

IDENTIFYING FRACTURES AND FLUID TYPES USING FLUID INCLUSION STRATIGRAPHY

Lorie M. Dilley¹, David I. Norman¹, and Jess McCulloch²

¹.Dept. of Earth and Environmental Sciences
New Mexico Tech
Socorro, New Mexico 87801, USA
E-mail: ldilley@hdlalaska.com, dnorman@nmt.edu

².Coso Operating Company
PO Box 1690
Inyokern, California 93527, USA
E-mail: jmcculloch@caithnessenergy.com

ABSTRACT

Fluid Inclusion Stratigraphy (FIS) is a method currently being developed for use in geothermal systems to identify fractures and fluid types. This paper is the third in a series of papers on the development of FIS. Fluid inclusion gas chemistry is analyzed and plotted on well log diagrams. The working hypothesis is that select gaseous species and species ratios indicate areas of groundwater and reservoir fluid flow and reservoir seals. Previously we showed that FIS analyses identify fluid types and fractures (Dilley et al, 2004). Here we look at the sampling interval and additional confirmation that FIS analyses identify fractures.

Sampling intervals of 20 ft and 10 ft. are evaluated to determine the optimal sampling interval and FIS are compared to fracture logs. Additionally, FIS samples were obtained from a core to evaluate the core interval is affected by a fracture fluid. The results show that generally a 20 ft sampling interval is sufficient, and that a vein affects the wall rock at distances of 5 to 10 feet beyond the fracture.

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).

Fluid Inclusion Stratigraphy (FIS) is currently being developed as a technique for use in geothermal system to assess reservoirs. The FIS method analyzes volatiles in fluid inclusions in drill cuttings, by mass spectrometry. The commercial process, developed in part by Fluid Inclusion Technology (FIT), is highly automated with thousands of analyses made in a day resulting in turnaround times in days and costs comparable to other logging methods. The procedure gives a downhole map of fluid distribution and chemistry plotted on borehole logs.

The purpose of this research, funded by the California Energy Commission, is to develop FIS technique for geothermal reservoir assessment. The assessment techniques seek to provide ways to: distinguish non-producing from producing wells; identify major fluid flow zones; and entrants of cold and steam-heated waters into the bore hole. This paper is the third in a series of papers on the development of FIS.

From the preliminary results, the question arose as to how accurately does this method reflect the location of fractures and what is the optimal sampling interval for the method. In order to address these questions we conducted studies on two sampling intervals to evaluate the optimal sampling spacing and we compare the gas analyses plotted on mud logs against a fracture density log. Additionally FIS samples were obtained from a COSO core to evaluate how far away from the fracture center there would be an indication of select chemical species and ratios we use in interpreting FIS analyses.

METHODS

Four wells from the Coso Geothermal Field were selected for the first round of analyses (Figure 1). Three of the wells are producers and one, Well # 3, a

non-producer. Of the three producing wells, Well # 4 has entrants of cold water. Splits of 10 to 20 grams were taken from drill cuttings at 20 foot intervals throughout each well. A total of 1,729 samples were submitted to FIT for analyses. Analyses were performed first by cleaning the samples, if necessary, then crushing a gram-size sample in a vacuum. The volatiles released are pumped through multiple quadrupole mass spectrometers where molecular compounds are ionized and separated according to the mass/charge ratio. The output data for each sample was the magnitude of mass peaks for masses 2 to 180. A volatile like CO₂ has a gram formula weight of 44 and will be measured by a peak at mass 44. FIT returned the raw data within three weeks.

