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CHEMICAL SIGNATURES OF AND PRECURSERS TO FRACTURES USING FLUID INCLUSION STRATIGRAPHY

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ABSTRACT

Fluid inclusion stratigraphy (FIS) uses gas analyses of fluid inclusions to determine fluid types in geothermal systems. Peaks in FIS data are assumed to be related to location of fractures. The working hypothesis is that open fracture systems can be identified by their FIS chemical signature; that there are differences based on the mineral assemblages and geology of the system; and that there are chemical precursors in the wall rock above open, large fractures. Correlating fracture locations in cores to peaks in the FIS data indicate that select chemical species are useful in distinguishing large fracture zones from small fractures. FIS data for Steamboat Springs, Karaha, and Glass Mountain wells supports our hypothesis that the fluid inclusion gas concentration of select species such as CO_2, H_2S, and select organic species are useful in locating fractures. High concentrations in fluid inclusions of CO_2 and H_2S occur 100 percent and 75 percent of the time within 10 feet of large fractures but only 18 and 13 percent of time in areas without fractures for Steamboat Springs Well 87-29. Identifying dense fracture areas as well as large open fractures from small fracture systems would assist in fracture stimulation selection for enhanced geothermal systems.

INTRODUCTION

Enhanced Geothermal Systems (EGS) are designed to recover heat from the subsurface by mechanically creating fractures in subsurface rocks. Open or recently closed fractures would be more susceptible to enhancing the permeability of the system. Identifying dense fracture areas as well as large open fractures from small fracture systems will assist in fracture stimulation site selection. Geothermal systems are constantly generating fractures (Moore, Morrow et al. 1987), and fluids and gases passing through rocks in these systems leave small fluid and gas samples trapped in healed microfractures. These fluid inclusions are faithful records of pore fluid chemistry. Fluid inclusions trapped in minerals as the fractures heal are characteristic of the fluids that formed them, and this signature can be seen in fluid inclusion gas analysis. Fluid inclusion stratigraphy (FIS) uses gas analyses of fluid inclusions to determine fluid types in geothermal systems. Peaks in FIS data are assumed to be related to locations of fractures. The working hypothesis is that open fracture systems can be identified by their FIS chemical signature; that there are differences based on the mineral assemblages and geology of the system; and that there are chemical precursors in the wall rock above open, large fractures.

Previous phases of this research verified that peaks in FIS data were often spatially associated with fractures, especially open fractures. The current work includes statistical analysis to quantitatively identify which fluid inclusion gas peaks (i.e. which chemical signatures) are associated with open and closed fractures in varying geologic regimes and lithologies.

This method promises to lower the cost of geothermal energy production in several ways. Knowledge of productive fractures in the boreholes will allow engineers to optimize well production. This information can aid in well testing decisions, well completion strategies, and in resource calculations. It will assist in determining the areas for future fracture enhancement. This will develop into one of the techniques that are in the "tool bag" for creating and managing Enhanced Geothermal Systems.

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METHODS

Three cores from three different fields had been logged and sampled for previous studies: one each from Karaha, Glass Mountain and Steamboat geothermal fields. Karaha in Indonesia is an active, single geothermal event at an active volcano. Glass Mountain in California is a single geothermal event system at the edge of the basin and range and more volcanic in nature than Steamboat Springs. Steamboat in Nevada is a classic basin and range, geothermal system with multiple events.

The cores are located at the Energy & Geoscience Institute in Salt Lake City, Utah. A continuous log of fractures, veins, fracture systems, and alterations was made for each core. FIS samples were collected every 30 feet along the core and every 10 feet where there were fractures, veins, and fracture systems. Select zones that contained fractures had FIS samples collected every 2 feet. Approximately 550 FIS samples were collected from each core and submitted to Fluid Inclusion Technology (FIT) of Oklahoma for analysis.

