

## DISPLAYING AND INTERPRETING FLUID INCLUSION STRATIGRAPHY ANALYSES ON MUDLOG GRAPHS

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### **ABSTRACT**

This is the fourth paper in a series on developing fluid inclusion stratigraphy (FIS) as a logging tool for geothermal bore holes. Here we address methods of displaying analyses and plotting gas ratios used for data interpretation on mudlog plots. The goal is to develop a rapid method of data display and interpretation for the up to 10,000 analyses returned by a geothermal well FIS analysis.

### **INTRODUCTION**

Fluids trapped in inclusions 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. Our working hypothesis is that samples of geothermal fluids are trapped in wall rock minerals within microfractures adjacent to veins. Mass spectrometer analyses of gases within these inclusions show fluid sources and processes within geothermal systems (Giggenbach 1997; Norman 1997; Blamey 2002, Dilley et al. 2004, Dilley and Norman, 2004, Norman et al., 2004).

California Energy Commission is funding us to develop Fluid Inclusion Stratigraphy (FIS) to use as a logging tool to assess geothermal bore holes. The assessment techniques seek to provide ways to: distinguish non-producing from producing wells; identify major fluid flow zones; and find entrants of cold and steam-heated waters into the bore hole. The FIS method analyzes volatiles in drill-cuttings fluid

inclusions by mass spectrometry. The commercial process, developed in part by Fluid Inclusion

Technology (FIT) for the hydrocarbon industry is highly automated. 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 vein distribution and chemistry plotted on borehole logs. Fluid source is determined from gas chemistry.

This is the fourth paper on developing FIS for application to geothermal wells. Other papers show the gas analyses on simple depth versus gas line charts, e.g. see the paper by Dilley et al. 2005 elsewhere in this Proceedings. Our problem is that a FIS analyses covers the mass spectrum from 1 to 180. A typical FIS analysis yields about 10,000 analyses when performed at 20 ft intervals on a 10,000 ft well. It is difficult to visualize the analyses and see relationships between them for numerous species and gas ratios when presented on a series of charts. Here we address methods of data display and analysis that enable us to understand how fluid inclusion gas chemistry changes and fluid source varies with depth in geothermal bore holes.

We need to be able to clearly display downhole changes in gas chemistry and downhole changes in gas ratios and sums. In order for FIS to be a viable tool we must be able to routinely return analyses to a client with little added time or cost for data analysis. This requires that there be routine methods of plotting, analyzing and interpreting fluid inclusion gas analyses