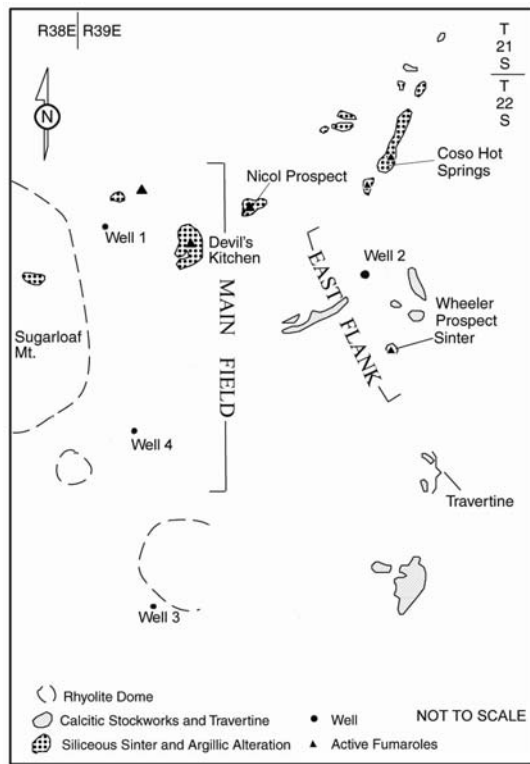


Figure 1. Location of wells used in the study and surface features of Coso. (After Lutz et al, 1999).

Select ratios and species were plotted next to each other and interpreted. Certain ratios were shown to indicate high temperature fluids, low temperature fluids and steam zones. See Dilley, Norman & Berard, 2004, for more on the interpretation and the FIS technique.

For this study, samples were collected at 10 foot intervals and plotted again to determine if the smaller sampling interval produced relevant results when compared to the 20 foot sampling interval. This was performed on portions of the three producing wells. Also samples were collected from a core to determine how far from a vein center, fluid inclusions would

extent. This was conducted for Well 64-16, which is located on the East Flank near Well 2. To determine if the peaks recorded by the various chemical species and ratios used in FIS are actually fractures in the borehole, select graphs were compared to a fracture density plot. The wide aperture fracture density plot was for Well 2 and was developed by Sheridan and Hickman (2004). This composite figure was compared to the temperature log for this well to determine how fracture density and the ratios developed would indicate high temperature fluids.

The chemical species and gas ratios selected for used in this study are H₂O, N₂/Ar (mass 28/40), CO₂/CH₄ (44/15), C₃H₈/C₃H₆ (mass 43/39, and (N₂/Ar + CO₂/CH₄) / (C₃H₈/C₃H₆). The ratios of N₂/Ar, CO₂/CH₄ and (N₂/Ar + CO₂/CH₄) / (C₃H₈/C₃H₆) are used to indicate reservoir fluids whereas the ratio of C₃H₈/C₃H₆ is an indicator of background or low temperature fluids (Norman et. al, 2004).

SAMPLING INTERVAL

Figure 2 is the temperature log for Well 2. The temperature logs for the well show entrants of hot fluids at depths of approximately 7,300 feet to 8,700 feet. This zone was targeted for the graphing of the various species and ratios.

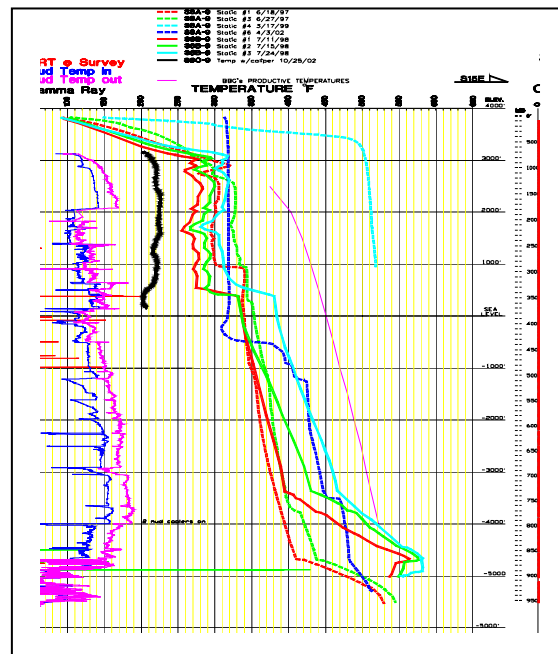
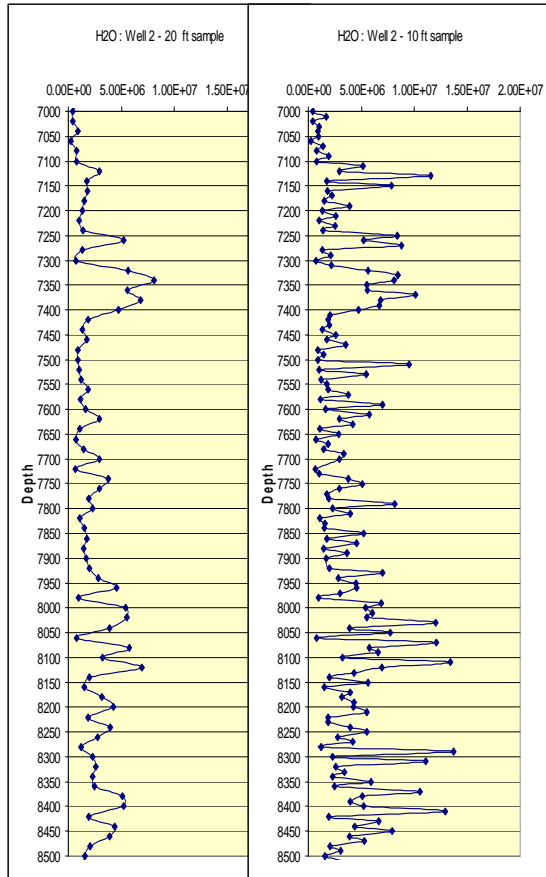


