Fluid Inclusion Stratigraphy: Interpretation of New Wells in the Coso Geothermal Field

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ABSTRACT

This paper is the fifth in a series about the development of the FIS method. Fluid Inclusion Stratigraphy (FIS) is a new technique being developed to map borehole fluids in geothermal fields by analysis of fluid inclusion gaseous species in drill cuttings. The working hypothesis is that selected gaseous species and species ratios can differentiate groundwater and reservoir fluid-bearing fractures, and can indicate reservoir seals. Analyses are performed by a commercial laboratory, Fluid Inclusion Technologies (FIT) and also by the research lab at NMT. This research is funded by the California Energy Commission.

The first four papers interpreted analyses of 4 bore holes. Here we report on the analysis of five additional wells. This paper focuses on the interpretation of the additional wells and comparison to the previous wells. Preliminary correlation between wells is also presented. Analyses from multiple boreholes show fluid stratigraphy that correlates from well to well. The wells include large producers, small to moderate producers, problem producers, injectors, and non-producers.

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. So far our research has focused on the four wells that were initially analyzed. From those four wells we have determined a number of ways to distinguish: 1) producing from non-producing wells, 2) fluid types including magmatic, crustal, and steam heated waters, 3) fracture patterns, and 4) boiling and gascaps (Dilley et al. 2004; Dilley and Norman, 2004; Norman et al., 2004). This paper focuses on the next stage of the research, consisting of analyzing samples from five additional wells and comparing the results to the previous research.

Methods

Four wells from the Coso Geothermal Field were selected for the first round of analyses (Wells 1 through 4) and five additional wells (Wells 5, 7 through 10) were selected for the second round (Figure 1). For the second round one well, Navy 38D-9 (Well 5) was analyzed while it was being drilled. Splits of 10 to 20 grams were taken from drill cuttings at 20-foot intervals throughout each well. Over 1,800 samples from the additional wells were submitted to FIT 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.

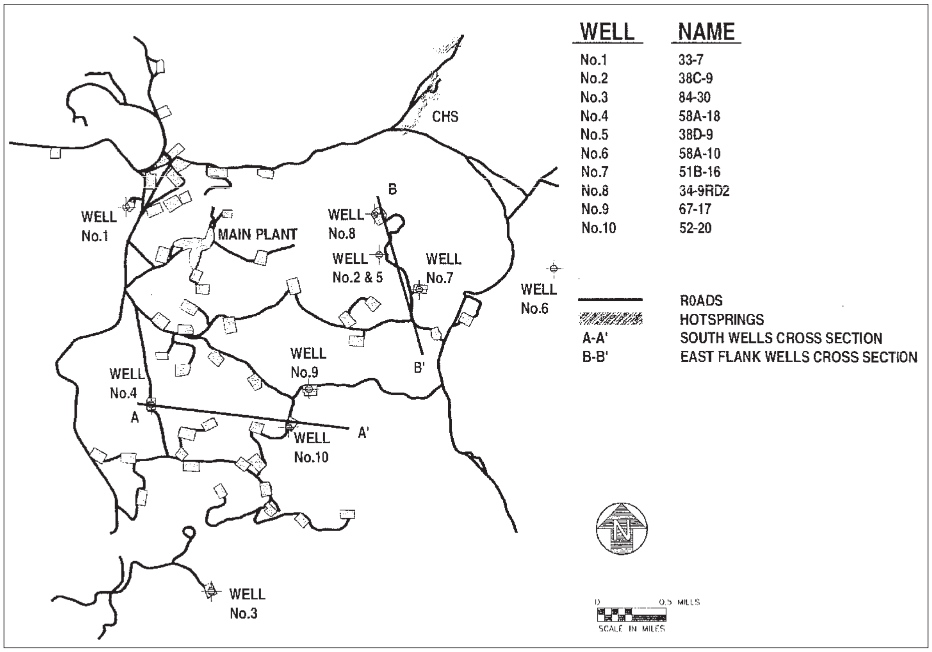

Figure 1. Location of wells used in the study and surface featuress of Coso Field (After Moor 2005).

