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FLUID INCLUSION STRATIGRAPHY

A New Method for Geothermal Reservoir Assessment

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PREFACE

The California Legislature created the Geothermal Resources Development Account (GRDA) and the Geothermal Program in 1980. Funding comes from revenues paid to the United States government by geothermal developers for leases on federal land in California. Under the Geothermal Program, the California Energy Commission has assisted numerous eligible private entities and local jurisdictions in geothermal research, development, demonstration, commercialization, planning, mitigations, and environmental enhancement projects related to geothermal energy. The purpose of the program is to enhance and promote geothermal development in California. For more information on the Geothermal Program, please visit the California Energy Commission's Web site at. http://www.energy.ca.gov/geothermal/index.html

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ABSTRACT

Fluid inclusion stratigraphy is a method for identifying fractures and fluid types in geothermal systems. Open fractures are needed to provide pathways for the migration of fluids (gases, hot geothermal water, or cooler waters) within the geothermal reservoir. Fluid inclusions sometimes occur in crystals contained in rock cuttings from geothermal wells. These fluids contain gases whose geochemistry can be analyzed and plotted in well logs and subsurface diagrams to show the distribution of different chemical components within portions of a geothermal reservoir. This study found that the relative proportions (ratios) of certain gaseous components can indicate zones of cool groundwater inflow, warm geothermal fluid flow and permeable and nonpermeable zones within the geothermal reservoir. Permeable zones, which allow the easy movement of liquids and gases, are indicated by a large change in the relative concentrations of carbon dioxide and nitrogen. Different fluid types in the inclusions can be recognized based on the occurrence of certain chemical compounds, such as water, and by the ratios of certain other compounds or elements such as nitrogen argon, carbon dioxide methane, and others.

Several subsurface diagrams and well logs were developed for the Coso geothermal reservoir in Inyo County, California, showing the distribution of fluid types by depth, and indicating the general sources and temperatures of origin of the fluids. This allowed recognition of critical areas within the reservoir that can be related to zones where fractures permit higher rates of fluid flow and higher temperatures of the geothermal fluids. Significant differences between the reservoir's western and eastern portions were found, corresponding to areas of increased permeability and present-day geothermal production. By combining the location of the reservoir fluids and permeable zones, likely production zones can be targeted in the future, potentially making reservoir management easier and less expensive.

Keywords: Fluid inclusion stratigraphy, geothermal systems, reservoir fluids, Coso geothermal reservoir, reservoir assessment

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EXECUTIVE SUMMARY

Introduction

Fluid inclusion stratigraphy is a relatively new method of assessing geothermal reservoirs that was originally developed by the petroleum industry and is being adapted to geothermal applications. The method involves using bulk chemical analysis of gases trapped in fluid inclusions. Fluid inclusions are formed when fluids and gases are trapped in crystal as they grow. These fluids and gases are good indicators of the chemistry of the fluids at the time of crystal growth. The bulk chemical analysis is conducted on 10- to 20-gram samples from well cuttings obtained during the drilling of the well. The distribution, both vertically and horizontally, of the chemicals observed in the analyses can be plotted on well diagrams to give a subsurface picture of the chemical patterns in portions of the geothermal reservoir. This distribution pattern is termed “stratigraphy” from the word “strata” or layers.

This research adapted fluid inclusion stratigraphy to geothermal reservoir assessment and demonstrated the method at a producing geothermal field. A geothermal reservoir is a large volume of underground hot water and/or steam that occurs in porous and fractured hot rock. The usefulness of fluid inclusion stratigraphy has been demonstrated in the petroleum industry for mapping drill holes using mainly the presence of hydrocarbons in fluid inclusions. Geothermal reservoirs do not have hydrocarbons but do contain a variety of gases including carbon dioxide, nitrogen, water vapor, argon, and methane.

Project Purpose

This research was conducted to determine the chemical types (“species”) that would prove useful in geothermal settings, how best to display the analytical data, what chemical proportions (species ratios, which are the relative proportions of chemical types) should be calculated, the optimum sample spacing from the well cuttings, and how to use the results to complement other subsurface information..

Specific goals for the project were:

- Developing a procedure for analyzing and displaying fluid inclusion stratigraphy analyses to interpret geothermal reservoir fluids.
- Verifying that fluid inclusion stratigraphy can provide useful and reliable information about subsurface fluids.
- Optimizing fluid inclusion stratigraphy sample frequency to minimize cost and maximize the information obtained.
- Verifying that fluid inclusion analyses done on multiple drillholes will show a “stratigraphy” (vertical sequence) of subsurface fluids that can be traced, or correlated, between wells.
- Testing the developed geothermal method on two wells drilled in an active geothermal reservoir currently being exploited, and evaluating the method’s value.

Project Results

This project showed that fluid inclusion stratigraphy can establish the relative temperatures of the fluids by the chemical signatures determined in the fluid inclusions. Fluid types were determined based on select chemical species, such as water, as well as ratios including nitrogen/argon, carbon dioxide/methane, and others by this method as peaks in chemical species plotted against depth. Recognizing fracture patterns in a geothermal reservoir is important because fractures can provide permeable pathways, which allow fluids and gases to move through the reservoir. Such permeable zones are essential for developing a geothermal reservoir. By identifying the relative temperatures of the fluids, fractures, and permeable zones, fluid inclusion stratigraphy can map potentially productive areas of geothermal reservoirs. Several cross-sections of the Coso geothermal field, located in Inyo County, California, were created using the fluid inclusion stratigraphy method. The cross-sections agree reasonably well with prior fluid inclusion temperature studies and the general knowledge of the field.

The Coso 38D-9 well was drilled, and researchers applied the fluid inclusion stratigraphy method to the well during drilling. The fluid inclusion stratigraphy method was able to identify zones of cold, mixed, and production-type fluids before other logging tools and was able to identify the production zone in conjunction with temperature logs. In addition to the Coso well, another well was drilled at Beowawe in northeastern Nevada (owned by the same company that operates Coso), and the fluid inclusion stratigraphy method was applied to identify a major fault zone. The new Beowawe well and an already producing well at the Beowawe field were sampled and the fluid inclusion stratigraphy method was used on each well. The location of the major fault zone and the producing zone were known in the older Beowawe well. From this information, and using the fluid inclusion stratigraphy method, the major fault zone was identified for the new Beowawe well while the drill rig was on location. This was a valuable test of the fluid inclusion stratigraphy method's ability to provide critical information during drilling.

Additional work can be conducted to refine this new method, including obtaining more detailed representation of the permeability zones and the relationship of the chemical peaks to fractures, applying the method to other fields, and determining precursors to upcoming hotter zones that can be identified using fluid inclusion stratigraphy.

Project Benefits

Fluid inclusion stratigraphy is a new tool that will greatly benefit the geothermal industry in California. The method provides a relatively cost-effective and rapid technique for identifying critical information about fluid chemistry, temperature, and likely productivity from a geothermal well. The information can be used while the drill rig is still on-site, preventing costs from delays in assessing the potential of the well. It can also be incorporated into an overall model of the field and used for targeting future exploration areas, potentially reducing the likelihood of drilling unproductive wells and as well as the cost of geothermal development. As a renewable energy source that can produce electricity around the clock, year-round, geothermal energy is a reliable addition to California's renewable policy goals. Reducing the cost of geothermal production benefits California's electricity ratepayers.

CHAPTER 1: Introduction

Fluid inclusions are formed in crystals as minerals grow. The fluids trapped in these inclusions are generally faithful indicators of the chemistry of fluids at the time of crystal growth. Inclusions are observed in a wide variety of geological settings and in a number of minerals including vein minerals formed by circulating waters, minerals within healing microfractures, and minerals that cement sediments. Inclusions can persist in the geological record long after the parent fluids have disappeared. Boiling, dilution, and fluid-rock interactions can change the chemical compositions of fluids, resulting in mineral growth and formation of inclusions.

Geothermal systems are found in active tectonic settings characterized by high strain rates. Accordingly, geothermal systems are constantly generating varying sizes of fractures through which fluids flow. Fluid inclusions are formed in geothermal systems as mineral growth occurs in fractures. Gases associated with and intermixed in the fluids are also trapped within the inclusions. Gases trapped within fluid inclusions from ore deposits and geothermal systems are well studied (Ohmoto 1968; Norman and Sawkins 1987; Landis and Hofstra 1991). The method of choice for analysis of a large number of gases at low concentrations is quadrupole mass spectrometery (QMS) (Graney and Kesler 1995). Mass spectrometer analyses of gases within fluid inclusions are used to show fluid sources and processes (Giggenbach 1997; Norman et al. 1997; Blamey and Norman 2002).

The purpose of this research was to adapt for geothermal reservoir assessment a relatively new method, currently used in the petroleum industry, of applying bulk chemical analysis of gases within fluid inclusions from well cuttings, and to demonstrate the method at a producing geothermal field. Fluid inclusion stratigraphy (FIS) has demonstrated its usefulness in the petroleum industry for mapping drill holes using mainly the presence of hydrocarbons in fluid inclusions (Hall 2002). This research was to determine the chemical species to use; how the data should be plotted; what species ratios should be calculated; the sample spacing, and how to use the results to complement other logging information.

Interpretations of geothermal fluid types are based on various assemblages of chemical species and the relative amounts of certain chemical ratios. A fluid type stratigraphy is produced by plotting the interpretations of several wells within a geothermal reservoir. This stratigraphy shows the locations of various fluid types and where boiling has occurred within the geothermal system. Because it is assumed that boiling occurs in highly permeable zones, permeable and non-permeable zones are also plotted. By combining the individual well stratigraphy, fluid inclusion stratigraphy can then be used to develop a fluid model of the reservoir.

The current level of knowledge about actual geothermal reservoirs is limited (Grant et al. 1982). A conceptual model of a reservoir will assist in predicting fluid behavior during exploitation. FIS will be used to develop a model of fluid flow for the Coso system. Models of geothermal systems need to accommodate the known pressure and temperature regimes that are evident on the surface as well as in the subsurface. Chemical signatures are also important in indicating changes within the system over time as well as current fluid flow paths. Dilution and boiling both have significant impacts on the behavior of a reservoir over time.

1.1 Rationale

Vital to the management and sustainability of a geothermal reservoir is an understanding of fluid movements and controlling structures within the reservoir. Tools currently available to understand the behavior of the fluids within a reservoir are well log data, alteration patterns, and fluid inclusion gas chemistry and thermometry. Geophysical data are also used to image the geometry of controlling structures in the subsurface. Well log data provide information on the temperature and flow of fluids and on fracture patterns (Roberts et al. 2001). Alteration patterns describe past behavior of fluids and identify the chemistry of fluids. Fluid inclusion gas chemistry and thermometry provide information on the chemistry, temperatures, and salinities of the fluids. Each of these techniques is expensive and time consuming. Well logging typically averages on the order of hundreds of thousands of dollars per well for a suite of logs (Berard 2003). Temperature logging requires many days to run several tests at various pumping rates to obtain accurate temperature profiles of the borehole. Determining alteration patterns requires detailed geological study of the core logs. Fluid inclusion gas chemistry has to this point in time been performed only on limited samples using high-precision mass spectrometers that require several days to obtain results. Fluid inclusion thermometry has been conducted on samples from core logs but again requires detail analysis and skilled interpretation. A goal of this project was to develop a methodology to show that FIS can provide a rapid (within the time frame of drilling the well), inexpensive (on the order of $5,000 to $10,000 per well) technique that will produce the same type of data as the above techniques on a detail scale and be useful to understanding a geothermal system.

The Coso geothermal system was chosen for the demonstration for several reasons. First, it is one of the larger geothermal systems in production. Second, with approximately 100 wells in production, the field offers a great variety of wells to choose from for study, including high-production geothermal wells that produce about 25 megawatts (MW) down to the geothermal wells that produce in the 2- to 3-MW range. Third, Coso is a young system, less than 10,000 years old (Kurilovitch et al. 2003), with recent deposition overprinting older geothermal signatures. It is one of the best-documented studies of a silicic dome system in the world (Ross and Yates 1943; Dupuy 1948; Bacon and Duffield 1980; Bacon et al. 1981; Adams et al. 2000).

Part of the project was conducted using data from Beowawe, Nevada. One well was being drilled in Beowawe by Coso Operating Company and it was decided that this well would be a good test case of applying FIS to well drilling decisions. Also, core samples were studied from Karaha Telga Bodas, Indonesia due to lack of cores from Coso and Beowawe.

1.2 Project Objectives

The project objectives were:

- To develop a methodology for applying fluid inclusion gas analysis of borehole cuttings to geothermal exploration.
- To test the FIS methodology developed for geothermal exploration wells drilled in an operating geothermal field.

Specific goals were:

- To develop a procedure for analyzing and displaying FIS mass spectrometer analyses to allow interpretation of geothermal reservoir fluids.
- To verify that FIS can provide useful and reliable information about subsurface fluids.
- To optimize FIS sample frequency to minimize cost and maximize information obtained.
- To verify that FIS done on multiple holes will show a "stratigraphy" (vertical sequence) of subsurface fluids that can be traced, or correlated, between wells.
- To test the developed geothermal FIS methodology on two wells drilled during the project period and evaluate the value of the method.

This project has shown that FIS can by the chemical signatures determined in the fluid inclusions arrive at the relative temperatures of the fluids. Fracture patterns can also be identified by FIS as peaks in chemical species plotted against depth. Permeable zones are identified by FIS through various chemical ratios. This method provides several of the more important elements in producing a model of a geothermal system: relative temperature of fluids, chemistry of fluids, and permeable zones within the system.

CHAPTER 2: Background

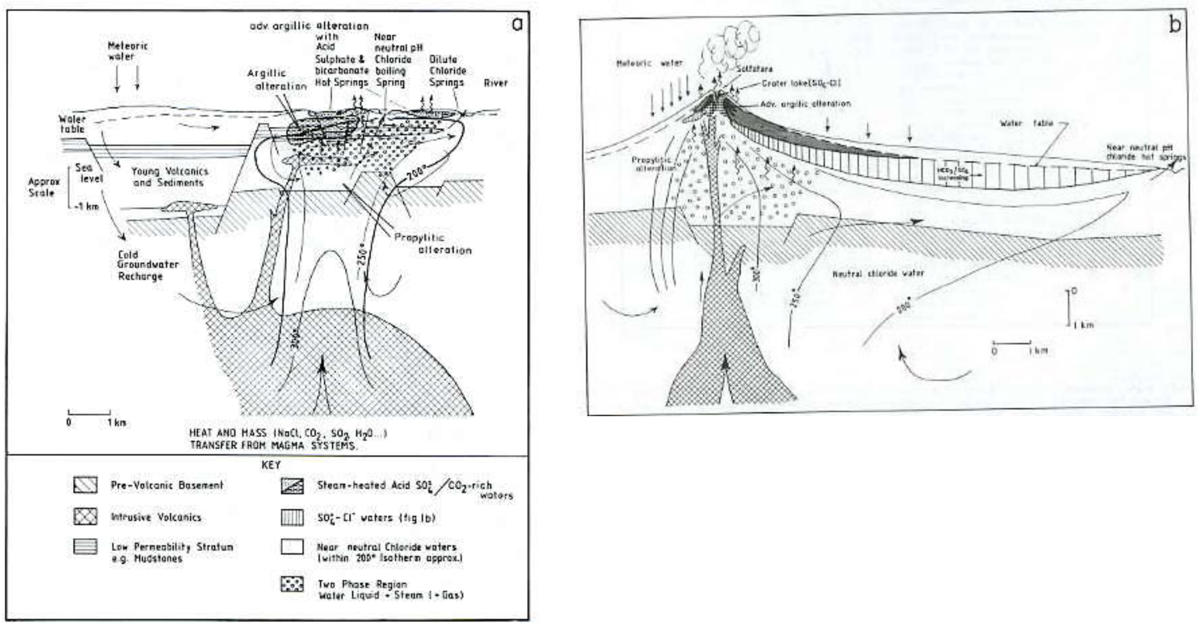
2.1 Geothermal Systems

Geothermal systems can be divided into volcanic hosted systems, sedimentary basin systems, and isolated systems. Volcanic hosted systems can be further broken down to island arc systems, typified by New Zealand systems; rift systems, typified by East Africa and Iceland systems; basin and range systems such as Dixie Valley and Beowawe in Nevada; and California-Sierra mixed with extensional and transverse fault systems such as Coso and Imperial Valley. In each of these systems there is a heat source either from current or recently solidified magma bodies. It is the flow of fluid in hydrothermal convective systems that determine the temperature and fluid distribution in the reservoirs. In addition to their geological setting, geothermal systems are classified as either vapor-dominated or hot-water systems. Vapor-dominated systems have pure high-temperature steam that is greater than 235°C (455°F). In liquid-water systems typical temperatures range is 150°C (302°F) to 300°C (572°F). Coso and Beowawe are liquid-water systems. As production continues at Coso, a steam zone is developed.

A variety of models have been developed over the years to explain specific systems, with only a few attempting to apply general principles to a "typical" system. Models for the Icelandic systems were developed in the 1940s, followed by White's model of Steamboat Springs, Nevada, in 1968. White's model had fluid originating at the ground surface, percolating to depths of 3 kilometers (km). At that depth the water is heated by a magma body to high temperatures, driving the fluid back up to the surface through permeable fractures. White's model assumed circulation in confined fault zones, but follow-on work suggests that layers of breccia and fractured volcanic material behave as large beds of permeable material.

In 1983, Henly and Ellis produced two generalized models of a typical liquid-dominated geothermal system in two types of volcanic environments: silicic and andesitic. Figure 1 shows these two models. In the first model (1a) chloride waters, created by chemical interactions of water-rock-magma at depth, rise and boil, and the resultant steam migrates to the surface. Near-surface condensation and oxidation of transported H_2S produces sulfate-dominated, steam-heated waters. Near-neutral pH chloride springs occur on the surface. High relief andesite volcanoes (1b) create lateral flow of hot chloride water, and near-surface exsolving gases escaping from solution produce acid-sulfate-chloride lakes and large argillic alteration zones.

Figure 1: Typical Geothermal Systems



a.)Typical geothermal system in silicic-volcanic environment. Temperature distribution is based on the system at Wairakei, New Zealand. b) Typical geothermal system in andesitic volcanics.
Note the extensive lateral flow and large advanced-argillic alteration zone related to high-level volcanism.
Source: Henley 1985.

Researchers now believe that geothermal systems are much more complicated than the simple models produced two decades ago. For example, how and why reservoir caps form is poorly understood. They may be lithologic (based on low permeability rock types) or the result of enhanced mineral deposition at boundaries between reservoir fluids and cooler ground waters (Moore et al. 2001). Fluid movement is complicated in geothermal systems. There are entrances (inflow zones) of steam-heated and cool surface waters into geothermal reservoirs, as is common at the Coso field (Brian Berard, personal communication). Cool, low-salinity ground waters are denser than the typical reservoir fluid; therefore, when cold water enters a fracture bearing thermal waters the cold water should sink and mix with the thermal water. The movement of gases in geothermal systems is also complicated such as the development of steam. Minerals get deposited as these various fluids and gases chemically interact in rock fractures. The minerals as they grow from these geothermal fluids trap the fluids and gases in inclusions. FIS tries to use these trap fluids and gases to identify fluid types and boundaries in geothermal systems.

2.2 Fluid Inclusion Gas Analysis – Previous Work

Distinctive assemblages of gases can assist in defining fluid types. Specific gases can be derived from high-temperature reactions within the system or may be introduced from external recharge waters. Reactive gases such as hydrogen (H_2), hydrogen sulfide (H_2S), methane (CH_4), and ammonia (NH_3) are derived from reactions with organic chemical species or with mineral phases in a reservoir. The species carbon dioxide (CO_2), sulphur dioxide (H_2SO_2), H_2S, hydrofluoric (HF), and hydrochloric (HCl) have been recognized in volcanic eruptions and geothermal systems (Giggenbach 1986). High concentrations of CO_2, H_2S, and HCl have been noted in Icelandic geothermal fields and are thought to be derived from active magmatic chambers at depth (Armannsson et al. 1982). Several fluid types exist in the geologic literature. Meteoric fluid is the term generally used for shallow, young groundwater. In Henley's model, Figure 1, these are the cold recharge waters. Deeper, older groundwater that is chemically complex is termed crustal fluids.

Meteoric waters contain a distinctive suite of gases including Ar and other noble gases, which are useful in identifying meteoric water influx in active geothermal systems (Norman and Musgrave 1995). Crustal fluids in rocks typically have H_2 and H_3, H_2S, CH_4, or heavier organic species derived from fluid interaction with organic-rich sedimentary rocks. Fluids from metamorphic processes are dominated by CO_2, with lesser amounts of CH_4 and H_2S (Landis and Hofsta 1991). Giggenbach (1986) introduced the nitrogen/argon (N_2/Ar) ratio, which can indicate the magmatic and meteoric gaseous constituents in geothermal fluids. Giggenbach proposed that higher nitrogen indicates magmatic gas components in geothermal fluids. Additional work by Norman and Musgrave (1995) has also shown that the N_2/Ar ratio is an important indicator of magmatic components. Meteoric fluids have N_2/Ar ratios between 38, value of ratio from air saturated water and 84 value of ratio for air, (Norman et al. 1997). Fluids in geothermal systems associated with recent magmatic activity have N_2/Ar ratios greater than 100. Giggenbach (1981) also showed that crustal fluids are enriched in CH_4, other hydrocarbons, and N_2/Ar ratios up to 350. Hot, deep crustal fluids may accumulate CH_4 through thermal degradation of organic material and/or oxidation reduction reactions involving iron-bearing minerals of CO_2.

Follow-on work by Norman et al. (1997) showed that steam-heated waters are distinguished by high concentrations of more soluble gaseous species, including CO_2, benzene (C_6H_6), and H_2S and that H_2S is low or absent in groundwater. However, highly evolved (older) groundwater may have high concentrations of H_2S as well as He and CH_4.

In addition to the high N_2/Ar ratio, magmatic gases generally have high CO_2/CH_4 content (Giggenbach 1986; Norman and Musgrave 1995; Norman et al. 1996). The ratio of CO_2/CH_4 was used by Lutz, et al. (1999) to evaluate the origins of fluids at Dixie Valley geothermal field in Nevada. Most of the geothermal vein samples from the wells were interpreted as mixtures of meteoric and crustal fluids. They determined that if the CO_2/CH_4 ratio is less than 4 the fluid is crustal. Moore et al. (2001) also found that in the Geysers field in California, the crustal fluids had CO_2/CH_4 ratios of less than 4. These fluids also had high N_2/Ar ratios and low helium He_3/He_4 ratios.

Boiling and condensation are important processes that occur within geothermal systems. Fluid inclusion gas analyses by Norman et al. (2002) indicate that vapor-filled inclusions will be enriched in methane, ethylene, and other similar insoluble species. Condensation will result in more soluble species including aromatic organic species, butylenes, and CO_2. Through successive crushing and extraction of gases from a single mineral, Norman (1987) showed that there is a sequence in the composition of gases within fluid inclusions trapped during boiling.

Methane, ethylene, and other insoluble species are initially trapped. As boiling continues, these components are removed from the system until inclusions with only CO_2 are left.

In summary, previous work on interpreting fluid sources and fluid processes from geothermal gas chemistry has shown the following (Table 1): (1) reservoir fluids are generally highly charged with gaseous species; (2) shallow groundwater has low concentrations of gaseous species; (3) steam-heated waters typically contain high concentrations of the more soluble gaseous species; (4) gas ratios can differentiate reservoir fluids, steam heated waters, and shallow meteoric waters; and (5) fluid boiling results in trapping of vapor-filled inclusions that have relatively high concentration of less soluble gaseous species.

Table 1: Summary of Fluid Inclusion Gas Chemistry and Fluid Types

Fluid Types	Gas Chemistry
Meteoric-Shallow Groundwater	$38 < N_2/Ar < 84$: CO_2/CH_4 low: H_2S low low gaseous species
Crustal-Deep Evolve Groundwater	CH_4, H_2S, He high: $N_2/Ar < 350$ heavy organics
Geothermal Fluids w/ Magmatic Component (reservoir)	N_2/Ar high: CO_2/CH_4 high high N_2 highly charged gaseous species
Steam-heated waters	high H_2S, CO_2, C_6H_6 soluble gaseous species are high
Boiling/Condensation	Methane→Ethylene→ CO_2 less soluble gaseous species are high

2.3 Well Logging/Testing

A geothermal well will typically cost between $1 million and $10 million, and there may be 10 to 100 or more wells in a fully developed field. Drilling can readily account for 30 percent to 50 percent of the total financial outlay of a geothermal project. Testing during drilling of the well and after well completion is essential for determining reservoir and fluid properties. FIS is capable of providing results rapidly, while a well is being drilled.

Frequently used well logging suites include resistivity, self potential (SP), gamma ray, densilog, spinner, and caliper logs. The purpose of the well logging is stratigraphic reconstruction and understanding fluid behavior. Circumferential borehole imaging logging is a new tool used to identify fractures in the borehole (Batini et al. 2002). Electric resistivity logs may be useful in identifying boiling zones (Roberts et al. 2001). Laboratory measurements have shown that there is a large increase in resistivity where active boiling occurs. SP monitoring is used to determine fluid flow in geothermal reservoirs (Akasak et al. 2003). Many of the techniques for well logging were developed from the petroleum industry; however, logging tools and cables are usually capable of performing only to temperatures of 260°C (572°F) or so (Batini et al. 2002). Temperatures above 260°C (572°F), such as those at Coso, are commonly encountered in geothermal fields. There is a continuing effort in the industry to develop new tools and techniques that can accommodate these higher temperatures. This project intended to demonstrate that FIS, already an established technique in petroleum field conditions, can be adapted to the geothermal environment, adding another, and less expensive, tool to the geothermal industry's arsenal.

Temperature, pressure, and spinner (TPS) logs are used in conjunction with well tests to define the reservoir. TPS data are used to locate individual transmissive fractures and flash points in a well before performing well tests (Morin et al. 1998). In addition, temperatures are measured during drilling and any break in drilling. Experiments have shown that by using an 8-hr drilling/16-hr recovery cycle, measured temperatures are within 20°C (68°F) of the original reservoir temperatures (Grant et al. 1982). Temperature measurements are also made during warm-up of the well and at various times during the life of the well. How the well warms up is indicative of permeability and heating. Slow, smooth warm-up is characterized by conductive heating and poor permeability. Uniform heating of one section more quickly than other sections indicates interzonal flow.

This project hopes to demonstrate FIS as a tool to be used while a well is being drilled, that will provide information on fluid types, permeability, and entrances of cold or hot fluids. FIS does not affect the well environment like testing and logging tools do and therefore FIS provides a picture of the well prior to development. Although FIS will not provide fluid flow rates, it can provide a gross measurement of the permeability of the well and a relative temperature of zones within the well. This is useful information prior to completing a well so that decisions can be made for further testing and logging.

2.4 Coso Geology

The geology of the Coso area results from the complex interaction of Basin and Range extensional forces with the right-lateral strike slip movement of the San Andreas fault system. The Sierra Nevada Range to the west and the Argus Range to the east are north-south trending ranges bounded by down dropped faults reflecting the east-west extensional nature of the Basin and Range area. The irregular and ill-defined boundaries of the Coso Range reflect the complex tectonic history of the area. Three sets of faults create the dramatic relief of the area including the giant staircase stepping down to the west of the Airport Lake area. The structural relationship is important because it allows for development of faults that are part of the continual expression of the movement of the magma body below the geothermal field. A detailed structural map of the Coso Range indicates a tremendous number of faults in the area, and this continual structural complexity is part of the reason the field has survived.

Pliocene and Pleistocene (5.3 to 0.01 million years ago) volcanic rocks are the most voluminous and widespread of the rocks in the area. There are approximately 400 cubic square kilometers of lava flows and domes. The relationship of the volcanic rocks to the underlying granitic basement was documented by Duffield et al. in 1980. Sugar Loaf Mountain is a rhyolite dome in the middle of the Coso field, surrounded by a series of basalt rocks. The Pleistocene volcanic rocks consist of 38 separate domes and flows of high-silica rhyolite, and most of them are quite young, younger than 300,000 years. Bacon et al. (1981) inferred from the rhyolite magma that there was a chemically stratified siliceous reservoir at depth. Most of the first production of the geothermal system was near Dome 53, which is near the Devil's Kitchen fumarolic area. The distribution of the siliceous vents and the volume of extruded magma combined with interpretations from geophysical measurements indicate that the siliceous magma body is approximately 5 km in diameter and more than 1 km thick, with a total volume of about 20 to 30 cubic km (Bacon et al. 1980). This magma body probably underlies the Coso volcanic field by a depth of at least 8 km and is thought to be still partially melted, based on most recent basaltic eruptions occurring as late as a few thousand years ago.

2.5 Coso Geothermal System

The Coso Geothermal system is approximately 30 miles north of Ridgecrest, California, within the western extent of the Basin and Range province. The system occupies approximately 30 square kilometers of the Mojave Desert. The reservoir has sustained 240 MW of electricity from fractured Mesozoic rocks that consist primarily of granitic plutons and metamorphics. Pliocene and Pleistocene volcanics with an age range of 4 to 0.04 Ma overlie the Mesozoic rocks.

The Coso geothermal system is a volcanic-hosted system. On the basis of the rocks observed on the surface, there appear to have been three episodes of thermal activity. Travertine deposits approximately 307,000 years old on the eastern side of the field are interpreted to be fossil fumarole systems representing the first episode of thermal activity. The second episode is recorded by the sinter deposits in the eastern and southern parts of the present-day field. These deposits are dated at about 238,000 years old. The most recent thermal episode began approximately 10,000 years ago (Kurilovich et al. 2003), based on potassium/argon dating of well chip samples. Fluid inclusion data and the rocks observed by Lutz, 1999 suggest that the first episode was a large-scale system but of low to moderate temperature. The second episode was produced by magmatic activity beneath the dome field that resulted in a large high-temperature system. The most recent event has heated up the eastern flank by 100°C (212°F) and reactivated the high-temperature center beneath the southern part of the field.

Crustal waters from sedimentary formations were probably the original waters in the system. Convection of the fluids caused the thermal fluids to flow longitudinally and upward to the north for much of the first and second thermal episodes. A non-thermal groundwater system capped the thermal system. The low-salinity groundwater disappeared, most likely at the end of the last glacial period (100,000 years BP). The last pluvial period in the area occurred approximately 10,000 years ago. After this period the Mojave Desert became drier. The present-day geothermal system is partitioned into at least two reservoirs that are weakly connected and one that is isolated. The segregation of the reservoir and the components may have occurred when the groundwater disappeared.

Fluid inclusions from the Coso geothermal system record a broad range of temperatures and salinities. Adams et al. (2000) indicates that fluid inclusions related to geothermal activity had homogenization temperatures ranging from 76°C (69°F) to 328°C (622°F) and salinities of 0 to 3.4 weight percent in chlorine (Cl) equivalent. The highest temperatures are found near the southern end of the field, where they define a shallow up-flow zone in the area that contains no surface manifestations. The variations in temperatures and salinities suggest that the high-temperature fluids were diluted by low-temperature water with essentially zero salinity.

A series of active acid-sulfate springs and mud lakes comprise the main Coso Hot Springs area. The hot springs occur along the north–northeast trending fault on the east side of the main fault block. Austin and Kringle in 1970 measured up to 3000 parts per million (ppm) chloride in deep well waters in this area (Wohletz and Heiken 1992). Downhole temperatures were measured at 142°C (288°F). The Devil's Kitchen area consists of a series of fumaroles on the tuff ring at Dome 53, and there is a present-day deposit of sulfur bearing minerals. Various fumaroles become active at different times, and it was noted during the site visit in 2003 that a new fumarole had developed in this area.

2.6 Beowawe Geology

The Beowawe geothermal field is located in northern Nevada within the Basin and Range geologic providence. Miocene (23.7 to 5.3 million years ago) volcanic rocks overlie older chert, shale and quartzite of the Valmy Formation (Garside et al. 2002). The reservoir is associated with a normal (down dropping) fault that cuts across the northern Nevada rift. Production occurs in the Valmy Formation from highly fractured rocks. Production fluid temperatures are about 143°C (289°F).

CHAPTER 3: Methods

The methods were formulated to answer several questions that arose before and during the research:

- What species are useful for determining fluid types?
- What sample spacing is applicable?
- How well do the data correlate to the temperature logs?
- Can producing and non-producing wells be identified?
- What are the fluid types in each well?
- Can permeable zones be identified?
- Do the analyses indicate fractures in the actual rock?
- How accurate is the fluid model developed?

The following methods were developed to answer these questions. In addition, the sampling method was developed to be easy and to be usable as a well was being drilled.

3.1 Wells

Fifteen wells from the Coso Geothermal Field were selected for analyses. Table 2 presents the well names and descriptions. Figure 2 presents the Coso site map and the well locations. Wells used for study from Coso included non-producers to wells with 8-MW capacity. The wells were from different parts of the field including the East Flank, the western edge, and the southern portion. Injection wells were also used in the study. One objective was to apply the FIS method to new wells being drilled. One well at Coso 38D-9 was drilled shortly after the start of the project and was used to apply the FIS method.