Figure 2. Temperature logs for Well 2.



Figures 3a and 3b: Graphs of H₂O for 20 ft and 10 ft sampling intervals. Note the 10 ft sampling interval indicates many more peaks and higher amounts sampling interval graph versus the 10 foot sampling interval graph.

Figure 3 shows the comparison of the select species and ratios for the two sampling intervals. The 10 ft. sampling in general provides more peak detail (Figures 3c and 3d). Mass peaks that are not evident in 20 ft. sampling are shown; see mass intervals (7,500, 7,690, 7,830 ft. Also from about 8,250 to 8,410 the broad peaks recorded by 20 ft sampling shows more detail by using a 10 ft. interval. The N₂/Ar peaks should be antithetic to propane/propene peaks. The former ratio indicates fluids with a magmatic contribution whereas high propane/propene indicates fluids with a magmatic contribution or cool fluids. That relationship is much clearer in 10 ft sampling interval graphs.

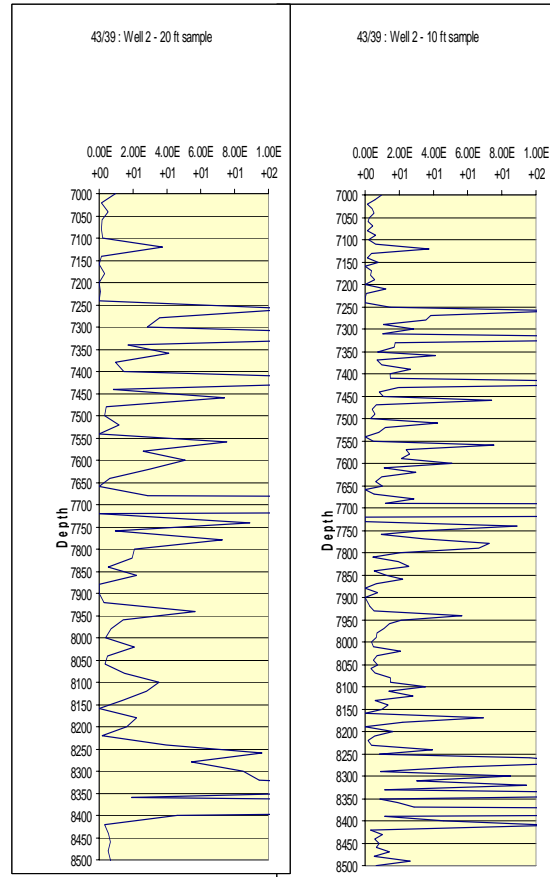
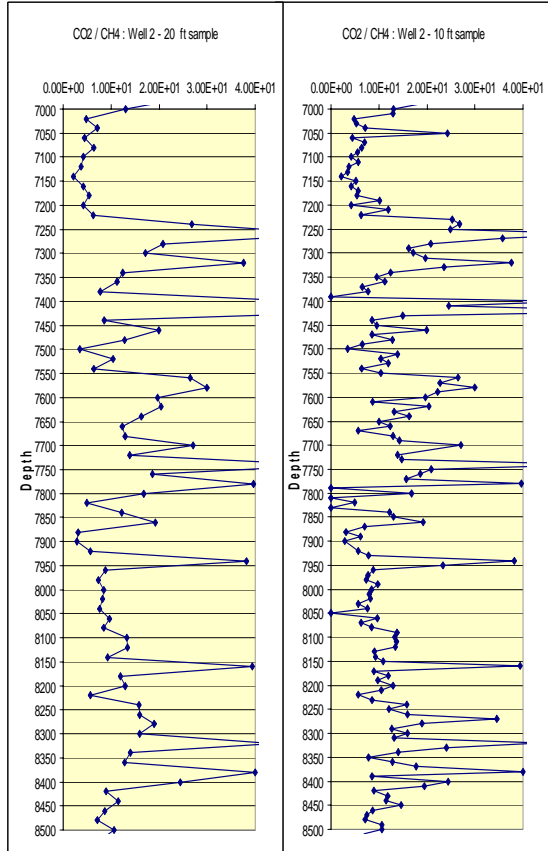


