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FLUID INCLUSION STRATIGRAPHY: NEW METHOD FOR GEOTHERMAL RESERVOIR ASSESSMENT PRELIMINARY RESULTS

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ABSTRACT

Fluid Inclusion Stratigraphy (FIS) is a new technique developed for the oil industry in order to map borehole fluids. This method is being studied for application to geothermal wells and is funded by the California Energy Commission. Fluid inclusion gas geochemistry 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 and reservoir seals. Analyses from multiple boreholes should show the stratigraphy of subsurface fluids. Analyses are performed by a commercial laboratory, Fluid Inclusion Technologies.

The FIS method modified for use on the Coso geothermal system has produced preliminary results indicating that reservoir assessment is possible. Approximately 1,700 samples from three producing and one non-producing well have been analyzed. Preliminary results show megascopic trends and much fine scale detail when the logs are analyzed in detail. Select species including carbon dioxide, nitrogen, argon, methane, and hydrogen sulfide show distinct differences between producing and non-producing wells as well as indicating fluid flow and locations of major fracture zones. Additional interpretation of the preliminary results and method will include consistency of results from one borehole to another, agreement of FIS with well logs, and appraisal of FIS analyses on well testing decisions, well completion strategies, and in resource calculations.

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; Blamey 2002).

Fluid Inclusion Stratigraphy (FIS) has been used in the oil industry to determine hydrocarbon bearing zones, seals that limit fluid flow, and fluid interfaces. Intervals of hydrocarbon fluids can be traced from hole to hole when several boreholes are analyzed, hence the use of "stratigraphy" in the name. The FIS method analyzes volatiles in fluid inclusions by mass spectrometry. The commercial process, developed in part by Fluid Inclusion Technology (FIT), is highly automated with thousands of analyses made in a day resulting in turnaround times in days and costs comparable to other logging methods. The procedure gives a downhole map of fluid distribution and chemistry plotted on borehole logs.

The purpose of this research, funded by the California Energy Commission, is to develop FIS technique for geothermal reservoir assessment. The assessment techniques seek to provide ways to distinguish non-producing from producing wells and to identify major fluid flow zones, and entrants of cold or steam-heated waters into the reservoir. The first step in developing the technique is to create a methodology that can be used in exploration. The methodology should include the sample spacing; the best species to use; how the data should be plotted; what ratios should be calculated; variations with rock type; and how to use the results to complement other logging information.

METHODS

Four wells from the Coso Geothermal Field were selected for the first round of analyses (Figure 1). Three of the wells are producers and one a non-producer. Of the three producing wells, one has entrants of cold water. Splits of 10 to 20 grams were taken from drill cuttings at 20 foot intervals throughout each well. A total of 1,729 samples were submitted to FIT for analyses. Analyses were performed first by 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 was 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.

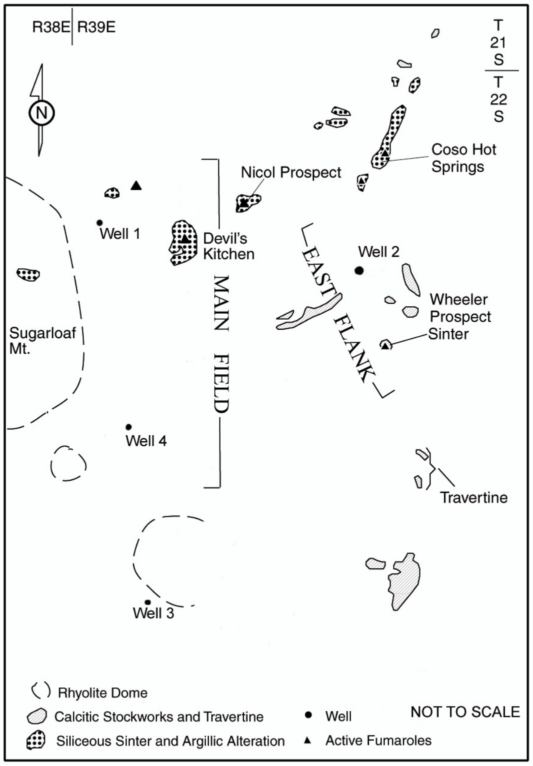

Figure 1. Location of wells used in the study and surface features of Coso. (After Lutz et al, 1999).

