GAS ANALYSIS OF GEOTHERMAL FLUID INCLUSIONS: A NEW TECHNOLOGY FOR GEOTHERMAL EXPLORATION

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Project Background and Status

In 1994 ideas about geothermal gas chemistry were vague. Gaseous species are commonly the principal dissolved component in geothermal fluids, but the significance of the gas chemistry was mostly overlooked. Giggenbach presents the basic geothermal equilibrium gas chemistry (Giggenbach 1980) and calculates how boiling might affect CO_2-CH_4-H_2 ratios in geothermal fluids (Giggenbach 1986). However, attempts at using gas equilibrium geothermometers for geothermal exploration largely failed.

I began collaboration with Joe Moore and Jeff Hulen, and later Sue Lutz at EGI, University of Utah, in 1994. We hypothesized that fluid inclusion gas analyses would complement their petrographic and fluid inclusion studies, and thus provide a comprehensive picture of geothermal system processes and evolution. That year I published a paper (Norman 1994), developing an idea brought forth by Giggenbach (1986), which shows that fluid inclusion gas analysis can identify a magmatic component in inclusion fluids. One of our goals was to apply this new tool to the study of active geothermal systems. Our collaboration has resulted in a number of publications that expand the science of geothermal gas chemistry and increase our understanding of geothermal processes and evolution (Moore 1995; Moore 1997; Lutz 1999; Adams 2000; Lutz 2002) (Moore 1997; Moore 1998; Moore 1998; Moore 1999; Moore 2000; Moore, Norman et al. 2001) (Norman 1994; Norman 1996; Norman 1997; Norman 1998; Norman 1999) (Norman 2001; Norman 2001; Norman 2002; Norman 2002)

In 1999 it was evident that with our increased understanding of geothermal gas chemistry that it could be a valuable tool for geothermal exploration. It was also apparent that geothermal gas chemistry had proven to be a valuable instrument for understanding evolution of geothermal systems, and that it order for Norman to spend more time on this work, funding was required. Therefore, funds were sought from the DOE university Geothermal Program.

Project Objective

The principal objective was to increase our knowledge of gaseous species in geothermal systems by fluid inclusion analysis in order to facilitate the use of gas analysis in geothermal exploration.

Approach

Update the New Mexico Tech fluid inclusion gas analysis facility.

1. Add to the merger data base of magmatic gases by measuring gases in magmatic glass inclusions.
2. Analyze the volatiles in Karaha fluid inclusions studied by Joe Moore.
3. Develop a technology base for the analysis of fluid inclusion organic compounds.
4. Develop methods of applying geothermal gas analysis to geothermal exploration using knowledge gained during the project

Research Results

Sub-objectives 1-4 above were completed and reported on (Blamey Nigel J.F. 2001; Norman 2001; Norman 2001; Blamey 2002; Norman 2002; Norman 2002). Here I will report new methods for applying geothermal gas analysis to geothermal exploration, which is the main subject of the proposal.

The unique approach that was developed is to look at gas chemistry as a product of components from meteoric, crustal, and magmatic sources that are modified by geothermal processes of boiling, mixing, and condensation. Five assumptions are made: 1) gas chemistry of geothermal reservoir fluids is different than gas chemistry of non-thermal waters; 2) reservoir fluids commonly have additions of magmatic volatiles that have specific He-N_2-Ar ratios; 3) there are three sources of volatile compounds: magmas, the crust by wall rock reactions, and the atmosphere; 4) boiling, condensation, and fluid mixing processes result in systematic changes in gas chemistry; and 5) gas chemistry of past geothermal systems may also be determined by fluid inclusion gas analysis. The rationale for the interpretations we use is explained in detail elsewhere (Norman 2001; Blamey 2002; Norman 2002) and references therein. I will discuss examples of applying geothermal gas analysis to grass roots exploration at the Lightning Dock geothermal area, NM; to drill core chips at the Coso geothermal field; and to monitoring production at the Cerro Prieto field.

