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IDENTIFYING FRACTURE TYPES AND RELATIVE AGES USING FLUID INCLUSION STRATIGRAPHY

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Team Members:

Hattenburg Dilley & Linnell , LLC
New Mexico Tech
Energy Geoscience Institute

Authors:

Lorie M. Dilley
David Norman
Lara Owens

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EXECUTIVE SUMMARY

Enhanced Geothermal Systems (EGS) are designed to recover heat from the subsurface by mechanically creating fractures in subsurface rocks. Understanding the life cycle of a fracture in a geothermal system is fundamental to the development of techniques for creating fractures. Recognizing the stage of a fracture, whether it is currently open and transmitting fluids; if it recently has closed; or if it is an ancient fracture would assist in targeting areas for further fracture stimulation. Identifying dense fracture areas as well as large open fractures from small fracture systems will also assist in fracture stimulation selection. Geothermal systems are constantly generating fractures, and fluids and gases passing through rocks in these systems leave small fluid and gas samples trapped in healed microfractures. 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. Our hypothesis is that fractures over their life cycle have different chemical signatures that we can see in fluid inclusion gas analysis and by using the new method of fluid inclusion stratigraphy (FIS) the different stages of fractures, along with an estimate of fracture size can be identified during the well drilling process. We have shown with this study that it is possible to identify fracture locations using FIS and that different fractures have different chemical signatures however that signature is somewhat dependent upon rock type. Open, active fractures correlate with increase concentrations of CO_2, N_2, Ar, and to a lesser extent H_2O. These fractures would be targets for further enhancement. The usefulness of this method is that it is low cost alternative to current well logging techniques and can be done as a well is being drilled.

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1.0 INTRODUCTION

Enhanced geothermal systems (EGS) are engineered geothermal systems wherein a body of hot rock is fractured or "stimulated" through hydraulic, chemical and/or thermal processes. The stimulation may occur in rock that has healed fractures, low fracture density, or no fractures. The purpose of EGS is to create a large, interconnected body of rock that has sufficient fracture permeability for flow of hot fluids, creating a geothermal reservoir.

Recognizing the stage of an existing fracture in a geothermal well: weather it is currently open and transmitting fluids; if it recently has closed; or is an ancient fracture would assist in targeting areas for fracture stimulation in creating an enhanced geothermal system. Identifying dense fracture areas as well as large open fractures from small fracture systems would also assist in fracture stimulation selection. The hypothesis of this project is that fractures over their life cycle have different chemical signatures that can be identified using fluid inclusion gas analysis and by using the new method of fluid inclusion stratigraphy (FIS) the different stages of fractures along with an estimate of fracture size can be identified during the well drilling process.

Locating fractures and accurately determining their relative "age" or degree of contribution to the current geothermal system is especially applicable to potential enhanced geothermal resources primed for artificial fracturing. Open and producing fractures and those only recently closed by mineralization are likely better candidates for localized EGS enhancement. Differentiating these fractures from those zones of paleomineralization associated with an extinct geothermal event using FIS gas signatures is critical for such an application.

Two working assumptions for this project are:

1) Fractures can be identified by a high fluid inclusion density, therefore FIS analyses when plotted verses depth will show a peak at fracture locations.

2) Fluids fluxing through fractures diffuse into wall rock through microfractures; therefore, fluid flowing in major fractures will affect enough rock to be detected in well cutting gas analysis.

The project primarily involved logging three well cores from three different geothermal fields, obtaining FIS samples and comparing the results. One issue of concern associated with FIS, in attempt to maintain the benefits of low cost and fast turn-over rates, is determining the minimum sample spacing required to accurately locate and characterize a significant fracture zone. Using fluid inclusion thermometry on several geothermal wells, we attempt to map the distribution of various fluid populations surrounding major fracture systems to determine the distal extent to which vein-hosted production fluids may be identified by FIS gas signatures. In addition, we hope to verify the assumption that fluids trapped within matrix dominated well cuttings are representative of those both currently permeating the substrata and thus hosted within vein mineralization associated with major fractures. Fluids trapped within microfractures of primary matrix mineral phases and secondary replacement mineralization, namely within crystalline-hosted geothermal systems, suggest extensive overprinting by hydrothermal fluids (Moore, 1987).

Specific goals for this project are:

- To verify that peaks observed in FIS data are related to fractures.

- To determine which chemical species work best for identifying specific fracture types at each of several fields.
- To verify that FIS can provide reliable information about fractures.
- To optimize FIS sample intervals in order to minimize cost and maximize information obtained.
- To verify that FIS can be used to target select areas in a borehole to create additional permeability through fracture stimulation.

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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2.0 BACKGROUND

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. Fluids deposit minerals within the open fractures and small amounts of the fluid can be trapped within the minerals as they grow creating fluid inclusions. The fluid inclusions trapped in the minerals as fractures are filled are characteristic of the fluids that formed them, and the chemistry of those fluids is obtained by conducting gas analyses of fluid inclusions. Fluid inclusion stratigraphy (FIS) uses gas analyses of fluid inclusions to determine fluid types (Hall 2002, Dilley et al., 2004; Dilley et al., 2005; Norman et al., 2005).

Fluid Inclusion Stratigraphy (FIS) is a method developed for the geothermal industry which applies the mass quantification of fluid inclusion gas data from drill cuttings and applying known gas ratios and compositions to determine depth profiles of fluid barriers in a modern geothermal system (Dilley et al., 2004; Norman et al., 2005). Identifying key gas signatures associated with fractures for isolating geothermal fluid production is the latest advancement in the application of FIS to geothermal systems (Dilley et al., 2005; Dilley and Norman, 2007).

Modern zones of production are often defined by open, large-aperture fracturing and/or fracture swarms. Production zones identified by temperature and geophysical logs have a fracture density of >5 fractures/30 ft. with apertures >20mm is common in production zones. Production fracture fluid inclusion populations exhibit uniform salinities and trapping temperatures for both vein and wallrock minerals that correlate well with production fluids. Currently FIS data, sampled at 15-30 ft. intervals over production zones, typically exhibit anomalously high intensities, or peaks, for most gaseous inorganic species; N2, Ar, CO2 and He are commonly associated with large-aperture (>50mm) fractures and fracture swarms (Normal et al., 1997; Dilley et al., 2004; and Dilley et al., 2005). Nonproducing zones have similar fracture densities as productive fractures systems, but differ by having multiple fluid inclusion populations typically recording trapping temperatures 20-50°C above current temperature profiles, and smaller FIS gas peaks.

2.1 Geological Settings

Understanding the rock stratigraphy of the geothermal system will assist in determining the applicability of FIS. The three wells used in the study are Karaha-Telaga Bodas; Glass Mountain, and Steamboat Springs.

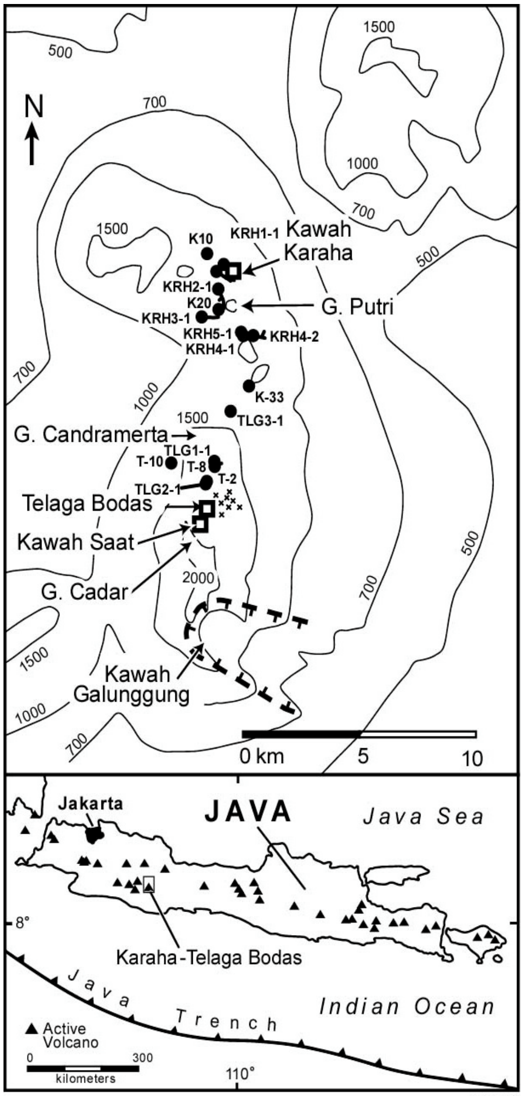

Figure 1: Map illustrating the distribution of volcanic features, thermal manifestations (Telaga Bodas, Kawah Saat, thermal springs (x's), and Kawah Karaha), and geothermal wells (filled circles) at Karaha-Telaga Bodas. Contour lines show surface elevations (masl). Kawah Galunggung is the main vent of Galunggung Volcano. From Moore et al. (2002).

Karaha-Telaga Bodas

Karaha-Telaga Bodas (Karaha) is a vapor dominated geothermal system on the Island of Java in Indonesia (Nemcock et al., 2004). The tectonics of this area is dominated by the subduction of the Australia Plate beneath the Eurasia Plate at the convergent margin of the Sunda arc (Lee and Lawver 1995). Volcanoes of the arc include Kawah Galunggung, an active vent which is geologically similar to Mt. St. Helens. Galunggung crater is horseshoe shaped, and is believed to have been shaped around 4200 years ago by massive slope failure (Katili and Sudradjat 1984). The geothermal field follows a volcanic ridge that stretches between Kawah Galungung and Kawah Karaha (Figure 1). Simple models of the gravity data of this field are consistent with a mushroom-shaped intrusion that extends to fairly shallow depths beneath a thermal area at Telaga Bodas and extends for about 10 km north as a thin sill underlying the bulk of the geothermal system. Petrologic data supports that this intrusion is likely the heat source of the system (Tripp et al., 2002).

The history of this system is considered to be relatively simple, as indicated by vein paragenesis (Moore et al. 2002). An initial liquid-dominated stage began when magma intruded the base of the volcanic cone. The geothermal system was capped by volcanic extrusives (lava and pyroclastic flows). Altered pyroclastics beneath the topmost andesite flows absorbed the deformation and left the andesite flows only weakly fractured. Many cycles of overpressuring resulted in tensile fractures in the system. Probably due to the catastrophic slope failure that formed Galunggung crater, the system experienced a sudden drop in fluid pressures that boiled the fluids of the system and resulted in the vapor dominated system encountered today. Downward percolating condensate and meteoric waters resulted in progressive downward sealing of fractures that extended the depth of the cap rock. Decreased pore pressure in the vapor zone caused collapse of fractures and left low perm abilities. Present day fractures in the cap rock show an overall strike-slip stress regime. Those in the reservoir show a normal-fault stress regime (Nemcock et al., 2004).

The present day system has been explored by drilling to depths of 1.86 miles. The vapor dominated system overlies a deeper liquid reservoir and temperatures up to 660°F are measured. A quartz diorite encountered at depth in drill holes is believed to be the intrusive supplying heat to the system (Moore et al., 2002). Well T2 was advanced to a depth of 4,400 feet on the northern side of Telaga Bodas (Figure 2) in 1997. The well was shallow and did not penetrate the magmatic vapor chimney but did below 3,000 feet (ft) encounter a vapor-dominated zone. The well encountered a series of lithic tuffs and andesitic tuffs. Temperatures dramatically increased at approximately 2,200 ft. from below 200°F to slightly above 500°F.

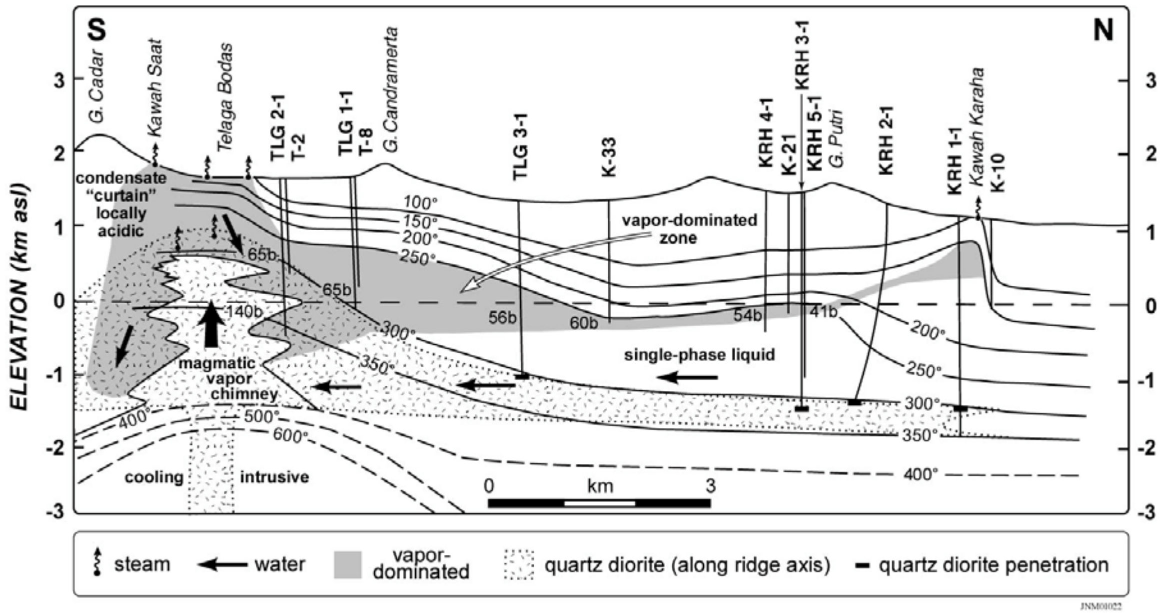

Figure 2: North-south cross section through the geothermal system. From Moore et al., (2002); Modified from Allis et al., (2000) and Tripp et al., (2002).