FIT has a proprietary system for rapid bulk analysis of fluid inclusion gases. A sample is crushed in a vacuum and the volatiles are analyzed with a quadropole mass spectrometer. The raw data is in the form of an Excel spreadsheet with relative concentrations per mass peak from 2 to 180. See Dilley & Norman, 2004 and Dilley, et al, 2005 for more on the FIS analysis process.

The raw data was plotted using the standard format for FIS (Norman, et al 2005). The species of interest are the principal gaseous species in geothermal fluids which include H_2, He, CH_4, H_2O, N_2, H_2S, Ar, CO_2, and select organic compounds. These species were plotted against known fracture and non-fracture areas to identify peaks.

We conducted a statistical analysis of these select species to determine percent difference in average fluid inclusion gas concentration between fracture locations and non-fracture areas. The analysis included averaging the data, obtaining standard deviations, identifying 84 percent and 98 percent of the population assuming a normal distribution, and determining the highest data points within each chemical species. The average plus one standard deviation would be 84 percent of the overall population.

Fracture identification was conducted using drilling logs from geologists and drillers for each well and identification from the cores. For Glass Mountain Well 88-28 we reviewed photos of some of the core, water-based mud reports from Calpine, daily mud logging reports from Calpine, some qualitative x-ray diffraction notes, and identification of fracture areas in the core. For Karaha Well T-2 we reviewed Karaha Bodas Company Lithology notes as well as identification of fractures from core. Steamboat Well 87-29 had a detailed log of fractures and sizes from the core.

Evidence of fractures was varied and included: visual evidence in photos, mud losses in drilling logs, or notes of fractures, veins, and vein-filling minerals in core logs. Fractures were identified as ‘open’ if mud losses or visual evidence of openness were noted, and sized (small/medium/large) if possible by observed size, amount of vein mineral present, or amount of mud loss. Closed fractures were identified where significant calcite, quartz, or pyrite, was noted in logs.

Peaks in FIS data were compared statistically with known fracture locations. The average and standard deviation was calculated and a percent difference between fracture locations and non-fracture locations was calculated.

STEAMBOAT SPRINGS WELL 87-29

Figure 1 presents a FIS log with fractures for Well 87-29 from Steamboat Springs, Nevada. The primary production zone for this well is from about 500 to about 1,200 feet with the hottest temperatures from about 600 to 850 feet. In the primary production zone from 500 to 1,200 feet there is a broad zone of fractures with maximum size of 10 to 100 millimeters and a few with larger openings. It can be seen that several of the peaks that occur in the FIS data corresponds to fracture openings. Peaks at 250, 825, 950, 1100, 2200, 3100, 3225, and 3700 feet correspond to open fractures. The deeper fractures are thinner and are cooler according to the temperature survey.

There are broader less defined peaks (some species not having peaks) on the FIS log that do not appear to correspond to open fractures such as 450, 2650, and 3800 feet. These broader peaks may correspond to older, closed fractures or alteration mineral