The raw data was converted through an Excel macro into a row of data for each sample in each well. Plotting of each mass peak versus depth for each well was conducted followed by comparing select species for all four wells on one graph. This allowed for determining if the non-producing well could be separated from the producing wells. In addition, ratios of select mass peaks were plotted. Select ratios and species were plotted next to each other and interpreted. These interpretations were compared to actual well logs to determine if the fluid inclusion data corresponded to other well information.

RESULTS

Figure 2 shows the results of plotting select species for all four wells on one graph. The species plotted are carbon dioxide, nitrogen, methane, and hydrogen sulfide. Well 3 is the non-producing well and it can be seen in the carbon dioxide, nitrogen, methane, and hydrogen sulfide graphs that this well does not contain the same amount of fluid inclusion gaseous species as the other three producing wells. This suggests that the geothermal fluids present in the producing wells were not present in Well 3. Although Well 3 analyses generally show lower amounts of carbon dioxide, nitrogen, methane, and hydrogen sulfide with respect to the other producing wells that is not the case with some other species, and selected intervals of Well 3 have analyses similar to producing wells. For example, at approximately 7500 to 7700 feet in Well 3, there is a distinct spike in the amounts of nitrogen and methane. Although the argon analyses from Wells 1 and 4 are generally higher than in Well 3 (Figure 3), the analyses for Well 2 (a production well) are similar to those of Well 3.

Megascopic trends can be observed with select gas ratios. Norman et al (1996) demonstrated that ratios of N_2/Ar ratios are indicators for the sources of gases trapped in fluid inclusions. They argued that low ratios of N_2/Ar indicate meteoric waters whereas magmatic gases are distinguished by high ratios. Fluid Inclusion Stratigraphy (FIS) analyses are not calibrated to give absolute amounts of each gaseous species. Hence N_2/Ar ratios can not be compared directly to N_2/Ar ratios measured by well gas analysis or by quantitative mass spectrometry. A N_2/Ar ratio is calculated for FIS data by dividing mass 28, the principal peak for nitrogen, by mass 40, the principal peak for argon. Plots of the fraction peaks for CO_2 and nitrogen indicate that mass peak 28 mostly represents nitrogen. We assume that lower N_2/Ar ratios in FIS analyses represent background meteoric water ratios, and that ratios significantly above background represent magmatic waters. In the case of Figures 4 and 5 background ratios appear to be between 100 and 200. Comparing downhole plots of