Glass Mountain KGRA

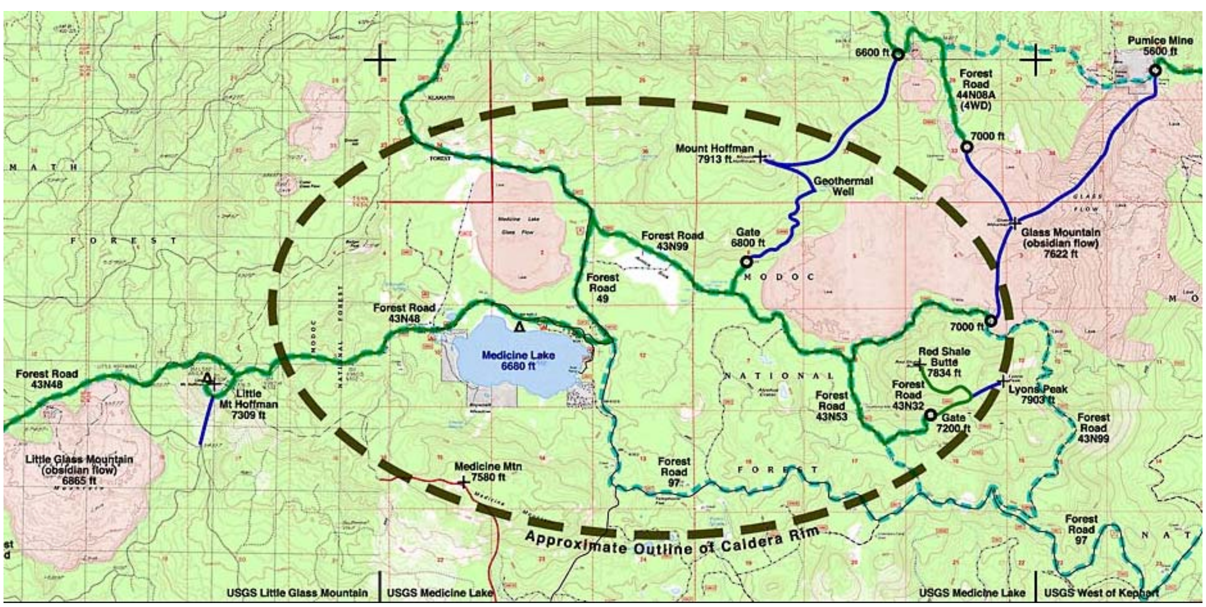

Figure 3: Glass Mountain and Caldera area of Medicine Lake Volcano.

The Glass Mountain known Geothermal Resource Area (Glass Mtn.) is located on Medicine Lake Volcano in the Cascade Range of Northern California (Figure 3). The Cascades are a convergent margin feature inland of the subduction of the Juan de Fuca Plate beneath the North American Plate. Medicine Lake Volcano (MLV) is shield volcano just east of the main arc of the Cascades in a basin and range-style E-W extensional environment on the Modoc Plateau. Regional N-S trending normal faults project under the volcano from the north and the south. The northwestern extension of the Walker Lane fault system also coincides with MLV (Donnelly-Nolan 2002). Volcanic activity at MLV seems to be strongly episodic, with the most recent episode ending about 900 years ago with the eruption of dacite and rhyolite at Glass Mountain and other east rim vents (Donnelly-Nolan 1990). MLV is the largest volcano by volume in the Cascades, and earlier volcanic vents connect MLV with Mt. Shasta, about 50 km to the west-southwest. Vent and fault alignments on MLV are generally N-S and rarely outside of 30 degrees of north. Exceptions to this include the southwest flank where vents trending 55 degrees east of north are likely influenced by the vents between MLV and Mt. Shasta and the presumed crustal weakness in this location, and the vents near the caldera, which tend to be tangential to the rim. Ground cracks are evident on the upper northwest flank and lower north, east and south flanks, oriented typically NNW to NNE but with east-west opening, consistent with the regional tectonic regime (Donnelly-Nolan 1990).

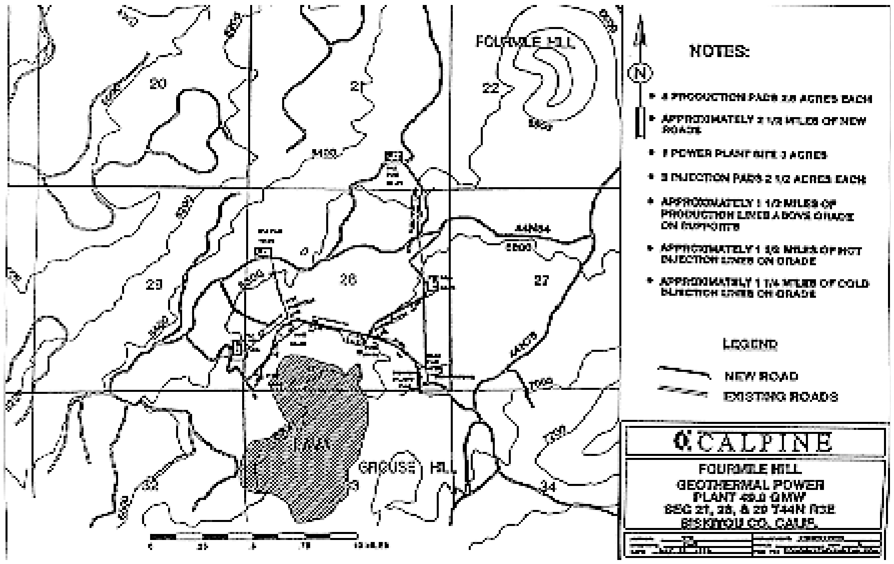

Figure 4: Fourmile Hill Geothermal project area within Glass Mountain KGRA (GHC Bulletin, Aug. 1996).

Lavas range in composition from basalt through rhyolite. Glass Mountain on the upper east flank of MLV is a rhyolite dome complex with rhyolite and dacite obsidian flows. It is believed that MLV is made up of many small, differentiated magma bodies and a complex of mafic dikes from the periodic injection of basalt, which ultimately provides the volcano's heat. MLV is a dry area within the rain shadow of the Cascades, and springs of any temperature are rare. One fumerolic area is present at a hot spot near Glass Mountain (Donnelly-Nolan 1990). Figure 4 presents a location map and Figure 5 presents a cross-section.

Well 88-28 is composed of felsic volcanics overlying mafic lavas. The well was advanced to a total depth of 8,000 ft. however core was available for only the top 3,600 ft. At approximately 1,200 ft. the lithology changes from mixed volcanics (altered basalts) to felsic volcanics. The estimated static temperature increases rapidly from 350°F at 1500 ft. to 400°F at 2800 ft.

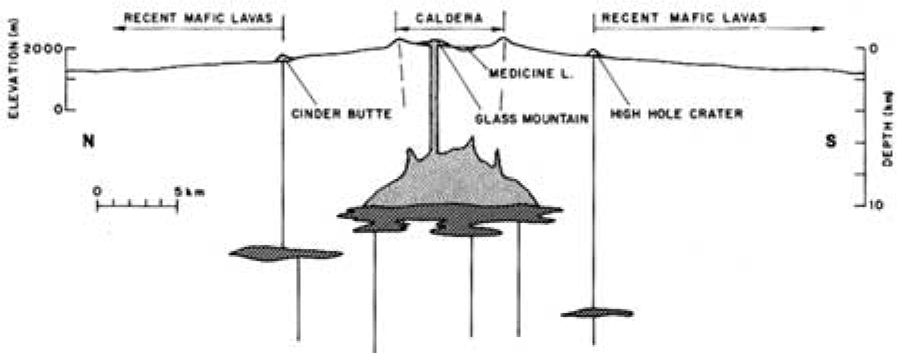

Figure 5: From Eichelberger (1981). A north-south cross section through the center of the Medicine Lake Highland volcano with major features projected onto the profile. Vertical exaggeration of surface topography is 2X. Silicic magma chamber is shown at depth discussed in text and intermediate in size between the minimum case, a small body at intersection of cone sheet caldera fractures (Heiken, 1978) and the maximum possible extent marked by position of flanking mafic vents.

Steamboat Springs

Steamboat Springs (Steamboat) is located in the Humboldt zone of the Basin and Range in northern Nevada. The Humboldt zone is a northeast-trending structural zone containing northeast-striking left-lateral and normal faults and northeast-trending folds. Several major geothermal fields lie in this zone (Faulds et al., 2002). North and northeast striking faults in the Steamboat area likely provide conduits for fluid flow (Figure 6).

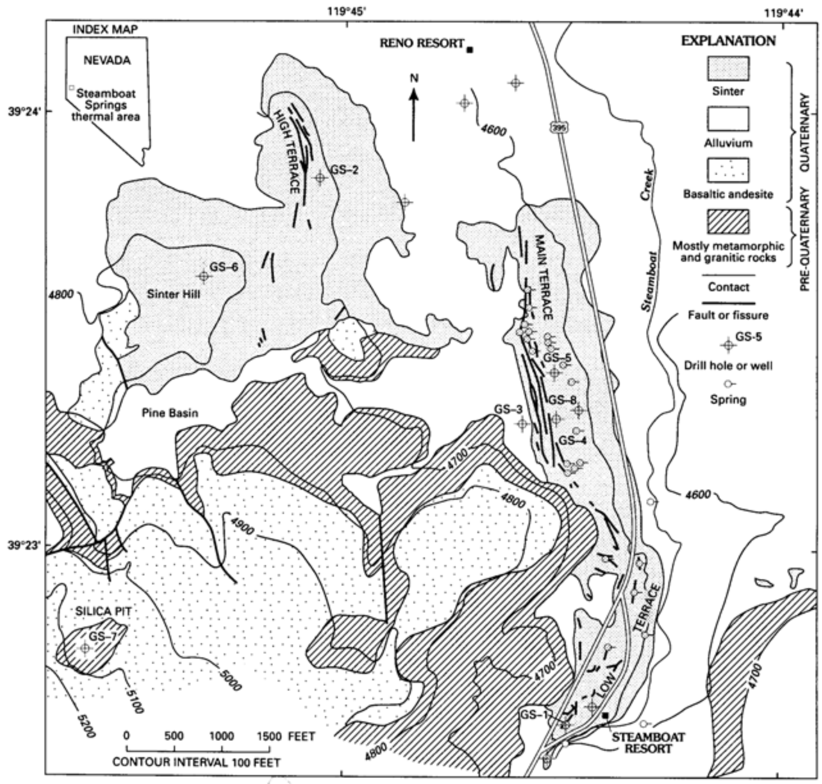

Figure 6: Location and Geology of Steamboat Springs, Nevada (from White et al., 1992).

The springs have been used and developed for purposes ranging from recreation to power since about 1860. Springs are almost boiling. One geothermal plant in the area produces power from an approximately 458°F reservoir in hydrothermally altered granodiorite and metamorphics located near a Cretaceous intrusive contact of the granodiorite. Another set of wells taps fluids with a maximum temperature of about 325°F (at about 1312 ft. depth) in fractured granodiorite along a north-northeast striking fault zone. It is believed that this fluid may be the cooled outflow plume of the resource tapped by the other set of wells (Garside et al., 2002).

Several 1.1 million year-old rhyolite domes occur in the area, another rhyolite intrusive may lie under the thermal area (White et al., 1964). The area has been hydrothermally active, at least intermittently, for over 2.5 million years (Silberman et al., 1979). There is debate about whether the hydrothermal system is due to circulation of fluids in an extensional environment or due to heat from a magmatic intrusion at depth. Both types of hydrothermal systems are present in the Basin and Range, and the extensional type system is nearly unique to this environment. Support for an extensional heat mechanism comes from close proximity to an active range front fault. Although there is no direct evidence for a magmatic system able to provide the needed heat, geochemical data supports this option, in a manner called "compelling" by the authors (Ahehart et al., 2003). The known rhyolite domes are too old to have provided this heat source, but younger intrusions may be buried.

Well 87-29 was advanced to a depth of 3990 ft. The matrix is composed of lahars, and a series of granodiorites. Primary production is from 500 to 1200 ft. with temperatures above 300°F.

3.0 METHODS

Four cores from three different fields were logged and sampled: two from Karaha, one each from Glass Mtn. and Steamboat geothermal fields. Well K-33 at Karaha was sampled at select intervals during the formulation of the proposal for this project. Karaha in Indonesia is an active, single geothermal event at an active volcano. Glass Mtn. 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 were 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 had FIS samples collected every one to two feet. Samples were also collected for petrographic analysis and fluid inclusion thermometry.

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 et al., 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 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. Geothermal fluid inclusion mass spectra generally show major peaks at 2 (H_2), 18 (H_2O), 28 (N_2) and 44 (CO_2), with other mass spectra at lower values. The peaks at high mass/electron values (above about 60) are typically heavier organic compounds. Intensities range up to 8 orders of magnitude. Figure 7 presents that mass spectra for one sample at a particular depth from a well at Coso geothermal field.

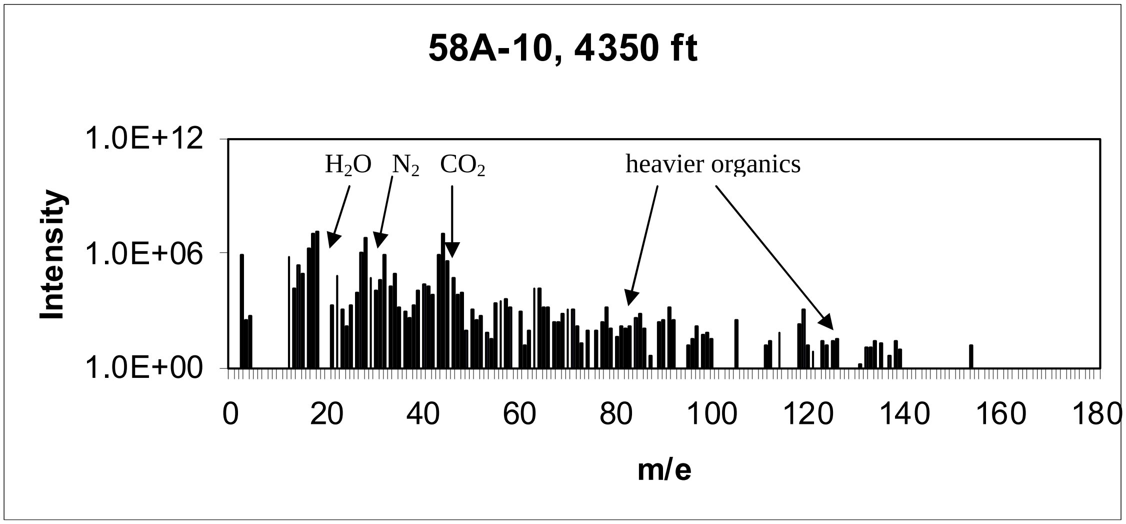

Figure 7: Typical FIT mass spectra of fluid inclusions in drill chips from a particular depth.

Due to the extensive amount of data (mass peaks from 2 to 180 for each of the over 1500 samples), data processing is required and a tool is needed to display the data. Figure 7 would not be useful for plotting the data for interpretation for each well. FIT generates mudlog type graphs as seen in Figure 8 and provides a report with interpretations (Hall 2002).