Figure 3c and 3d: Graphs for Mass 43/39 for 20 ft sampling interval and for 10 ft sampling interval. Note the number of peaks from 8250 to 8400 feet in the 10 ft sampling interval versus the 20 ft sampling interval.

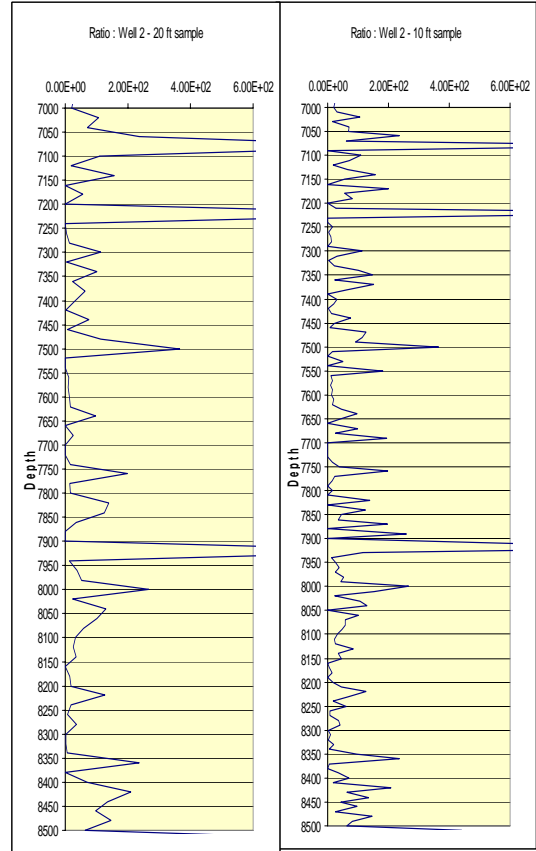
For the remaining ratios, the smaller sampling interval did not appear to make that much difference. For CO₂/CH₄ ratio (Figures 3e and 3f) one peak was missed at 7050 feet, but all of the other peaks were indicated when the sampling interval was 20 feet. For this ratio there were a few low points (7390, 7800, and 8050 feet) indicated in the shorter sampling interval than in the larger sampling interval.

For N₂/Ar ratio (Figures 3g and 3h) some of the minor peaks are missing or are subdued in the 20 ft sampling interval, but in general most of the peaks are similar in the 10 ft sampling interval as in the 20 ft sampling interval. The large ratio, (N₂/Ar + CO₂/CH₄) / (Mass 43/Mass 39), (Figures 3i and 3j) appeared to work equally well for both sampling intervals. These ratios have been used to identify high temperature fluid zones.