Lightning Dock

The Lightning Dock, Animas Valley, New Mexico geothermal area was discovered when a rancher found boiling water while drilling a shallow stock tank well (Elston, Deal et al. 1983). There are no surface manifestations of present or past geothermal activity in the Animas Valley. There is no geophysical low-resistivity anomaly. The only item to investigate is the waters in stock tank wells. Norman and Bernhart (Norman 1982) analyzed the gases, and water chemistry in the discovery well and 15 stock tank wells nearby (Fig. 1). The well temperatures are typical of shallow well waters; we did not know how to interpret the gas analyses at that time, and other geochemical analyses showed no identifiable geothermal input. AMAX Geothermal failed to find reservoir fluids in 8 boreholes drilled there in the late 70's.

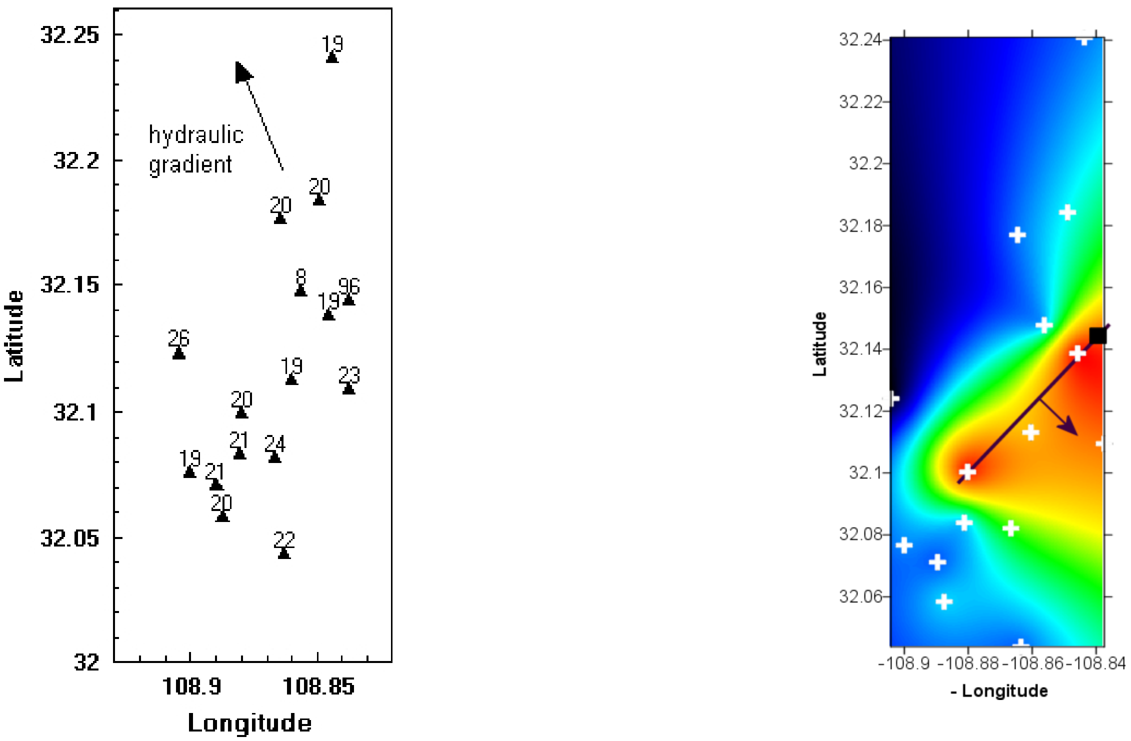


Figure 1 (Left) Location of the wells sampled in the Lightning Dock geothermal area. The number above each well is the measured well temperature. (Right) The right-hand figure is a Surfer® contour-image plot that shows the location of a vapor plume at Lightning Dock. The highest values of total gas are red and lowest values in dark blue. The white crosses are well locations; the black square is the discovery well. An inferred fault is shown with the dip direction. This newly developed method of using gas analyses to find condensed vapor shows a drilling target, whereas common geochemical methods used in geothermal exploration do not work at Lightning Dock..