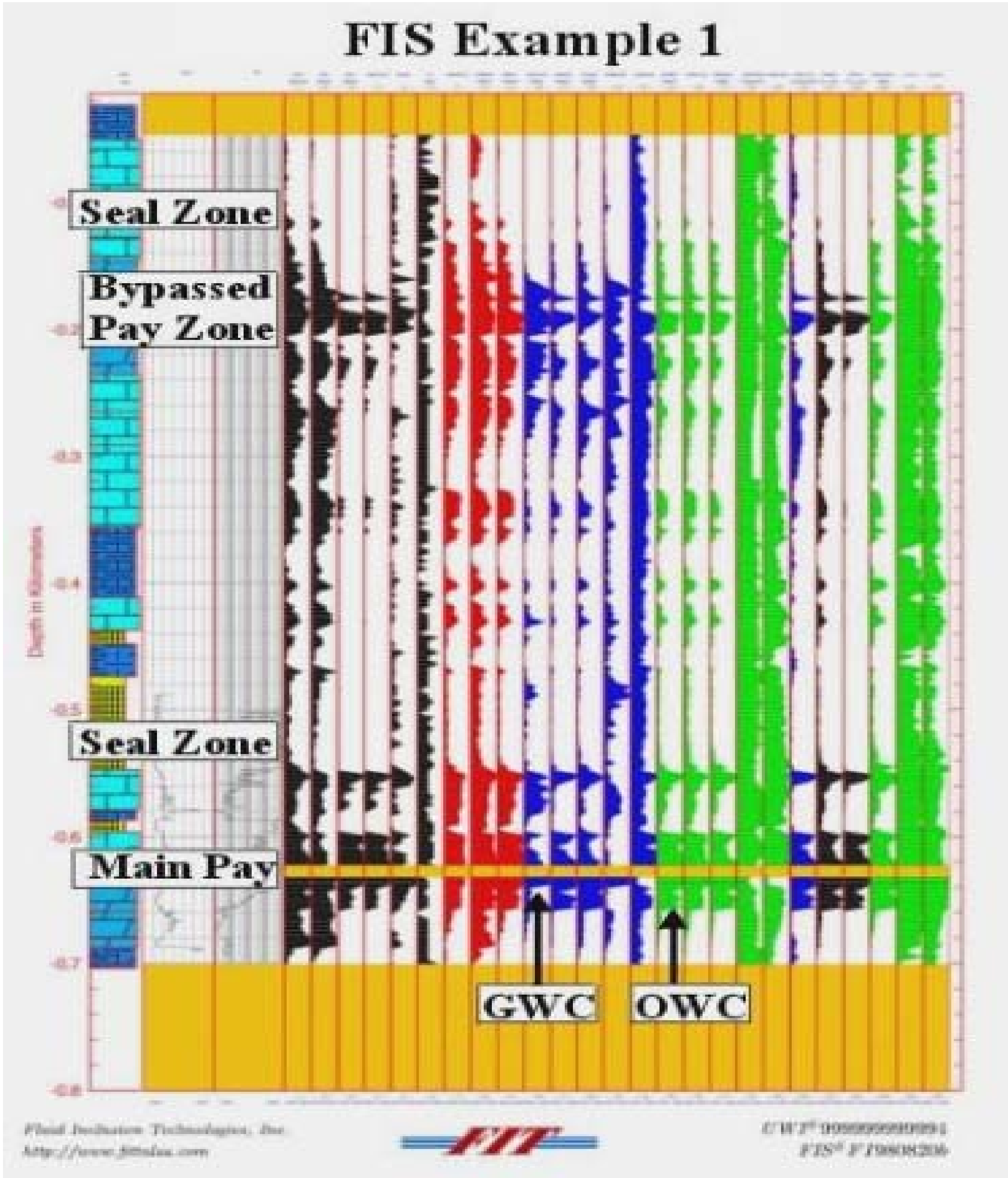

Figure 8: FIT's mudlog type graph presentation of mass spectra.

In order for FIS analyses to be useful and economically applied to the geothermal industry an approach similar to FIT was adopted. The Rockware® program Logger was selected for plotting the mass spectra because it was low cost, adequate for the job, and data files can be transferred into industry programs. Logger produces graphic strip logs from user-created or imported data files. The data files were created in Excel from the ASCII file supplied by FIT. For each gas species a major gas peak that had little interference from other species were chosen. For example for methane this is mass 15, not 16 (the weight of methane). The format of the logs can be designed by the user. For each well a mudlog displaying mass peaks of various compounds were plotted (Norman et al., 2005). For each species, the scaling of the graphic strip is set using as a maximum as the mean plus two times the standard deviation.

On the mudlogs developed the species are grouped by chemical type, which are plotted in different colors. Helium and water are plotted in blue with water distinguished by a lighter blue color. The inorganic species N_2, Ar, and CO_2 are plotted in red. The C_2-C_6 straight chain organic species are plotted in red (C_2H_6, C_3H_6, C_3H_8, C_4H_8, C_4H_{10}); the sulfur species are plotted in orange; and organic aromatic peaks are plotted in gray. 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 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 concentrations are in the low ppm and ppb range (Norman et al., 2004).

Vein and vug material, and surrounding host rock associated with major fracture swarms for each well were sampled from various intervals for thermometric analysis of fluid inclusions and their fracture aperture measured. Thermometric analysis of secondary quartz and calcite-hosted fluid inclusions were compared with transparent mineral phases from the adjacent wallrock (≤2cm away) using a Linkam PR600 thermometric stage (Figure 9). Multiple Tm (ice, eutectic) and Th values were used to determine fluid populations for each fracture system. Core from Steamboat 87-29 was selected to characterize the distance and pervasiveness over which fracture-generated fluids effect hostrock fluid inclusions. Two major fracture intervals were isolated for study: 818 ft. (Region 1) representing a zone of major production and 1112 ft. (Region 2) representing a significant, yet cooler zone of production. In addition to the central vein mineralization, surrounding matrix material was sampled at increasing spatial intervals from both central fractures: *approximately* 1/2, 4, 20 inches, and every 10 ft. to 100 ft. from the fracture. Core intervals containing fracture swarms were selected to analyze fluid inclusion homogeneity among dendritic extensions of the main fracture. Fracture frequency, aperture, and degree of mineralization were measured and noted in detail for both systems.

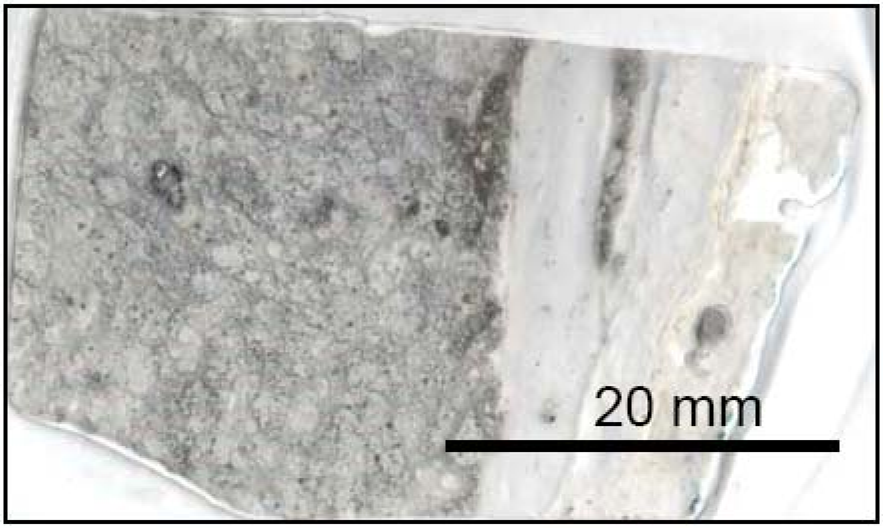

Figure 9: Example of thick section of vein and hostrock: sampled from 226' in Steamboat 87-29 exhibiting grey quartz and milky white quartz in vein fracture, propylitic alteration, and strong siliceous alteration of matrix.

The FIS and fluid inclusion thermometry were compared to the core logs developed. The core logs were plotted along the laboratory data collected in order to evaluate how the FIS samples correspond to the fractures observed.

4.0 DATA

This study began with select sampling of two wells from Karaha T2 and K33. Six fracture zones were selected from the Karaha wells. The fracture zones consisted of calcite, quartz, pyrite, and a combination of the three mineral types. Figure 10 shows select results of mass spectra plotted against depth for Well K-33, with a fracture at 5458 feet. It can be seen that H_2O, CO_2, and ratio of 43/39 all indicate sharp peaks at this location, with H_2O having a broader peak.

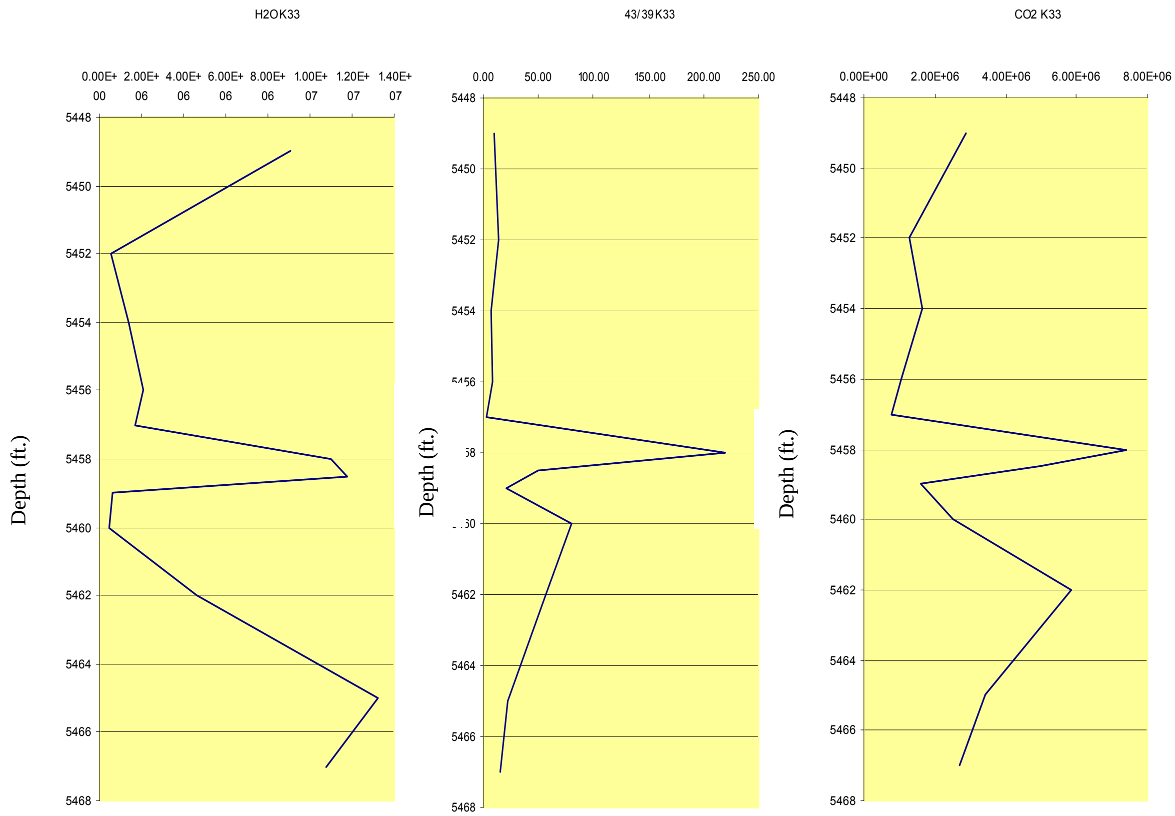

Figure 10: Graphs of various ratios for Karaha Well K-33. Note the peaks all correspond to location of vein at 5458 feet.

Table 1 presents the type of mineral infilling a fracture and locations of peaks for select chemical species observed relative to the fracture. Table 1 was compiled from the fracture zones studied for the two wells. It can be seen that the peaks for a number of the chemical species and ratios of interest occur at fractures. In the case of the altered zone, there were several distinct fractures and corresponding chemical species peaks. Pyrite filled fractures did not produce a peak in the concentrations of H_2O, CO_2, or propane/propene (43/39) ratio.

Table 1. Select chemical species and their occurrence in the fluid inclusion gas chemistry in relation to the fracture.

Mineral	CH4	H2O	N2	H2S	Ar	CO2	Gas/H2O	N2/Ar	CO2/CH4	43/39
Calcite	X	X	X	X	X	X	X	X	X	
Quartz	X	X	X	X	X	X				X
Pyrite	X		X	X	X			X		
Calcite & Pyrite		X	X	X	X	X	X	X	X	X
Quartz & Pyrite	X	X	X		X	X	X	X	X	X
Altered	X	X	X	X	X	X			X	X

4.1 FIS Logs

Figures 11 through 13 present the fluid inclusion stratigraphy (FIS) logs for each of the three main cores studied. It can be seen on the FIS logs that at certain depths there are a series of peaks occurring in many of the chemical species. For instance in Figure 11, the Karaha T2 log, at a depth of between 1900 and 1950 feet there are significant peaks in Ar, CO_2, throughout the organic species except CH_4, and in three of the aromatic species but not in H_2O. These series of peaks also occur at about 1300 ft, 1550 ft, 2450 ft, 2900 ft, and 3225 ft. Peak location varies between wells. For Glass Mtn. 88-28 (Figure 12) the peaks are observed at 800 ft, 1050 ft, 1200 ft, 1700 ft, 1850 ft, 2100 ft, and 3150 ft. For Steamboat 87-29 (Figure 13) there is a series of peaks from about 400 feet to 1100 feet and then again from 2850 feet to 3200 feet. There are some areas in each log that have a series of peaks however the peaks do not occur in the majority of the species or in only the heavier organic species, such as in Steamboat Springs 87-29 at 3500 ft. Also peak thickness varies. When this occurs throughout the species at the same depth the thickness may be due to the sampling interval. For instance in Figure 12, Glass Mtn. 88-28 at 2100 feet the thinness of the peak is due to the sampling interval being only a few feet. When it occurs with only a few species at a select depth, it is most likely due to the concentration of the chemical species, Figure 11 at 4450 ft.

