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FLUID STRATIGRAPHY OF THE COSO GEOTHERMAL RESERVOIR

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ABSTRACT

A fluid model for the Coso geothermal reservoir is developed from Fluid Inclusion Stratigraphy (FIS) analyses. Fluid inclusion gas chemistry in well cuttings collected at 20 ft intervals is analyzed and plotted on well log diagrams. The working hypothesis is that select gaseous species and species ratios indicate areas of groundwater and reservoir fluid flow, fluid processes and reservoir seals. Boiling and condensate zones are distinguished. Models are created using cross-sections and fence diagrams. A thick condensate and boiling zone is indicated across the western portion of the field. The east flank area has a thinner condensate zone and thicker seal zone than the western portion. The boiling zones for both the western portion of the field and the east flank correspond to areas of increase permeability and present day production zones. Reservoir fluids are shown to rise to the north, which agrees with fluid inclusion studies. The boundary between the east and western sides of the field are evident in the cross-sections developed using this method.

INTRODUCTION

Fluids trapped in inclusions as minerals develop are generally faithful indicators of pore fluid chemistry. Temperatures and composition of geothermal fluids are sensitive indicators of their origins, evolutions, and the processes that have affected them. Samples of these fluids are trapped in inclusions in vein minerals formed by circulating waters and in minerals within microfractures that form in the surrounding wall rocks. Mass spectrometer analyses of gases within these inclusions have shown fluid sources and processes within geothermal systems (Giggenbach 1997; Norman 1997; Dilley et al. 2004; Dilley and Norman, 2004; Norman et al., 2004; Norman et al., 2005).

The purpose of this research, funded by the California Energy Commission, is to develop the FIS technique as a low cost, fast logging tool for evaluating geothermal bore holes, and to map reservoir fluid stratigraphy. The assessment techniques seek to distinguish non-producing from producing wells and to identify major geothermal fluid-bearing fractures, and entrants of cold or steam-heated waters. Analysis of multiple wells should allow mapping reservoir fluid stratigraphy. Based on our analyses we have developed a fluid model for the Coso geothermal reservoir using the FIS technique. This is the seventh paper in this series presenting the new technique of fluid inclusion stratigraphy.

COSO GEOTHERMAL FIELD

Coso geothermal system is a volcanic hosted system and is a mixed California-Sierran and Basin and Range system. Based upon the rocks observed on the surface and fluid inclusion data, there appears to be three episodes of thermal activity (Adams, et al, 2000). The first episode was a large-scale system but of low to moderate temperature. The second episode was produced by magmatic activity beneath the dome field resulting in a large, high temperature system. The most recent event has heated up the eastern flank by 100º C and reactivated the high temperature center beneath the southern part of the field. The present day geothermal system is partitioned into at least two reservoirs that are weakly connected. Chemical and fluid inclusion data suggest that fluids move up and outward from the southern section of the field towards the north and east (Moore, et al, 1989).

METHODS

Since the project started in 2004, we have analyzed a total of 15 wells from the Coso Geothermal Field (Figure 1). For each well, splits of 10 to 20 grams were taken from drill cuttings at 20-foot intervals throughout each well. Over 5,000 samples were submitted to Fluid Inclusion Technology laboratory for analyses. Analyses are performed by first cleaning the samples, if necessary, then crushing a gram-size sample in a vacuum. The volatiles released are pumped through multiple quadrupole mass spectrometers where molecular compounds are ionized and separated according to the mass/charge ratio. Electronic multipliers detect the signal, which is processed creating a mass spectrum for each sample. The output data for each sample is the magnitude of mass peaks for masses 2 to 180. A volatile like CO_2 has a gram formula weight of 44 and will be measured by a peak at mass 44. FIT returned the raw data within three weeks, however upon request this time can be reduced to a few days.