Reevaluating our analyses now it is apparent that the discovery well gas chemistry indicates boiling. The discovery well water has about 1/1000 the N_2 common in groundwater, which implies that the well fluid was degassed by subsurface boiling. The working assumption is that vapor generated by boiling Lightning Dock waters should exit the surface because there is no sign of vapor blockage and resulting hydrothermal eruptions. This flux of volatiles should condense some soluble species in shallow ground water. A gas mixing-condensation diagram (Norman 2002) was constructed (Fig. 2) that clearly confirms condensation, and as well shows mixing between groundwater and the discovery well. The wells that exhibit fluid mixing are the two wells that are NNE and down the hydraulic gradient from the discovery well. Total gas amounts, save for the discovery well, were projected onto the condensation line, and the values kriged and contoured using Surfer® software (Fig. 1). This analysis shows the location of a gas plume, and suggests a structure trending NE-SW from the discovery site dipping to the SE. There are structures trending NE in the Lightning Dock district (Elston, Deal et al. 1983). However, the structure the gas data suggests is not shown on maps because the Animas Valley is covered by thick gravel.

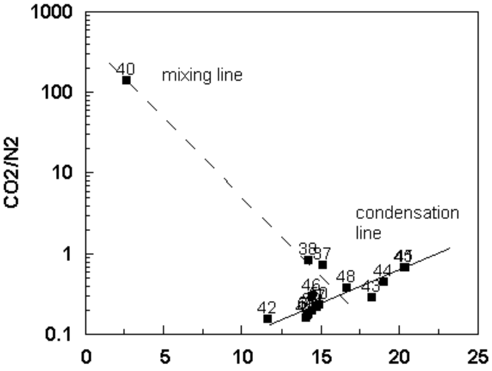


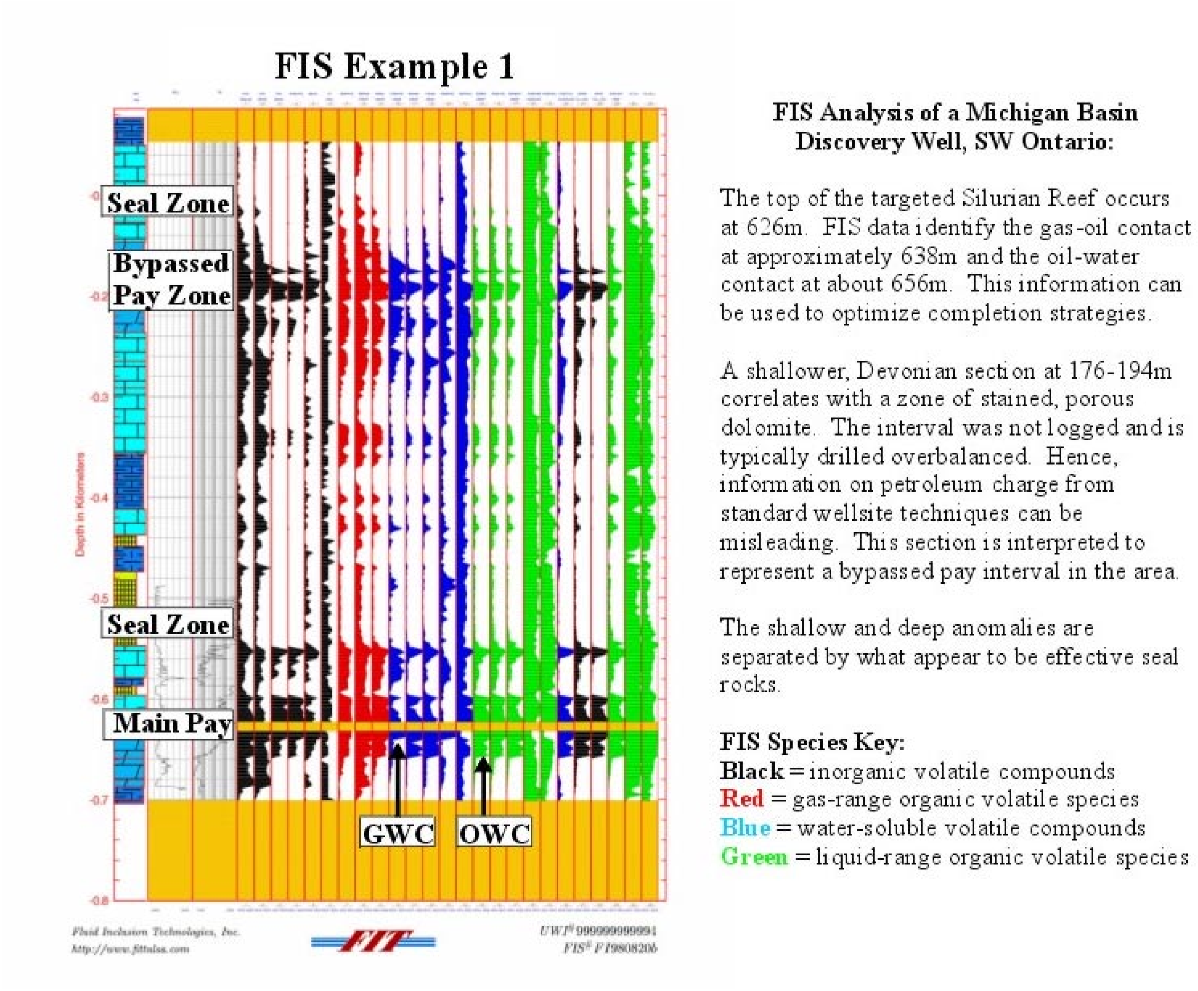
Figure 2. Analyses of Animas Valley wells shown in Figure 1 are plotted on a condensation diagram (Norman 2002). Numbers above data points are the well number. The condensation trend is labeled. A mixing line is constructed from the discovery well #40 through wells # 37 and 38. This diagram shows how gas data may be used to construct a fluid-mixing diagram. Mixing diagrams are a standard tool is interpreting geothermal fluids, however mixing diagrams to date use dissolved solids. Stock-tank well analyses fall on a condensation line (Norman 2002) hence; indicate a rising plume of volatiles modifies groundwater gas compositions.