The FIT data was presented to us for interpretation. No other logs or well information such as production fluid temperature or rock types was provided for the new set of data. The idea is to test the FIS method by making interpretations independent of temperature logs or well logs. Based on the previous work with the first four wells and subsequent work with core samples 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 on 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 deep high temperature production fluids. Gas ratios and sums that are used, and their interpretations are as follows:

- *Magmatic fluids* 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. In Figures 2, 4, and 5 these are referred to as R1 and R2, respectively.
- *Crustal fluids* are indicated by N^2/Ar ratios < 200, CO^2/CH^4 < 4, propane/propene >1, and 1/Ratio 1 > 0.5
- *Steam heated waters* 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.
- *Mixed fluids* are indicated by a combination of the various ratios mentioned above.
- Boiling and gas caps are indicated by high gas/water ratios and by high total gas.

Results

The new set of wells is compared to the existing four wells and their previous interpretations. Figure 2 presents two distinct wells from the first set: Navy 38C-9 (Well 2) a significant producer and BLM 84-30 (Well 3) a non-producer. Navy 38C-9 has a significant number of peaks that we interpret as fractures with elevated of N_2/Ar and CO_2/CH_4 ratios, especially at depths below about 7500 feet, which indicates that there is

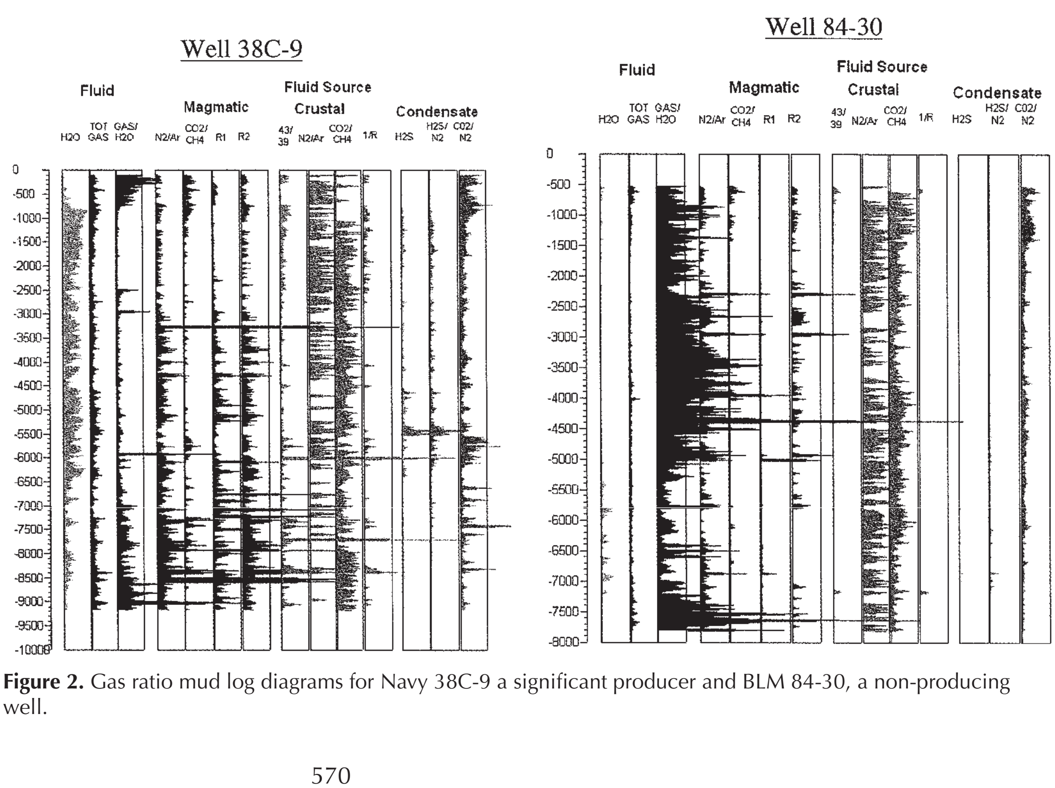

Figure 2. Gas ratio mud log diagrams for Navy 38C-9 a significant producer and BLM 84-30, a non-producing well.

a significant contribution from magmatic fluids. Comparing this well (Navy 38C-9) to the non-producer (84-30) shows that the analysis for 84-30 indicates few fractures with magmatic gas ratios, and the amounts of water gas/water and H_2S vary remarkably between the wells. Well 84-30 is interpreted as background (Dilley & Norman, 2004).