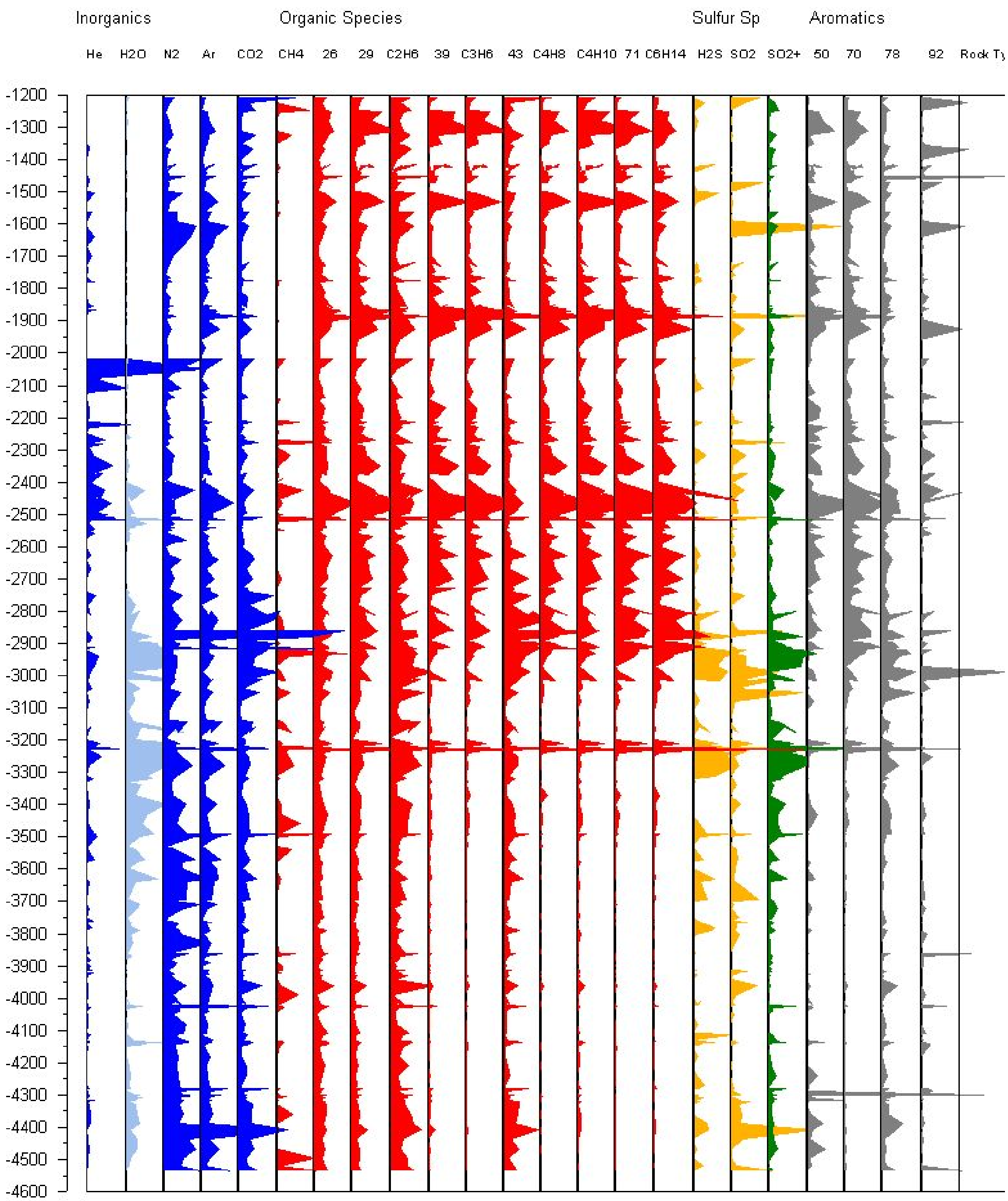

Figure 11: FIS Log for Karaha Well T2.

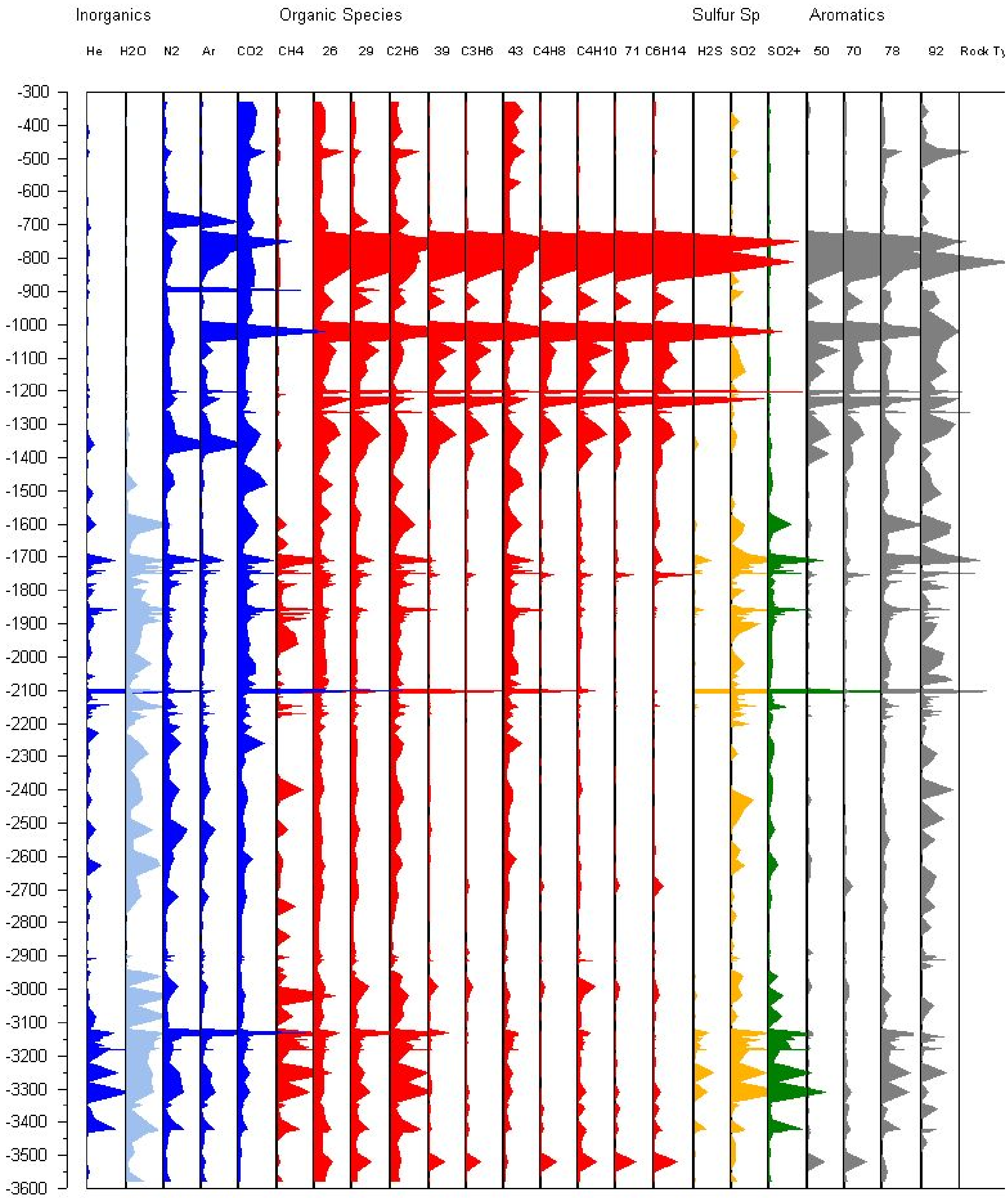

Figure 12: FIS Log for Glass Mtn. Well 88-28.

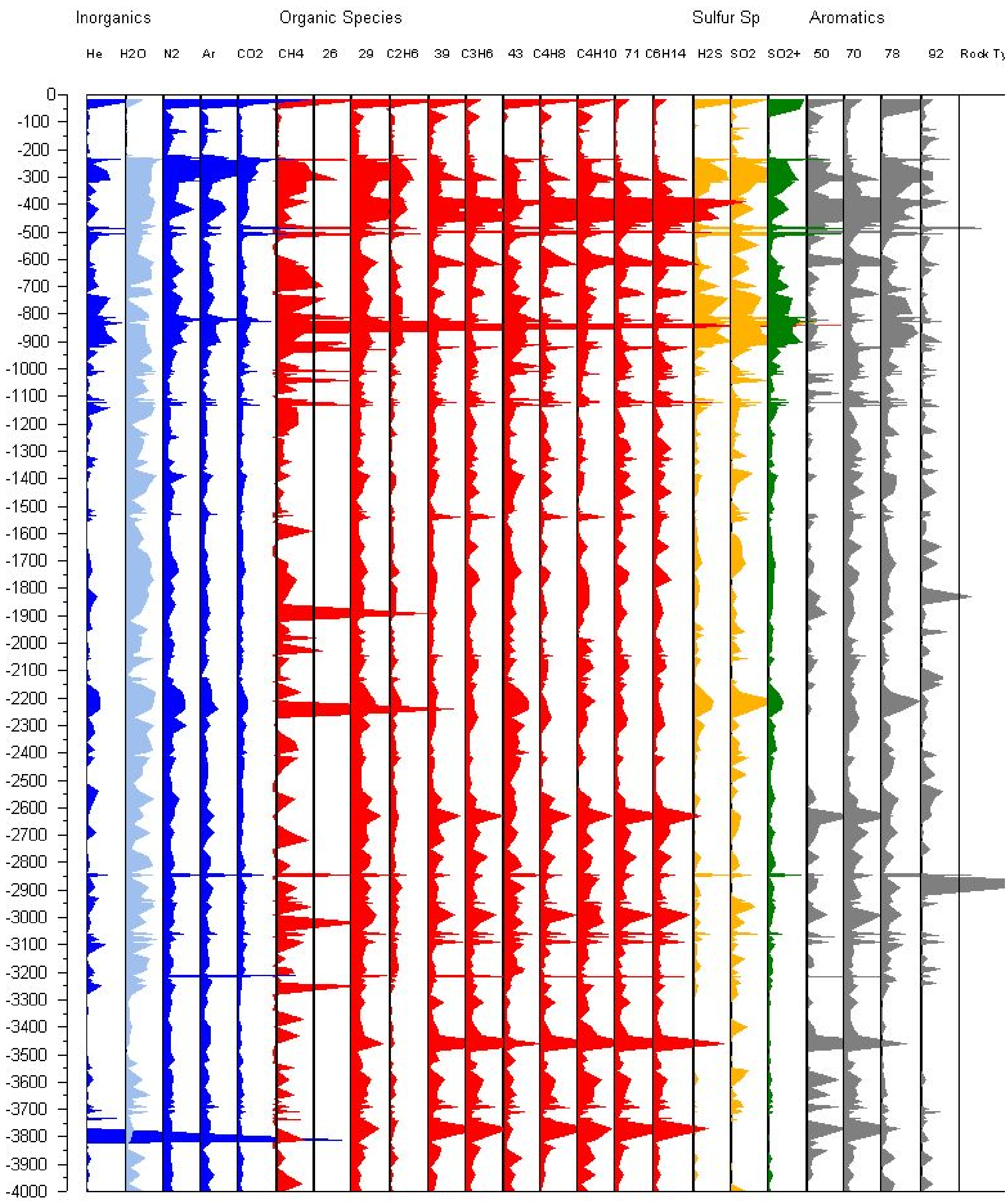

Figure 13: FIS Log for Steamboat Well 87-29.

Figures 14 and 15 present the fracture log developed for Karaha T2 and Glass Mtn 88-28. These fracture logs were developed from logging of the core and from data provided by Joe Moore and Jeff Hulen of EGI. For Steamboat the fracture log was developed by Jeff Hulen of EGI. This fracture log is presented in Figure 16. Each fracture log is plotted against the FIS log for each well. These logs include fractures, veins and vugs which are referred herein collectively as fractures.

In Figure 14, for Karaha T2 it can be seen that there are a series of veins, vugs, and fractures that are greater than about 3 mm located from about 1600 ft to about 2000 ft., at 2250 to 2750 ft.; at 3300 to 3400 ft.; and from 3600 to 4000 ft. The FIS log correlates to the larger veins, vugs and fractures at 1900 ft and 2300 to 2500 ft. The FIS log indicates a peak at 3250 ft. which is about 50 ft. above a large vein/vug at 3300 to 3400 ft. This may be due in part to the sampling interval. There is no correlation of the large fracture, vein/vug zone at 3600 to 4000 ft. with peaks on the FIS log.

For Glass Mtn. Well 88-28 (Figure 15), the fractures log correlates with peaks in the FIS log at 900 ft, 1200 ft, 1900 ft, 2100 ft, and to a lesser extent from 3150 to 3400 ft. Most notable of the correlations is the peak at 2100 feet which the fracture log indicates to be a large vein. There are several depths that indicate peaks on the FIS log that do not correspond to the fracture log such as at 800 and 1000 ft.

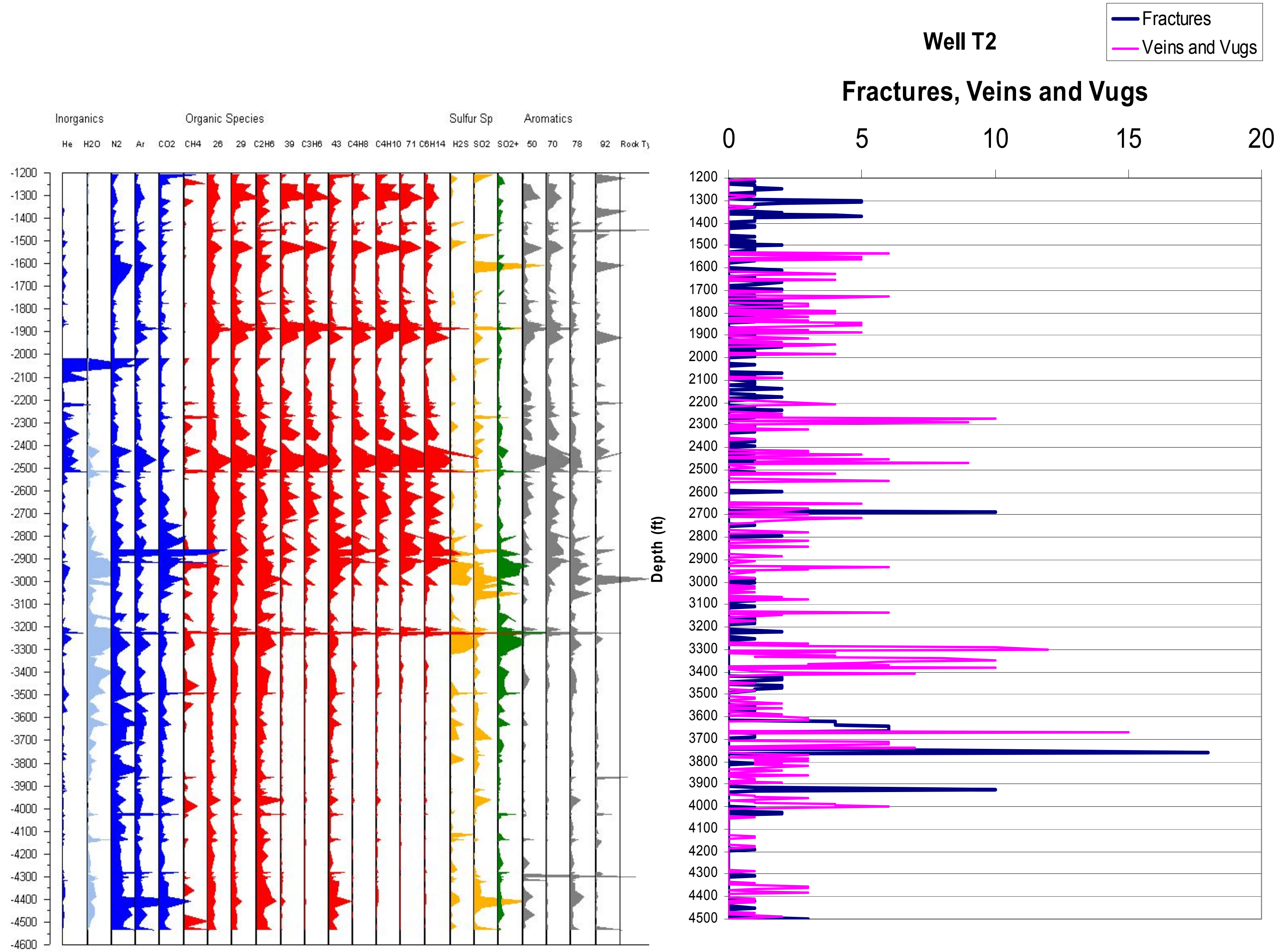

Figure 14: Combine FIS Log and Fracture Log for Karaha Well T2. Note Well T2 did not encounter a production zone but did encounter a vapor dominated zone below 3000 feet.