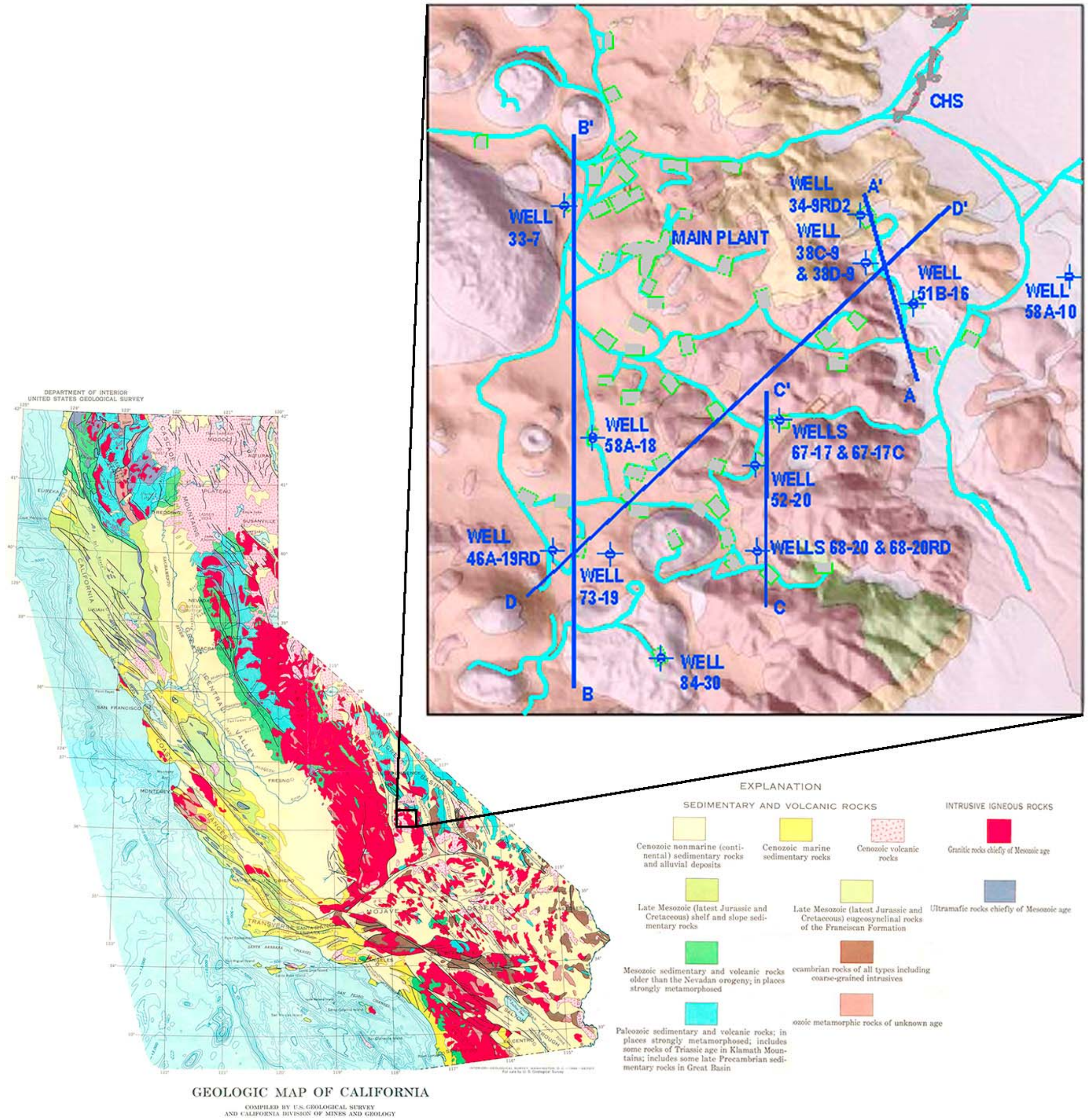
In 2006 a new well being drilled in the Beowawe field was selected as the second test well. As the well was being drilled, decisions were needed about the fault location and whether the production zone had been encountered. This situation tested the utility of the FIS method to determine the location of the fault and the production zone. A second well at Beowawe where the fault location and the production zone were known was also analyzed. Table 3 presents the well names and Figure 3 presents a site map for Beowawe.

Table 2: Coso Geothermal Field Well Names and Descriptions

Well Name	Type	Temperature	Capacity (MW)	Sampling Interval (ft)
33-7	Producer	LE	2	760-9860
38C-9	Producer	ME	8	100-9180
84-30	Non-Producer	N/A	-	540-7820
58A-18	Producer	LE	4	2580-8660
38D-9	Producer	ME	7	6100-9450
58A-10	Non-Producer	Unknown	-	60-9860
51B-16	Non-Producer	HE	-	780-9800
34-9RD2	Injection	HE	3+	1590-4080
67-17C	Injection	LE	-	540-7780
67-17	Injection	LE	-	497-9020
46A-19RD	Non-Producer	HE	-	2360-13020
68-20	Injection	LE	-	1000-6380
68-20RD	Injection	LE	-	2600-6960
52-20	Producer	LE	3	520-7780
73-19	Producer	HE	3	800-6050

Temperature: E: enthalpy; L: low; M: medium; H: high

Figure 2: Location of Wells Used in the Study and Surface Features of Coso Field.



Source: Geologic Map of California from USGS and Coso Map.

Table 3: Beowawe, Nevada, Geothermal Field Well Names and Descriptions

Well Name	Type	Temperature	Capacity (MW)	Sampling Interval
77-13	Large Producer	ME	Unknown	0 - 8,300
57-13	New Well	Unknown	Unknown	0 - 10,600

Figure 3: Location of Beowawe, Nevada.

The analyses were divided into several rounds. The first round consisted of analyzing four wells (33-7, 84-30, 58A-18, and 38C-9) to determine if the technique would work. These samples were collected in May 2003 by the author. During the first round, Coso Well 38D-9 was proposed to be drilled. This was an excellent opportunity to determine if the method would be applicable to a well while it was being drilled. Samples were collected by a mud logger every 20 feet while this well was being drilled in 2004. The second round consisted of sampling Wells 51B-16, 34-9RD2, 67-17, and 52-20 in late 2004. These wells were sampled by a Coso geologist from stored drill cuttings. Well 46A-19RD was sampled in March 2005 by a Coso geologist. The final Coso sampling was conducted in October 2005 at the core laboratory at Energy & Geoscience Institute (EGS) at the University of Utah by the author. Drill cuttings from Wells 68-20, 68-20RD, 67-17C, and 73-19 stored at the laboratory were sampled. The Beowawe samples were collected by a company geologist in January 2006.

3.2 Rock Cores

Additional samples from rock cores were collected to determine if the peaks seen in the fluid inclusion gas data indicated fracture zones. Samples were collected from a select interval from one well at Coso and select intervals from two wells at Karaha Telga Bodas, Indonesia (Karaha). The wells from Karaha were sampled because of the limited availability of geothermal cores. The cores were located at EGS, University of Utah laboratory, and were sampled in October 2005. The interval along each core was selected based on the presence of a distinct fracture or vein. The veins were typically composed of one or two minerals. Chip samples were collected at 1- to 2-foot spacings along the core for about 10 to 20 feet in both directions away from the center of the fracture. The wells and sampling intervals are presented in Table 4.

Table 4: Sampling Interval of Rock Cores

Field	Well Name	Type	Sampling Interval (ft)
Karaha	K-33	Producer	4339-4347
Karaha	K-33	Producer	5449-5459
Karaha	K-33	Producer	5460-5467
Karaha	T-2	Producer	3512-3521
Karaha	T-2	Producer	3549-3567
Karaha	T-2	Producer	3650-3659
Karaha	T-2	Producer	3669-3699
Coso	64-16	Unknown	560-720

3.3 Sampling

Sampling of the wells consisted of obtaining 10 to 20 grams of well cuttings at 20-foot intervals. The cuttings ranged in size from coarse sand to fine sand. The 10 to 20-gram samples were randomly pulled from the well cuttings for that sampling interval. No effort was made to collect a specific chip size or specific minerals within the well cuttings; this would have made the sampling more time consuming (and expensive) and was not needed for the analytical method.

Select intervals of Well 38C-9 were resampled at 10-foot intervals to evaluate sampling intervals. One Coso well, Well 38D-9, and Beowawe Well 57-13 were sampled during drilling; all other wells were sampled from stored well cuttings several years after drilling and logging had occurred. One well, 84-30, was sampled for background data. Two wells, 68-20 and 68-20RD, were drilled seven years apart. The two wells started at the same location and deviated from each other about 150 feet at 5500 foot depth. These wells were sampled to determine if there was a difference in the fluid inclusion gas chemistry after seven years of scale deposition in the well.

3.4 Laboratory Analysis

Over the course of two years during this study, more than 5000 samples from the wells were submitted to Fluid Inclusion Technology (FIT), a commercial laboratory, in Oklahoma for analyses over the course of two years. Appendix A presents the entire data set returned from FIT. FIT has developed a proprietary system for rapid bulk analysis of fluid inclusion gases and has used the technique for evaluating petroleum reservoirs. Analyses are performed by first cleaning the samples, if necessary, then crushing a gram-size sample in a vacuum and analyzing the volatiles with a quadrupole mass spectrometer. A diagram of a mass spectrometer is presented in Figure 4.

A mass spectrometer works by deflecting ions by magnetic field and then electrically detecting those ions. There are four stages to a mass spectrometric analysis: (1) ionization; (2) acceleration; (3) deflection; and (4) detection. A vacuum is maintained in the machine so ions do not hit air molecules. A vapor sample is pumped into an ionization chamber. The atoms/molecules within the sample are bombarded with a stream of electrons, which create positively charged ions. A metal plate with a positive charge in the ionization chamber repels the newly created positive ions into the acceleration area. In the second stage the ions pass through a number of slits in plates that carry a voltage. This creates a focused ion beam. In stage three, the ion beam passes through the electromagnet and is deflected based on the mass of the ion and the charge on the ion. This is the mass/charge ratio. Typically the ions carry a +1 charge; however, there could be multiple charges on the ions. In the third stage, the deflected ion stream passes to the ion detector. There is some contamination on the sides of the machine where other ions have collided with the walls. The contaminating ions are eventually removed by the vacuum pump. When an ion hits a metal box in the detector, its charge is neutralized by an electron. The movement of the electrons is detected as an electric current, which is recorded. Varying the magnetic field creates different mass/charge ion streams that can then be detected. The mass of each ion being detected is related to the size of the magnetic field. A lighter mass/charge ion stream can be detected by using a smaller magnetic field. The machine is calibrated to record current against mass/charge ratio. The mass is measured against the atomic weight for the carbon 12 atom.

Generally the geothermal samples are clean when sampled and therefore do not require any additional cleaning at the laboratory. The samples are loaded into a 630-hole tray with appropriate standards and placed in a vacuum oven at elevated temperatures for a minimum of 24 hours, followed by another vacuum oven at lower temperatures for a minimum of 24 hours (Hall 2006). This removes adsorbed organic and inorganic volatile materials from the samples. The volatiles released as a result of crushing by an automated mechanical crusher are dynamically pumped through four quadrupole mass spectrometers where molecular compounds are ionized by electron bombardment and separated according to the mass/charge ratio. The separation occurs by a combination of radio frequency and direct current electrical fields. Electronic multipliers detect the signal, which is processed to create a mass spectrum for each sample. The output datum for each sample is the magnitude of mass peaks for masses 2 to 180. A volatile such as CO_2 has a gram formula weight of 44 and will be measured by a peak at mass 44. Table 5 presents the more common mass formula and chemical species associated with the mass. As can be seen in Table 5, at mass 14 there is the possibility of having nitrogen or a fractionation of carbon dioxide. To determine if mass 14 represents nitrogen or carbon dioxide, the values for mass 14 are plotted against mass 28 (N_2) and against mass 44 (CO_2). Figure 5 presents the results. A linear trend for mass 14 against mass 28 indicates that the mass 14 represents nitrogen and not carbon dioxide.

Figure 4: A Schematic of a FIT Analysis Process

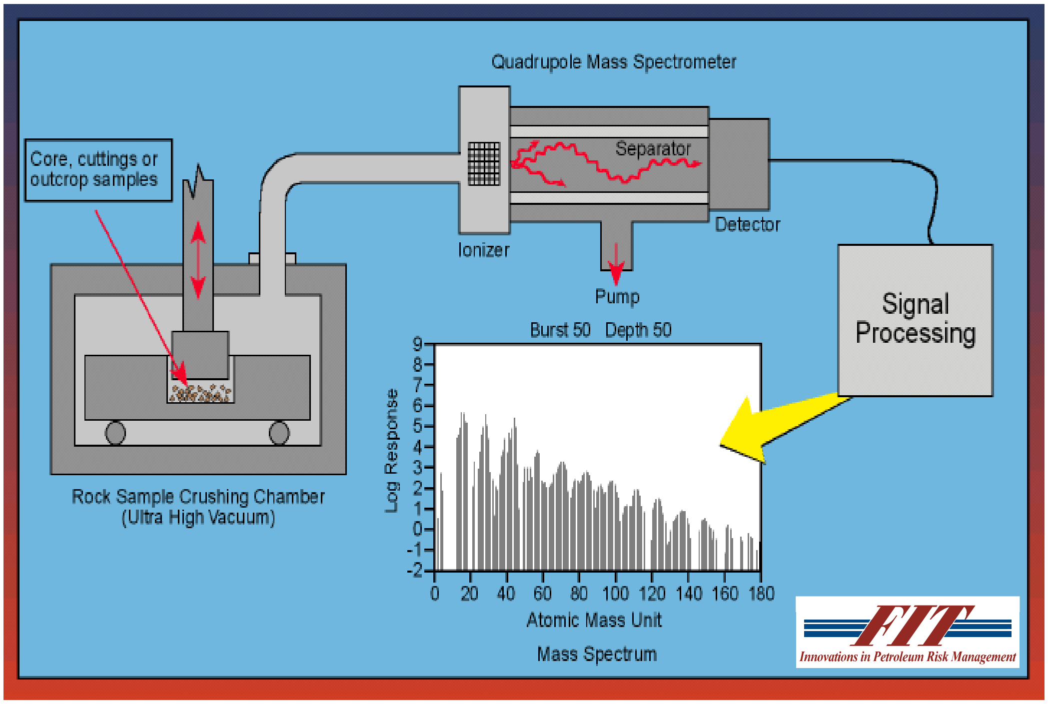
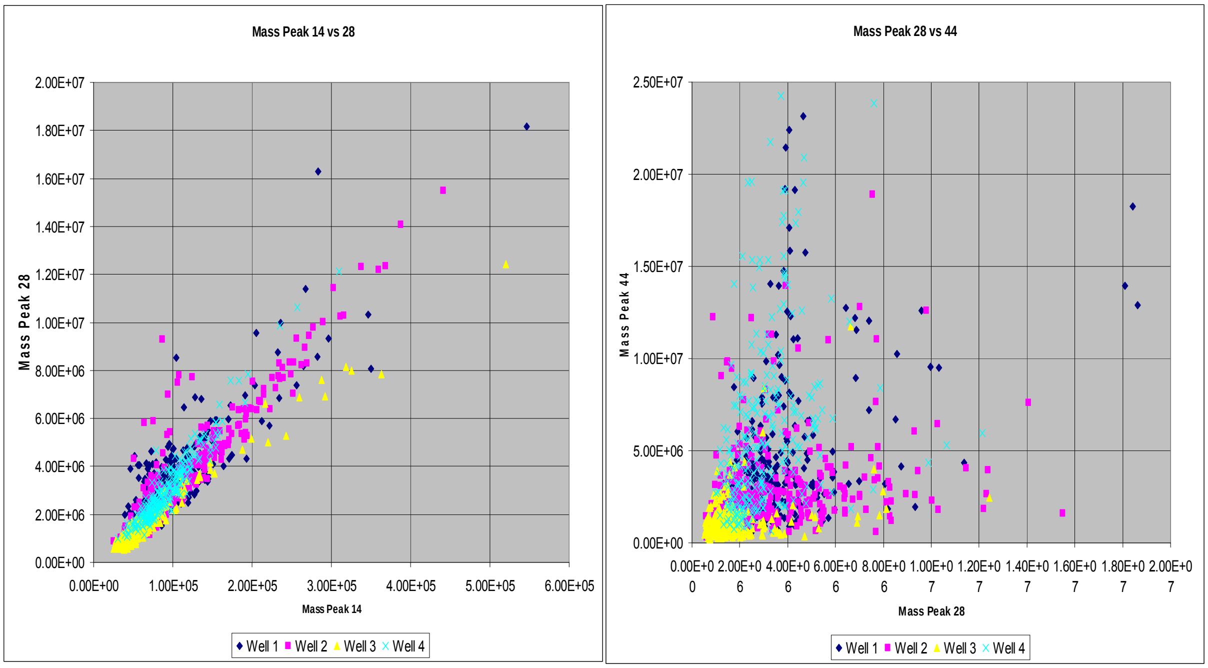


Figure 5: Plots of Mass 14 against Mass 28 and Mass 28 against Mass 44



Blue: Well 33-7; Pink: Well 38C-9; Yellow: Well 84-30; Light Blue: Well 58A-18. The linear correlation between mass 14 and 28 indicates mass 28 is recording N2, not CO2.

Table 5: Common Chemical Species and their Mass Number

Mass #	Chemical Species
2	H_2^+
4	He^+
14	N^+ CH_2+ CO^{++}
15	C_1 fragment (CH_3+), methane
16	CH_4^+ (methane)
18	H_2O^+
28	N_2 $C_2H_4^+$ (ethylene)
30	$C_2H_6^+$ (ethane)
34	H_2S^+
39	$C_3H_6^{+++}$ (propene)
40	Ar^+
43	$C_3H_8^{++}$(propane)
44	CO_2^+
56	$C_4H_8^+$ (butylenes)
58	$C_4H_{10}^+$ (butane)
64	SO_2^+
78	$C_6H_6^+$ (benzene)
92	$C_7H_8^+$ (toluene)

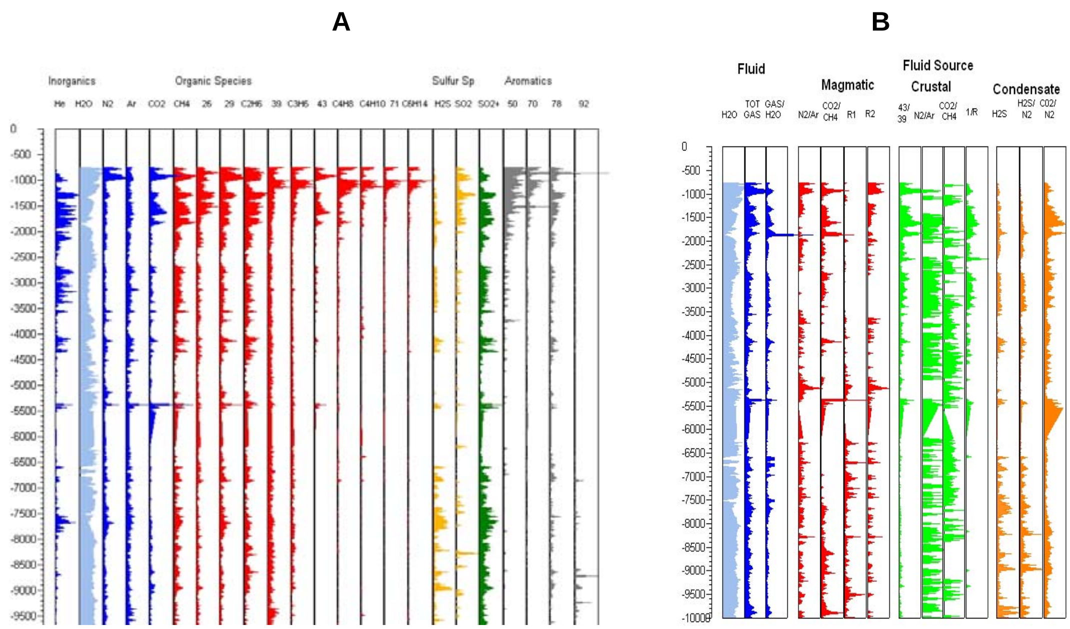
FIT returned the raw data within about three weeks of each submittal; however, upon request and for an added cost, this time can be reduced to about a week. The data package from FIT consisted of an ASCII file with values for all 180 masses analyzed in the mass spectrometer per sample. This file was then compiled into an Excel spreadsheet. At first, select species were plotted with Excel charts. Later, Rockware® Logger was used. Data were analyzed to determine which gas ratios and which mass peaks could be used for identifying the different fluids on borehole log diagrams. Interpretative plots were done using raw ratios.

3.5 Logs

As the research continued, it became apparent that an industry tool should be used. The Rockware® program Logger was selected for use. This program produces graphic strip logs from user-created or imported data files. Appendix B presents the Excel logger files and the Logger file. The format of the logs can be designed by the user. For each well, two types of log diagrams were plotted (Norman et al. 2005). One diagram displays mass peaks of various compounds, which provides information on the relative concentrations of a gaseous species downhole. The other diagram plots gas ratios and species that are used to interpret fluid types.

Logger allows for user-defined log plots (Figure 6). For each species and ratio, the size of the graphic strip had to be determined. Each log was plotted to the same scale for each field. It was found that for the wells from Beowawe, the scale that was used for the Coso wells did not produce suitable logs. A technique was developed using two times the standard deviation of the values for each species or ratio as the largest value for the strip. Values outside this value would create large peaks that carried across a number of other strips. To plot the logs, the width of the columns for each volatile had to be determined. For each species and ratio plotted, the minimum, maximum, and standard deviation was calculated. Each of these values was averaged using the wells for only one field at a time. The logs were then developed by setting the column width to two times the average standard deviation for each species. This would allow for 95 percent of the values to fall within the width of each column for each species.

Figure 6: Logs Developed to Display Fluid Inclusion Bulk Analysis.



A is a log of various gas species. B is a log of ratios and interpretations.

The FIT data were presented to the researchers for interpretation. No other logs or well information such as production fluid temperature or rock types were initially provided for each new set of data. The idea was to test the FIS method by making interpretations independent of temperature logs or well logs. The interpretations were then checked against the temperature logs and rock types for select Coso wells. The interpretations were also submitted to the Coso Operating Company geologist for review and comment.

A reservoir model for the Coso field based on FIS was developed and compared to existing data from other researchers. The model was produced by creating cross-sections of interpreted fluid types and zones of permeability.

CHAPTER 4: Data Quality

To compare the data sets, differences between FIT and research-grade, quantitative analyses such as those conducted at New Mexico Tech (NMT) should be understood. Both laboratories crush samples in a vacuum chamber attached to high-vacuum pumps. Crushing releases a brief puff of inclusion volatiles, including water, that are recorded by quadrupoles scanning at rates of 5 to 10 times per second. Species with high volatility and low melting points such as the noble gas species are quickly removed from the vacuum system, hence the mass peak is on the order of a second or two in width. Polar and low-volatility species briefly sorb onto vacuum system surfaces, so the mass peaks for these species are wider. Water sorbs most strongly; the mass peak typically is 10 to 15 seconds. FIT analyses are peak heights; NMT integrates peak area. This makes a considerable difference in some mass peaks. FIT analysis under-measures less volatile species such as CO_2 and severely under-measures water.

Gaseous species fragment when ionized in the mass spectrometer, and some fragments become doubly charged. Nitrogen, for example, has mass peaks (m/e^-) at 28 (N_2^+) and mass 14 (N^+, N_2^{++}). Carbon dioxide has mass peaks at 44, 28, 22, 16, and 12. In addition, both N_2 and CO_2 exhibit minor isotope peaks because of small amounts of ^{15}N, ^{18}O, and ^{13}C.

Fragmentation and percentage of doubly charged species is related to the ionizing potential. NMT uses a voltage of 90 volts, whereas FIT uses a lower voltage. The exact details of FIT's analytical procedures are proprietary. FIT's use of a lower voltage is apparent in reduced fragmentation and virtually no doubly charged species. It also lowers FIT's precision for hard-to-ionize non-organic species.

Other differences are that NMT measures selected mass peaks to maximize precision and calibrate the system with known gas ratios and fluid inclusion standards. Calibrating the analytical system allows NMT to make quantitative analyses. This involves elaborate data reduction programs that use matrix algebra to deconvolute mass spectra with interfering peaks. NMT analyses are presented in mol percent or parts per million (ppm) of various species. Currently, NMT uses two mass spectrometers and measures 12 species at a time.

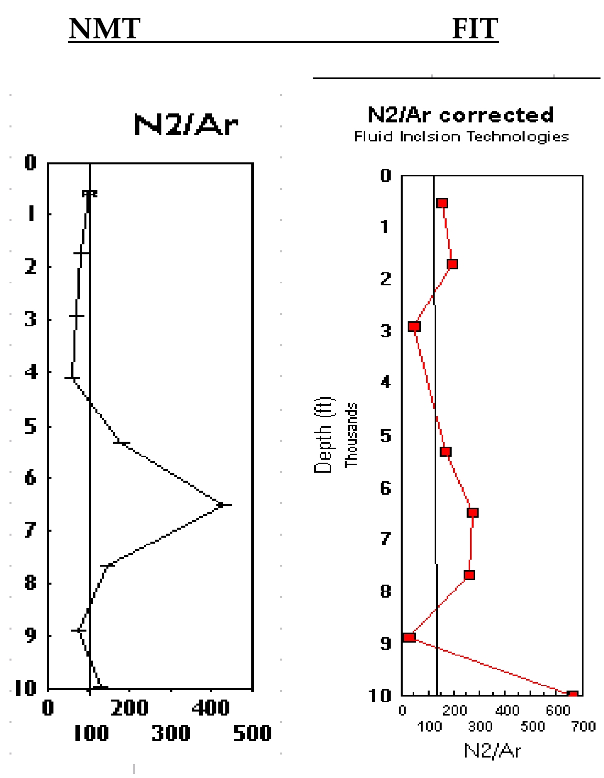
FIT crushes the sample once and applies a uniform crush using a solenoid. Total signal from crush to crush varies at most by a factor of 20. NMT sequentially crushes a sample several times by hand. Burst size varies by a factor of 1000. Sequential crushing gives information about inclusion heterogeneity. Drill chips generally can be crushed two to five times. FIT analyses indicate inclusion density assuming drill chips all have the same mechanical properties. The amount of volatiles released by NMT crushing varies with the force applied. NMT's procedure is to vary the crush force so that a burst size of about 1×10^{-6} is achieved. That burst size gives maximum measurement precision. Burst sizes from 0.01 to 0.05×10^{-6} are suspect, and burst sizes $< 0.01\times10^{-6}$ are unreliable.

4.1 FIT Compared to NMT

FIT runs internal standards to control analytical drift. These standards include oil inclusion reference standards; clean quartz sand devoid of hydrocarbons; and clean quartz sand heated to 1000°C (1832°F) to remove a large percentage of fluid inclusion population (Hall 2006). The oil inclusion standards are used to verify effectiveness of the crushing process and sample position. Both of the clean sand standards are used to check the post-analytical processing software. The spectra for both of these standards should show no response for mass/charge greater than 60.

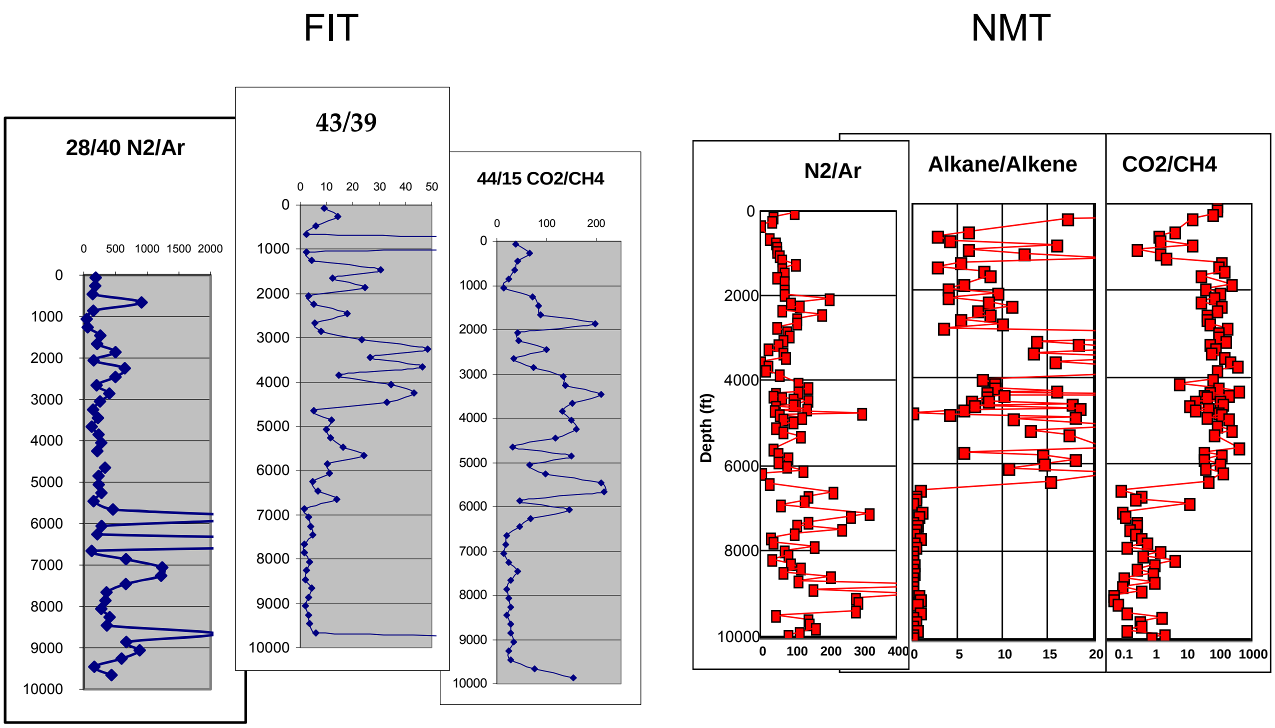
FIT does not process the data to determine exact abundances because the relative concentrations are found to be sufficient. When this research project was being developed it was thought a “calibration factor” would be needed to determine exact values so that the values from FIT could be compared with quantitative values developed by a laboratory such as that at NMT. Ultimately, the FIT data were used without processing. Ratios such as N_2/Ar are low for shallow meteoric fluids and high for reservoir fluids. Comparing relative ratios proved adequate for seeing differences in fluid sources. Before developing this research, a select number of samples from Coso Well 83-16 were submitted to both FIT and NMT facilities to evaluate the differences in the data. Figure 7 presents the results. The analyses from FIT corresponded to NMT’s high-quality and much more costly analyses.

Figure 7: NMT and FIT Data for N_2/Ar Samples from Coso Well 83-16.



Note the increase in the sample between 6000 and 7000 feet for both sets of data.

Figure 8: FIT and NMT Data for Several Ratios for Samples from Coso Well 83-16.



Although the absolute abundances differ, the patterns of high and low concentrations are similar.

Figure 8 presents plots developed by Norman et al. (2004) for the FIT analyses versus the NMT analyses for the samples from Well 58A-10. Although there are differences in the exact values, the overall patterns appear similar. For N_2/Ar ratio (the first graph in each group) the majority of the peaks occur below 6000 feet. The propane/propene ratio graphs (second graph in each group) indicate peaks above 6000 to 6500 feet in both graphs. The graphs are also similar for the CO_2/CH_4 ratios, with peaks occurring in the upper portion of both graphs. From this study, it was concluded that although exact values are not obtained, the FIT data provides relative amounts that can be comparable with results obtained by NMT's more quantitative process.

4.2 FIT Analyses Examination

Geothermal fluid inclusion mass spectra generally show major peaks at 2 (H_2), 18 (H_2O), 28 (N_2), and 44 (CO_2) (Figure 9). Simple inspection of data sets can tell if the columns of data are correctly labeled. NMT found analyses of one "well" that had mass peaks offset because the analyses for mass 1 were omitted.

The principal worry about FIT analyses is if CO_2 and organic fragmentation peaks significantly interfere with N_2, commonly measured at mass 28. To determine this, the principal peak for N_2 (mass 28) is plotted versus the principal fragment (mass 14). The same is done for masses 44 and 28, the principal peak and principal fragmentation peak, respectively, for CO_2. If there are no significant interferences, the 14 vs. 28 plot should be linear, with an R^2 value of 0.9 or better, whereas the 28 vs. 44 plot shows a shotgun pattern (Figure 10).

Figure 9: Typical FIT Mass Spectra of Fluid Inclusions in Drill Chips from Well 58A-10, 11,780 feet.

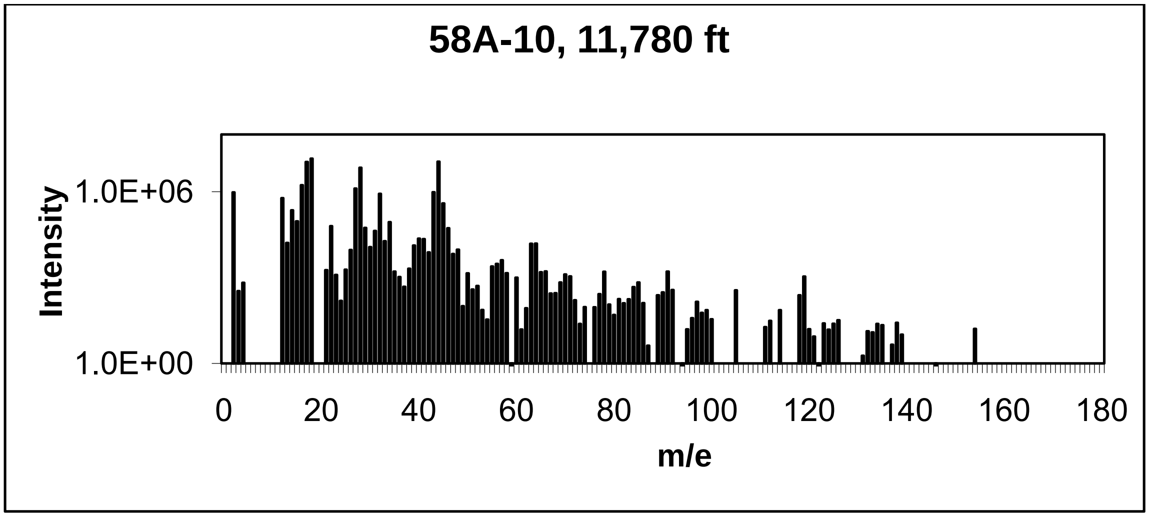
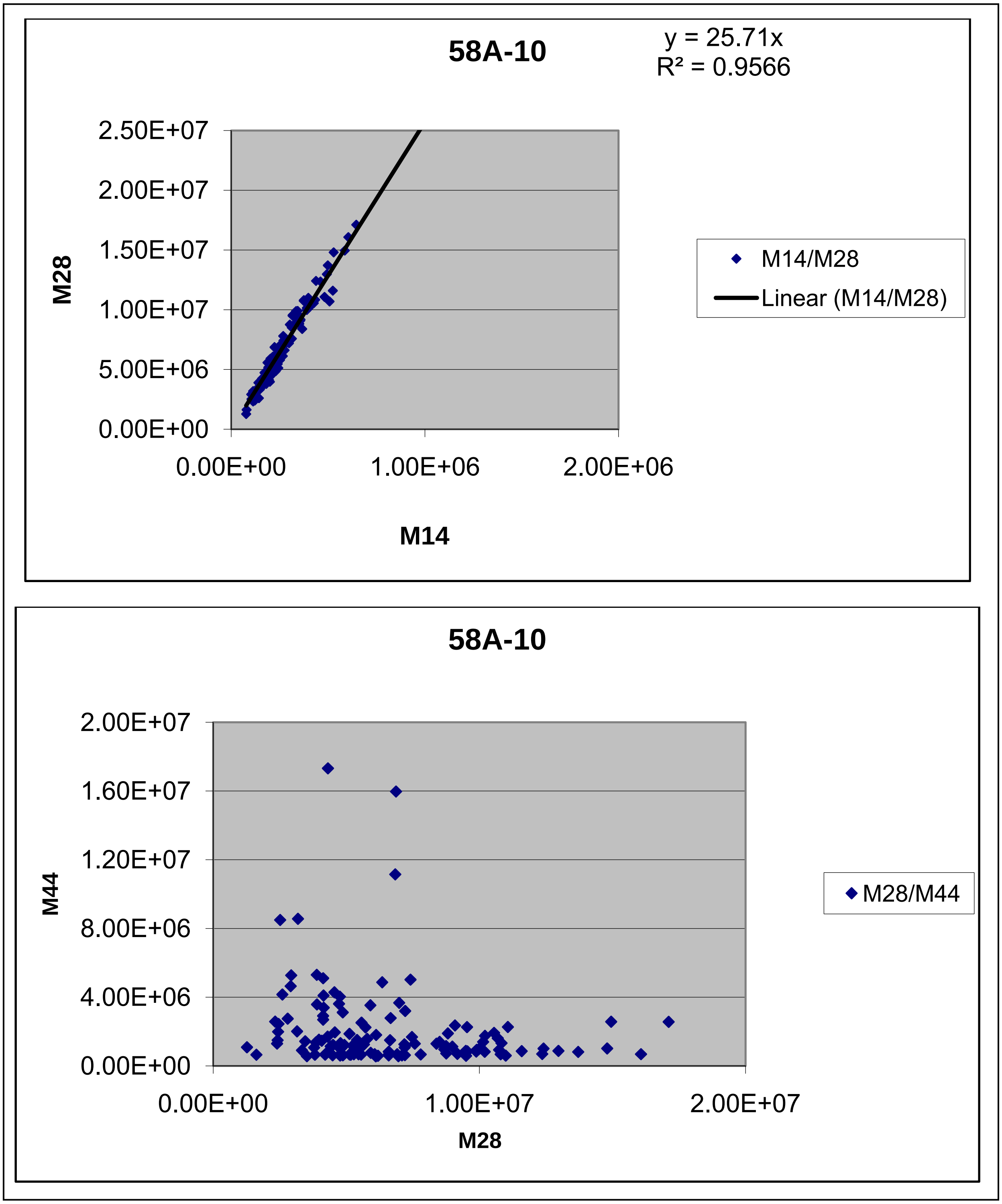


Figure 10: Comparing FIT Analyses Plots for Masses 14, 28, and 44.