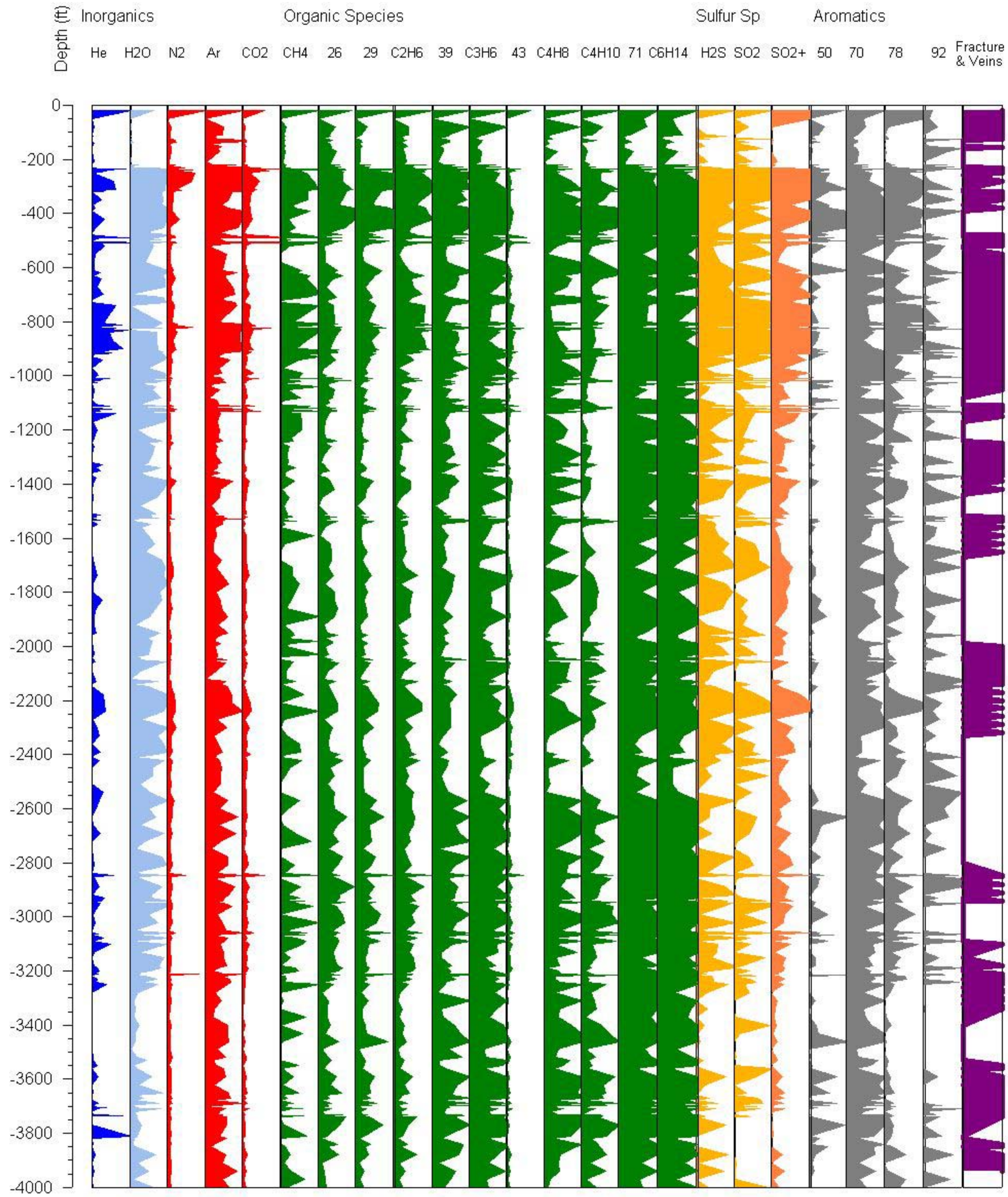

Figure 1: FIS log and fracture log for Steamboat Springs Well 87-29. Temperature survey indicates that the primary production zone occurs from about 500 to 1200 feet. Note the larger, broader peaks in all of the chemical species in this zone. At 3000 feet and below several of the chemical species do not have sharp peaks.

assemblages. In several of these zones, 2650 and 3800 feet, the CO_2 and several of the heavier organic species appear to have low values. The fractures below 3000 feet have peaks in a number of the organic compounds and aromatics but low values of H_2O, CO_2, N_2, and Ar. These fractures are not in the production zone.

Massive calcite occurs as fracture infilling and as veins in this well. Stibnite (antimony sulfide) also occurs as an infilling mineral (Jones 1912). Peaks in the concentration of CO_2 correspond with fracture locations particularly in the production zone. Peaks in the concentration of the sulfur species also correspond with the fracture locations particularly in the production zone and to a lesser degree in the non-production zone.