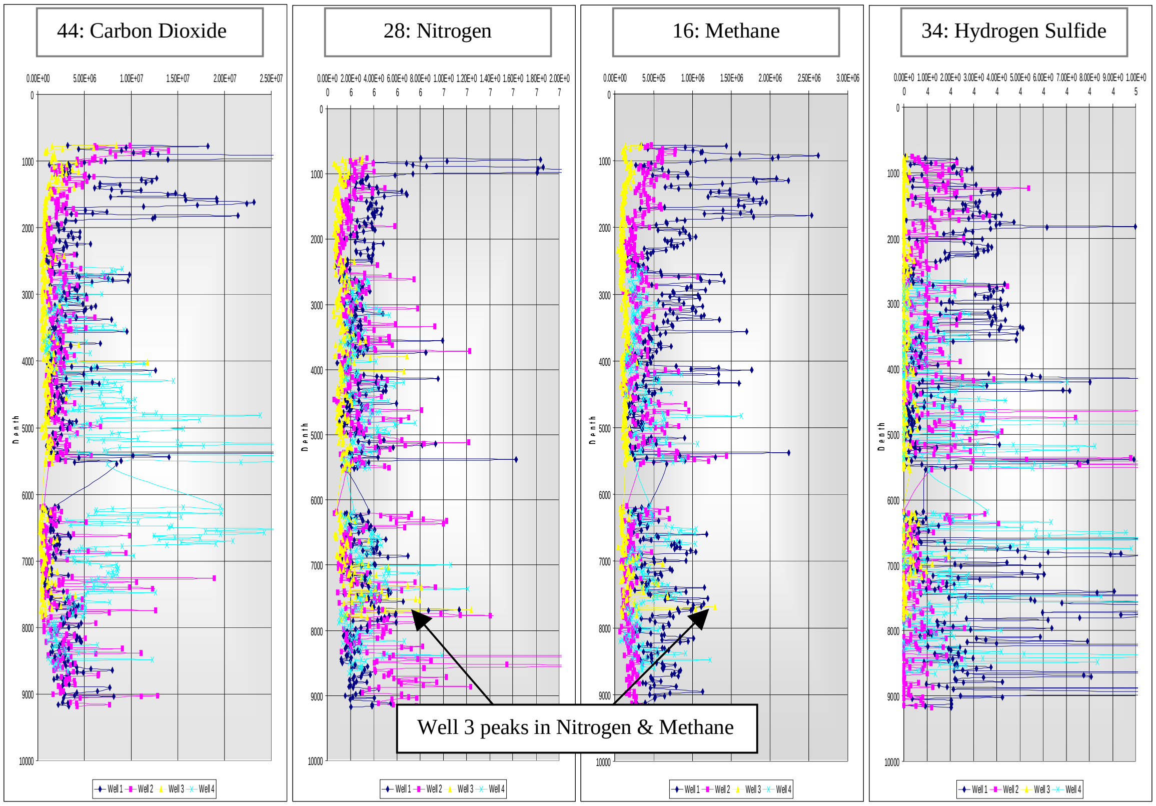

Figure 2. Select species plotted for comparison for all four wells. Wells 1, 2, and 4 are producing wells, Well 3 (black line) is a non-producing well. Well 3 fluid inclusions contain smaller amounts of carbon dioxide (graph 1), nitrogen (graph 2), methane (graph 3), and hydrogen sulfide (graph 4) than the other three producing wells.

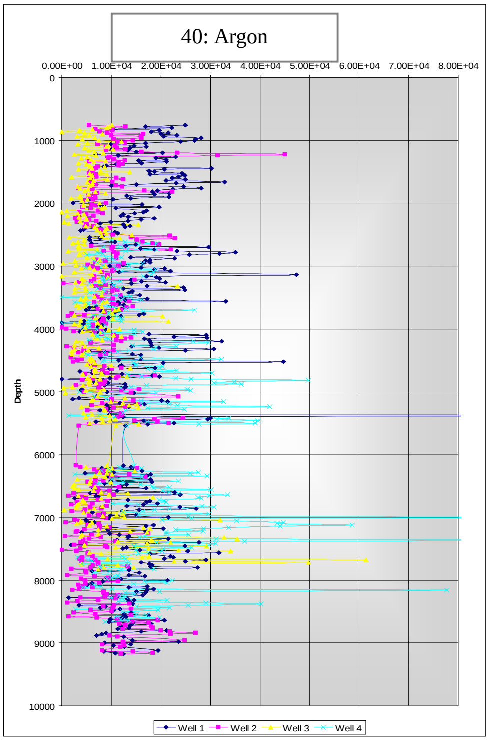

Figure 3. Comparison of argon content for all four wells. Note Well 3 (black line) has variable amounts of argon as do the other three wells. Compared to Figure 2, distinguishing producing from non-producing based on the argon content would be difficult.