Exploration Using Drill Chips

Several oil companies routinely use "Fluid Inclusion Stratigraphy" (FIS) whereby fluid inclusion volatiles in exploration-well drill-chips are analyzed at intervals of 10 or 20m (Hall 2002). Gas concentrations are plotted on well strip chart or mudlogs, and the stratigraphic intervals that act as seals and pay intervals for oil and methane are readily apparent (Fig. 3). This type of correlation should work for geothermal system exploration as well. Minor fractures penetrate far into the county rock from major structures in geothermal systems (Hickman, Barton et al. 1998), and they form secondary inclusions as they heal within a few years at geothermal system temperatures. FIS is not used in the geothermal industry because it was not known how to distinguish reservoir fluid inclusions from groundwater-filled fluid inclusions. Hydrocarbon-bearing fluids are easily distinguished by inclusions that contain organic compounds.

In order to test FIS for geothermal exploration, we analyzed Coso well 83-16 drill chips selected at 1000 ft intervals by Joseph Moore. Sequential crushes done by our CFS (crush-fast-scan) method (Norman 1996) show that chips have a high density of homogeneous fluid inclusions. Analyses were averaged and plotted verses depth (Fig. 4), and interpreted (Figs 4 and 5). Fluid inclusion gas analyses done on vein minerals from drill hole 68-6 that we earlier analyzed (Adams 2000) were plotted for comparison (Fig. 4) in order to confirm that similar analyses are obtained from chips and vein minerals.

It is apparent looking at Fig. 4 that fluid inclusion analysis detects a change in gas chemistry at about 5,500 ft, which is the top of the Coso production zone. Analyses for both wells show: 1) boiling fluids with a magmatic component below about 5000 ft; 2) a change in gas chemistry at 5000-6000 ft; 3) non-boiling, meteoric fluids immediately above 5000 ft; and 4) fluids with a magmatic component or boiling in waters < 1700'. Our interpretation of well 83-16 is that inclusions below 6,000 ft are samples of boiling reservoir waters (Fig. 5). Lack of boiling and meteoric N_2/Ar ratios above 5000 ft indicate the geothermal system is dominated by cooler meteoric waters there. The change in fluid chemistry and drop in fluid temperature at 5000-6000 ft. is best explained by a permeability seal. The indicated gas cap at about 5,500 ft in well 68-6 also indicates a seal. Near-surface fluids have the characteristics of steam-heated waters with elevated H_2S and C_6H_6 and or a magmatic component. The difference in chemistry between surface waters and the immediately deeper fluid suggests a seal that must be penetrated by a few fractures transmitting steam from boiling reservoir fluids. The interpretation agrees well with the well log for bore hole 83-16 that shows the well cased to 6,000 ft, a decrease in fluid temperatures at depths above 5,500 ft, and an increase in temperatures at depths <1,700 ft. Our trial analyses roughly indicate the Coso reservoir top. In actual practice, where analyses are done at more closely spaced intervals, we expect much better precision in determining reservoir boundaries. We expect that a greater density of analyses will also identify productive fractures as well.