The average and standard deviation for fracture zones and for non-fracture zones for select species are shown in Table 1 for this well. The percent difference in the average fluid inclusion gas concentration, and the average plus one standard deviation are provided. The percent difference in the average concentration for several chemical species in fracture zones compared to non-fracture zones are 83 percent to 225 percent difference. The chemical species are CO_2, N_2, CH_4 and H_2S. The fluid inclusion gas concentration of H_2O is similar in both zones with a -6 percent difference. The minus sign indicating that the average fluid inclusion gas concentration of H_2O is slightly higher in non-fracture zones than in fracture zones.

Table 1: Percent difference in the concentration of select species for fracture zones and non-fracture zones for Steamboat Springs Well 87-29.

	87-29 Steamboat	16 CH4	18 H2O	28 N2/CO	34 H2S	44 CO2	Total Gas -CO2
Fractures							
	Average	2.68E+06	7.28E+06	2.17E+06	1.53E+05	5.72E+06	2.36E+06
	Std Dev	3.22E+06	5.62E+06	1.57E+06	1.28E+05	3.68E+06	1.90E+06
	Avg + std	5.89E+06	1.29E+07	3.74E+06	2.81E+05	9.40E+06	4.25E+06
No Fracture							
	Average	1.07E+06	7.75E+06	1.10E+06	4.71E+04	3.13E+06	2.51E+06
	Std Dev	1.78E+06	4.74E+06	6.20E+05	8.98E+04	2.87E+06	2.54E+06
	Avg + std	2.85E+06	1.25E+07	1.72E+06	1.37E+05	5.99E+06	5.05E+06
% Difference for Average		150	-6	98	225	83	-6
% Difference for Avg+std		107	3	118	105	57	-16

KARAHA WELL T-2

Figure 2 presents the FIS log with fracture locations for Karaha Well T-2. There are fewer fracture zones than in the Steamboat Springs well. The vapor zone in this well begins at about 3000 feet. The concentrations of the heavier organic species decrease at about 3200 feet indicating a change from meteoric water to a vapor zone. On the FIS log the heavier organic species are shown in green. Water, (H_2O) also occurs at about 2900 feet to 3650 feet suggesting a transition at this depth. Significant fractures occur associated with peaks across numerous chemical species including at 2500, 2900, 3200, and at 4300 feet. In addition there are fracture locations that are not associated with peaks in any chemical species such as 3750, 3900 and 4100 feet. However there are smaller peaks at approximately 3950 feet which maybe due to the fracture at 3900 and/or 4100 feet.

Vein minerals in Well T-2 included pyrite and calcite. The fracture noted at 2500 feet is associated with several pyrite veins. Multiple peaks are common also in the fracture starting at about 2850 feet. Additional fractures and veins with pyrite and calcite occur in this as well. Peaks in the concentration of H_2S tend to occur where pyrite is noted.

The statistics developed for Karaha Well T-2 are shown in Table 2.

Table 2: Percent difference in the concentration of select species for fracture zones and non-fracture zones for Karaha Well T-2.

	T2 Karaha	16 CH4	18 H2O	28 N2/CO	34 H2S	44 CO2	Total Gas -CO2
Fractures							
	Average	7.47E+05	2.72E+06	1.14E+06	6.12E+03	1.33E+06	2.66E+06
	Std Dev	1.27E+06	3.26E+06	6.49E+05	9.96E+03	1.33E+06	1.79E+06
	Avg + std	2.02E+06	5.98E+06	1.79E+06	1.61E+04	2.67E+06	4.45E+06
No Fracture							
	Average	2.76E+05	8.76E+05	1.14E+06	1.64E+03	1.14E+06	2.02E+06
	Std Dev	6.55E+05	1.46E+06	1.03E+06	2.93E+03	9.89E+05	1.44E+06
	Avg + std	9.31E+05	2.34E+06	2.17E+06	4.57E+03	2.13E+06	3.46E+06
% Difference for Average		171	211	0	272	17	32
% Difference for Avg+std		117	156	-18	251	25	29