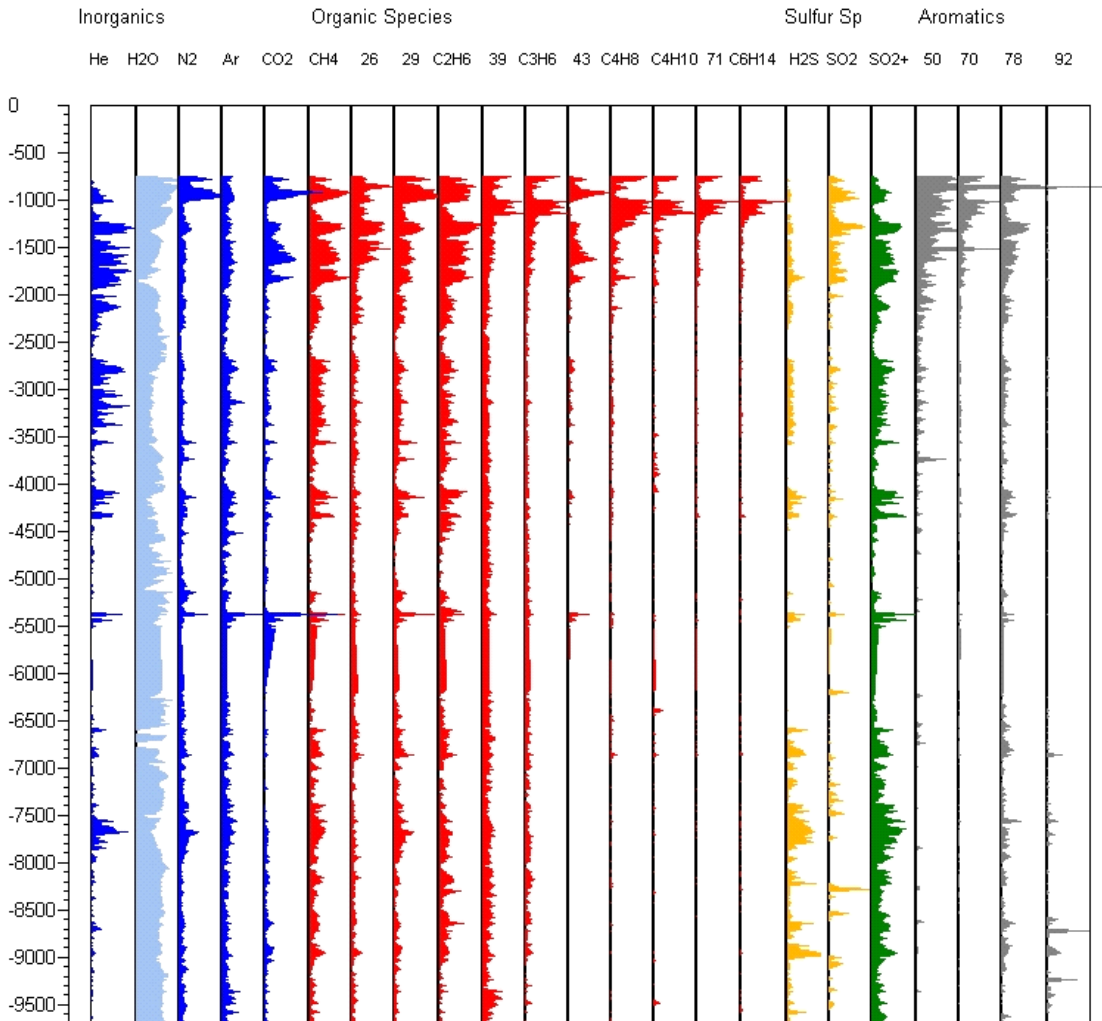


Figure 1. Well 1 species plotted versus depth. See text for details including species represented in columns headed by a number.

The volatile species of interest are the principal gaseous species in geothermal fluids and trace hydrocarbon species, which include H<sub>2</sub>, He, CH<sub>4</sub>, H<sub>2</sub>O, N<sub>2</sub>, H<sub>2</sub>S, Ar, CO<sub>2</sub>, C<sub>2</sub>H<sub>4</sub>, C<sub>2</sub>H<sub>6</sub>, C<sub>3</sub>H<sub>6</sub>, C<sub>3</sub>H<sub>8</sub>, C<sub>4</sub>H<sub>8</sub>, C<sub>4</sub>H<sub>10</sub>, benzene, and toluene. Gas ratios and gas sums that we use, and their interpretations are as follows:

- Magmatic fluids are indicated by N<sub>2</sub>/Ar, CO<sub>2</sub>/CH<sub>4</sub>, (N<sub>2</sub>/Ar + CO<sub>2</sub>/CH<sub>2</sub>)/propane/propene that we term ratio 1, and (N<sub>2</sub>/Ar + CO<sub>2</sub>/N<sub>2</sub>) that we call ratio 2. Correctly magmatic fluids are indicated by N<sub>2</sub>/Ar > 105; however FIT analyses are not calibrated. Instead we use the mass peak ratio of 28/40 to represent N<sub>2</sub>/Ar. Duplicate analyses of Coso chip inclusions by FIT and
- Fractures are indicated by water and gas peaks.
- quantitative fluid inclusion gas analyses at New Mexico, indicate that the magmatic 28/40 ratios by FIT are values > 200 .
- Crustal fluids are indicated by 28/40 ratios < 200, 44/15 (CO<sub>2</sub>/CH<sub>4</sub>) < 40, propane/propene (mass ratios 43/39) >1, and 1/ratio 1 > 0.5
- Steam heated waters have elevated H<sub>2</sub>S and H<sub>2</sub>S/N<sub>2</sub> and sometimes elevated CO<sub>2</sub>/N<sub>2</sub>. Elevated CO<sub>2</sub>/N<sub>2</sub> is common in deep reservoir waters that can condense magmatic volatiles.
- Boiling and gascaps are indicated by high gas/water ratios and a gapcap by high total gas.