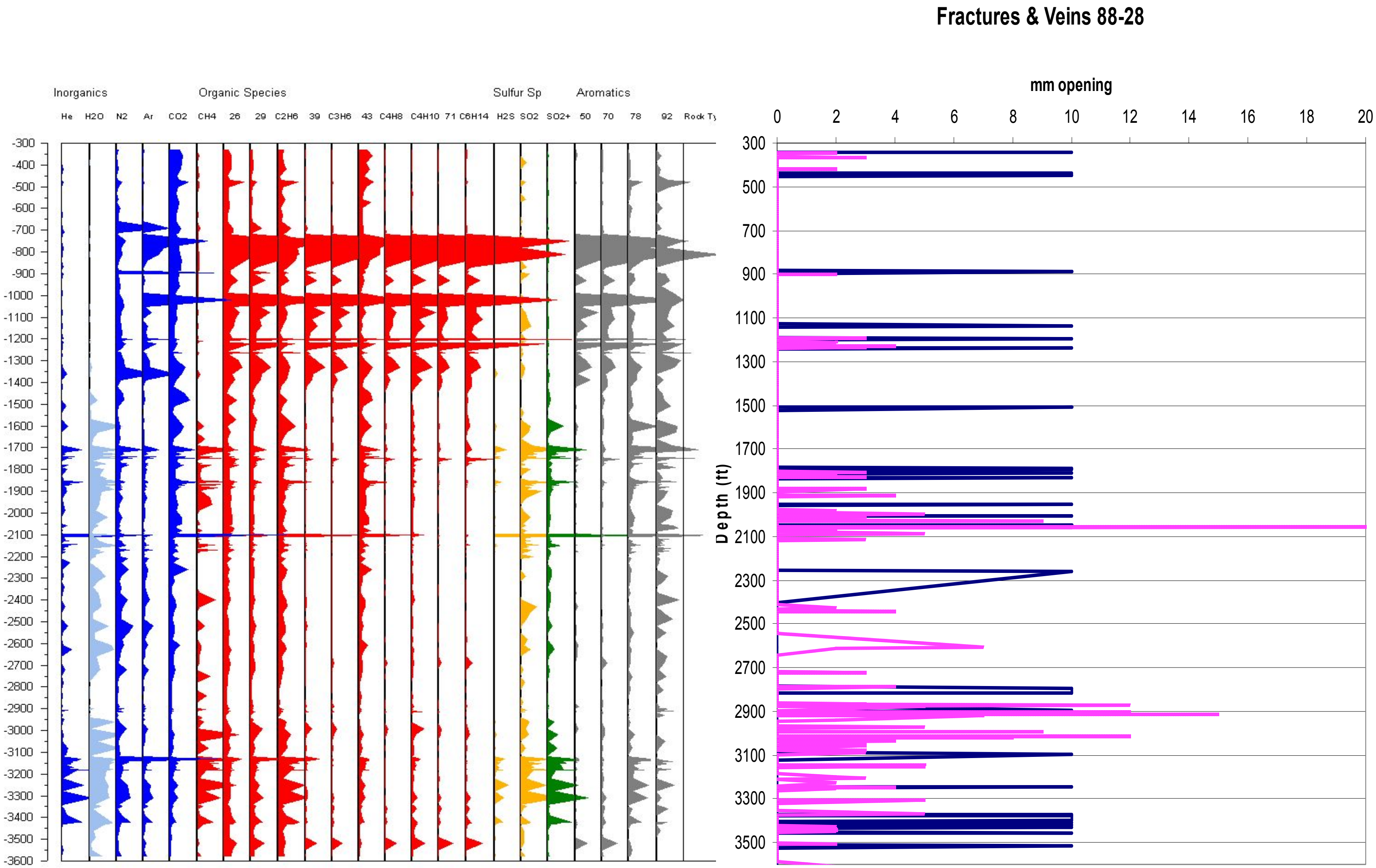

Figure 15: Combine FIS Log and Fracture Log for Glass Mtn. Well 88-28. Note lack of correlation of FIS peaks and veins at 2900 to 3000 feet and the significant vein at 2100 feet.

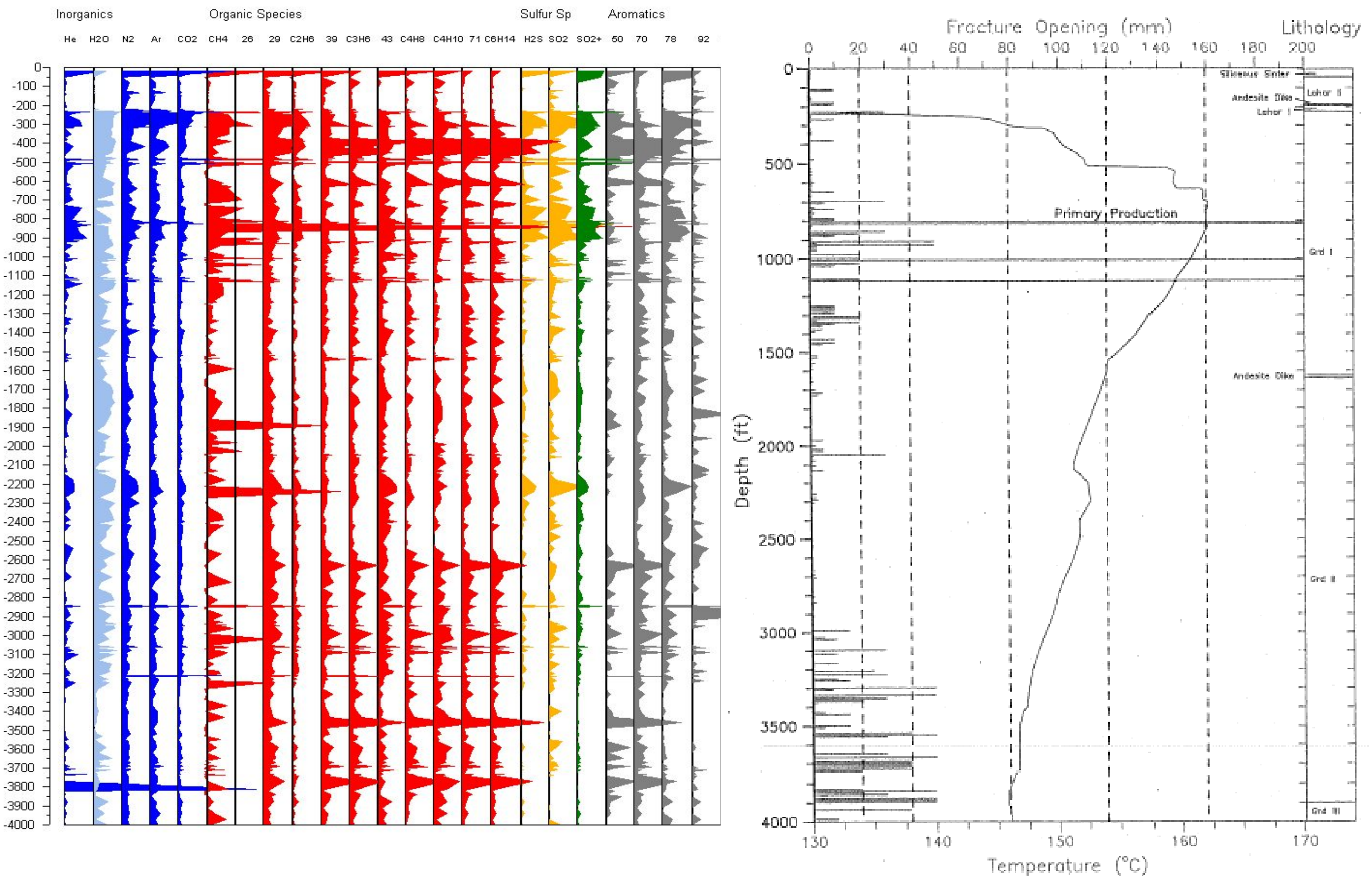

Figure 16: FIS log and fracture log for Steamboat Springs Well 87-29. Temperature survey indicates that the primary production zone occurs from about 500 to 1,200 feet. Note the larger, broader peaks in all of the chemical species in this zone. At 3000 feet and below several of the chemical species do not have sharp peaks.

Figure 16 presents the results of combining the FIS log with fracture, temperature, and general lithology information for Steamboat 87-29. 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, 3100, 3225, and 3700 ft. correspond to open fractures. The deeper fractures are thinner and are cooler according to the temperature survey.

There are broader less define peaks (some species not having peaks) on the FIS log that do not appear to correspond to open fractures such as 450, 600, 2200, 2650, and 3800 ft. In several of these zones, 2200, 2650, and 3800 ft., 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.

4.2 FLUID INCLUSION THERMOMETRY

Salinity and temperatures of homogenization analyzed at various depths for the three wells (Figure 17) indicate that fluids from both veins and wall rock represent overlapping fluid populations. The broad salinities and trapping temperatures encountered, however, imply either heterogeneous trapping from mixed fluids, boiling or a long and varied hydrothermal history exhibiting fluid signatures from current as well as past fluids.

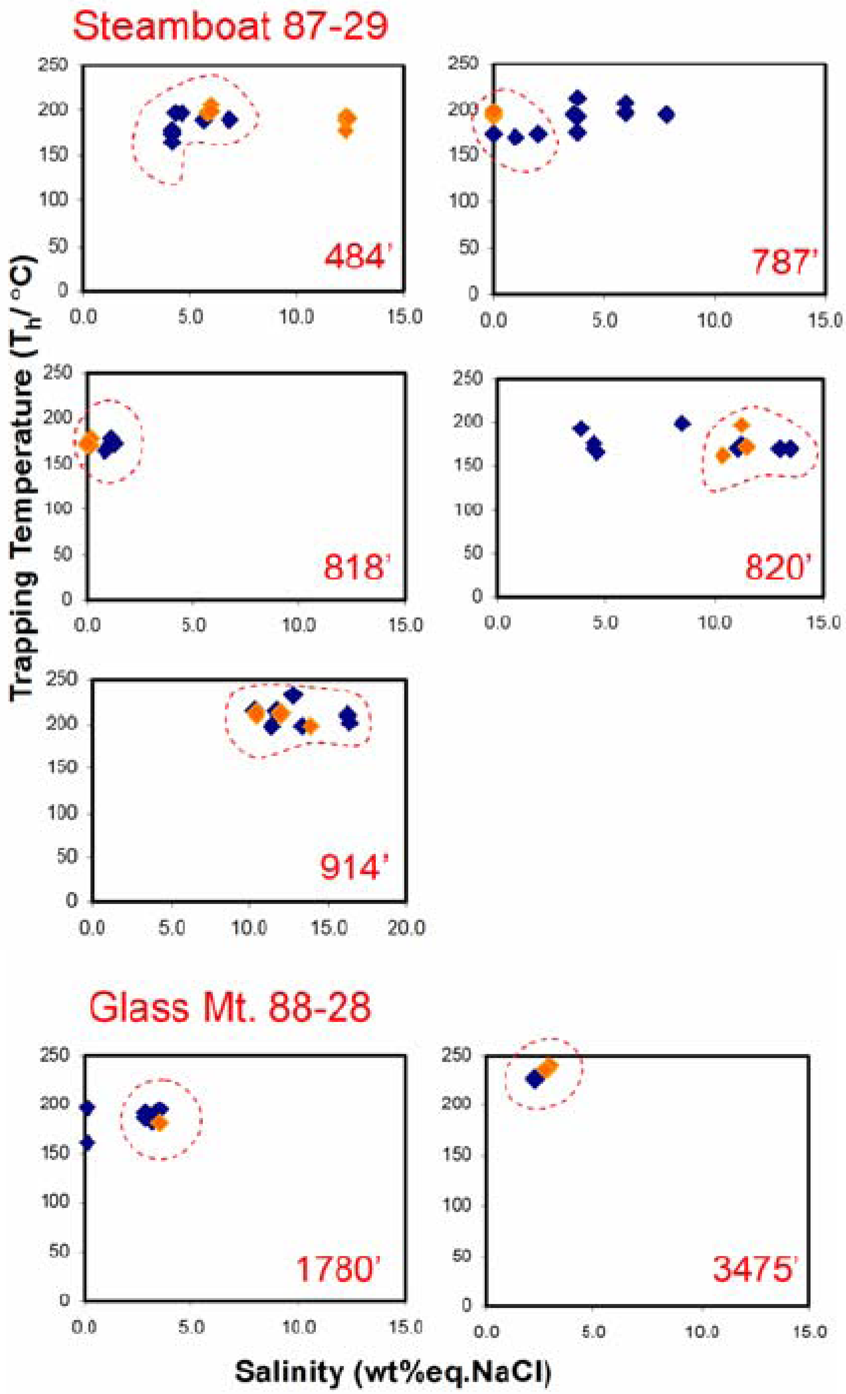

Figure 17: Salinities (as a function of Tm(ice)) plotted against trapping temperature (as a function of Th) indicating populations of entrapped production fluids. Orange (vein) samples and blue (matrix) samples are represented in each population.