The new well's analyses are presented in Figure 3. There are distinct differences between the wells. Each of the wells appears to have had water moving through them suggesting producing wells. Comparing the five wells to the large producer Navy 38C-9 (Figure 2) there is one strong well, 51B-16. This well below about 6500 feet has numerous fractures with high magmatic ratios. There are only minor H_2S peaks. This zone to about 7700 feet is interpreted as a mixed fluid zone. After about 8500 feet, the CO_2/CH_4 ratio indicating crustal fluids decreases to only a few minor peaks. This suggests a change in fluid chemistry at this depth. There are multiple peaks in the magmatic ratios below this depth and the CO_2/CH_4 magmatic ratio has several large peaks below 9000 feet. The interpretation is that the production zone with the highest temperatures will start at 9000 feet and extend downward.

Well 38D-9 is more complicated. There are several depths with changes in the various ratios suggest changes in fluid chemistry. From approximately 5200 feet to about 6100 feet the condensate ratios suggest that this is a steam zone. Ratio 43/39 shows several peaks from 6100 to about 6500 feet indicating fractures with cold water inflow. From 7300 to about 7500 feet there are a few peaks in the magmatic ratios suggesting fractures with hotter waters, then at 7600 feet the ratio 43/39 has a high peak. This entire zone from 6100 feet to about 8800 feet is interpreted as a mixed fluid zone with fractures that have cold water inflows and other fractures with hotter water inflow. Below 8800 feet the fluid chemistry changes again with the crustal ratios going to zero and multiple peaks with the magmatic ratios. There is interpreted as the production zone for this well.