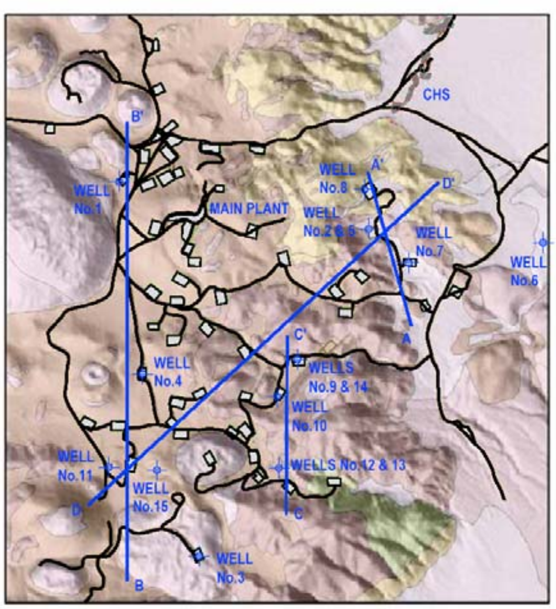

Figure 1. Map of the Coso Geothermal Field showing the cross-section and well locations (After Moore, 2005).

The FIT data was presented to us for interpretation. Logs and some limited well information such as production fluid temperature or rock types were provided after the preliminary analysis for several of the wells. Based on the previous work with the first four wells and subsequent work with core samples and the additional 11 wells, we have been able to show that certain gas ratios indicate certain present day fluid types as well as present day fractures (Dilley and Norman, 2004; Dilley et al, 2004).

Rockware® program Logger was used to plot for each well two types of mud log diagrams (Norman et al, 2005). One diagram displays mass peaks, which provides information on the relative concentrations of a gaseous species down hole. The other diagram plots gas ratios and species that are used to interpret fluid types. The species of interest are the principal gaseous species in geothermal fluids and trace hydrocarbon species, which include H_2, He, CH_4, H_2O, N_2, H_2S, Ar, CO_2, C_2H_4, C_2H_6, C_3H_6, C_3H_8, C_4H_8, C_4H_{10}, benzene, and toluene. Analysis of Coso fluid inclusion gases and analyses of early well gas chemistry indicate production fluids have magmatic N_2/Ar ratios and low CO_2/CH_4; hence these ratios are used to identify high-temperature reservoir fluids. Gas ratios and sums that are used, and their interpretations are as follows:

- <u>Reservoir fluids</u> are indicated by N_2/Ar (mass 28/mass 40) > 200, CO_2/CH_4 (mass 44/mass 16) > 4, (N_2/Ar + CO_2/CH_2)/ (propane/propene (mass 43/mass 39)) termed Ratio 1, and (N_2/Ar + CO_2/N_2) called Ratio 2.
- <u>Shallow Meteoric fluids</u> are indicated by N_2/Ar ratios < 200, CO_2/CH_4 < 4, propane/propene >1, and 1/Ratio 1 > 0.5
- <u>Steam heated waters</u> have elevated H_2S and H_2S/N_2 and sometimes elevated CO_2/N_2. Elevated CO_2/N_2 is common in deep reservoir waters that can condense magmatic volatiles. We expect that steam-heated waters will have magmatic mass 28/ 40 ratios because the condensed fluids are a source from boiling deep production fluids.
- <u>Mixed fluids</u> are indicated by a combination of the various ratios mentioned above.
- <u>Boiling and gas caps</u> are indicated by high gas/water ratios and by high total gas.
- <u>Seals</u> are areas that show little to no peaks for any of the compounds. It is assumed that this indicates little fluid flow through these areas.

Figure 2 presents the two well logs for Well 2. Based on the above, an interpretation of fluid types and seal locations was made for each well. For the first four wells these interpretations were checked against temperature logs and based on knowledge from Coso geologist appears to indicate reservoir conditions.

Subsequent wells were checked against temperature logs and other information from other studies. From these interpretations the cross-sections for four separate sections of the field were developed.