The percent difference in the average concentration for CH_4, H_2O, and H_2S in fracture zones compared to non-fracture zones ranges from 171 percent to 272 percent. There is the same fluid inclusion concentration of N_2 in both zones and maybe slightly more CO_2 in fracture zones than in non-fracture zones. The total gas without CO_2 is the concentration of the organic species and aromatics and there is a difference in this concentration between fracture and non-fracture zones. This difference can be seen on Figure 2.

GLASS MOUTAIN WELL 88-28

Figure 3 presents the FIS log with fractures for Glass Mountain Well 88-28. Many of the fracture zones correspond to numerous peaks in the chemical species. The one fracture zone that appears not to have corresponding peaks is at a depth of about 2900 feet however there are a number of peaks in the organic species at approximately 3000 feet. This may correspond to the fracture location at 2900 feet. There are several areas where peaks in the chemical

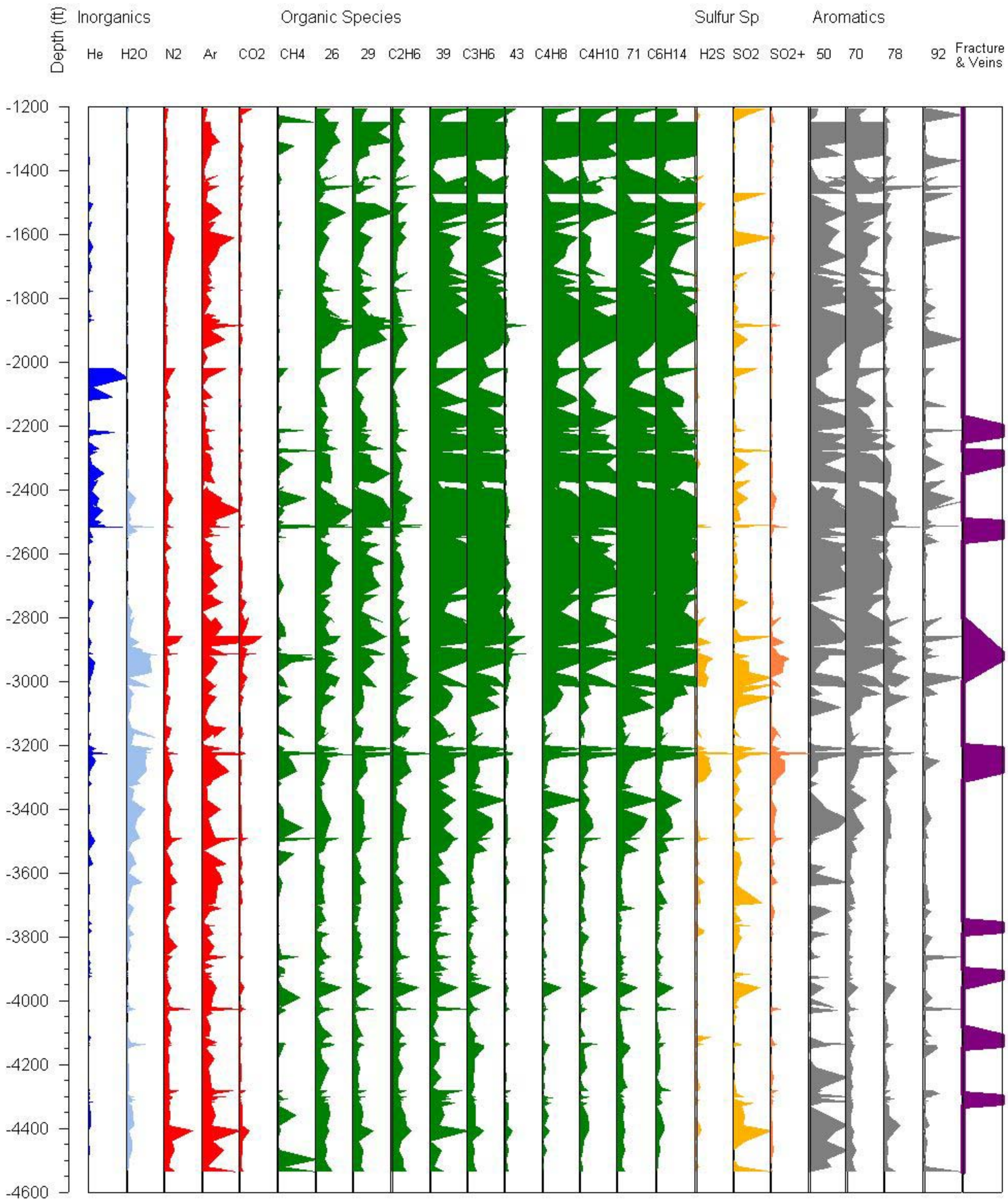

Figure 2: FIS log and fracture log for Karaha Well T-2. A vapor zone starts at about 3000 feet in this well.