Comparing FIT Analyses Plots for masses 14, 28, and 44. If the N_2 28 peak is little interfered with, the 14 and 28 analyses should plot linearly and the 28 and 44 analyses should show little relationship.
See Figure 5 and text for a complete explanation.

4.3 Duplicates

Fifty-eight samples were submitted in duplicate from the first four wells. Appendix C presents the data from these samples. The samples submitted for duplication were from the first four wells that were sampled (33-7, 38C-9, 84-30, and 58A-18). Analysis repeatability depends on inclusion heterogeneity, analytical precision, and uniformity of crushes from one sample to the next.

The difference compared to the mean of the two samples for each of the species was calculated and the minimum, maximum, average and standard deviation of result was also calculated. Table 6 presents the summary statistics for each species. The following was used to calculate the percent difference compared to the mean of the two samples:

[(value sample 1 – value sample 2) / (average of the two values)] * 100

The standard error was not calculated because of the low population size (two samples). The standard error is dependent upon the population size. The population size could not be all 58 samples because each duplicate was taken at different depths within the wells. Table 7 presents the results in terms of how many values were above 100 percent, 100 percent to 50 percent, 50 percent to 25 percent, and below 25 percent for each species. Table 8 presents the results compared to the means for each species. The means for the species range from 26 percent for species 26 to 143 percent for species 48. If the values above 100 percent are assumed to be outliers, the means reduce to 9 percent for species 92 and to 35 percent for species 43, with most of the means ranging in the mid 20 percent to low 30 percent. In general, the difference between any two samples obtained at a specific interval was between 20 percent and the low the 30 percent, depending upon the species.

4.4 Conclusions

FIT analyses are less precise than NMT analyses as a result of FIT's fast throughput. But the analyses show order of magnitude changes that can be interpreted as representing different fluids.

FIT analyses cannot be directly used to estimate gas ratios, but their analyses can be calibrated by duplicate analyses and standards analyses. For example, measurement of N_2/Ar (mass 28/mass 40) by NMT commonly shows ratios typical of ground water from 30 to 70; FIT ratios of mass 28 to mass 40 are mostly in the range of 200 to 450. Multiplying the N_2/Ar ratio from FIT by 0.15 produces a N_2/Ar ratio close to that measured by NMT.

A few FIT analyses show some interference of the N_2 (28 mass) peak, but this has little effect on plots of N_2/Ar ratio. Other interferences are negligible because of the low fragmentation in FIT mass spectrometers and low amounts of organic species.

FIT precision is below that of NMT. However, analysis-to-analysis differences used in interpreting the data typically are on an order of magnitude change. FIT does well for what it is intended—picking up changes in fluid inclusion volatiles with depth, not precision fluid inclusion gas analysis.

Table 6: The Minimum, Maximum, Standard Deviation and Mean of the Difference between the Two Sample Values Compared to the Mean of the Two Sample Values

Species	Minimum	Maximum	Standard Deviation	Mean
15	0.01	1.76	0.36	0.35
16	0.04	2.00	0.39	0.45
18	0.01	2.00	0.41	0.40
26	0.00	1.25	0.24	0.26
28	0.02	1.11	0.26	0.29
29	0.00	1.26	0.28	0.33
30	0.00	1.09	0.28	0.32
34	0.00	2.00	0.69	0.89
39	0.00	1.81	0.49	0.50
40	0.04	2.00	0.49	0.52
41	0.02	1.20	0.32	0.39
42	0.01	1.67	0.45	0.49
43	0.01	1.74	0.38	0.50
44	0.03	1.52	0.36	0.47
48	0.00	2.00	0.69	1.43
50	0.12	2.00	0.76	1.15
56	0.00	2.00	0.66	0.71
58	0.03	2.00	0.78	1.13
64	0.00	2.00	0.59	0.64
70	0.00	2.00	0.39	0.34
71	0.02	2.00	0.37	0.44
78	0.00	2.00	0.66	0.70
85	0.00	2.00	0.70	0.88
92	0.00	2.00	0.83	1.18

Table 7: Results of the Difference in the Two Duplicate Sample Values Compared to the Mean from A Sampling Size of 58

Species	# Above 100%	# From 100% to 50%	# From 50% to 25%	# Below 25%
15	4	5	21	28
16	5	13	16	24
18	5	11	11	31
26	1	7	14	36
28	1	9	14	34
29	1	10	19	28
30	2	13	13	30
34	25	11	5	17
39	9	14	13	22
40	10	8	18	22

Species	# Above 100%	# From 100% to 50%	# From 50% to 25%	# Below 25%
41	5	11	19	23
42	9	11	12	26
43	7	12	22	17
44	7	11	21	19
48	42	5	7	4
50	31	7	10	10
56	16	12	10	20
58	29	10	7	12
64	14	12	13	19
70	3	7	16	32
71	4	17	17	20
78	15	14	9	20
85	23	9	8	18
92	35	5	4	14

Table 8: Results of the Difference in the Two Duplicate Sample Values Compared to the Mean from A Sampling Size of 58 if more than 100% are Assumed to be Outliers

Species	Maximum	Standard Deviation	Mean	# From 100% to 50%	# From 50% to 25%	# Below 25%
15	0.98	0.22	0.26	5	21	32
16	0.99	0.26	0.33	13	16	29
18	0.93	0.25	0.27	12	11	35
26	0.88	0.21	0.24	7	14	37
28	0.97	0.24	0.27	9	14	35
29	0.94	0.25	0.31	10	19	29
30	0.98	0.25	0.28	13	14	31
34	0.91	0.29	0.21	12	6	40
39	0.96	0.27	0.28	14	13	31
40	0.99	0.24	0.27	9	19	30
41	0.91	0.24	0.29	11	19	28
42	0.95	0.27	0.28	11	13	34
43	0.92	0.26	0.35	12	22	24
44	0.95	0.27	0.33	12	21	25
48	0.85	0.23	0.12	6	8	44
50	1.00	0.27	0.20	8	11	39
56	0.90	0.29	0.26	13	11	34
58	0.92	0.28	0.20	11	8	39
64	0.99	0.28	0.27	13	13	32
70	0.93	0.20	0.24	7	16	35
71	0.92	0.23	0.34	17	17	24

Species	Maximum	Standard Deviation	Mean	# From 100% to 50%	# From 50% to 25%	# Below 25%
78	0.96	0.29	0.27	15	9	34
85	0.99	0.30	0.23	9	8	41
92	0.96	0.23	0.09	6	4	48

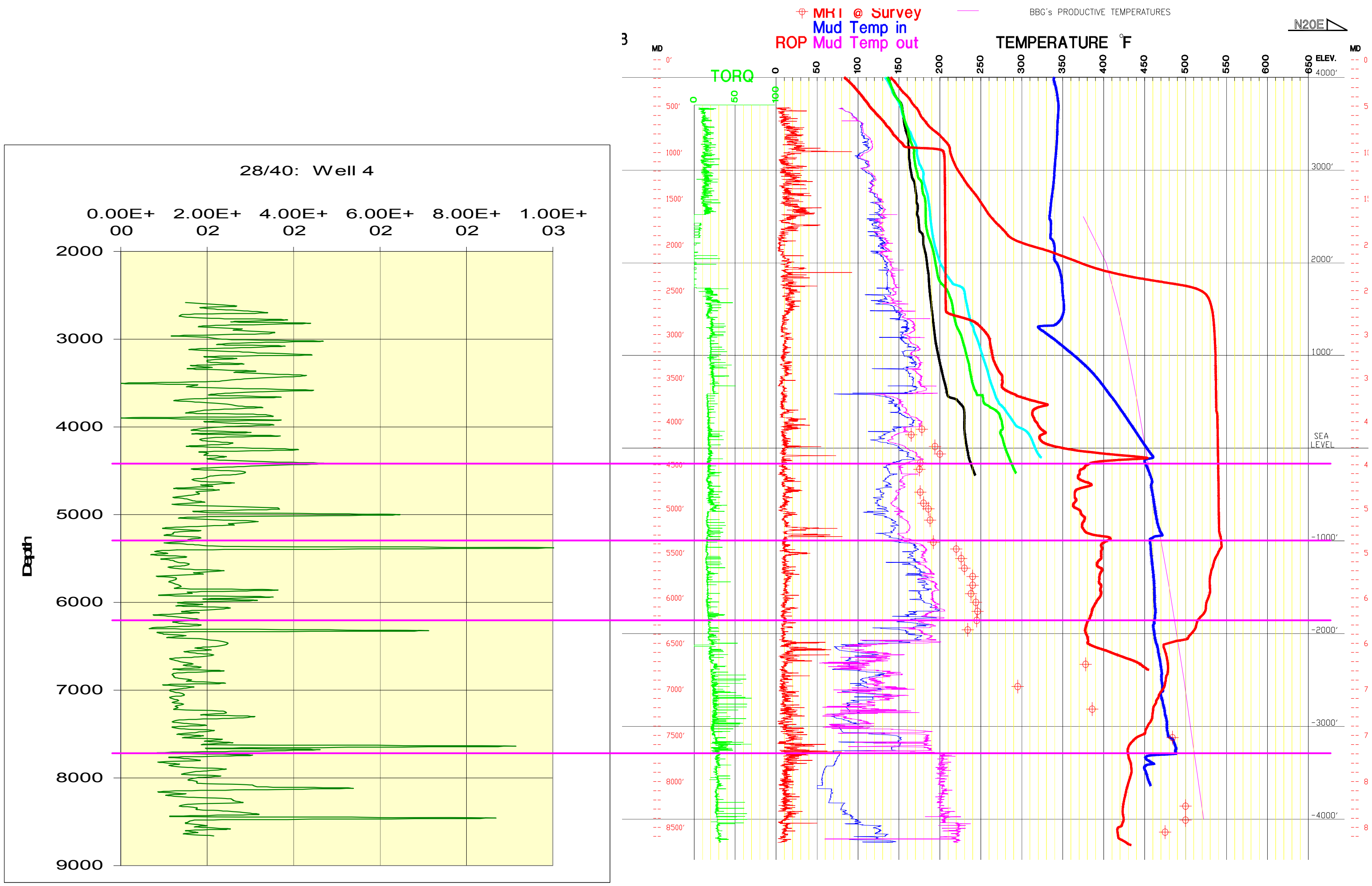
CHAPTER 5:
Data

5.1 Correlation to Temperature Logs

Temperature logs are a primary source of data from any well. Hotter zones are considered target areas for production. The first step in developing the FIS method was to determine which species or ratios would correspond with higher temperature. The N_2/Ar ratio from the literature has been used to distinguish between meteoric fluids and fluids having a magmatic component (Norman and Musgrave 1995). An initial check on the first set of data was to compare the FIT analysis for the N_2/Ar ratio against the temperature log for one of the initial Coso wells, 58A-18. Well 58A-18 is known to have multiple entrances of colder waters, so that well provided a good test to evaluate how well the N_2/Ar ratio could pick out the colder waters. The idea was that colder waters would have a meteoric signature or a low N_2/Ar ratio and zones with a high N_2/Ar ratio would indicate zones where the waters had a magmatic component or would be hotter fluids.

Figure 11 presents the temperature logs and a plot of the N_2/Ar ratio for Coso Well 58A-18. Peaks in the N_2/Ar ratio generally correlate with temperature peaks. From approximately 4200 feet to about 5350 feet there is a decrease in the temperature profile, which is reflected in the N_2/Ar ratios. There is a peak in the ratio at about 5000 feet that is not reflected in the temperature profile and may indicate an older closed fracture. Additionally, at approximately 6500 to about 7700 feet, there is a decrease in the mud temperatures as well as the temperature profile. This zone appears to be bounded by sharp peaks in the N_2/Ar ratios. There are additional peaks in the ratio that are not necessarily reflected in the temperature profile.

Figure 11: Comparison of N2/Ar Ratio and Temperature Profile for Well 58A-18



Note decreases in temperatures from about 4200 feet to 5350 feet and again between 6500 to 7700 feet. These decreases in temperature are bounded by sharp peaks in the N_2/Ar ratios. The ratio is decreased in the areas of temperature decreases. The decreases in temperature and the N_2/Ar ratio indicate entrances of cold water. The peak at 5000 feet is not reflected in the temperature profile.

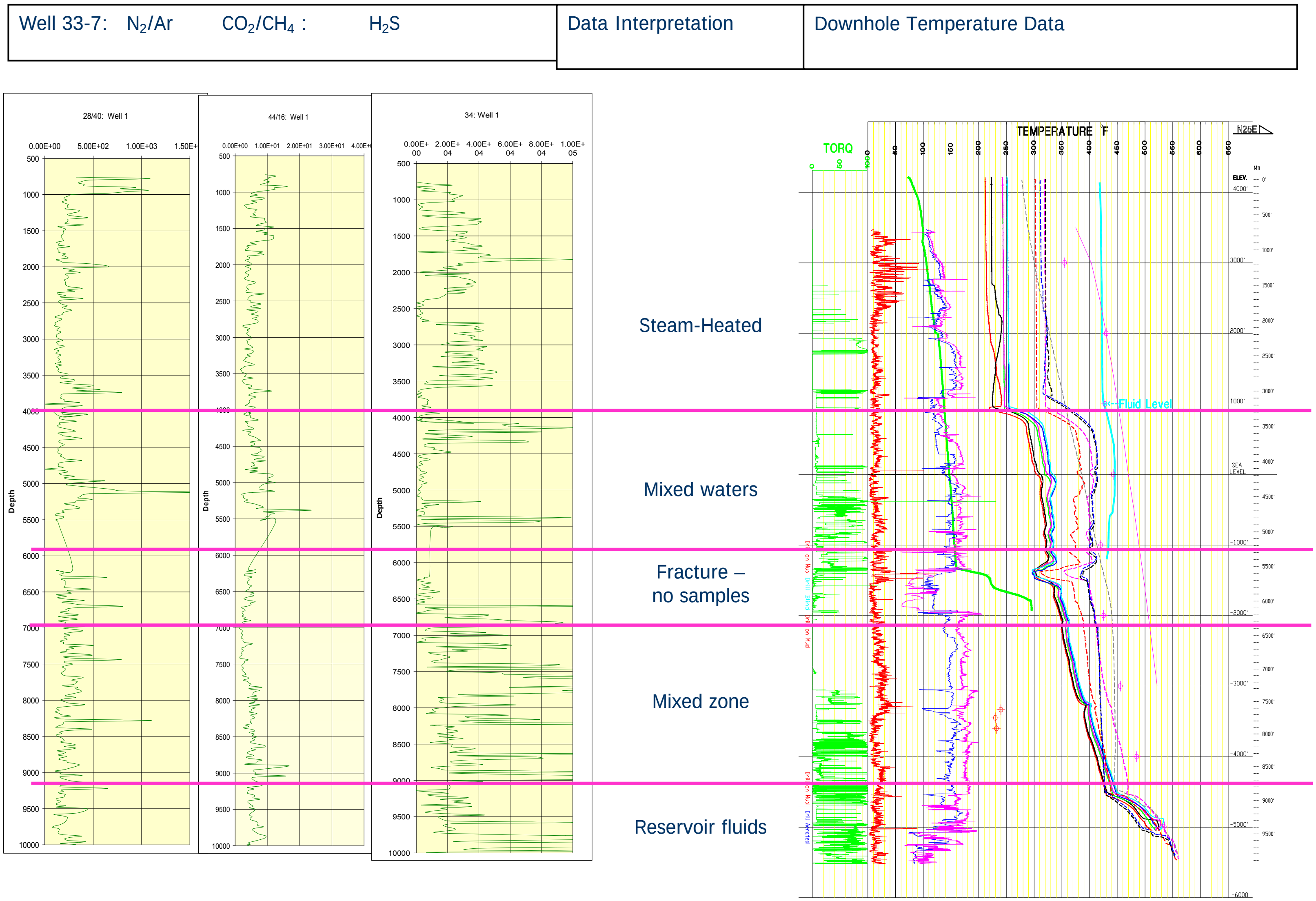
For three of the initial four Coso wells (33-7, 38C-9, and 58A-18) the ratios of N_2/Ar, CO_2/CH_4, and H_2S were plotted against the temperature logs. These ratios, as discussed in Section 2, have been used previously to determine meteoric waters, waters with magmatic components, and steam-heated waters, respectively. The fourth well, Coso Well 84-30 was not used because a temperature log was not available for that well.

Figures 12, 13, and 14 present the plots for wells 33-7, 38C-9, and 58A-18. The interpretations were made before looking at the temperature logs for each of the wells. The process involved observing where changes in the species ratios occurred and determining if those changes occurred in more than one ratio. N_2/Ar and CO_2/CH_4 ratios were used to differentiate fluids that had a magmatic component from meteoric fluids, and hydrogen sulfide (H_2S) was used to indicate steam-heated fluids. Magmatic fluids would tend to have high concentrations of CO_2 and low CH_4. Magmatic fluids at depth would most likely be hotter than cold meteoric fluids traveling downward. Thus, high CO_2 and CO_2 ratios indicate hotter fluids with some magmatic components. In Henley's (1984) model of a typical geothermal system (Figure 1, Section 2.1) boiling occurs as waters carrying chloride and hydrogen sulfide rise through the system. The resulting steam migrates to the surface where condensation and oxidation of hydrogen sulfide produces sulfate-dominated steam-heated waters and acid sulphate hot springs such as the main Coso Hot Springs.

Delineating the changes in the species ratios and hydrogen sulfide quantities allows the recognition of zones bearing meteoric fluids, mixed fluids, steam-heated fluids, or hotter fluids. High H_2S amounts indicated steam-heated fluids, whereas high ratios of N_2/Ar and CO_2/CH_4 indicated reservoir fluids. Low values for the ratios of N_2/Ar and CO_2/CH_4 indicated meteoric fluids. Where there were moderate amounts of N_2/Ar, CO_2/CH_4, and H_2S, this was interpreted as mixed fluids.

As shown in Figure 12 for Coso Well 33-7, the ratios and hydrogen sulfide content change at 3500 feet, 6300 feet, and 8700 feet. The zone from about 600 feet to the first change in the ratios and H_2S at 3500 feet was interpreted as a steam zone. Hydrogen sulfide has a number of high peaks, while the ratios are low in value. From 3500 feet to 6300 feet there are some peaks in all three plots, indicating a mixed zone. The area from 5500 to 6000 feet represents a large fracture zone. There were no well cuttings recovered in this zone. Hydrogen sulfide and N2/Ar ratio have multiple peaks from 6300 feet to about 8700 feet.

Figure 12: Initial Interpretation of Well 33-7 and Comparison to Temperature Logs



Note that breaks in the slope of the temperature logs correspond to interpreted fluid zones.

Figure 13: Initial Interpretation for Well 38C-9 and Comparison to TemperatureLog

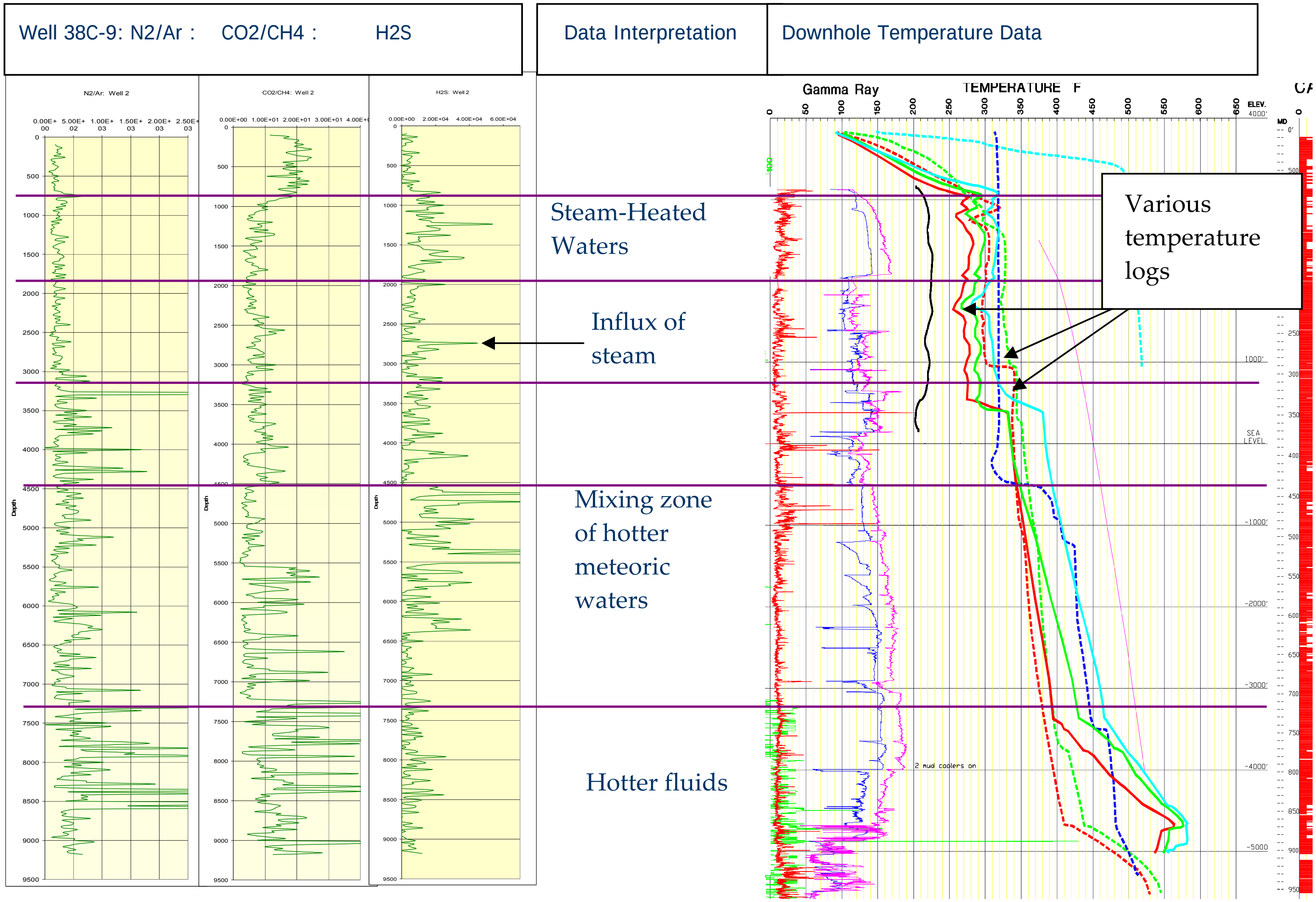
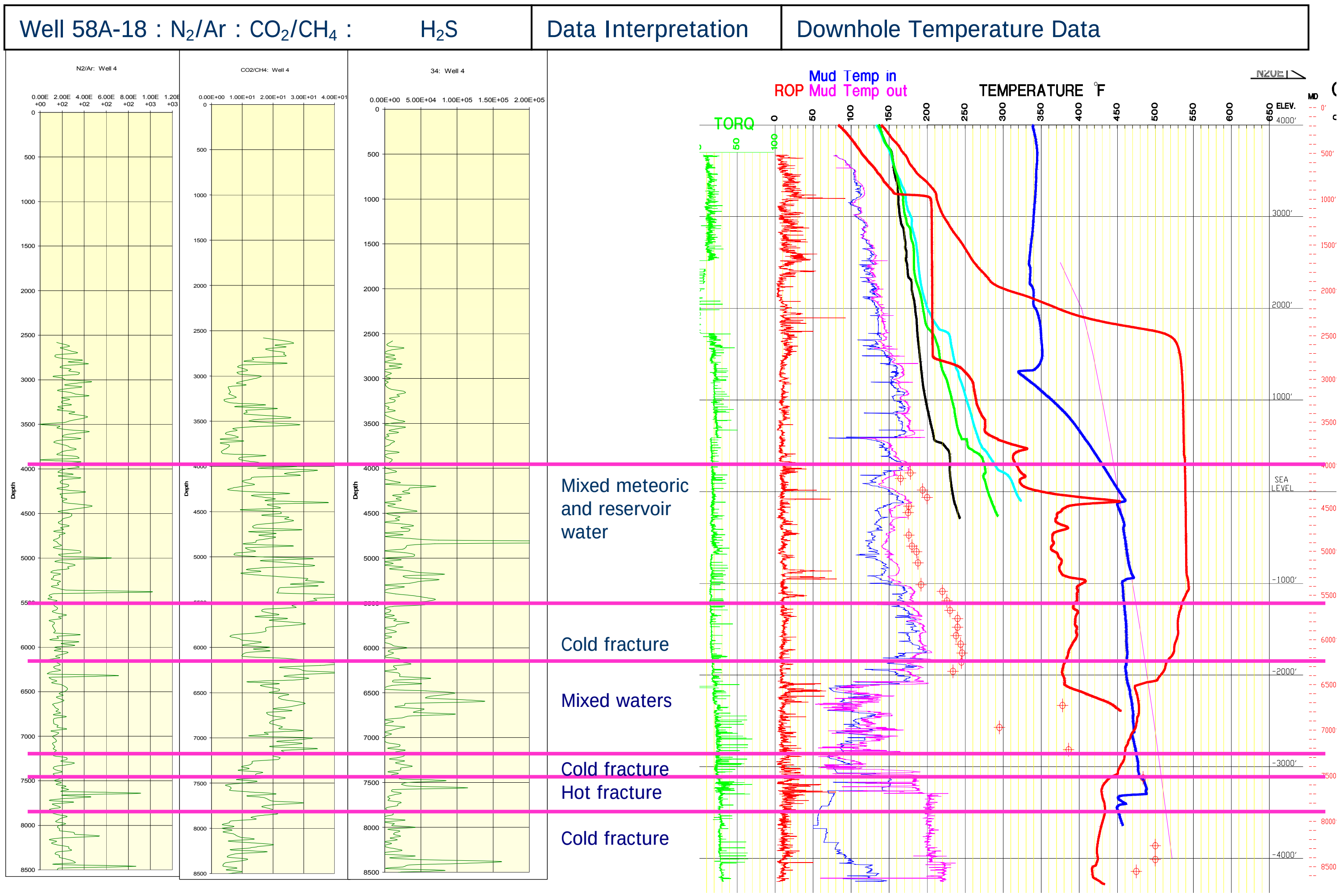


Figure 14: Initial Interpretation for Well 58A-18 and Comparison to Temperature Logs



This zone may indicate a mixed fluid but is warmer than the previous mixed zone. Below 8700 feet, an increase in N_2/Ar and CO_2/CH_4 indicates a high-temperature fluid. When the above interpretation is plotted next to the temperature log, it corresponds. There is an increase in temperature at 3200 feet, at 5700 feet, at 7500 feet, and at 9000 feet. The increase in temperature at 7500 feet is also indicated by a peak in the N_2/Ar ratio and the H_2S value.

Figure 13 shows N_2/Ar and CO_2/CH_4 ratios as well as H_2S content for Well 38C-9 versus the downhole temperature.

The graph for N_2/Ar ratio indicates three distinct zones: (1) from 0 to about 3300 feet; (2) from 3300 to about 7000 feet; and (3) from 7000 feet to about 8500 feet. The graph for the CO_2/CH_4 ratio appears to have at least three distinct zones: (1) from 750 to about 5500 feet; (2) from 5500 to about 7200 feet; and (3) from 7200 feet to the depth of the hole. The H_2S graph has a high zone from about 750 feet to about 1800 feet and again from about 4500 feet to about 5800 feet. The high N_2/Ar with high CO_2/CH_4 ratios from about 7000 feet to the depth of the hole was considered to represent reservoir fluids, whereas high H_2S amounts represented steam-heated waters such as the zone from 4500 to 5800 feet. Where the ratios and the species were low, this was interpreted as an area of little to no geothermal activity. Where there was variability in the ratios, this was considered to be a zone of mixing. As can be seen in Figure 13, the temperature profiles appear to correspond to the fluid inclusion data interpretation.

Figure 14 presents the ratios and H_2S for Well 58A-18 and the interpretation. It can be seen that the CO_2/CH_4 ratio is generally high throughout the well and that low zones in the values generally correspond with a low N_2/Ar ratio and lower temperatures. These zones, such as that from 5500 to 6200 feet, were interpreted as cold-water entrance zones. Mixed fluids are indicated in the other zones where the ratios and the H_2S are high. Well 58A-18 is a low-temperature, moderate producer.

The fluid inclusion data presented in Figures 12 through 14 indicate the complexity of the system. Prior studies relied on a few samples per well and therefore the interpretations showed major zones. It is interesting to note the multiple smaller zones that can be observed with this data set. For instance, the pulse in the H_2S data at about 2700 feet for Well 38C-9 and the corresponding increase in the borehole temperature were interpreted as a small influx of steam-heated waters.

The above correlations of the N_2/Ar and CO_2/CH_4 ratios and H_2S to the temperature logs and the corresponding interpretations were presented to the geologists at Coso Operating Company, who had independently interpreted the wells based on traditional well log information. They agreed with the FIS interpretations of each well. Because the initial three wells appeared to indicate hotter fluid zones and likely production targets, additional ratios and chemical species were evaluated for use in interpreting the fluid regime in a well. Again, for verification of the FIS method, it is emphasized that the fluid inclusion data were interpreted before the temperature profiles were reviewed.

5.2 Sampling Interval

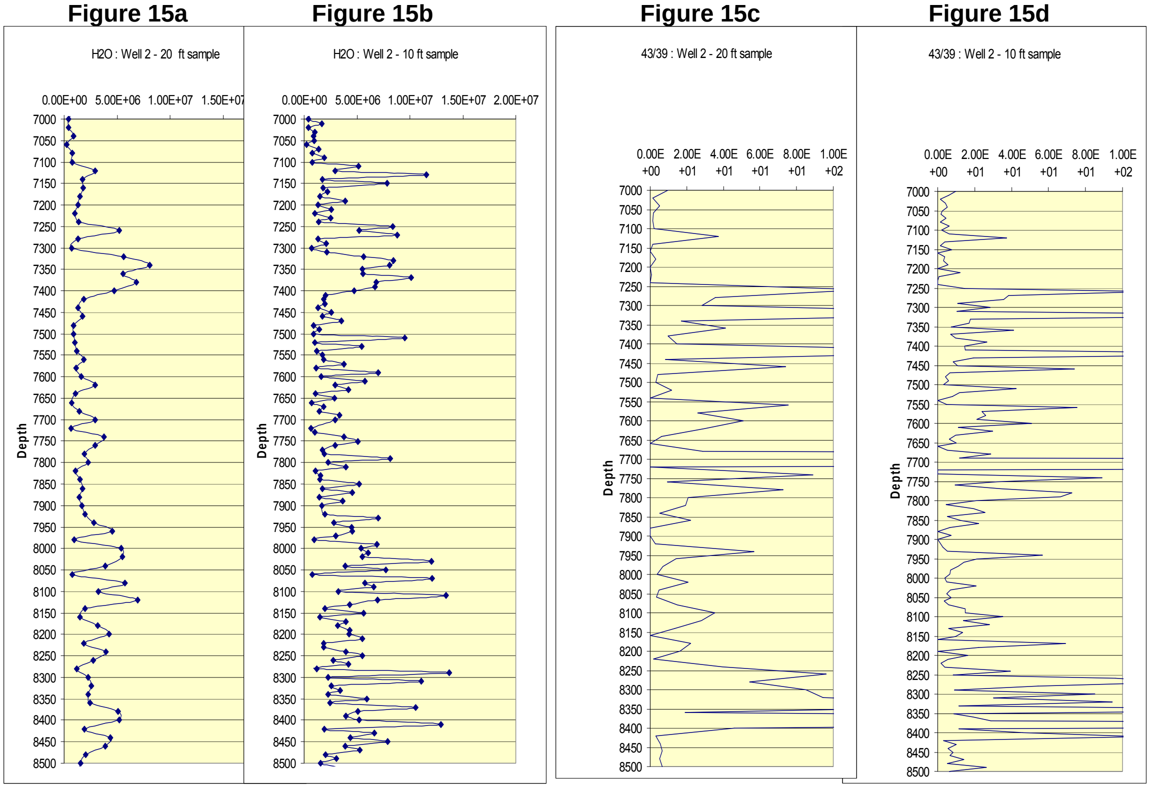
Samples for this research were collected at 20-foot intervals. Well cuttings were taken during drilling at 10-foot intervals. To determine whether sampling intervals (frequency) might significantly change the FIS results, a sensitivity exercise was conducted: Coso Well 38C-9 was re-sampled at 10-foot intervals. The 10-foot sampling interval data were plotted against the 20-foot sampling interval data to determine if the smaller sampling interval would produce comparable results to the 20-foot sampling interval.