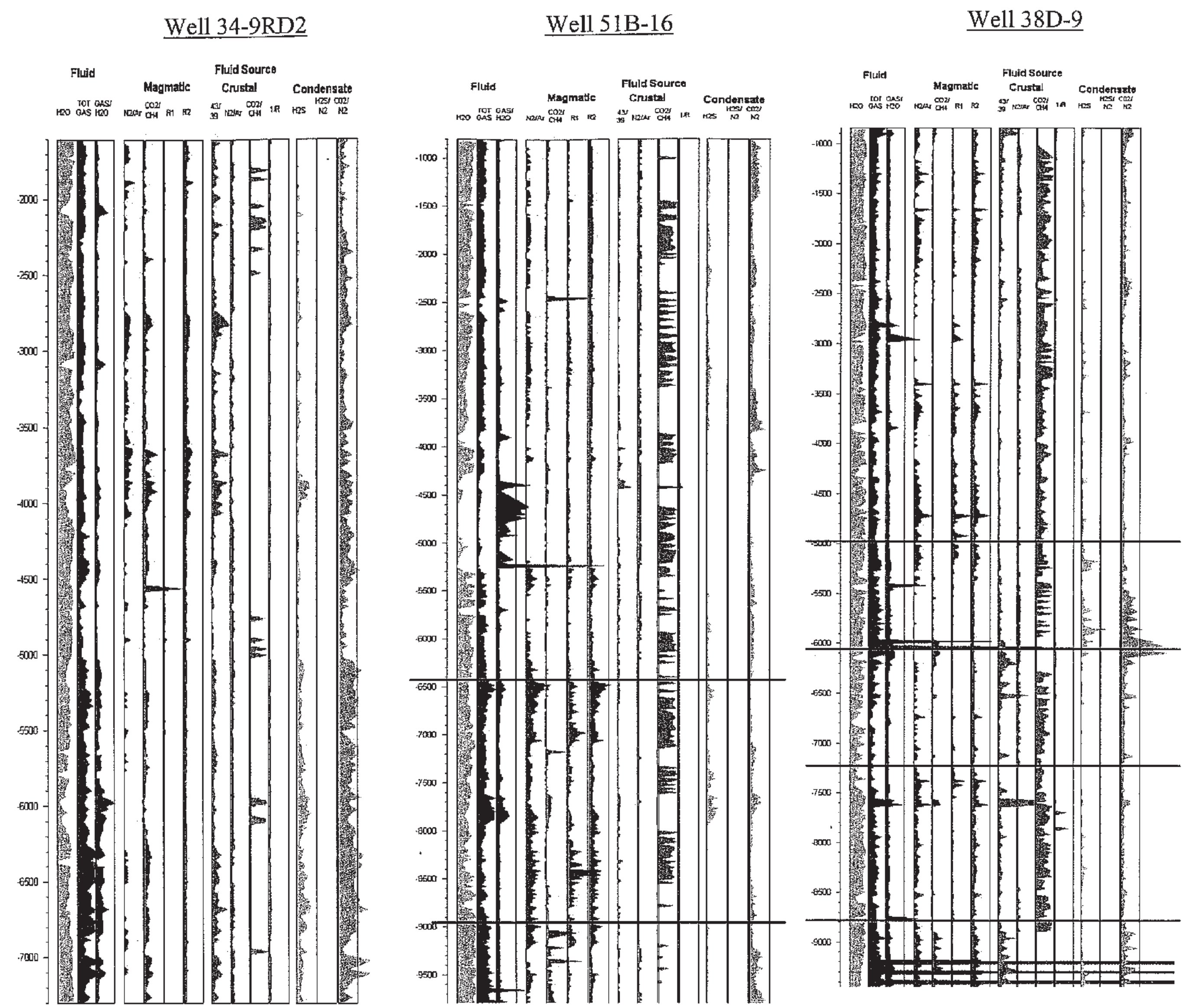

Figure 3(a). Mud log diagrams for Wells 34-9RD2, 51B-16, and 38D-9.