Some zones of hydrothermal mineralization do not comply well with matrix fluid entrapment (Figure 18). In the case of deeper, non-productive zones (Karaha T2 at 4344 ft. and Steamboat 87-29 at 1130 ft.) distinctive populations recorded separately by both matrix and vein material are observed. However, the scope of FI thermometry in this investigation is limited. The standard deviation observed within some alteration zones with solely matrix-trapped fluids (Figure 19) indicate the same degree of deviation observed between vein and matrix inclusion as exemplified by Steamboat 87- 29:1130 ft. (Figure 18). In addition, leaking of fluids within friable vein mineralization is overwhelmingly encountered during the heating and freezing analyses of Glass Mt and Karaha samples, drastically limiting the number and size of inclusions which may be measured as well as the population count on those veins representing a higher homogenization temperature (Th>200ºC).

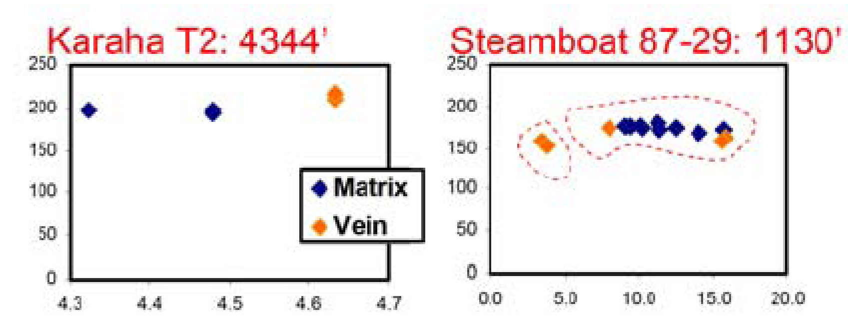

Figure 18: Vein (orange) and matrix (blue) inclusions representing separate fluid populations.

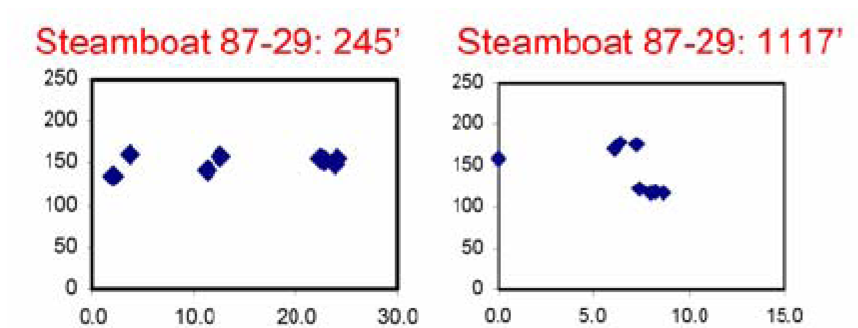

Figure 19: Spectrum of fluid compositions observed within single matrix phenocrysts, representing potential range of fluids trapped within host rock and standard deviation for

fluid inclusion thermometric measurements. Trapping temperature (C) is represent on the x-axis, weight percent equivalents NaCl represented on the y axis.

Over a broad range of analyses, matrix or wall rock mineralization behaves similarly to vein material along fractures in its ability to trap production fluids for analysis by FIS. Friability and limited volume of vein material inhibit its usefulness as a major source of trapped fluids.

5.0 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, veins and vugs. 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 between minimum and maximum for these individual peaks ranges from 42 to 100 percent for the various species plotted, suggesting the peaks are from more than just precision of the measurements. The FIS peaks readily correlate to veins/vugs in 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.

From the limited study of the two wells at Karaha T2 and K33 (Figure 10 and Table 1) it seems not to matter whether the fracture filling material was calcite, quartz, pyrite, or some mixture of the minerals; there were several mass spectra with peaks that corresponded to the filled fractures. In the highly altered zones the peaks were much broader suggesting infiltration of the various chemical species throughout the entire altered zone.

5.1 CHEMISTRY OF FRACTURES

Figure 20 presents a FIS log for Karaha T2 for H_2O, total gas and fracture size. Total gas is the summation of the concentrations of masses 1 through 180 subtracting H_2O (mass 18). Typically the predominate gaseous species is CO_2. Fracture size includes veins and vugs. In this well are lithic tuffs, crystal tuffs, and andesites with veins of pyrite, calcite, and quartz. The occurrence of H_2O in fluid inclusion gases has been associated with crystalline rocks when there was a stratigraphic sequence of metasedimentary rocks with dikes of crystalline rocks (Dilley 2008). However, in this well, the change in the H_2O concentration with depth is not completely related to changes in rock types. The occurrence of andesite and andesitic tuffs coincides with the increase in H_2O however at depth of 3360 to 3410 feet, a tuff breccia is encountered and while the H_2O concentration is decreased it does not go to zero. Also from 3610 to 3720 feet, the matrix is composed of lithic tuffs, a "rubble" zone, and clay altered breccia tuff and the H_2O concentration remains consistent with slight peak at 3630 ft.

H_2O (when it occurs) and the total gas correlate well with the fracture locations. The zone from about 3200 to 3500 feet had many vugs and open spaces when compared to the zone from 2800 to 3000 feet. The higher total gas in the upper zone correlates more with particular veins as oppose to the lower zone where the total gas is lower but the H_2O is about the same. The FIS log in Figure 14 indicates that in the concentration of CO_2 and the organics were higher from 2800 to 3000 feet than in the lower zone. Calcite is not as prevalent a secondary mineral in the lower zone than in the 2800 to

3000 ft. range. N_2, Ar, and the lighter hydrocarbons also had similar concentrations in the lower zone to the upper zone, except for the extremely sharp increase in N_2 at 2880 ft. From the logs there does not appear to be a major change in rock or secondary minerals at this depth. At 2919 ft. there is an open partially pyrite filled, fracture is the only notable change on the log. From 3900 to 4200 ft. there is little H_2O but several total gas peaks that correlate with fractures. The total gas peaks correspond to zones with multiple veins filled with pyrite and quartz; chlorite alteration is throughout the rock.

A vapor zone was encountered in this well below about 3000 ft. and temperatures increase dramatically below 2200 ft., suggesting the fractures encountered are associated with the geothermal system and are open and active. From the FIS log Figure 11, below 3600 ft., many of the species do not have peaks at fracture locations including heavier organics, He, aromatics and H_2O. This suggests that in vapor-dominated systems it is the total gas concentration particularly CO_2, N_2 and Ar and to a lesser extent the sulfur species and CH_4 that indicate open, active fractures.

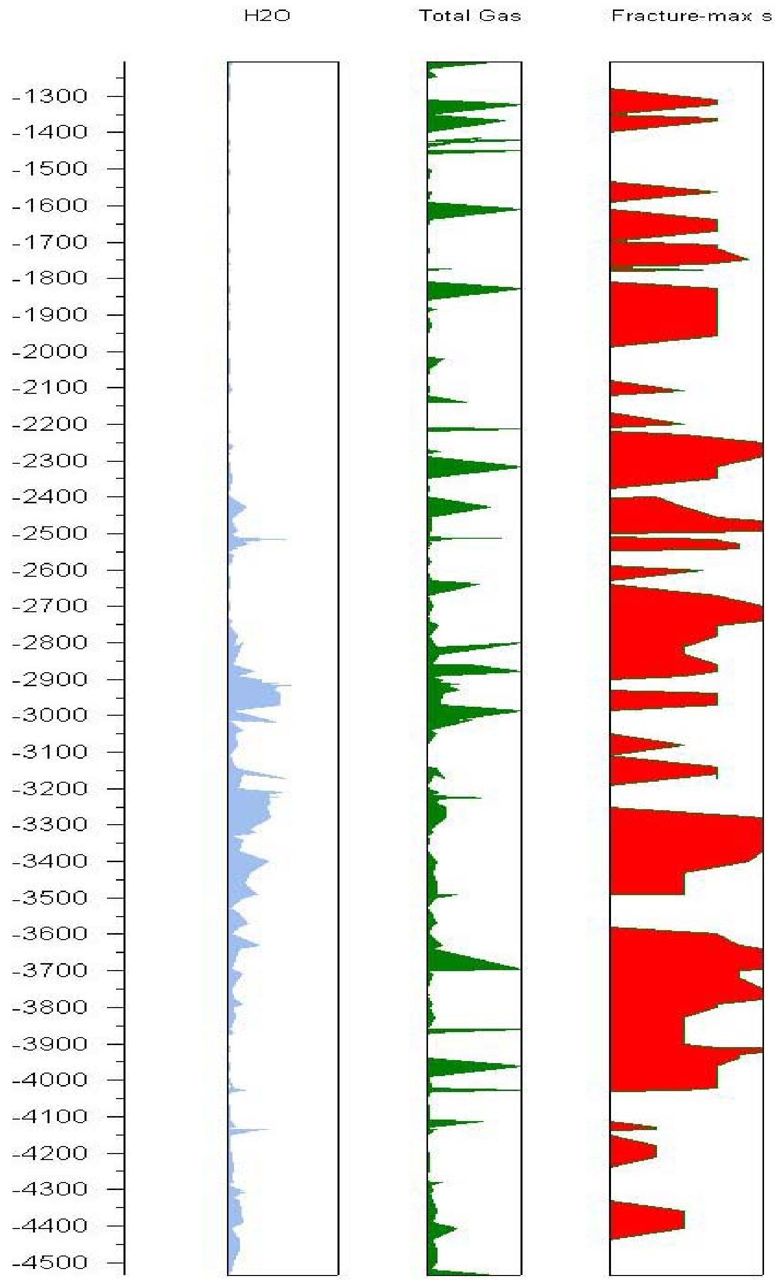

Figure 20: Karaha Well T2 H_2O, total gas concentrations from FIS analysis compared to maximum size of fractures, veins and vugs.

Figure 21 presents the H_2O, total gas, and fracture log for Glass Mtn., well 88-28. This well is composed of mixed volcanics and felsic volcanics. The mixed volcanics are series of highly altered basalts to about 1266 feet. At this depth to 1722 feet are white to red tuffs with some layers of sandy sediments. Below 1722 feet are the felsic volcanics. A static water level in the well occurred at approximately 1500 feet and the static temperature increased drastically at this depth according to the geology logs. As seen in Figure 21 this is also the depth (1500 to 1700 feet) where the H_2O concentration increases and becomes significant. The total gas concentration also has peaks at the 1700 foot depth. The total gas and the H_2O concentrations increase from about 3000 feet to 3400 feet. This is a zone of a matrix of basalt but numerous calcite veins, some open vugs, and small bladed calcite. Just above this zone from 2890 to 2920 feet, is a series of fractures about ¼ inch thick spaced at about 1 to 2 feet for about 20 feet in length. These fractures are infilled with calcite. The total gas and H_2O in this zone is near zero, suggesting that these are older fractures as oppose to the zone from 3000 to 3400 feet. Although it is unknown what the production zone is in this well, the hottest temperatures in the well according to the geological records are from approximately 2900 feet to 3300 feet. There are two peaks at 1600 ft. and 1700 ft. that do not correspond to a fracture, vein or vug. At this depth the rock was a tuff that had amygdules and veins filled with quartz and calcite. The peak at 2100 is a fracture containing bladed calcite. The next set of large peaks is at 3100 to 3400 ft. From 1700 ft. to 3400 ft. the total gas concentration is primarily He, H_2O N_2, Ar, CO_2, CH_4, lighter organics and the sulfur species. The heavier organics are lacking.

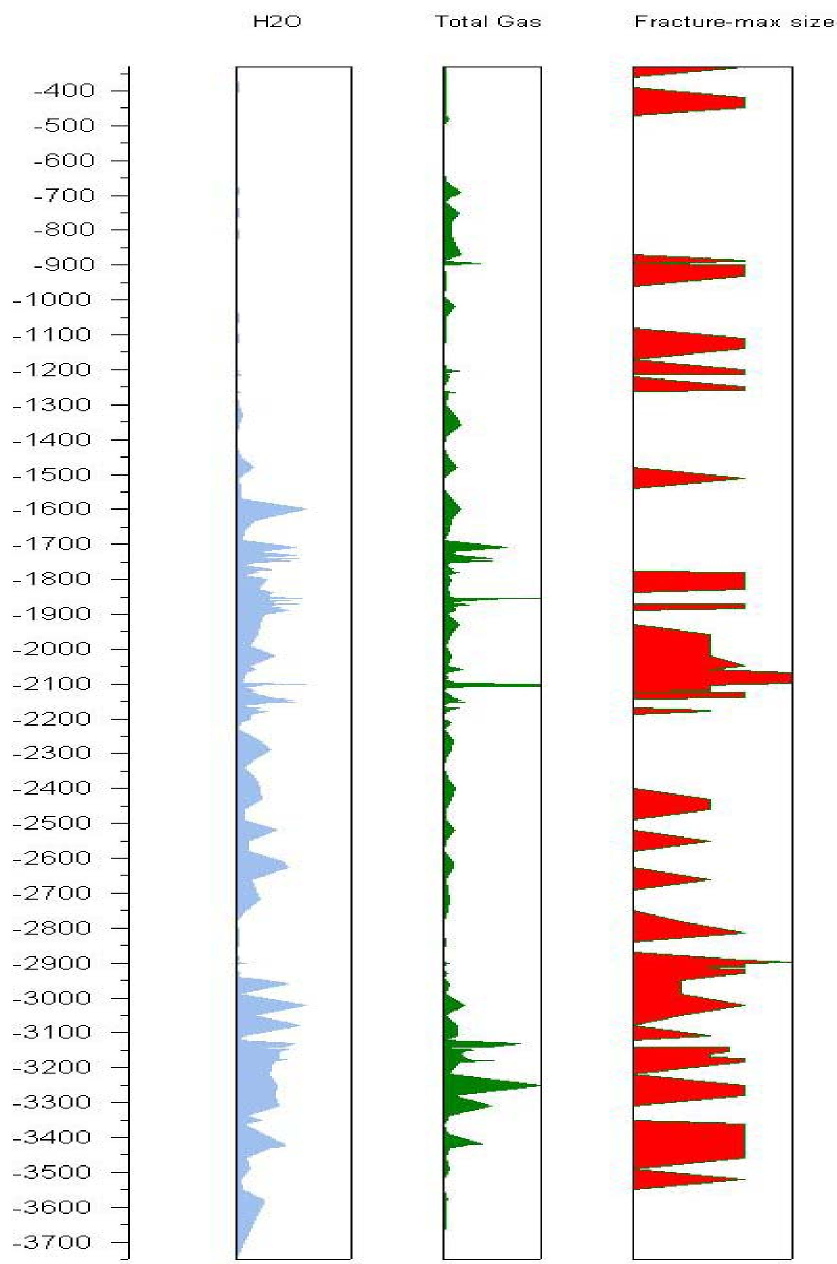

Figure 21: Glass Mtn. 88-28 H_2O, total gas concentrations from FIS analysis compared to maximum size of fractures, veins and vugs.