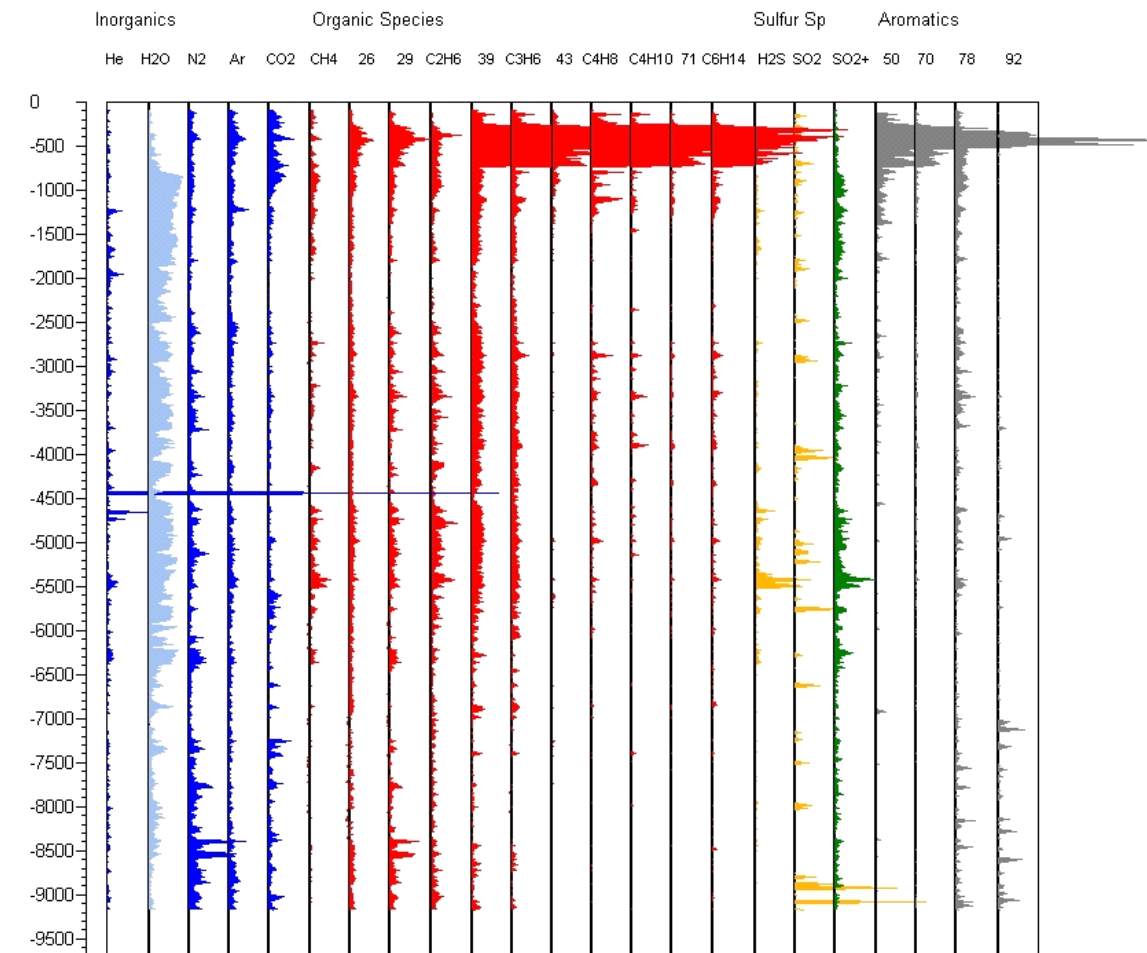


Figure 2. Well 2 species plotted versus depth. See text for details including species represented in columns headed by a number.

## **METHODS**

Gas analyses for the four Coso wells previously reported on (Dilley et al., 2004) were plotted on the new diagrams. These are Well 1: BLM 33-7, Well 2: Navy 1 38C-9, Well 3: BLM 84-30, and Well 4: 58A-18. These wells were selected by COSO staff because Well 2 is an excellent producer, Well 1 is an average producer, Well 4 a problem producer, and Well 3 a nonproducer. For well locations see Fig. 1 in Dilley et al. 2005 in these Proceedings.

Analyses are plotted on two mudlog diagrams, one the displays inclusion gas chemistry, and the other gas ratios and species that are used for fluid source and fluid processes interpretation. We use the Rockware® program Logger to plot data in mudlog fashion. For each gas species we chose a major gas peak that has little interference from other species. For example, for He this is mass 4, and for methane this is mass 15. As explained in Dilley et al. (2004)

we check analyses to make certain that a mass peak like 28 represents nitrogen and the analyses interfere by a fragment of another species. To scale the species plots we calculated the mean and standard deviation for individual species. Generally the scale maximum is set at the mean plus  $2\sigma$ . Analyses are plotted on a linear scale. We chose not to truncate the few analyses that exceed the scale maximum. Analyses are plotted using the Logger bar graph option.

On the species diagrams (Figs. 1, 2, 3, & 4) the species are grouped by chemical type, which are plotted in different colors. Inorganic species are plotted in blue with water distinguished by a lighter blue color. The  $C_2$ - $C_6$  straight chain organic species are plotted in red; the sulfur species are plotted in orange and green; and organic aromatic peaks plotted in gray (Fig. 1 to 4). Sulfur species plotted are  $H_2S$  (mass 34),  $SO_2$  (mass 48) and mass 64. Mass 64 is a major peak for  $SO_2$  and  $CS_2$ , and it a minor fragment