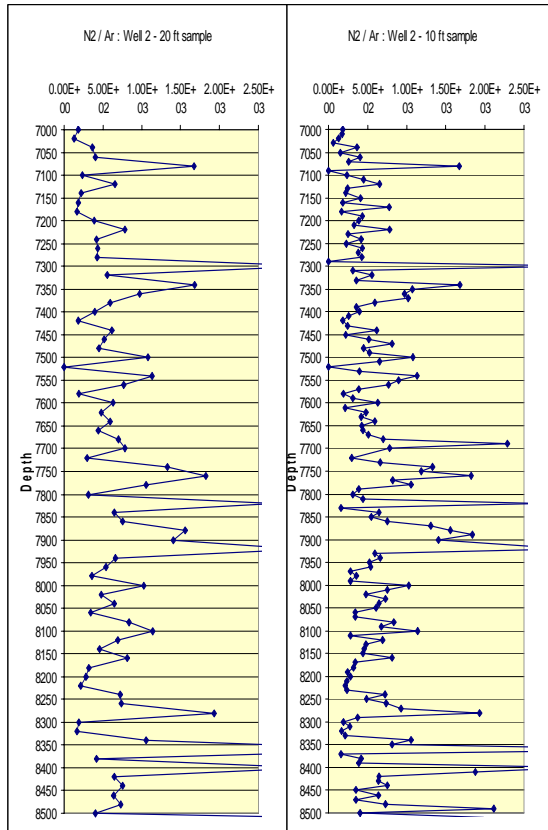
(3e)

(3f)



(3i)

(3j)



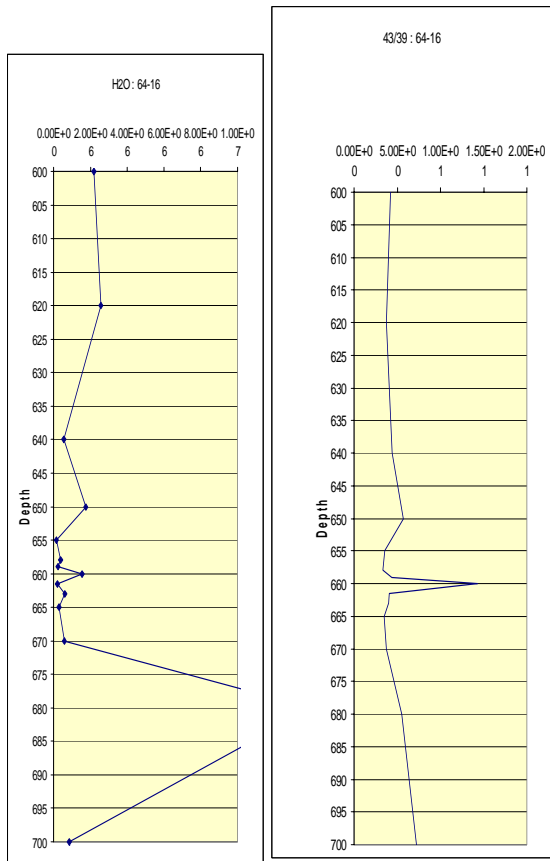
(3g)

(3h)

Figures 3e through 3j are graphs for CO_2/CH_4 , N_2/Ar , and the ratio of $(N_2/Ar + CO_2/CH_4) / (Mass\ 43/Mass\ 39)$. Each of these ratios has been used to identify high temperature fluids using FIS. The smaller sampling interval (10 ft) does not indicate any additional high or low zones when compared to the larger sampling interval (20 ft).