The chemical species and gas ratios selected for use in this part of the study were H_2O, N_2/Ar, CO_2/CH_4, and C_3H_8/C_3H_6. The ratios of N_2/Ar and CO_2/CH_4 are used to indicate hotter fluids; the ratio of C_3H_8/C_3H_6 is an indicator of background or low-temperature fluids (Norman et al. 2004).

Figures 15 show the comparison of the select species and ratios for the two sampling intervals. The 10-foot sampling in general provides more peak detail (Figures 15a through 15h). Mass peaks that are not evident in the 20-foot sampling interval are shown in the 10-foot sampling; see intervals 7500, 7690, and 7830 feet. Also, from about 8250 to 8410 the broad peaks recorded by 20-foot sampling show more detail when a 10-foot interval is used. The N_2/Ar peaks should be antithetic to propane/propene peaks. The former ratio indicates hotter fluids, whereas high propane/propene indicates cooler fluids. That relationship is much clearer in 10-foot sampling interval graphs.

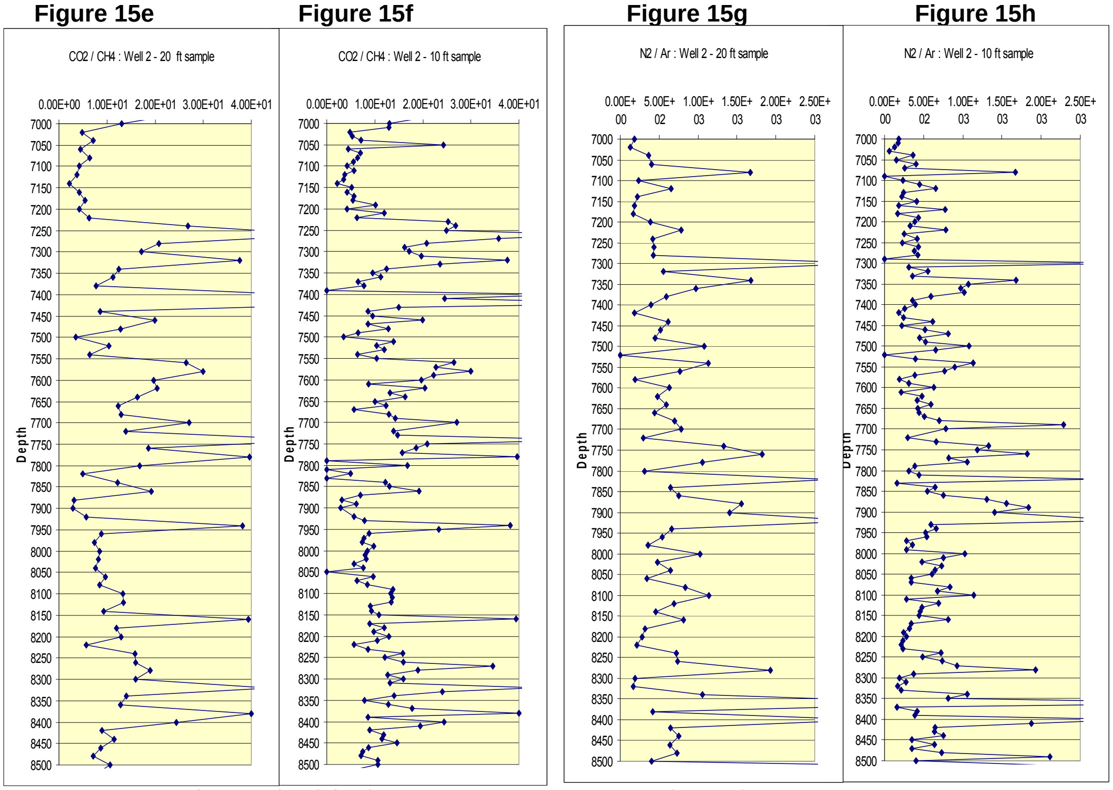
Figure 15: The Comparison of the Select Species and Ratios for the Two Sampling Intervals

Figure 15a **Figure 15b** **Figure 15c** **Figure 15d**



Figures 15a and 15b: Graphs of H_2O for 20-ft and 10-ft sampling intervals. Figures 15c and 15d: Graphs for Mass 43/39 for 20-ft sampling interval and for 10-ft sampling interval. Note the graphs for the 10-ft sampling interval indicates many more peaks versus the graphs for the 20-ft sampling interval.

Figure 15e **Figure 15f** **Figure 15g** **Figure 15h**



Figures 15e through 15h: Graphs for CO_2/CH_4 and N_2/Ar, respectively, for 20-ft sampling intervals in Figures 15e and 15g and 10-ft sampling interval in Figures 15f and 15h.

For the remaining ratios, the smaller sampling interval did not appear to offer significant improvement in detail. For the CO_2/CH_4 ratio (Figures 15e and 15f) one peak was missed at 7050 feet, but all of the other peaks appeared with the 20 foot sampling interval (Figures 15a–15h). For this ratio there were a few low points (7390, 7800, and 8050 feet) indicated in the shorter sampling interval that did not appear in the larger sampling interval.

For the N_2/Ar ratio (Figures 15g and 15h), some of the minor peaks are missing or are subdued in the 20-foot sampling interval, but in general most of the peaks are similar in the 10-foot and 20-foot sampling intervals.

On the basis of the sampling interval experiment, 20 feet is considered a reasonable sampling interval for the collection of FIS data. The more mobile gases of CO_2 and N_2 diffuse into the wall rock to a greater extent than H_2O and the organic peaks of Mass (43/39), the gases CO_2 and N_2 also create a broader range in the peaks. This would indicate that large amounts of fluid inclusions extend outward from a vein center and that these fluid inclusions contain only the more mobile gases.

5.3 Correlation with Rock Types

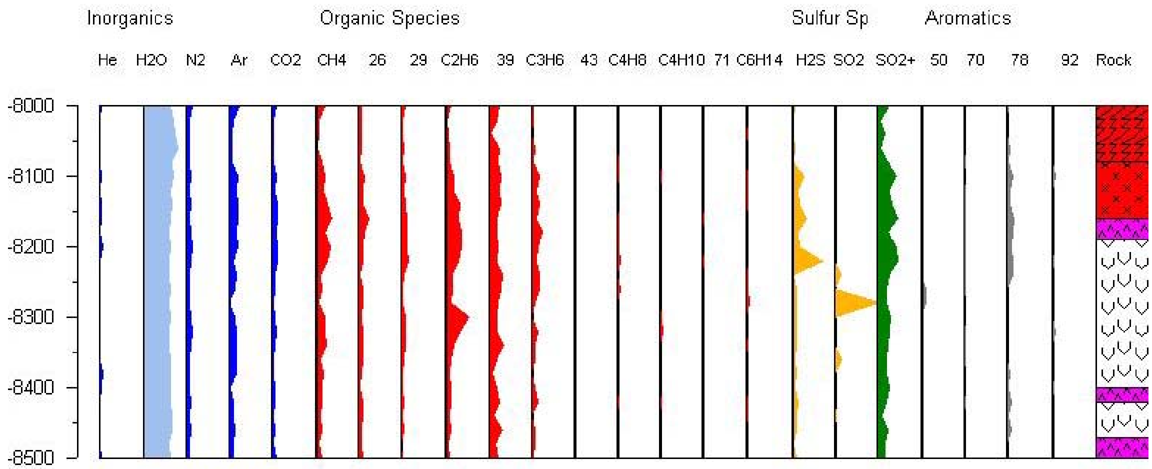
Coso Operating Company provided logs from Wells 33-7 and 58A-18 for comparison of the rock types with the FIS data. There are only a few main rock types encountered in the wells at Coso: diorites, granodiorites, and quartz diorites; felsic-silicic dikes; and altered zones. The major alteration mineral is calcite, followed by hematite, clay, and chlorite. If the rock types correspond to the changes observed in the FIS data, then the data are recording in part the rocks and not the fluids in the system. If the rock types do not correspond directly with the FIS data, then the data are recording mainly the effect of the fluid on the system.

Figure 16 presents the comparison of the logged rock type with the FIS logs developed for each well. It can be seen that there is no correlation between any of the rock types and the fluid inclusion gas analysis. In Well 33-7, there is an increase in Ar, CH_4, and a few of the lighter organic species from approximately 8060 to 8240 feet, and there are three different rock types in this zone. In Well 58A-18, CO_2, Ar, CH_4, and several organic species have high values at approximately 5240 to 5320 feet and again from 5400 to 5540 feet. In the upper zone, a quartz diorite, diorite, and felsic-silicic dike all occur. In the lower zone the granodiorite starts at 5400 feet; however, there is no change in the various species values for the felsic-silicic dike.

Well 34-9RD2 is situated on the northeast corner of the field, and granite occurs in the well from approximately 5000 to 6800 feet. Granite is typically a minor rock within the reservoir (Kovac et al. 2005). As can be seen in Figure 17, the occurrence of granite (shown in pink) appears to correspond with an increase in He, CO_2, CH_4, all of the organic species plotted, H_2S, and SO_2^+. However, throughout the granite there are changes in the values of all of the mentioned species, particularly at 5300 to 5350 feet. The fluid inclusion gas analysis seems to be affected by the granite; however, there are additional changes that do not seem to correspond to the presence of granite. This co-occurrence or correlation of granite and changes in the fluid inclusions is also found in another geothermal field with differing geology, as shown in Figure 18. Here the occurrence of rhyolite dikes (shown in white) is indicated by the presence of H_2O and to a lesser extent CO_2. However, there are changes in the amounts of the various species within the rhyolite dikes.

Figure 16: Rock Types Plotted with Gas Analyses for Two of the Coso Wells

<u>Well 33-7</u>



<u>Well 58A-18</u>

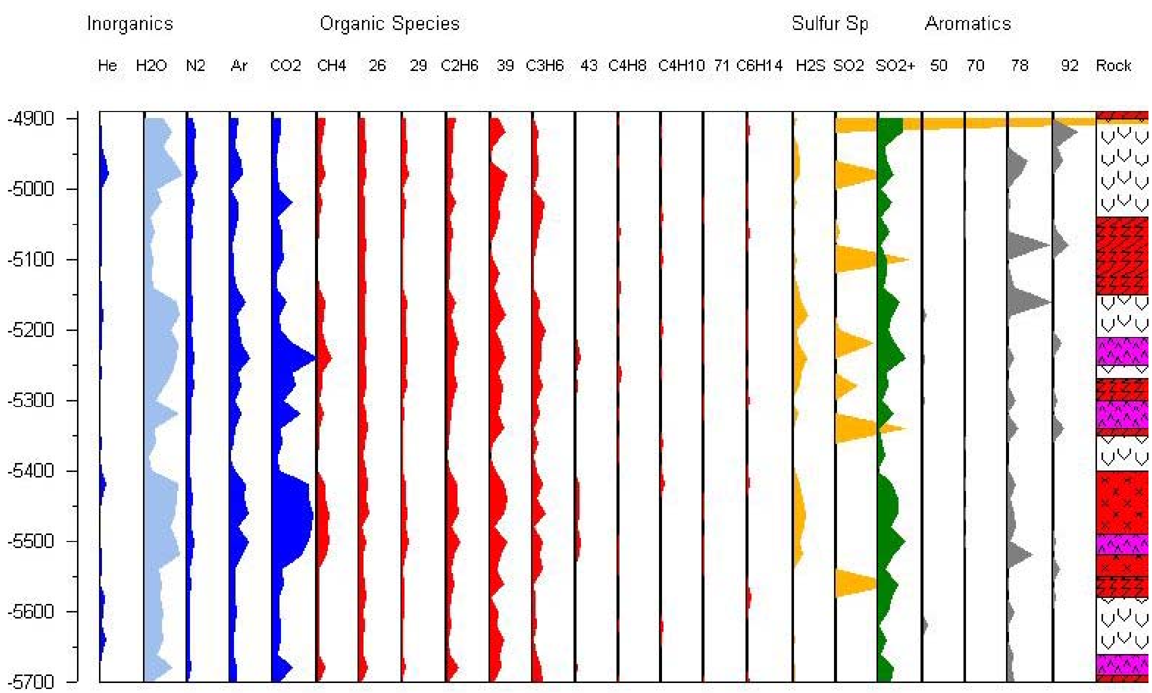
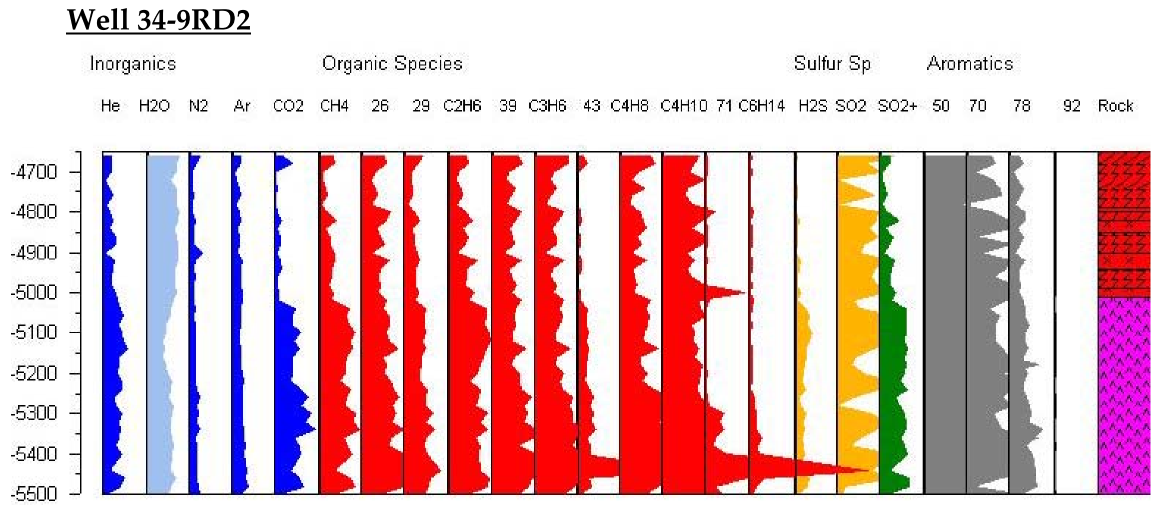
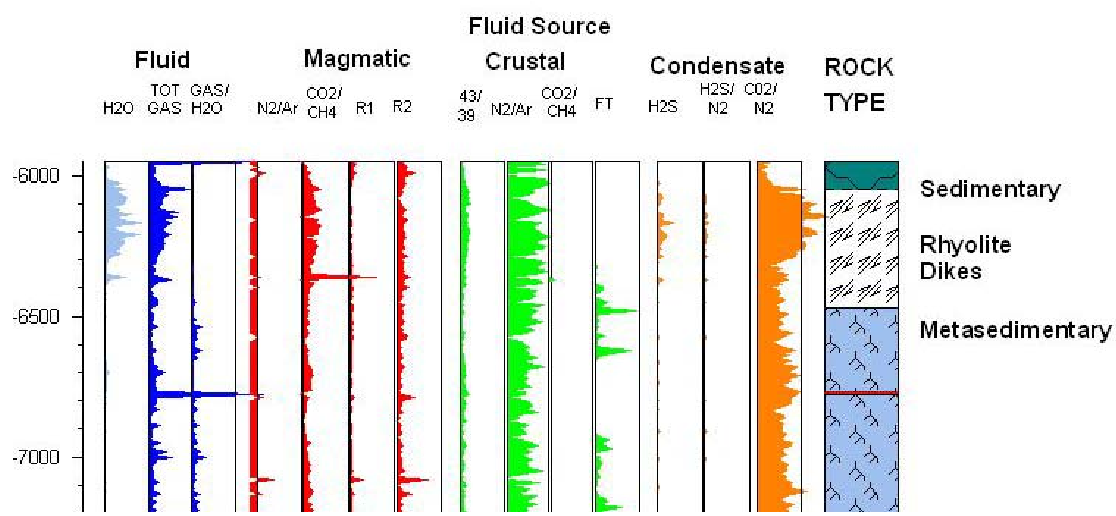


Figure 17: Well 34-9RD2 Fluid Inclusion Data with Rock Type



Reds: diorites/granodiorites; Pink: granite.
Rock types by K.M. Kovac et al. 2005.

Figure 18: Well Log from a Different Field



Note the increase in H_2O and total gas in the rhyolite dike. There are multiple peaks throughout the metasedimentary rock.

When compared to sedimentary rocks, crystalline rocks show noticeable differences, including a higher density of inclusions, and the analyses indicate higher water and higher amounts of all gaseous species. There are major changes even within the crystalline rocks that do not correspond solely to rock type. The changes seen in the gas composition of inclusions do not correspond to changes in rock type; there are significant changes to many of the gases within the same rock type. In addition, in zones with multiple rock types there are little to no changes in various gases.

5.3.1 Vein Assemblage

Calcite is a major secondary mineral throughout the Coso reservoir and occurs in vein assemblages consisting of calcite, hematite, and chlorite; with calcite and quartz intergrown, which indicates boiling; and as calcite with several generations. The assemblage of calcite, hematite, and chlorite indicates recharging, cool, oxidizing waters. Hematite (Fe_2O_3) contains he oxidized iron compared to the reduced iron in pyrite (FeS_2). Based on the chemistry of calcite ($CaCO_3$) and quartz (SiO_2) as explained below, the quartz and calcite assemblages and the calcite with several generations are the result of higher temperature fluids such as mixed and reservoir fluids.

Calcite has a reverse solubility; as the temperature increases, the solubility of calcite decreases, causing precipitation (Fournier 1985). Calcite will precipitate during heating, and cooling without boiling will cause the calcite to dissolve. As geothermal fluids move upward and boiling occurs as a result of adiabatic cooling (decompression), calcite will precipitate.

The solubility of quartz increases as the temperature increases. Quartz, a crystalline form of silica, controls aqueous silica if water remains in contact with rocks at a given temperature for a time. Quartz will deposit under slow cooling, if the initial temperatures are between 200°C (392°F) and 340°C (644°F). Rapid cooling such as decompression boiling will result in supersaturated silica solutions (Fournier 1985b). Various types of silica (chalcedony, amorphous silica, siliceous sinter) will then precipitate at different temperatures and alkalinity of the waters. Above 300°C (572°F), quartz will precipitate under boiling conditions.

Figures 19 and 20 present the FIS logs and the calcite occurrences for Wells 33-7 and 58A-18, respectively. Fluid types, based on FIS interpretations are shown to the right of the logs. The assemblage of calcite, hematite, and chlorite (shown in red) occurred only at the top of each well. The calcite, chlorite, and clay assemblage (shown in white) occurred following the assemblage with hematite. Hematite did not occur in this assemblage. This was interpreted as being warmer, more reduced fluids rather than cool, oxidized fluids, and therefore is a mixed fluid type. The calcite and chlorite assemblage (green) dominated the majority of the middle portion of each well. This was interpreted as warmer fluids or mixed fluids. The calcite assemblage (shown in blue) was interpreted as being indicative of warm reservoir fluids. The interpretations were based on the geochemistry of the minerals as described at the beginning of this section. The only occurrence of calcite and quartz (shown in pink) was in Well 58A-18.

Both of these wells are low enthalpy small producers of 2 and 4-MW. The greater variability seen in the calcite occurrences in Well 58A-18 is most likely a result of the multiple cold water entrances that occur in this well, changing the temperature and therefore the chemistry of the fluid. The fluid types indicated on the logs in Figures 19 and 20 correspond to those interpreted from the fluid inclusion gas compositions. There is a good correlation between the alteration assemblages and fracture filling minerals and the fluid types that occur in the wells.

Figure 19: Log of 33-7 with Calcite Occurrences and Interpreted Fluid Types

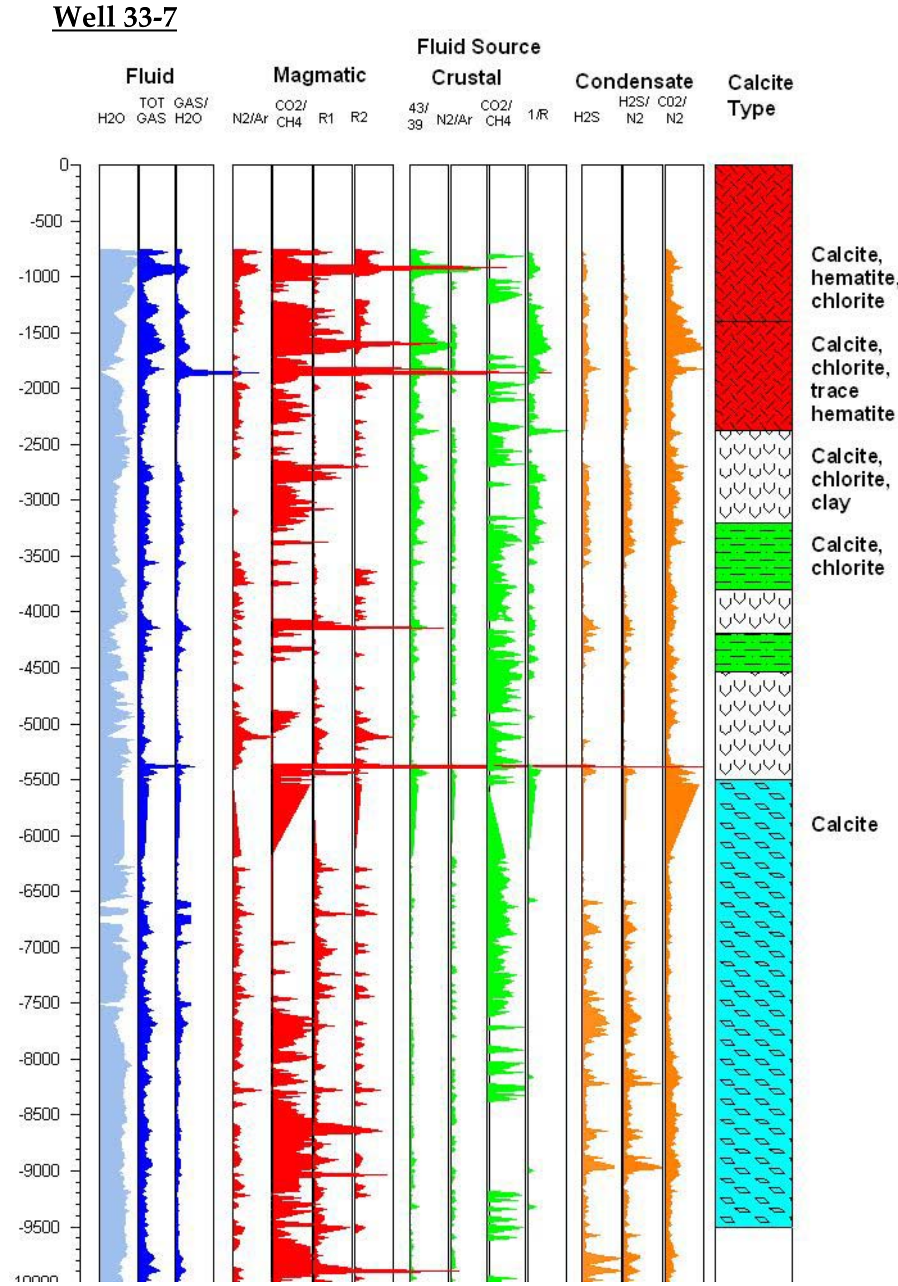
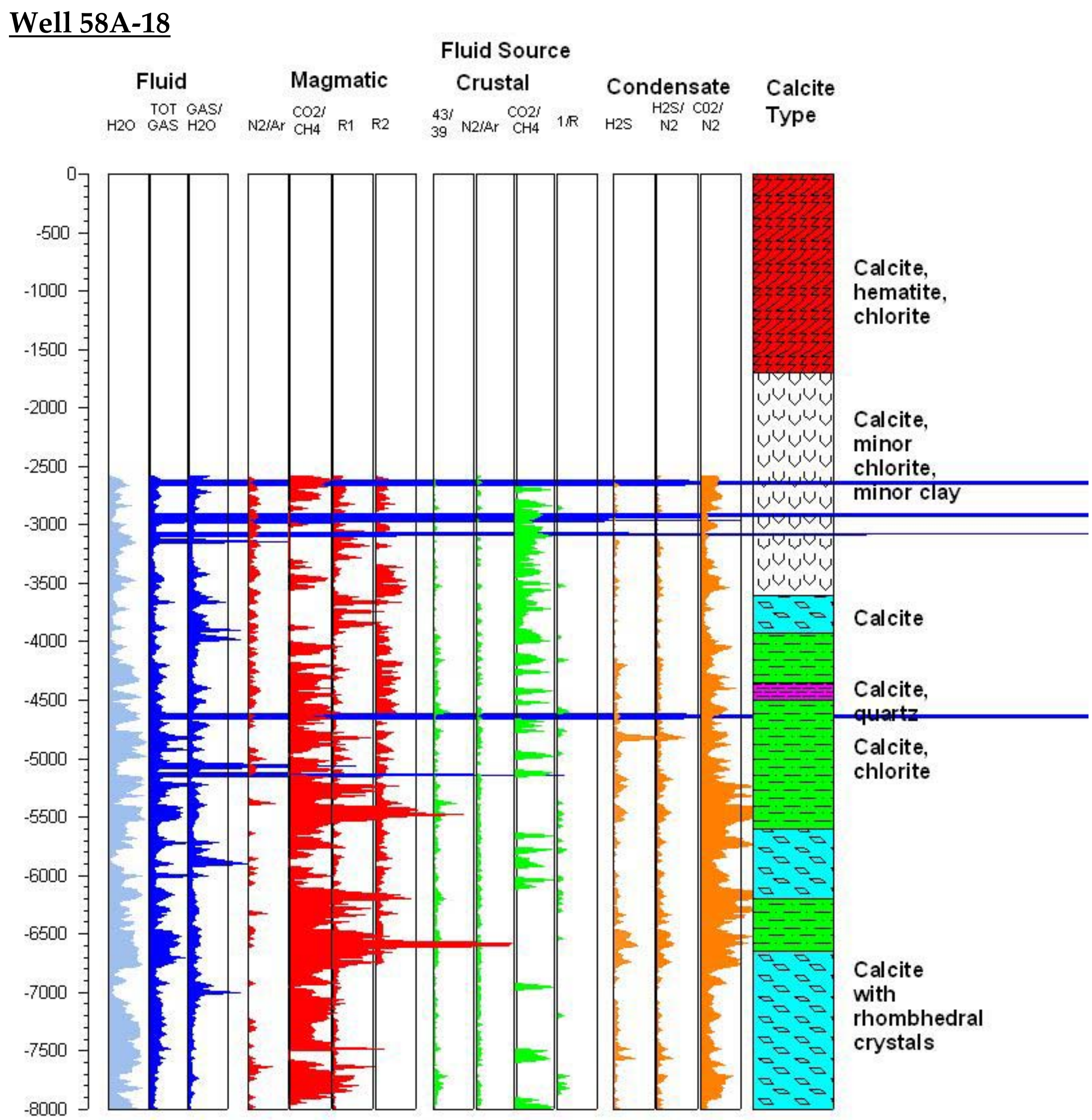


Figure 20: Log of 58A-18 with Calcite Occurrences and Interpreted Fluid Types



5.4 Relation to Fractures

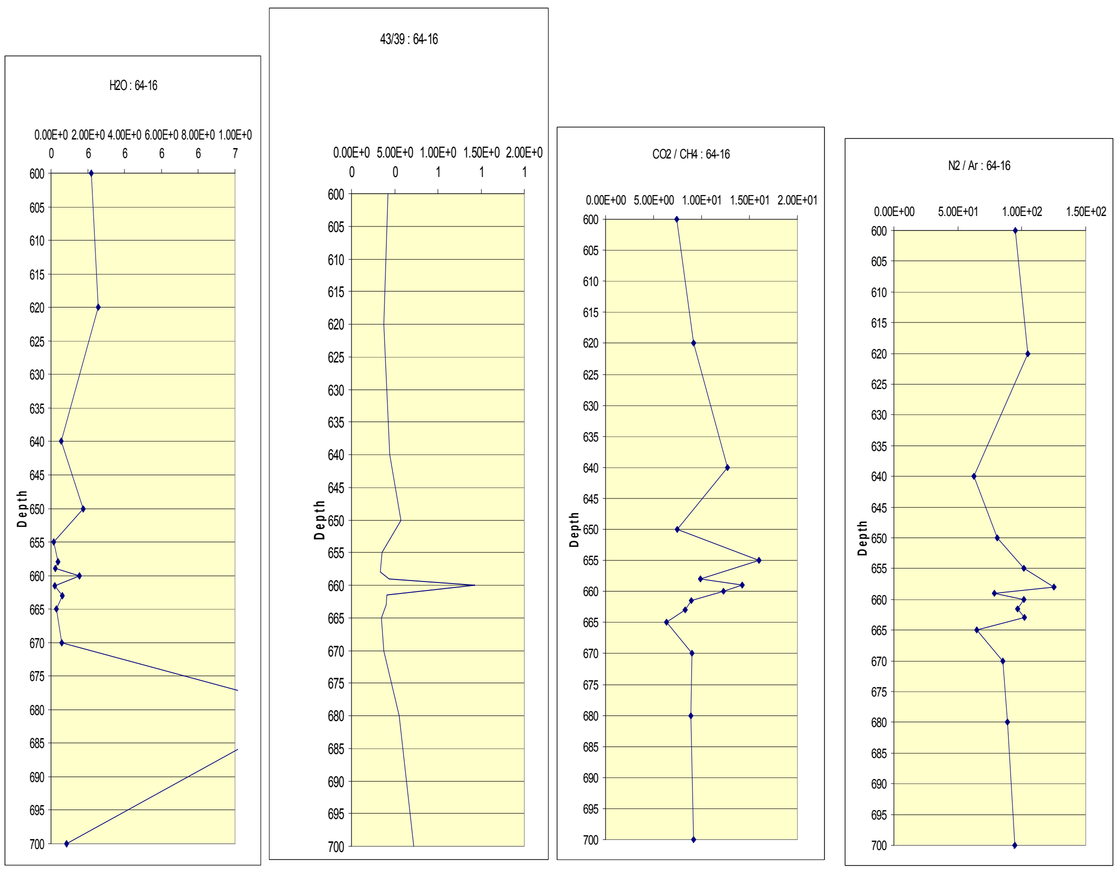
5.4.1 Coso Wells

Rock samples were obtained from the Coso Well 64-16 core. Sampling was conducted to determine how far from the vein the various ratios and chemical species signatures could be observed. The samples were crushed in a mechanical crusher and sieved to obtain fragments about the same size as the drill cuttings. The sampled core contained a noticeable calcite vein between 659 and 662 feet, with the vein center at 660 feet. The sampling interval ranged from 20 feet at 600 feet to 1 foot at the vein center. The 660-foot sample is calcite; all other samples were green altered host rock. Figures 21a through 21d show the results of the sampling.

It can be seen that for H_2O (Figure 21a) there is a small peak centered at 660 feet. A much larger peak is 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. For mass 43/39 ratio (Figure 21b), there also is a very sharp peak at the vein center, with no other peaks observed on the graph in this zone. A high 43/39 ratio indicates that cool waters were depositing this vein. For CO_2/CH_4 (Figure 21c) and N_2/Ar (Figure 21d), the peaks are broader and the highest points of the peaks are above the center of the vein. For CO_2/CH_4, the width of the peak is about 15 feet, while for N_2/Ar the width of the peak is about 10 feet. The low CO_2/CH_4 ratio and high propane/propene ratio indicate low-temperature fluids. The elevated N_2/Ar coupled with low CO_2/CH_4 is characteristic of steam-heated water (Dilley et al. 2004).

Figure 21: Graphs of the Various Ratios for a Calcite Vein Centered at 661 feet from Well 64-16

Figure 21a **Figure 21b** **Figure 21c** **Figure 21d**

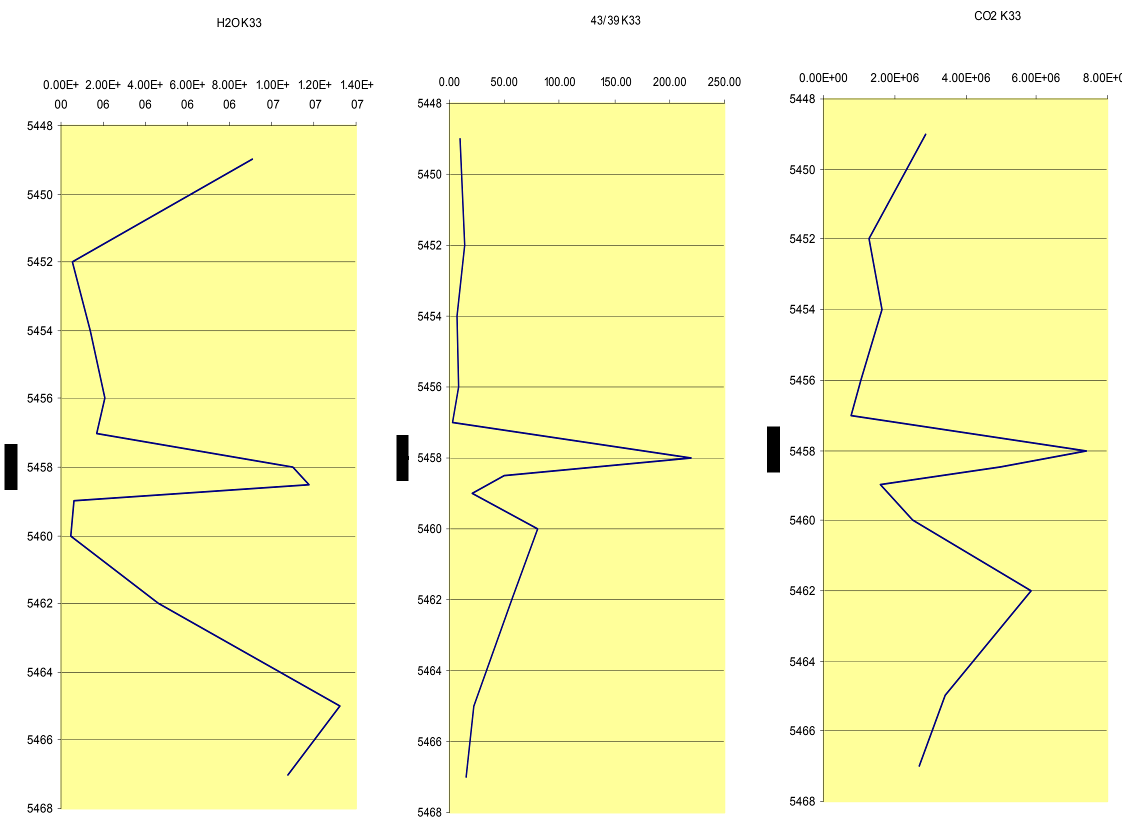


There appears to be a correlation between the location of the peaks and the vein. The more mobile species such as CO_2 and N_2 make broader peaks around the vein than do the heavier organic species.