Figure 22 presents a FIS log for Well 87-29 from Steamboat Springs, Nevada, for H_2O, total gas and fracture size. 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. Most of the lost core in the drill hole occurred while drilling through two clay-rich zones at depths of 90 and 160 feet. Approximately 5.3 feet of core was lost in a major fracture zone between 815 and 823 feet. An additional 1.8 feet of core was lost at a depth of 1,011 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. The total gas and H_2O concentration are high in this zone as well. The total gas concentration from fluid inclusion analysis increases with the fracture opening. Deeper in the well from 2,700 feet to depth the concentration of total gas is lower but the H_2O concentration is similar to the production zone. Peaks in the H_2O concentration correspond to these smaller, perhaps older fractures. In the non-productive zone, there is a greater chance for fractures to fill in due to lack of hot, moving fluids generating open fractures.

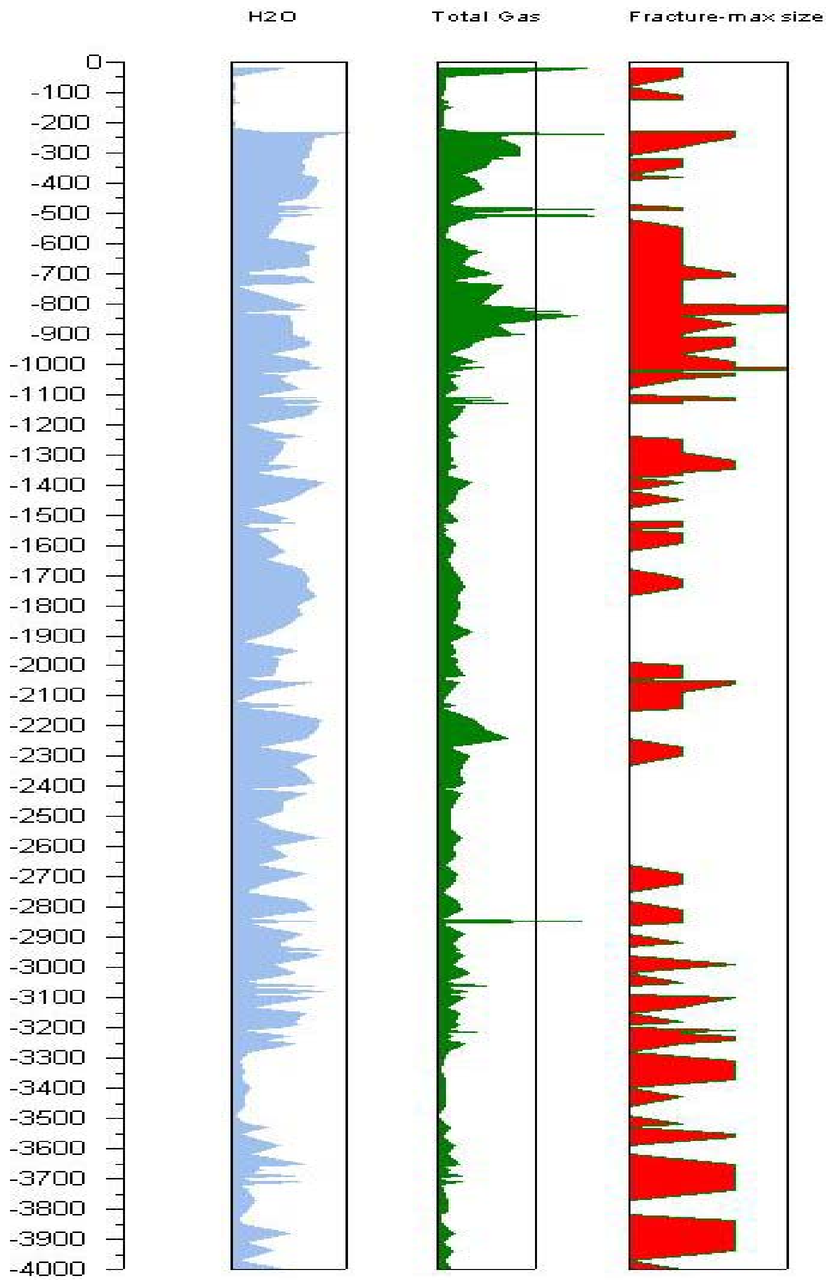

Figure 22: Steamboat 87-29, H_2O, total gas concentration from FIS analysis compared to maximum size of fractures, veins, and vugs.

Glass Mtn. Well 88-28 temperature profile indicates that 300^0F fluids are reached at a depth of about 2000 feet. It can be seen in Figure 15, the majority of fractures, veins and vugs occur below about 1800 feet. As in Karaha Well T2, H_2O does not occur throughout the well but is significant from about 1600 feet to the depth of the well with no H_2O occurrence from 2750 to about 2950 feet. There is a general lack of other chemical species below about 2100 feet as well. There are two distinct peaks throughout the majority of the chemical species on the FIS log: 1700 and 2100 feet. The most notable exceptions are the heavier organic compounds.

The Steamboat Springs core suggests that differences in gas chemistry can indicate production zones from non-producing zones. The mass spectra signature for the Steamboat Springs core in Figure 16 show peaks in N_2, Ar, CO_2, and the sulfur species in the production zone and not in the non-producing zone.

5.2 PERMEATION OF FRACTURE HOSTED FLUIDS

Two producing fracture systems at Steamboat Well 87-29 were identified for study by 'positive' FIS gas signatures (Dilley 2007) in agreement with temperature and drilling logs.

Region 1 (Steamboat 87-29: 818 ft.)

A major zone centered at 818 ft. contains a central fracture, measuring over 2.5 inches in aperture and hosting a white calcite vein on one side (~1/2 inch) and grey quartz on the other side (~1 inch). Chlorite and sericitic alteration are observed in a broad, 25 inch wide areole surrounding the central vein, accompanied by an apparent swarm of large (>5mm wide) and open fractures extending from 785 ft. to 825 ft. Extensive chlorite alteration of the host-rock associated with swarms of thin (<3mm wide) clayfilled fractures and dense configurations of microfractures (≤1mm; often 2-3 per foot of core) may be observed at the more distal extensions of this zone from 755 ft. to 860 ft.

FIS logs characterize this zone as containing broad peaks in CO_2, Ar, H_2O and Total-Gas spanning from 750 ft. to 925 ft. with the strongest signal occurring at ~820 ft. (Figure 23). This zone also represents the hottest region of production in the well according to temperature logs, peaking at 162°C (Figure 24).

Thermometric measurements of quartz and calcite vein mineralization and transparent (mostly quartz) matrix-hosted inclusions throughout this region indicate multiple populations of fluid-rich phases exhibiting widely variable salinities (wt% NaCl) and temperatures of homogenization (Th). Vein-hosted fluid inclusions at 818 ft. best resemble actual well temperature values; however, surrounding matrix and vein inclusions contain Th values upwards of 200°C (Figure 24). Th (vein) and Th (matrix) overlap consistently at 787, 818, 820, and 914 ft., suggesting that productions fluids have sufficiently permeated the host formation. Samples from 755, 787, 780, and 829 ft. contain fluid inclusion populations resembling the lower salinity and minimal Th values observed at 818' surrounding the central fracture (Figure 25). In particular, sampled fracture-fill quartz veining at 755ft. represents fluid inclusions of similar compositions implying a genetic relationship of these minor fractures to the central fracture. The broad distribution of signature fluid compositions with depth through both dendritic fractures and wallrock alteration observed within this zone of study comply well with the broad nature of the FIS fracture signatures. The occurrence of multiple fluid populations at various depths of study is likely evidence of overprinting from earlier stages of the Steamboat geothermal system or heterogeneous distribution of production fluids through fracture units of opposing stress and origin. In either case, locating fluids associated with this main-production fracture based on agreement with overlapping fluid populations may be accomplished with FIS sampling as coarse as 30 ft (~10m) intervals, likely due to the dense configuration and open apertures of the surrounding fracture swarm.

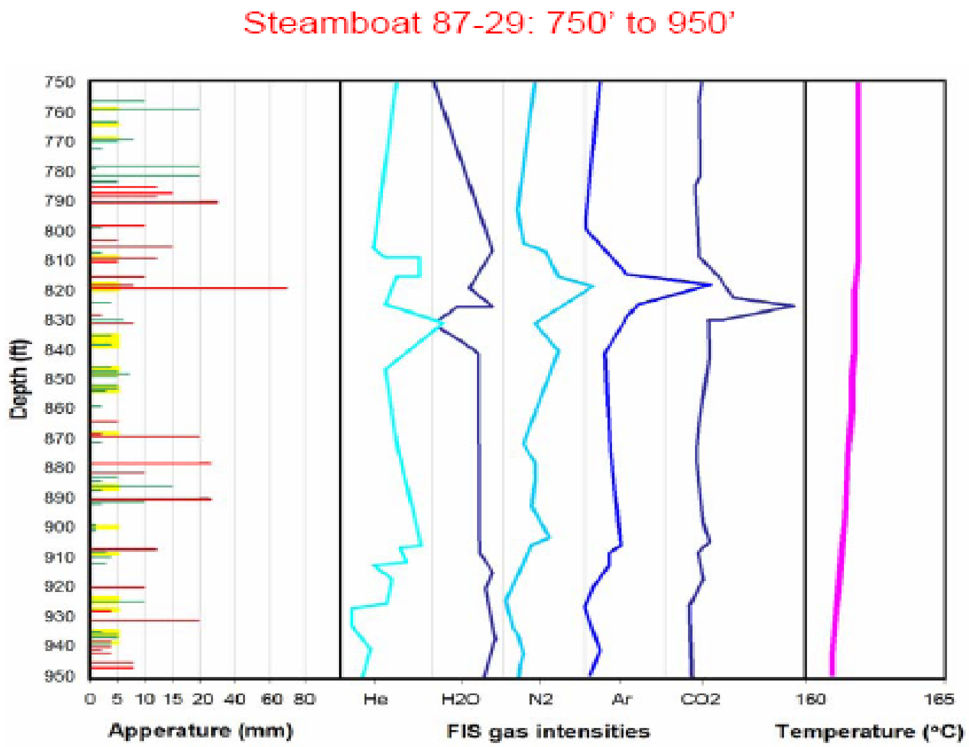

Figure 23: Logs of fracture occurrence. Fluid Inclusion Stratigraphy (FIS) gas values: and temperature log as a function of depth for Region 1 of Steamboat 87:29 surrounding main fracture at 818 ft. Log of observed fractures in core plotted for frequency, aperture (mm) and degree of vein fill; open fractures (red), closed fractures (green) and extensive replacement mineralization of matrix (yellow).

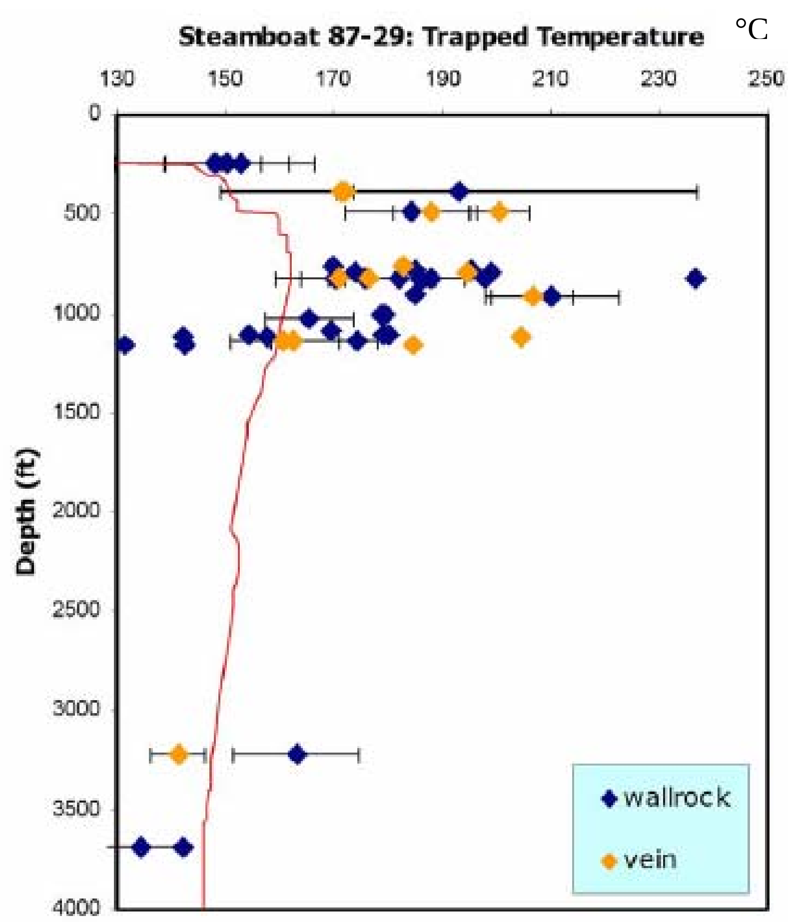

Figure 24: Mean fluid inclusion trapping temperatures (Th) measured from transparent mineral phases at various depths of Steamboat 87-29 plotted against actual temperature log (red line). X-error bars represent 1-sigma standard deviation of all measured values (≥12 total) at that depth.