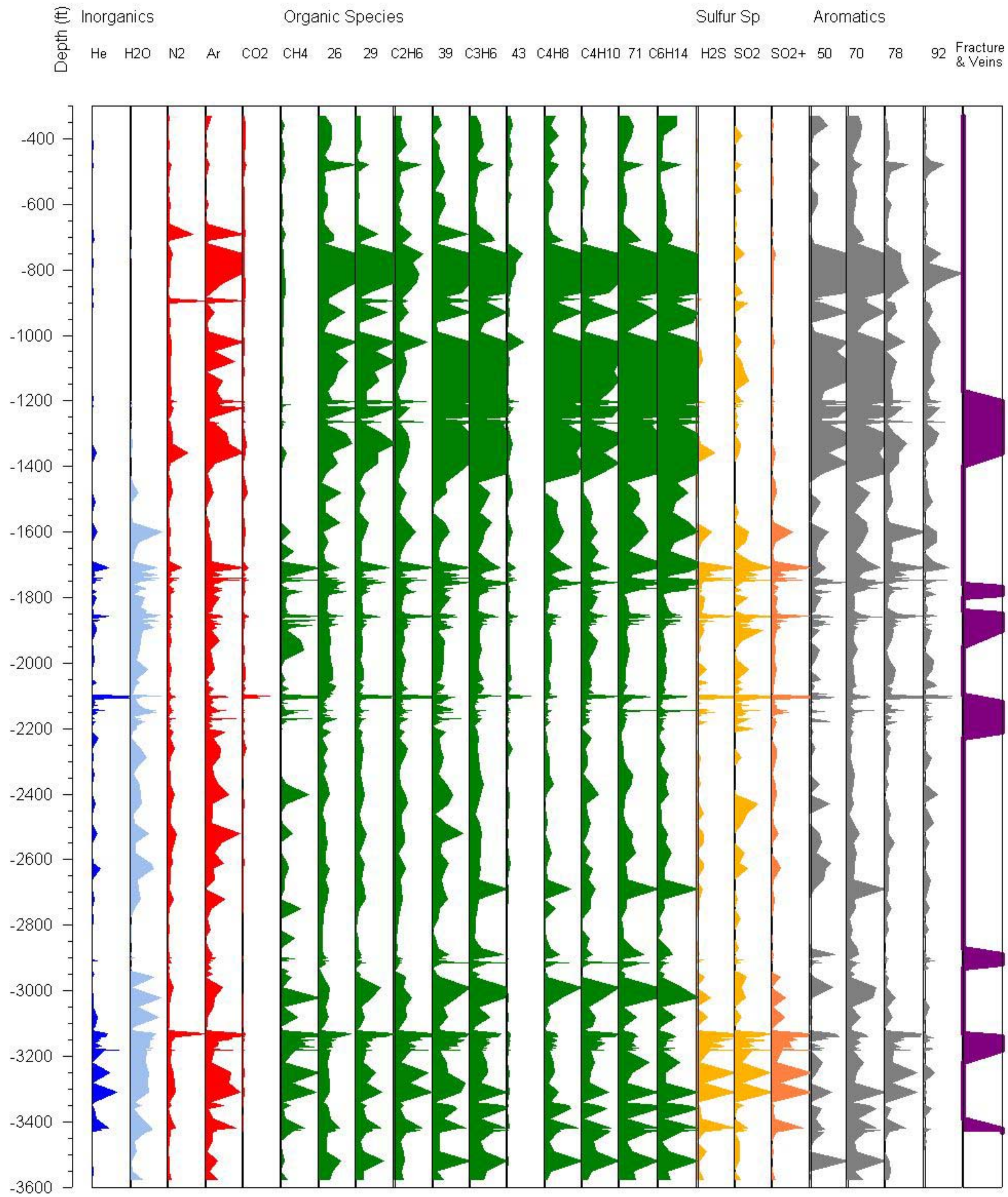

Figure 3. FIS log and fracture log for Glass Mountain Well 88-28.

species are evident however there is not a corresponding fracture location. This occurs as a broad peak from about 750 to 850 feet and again near the bottom of the well from 3250 to 3350 feet.

There is also a change in the chemical signature starting at about 1600 feet. The fluid inclusion concentration of H_2O occurs and to a lesser degree the sulfur species. The organic species have lower concentrations until about 3000 feet.

The fractures from about 1750 to 1900 feet are associated with small veins and fractures containing bladed calcite. The peaks in FIS data from about 2900 feet to 3150 feet and again the broad peaks from 3250 to 3350 feet correspond to areas of observed hydrothermal breccia veins. The fluid inclusion concentration of CO_2 is very low in these areas and is probably due to the release of CO_2 with steam during hydrofracturing.

Table 3 presents the statistics for Glass Mountain Well 88-28. The highest percent difference is in the average concentration of H_2S and this is readily seen on the FIS log in Figure 3. Methane (CH_4) and H_2O also have a high percent difference in their average concentration. For CO_2 the percent difference between the average plus one standard deviation is higher than the percent difference for the average only. This suggests that the highest concentrations of CO_2 are related to the calcite observed in the veins and infilling fractures.