5.4.2 Karaha Wells

Because of the limited number of cores from Coso, cores from Karaha were used for additional confirmation testing. As explained in Section 3.2, Karaha is a geothermal system in Indonesia. The geothermal system is young and composed of felsic volcanics similar to Coso. 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. Appendix D presents the results for the various veins. Figure 22 shows select results for well K-33, with a fracture at 5458 feet. It can be seen that H_20, CO_2, and ratio of 43/39 all indicate sharp peaks at this location with H_2O having a broader peak.

Figure 22: Graphs of Various Ratios for Karaha Well K-33



Note the peaks all correspond to location of vein at 5458 feet.

Table 9 presents the type of fracture and locations of the peaks for select chemical species that were observed relative to the fracture. Appendix A presents the data for all of the core samples and analysis. The fracture served either as a source or a sink for the various species. The fracture was considered a source if there was a positive peak and a sink if there was a negative peak. The source species were considered to migrate out into the wall rock, whereas a species that was a sink was considered to be present in the wall rock but not in the fracture material. The width of the peak also is considered to be based on the dispersal of the chemical species into the wall rock. For the calcite, quartz, pyrite fractures, a few of the species had peaks above the fracture. This would indicate that those species migrated upward into the wall rock.

Table 9: Karaha Cores: 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	L	X	X	Above	X	X	Above	
Quartz	X	X	X	X	X	X				X
Pyrite	X		X	X	X			L		
Calcite & Pyrite		X	X	L	X	X	X	L	X	X
Quartz & Pyrite	X	Above	Above		Above	X	X	X	X	X
Altered	X	X	X	X	X	X			X	X

Note: X indicates a positive peak; L indicates a negative peak: Above indicates peak occurred above the fracture: Blanks indicate peaks occurred elsewhere

It can be seen that the peaks for a number of the chemical species and ratios of interest occur near the fracture or above the fracture (see Table 9 and Appendix D). Calcite and quartz have the most peaks lying near the fracture. For calcite fracture, the CO_2 has migrated upward. The altered zone also had peaks occurring near distinct fractures. In the case of the altered zone, there were several distinct fractures and corresponding peaks.

The bulk analysis of volatiles within fluid inclusions corresponds with several types of fracture infilling minerals including quartz, calcite, and pyrite. Distinct strong peaks of several of the chemical species that are analyzed for in the bulk analysis occur at fracture locations without much dispersion into the surrounding wall rock. This suggests that the peaks observed with the FIS logs are related to fractures within the wall rock.

5.5 Timing of Fluid Inclusions

Because the fluid inclusions are not individually picked out for study but rather a bulk sample is submitted for analysis, there is no control over which inclusions are used. Secondary, pseudo-secondary, and primary inclusions are all included in the crushing process. Most cuttings from an interval reflect the wall rock at that interval and the bulk analyses of fluid inclusions see mainly the predominant inclusions. The use of FIS is predicated on the hypothesis that the youngest geothermal activity will result in fluid trapping and will destroy older inclusions as rock is re-fractured and new minerals are formed.

As mentioned in the Methods Section 3.3, two wells at Coso, 68-20 and 68-20RD, were drilled at the same location with a deviation of 150 feet at depth of 5500 feet. Well 68-20RD is a redrill of the older well, 68-20, which after seven years of use as an injection well, had developed extensive scaling. Figure 23 presents the trace of each well with depth and shows the deviation from the original Well 68-20 that occurred as Well 68-20RD was being drilled. The injection fluid is 110°C (230°F) fluid from the flashed plant and is free of condensable gas. During injection in 68-20RD there was a break in the casing at 2700 feet. This original well and re-drill represent a comparison based on recent changes in a geothermal system and would indicate if the fluid inclusion gas analysis could change within a brief span of time. If the bulk analyses of the fluid inclusions showed different results in the same well, this would indicate that new minerals are formed fairly rapidly and older minerals are destroyed or overprinted.

Figure 23: Well traces for Wells 68-20 Series

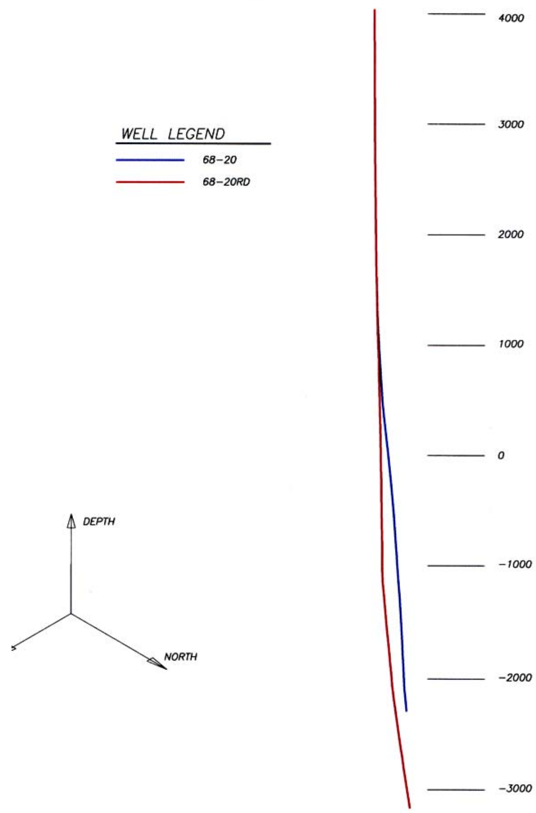


Figure 24: Well 68-20 Drilled Seven Years Rrior to Well 68-20RD

Figure 24a: Well 68-20 Figure 24b: Well 68-20RD

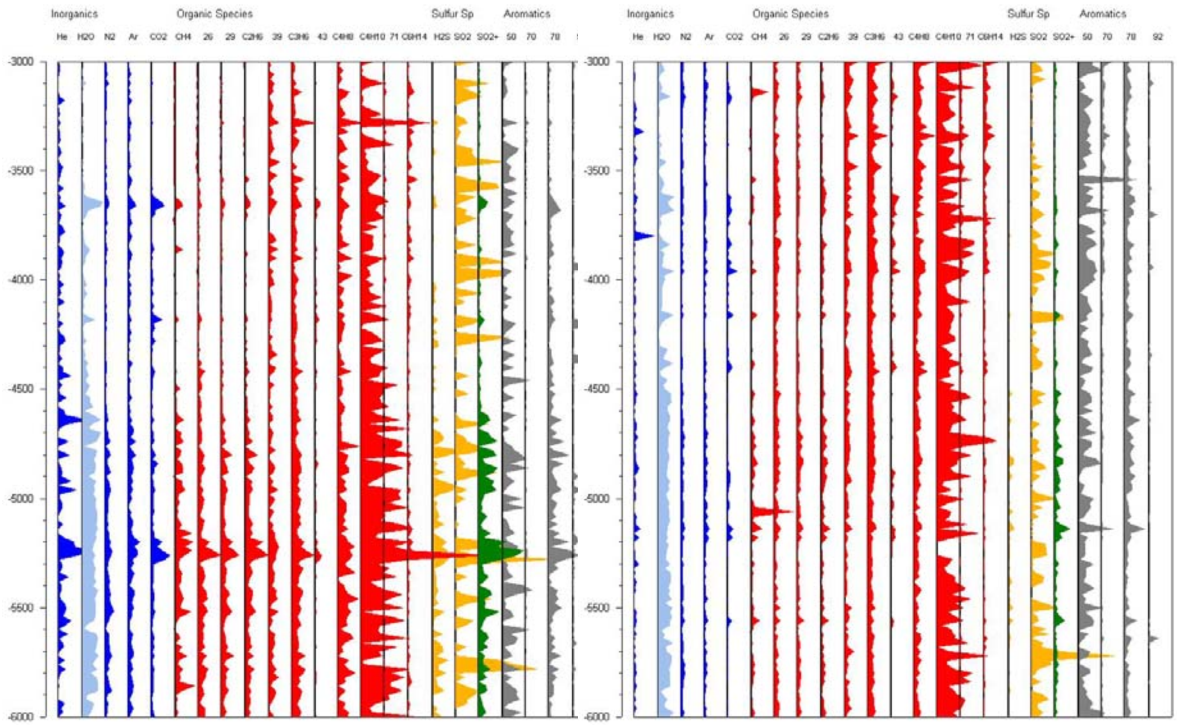


Figure 24 presents the fluid inclusion stratigraphic logs for each of the wells from 3000 to 6000 feet. The logs are at the same scale. It can be seen that Well 68-20RD (Figure 24b) is different from Well 68-20 in a number of intervals. In Well 68-20 below about 4700 feet there is a significant amount of organic species, which do not occur in the second well, 68-20RD. Well 68-20 also shows peaks at 3650 feet and 5200 feet, which do not occur in Well 68-20RD. Well 68-20RD overall appears to have less fluid inclusion density, which would correspond to the fact that the well was a re-drill of a scaled-up well. A scaled well would have less fluid moving through it as the scale increased, reducing the number of fluid inclusions. There are also peaks in Well 68-20RD that clearly correspond to the first well, particularly at 3100 feet; the CH_4 peak at 5050 feet; and from 5100 to 500 feet. This comparison shows that within seven years some of the older fluid inclusions were destroyed and replaced with newer ones.

The graphs in Figures 25(a)–25(e) indicate the differences and make the contrast between the two wells and the top of and the bottom of wells even clearer. For each of the chemical species used there are significant peaks between approximately 2700 feet and 3000 feet. This corresponds to the break in the well casing that became the injection site. The differences in graphs for various species in Figure 26 indicate significant changes between the two wells.

Figure 25: Graphs Indicating the Changes in the Fluid Inclusion Bulk Gas Analysis for Select Species for Wells 68-20 and 68-20RD

Figure 25a

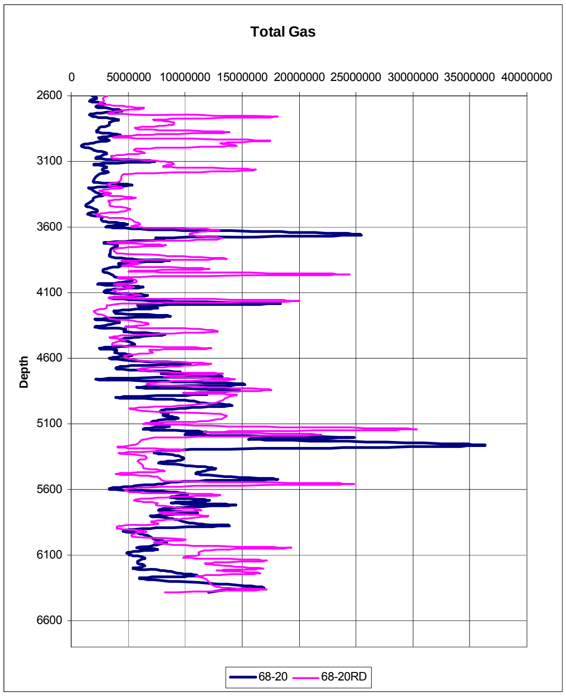


Figure 25b

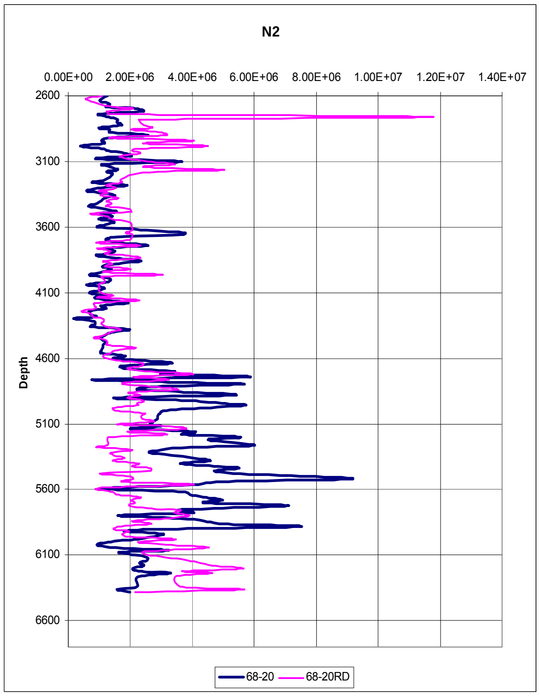


Figure 25c

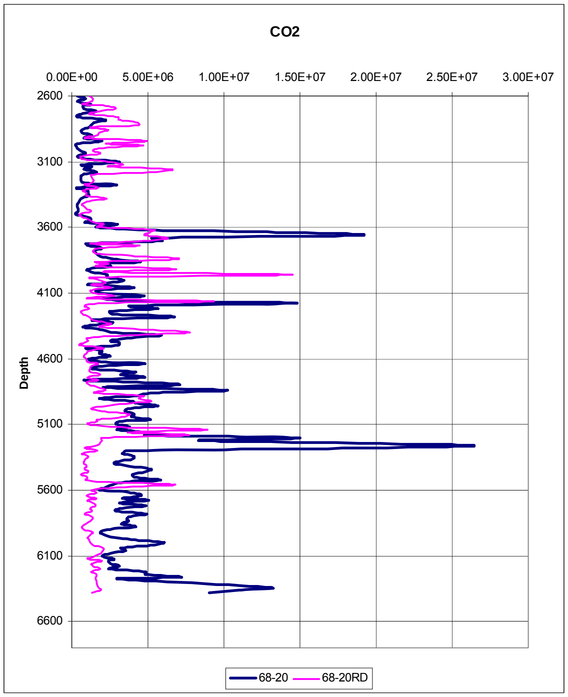


Figure 25d

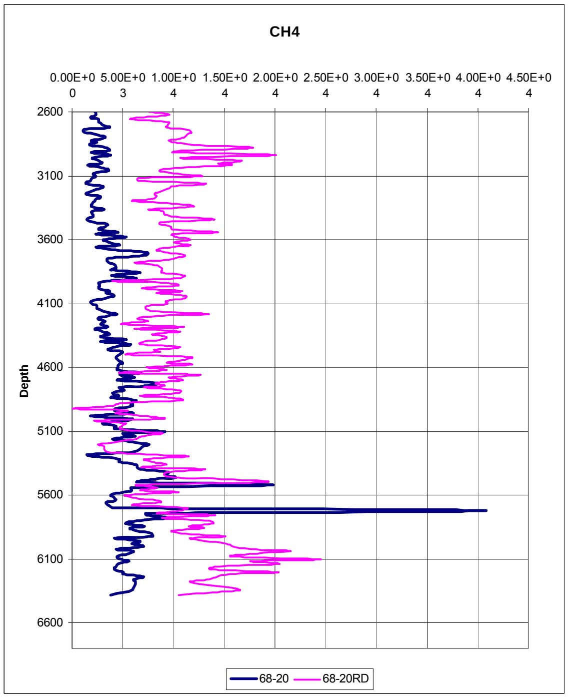


Figure 25e

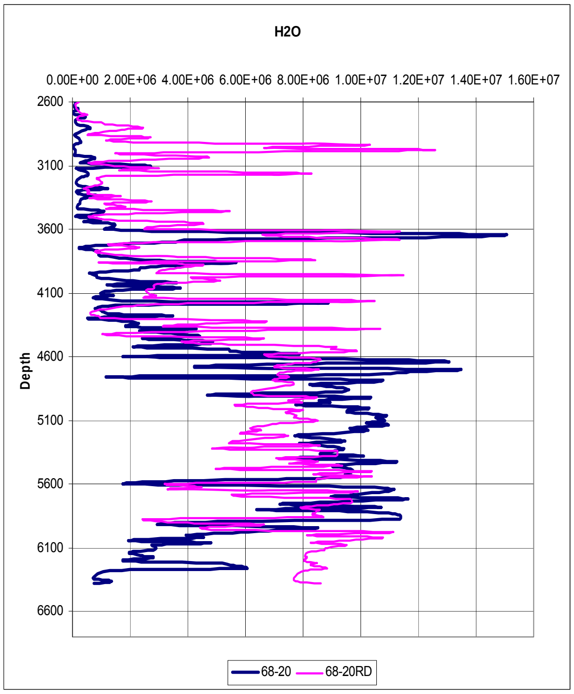


Figure 26: Differences in Various Compounds between Well 68-20RD and Well 68-20

Figure 26a

Figure 26b

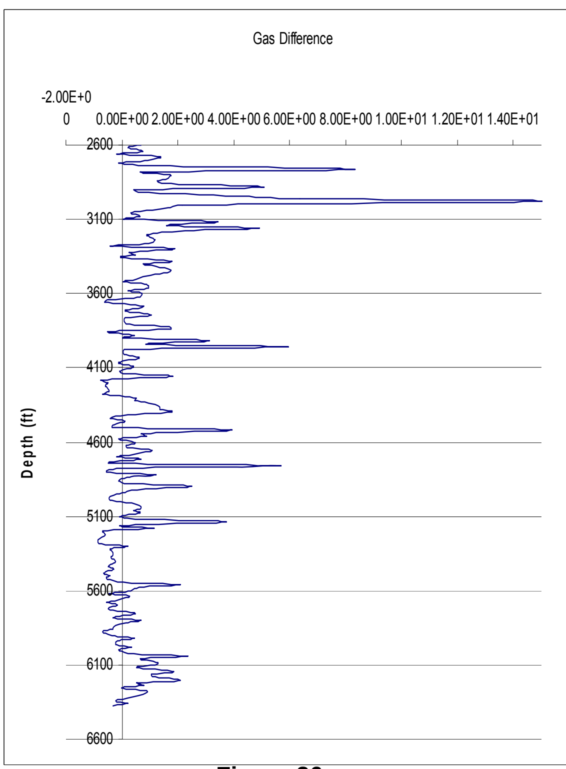


Figure 26c

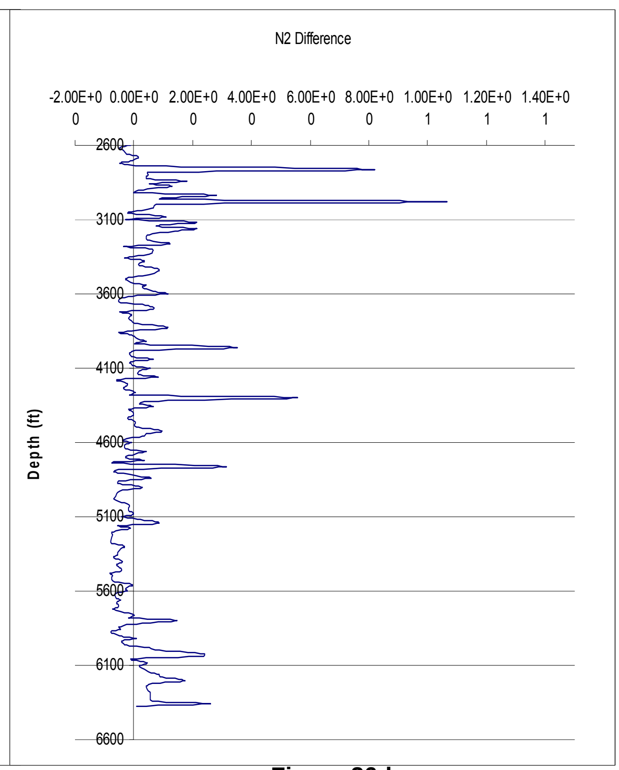
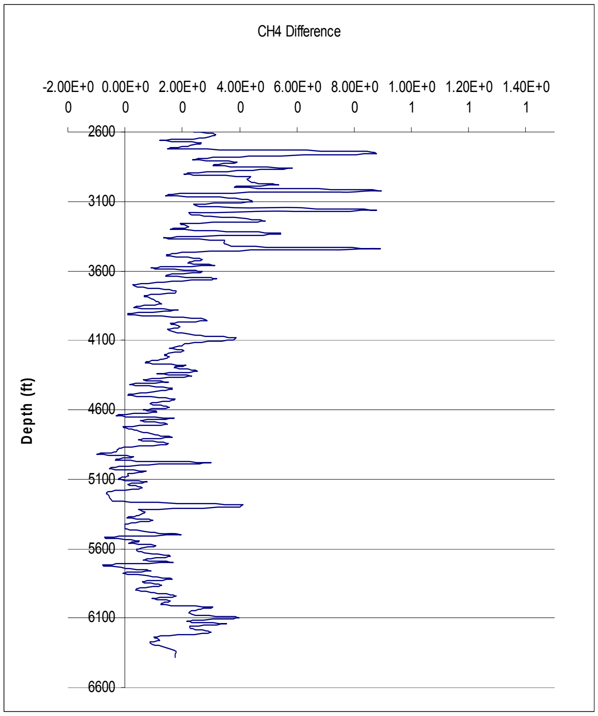


Figure 26d



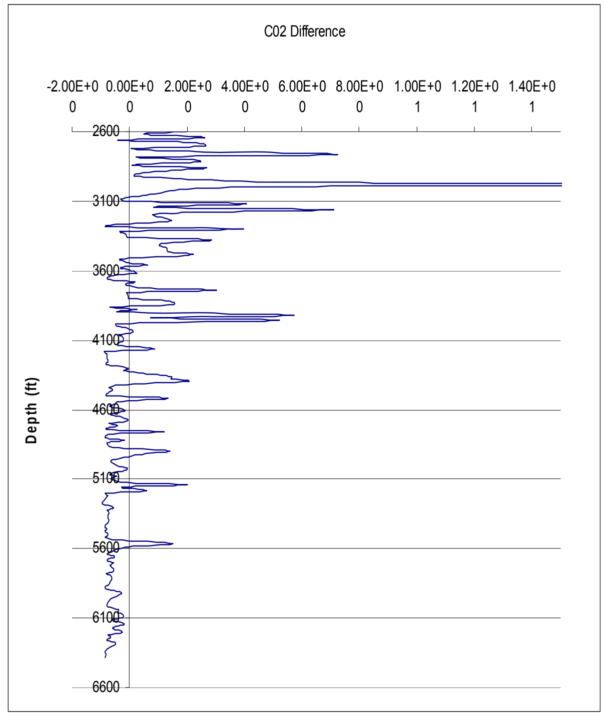
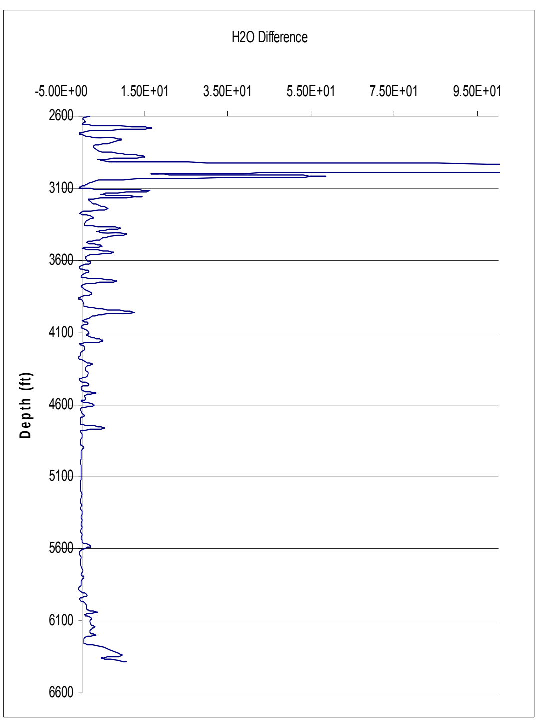


Figure 26e



Note the significant peak at about 2900 foot depth, which corresponds to break in well casing.

The graphs presented above for the differences in Wells 68-20 and 68-20RD argue that the FIS analyses of the wells at the Coso field are seeing the modern system. The water changes observed indicate that the inclusions are being replaced. The log of Well 68-20RD in Figure 26b shows a reduction in various chemical species peaks compared to those observed in Well 68-20, suggesting that the flashed injection water is creating new inclusions as the older inclusions formed from fluids with geothermal chemical species are being destroyed. The changes in the bulk fluid inclusion chemistry from one that shows significant peaks of CO_2, N_2, and CH_4 to a more subdued log with less significant peaks of these compounds indicate that fluids within the newer well are creating new fluid inclusions that are overprinting the older fluid inclusions.

The largest changes in the ratios occur at depths of fluid injection identified by FIS analyses and petrography study of re-drill cuttings that show abundant secondary minerals. The changes also drop off with depth of the well, further suggesting that the changes are a result of the injection water creating new fluid inclusions and destroying the geothermal gas fluid inclusions. The discrete peaks are assumed to represent fractures that dip, controlling the flow of injection fluid. Fractures in Coso are generally steeply dipping (Unrh and Hauksson 2006). The re-drill and the original are at most 150 feet away from each other and the steeply dipping fractures would allow the injected fluid at about 2800 feet to travel down to the 4600-foot level, where there is a change in the relative concentrations. The fractures would not have to go through the full depth but rather could intersect at various levels. Based on stress and strain rates, cold water entering the hot rocks through the existing fractures would cause thermal fracturing of the rock with reopening of old inclusions and, as the cold water equilibrates with the hot water, a deposition of minerals and creation of new fluid inclusions representing the injection events.

A geothermal system, particularly one that is being exploited, is a dynamic environment. Multiple small-magnitude earthquakes occur frequently, resulting in fractures of various dimensions opening and closing (Feng and Lees 1998). Fluid flows either naturally or by being pumped. Pressure, temperature, and chemical changes that occur as the fluid moves naturally through the system and as wells are pumped leads to an environment of mineral dissolution, chemical species movement, and mineral deposition. These minerals would naturally trap new, modern-day fluid inclusions. Based on the study and the nature of geothermal systems, it is likely that the majority of the fluid inclusions that are analyzed in the bulk analysis are present-day inclusions associated with the modern system.

Our data shows that geothermal fluid inclusions assemblages can change chemical compositions in a few years and that the changes in inclusion contents are most pronounced in areas of high fluid flux. Thus, bulk fluid inclusion gas analyses of drill cuttings show chemistry of Recent fluids. An implication is that all types of geothermal-system bulk-geochemical analyses will be biased toward the most recent hydrothermal event, the last changes in the system.

5.6 Permeable Zones

Permeability is an important factor in determining if the well is a producer. There are several high enthalpy wells at Coso that do not produce. If a fracture is an open system (permeable), there would be a drop in pressure, resulting in boiling. As steam separates from liquid during boiling, gases such as H_2, N_2, and CH_4 preferentially move into the vapor phase. The more soluble gases, CO_2 and H_2S, stay partially in the liquid phase. A change in the ratio of CO_2 to

NO_2 would indicate that boiling had occurred and that the zone where the change took place would be permeable.

Plotting the change in the ratio of CO_2/N_2 over 80-foot intervals against total gas and determining if the slope (change) is positive, negative, or static (no change) would indicate permeability. The positive and negative change would indicate permeable zones; the static condition would indicate no permeability. Figure 27 presents the results of this analysis for two wells. Well 38C-9 is an 8-MW producer of medium enthalpy. Well 46A-19RD is a high enthalpy well; however, it is a non-producer. The relative changes in the CO_2/N_2 ratio are higher in Well 38C-9 than those in Well 46A-19RD. There are several instances where the change in the ratio in Well 38C-9 is higher than 1XE-6, whereas in Well 46A-19RD the majority of the changes are near the zero line.

Figure 27: Two Wells are Presented that Indicate Permeability Zones

Well 46A-19RD is a tight well with low permeability; Well 38C-9 is a major producer

Figure 27a

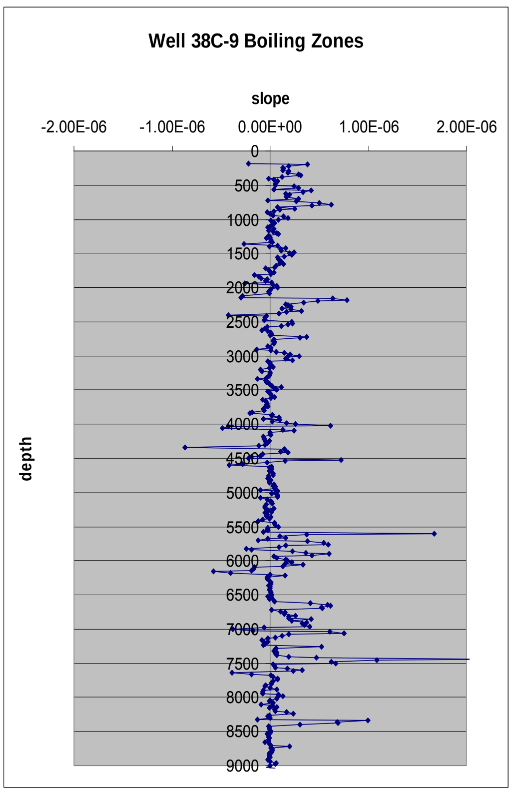
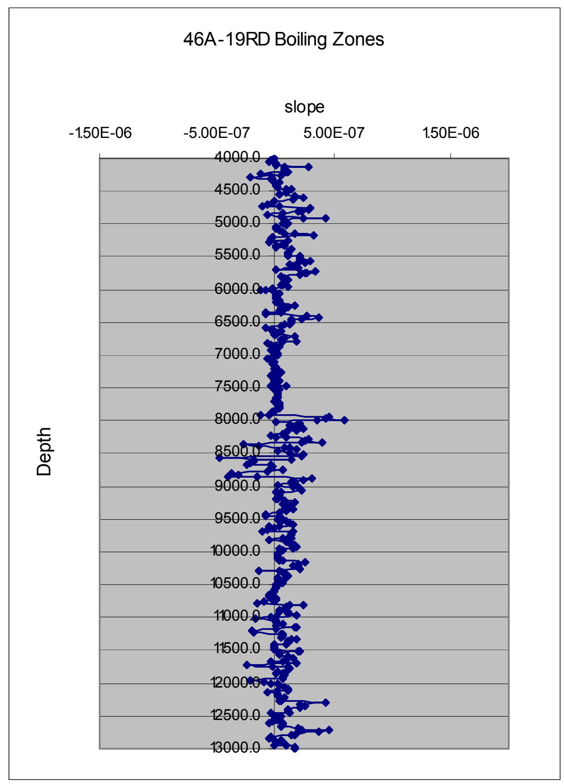


Figure 27b



5.6.1 Producing Wells

The producing wells in the field are 38C-9, 33-7, 58A-18, 38D-9, 52-20, and 73-19. The CO_2/N_2 ratio method indicates permeability to varying degrees in all of the wells. Figure 28 presents the plots for the producing wells. Wells 33-7, 58A-18, and 38D-9 do not show large changes; however, the values do not lie along the zero line. These wells range in enthalpy from low to high. The higher enthalpy wells (33-7 and 38D-9) have more values near the zero line.

Comparing these wells with those in Figure 29 in the next section on non-producing wells, there is still variability in the values.