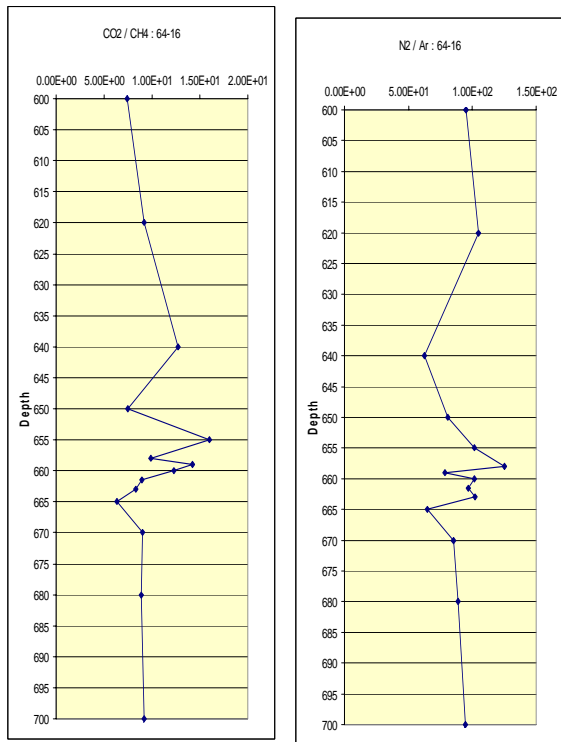
Rock samples were obtained from Coso Well 64-16 core. Sampling was conducted to determine how far from the vein the various ratio signature could be observed. The samples were crushed in a mechanical crusher and sieved in order to obtain fragments about the cutting size. The core sampled contained a noticeable calcite vein between 659 and 662 feet, with the vein center was at 660 feet. The sampling interval ranged from 20 ft at 600 feet to 1 ft at the vein center. The 660 ft sample is calcite, all other samples were green altered host rock. Figures 4a through 4d show the results of the sampling conducted.

It can be seen that for H_2O (Figure 4a) there is a small peak centered at 660 feet. There is a much larger peak centered at 683 feet. The small peak at 660 feet does not extend in depth more than about a foot on either side of the vein center.



(4a)

(4b)



(4c)

(4d)

Figures 4a through 4d are graphs of the various ratios for a calcite vein centered at 661 feet from Well 64-16. Note that the scales on the H₂O, N₂/Ar and CO₂/CH₄ graphs are expanded from graphs in Fig. 3 in order to show detail

For Mass 43/39 ratio (Figure 4b) at the vein center is a very sharp peak as well with no other peaks observed on the graph in this zone. A high ratio indicates cool waters were depositing this vein.

For CO₂/CH₄ (Figure 4c) and N₂/Ar (Figure 4d) the peaks are broader and the highest point of the peaks are above the center of the vein. For CO₂/CH₄ the width of the peak is about 15 feet, while for N₂/Ar the width of the peak is about 10 feet. The low CO₂/CH₄ ratio and high propane/propene ratio indicate low temperature fluids. The elevated N₂/Ar coupled with low CO₂/CH₄ is characteristic of steam heated water (Dilley et al., 2004).

FRACTURE PATTERN

Figure 5 is a composite of a fracture density log developed by Sheridan & Hickman in 2004 for Well 2 and the fluid inclusion gas analysis for the ratios of CO₂/CH₄ and N₂/Ar. The fracture density log is based on fractures with significant apparent apertures. There are several intervals where there is high fracture density and corresponding high ratios particularly from about 7,200 to about 7,900 feet. This zone is where the temperatures logs (Figure 2) show an increase in temperature. This composite figure ranges from 6000 feet to 9500 feet. When compared to the increase in temperature logs (Figure 2) the fracture density is high, and the ratios are high. This occurs from approximately 7,300 feet to about 8,600 feet. This is considered the production zone for this well.

Individual high fracture densities do not appear to always correspond to high peaks in the ratios however; this is most likely due to the lack of these compounds within these fractures. In general when there are peaks on either of the ratios this corresponds to the fracture density except in the production zone. For instance from approximately 6,700 to 7,100 feet there is a zone of low fracture density and the ratios are generally low with only a few high peaks. The highest fracture densities at 7,600, 7,700, 7,900 and 8,100 feet each have high CO₂/CH₄ and N₂/Ar ratios.

