early Miocene sericite alteration. Using hydrothermal alteration products, and fluid-inclusion temperatures, pressures, and compositions, they estimate up to 6 km of vertical displacement of the footwall of the Dixie Valley fault. In the hanging wall of the Stillwater fault in northern Dixie Valley, most of the fluid inclusions are only moderately saline and there is no evidence for significant amounts of CO_2. Sericite alteration at the nearby Dixie Comstock mine is mid-Miocene in age. Stratigraphic relationships suggest only about 3 **km** of offset between Miocene basalts in the northern Stillwater Range and those in the adjacent Dixie Valley geothermal field.

The differences observed in the alteration mineralogy and fluid-inclusion data between footwall rocks of the southern Stillwater Range and the hanging wall reservoir rocks in northern Dixie Valley represent differences in the timing of Cenozoic structural events in the region. Vikre (1994) recognized three major epochs of faulting and thermal activity in the Dixie Valley area; the earliest occurring during the late Oligocene-early Miocene, a mid-Miocene episode, and a Quaternary episode. In the southern Stillwater Range, Oligocene activity appears to be represented by high temperature and salinity fluid inclusions, and sericite that has yielded ages of 21-25 Ma (Parry et al., 1991). The high fluid-inclusion temperatures suggest that this event may have been related to magmatic-hydrothermal alteration and late Oligocene faulting and tilting of the Stillwater caldera complex (Hudson and Geissman, 1991; John, 1995). The Stage I inclusions found in the Dixie Valley geothermal field, which yielded temperatures of up to 325°C, and the associated epidote-bearing assemblages, may be possible manifestations of this Oligocene event.

In the northern Stillwater Range, mid-Miocene activity is represented by sericite that has been dated at 11-15 Ma at the Dixie Comstock mine (Vikre, 1994) and by andesitic dikes dated by Dilek and Moores (1995). Stage II illite alteration and andesitic dikes encountered in the geothermal wells may be of similar ages. In the wells, the dikes are associated with the presence of Stage III wairakite-quartz-calcite-prehnite veins. Fluid inclusions from these veins have homogenization temperatures averaging 235°C and salinities of 1.2 weight percent NaCl equivalent.

Carbonate-barite veining, gold mineralization and associated quartz sinters at the Dixie Comstock mine (Vikre, 1994) represent Quaternary thermal events. From fluid-inclusion and stable isotope determinations, Vikre showed that the mineralizing fluids were meteoric waters with relatively low temperatures. Based on the offset and stratigraphic position of fossil hot-spring sinters along the Dixie Comstock fault, Vikre concluded that the mineralization was mid-Pleistocene in age. We suggest, based on the similarities in the composition of the Stage V mineral assemblage in the geothermal wells (chalcedonic quartz-calcite-dolomite-barite-hematite), that this stage was contemporaneous with mineralization at the Comstock mine. Stage V inclusions record temperatures of less than 160°C and salinities of zero.

The presence of chalcedony within the present-day geothermal reservoir is inconsistent with its thermal stability (Fig. 2; and Fournier, 1985). Although mineralization clearly related to the modem geothermal activity is poorly constrained by cross-cutting relationships in the well cuttings, geochemical modeling by Bruton et al. (1997) indicates that calcite and quartz should be stable mineral phases within the present reservoir. We have found fluid inclusions in calcite vein fragments with temperatures and salinities that are consistent with the reservoir fluids in the Jurassic reservoir rocks. These inclusions yielded an average temperature of about 230°C and salinities ranging from 0.0 to 0.5 weight percent NaCl equivalent. In well 45-33, part of the low-salinity inclusion population exhibits homogenization temperatures of up to 270°C. Since the maximum fluid temperature in this well is about 248°C, this suggests some cooling of the modern geothermal system since its emplacement along the Stillwater fault.

SUMMARY

Fluid inclusions from the central portions of the Dixie Valley geothermal field record deposition from multiple thermal events. Although temperatures vary from 120" to 325" C, the fluids related to these events generally appear to have been of low to moderate salinity. Fluid inclusions with moderate apparent salinities (1.2 to 1.9 wt % NaCl equivalent) correspond to thosa with the higher homogenization temperatures (235°to 325°C) that represent the older (pre- late Miocene] Stage I to III alteration assemblages. Field relationships and petrographic analyses suggest that the Stage II sericite (illite) and Stage III wairakite veins represent Miocene alteration events associated with north-northwest faulting and intrusion of andesitic dikes during the initial stages of Basin and Range extension in the northern Dixie Valley area. The fluids associated with these events are represented by moderate-salinity fluid inclusions (1.2 to 1.9 wt % NaCl equivalent) with homogenization temperatures in the 220" to 270°C range. Descent of the hanging wall of the northeast-trending Stillwater fault occurred after the deposition of Miocene basalt flows and dike intrusion. Low-salinity Stage IV and V fluid inclusions suggest the presence of cool fluids at shallow depths along the Stillwater fault. Stage VI quartz and calcite veins appear to have been deposited by the modem geothermal system (Tmax = 248°C, salinity = 0.1-0.2 wt %) after the Jurassic rocks descended to their present depth of 2-3 km along this still-active fault. Stage VI fluid inclusions with zero salinity and homogenization temperatures of up to 270°C may represent slightly higher fluid temperatures earlier in the history of the modern geothermal system.

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