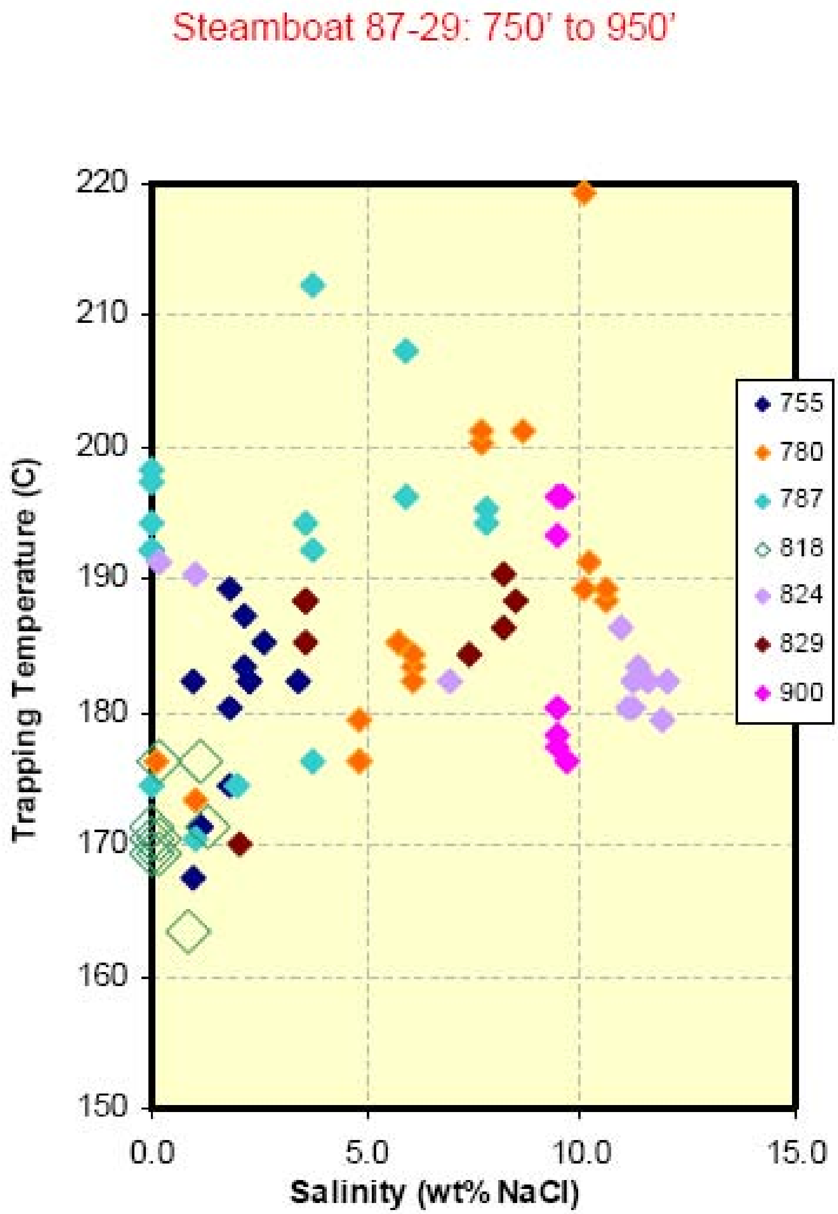

Figure 25: Distribution of fluid populations determined by congruent Th and Tm (ice) values for Region 1 of study at Steamboat 87:29 surrounding main production fracture at 818 ft.

Region 2 (Steamboat 87-29: 1112 ft.)

A second major production zone centered at 1112 ft. also contains a singular major fracture, measuring approximately 2.5 inches in diameter and partially filled with quartz. The hostrock in this zone exhibits pervasive chlorite alteration throughout, however the extent of modern secondary fracture permeability appears limited. Fractures in this zone occur with less frequency (<1 fractures per foot) and are on average thinner (<2mm) and closed due to clay fill. This region also lies within the designated production zone though exhibits a slightly lower temperature and is positioned at the top of a steep decline in thermal gradient (Figure 26). FIS logs identify at least 2 major fracture swarms occurring at approximately 1010 and 1112 ft. marked by consecutive apical peaks in all inorganic gaseous species, particularly CO_2, N_2 and total gas (Figure 26). One series of closed fractures at ~1035 ft. indicate a slight negative signal in H_2O and CO_2, possibly representing a sink for mobile, gaseous species (Dilley, 2007).

Thermometric measurements of this region indicate little communication between open, producing fractures and surrounding swarms of veins and microfractures. Minor overlap in fluid populations is observed between open fracture swarms observed at 1004' and 1112 ft. (Figure 27). Fluids measured at 1117 ft. strongly correlate with the salinity and the compositions of producing fluids (812 ft.) in Region 1 above in addition to best matching the well log temperature (~158°C), though their FIS signature is indistinguishable from that observed at 1112 ft. (Figure 26). In addition, matrix (Th) and adjacent vein (Th) fluid inclusions from the same depth interval represent little overlap. The ubiquitous matrix alteration in this region signifies extensive regional hydrothermal influence, unlike the more localized, fracture-directed permeability observed above. A reduction in primary porosity due to matrix alteration is congruent with a reduction in microfracture and matrix permeability. Multiple geothermal stages and an evolved history of geothermal fluids may be responsible for the scattered distribution of fluid compositions not associated with presumed, open fractures. Overprinting by current production fluids, as demonstrated in this region, are clearly highlighted in FIS profiles.

According to fluid inclusion thermometry, fluids trapped in matrix mineralization along secondary microfractures agree reasonably well with fluids observed within adjacent (<2-3cm) secondary mineralization of large-aperture vein material. This expands the minimum sampling interval of wallrock cuttings which may help identify producing fracture in FIS analysis by also exhibiting signature gas ratios. Microfractures, particularly those observed within primary quartz; thin, dendritic fracture swarms; and pervasive replacement mineralization of wallrock is thought to aid in the distribution of production fluids beyond the arterial fractures of a geothermal system. Where secondary permeability is dominant and fractures are abundant and open, as observed near 818' depth of Steamboat 87-29, current production fluids infiltrate fluid inclusions upwards of ~25m (75 ft) from the apparent source. Here, FIS signatures thought to be associated with fractures are expansive and dictated by the occurrence of open, prolific secondary permeability. In contrast, a lack of both primary porosity and open fracture swarming due to extensive hydrothermal alteration may limit the pervasiveness of production gas signatures into new fluid inclusions; hence FIS fracture signatures appear narrow and apical, as observed near 1112 ft. of the same well. Production is measurable at both 818 ft. and 1112 ft. depth in this well and FIS signatures are detectable regardless of their shape and extent, largely aided by tight sample spacing near known fractures.

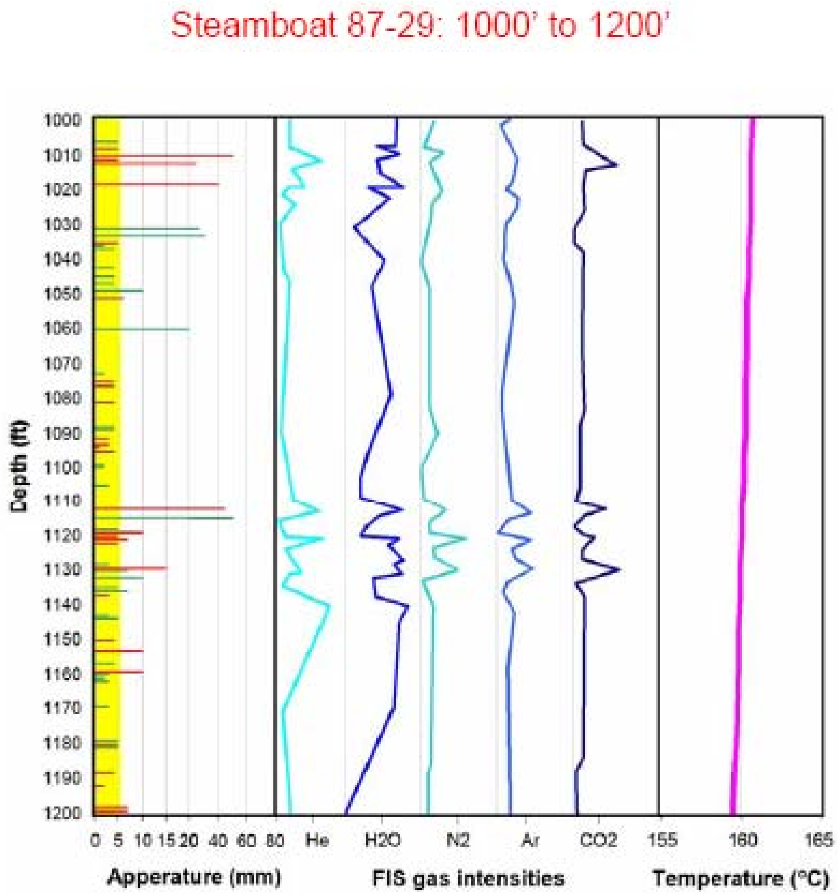

Figure 26: Logs of fracture occurrence, Fluid Inclusion Stratigraphy (FIS) gas values and temperature log as a function of depth for Region 2 of Steamboat 87:29 surrounding main fracture at 1112 ft. Log of observed fractures in core plotted for frequency, aperture (mm) and degree of vein fill; open fractures (red), closed fractures (green) and extensive replacement mineralization of matrix (yellow).

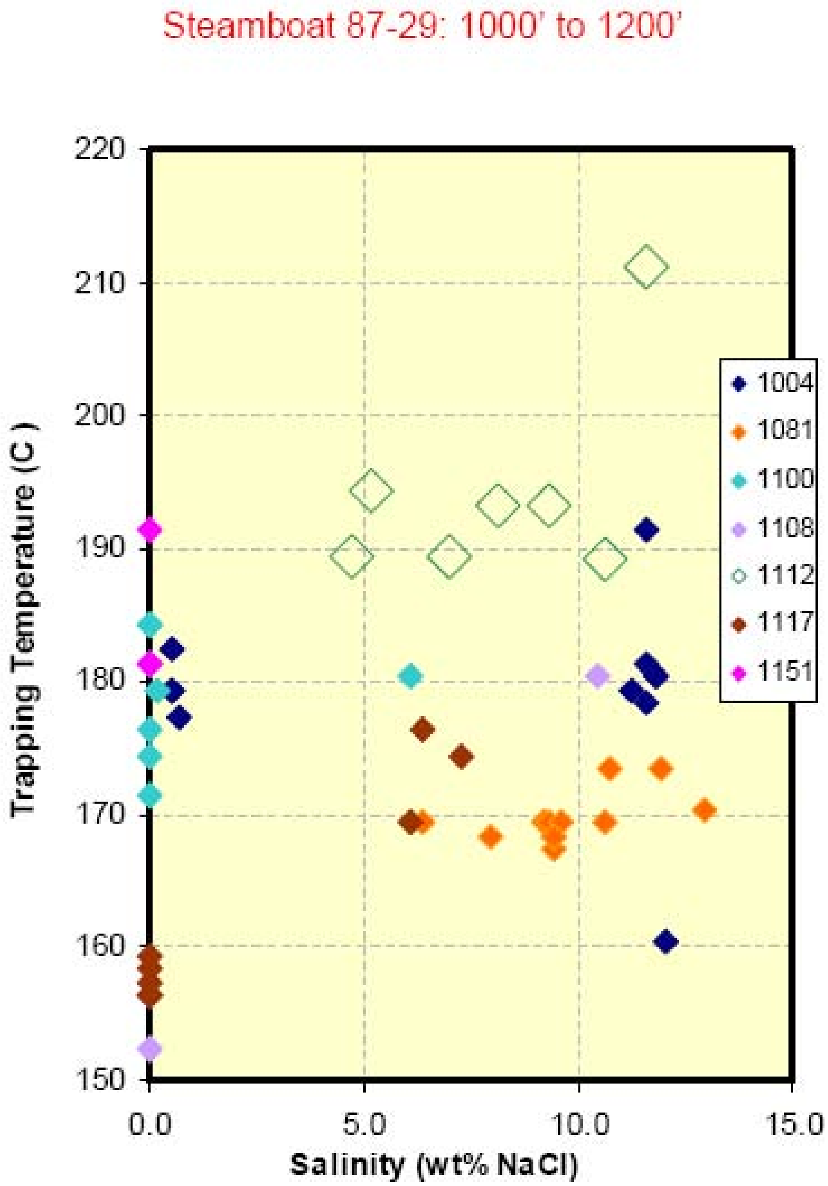

Figure 27: Distribution of fluid populations determined by congruent Th and Tm (ice) values for Region 2 of study at Steamboat 87:29 surrounding main production fracture at 1112 ft.

6.0 CONCLUSIONS

Results indicate the following:

1) Fractures, veins and vuggy areas can be identified on FIS logs by distinct strong peaks (increase concentration) in multiple chemical species.

2) The bulk analysis of volatiles within fluid inclusions appears to correspond with several types of fracture infilling minerals including quartz, calcite, and pyrite.

3) Sampling intervals of 3 to 15 ft from well cuttings is sufficient to accurately observe fracture signatures where fracture swarms are rehealed, sparse (<2x2mm/ft) and alteration mineralization limits both primary and secondary permeability – as in the case of Region 2 surrounding 1112 ft in Steamboat 87-29. These fractures have experienced multiple hydrothermal events.

4) Greater sampling intervals of 15-30 ft are sufficiently frequent to detect major producing fracture zones using FIS where the crystalline host rock is largely unaltered and permeability is dominated by microfractures and fracture swarms. These fracture zones prove to be larger and less mineralized.

5) H_2O concentrations increase significantly in felsic and/or crystalline rocks. In rocks such as at Steamboat concentrations of H_2O occurred throughout the well and varied in peak height. In Glass Mtn and Karaha, H_2O did not occur in the basaltic rock zones and only occurred in varied in concentration in the more felsic rocks in both wells.

6) The concentration of H_2O correlated with fractures, veins and vugs in the felsic rocks in Glass Mtn. and Karaha. In Steamboat where the H_2O was

more pervasive, the concentration of H_2O did not always correlate with fractures, veins and vugs.

7) Total gas concentration correlated with fractures in the three wells. Significant peaks in the total gas concentration occurred with select fractures in the three wells.

8) For Steamboat which had an identifiable production zone, the total gas concentration was much higher in the producing zone than in the non-producing zone. In the other two wells the variability in the total gas concentration was in part a function of the presence of calcite and the increase in CO_2 gas.

9) The concentration of CO_2, H_2O, Ar, N_2 and sulfur species appear to increase significantly when the fractures, veins and vuggy areas are in a producing zone or zone of higher temperatures suggesting active, open fractures.

10) The concentrations of heavier organics appear to be higher in zones that would have fractures that were older and closed for a length of time.

11) This study indicates that FIS is a useful tool for identifying fracture locations, and that active, open fractures that would need additional stimulation for higher production are identifiable by higher concentrations of CO_2, H_2O, Ar, N_2, and sulfur species.

12) Additional work on identifying recently closed from older fractures should be conducted to determine how the chemical signature has changed over time. This method should also be field tested during the actual drilling of well to determine the cost/benefit ratio of the method.

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