FIS Analysis of a Michigan Basin Discovery Well, SW Ontario:

The top of the targeted Silurian Reef occurs at 626m. FIS data identify the gas-oil contact at approximately 638m and the oil-water contact at about 656m. This information can be used to optimize completion strategies.

A shallower, Devonian section at 176-194m correlates with a zone of stained, porous dolomite. The interval was not logged and is typically drilled overbalanced. Hence, information on petroleum charge from standard wellsite techniques can be misleading. This section is interpreted to represent a bypassed pay interval in the area.

The shallow and deep anomalies are separated by what appear to be effective seal rocks.

FIS Species Key:
Black = inorganic volatile compounds
Red = gas-range organic volatile species
Blue = water-soluble volatile compounds
Green = liquid-range organic volatile species

Figure 3. A "Fluid Inclusion Stratigraphy" example for a hydrocarbon well. Fluid inclusion analyses are performed on drill-chips taken at intervals of 30 or 60 feet and the relative heights of mass peaks corresponding to major species are plotted on mudlogs.

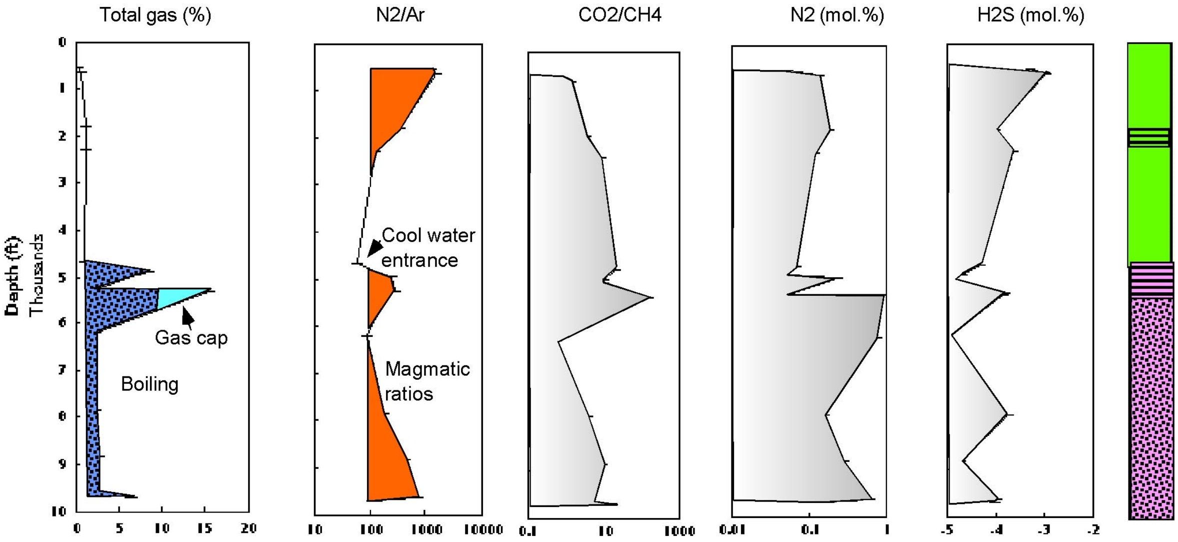


Figure 4 (Upper) Analysis of nine Coso well 83-16 drill-chip samples plotted verses depth in thousands of feet. TOT GAS is total gaseous species, K" is the Fischer-Tropsch reaction coefficient, and TORG is the sum of C_2-C_7 organic species. Orange-filled areas indicate magmatic ratios; blue-filled areas on TOT GAS and K" columns are values that indicate boiling. (Lower) Analyses of twelve vein samples from Coso well 68-6 are plotted verses depth. Filled areas in N_2/Ar columns and total gas columns respectively indicate values for magmatic fluids and fluid boiling. See Fig. 5 for the explanation for the interpretive column at the right.