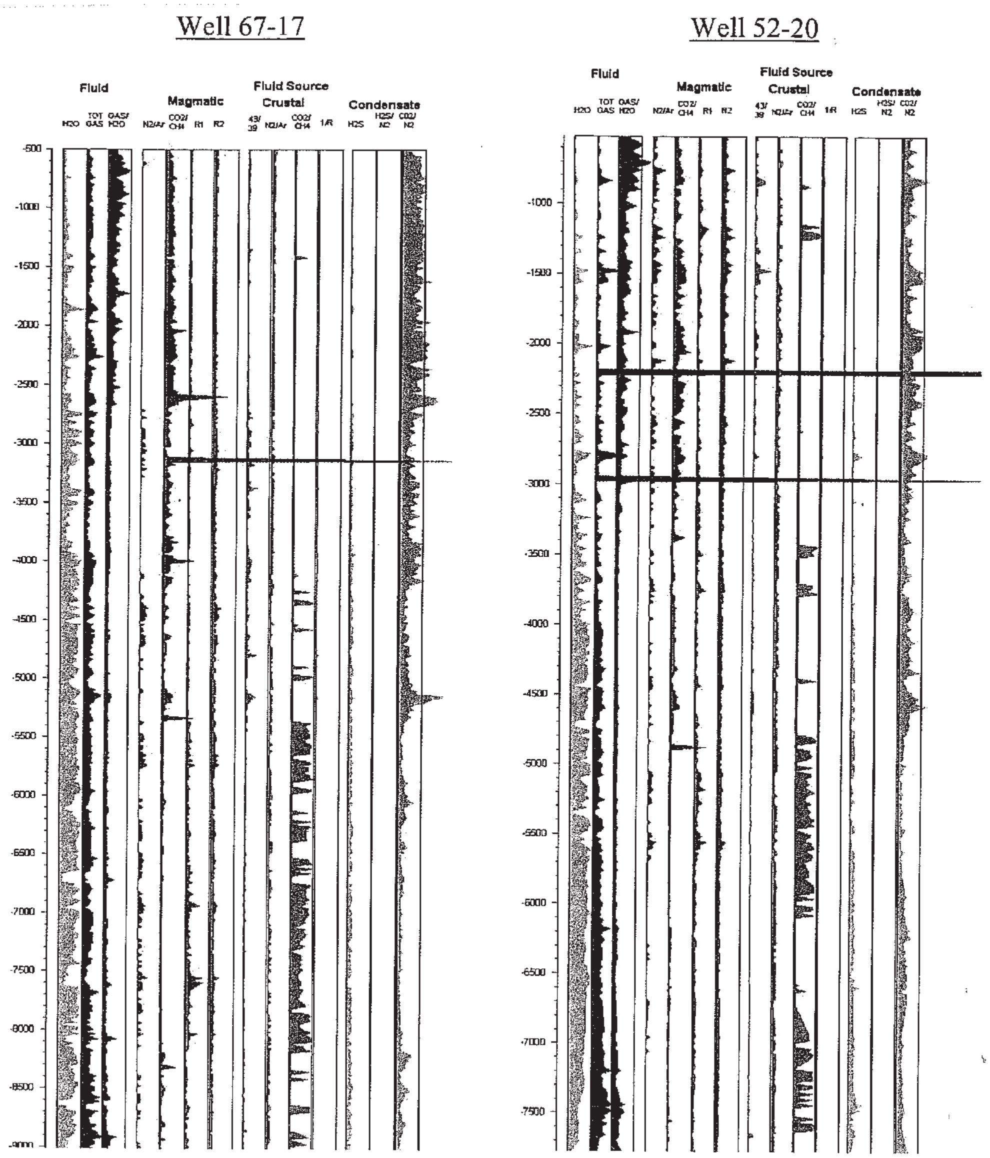

Figure 3(b). Mud log diagrams for Wells 67-17 and 52-20.

In Well 34-9RD2, there is moderate to large peaks of H_2S at depth. There are very little peaks in the magmatic ratios except higher in the system. This well is interpreted as having a large steam zone with low production.

The remaining wells, 67-17 and 52-20 have few peaks indicating a magmatic fluid source. There are also H_2S peaks. The magmatic and condensate fluid sources indicate that the geothermal fluids in the well are mixed with cold water influxes particularly where there is no magmatic N_2/Ar ratio. There are significant gaps in the magmatic ratios from about 4500 to 6200 feet in 52-20 and from 6700 to 8000 in 67-17. Both of these wells are interpreted as small producers with numerous inputs of cold water deep in the wells.

One of the main hypotheses of the FIS method is that present day fluid types can be identified from the fluid inclusion gas chemistry sampled in drill chips from the wells and that the fluid types can be correlated between wells to provide a stratigraphic picture of the reservoir. A preliminary stratigraphic diagram was developed using the magmatic ratios and H_2S to determine fluid types (Figure 4). The significant ratios that indicate magmatic fluids are the N_2/Ar and the CO_2/CH_4 ratios. When both of these ratios are high, magmatic fluids are indicated. Elevated H_2S indicates steam-heated waters. Topographic elevations of the wells were not provided at this time. We will set the cross-sections to the correct elevations once they are provided. The stratigraphic diagram was constructed along the A-A' line shown in Figure 1. These are three southern wells: 58A-18, 52-20, and 67-17.

Well 58A-18 is a small producer with influxes of meteoric fluids at various depths: 4500 to 5100, and 6500 to 7000. The other two wells are from the second round of sampling. Both appear to have sporadic N_2/Ar and CO_2/CH_4 similar in nature to Well 58A-18. The dashed line at about 5000 to 5500 feet to the second dashed line of about the 6500 foot depth indicate a zone of fractures with cold water influxes and fractures with fluids with magmatic components. Where the N_2/Ar and CO_2/CH_4 ratios are both high these areas are interpreted as fractures with fluids that have a magmatic component.

Discussion

The new set of data has presented challenges in interpretation. Wells were compared to each other to evaluate trends in species and ratios. Distinct differences occurred between the wells. Wells interpreted as small producers have ratios low in magmatic components and have condensate components at depth. Certain wells (51B-16 and Navy 38D-9) show ratios high in magmatic components and low condensate components at depth of the reservoir. These were interpreted, when compared to Navy 38C-9 (Figure 2), as moderate to large producers.

By plotting the magmatic ratios and H_2S for various wells, fluid types can be correlated between wells. More work is needed to correlate between wells including setting the wells to their correct elevations and develop a fence diagram.