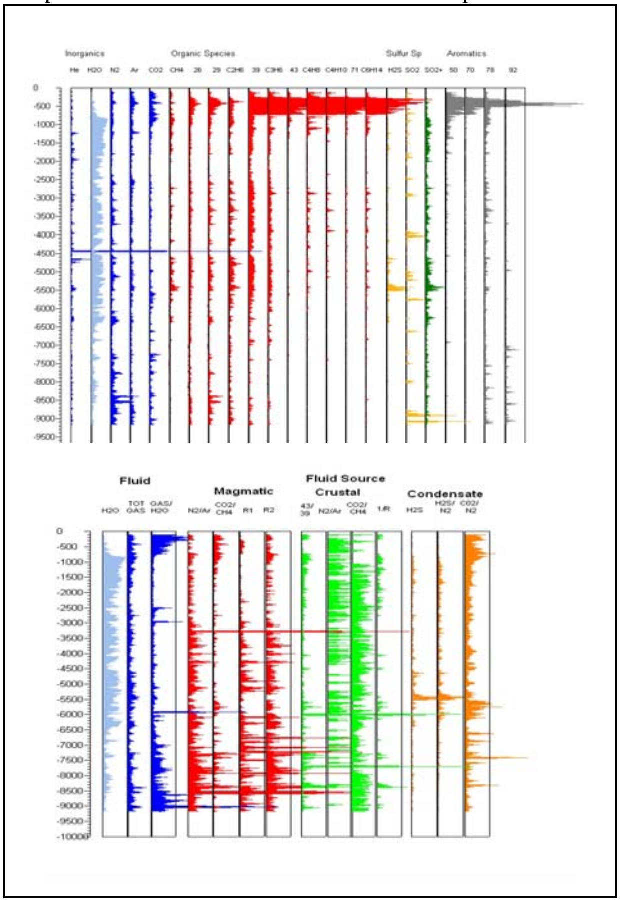

Figure 2: Well logs for Well 2. Note the large organic peaks near the surface indicating shallow meteoric fluids and the high N_2/Ar and CO_2/CH_4 ratios at depth indicating reservoir fluids.

EAST FLANK

Figure 3 presents a cross-section developed for the area of the field known as the East Flank. Four wells were studied from this area, Wells 2, 5, 7 and 8. Wells 2 and 7 are considered moderate to large producers. Well 8 is currently an injection well. Well 5 was sampled for FIS analysis during the drilling process and is a moderate to large producer.

It can be seen in Figure 3 that a seal occurs separating the shallow meteoric fluids from a steam/condensate zone and a mixed fluid zone. Below zones is an area interpreted to represent fluids that have undergone boiling. The boiling limit was define as the area were gas/water ratios changed significantly and high amounts of various gases such as CO_2, N_2, and CH_4 are present in the fluid inclusion gas chemistry. These fluids are considered reservoir fluids. On the East Flank the reservoir fluids have a magmatic derived component. Typically these fluids have high amounts of nitrogen and carbon dioxide. The production zone lies below the boiling limit and within the reservoir fluids.

Well #8 is an injection well. The fluid inclusion gas chemistry indicates that the majority of fluids within the well are shallow meteoric fluids. There is some evidence for boiling and reservoir fluids at shallower depths than in the other wells along the East Flank. The boiling limit at approximately 5,100 feet in depth, determined from the fluid inclusion gas chemistry for this well is within 200 feet of an increase in homogenization temperatures from fluid inclusion work conducted by Kovac, et al, 2005 for this well. For this well this level also corresponds to a change in rock type from diorites and granodiorites to granites.