Figure 28: Permeability Plots for Producing Wells

Figure 28a

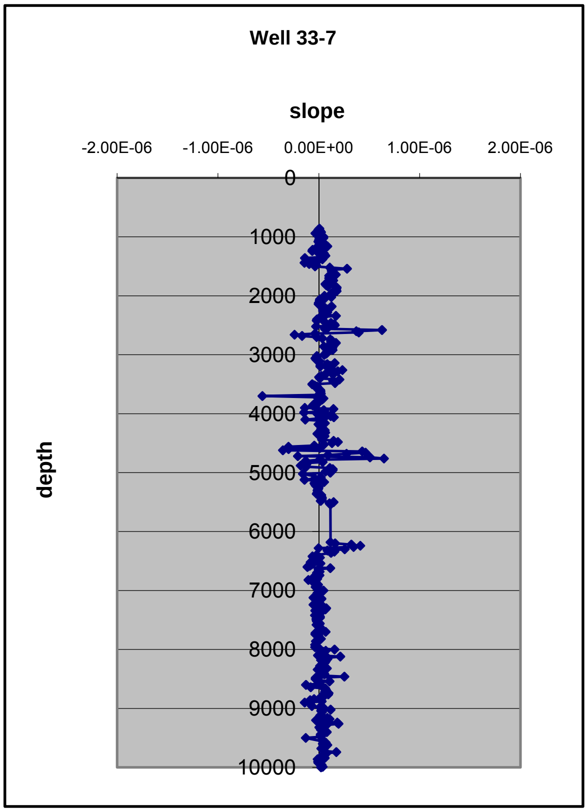


Figure 28b

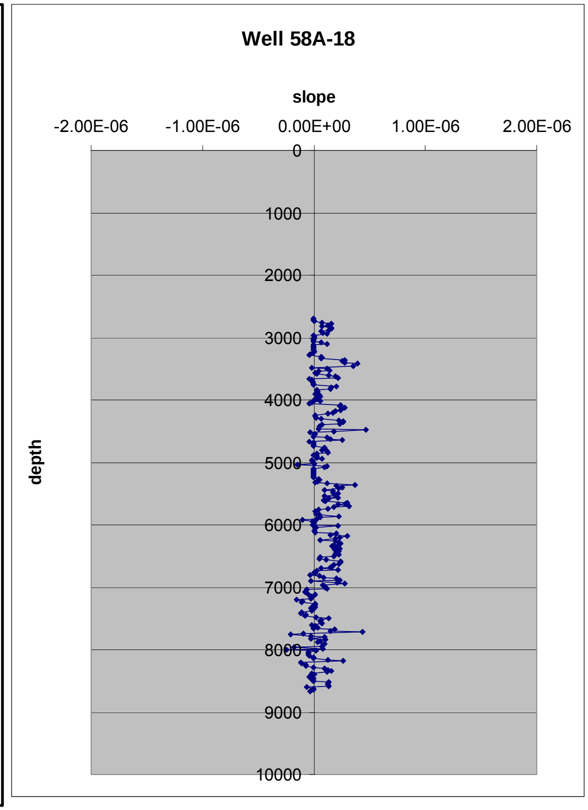


Figure 28c

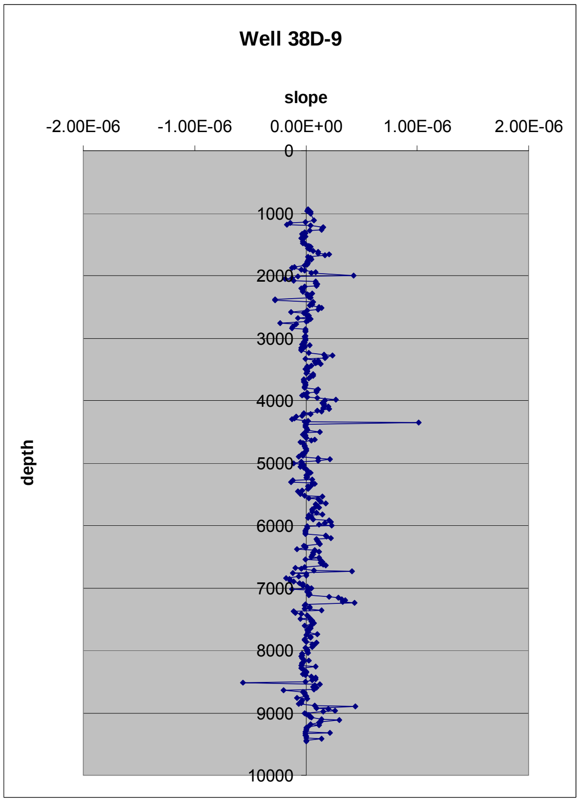


Figure 28d

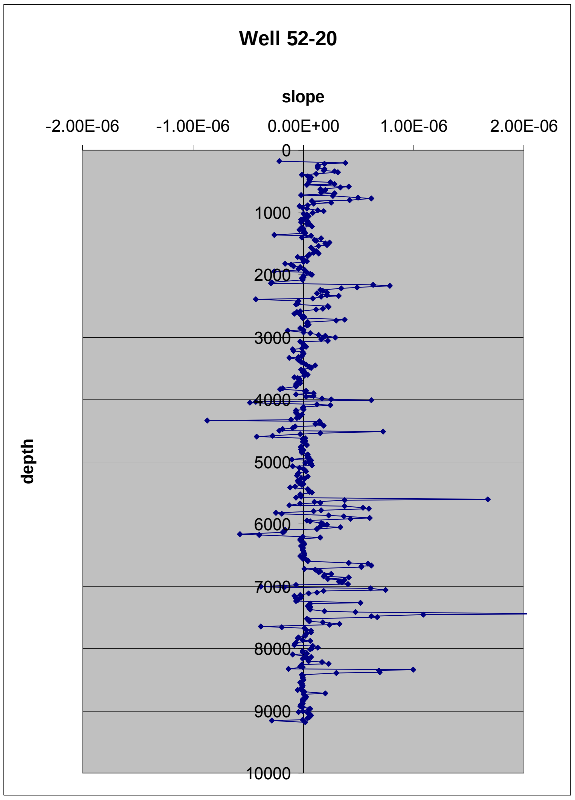
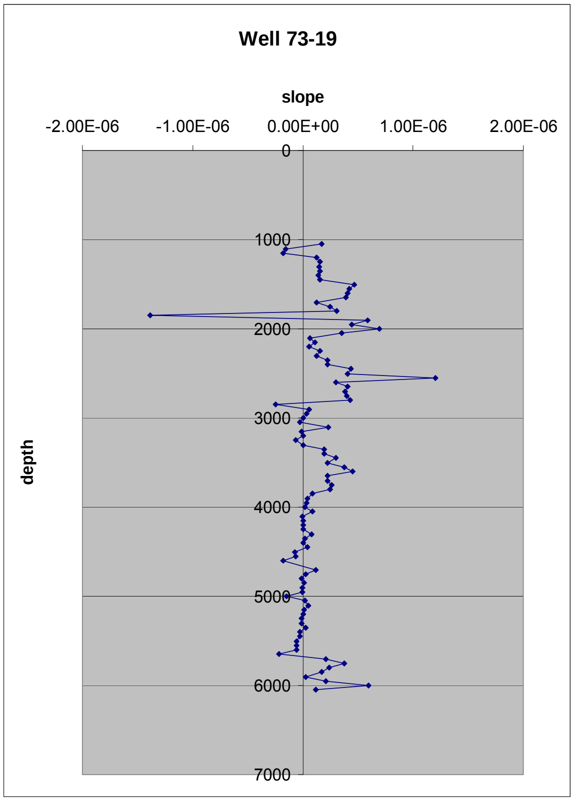


Figure 28e



5.6.2 Non-Producing Wells

Wells 84-30, 58A-10, and 51B-16 are non-producing wells. Figure 29 presents the plots of these wells. Wells 84-30 and 58A-10 are situated on the margins of the field and both show changes in the slope of the CO_2/N_2 ratio. Both wells have very low temperatures in the wells, making them non-producers. Well 51B-16 is in the East Flank of the field and has high enthalpy; however, it is a non-producer. The values for the slope of the CO_2/N_2 ratio are close to the zero line, with only a few larger values near 4000 feet. This lack of change in the slope indicates a lack of permeability in the well, which also argues for it being a non-producer.

Note the difference between Well 51B-16 and the producing wells in Figure 28. Even though most of the slope values are low in Wells 33-7 and 38D-9, there appears to be more variability in the values for those wells than in those for Well 51B-16. Well 51B-16 has a long interval from about 4500 feet to the depth of the well where the values are very near the zero line.

Figure 29: Permeability Plots for Non-Producing Wells

Figure 29a

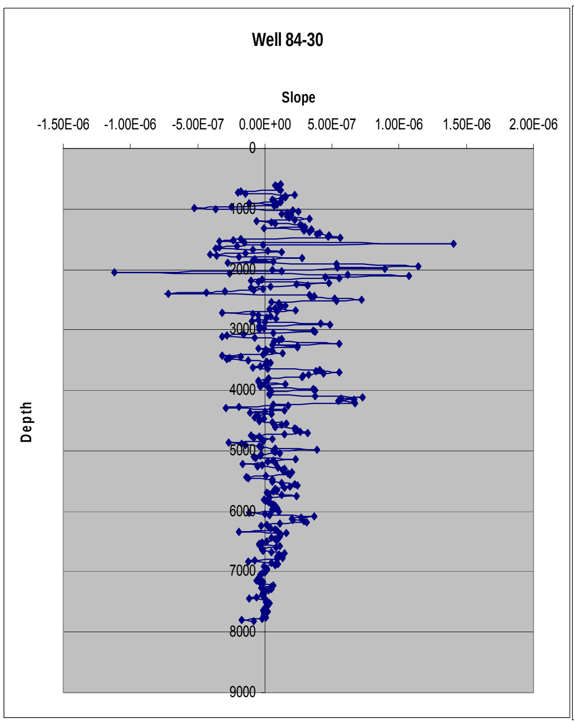


Figure 29b

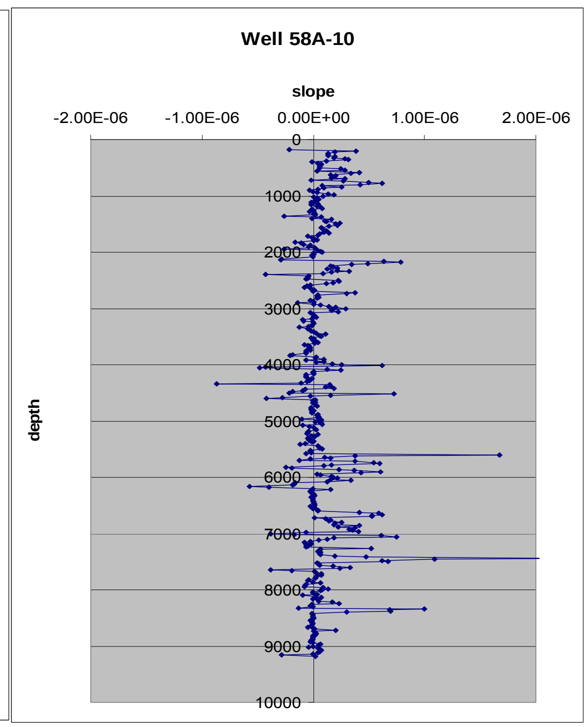
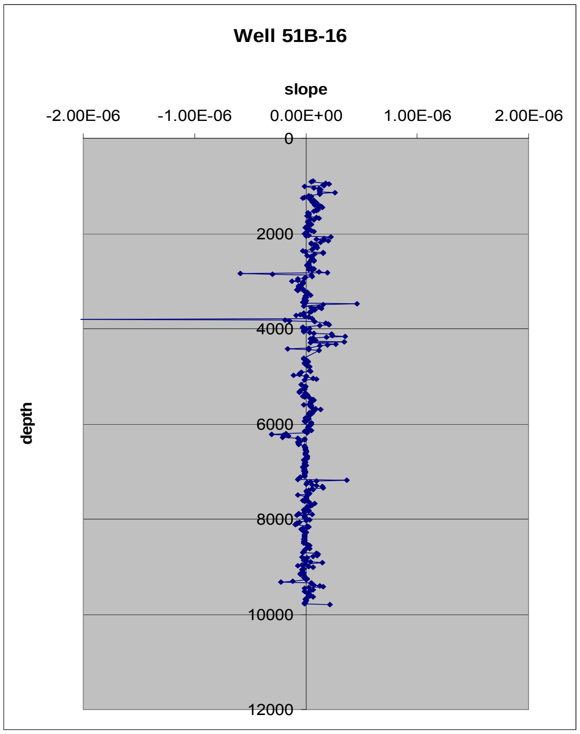


Figure 29c



Wells 84-30 and 58A-10 are low enthalpy, on the margins of the field. Well 51B-16 has high enthalpy but low permeability. Compare Figure 29(c) to Figures 28(a)—28(e)

Chapter 6: Results

6.1 Fluid Types in Coso Wells

The research started with plotting the N_2/Ar and CO_2/CH_4 ratios and H_2S, which were plotted with the first set of data. Fluid types were interpreted for the first set of wells assuming that the N_2/Ar and CO_2/CH_4 ratios could indicate the difference between deep reservoir fluid and meteoric fluids and that high H_2S indicated steam-heated waters. These interpretations were then compared to the temperature logs to see if there was a correlation.

6.1.1 Species Used

As the research continued, the first 60 mass peaks and select ratios were plotted to see if there was any correlation to the temperature logs. A high ratio of propane to propene (mass 43 to mass 39) was found to indicate colder waters. This is expected, since propane is an oxidized state of propene and would suggest that cold, oxygen-rich waters would have a higher proportion of the oxidized form. Additional ratios were developed based on solubility of gases such as H_2S/N_2 and CO_2/N_2 to determine condensate zones. Of the 180 species analyzed, 23 species and nine ratios proved to be useful in determining fluid types. The species of interest are the principal gaseous species in geothermal fluids and trace hydrocarbon species, which include H_2, He, CH_4, H_2O, N_2, H_2S, Ar, CO_2, C_2H_4, C_2H_6, C_3H_6, C_3H_8, C_4H_8, C_4H_{10}, benzene, and toluene. The ratios used were N_2/Ar; CO_2/CH_4; H_2S/N_2; CO_2/N_2; propane/propene; (N_2/Ar + CO_2/CH_2)/propane/propene termed ratio 1, and (N_2/Ar + CO_2/N_2) termed ratio 2; and the inverse of ratio 1. Total gas and gas/water ratio were also used to indicate certain fluid types.

Abundances of species can be changed by lithologic and diagenetic controls on inclusion formation and distribution such as size distribution of inclusions, inclusion formation, time of fluid within the fractures, and relative proportion of fluid with the same composition moving through the system. Ratios are useful for showing trends and characterizing chemical variability related to timing and source of fluid. Inclusion abundance will affect the intensity of the mass spectrometer response somewhat non-linearly. Both types of plots are therefore useful in the interpretation of fluid type.

The following ratios and species were developed for indicating fluid types in the various wells:

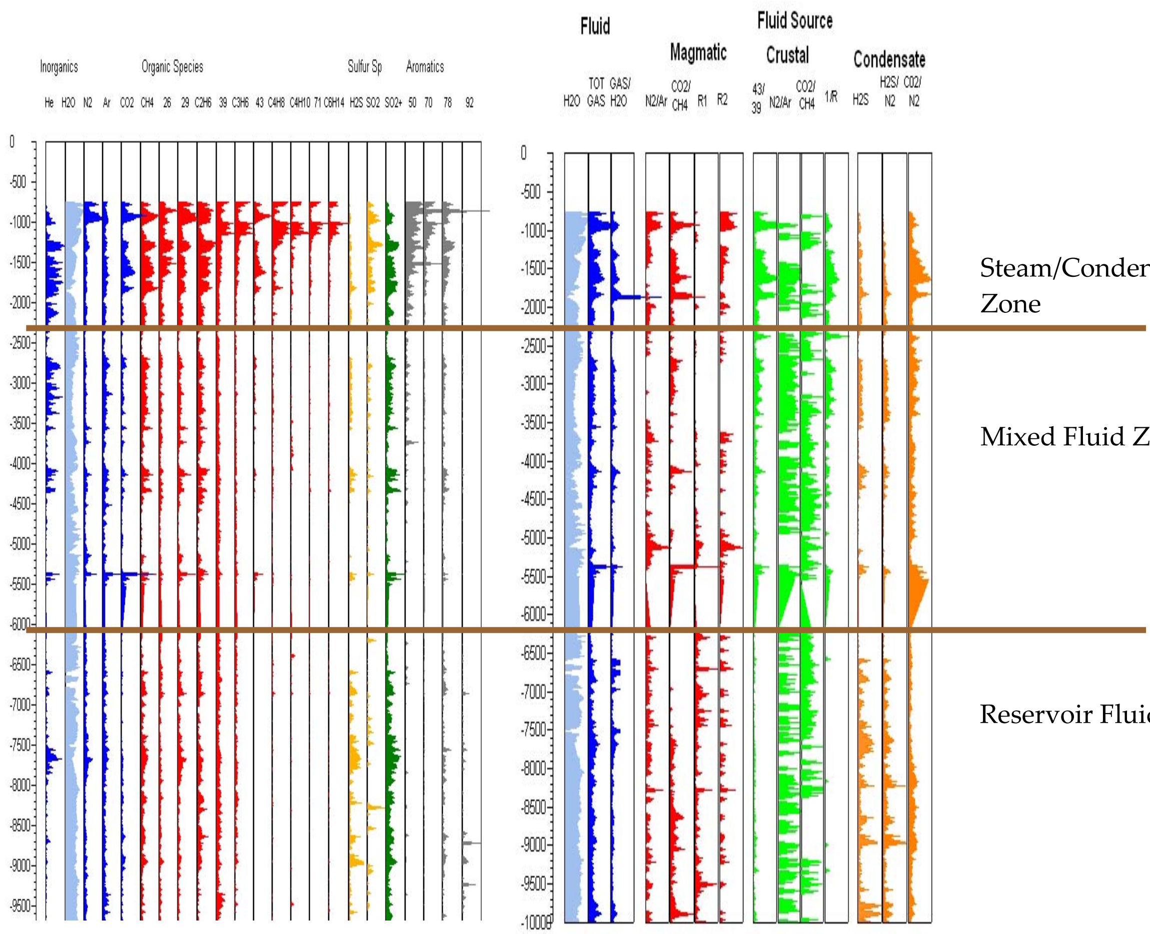
- Reservoir fluids are indicated by (28/40) $N_2/Ar > 200$ and (44/15) $CO_2/CH_4 > 4$.
- Shallow meteoric fluids are indicated by (28/40) N_2/Ar ratios < 200, 44/15 (CO_2/CH_4) < 4, propane/propene (43/39) >1, and 1/ratio 1 > 0.5.
- Steam-heated waters have elevated H_2S and H_2S/N_2 and sometimes elevated CO_2/N_2. Elevated CO_2/N_2 is common in deep reservoir waters that can condense magmatic volatiles. Condensate has high water, low volatiles. Steam has low water.
- Boiling zones are indicated by high gas/water ratios and by high total gas.

6.1.2 Coso Wells

The fluid types in each well were interpreted using the above criteria. Figures 30 through 45 present the well logs and the interpretations made for each Coso well. These interpretations were made before confirmation with the Coso geologist and other data. The discussions of the following wells indicate how fluid inclusion gas chemistry was used to interpret fluid types in the wells. Distinct zones in each well are readily seen, with several smaller zones within each larger zone.

Well 33-7: Well 33-7 is a producing well on the northwestern side of the field. It a low enthalpy well and produces about 2 MW. From the surface to about 1200 feet the fluids are interpreted as shallow meteoric followed by a steam/condensate zone. From about 2600 feet there is a change in fluid inclusion gas chemistry, indicating a mixed fluid zone. There appear to be some areas that are fractures producing hotter fluids such as those areas at 4100 feet; 5100 feet and 5400 feet. The change in fluid inclusion gas chemistry at about 6200 feet represents reservoir fluids with higher and more consistent N_2/Ar and CO_2/CH_4 ratios and the possible presence of boiling indicators such as high total gas.

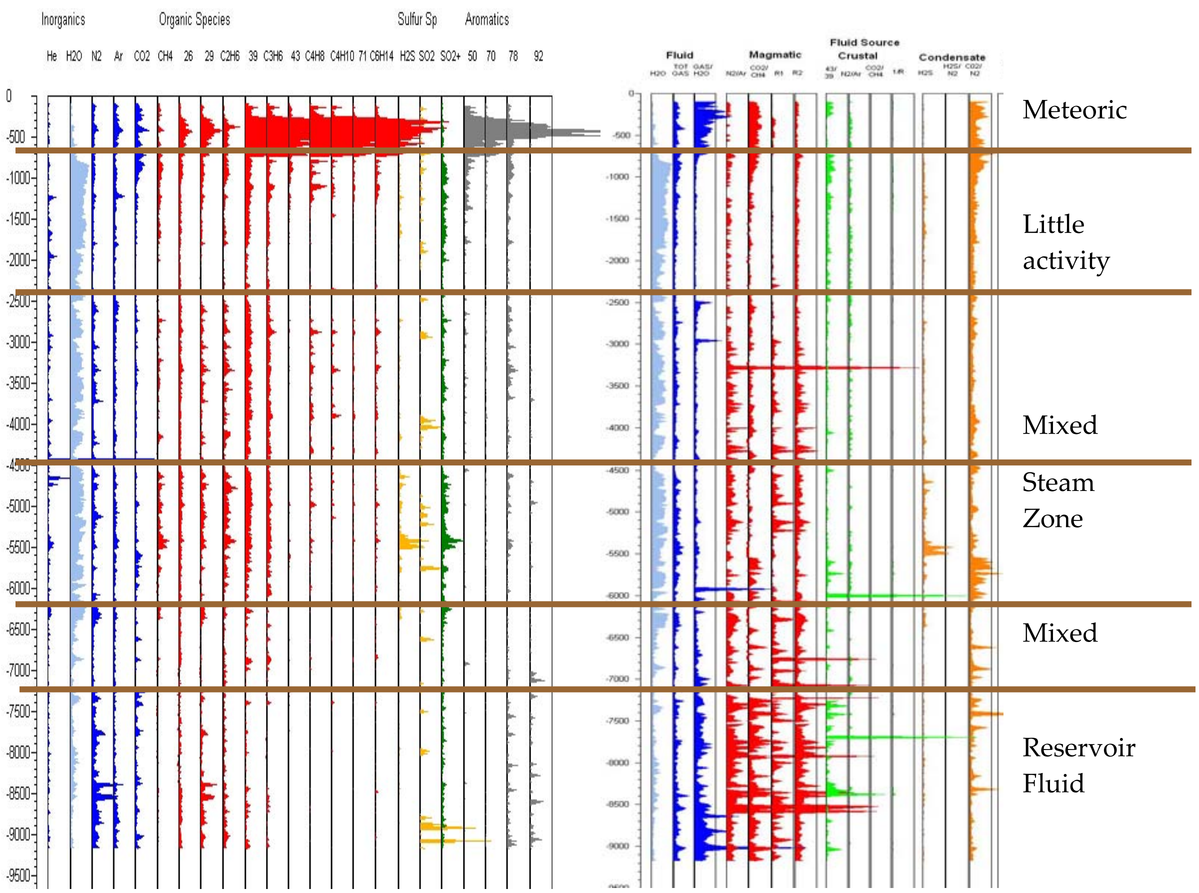
Figure 30: Well 33-7 Interpreted FIS Logs



Well 38C-9: Well 38C-9 is on the East Flank. The well is medium enthalpy and is a major producer at 8 MW. From the surface to about 600 feet is a zone interpreted as meteoric fluids. A zone of little geothermal activity (few inclusions) occurs from 600 feet to about 2400 feet. A mixed fluid zone is interpreted from 2400 feet to about 4200 feet. Although there are high N_2/Ar ratios, there are also organic and CO_2/ N_2 ratio. A steam zone occurs from 4200 feet to 6200 feet.

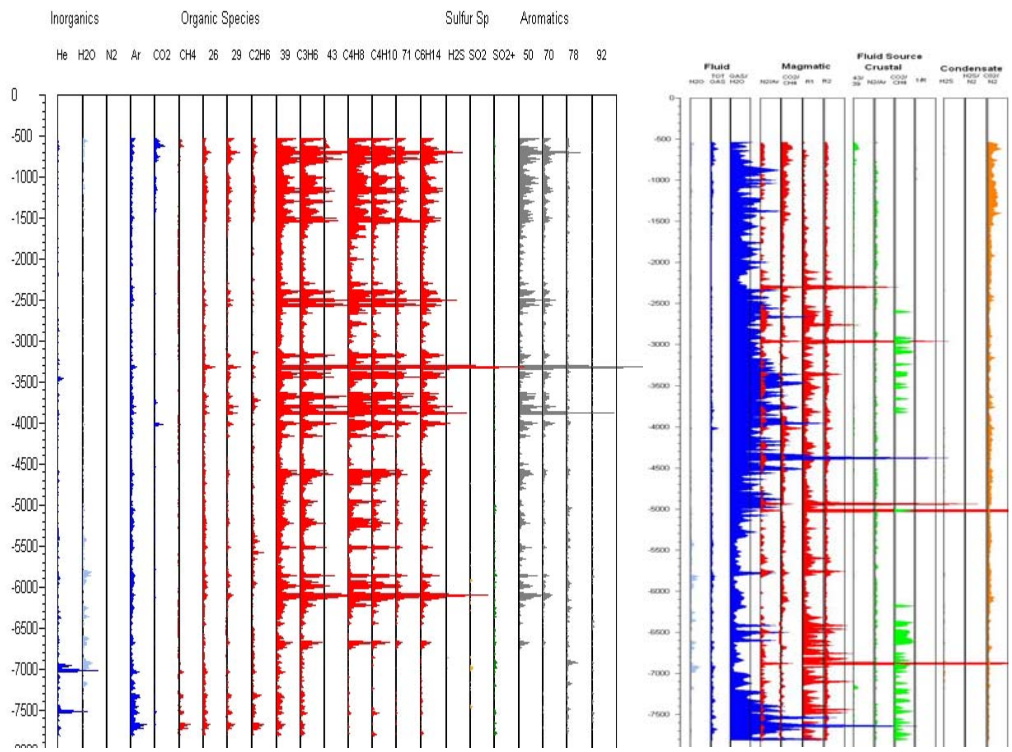
The ratios indicating steam/condensate occur in this zone, as well as some total gas. The zone from 7200 feet to depth of the well is interpreted as reservoir fluids. All of the ratios indicating magmatic fluid are high. Total gas and gas/water ratio are moderate to high, possibly indicating boiling. N_2 and CO_2 are high indicating magmatic components to the fluid at depth of 8500 to 9000 feet.

Figure 31: Well 38C-9 Interpreted FIS Logs



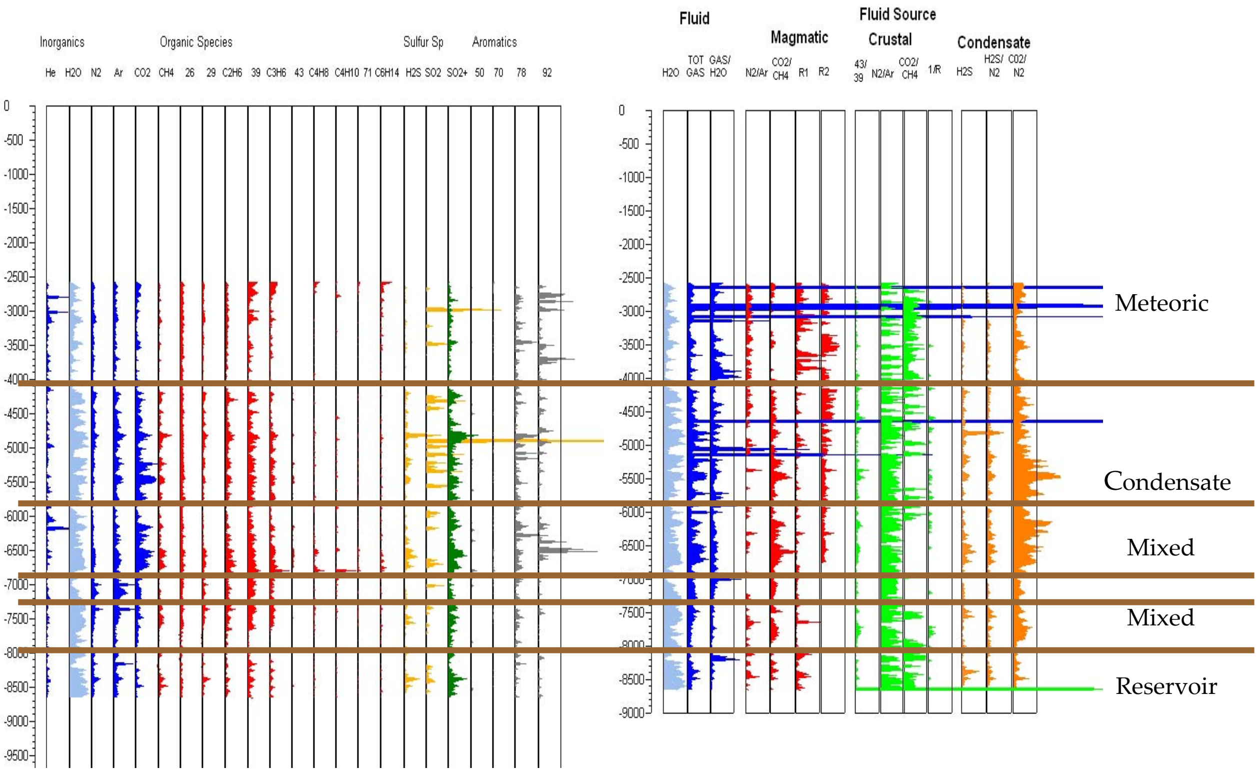
Well 84-30: Well 84-30 is south of the field and is a non-producing well. The fluid inclusions gas analysis shown in Figure 32 represents the background. The results show mainly heavy organics, benzene, and toluene. Argon occurs throughout the depth of the well. Minor amounts of CO_2 and CH_4 also occur. The ratios are large because there are limited amounts of the volatiles in the denominator.

Figure 32: Well 84-30 FIS Logs Indicating Little Fluid Activity



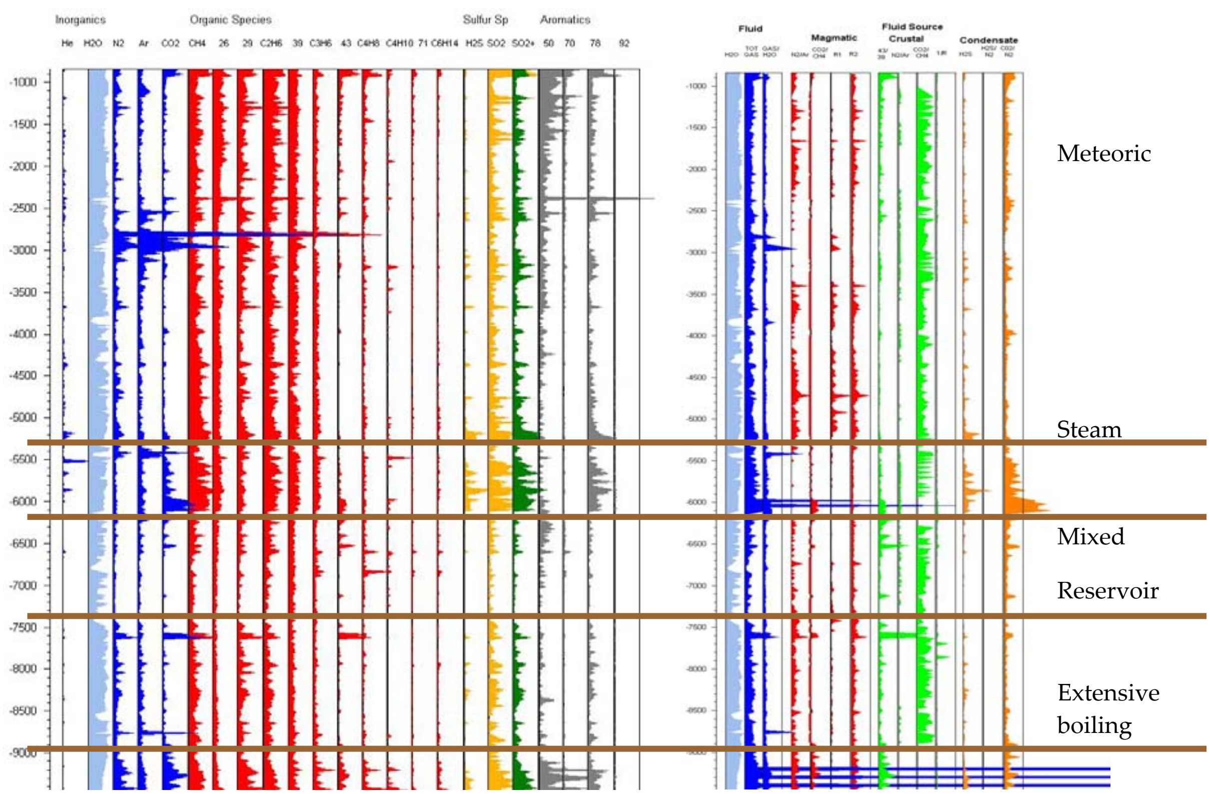
Well 58A-18: Well 58A-18 is a well of low enthalpy but produces 4 MW. The mixed zones indicated from 5800 to 7000 below 7300 feet have CO_2/CH_4 in magmatic fluids, indicating warmer fluids. The zones from 5500 to 5800 and 6900 to 7200 feet have low to no N_2/Ar and CO_2/CH_4 and low condensate ratios, indicating cooler waters.

Figure 33: Well 58A-18 Interpreted FIS Logs



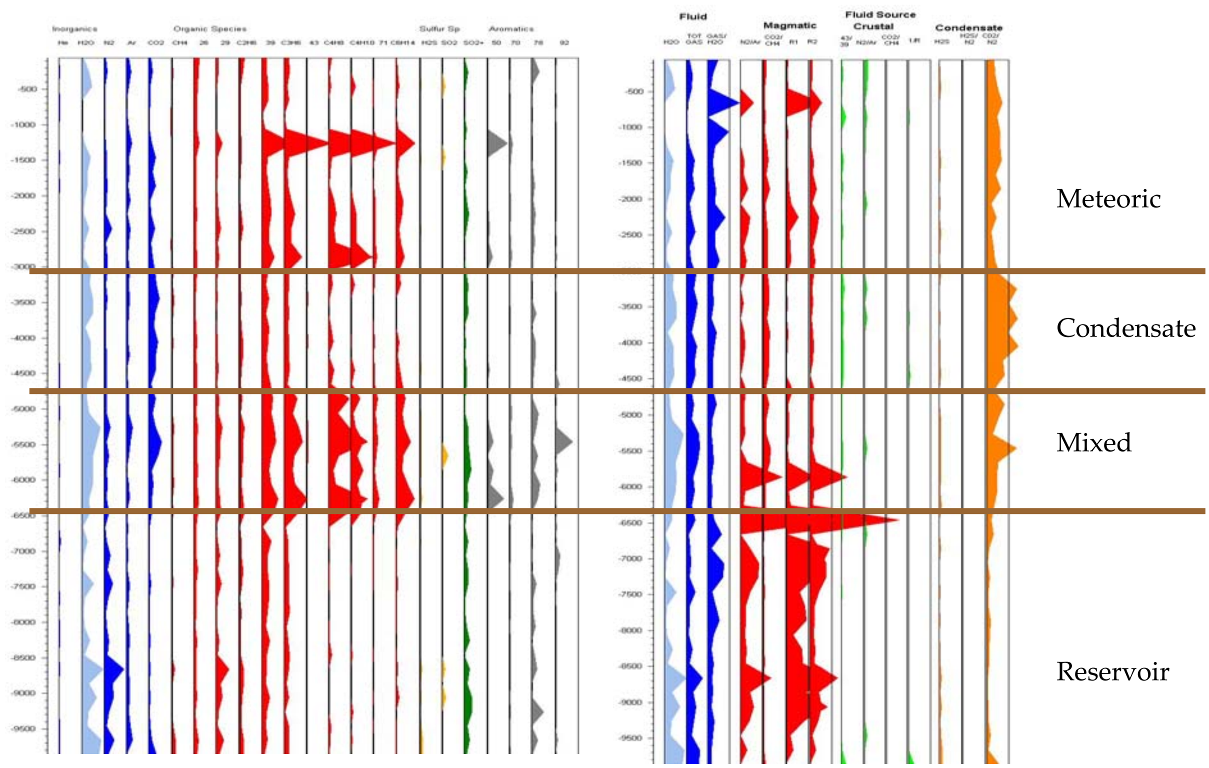
Well 38D-9: Well 38D-9 is a 7-MW producer of medium enthalpy. The well was sampled while being drilled. A steam zone is interpreted from 5400 feet to 6200 feet. The CO_2 and CH_4 values are high, and the condensate ratios are high. The zone from 7400 feet to the depth of the well is interpreted as reservoir fluids. There are high N_2/Ar and CO_2/CH_4 ratios as well as high N_2, CO_2, and CH_4 values, indicating magmatic components. The very high total gas indicates possible boiling.