Table 3: Percent difference in the concentration of select species for fracture zones and non-fracture zones for Glass Mountain Well 88-28.

88-28 Glass Mtn	16 CH4	18 H2O	28 N2/CO	34 H2S	44 CO2	Total Gas -CO2
Fractures						
Average	7.75E+05	3.84E+06	9.75E+05	2.37E+04	1.35E+06	2.56E+06
Std Dev	1.10E+06	3.40E+06	6.56E+05	7.79E+04	1.98E+06	2.00E+06
Avg + std	1.88E+06	7.24E+06	1.63E+06	1.02E+05	3.34E+06	4.56E+06
No Fracture						
Average	4.85E+05	2.52E+06	1.06E+06	7.28E+03	1.11E+06	2.25E+06
Std Dev	8.59E+05	3.14E+06	1.94E+06	1.71E+04	6.66E+05	2.59E+06
Avg + std	1.34E+06	5.66E+06	2.99E+06	2.43E+04	1.78E+06	4.85E+06
% Difference for Average	60	53	-8	226	22	14
% Difference for Avg+std	40	28	-46	318	88	-6

ADDITIONAL STATISTICAL STUDY

Typically FIS samples are collected from well chips at either 10 or 20 foot intervals in a well. With this difference in spacing compared to sampling a core we wanted to see if a fracture could be identified with a 10 foot zone. An Excel routine was developed that searches for and records peaks near identified features such as fractures, closed fractures, and open fractures. The routine searches for peaks in areas with no fractures identified, as comparison. The user can input the distance (10 or 20 feet) from features to search for peaks. Table 4 presents the results of this routine for Steamboat Spring Well 87-29.