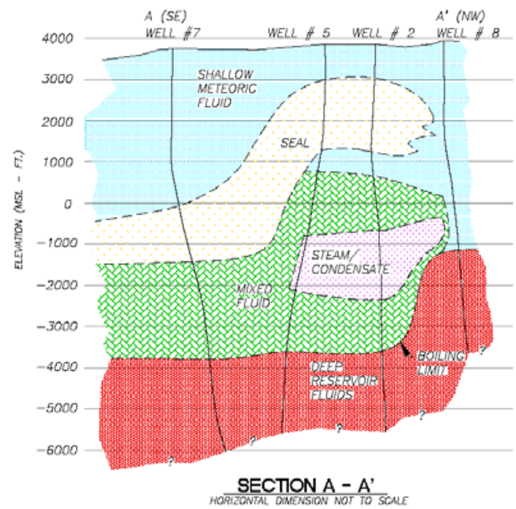

Figure 3: Cross-section based on FIS of the East Flank area.

WESTERN EDGE

Figure 4 presents a cross-section developed for the western edge of the field. Three wells were placed along this cross-section: Well 1, 4 and 11. Well 11 is the deepest well we have interpreted in the study extending to approximately 9,000 feet below sea level in elevation. Wells 1 and 4 are moderate producers. Well 11 is an injection well. It is hot however, the permeability is low. Well 4 was one of the first wells to be interpreted and was included in the study to determine if cold water entrances could be determined from the fluid inclusion gas chemistry. Based on previous work reported in Dilley, et al, 2004, there is a correlation between the fluid inclusion gas chemistry indicating meteoric water entrances and reductions in the temperature log. Thus we interpret the occurrence of fluids with a meteoric signature in a zone dominated by reservoir fluid gas chemistry as a cold water entrance.

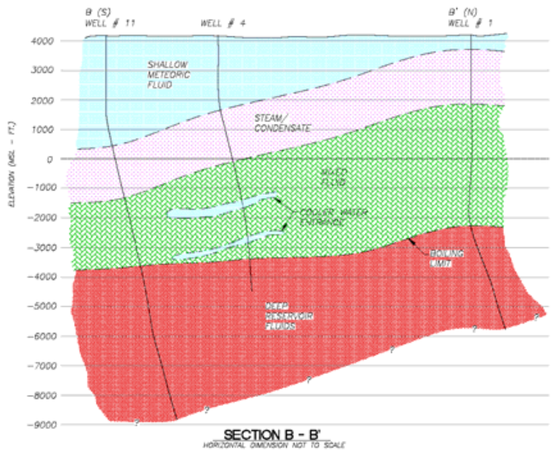

Figure 4: Cross-section based on FIS of the western edge of the Coso field. Well 1 is to the north end of the field.

From the cross-section there appears to be a rise in the deep reservoir fluids and the steam/condensate zone from the south (Well 11) to the north (Well 1). This cross-section is similar to the cross-section of homogenization temperatures and salinities shown in Figure 5. This cross-section is presented in Adams, et al, 2000 and was prepared from fluid inclusion studies by Joe Moore and Dave Norman. The low salinity fluids, Th~ 150-200 C fluids are interpreted as steam condensate fluids, and their location corresponds well to our interpreted steam/condensate zone. Adams et al (2000) high salinity, high-temperature fluids are interpreted as reservoir fluids and the location of these fluids match the location of our reservoir fluids.

It was further suggested in the Adams paper that there was a change between the early and modern systems with the disappearance of the low-salinity groundwater since the last pluvial period in the area around 10,000 years ago. From the fluid inclusion gas chemistry, the area indicated in Figure 4 as shallow meteoric fluid has low N_2/Ar and low CO_2/CH_4 ratios suggesting meteoric fluid rich in organic compounds that commonly include organic species as butane, propane, and ethylene. The organic signature is thought to be playa waters that fed the system in the past.