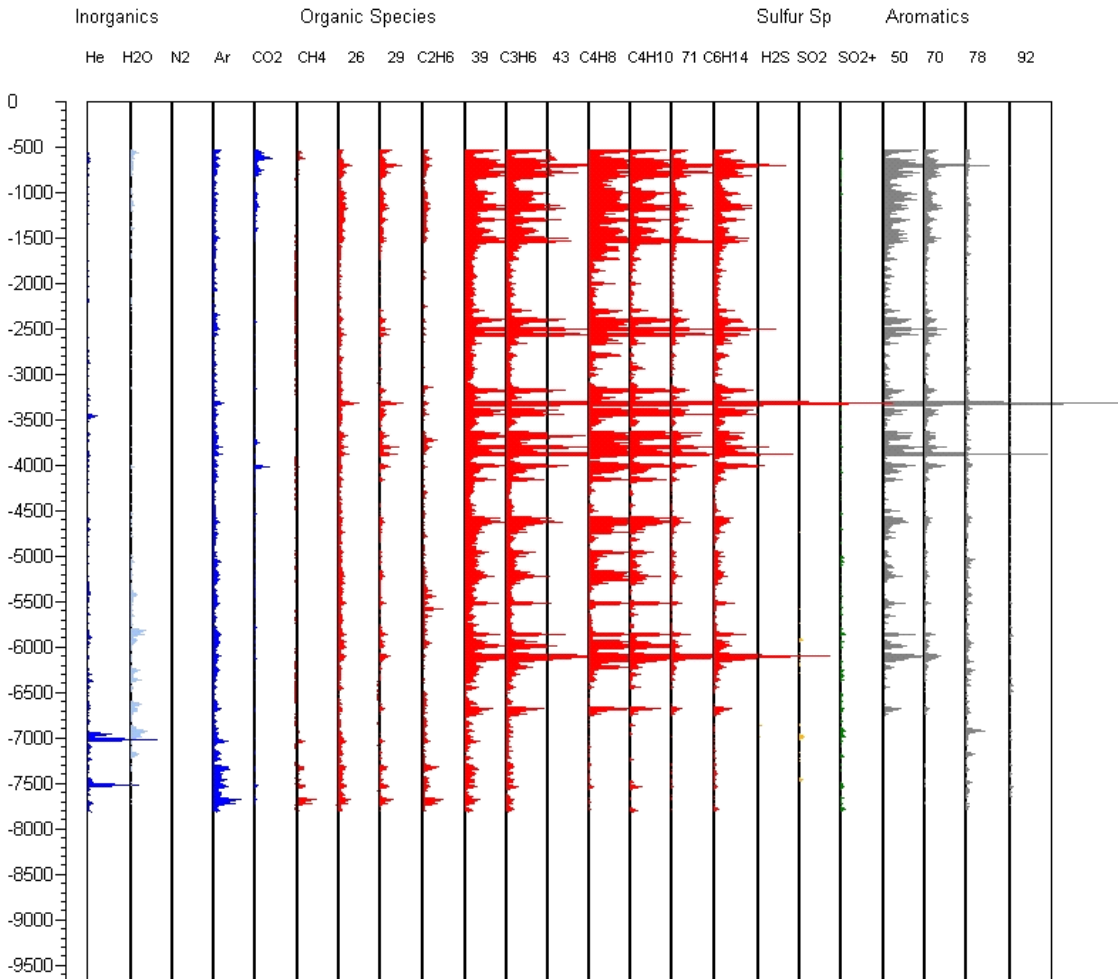


Figure 3. Well 3 species plotted versus depth. See text for details including species represented in columns headed by a number.

peak for some organic species. Hence mass 64 is distinguished by a different color than orange used for mass 34 and mass 48. Mass peaks 70, 78 and 92 are respectively the principal peaks for cyclopentane, benzene and toluene. Mass peak 50 is a common fragment peak for aromatic compounds. Quantitative analysis of fluid inclusion organic species shows that their concentrations are in the low ppm and ppb range (Norman et al., 2004). A quadrupole mass spectrometer can routinely measure species at concentrations of 1 part in  $10^8$ .

The second diagram (Figs 5, 6, 7 & 8) shows interpretive gas ratios, gas sums, and individual gaseous species. Gas ratios explained above are scaled identically to how they were scaled in Dilley et al. (2004), Dilley and Norman, 2004, and Norman et al. (2004). Two quantities not used before are

included. They are total gas, which is the sum of mass peaks from 2 to 180 minus mass 18 (water), and total gas/water. They are scaled in a similar fashion to the gaseous species. Water, total gas and gas/water ratio plotted in blue with water a lighter shade of blue. Deep hot reservoir fluid indicators are red; crustal fluid indicators in green; and condensate indicators are plotted in orange.

Interpretive gas ratios for  $N_2/Ar$  and  $CO_2/CH_4$  ratios are plotted in both the magmatic and crustal columns. The  $N_2/Ar$  ratio is plotted on the magmatic column only if that ratio has a magmatic value or  $> 200$ . Analyses with  $N_2/Ar < 200$  are plotted in the crustal column. Scaling for the crustal fluid is 0 to 200; scaling for the magmatic column is as used in previous papers, which is from 0 to 1200. The  $CO_2/CH_4$  ratios are plotted in a similar manner.