Table 4: Percent chance of peaks near features in Steamboat Springs Well 87-29.

87-29 Steamboat	These numbers are the percent chance that there are peaks at least one standard deviation above the mean within 10' of the feature					
	18 H_2O	34 H_2S	44 CO_2	Tot gas except CO_2	Total gas	Total Organics
All depths in well	42%	26%	25%	31%	27%	29%
Small Fracs	37%	31%	20%	35%	29%	30%
Med Fracs	43%	30%	25%	32%	21%	32%
Large Fracs	31%	75%	100%	100%	100%	100%
No Fracs	46%	13%	18%	18%	19%	18%

As seen in Table 4, high concentrations in CO_2, total gas except CO_2, total gas, and total organics occur 100 percent of the time within 10 feet of a large fracture. There is a 75 percent chance of a peak in H_2S within 10 feet of a large fracture. High fluid inclusion gas concentrations of these species only occur between 13 to 19 percent of the time. The high concentration was based on the values above the average plus one standard deviation.

INTERPRETATIONS

Locations of fractures are identifiable on the FIS logs as peaks in the majority of chemical species as evident by the correlation in all three wells of the FIS peaks and the noted fractures and veins. The peaks may also represent the variability in the precision of the measurements. Based on studies conducted on FIS samples from Coso Geothermal Field and fluid inclusion standards, precision is about 25 to 35 percent (Dilley 2008). The percent difference in the average fluid inclusion gas concentration for select species is greater than the precision noted for the Coso samples. In some cases they are greater than 100 percent difference between fracture zones and non-fracture zones indicating that the difference is due to actual gas concentrations and not the precision of the measurements. The FIS peaks appear to readily correlate to veins and to a lesser degree to fractures which may be due to the infilling material in a vein having a greater density of fluid inclusions than the material surrounding an open fracture.

Preliminary results of current research on statistical correlations between FIS peaks and fractures seems to show that the best species to identify fractures are H_2S, CH_4, and to a lesser degree CO_2, total gas without CO_2, and total gas. The higher peaks also tend to occur near large, open, active fractures. This correlation seems to be best for large fractures in productive parts of the well, and varies, perhaps with the geology of the system.

Generally, H_2S peaks are associated with open fractures and pyrite mineralization, and with the production zone in the Steamboat Springs well (the depths studied in the other wells do not intersect a production zone). The percent difference for the average concentration of CO_2 ranged from 83 percent in Steamboat Springs Well 87-29 to 17 percent in Karaha Well T-2. This may be due to the development of the vapor zone and boiling that has occurred in the Karaha well. The Karaha well also shows a high percent difference in H_2O average concentration between fracture and non-fracture zones. The Steamboat Springs well has a very low percent difference in the average concentration of H_2O between the fracture and non-fracture zones. A similar trend occurs in Glass Mountain well as in the Karaha well but to a lesser degree. The production zone was not intersected in Karaha Well T-2 or in Glass Mountain Well 88-28 samples collected. Both of the wells are single geothermal events at or near volcanoes. Steamboat Springs is an active, classic basin and range geothermal system with multiple events.

CONCLUSIONS

Based on the wells studied there is a statistical difference in the average fluid inclusion gas concentration of select species between fracture and non-fracture zones. This suggests that FIS analysis can be used to find fracture zones within wells and be used to identify areas for fracture simulation in Enhanced Geothermal Systems. The applicability of FIS to determine a fracture zone will in part be based on the chemistry of the overall geothermal system. There appears to be trends within the data set that indicate specific geothermal systems will have certain chemical species that may be more useful than others, particularly H_2O, CO_2, CH_4, and H_2S.

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