MIDDLE SOUTHERN PORTION

Figure 6 presents the cross-section developed for the middle southern portion of the field. Noticeable is a significant seal and lack of geothermal reservoir

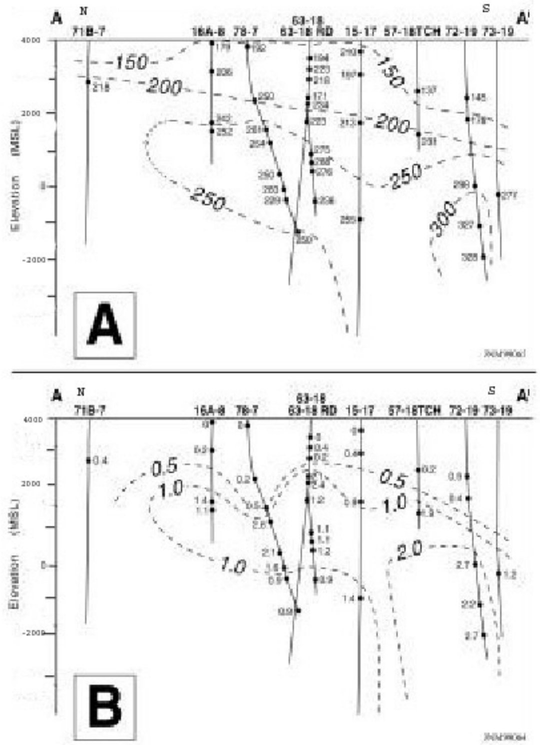

Figure 5: North-south cross-sections of the reservoir prepared based on fluid inclusion studies in 1999/2000 in Adams et al, 2000. A) Maximum fluid-inclusion homogenization temperatures and B) maximum salinities of inclusion in weight percent NaCl equivalent. A on the cross-section is to the north and A' is to the south.

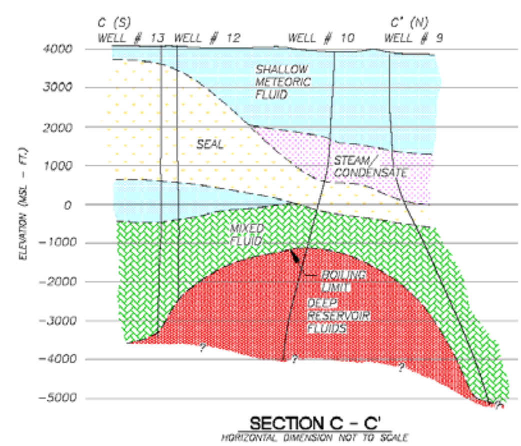

Figure 6: Cross-section based on FIS of the middle southern portion of the Coso field.