Figure 34: Well 38D-9 Interpreted FIS Logs



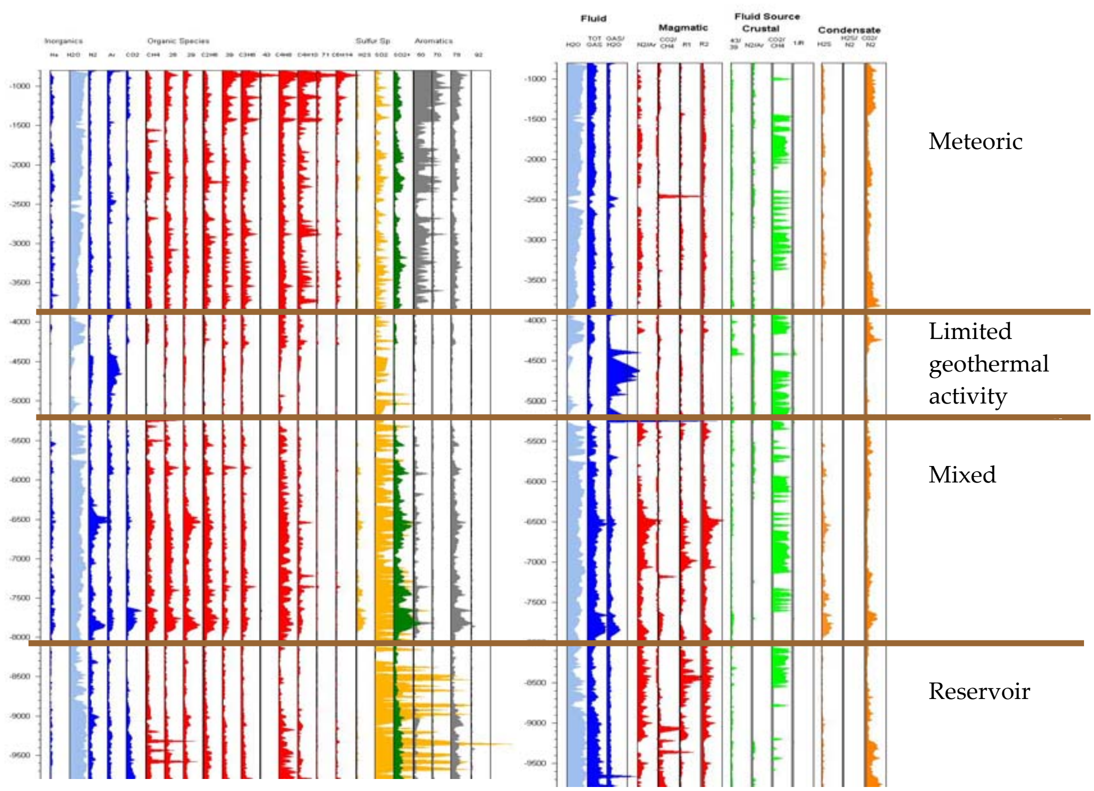
Well 58A-10: Well 58A-10 is on the eastern margin of the field and is a non-producer. It was sampled during drilling at 50-foot intervals. Overall the values on all columns appear to be lower than in other wells. There is little to no CH_4, lighter organics, He, H_2S, SO_2, and aromatics compared to the other wells. Also, the CO_2 occurs higher in the well, with very little CO_2 at depth. Many of the other wells have significant amounts of CO_2 at depth. Well 58A-10 is similar to Well 84-30 in the lack of CH_4, CO_2, light organics, He, H_2S, and SO_2. The lack of these volatile compounds is typical of wells on the margins of the field.

Figure 35: Well 58A-10 Interpreted FIS Logs



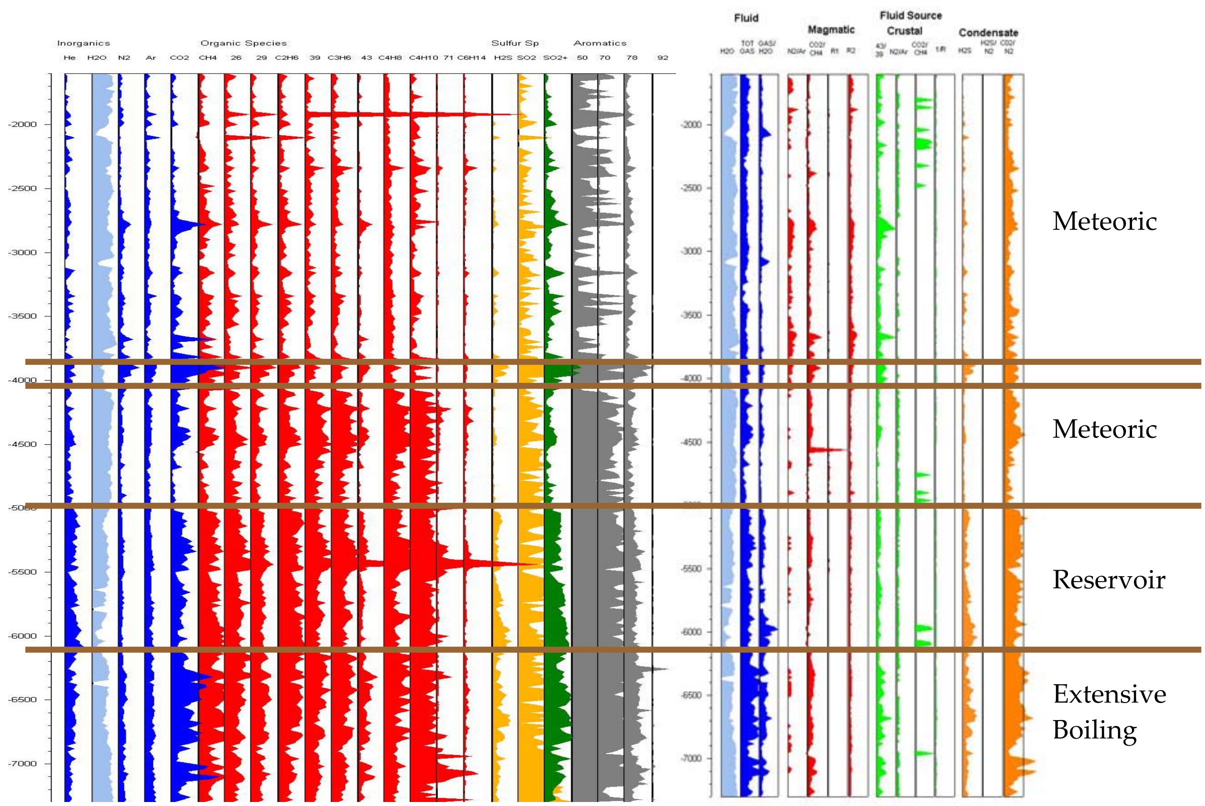
Well 51B-16: Well 51B-16 is on the east flank of the Coso field and is a high enthalpy well. However, it has low permeability and is a non-producing well. The upper part of the well has a large amount of organics, H_2O, and CO_2/CH_4 ratio that plots on the graph in the crustal waters area (below 4). This zone is characteristic of shallow meteoric fluids. At a depth of 4300 feet there appears to be a change in the chemistry, indicating a seal at this depth. Below this seal is a lack of fluid inclusion gas chemistry, indicating a lack of geothermal activity. At 5200 feet there is another change in the fluid inclusion gas chemistry, indicating another seal. Below this seal there is a large amount of organic compounds; in addition, the N_2/Ar ratio is high, indicating reservoir fluids. However, the CO_2/CH_4 ratio indicates crustal fluids. This zone was interpreted as mixed fluid zone. Another change in fluid inclusion gas chemistry occurs at 8000 feet. There is a lack of organics except for CH_4, and the ratios of N_2/Ar and CO_2/CH_4 indicate magmatic fluids. This zone is interpreted as reservoir fluids. Evidence of boiling (the high total gas, high amounts of CO_2, N_2, and CH_4) appears from 9200 feet to the depth of the well. The overall signature for the reservoir fluids also appears more distinctive than in Well 33-7. The reservoir fluid area and boiling indicators are more pronounced in Well 51B-16 than in Well 33-7.

Figure 36: Well 51B-16 Interpreted FIS Logs



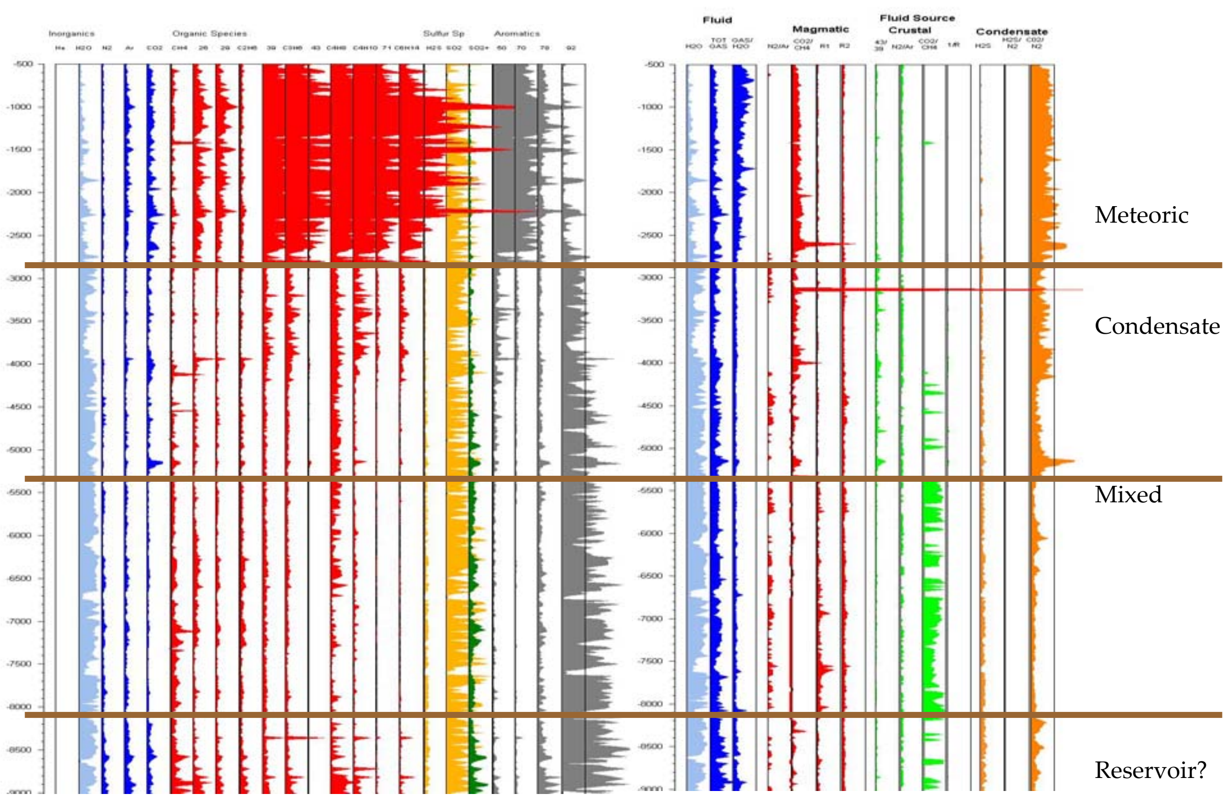
Well 34-9RD2: Well 34-9RD2 is a high enthalpy well and was a 3-MW producer. It is now an injector well because of its location on the northeast corner of the field. It is the nearest well to the Coso Hot Springs. Below 3800 feet, the values for most of the volatiles are high. Significant CO_2, CH_4, total gas, and condensate values occur below 5000 feet to depth of well and from 3800 feet to 4100 feet, indicating a similar zone of fluids in those ranges.

Figure 37: Well 34-9RD2 Interpreted FIS Logs



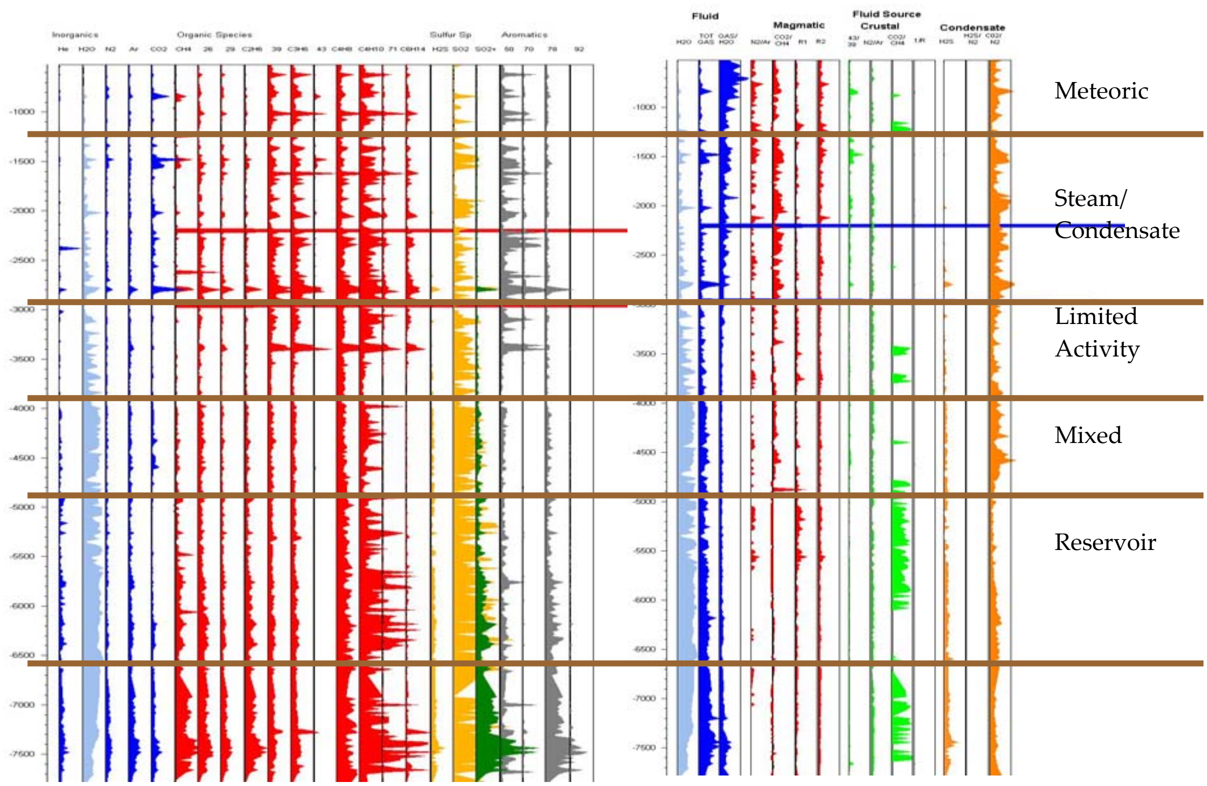
Well 67-17: Well 67-17 is a low enthalpy non-producer. It is an injection well. The fluid signature appears to represent meteoric fluids to 2900 feet, followed by a steam/condensate zone to 5400 feet. A mixed zone occurs below 5400 feet to 6100 feet. From 6100 feet to depth of well it is difficult to determine if the signatures indicate mixed fluids or reservoir fluids. In this zone there is more CO_2 and CH_4 than there is higher in the well.

Figure 38: Well 67-17 Interpreted FIS Logs



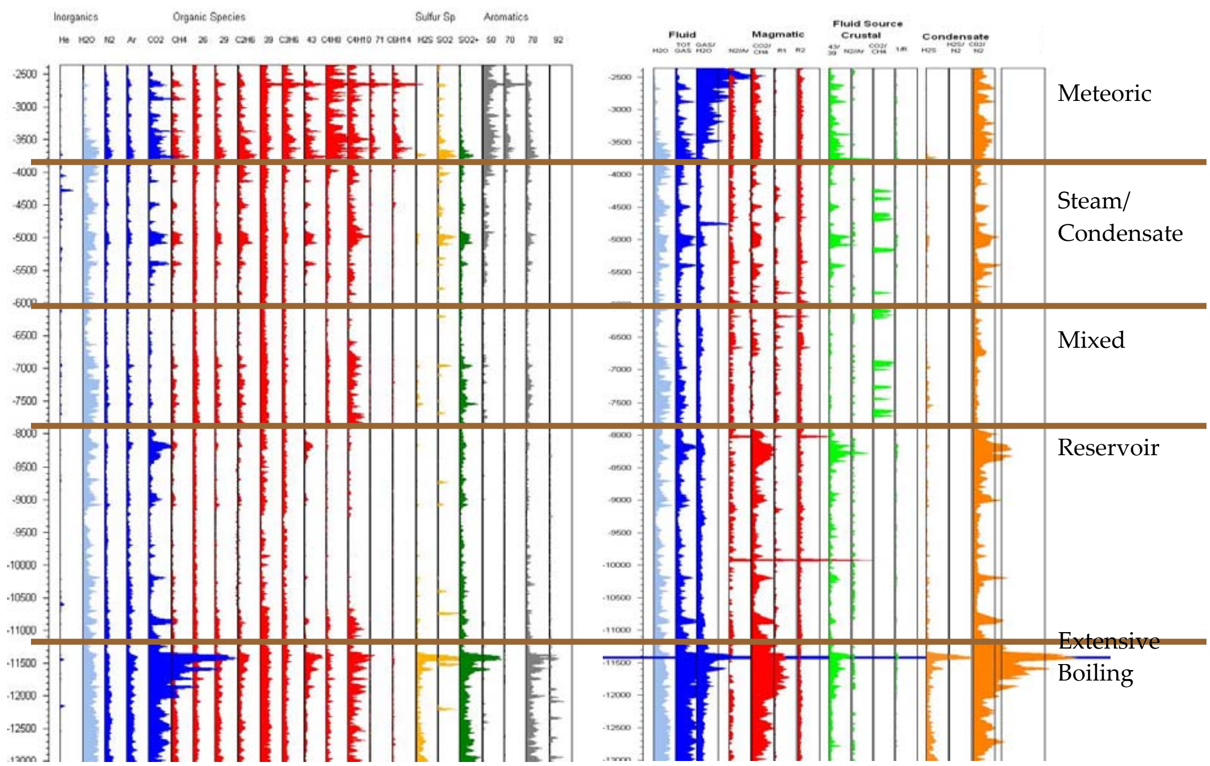
Well 52-20: Well 52-20 is a low enthalpy, 3-MW producer. The meteoric zone occurs to 3500 feet. Large CH_4 peaks correspond to high total gas peaks. A zone of limited activity occurs from 3500 feet to 4000 feet. Below 4000 feet is a steam/condensate zone to 4900 feet. From 4900 feet to the depth of the well is a zone interpreted as mixed fluids. From 6700 feet down, CH_4 increases significantly; CO_2 increases somewhat, as do some of the heavier organics. These values are consistent with reservoir fluids.

Figure 39: Well 52-20 Interpreted FIS Logs



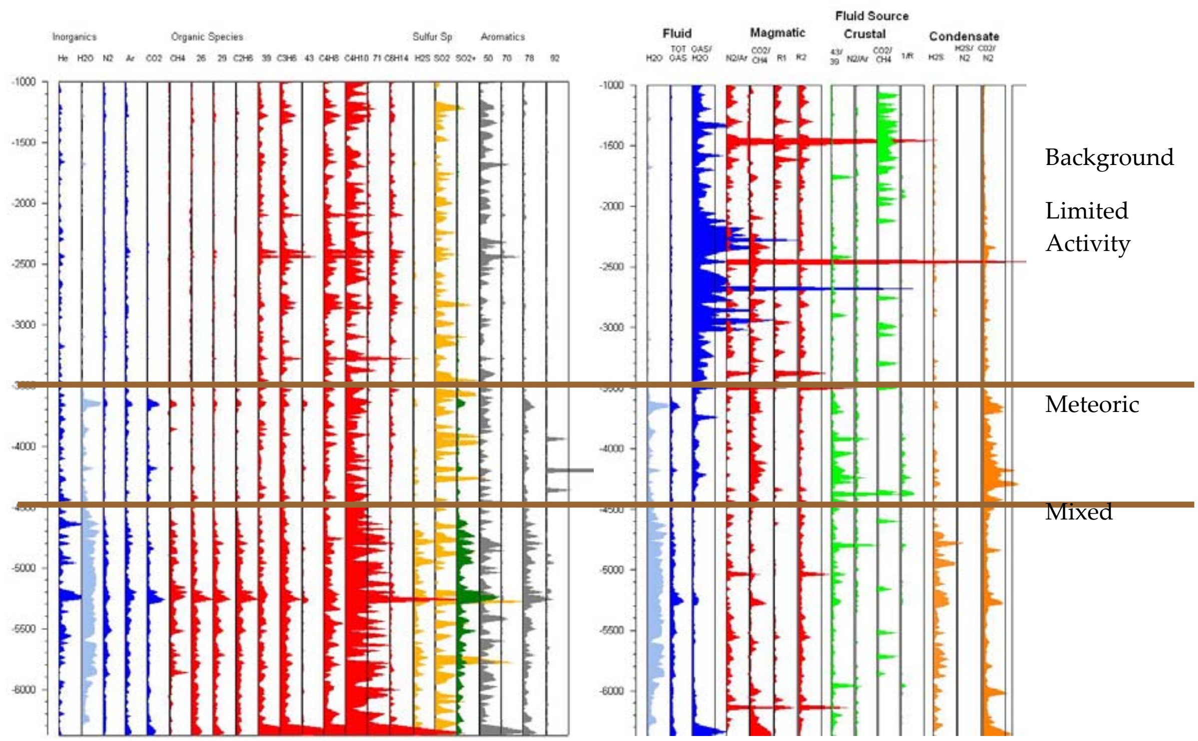
Well 46A-19RD: Well 46A-19RD is the hottest and deepest well in the field. It is a non-producer because of lack of permeability. This well will be hydrofractured in the future to increase the permeability. The zone to a depth of 3900 feet is interpreted as meteoric fluids followed by a steam/condensate characterized by high total gas and condensate ratios. A mixed zone occurs from 5800 feet to 8000 feet. Below 8000 feet CO_2 increases significantly, indicating a reservoir zone. From 11,400 feet N_2, CH_4, and Ar organic species also increase. The CO_2 peak at 11,500 feet corresponds to a rhyolite rock type that only occurs in this well (Kovac 2004). This zone is interpreted as extensive boiling and the sharp rise in CO_2 also corresponds with the rhyolite rock.

Figure 40: Well 46A-19RD Interpreted FIS Logs



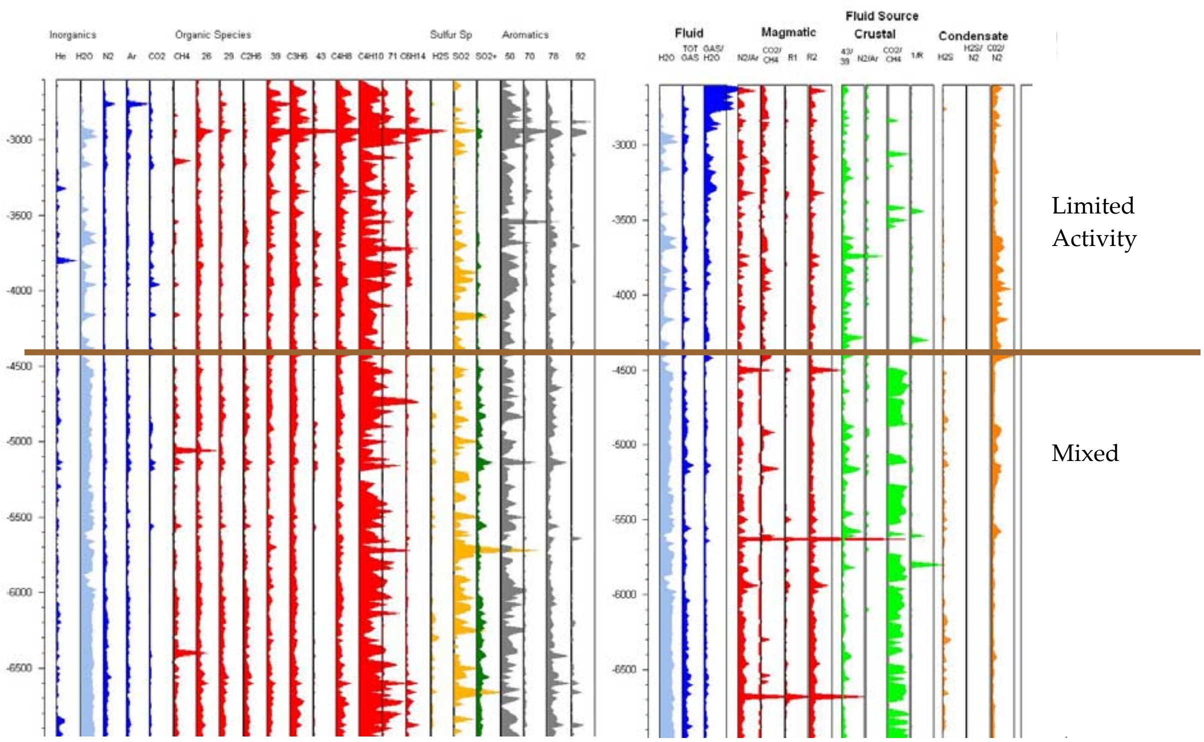
Well 68-20: Well 68-20 is a low enthalpy well that is a non-producer. The well now is an injector. The upper portion of the well to depth of 3100 feet looks similar to Well 84-30 (Figure 30) and is interpreted as meteoric. A steam/condensate zone occurs from 3100 feet to about 4500 feet. Below this zone the fluid signature represents a mixed fluid zone. There is an increase in a number of volatiles from 5200 feet to 5300 feet.

Figure 41: Well 68-20 Interpreted FIS Logs



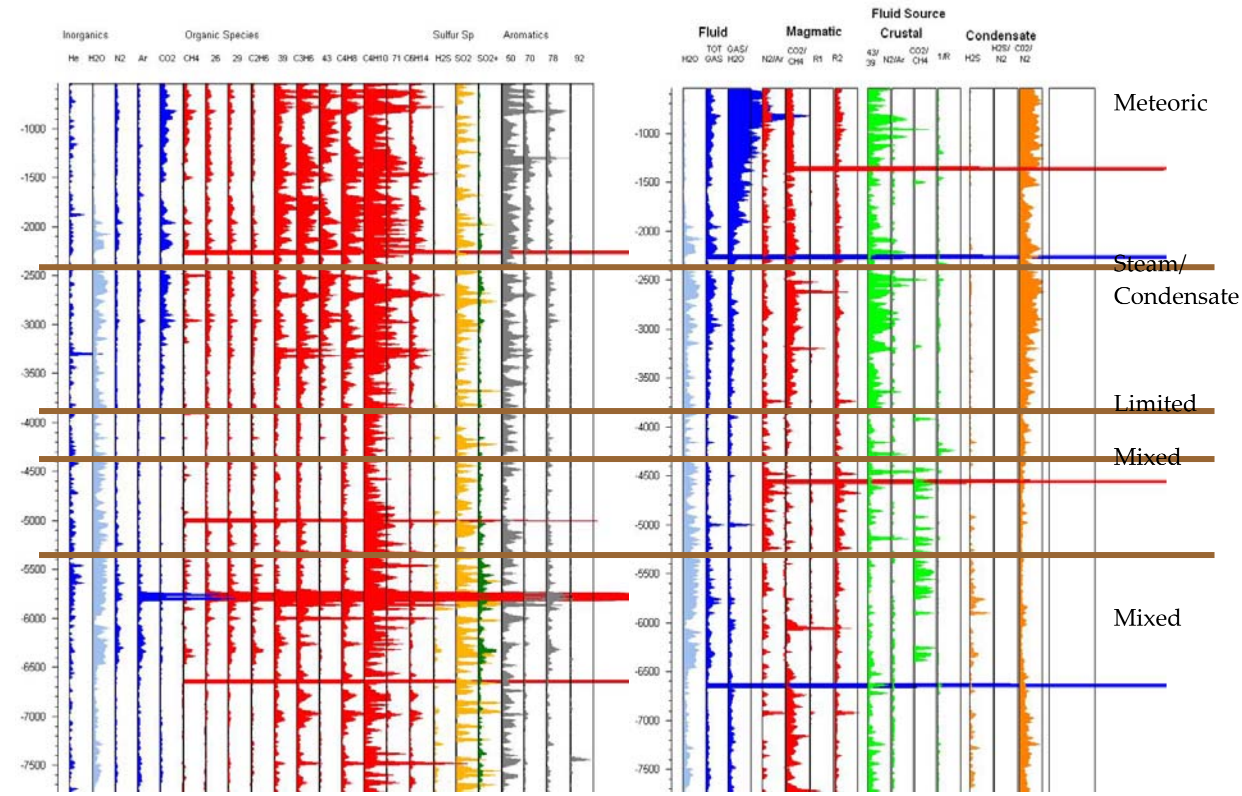
Well 68-20RD: Well 68-20RD is a re-drill of Well 68-20. The re-drill took place seven years after 68-20 was installed. Section 5.5 discusses how these two wells are dissimilar and how they contribute to our understanding of timing of the fluid inclusions. The zones in 68-20RD are interpreted similarly to those of Well 68-20; however, the mixed zone in Well 68-20RD contains larger N_2/Ar ratios and the CO_2 and CH_4 values are lower than those in Well 68-20. The larger N_2/Ar ratios indicate hotter waters than in Well 68-20RD.

Figure 42: Well 68-20RD Interpreted FIS Logs



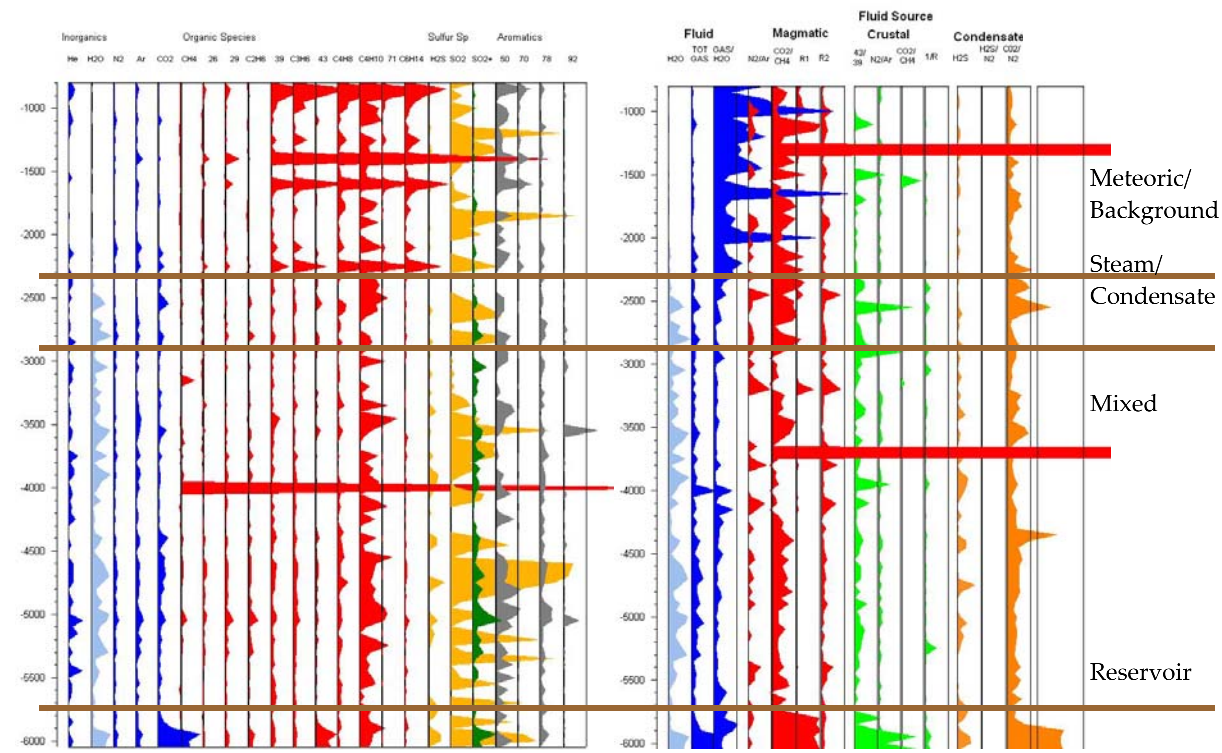
Well 67-17C: Well 67-17C is a low enthalpy well that was drilled near 67-17. The lower portion of 67-17C deviates compared to Well 67-17. None of the zones appear to represent reservoir fluids. There is a lack of water below 6500 feet, and except for the gas/water ratios that zone appears similar to the meteoric fluids in the top portion of the well. There is a zone of little activity from 4000 feet to about 4400 feet.

Figure 43: Well 67-17C Interpreted FIS Logs



Well 73-19: Well 73-19 is a high enthalpy, 3-MW producer. This well was sampled at 50-foot intervals. The upper zone to 2300 feet appears similar to Well 84-30. From 2300 feet to about 2700 feet the condensate ratios are high, as well as the beginning of the total gas. A mixed fluid is interpreted below 2700 feet to 5700 feet. Near the bottom of the well CO_2, CO_2/CH_4, total gas and water increase, indicating reservoir fluids.

Figure 44: Well 73-19 Interpreted FIS Logs



The discussions of the preceding wells indicate how fluid inclusion gas chemistry was used to interpret fluid types in the wells. Distinct zones in each well can be readily seen, with several smaller zones within each larger zone. If the peaks do represent fractures, then these smaller zones represent fractures with fluids of slightly different origins. Several of the wells (84-30, 67-17, 52-20, 68-20, 68-20RD, and 67-17C) did not appear to have reservoir fluid zones. Except for reservoir fluids in Well 67-17 and indications of two cold-water fracture zones in Well 46A-19RD, the original interpretations agreed with how the Coso geologists have understood these wells.

Low enthalpy wells (33-7, 58A-18, 67-17, 67-17C, 68-20, 68-20RD, and 52-20) tended not to have large reservoir sections, and indications of boiling were limited. The producing wells from this group (33-7, 58A-18, and 52-20) had larger reservoir zones. The remaining wells (38C-9, 38D-9, 51B-16, 34-9RD2, 46A-19RD, and 73-19) tended to have larger reservoir sections and boiling was evident. Extensive boiling occurred in several of the wells (38D-9, 34-9RD2, and 46A-19RD). This was indicated by high CO_2 values and high total gas. Some of the other volatiles such as N_2 and CH_4 were also high in these zones.