Conclusions

1.) The data presented here still needs to be compared to temperature logs and well logs to further the development of FIS.
2.) FIS appears to be able to distinguish among the different types of wells with little other information needed.

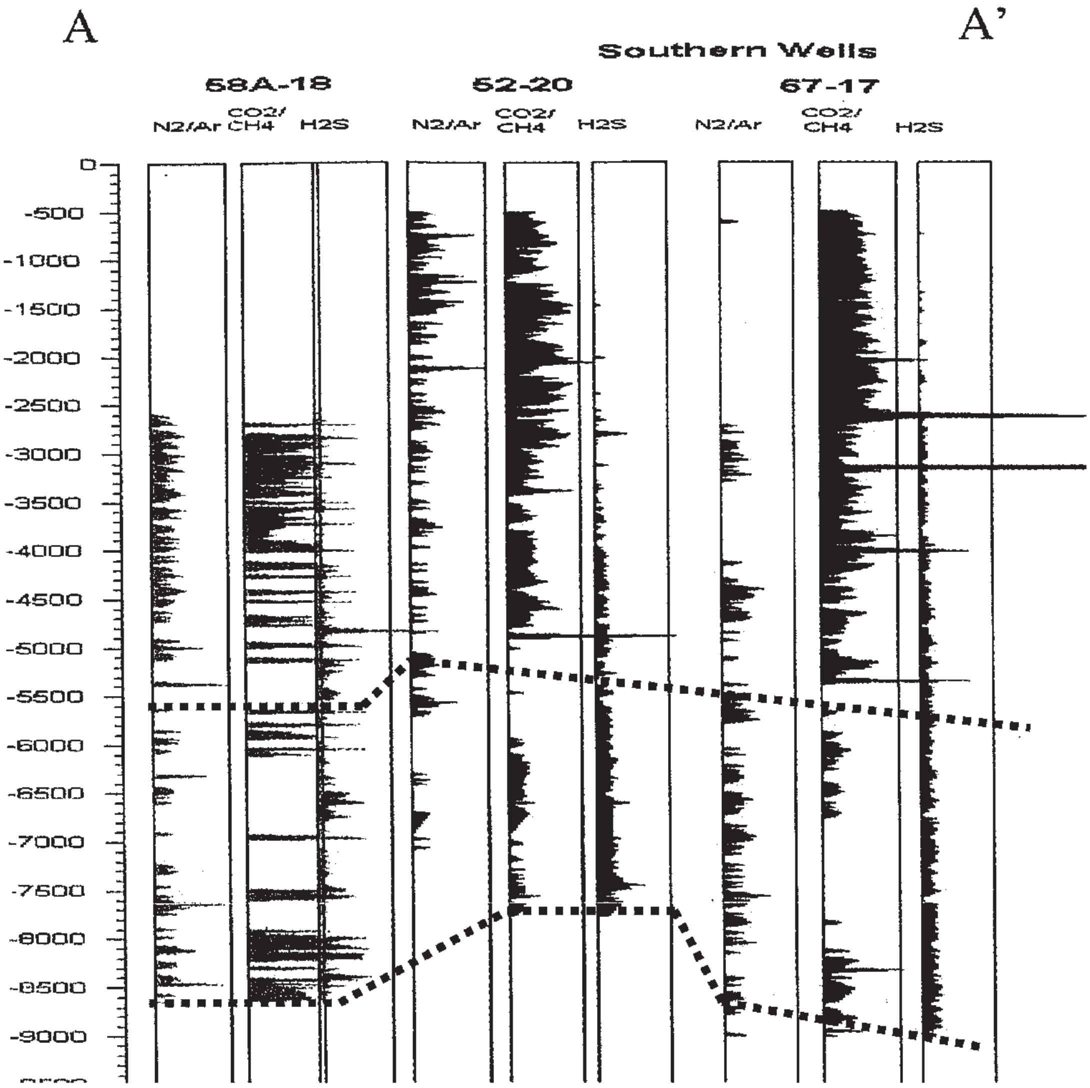

Figure 4. A stratigraphic diagram of the southern wells.

3.) In addition the correlation between wells appears to be working. Additional correlations will be conducted among all of the wells to develop a model of the geothermal reservoir.

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