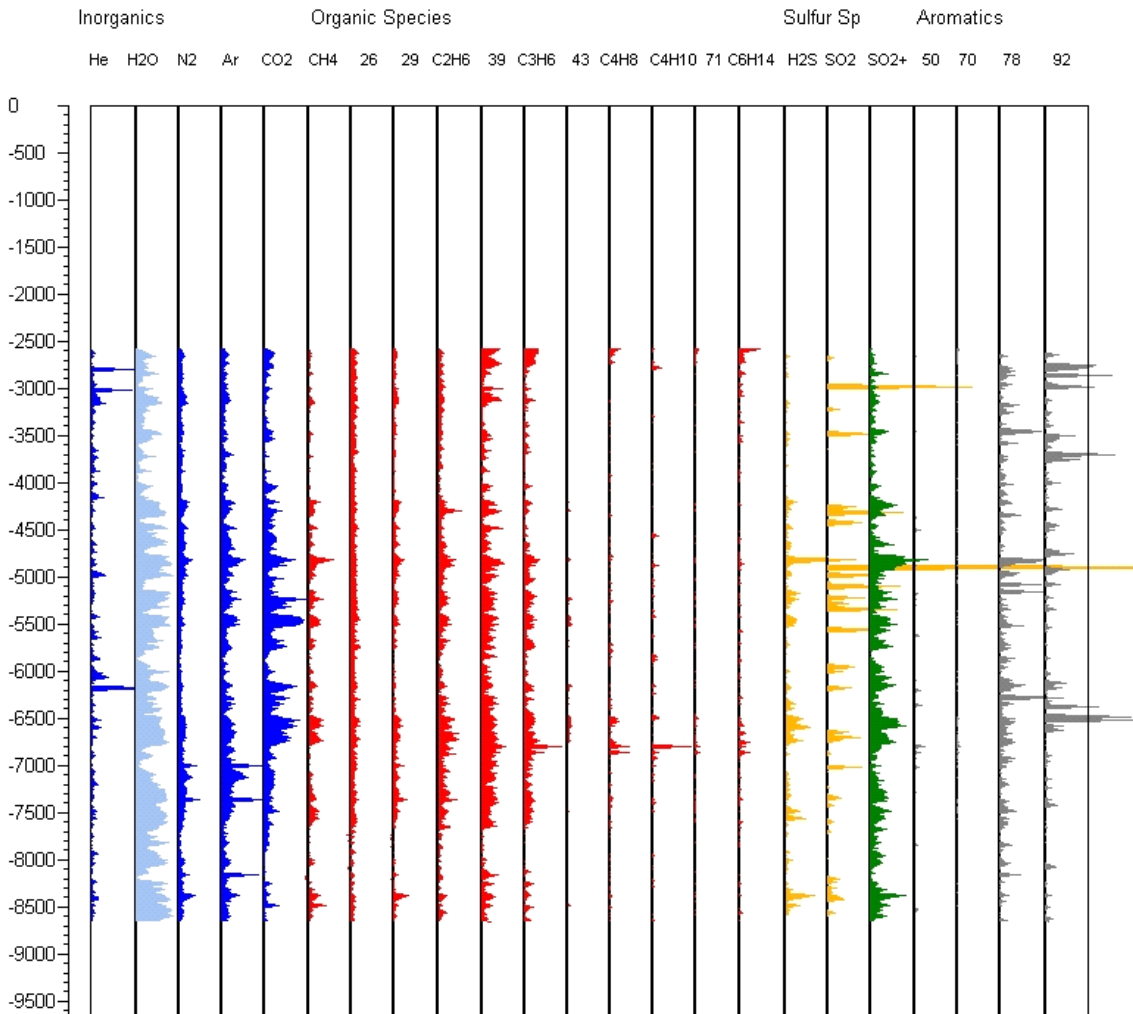


Figure 4. Well 4 species plotted versus depth. See text for details including species represented in columns headed by a number.

## RESULTS

The gas analyses plotted in Figs 1 to 8 show clear differences between the wells. Analyses of the nonproducing well 3 differ remarkably from the analyses of the three producing wells. The species plot (Fig. 3) shows that Well 3 inclusions have significant amounts of the heavier hydrocarbon species and low concentrations of the lighter species. The producing wells (Figs. 1, 2, &4), except for the first few thousand feet show the opposite. Well 3 analyses differs from analyses of the producing wells in exhibiting little sulfur species gases and little water. The latter we interpret as indicating a low density of inclusions (Norman et al., 2004).

The Well 3 interpretive plot (Fig. 7) likewise shows clear differences between plots for the producing wells. The most remarkable difference is in the gas/water ratio, which is remarkably higher than the

ratios for production well analyses (Figs. 5, 6 & 8). Also, the Well 3 interpretive plot shows virtually no sulfur species gases and little indication of magmatic gases ratios.

There are distinct differences between the excellent producing well #2 and the two other producing wells (Fig. 5, 6 & 8). Principal production for Well 2 is from the interval 7,300 to 8,700 ft. The magmatic indicating ratios are higher than for the other two producing wells, and they are especially prominent in the producing interval. Below 6,000 ft. there is no indication of steam heated waters in H<sub>2</sub>S and H<sub>2</sub>S/N<sub>2</sub> plots; the fracture density indicated by water peaks is low; and fluid boiling indicated by elevated gas/water ratios is common, which is not true of the other two wells.