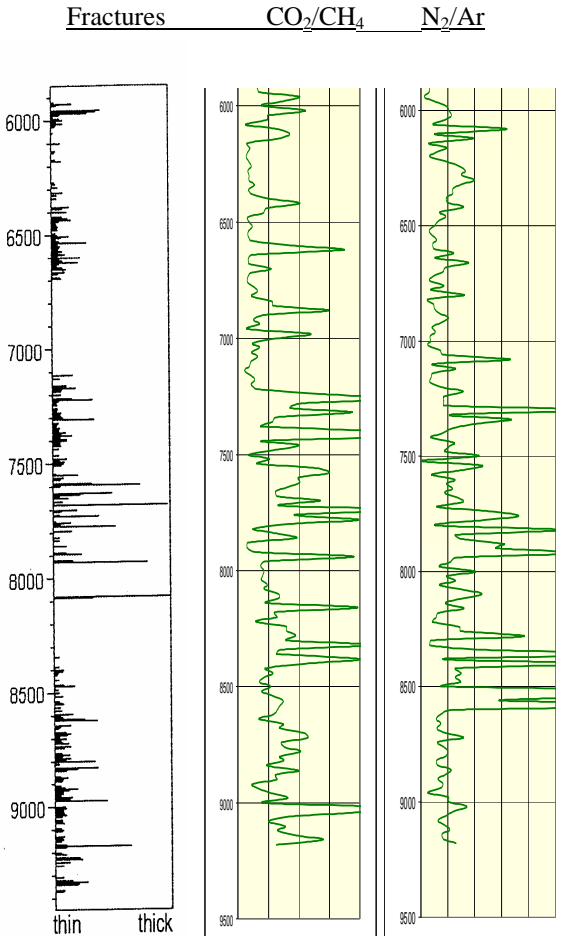


Figure 5: Fractures with significant apparent apertures, CO_2/CH_4 ratio and N_2/Ar ratio composite. Note that the where there is a high density of fractures, there appears to be corresponding peaks for the ratios. Note also the zone from 7,100 feet to about 7,900 feet with high fracture density and high CO_2/CH_4 and N_2/Ar ratios.

DISCUSSION

It is apparent from the core analyses that the analysis of calcite is little different than analyses of rock chips adjacent to the vein. The peaks across the vein are relatively low in comparison to the H_2O and ratio peaks in Well 2, and similar to analyses of the non-productive Well 3 (Dilley et al., 2004). The reason for this is not evident, but could be that the calcite vein is quite a bit older than veins in Well 2 that are in reservoir rocks where fluids are currently fluxing.

Analysis of Well 2 and for Well 64-16 both show H_2O and Mass 43/39 as sharp define peaks. Well 64-16 data for these species indicate they do not extend into the wall rock more than a few feet. For the gas ratios CO_2/CH_4 and N_2/Ar , there appears to be broad peaks and that the gases extend into the wall rock on

the order of 15 feet. This maybe due to an osmotic affects favoring of small molecular diameter gaseous species.

Based on the sampling interval analysis conducted it appears that a sampling interval of 20 feet would be sufficient for most of the well depth, however in areas of particular interest, a 10 foot sampling interval would provide more information. The more mobile gases of CO_2 and N_2 appear to pass into the wall rock and thus show a broader data for the core and well chips suggests an average anomaly for N_2/Ar and CO_2/CH_4 ratio peaks on the order of 15 feet in thickness.

The fracture analysis conducted would indicate that the peaks on the graphs from the fluid inclusion gas analysis do represent fractures either individual fractures or large densities of fractures. In the zone of increasing temperatures the density of large fractures was high, and the ratios of N_2/Ar and CO_2/CH_4 were also high indicating that the zone is near the reservoir fluids. In the production area, the fracture density was moderate however, the signatures for the ratios was low.

CONCLUSIONS

1. The gas chemistry of vein fluids in recorded in wall rock extending 5 to 10 feet from vein center.
2. A twenty-foot sample spacing will detect the most veins. However for better vein detail, and recording water and 43/39 ratio peaks a 10 ft. sampling interval is better.
3. Crushing wall rock adjacent to veins yields gas ratios similar to those in vein minerals.
4. The peaks developed from the ratios apparently indicate fractures, however not in all cases. Based on the core analysis conducted there is some diffusion of the gases into the wall rock.

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