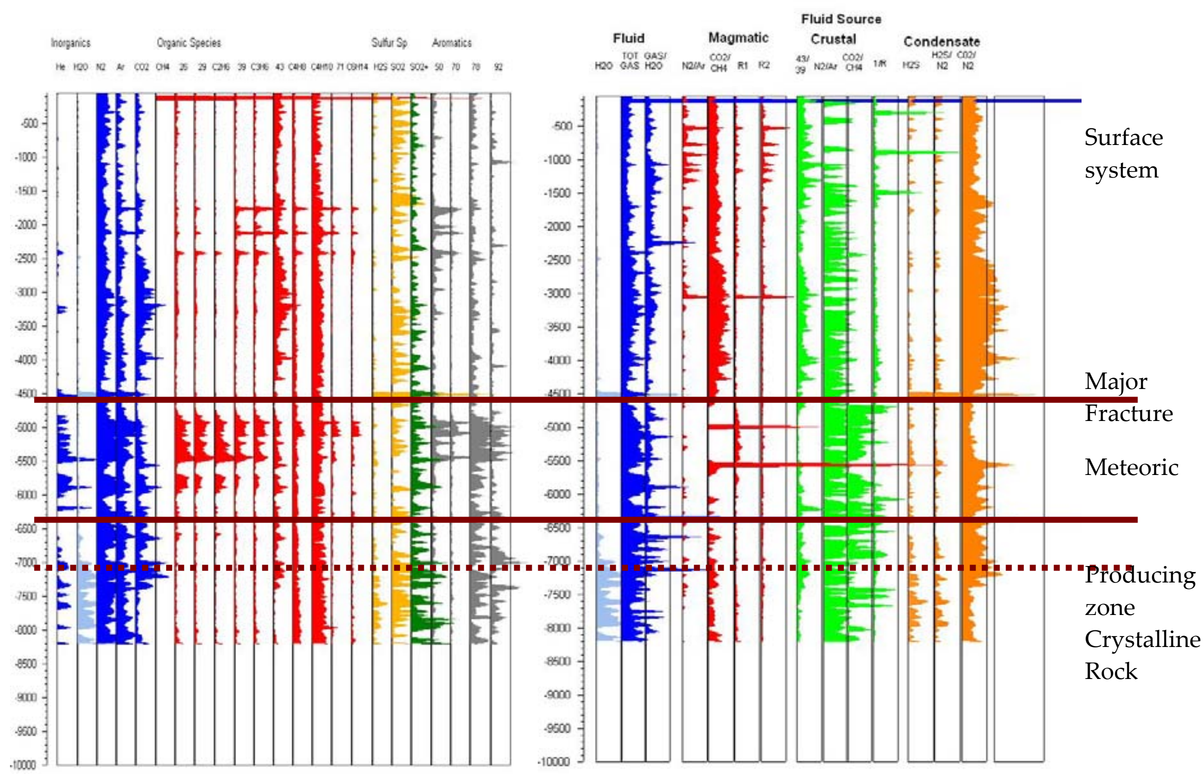
6.2 Fluid Types in Beowawe Wells

The same criteria applied to the Coso wells for determining fluid types were applied to the Beowawe Wells. This was a test to determine if the method would work at a different field and also provide real-time data for well decisions. Two wells, 57-13 and 77-13, were provided for analysis. Well 77-13 is a large producer at Beowawe. Temperatures range up to 200°C (392°F). Well 77-13 penetrates a fault at approximately 5500 feet and again at about 8000 feet. Well 57-13 was drilled in December 2005. The purpose of the well was to intersect the fault. The well was drilled to 10,600 feet, and it was unknown from the drilling logs if the fault was intersected. Bulk analysis of the drill cuttings fluid inclusions was conducted to determine if the fault could be recognized. At the time of the analysis, the drill rig was idling on-site costing the company thousands of dollars a day in downtime. The analysis took approximately four days and was used to determine if drilling should continue or if the well should be completed for production. Figures 43 and 44 present the results.

Although this was a different field from Coso, the analysis indicated that it was possible to use FIS to interpret the well conditions. Since this was a different field from Coso, this was also a good experiment to see how applicable the FIS method was to another field. As described in the Methods section, a technique for plotting the chemical species on the log was developed. For each chemical species for the field, two times the standard deviation added to the average was used as the maximum for plotting the strip log of each chemical species. This resulted in the logs presenting results that were readable and useable.

Well 77-13: Beowawe is in the Basin and Range province of Nevada and has a series of metasediments that infill the basin. As discussed in Section 2.5, the production temperatures are about 140˚C (284°F) and production is from the highly fracture crystalline rocks. Well 77-13 indicates three main zones: a surface system zone, a major fracture with meteoric fluid signature, and a producing zone. The fault in this well, between about 5500 and 8000 feet, is approximately indicated by the major fracture zone with the meteoric fluid signature. Below this is the producing zone. The presence of water in the fluid inclusion data at about 7000 feet indicates a crystalline rock rather than metasediments.

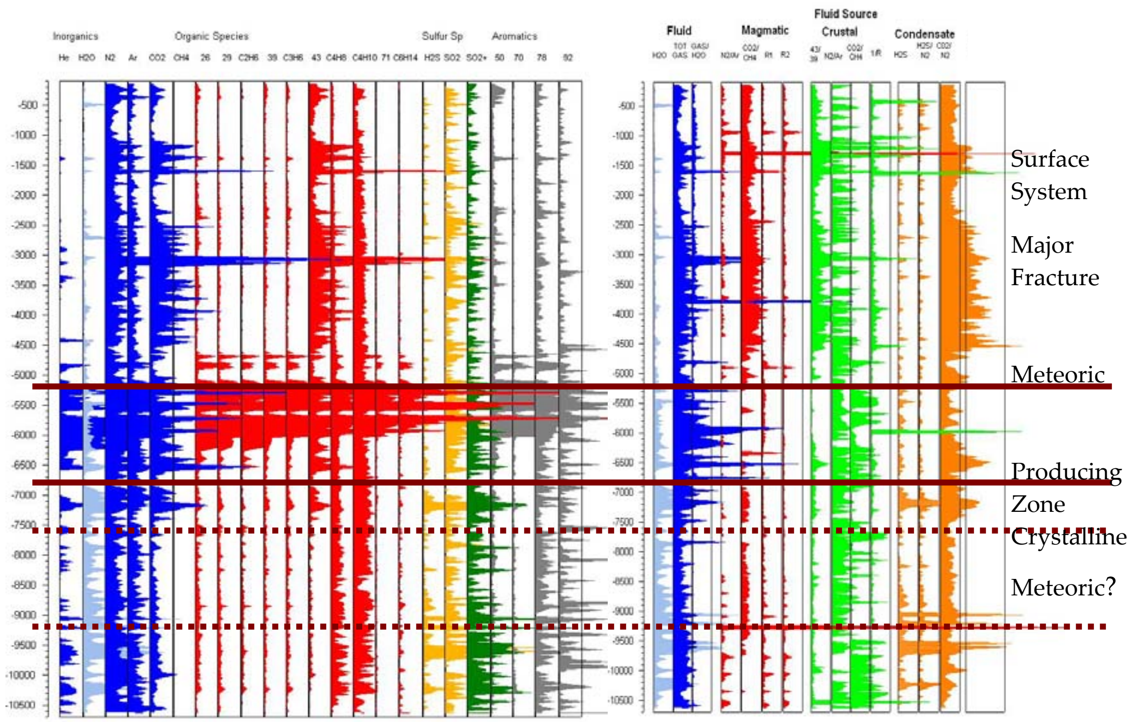
Figure 45: Beowawe Well 77-13 Interpreted FIS Logs



Well 57-13

Comparing the logs for Well 57-13 with those developed for Well 77-13 (Figures 43 and 44), there are similar zones including the major fracture zone with a meteoric signature and a producing zone that has a high water value. This would indicate that the fault was encountered in this well from about 5100 feet to about 6700 feet and that the producing zone is below this fracture zone.

Figure 46: Beowawe Well 57-13 Interpreted FIS Logs



Although not much information was provided by the geologist at Beowawe regarding depth of the production zone, stratigraphy, or fluid types, the FIS logs presented for both wells analyzed indicate major zones and can be used to assist in well development. Based on the FIS analysis it was determined that Well 57-13 had penetrated the production zone and drilling was stopped. Production was expected, however the fluid flow necessary for production was not encountered.

A key to applying FIS to other fields is the need to have at least one well that has undergone some interpretation such as whether it is a producer, its temperature logs, litholgic logs, or other diagnostic information. This prior knowledge of one well in the field can be used to compare against new wells and new FIS data. Each field will need calibration, however FIS can be applied to solve exploration problems such as presented. The only prior knowledge was the location of the fracture zone in Well 77-13, which once the FIS signature was determined, it was readily identified in Well 57-13.

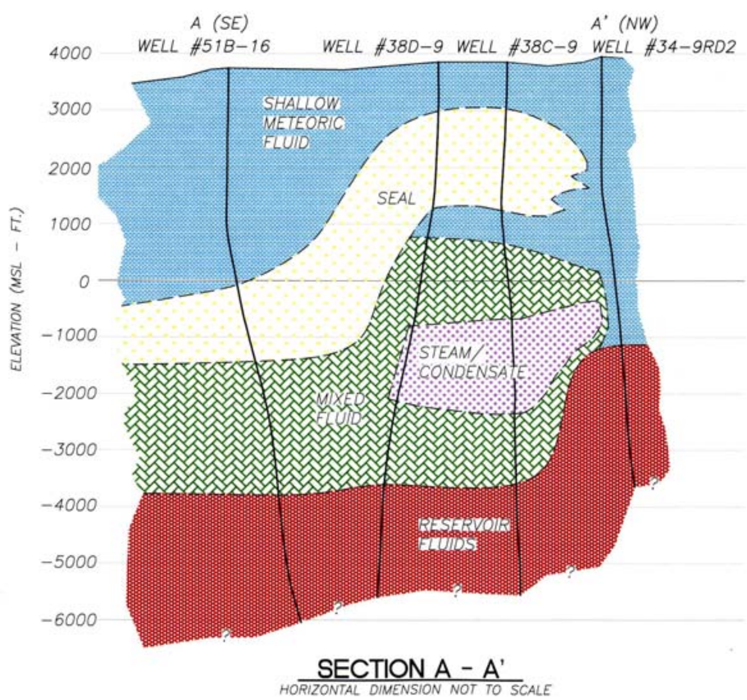
6.3 Fluid Model

A fluid model was developed for the Coso geothermal field using the fluid inclusion stratigraphy developed for each well. Several cross sections were prepared based on the well interpretations and compared to existing data. Coso geologists approved of the cross-sections developed. Presented here are three cross-sections: western, eastern, and diagonally across the field (Figures 47, 48 and 50). The locations of the cross-sections are shown in Figure 2.

6.3.1 East Flank

Figure 47 presents a cross-section developed for the area of the field known as the East Flank. Four wells were studied from this area: 38C-9, 38D-9, 51B-16, and 34-9RD2. Wells 38C-9 and 51B-16 are considered moderate to large producers. Well 34-9RD2 is currently an injection well. Well 38D-9 was sampled for FIS analysis during the drilling process and is a moderate to large producer.

Figure 47: Cross-Section Based on FIS of the East Flank Area



It can be seen in Figure 47 that a seal separates the shallow meteoric fluids from a steam/condensate zone and a mixed fluid zone. Below the zones is an area interpreted to represent fluids that have undergone boiling. The boiling limit was defined as the area where gas/water ratios changed significantly and high amounts of various gases such as CO_2, N_2, and CH_4 were present in the fluid inclusion gas chemistry. These fluids are considered reservoir fluids. On the East Flank the reservoir fluids have a magmatic-derived component. Typically these fluids have high amounts of N_2 and CO_2. The production zone lies below the boiling limit and within the reservoir fluids.

Well 34-9RD2 is an injection well. The fluid inclusion gas chemistry indicates that most fluids within the well are shallow meteoric fluids. There is some evidence for boiling and reservoir fluids at shallower depths than in the other wells along the East Flank. The boiling limit at approximately 5100 feet in depth, determined from the fluid inclusion gas chemistry for this well, is within 200 feet of an increase in homogenization temperatures from fluid inclusion work conducted by Kovac et al. (2005) for this well. For this well this level also corresponds to a change in rock type from diorites and granodiorites to granites.

6.3.2 Western Edge

Figure 48 presents a cross-section developed for the western edge of the field. Three wells were placed along this cross-section: 33-7, 58A-18, and 46A-19RD. Well 46A-19RD is the deepest well interpreted in the study, extending to approximately 9000 feet below sea level. Well 33-7 is a low enthalpy, 2-MW producer, and Well 46A-19RD is a high enthalpy non-producer. Well 58A-18 was one of the first wells to be interpreted and was included in the study to determine if cold water entrances could be determined from the fluid inclusion gas chemistry. Well 58A-18 is a low enthalpy, 4-MW producer. Based on previous work reported by Dilley et al. (2004), there was a correlation between the fluid inclusion gas chemistry indicating cold-water entrances and reductions in the temperature log.

Figure 48: Cross-Section Based on FIS of the Western Edge of the Coso Field. Well 33-7 is to the North End of the Field

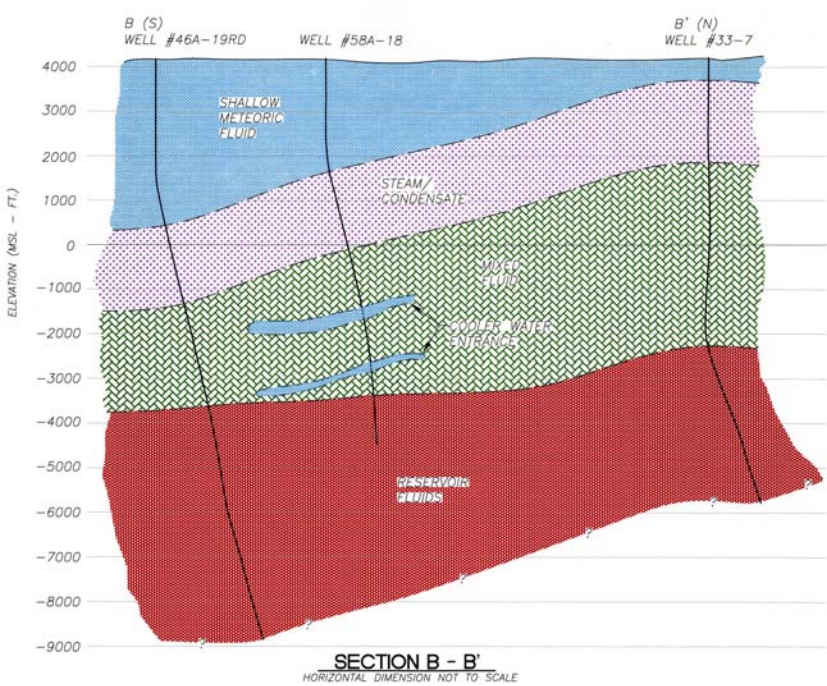
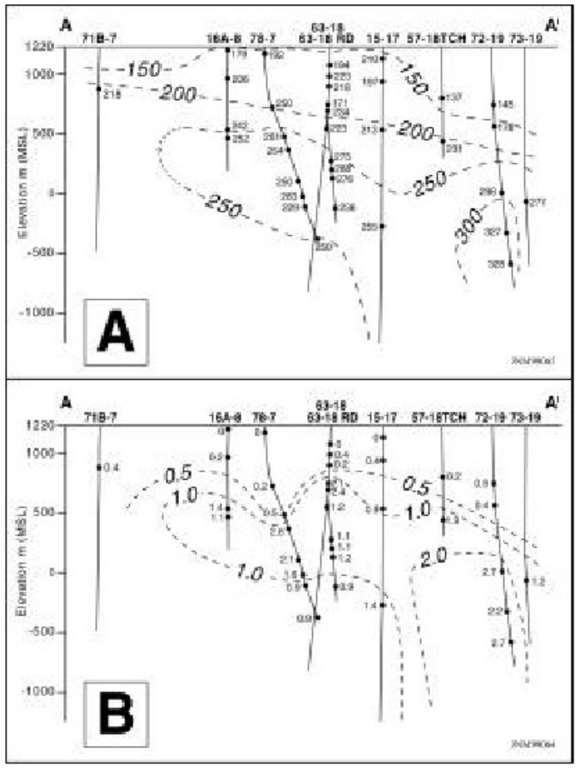


Figure 49: North-South Cross-Sections of the Reservoir Prepared Based on Fluid Inclusion Studies in 1999/2000 in Adams et al. (2000)



A) Maximum fluid-inclusion homogenization temperatures and B) maximum salinities of inclusion in weight percent NaCl equivalent. A on the cross-section is to the north and A' is to the south.

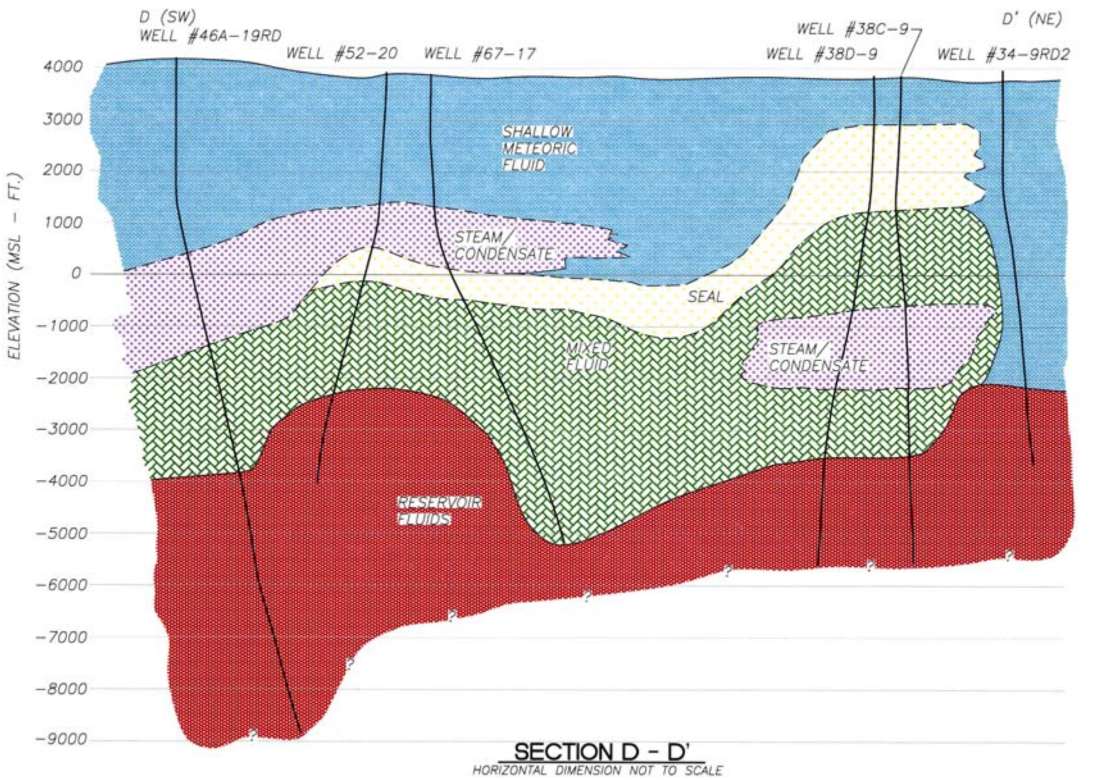
From the cross-section there appears to be a rise in the deep reservoir fluids and the steam/condensate zone from the south (Well 46A-19) to the north (Well 33-7). This cross-section is similar to the cross-section of homogenization temperatures and salinities shown in Figure 49. This cross-section is presented in Adams et al. (2000) and was prepared from fluid inclusion studies by Joe Moore and Dave Norman. The low-salinity fluids correspond to the steam/condensate zone, and the high-salinity and high temperatures correspond to the deep reservoir fluids.

It was further suggested in the Adams paper that there was a change between the early and modern systems with the disappearance of the low-salinity groundwater since the last pluvial period in the area around 10,000 years ago. From the fluid inclusion gas chemistry, the area indicated in Figure 49 as shallow meteoric fluid has low N_2/Ar and low CO_2/CH_4 ratios, suggesting meteoric fluid, and also has large peaks for organic species. The organic species include butane, propane, and ethylene. The organic signature could be the result of the organics within the playa lakes that fed the system in the past.

6.3.3 Across the Field

Figure 50 presents a cross-section diagonally across the field from southwest to northeast. Wells 38C-9, 38D-9, and 34-9RD2 are on the portion of the field known as the East Flank. The area of no geothermal activity that started in the middle portion of the field appears to continue across the field and occurs in the East Flank. Based on the elevation of this zone there may be a fault that occurs where the area rises near the East Flank wells. It is unknown whether the East Flank is connected to the rest of the field as suggested in Figure 50 or if it isolated by a fault structure. The interpretations for these cross-sections correspond with the interpretations made by others using other data (Adams et al. 2000).

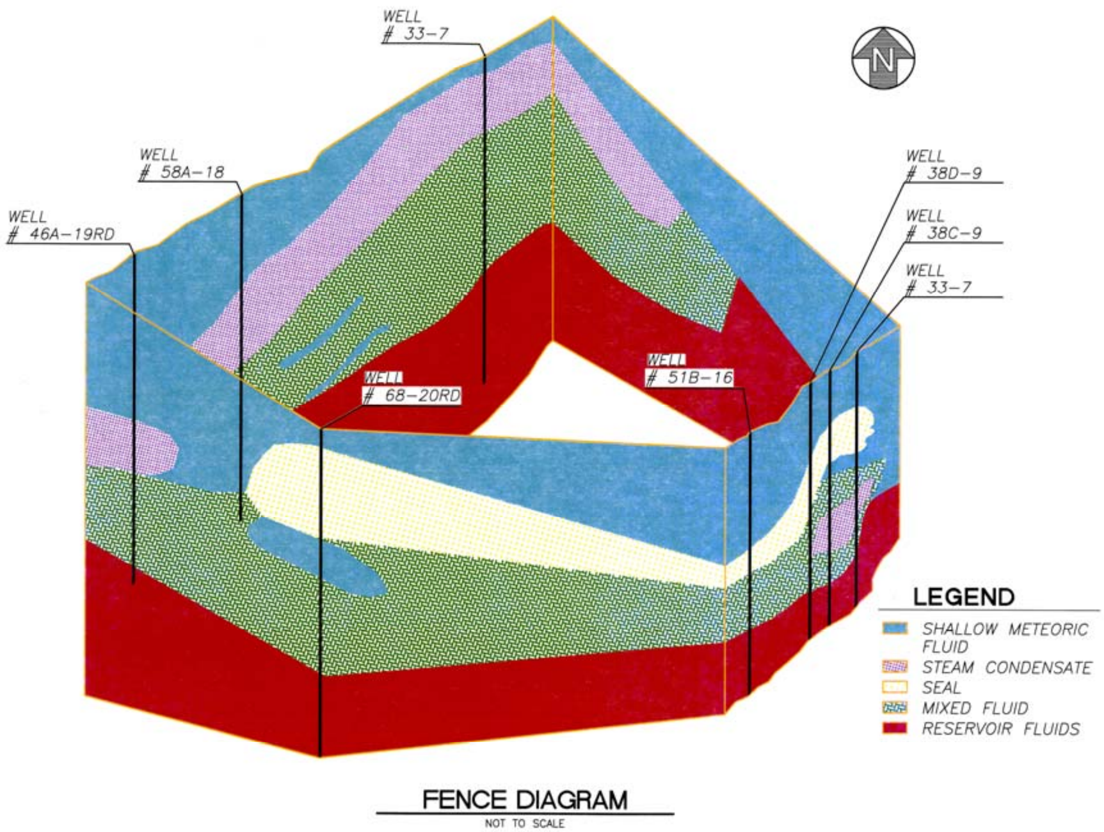
Figure 50: Cross-Section Based on FIS Diagonally Across the Coso Field from the Southwest to the Northeast



6.3.4 Reservoir Model

Based on the permeability plots in Figures 27 through 29 and the fluid cross sections in Figures 47, 48, and 50, a model of the reservoir was created. A fence diagram of the field is presented in Figure 51. The fence diagram shows a rise in the reservoir fluids from the southwestern section of the reservoir towards the middle and north. This rise in the deep reservoir fluids is evident in wells along the western edge. A zone of little activity

Figure 51: Fence Diagram of the Coso Geothermal Field



Starting in the middle portion of the field continues to the East Flank, however based on the elevations of the seals it appears there may be a fault offsetting the East Flank from the rest of the field. Steam/Condensate zones are shown to occur along the western side of the field and appear to migrate over the seal toward the middle of the field, further suggesting a fault or isolation of the East Flank.

CHAPTER 7: Discussion

7.1 Applicability to Other Fields

FIS is applicable to other fields. Although this study focused on the Coso Reservoir, the Beowawe field was also used in the study. The Beowawe samples show that the FIS method is highly applicable. To apply the method to a new field, a known producing well would be useful to calibrate the method to the new field. With the use of the stratigraphy of the known producing well and geological knowledge of the new field, FIS could be readily used for interpreting new wells in that field. As seen with the Beowawe samples, knowing that the general stratigraphy is a sedimentary package over igneous rocks helped determine the major breaks in the FIS logs. Plotting of the logs can be accomplished by using two times the standard deviation plus the average as the high value for plotting and the lowest number in each species as the lowest number for plotting.

If the field is new and the FIS method is applied, major changes in inclusion chemistry could be seen on the logs, however what fluid type one particular group of inclusion chemical signatures would indicate would be open for discussion. Much like at the beginning of this research, overall chemical signatures suggestive of certain types of fluids would have to be used to determine what one particular group of inclusion chemical signatures indicate. For instance, a large amount of organics with low N_2/Ar ratios would most likely indicate a cooler possibly meteoric type fluid. Separating hotter zones from mixed zones may be difficult with a new field since the inclusion chemical signatures may be similar.

7.2 Usefulness

The usefulness of the FIS method is indicated by the various experiments conducted during the course of this research. The differences between Well 68-20 at Coso and its redrill, 68-20RD, indicate that the inclusion chemistries reflect most recent fluids.

Each of the experiments was designed to solve a particular reservoir problem. The most useful tool is the identification of fractures and permeable zones. The FIS method has shown at least on a preliminary level that the peaks in the data indicate fractures. Permeable zones and fracture locations are important to producing reservoirs. In addition to the obvious need to know permeable areas, understanding the nature of fractures can assist in future enhanced geothermal projects.

The method also distinguishes hotter fluids from colder fluids and allows a fluid stratigraphy across the field to be developed. This, along with permeable areas, could be easily used to identify future exploration areas. Having a picture of the geothermal reservoir improves its management.

This study demonstrates that FIS can be used for geothermal reservoir assessment and management and that it shows great promise for application in many geothermal reservoirs beside Coso.

7.3 Fractures

From the limited fracture study using cores from Coso and Karaha, it can be seen that peaks observed on FIS logs are based on fractures in the rock. When FIS is used for the petroleum industry, they have assumed that the peaks observed in their data are also fractures within the reservoir. From the study conducted for this project it appears that the more volatile compounds create broader peaks around the fracture, whereas the less mobile compounds create sharp peaks. From the Karaha samples it appeared not to matter whether the fracture filling material was calcite, quartz, pyrite, or some mixture of the minerals; there were several compounds with peaks that corresponded to the filled fractures. In the highly altered zones the peaks were much broader as a result of the infiltration of the compounds throughout the entire altered zone.

7.4 Technology Transfer

Technical papers were presented at several conferences about FIS during its development. These included:

- Geothermal Resource Council Annual Meeting 30 in San Diego, 2006
- The 31st Workshop on Geothermal Reservoir Engineering at Stanford University, 2006
- Goldschmidt Conference on Geochemistry in 2006
- Geothermal Resource Council Annual Meeting 29 in Reno, 2005
- Presentation to Iceland Geosurvey on FIS in June 2005
- Geothermal Resource Council Annual Meeting 28 in Palm Springs, 2004
- The 29th Workshop on Geothermal Reservoir Engineering at Stanford University, 2004

In addition to these technical presentations at these conferences the FIS method has also been tested on an additional field in California. The transfer of this technology to the geothermal community is occurring through these technical presentations and by use by other researchers.

The Department of Energy has funded additional work using the FIS method under the Enhanced Geothermal Program. The project is titled*: Identifying Fracture Types and Relative Ages Using Fluid Inclusion Stratigraphy*. By using the FIS method the hope is to be able to identify fractures for enhancement.

The FIS method offers a useable, cost effective method that will continue to be used in the geothermal industry as it is marketed to the industry.

CHAPTER 8:
Conclusion

This project has shown that FIS can, by the chemical signatures determined in the fluid inclusions, arrive at the relative temperatures of the fluids. Fracture patterns can also be identified by FIS as peaks in chemical species plotted against depth. Permeable zones are identified by FIS through various chemical ratios. This method provides several of the more important elements in producing a model of a geothermal system: relative temperature of fluids, chemistry of fluids, and permeable zones within the system.

Fluid inclusion gas chemistry of well cuttings from geothermal reservoirs provides significant information about geothermal wells. Fluid inclusion gas chemistry does not correlate to rock type but does correlate to alteration mineral assemblages. Fluid types can be determined through the use of various species and gas ratios. The analyses of two wells drilled in the same location seven years apart indicate that fluid inclusions can develop within seven years and that this can be seen in the analysis. The dynamic fluid environment, as well as the high stress rates wherein fractures are continually being opened and closed also lends credence to the conclusion that the fluid inclusion gas analysis is mainly analyzing modern fluids.

Based on fluid inclusion gas chemistry and the FIS method, several cross-sections were developed for the Coso geothermal field. The cross-sections show reasonable match from well to well showing a fluid stratigraphy, and the results agree well with prior fluid inclusion studies and the general knowledge of the field. The FIS method will provide a useful, economical tool for geothermal reservoir assessment.

8.1 Additional Work to be Done

Additional work to be done includes the following:

- Refinement of the permeability zones, which also leads to relationship with fractures.
- Further study on fractures and relationship to FIS peaks.
- Further study on other fields and how well FIS works.

Determine if there are precursors to upcoming hotter zones that can be identified using FIS.

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GLOSSARY

Adiabatic Cooling	A process in which the temperature of a system is reduced without any heat being exchanged between the system and its surroundings.
Analytical Drift	A gradual shift in laboratory equipment over time producing slightly different results.
Andesite	An extrusive usually dark grayish rock consisting essentially of oligoclase or feldspar.
Argillic Alteration	A rock alteration in which certain minerals are converted to minerals of the clay group.
Breccia	A rock consisting of sharp fragments embedded in a fine-grained matrix (as sand or clay).
Condensate	A product of condensation; *especially*: a liquid obtained by condensation of a gas or vapor <steam *condensate*>.
Correlate	Indicate relationship between similar fluid/rock types.
Cuttings	Small grain size pieces of rock retrieved during the drilling of a well.
EGS	Energy & Geoscience Institute.
Enthalpy	The sum of the internal energy of a body and the product of its volume multiplied by the pressure; similar to heat.
Felsic	Containing a group of light-colored silicate minerals that occur in igneous rocks.
FIT	Fluid Inclusion Technology Laboratory
Fluid Inclusion Stratigraphy (FIS)	A tiny fluid-filled cavity in a rock that forms by the entrapment of the liquid from which the rock crystallized.
Ft	Foot or feet.
Fumerole	A hole in a volcanic region from which hot gases and vapors issue.
Geothermal	Of, relating to, or utilizing the heat of the earth's interior; *also* **:** produced or permeated by such heat.
GRDA	Geothermal Resources Development Account
Hydro fracture	An opening in a rock body produced by a fluid.
Injection well	A deep well into which water or pressurized gas is pumped in order to push resources out of underground reservoirs toward production wells, so as to increase their yield.
KM	Kilometer
Ma	Millions of years ago.
Magma	Molten rock material within the earth from which igneous rock results by cooling
Meteoric	Of, relating to, or derived from the earth's atmosphere <*meteoric* water>.
MW	Megawatt
NMT	New Mexico Tech

Permeable Zone The ability of a material to allow the passage of a liquid, such as water through rocks. Permeable materials, such as gravel and sand, allow water to move quickly through them, whereas unpermeable materials, such as clay, don't allow water to flow freely.

Petrography The description and systematic classification of rocks

Pluton A typically large body of intrusive igneous rock

ppm Parts per million.

Quadrapole Mass Spectrometoery (QMS) A quadrupole mass filter consists of four parallel metal rods arranged such that two opposite rods have an applied potential of (U+Vcos(wt)) and the other two rods have a potential of -(U+Vcos(wt)), where U is a dc voltage and Vcos(wt) is an ac voltage. The applied voltages affect the trajectory of ions traveling down the flight path centered between the four rods. For given dc and ac voltages, only ions of a certain mass-to-charge ratio pass through the quadrupole filter and all other ions are thrown out of their original path. A mass spectrum is obtained by monitoring the ions passing through the quadrupole filter as the voltages on the rods are varied. There are two methods: varying w and holding U and V constant, or varying U and V (U/V) fixed for a constant w.

Reservoir A place in the ground where geothermal fluids/gases are kept in store.

Silica SiO_2 occurring in crystalline, amorphous, and impure forms (as in quartz, opal, and sand respectively).

Silicic dome A rise in the earth crust caused by magma having a high concentration of silica.

Solenoid A coil of wire usually in cylindrical form that when carrying a current acts like a magnet so that a movable core is drawn into the coil when a current flows and that is used especially as a switch or control for a mechanical device (as a valve).

SP Self potential

TPS Temperature, pressure and spinner

Travertine A mineral consisting of a massive usually layered calcium carbonate (as aragonite or calcite) formed by deposition from spring waters or especially from hot springs

Volatile Readily vaporizable at a relatively low temperature.

Well Logging The analysis and recording of the strata penetrated by the drill of an oil well as an aid to exploration.

APPENDIX A:
Fit Data Set for Entire Project (CD)

APPENDIX B:
Excel Logger Files and Logger File (CD)

APPENDIX C:
Data File for Duplicate Samples (CD)

APPENDIX D:
Data for Karaha Core Sam