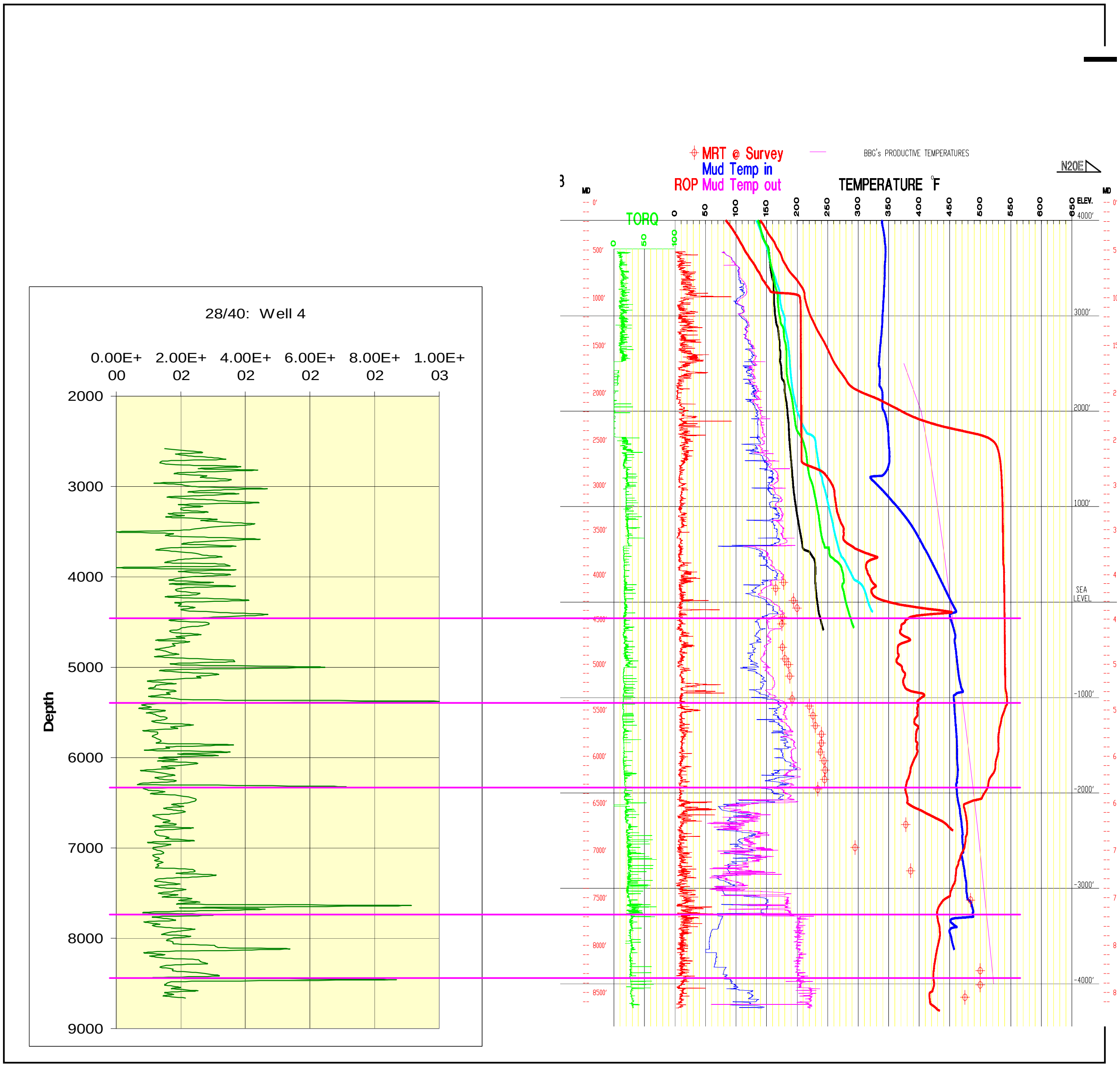

Figure 4. Comparison of N_2/Ar ratio and temperature profile for Well 4. Note decreases in temperatures from about 4200 feet to 5350 feet and again between 6500 to 7700 feet. These decreases in temperature are bounded by sharp peaks in the N_2/Ar ratios. The ratio is decreased in the areas of temperature decreases. The decreases in temperature and the N_2/Ar ratio indicate entrants of cold water. The peak at 5000 feet is not reflected in the temperature profile.