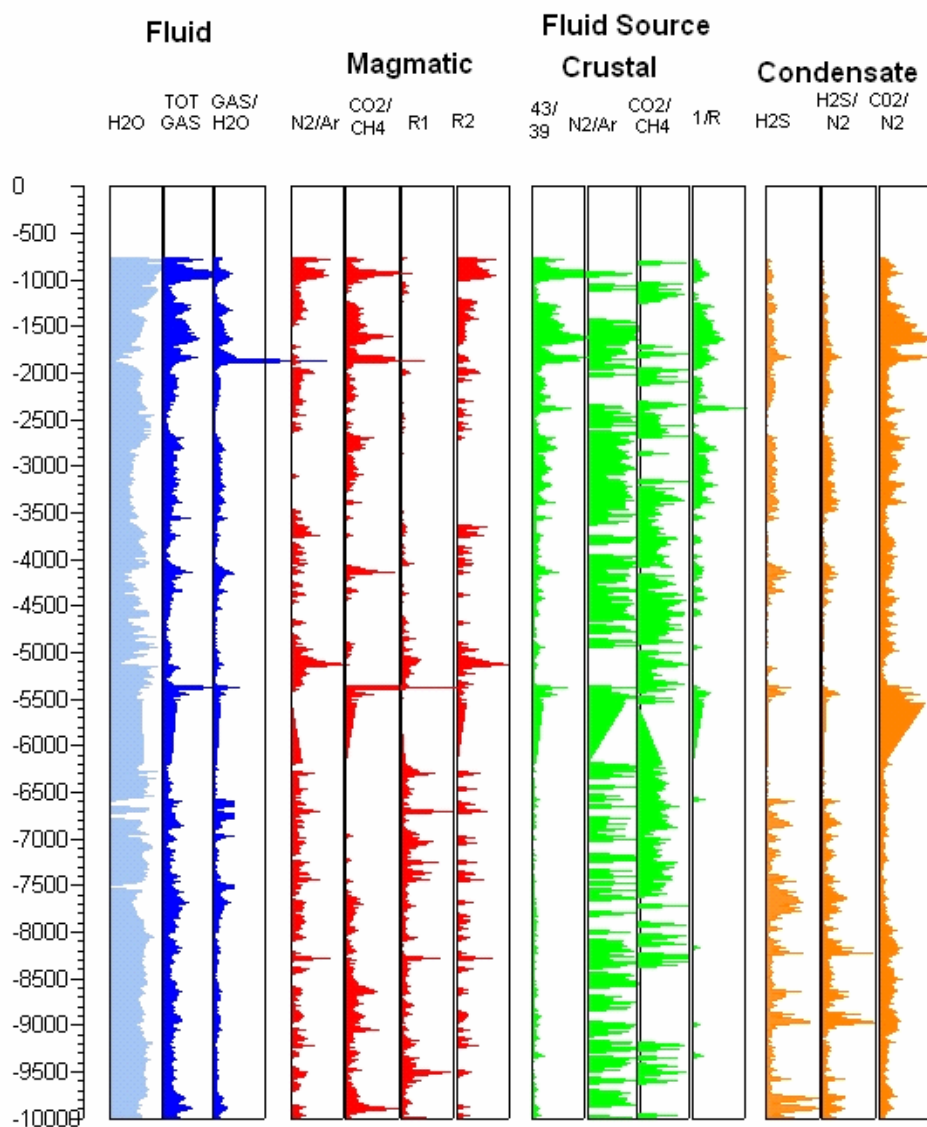


Figure 5. Well 1 interpretive mudlog plot. See text for details.

## DISCUSSION

Plotting gas analyses on plots mud logs that show multiple species and multiple interpretations on a single diagram provides new insights into the analyses. The difference in the composition and concentration of organic species between producing wells and the nonproducer were not evident in past data analysis. The gas/water ratio shows inclusions with high gas contents, or assemblages of inclusions that include vapor-filled inclusions. The ubiquitous high gas water ratios in well 3 inclusions agree with a metamorphic origin for the inclusion fluids, because metamorphic fluid inclusions commonly have an order of magnitude or greater amounts of CO<sub>2</sub> and other volatiles than trapped geothermal fluids. It is to be expected that metamorphic inclusions should be

common in the countryrock that has been metamorphosed to amphibolite facies. The elevated gas/water ratios below 6,000 ft in well 2 (Fig. 6) suggest fluid boiling, which agrees with fluids having a major magmatic component. Extreme gas/water ratios and total gas exhibited in well 4 (Fig. 8) is what we expect for inclusions forming in a gas cap.

There are some unresolved problems with the methods of plotting gas analyses presented here. Scaling on the 1/ratio 1 plots in Figs. 5 to 8 needs to be addressed because using the current scheme this ratio provides little information. Attempts in using logarithmic values for 1/ratio 1 data were not helpful, and decreasing the scale resulted in peaks, like those for the gas/water ratio, that are extending beyond the plot. Not truncating peaks results in peaks that cover