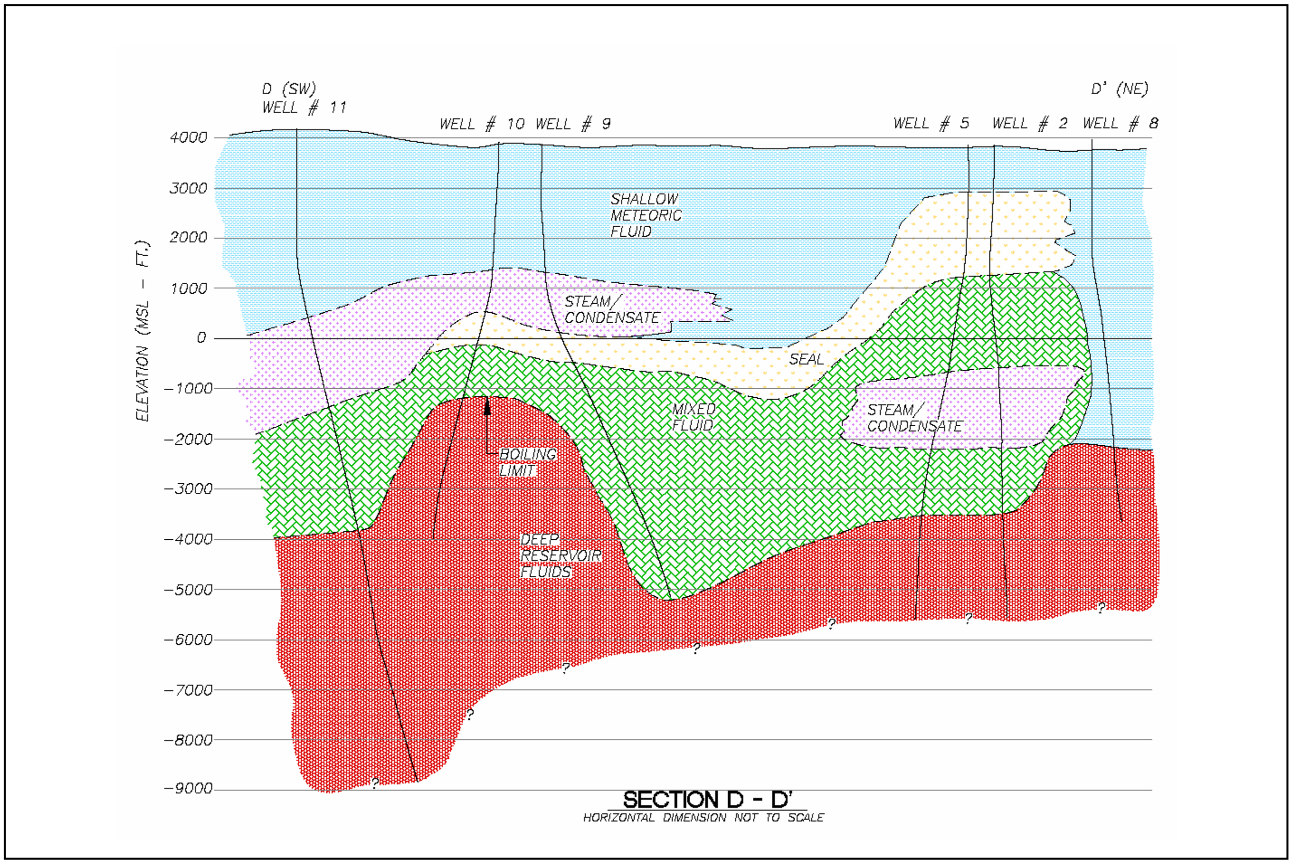

Figure 7: Cross-section based on FIS diagonally across the Coso field from the southwest to the northeast.

fluids in Wells 12 and 13. Wells 9 and 10 show an isolated steam/condensate zone. This at first glance appears incorrect. However, the occurrence of the Section C-C' steam condensate is explained by Section D-D' (Figure 7). Figure 7 shows that the steam/condensate zone is connected more to the south-western portion of the field and not to the underlying reservoir fluids in Wells 9 and 10. The steam/condensate zone flows over the seal.

It is unknown whether the East Flank is connected to the rest of the field as suggested in Figure 7 or if it is isolated by some fault structure. The deep reservoir fluid and boiling limit appears to rise up from the south to the middle portion of the field. The seal that started in the middle portion of the field as shown in Figure 6 and 7 appears to continue across the field and occurs in the East Flank. Based on the elevation of the seal there may be a fault that occurs where the seal rises near the East Flank wells. The steam/condensate zone on the East Flank does not appear to be connected to the rest of the field further suggesting a fault of isolation of the East Flank.

CONCLUSIONS

Based on fluid inclusion gas chemistry and the Fluid Inclusion Stratigraphy method several cross-sections were developed for the Coso geothermal field. These cross-sections show reasonable match from well to well showing a Fluid Stratigraphy, and the results agree well with prior fluid inclusion studies.

The sections show a rise in the reservoir fluids from the southwestern section of the reservoir towards the middle and north. This rise in the deep reservoir fluids is evident in Wells 11, and 9 (Figure 7) and in Well 1 (Figure 4). A seal starting in the middle portion of the field continues to the East Flank, however based on seal elevations it appears there may be a fault offsetting the East Flank from the rest of the field.

Steam/Condensate zones are shown to occur along the western side of the field and appear to migrate over the seal toward the middle of the field, further suggesting a fault or isolation of the East Flank.

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