N_2/Ar ratios and temperature profiles shows a relationship between the two (Figure 4). Peaks in N_2/Ar generally correlate with temperature peaks indicating entrants of hotter water. Peaks in N_2/Ar ratio are generally 10 to 20 feet below the temperature peak which is understandable considering the 20 foot samples spacing and that analyzed samples were cuttings. Well 4 is known to have multiple entrants of colder waters. From approximately 4200 feet to about 5350 feet there is a decrease in the temperature profile which is reflected in the N_2/Ar ratios. There is a peak in the ratio at about 5000 feet that is not reflected in the temperature profile and may indicate a closed fracture. Additionally at approximately 6500 to about 7700 feet is a decrease in the mud temperatures as well as the temperature profile. This zone appears to be bounded by sharp peaks in the N_2/Ar ratios. There are additional peaks in the ratios that are not necessarily reflected in the temperature profile.

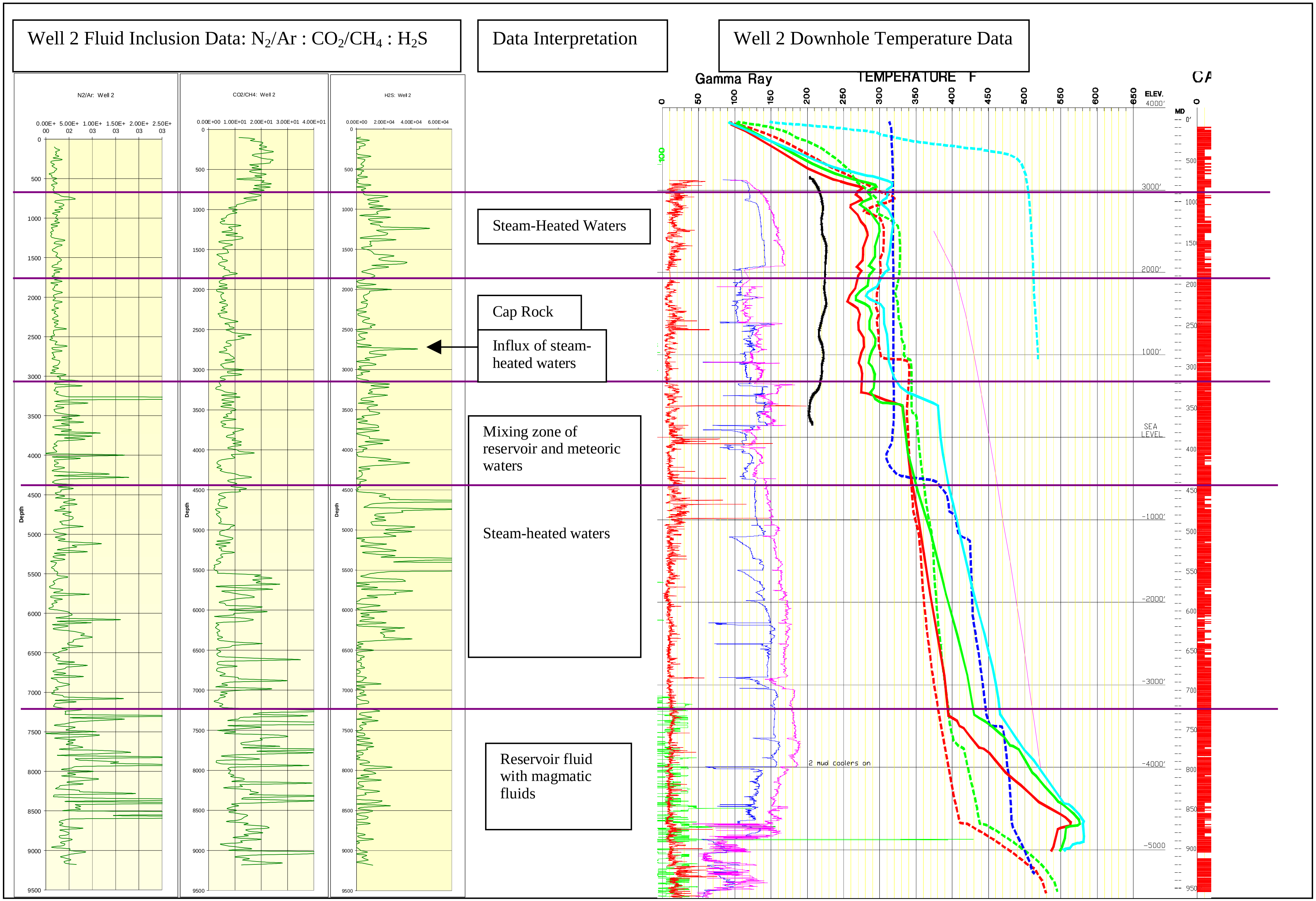

Figure 5. Fluid inclusion data interpretation compared to temperature data. The zones interpreted appear to correspond to the temperature profile.