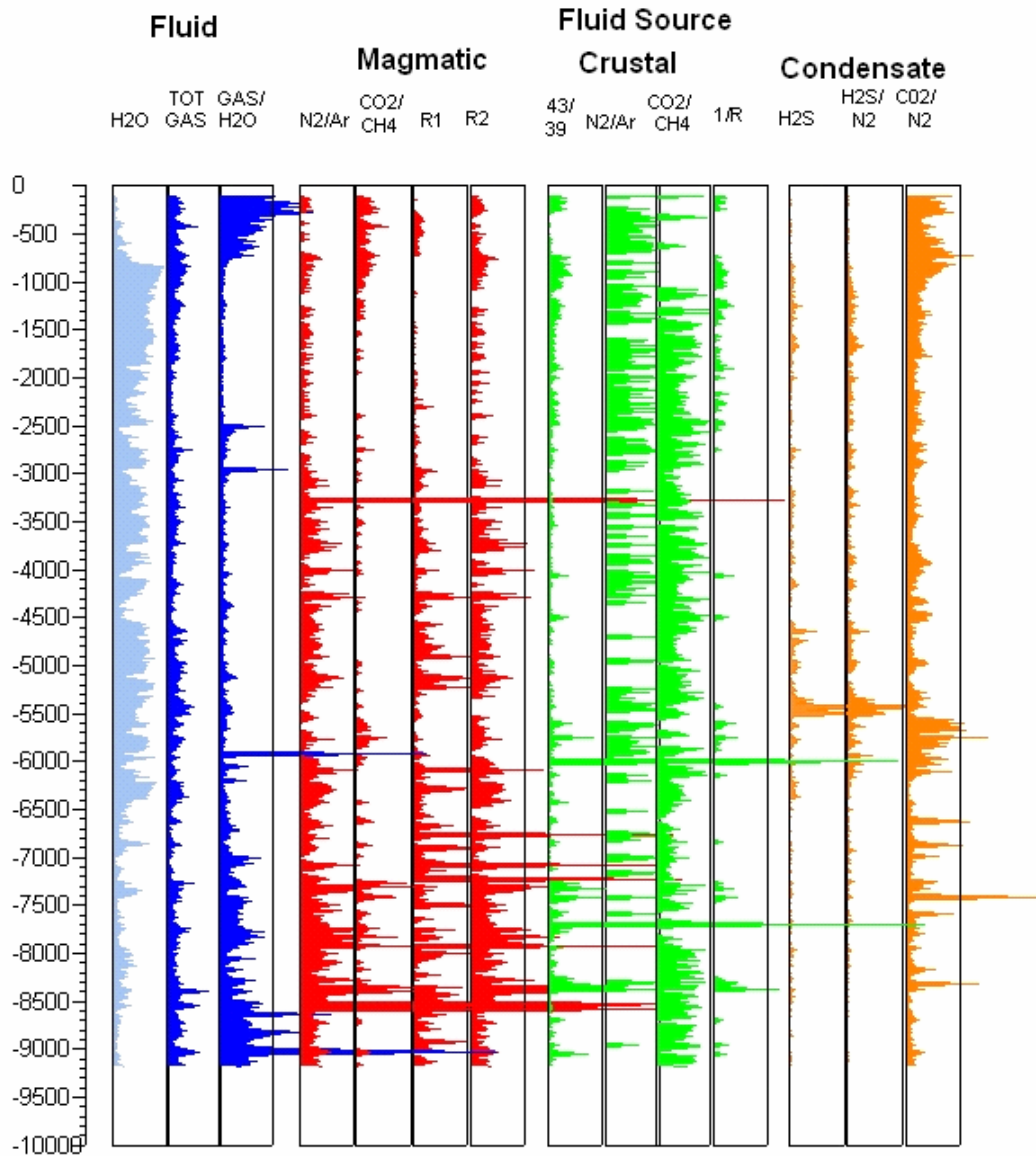


Figure 6. Well 2 interpretive mudlog plot. See text for details.

information in adjacent plots of the same color like the total gas column in Fig. 8. One way to correct this is to change the color for columns where information is obscured by not truncating. The mudlog diagrams were scaled for publication and presentation size. Using this scaling individual bars are hard to see. We plan to routinely scale graphs like those presented here to a 30" length rather than 10" length we used, and to print them in that size. Then individual analyses can be seen easily.

Graphs can be improved by automating data interpretation. At present we closely examine data downhole over small intervals and decide based on

the evidence if the analyses indicate reservoir fluids, mixed reservoir and recharging cool fluids, steam heated waters, shallow cool fluids, and background inclusions. This can be done on a spreadsheet using IF statements. The interpretation can be added to the mudlog graphs we present here. Spreadsheet generated interpretations of well analyzed will have to be checked to make certain the interpretations are reasonable. We expect that application of FIS analyses to another geothermal system will require some recalibration.

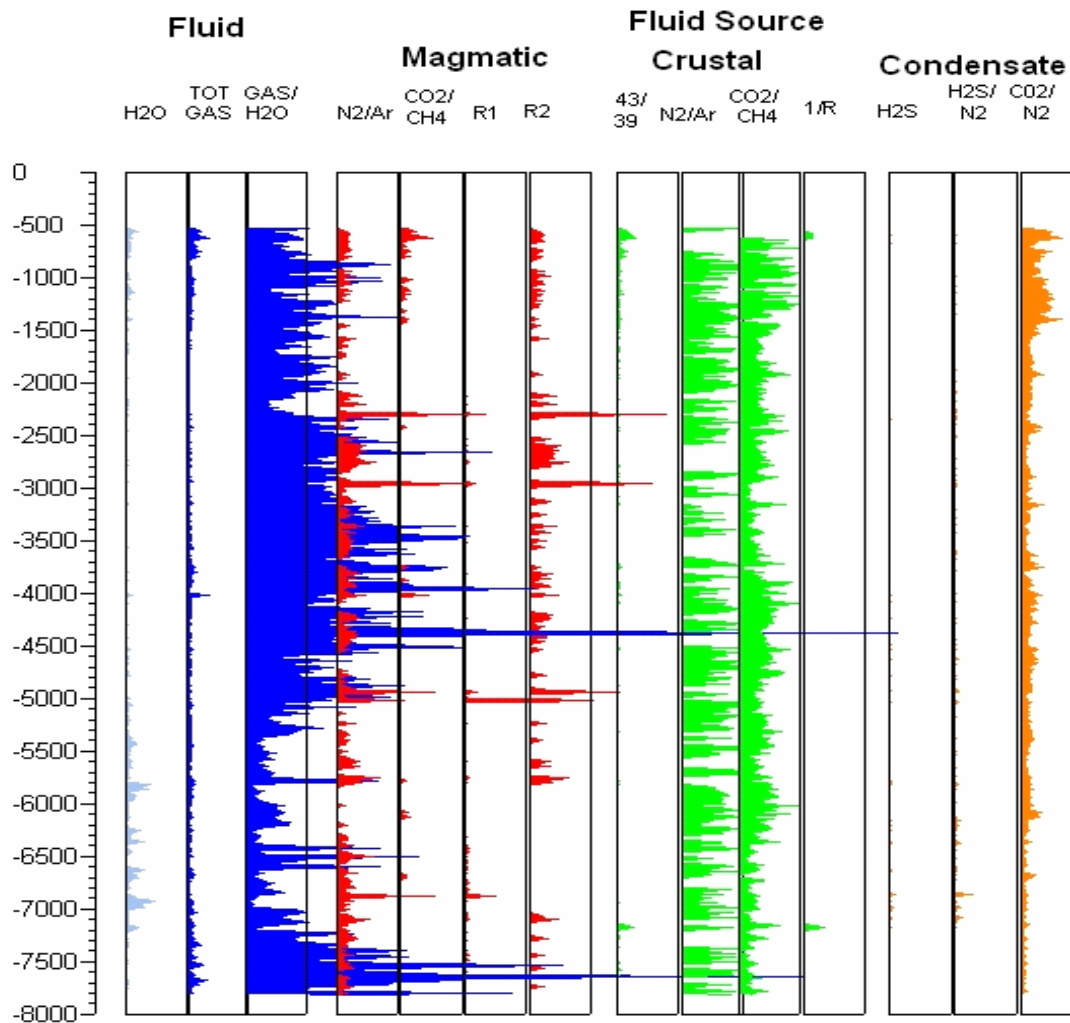


Figure 7. Well 3 interpretive mudlog plot. See text for details.

Data processing is required of FIT analyses. Analyses received from FIT are peak heights of mass peaks 1 to 180. For hydrocarbon companies FIT generates mudlog type graphs similar to Figs. 1 to 4 and provides a report with interpretations (Hall, 2002). Geothermal system FIS analyses are much more complicated to interpret in comparison to identifying a hydrocarbon reservoir. In order for FIS analyses to be economically applied to the geothermal industry the same approach to data analysis used by FIT has to be used. Preparation of diagrams for data interpretation has to be made quickly, and the interpretations have to be straightforward. The mudlogs here shown are rapidly prepared by use of spreadsheet template and macro to reduce analyses for plotting. The method of data plotting we show here is first step in simplifying geothermal-system FIS analysis data presentation and interpretation.

Mudlog graphs for a number of variables are more difficult to read that plotting analyses for individual

ratios or species versus depth. The advantages of Mudlog graphs are two fold. A significant number of variables can be easily compared. Analyses and gas ratios constructed for mudlog plots can be supplied in that form to the end users. They can then combine FIS data with other types of logs.

### CONCLUSIONS

1. Mudlog type plots of FIT analyses provide an easy to comprehend way of presenting thousands of analyses.
2. Plotting multiple species and interpretive gas ratios on mudlogs has provided new insights into the four Coso borehole FIS analyses previously studied.
3. Analyses of the ten Coso boreholes planned for the near future as this study continues will be immediately plotted on mudlog diagrams.

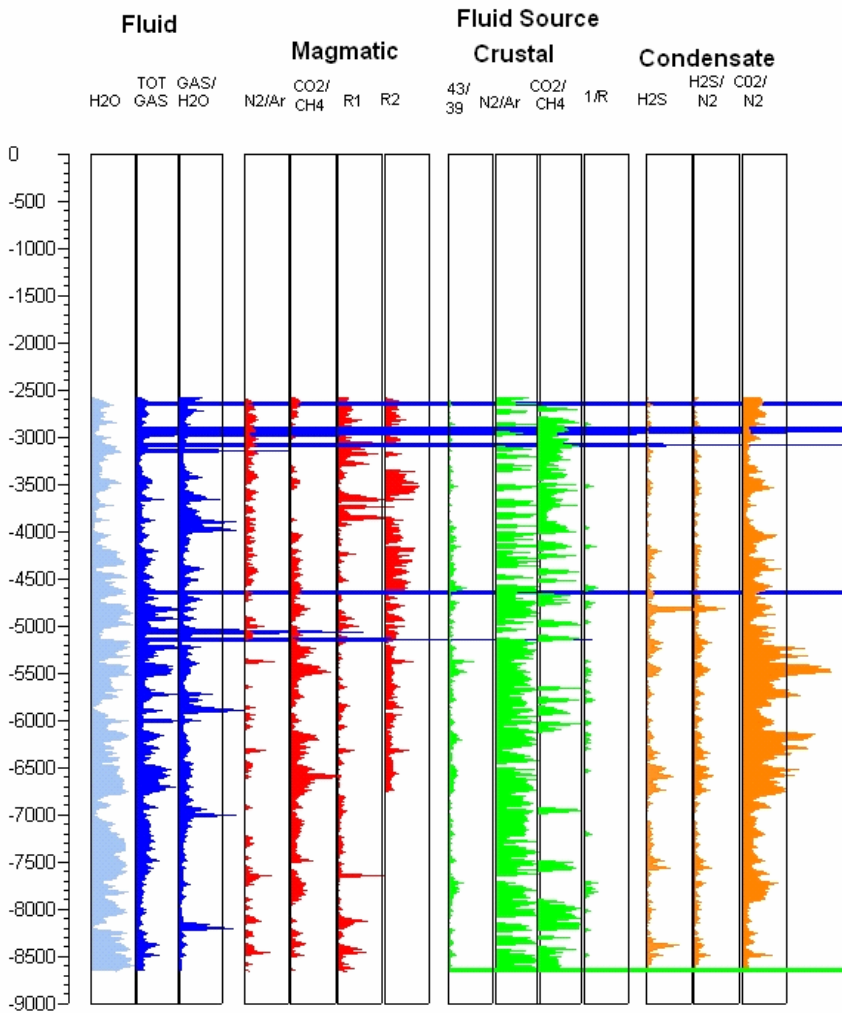


Figure 8. Well 4 interpretive mudlog plot. See text for details.

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