In addition to the high N_2/Ar ratio, magmatic gases generally have high CO_2/CH_4 content (Giggenbach, 1986; Norman and Musgrave, 1995; Norman et al., 1996). Follow-on work by Norman et al., 1997, showed that steam-heated waters are distinguished by high concentrations of more soluble gaseous species, including CO_2, C_6H_6, and H_2S and that H_2S is low or absent in groundwater. However, highly evolved groundwater may have high concentrations of H_2S as well as He and CH_4. Figure 5 shows N_2/Ar and CO_2/CH_4 ratios as well as hydrogen sulfide content for Well 2 versus the downhole temperature. It is important to note that for verification of the method, the fluid inclusion data was interpreted prior to reviewing the temperature profiles. The graph for the N_2/Ar ratios indicates three distinct zones: 1) from 0 to about 3300 feet; 2) from 3300 to about 7000 feet; and 3) from 7000 feet to about 8500 feet. The graph for the CO_2/CH_4 ratios appears to have at least three distinct zones: 1) from 750 to about 5500 feet; 2) from 5500 to about 7200 feet; and 3) from 7200 feet to the depth of the hole. The H_2S graph has a high zone from about 1200 feet to about 1800 feet and again from about 4500 feet to about 5800 feet. The high N_2/Ar with high CO_2/CH_4 ratios was considered to represent magmatic waters whereas high H_2S amounts represented steam-heated waters. In the area where the ratios and the species were low, this was interpreted as an area of cap rock. Where there was variability in the ratios, this was considered to be a zone of mixing. As can be seen in Figure 5, the temperature profiles appear to correspond to the fluid inclusion data interpretation.

The fluid inclusion data presented in Figure 5 indicate the complexity of the system. Prior studies relied on a few samples per well and therefore the interpretations showed major zones. It is interesting to note the multiple smaller zones that can be observed with this data set. For instance the pulse in the H_2S data at about 2700 feet and the corresponding increase in the borehole temperature were interpreted as a small influx of steam-heated waters.

CONCLUSIONS & FUTURE WORK

The data presented is preliminary at this point, but it does appear that large and small scale features can be observed and interpretations can be made about the reservoir fluids and whether a well is or will be a producer. The following conclusions have been developed to this point:

1) A producing well can be distinguished from a non-producing well by plotting select species against each other. Non-producing wells will typically have lesser amounts of common geothermal gaseous species such as carbon dioxide, methane, nitrogen, and hydrogen sulfide.

2) The N_2/Ar ratio appears to correspond to temperature fluxes indicating areas of cooler and warmer waters into the system.

3) By comparing several ratios and select species, the fluid inclusion data can lead to a subsurface profile that correlates with the temperature profile.

Additional work is still needed. Other species as well as gas ratios still need to be analyzed to determine which set of ratios and species are useful. Organic species, different gas ratios, and whether the raw data plots can be used, remain to be investigated. Samples from one well will be analyzed by New Mexico Tech's mass spectrometer to verify the data from FIT. This verification will also assist in the developing gas ratios and in comparing values already established in the literature. The fluid inclusion data also should be compared to the lithology logs to determine if the peaks observed correspond to increases in certain minerals.

Once the methodology for sampling and data analysis is developed, eight additional wells will be sampled. Fluid inclusion stratigraphy logs will be constructed using the methodology. These logs will be compared to other models of the Coso field. The method will then be tested against two wells drilled at Coso in a real time trial to analyze the method in terms of assisting in resource evaluation.

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