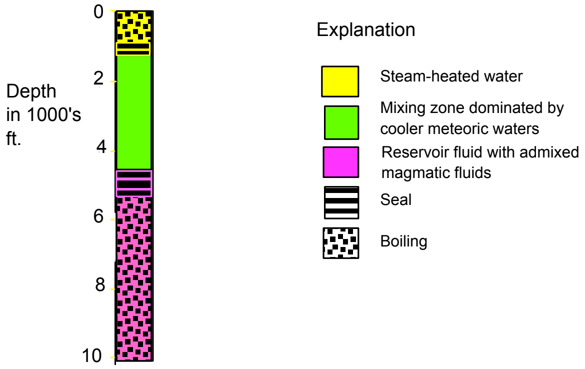


Figure 5. An interpretation of fluid types, fluid processes, and seal locations in Coso well 83-16, based on fluid inclusion gas analysis. The gas data is displayed in Figure 4. See text for an explanation of how the interpretations are made.

The preliminary analyses strongly indicate that FIS stratigraphy can be applied to geothermal systems. FIS will provide the same type of benefits it does in hydrocarbon exploration. It can be used with other well logging tools to maximize well production by showing productive and non-productive bore-hole intervals. Commercial lab analyses are relatively inexpensive at $2,000 to $6,000 per bore hole (Hall 2002), the turnaround is in days, and data from commercial labs are formatted to be accepted by common strip log and mudlogging computer programs.

FIS analyses will have to be plotted differently than is done for the oil industry. Ratios of gaseous species that indicate fluid sources and fluid boiling will have to be added, and analyses of many organic compounds can be reduced. A valuable side benefit of FIS analyses is that analyses from a number of drill holes can be combined to provide a cross-sectional map of the reservoir (see Fig. 6).

<u>Producing Systems - Cerro Prieto</u>

A new way to monitor producing fields is introduced in (Norman 2002). The flow of geothermal fluids is mapped at the production level by use of gas chemistry obtained in routine field monitoring. Cerro Prieto gas analyses collected by Cathy Janik and Alfred Truesdell from 1977 to 1998 are used for the demonstration analyses (Fig. 7). Cerro Preito CO_2/N_2 and N_2/Ar ratios correlate (N_2/Ar ratios show contributions of magmatic volatiles), thus the sum of these ratios is used to tag magmatic-volatile-rich reservoir fluids.

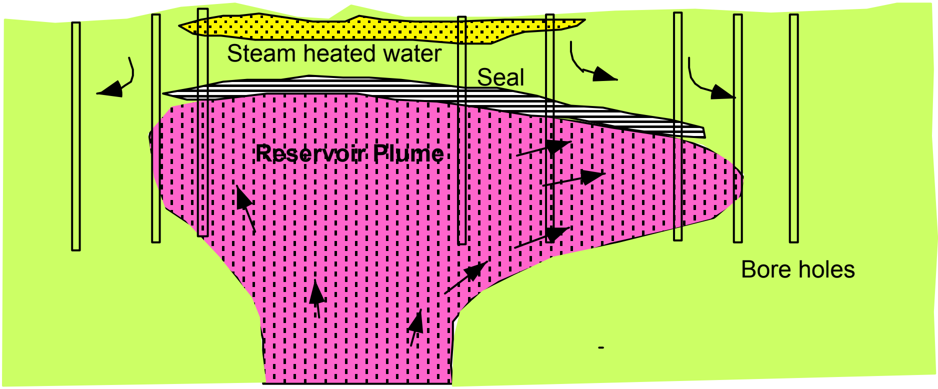


Figure 6. Schematic cross section of a geothermal system like Coso showing conceptually how fluid inclusion stratigraphy interpretations, like those in Figs. 4 and 5, may be used to determine the location of a well site with respect to the center, margin, or outside of the geothermal system.

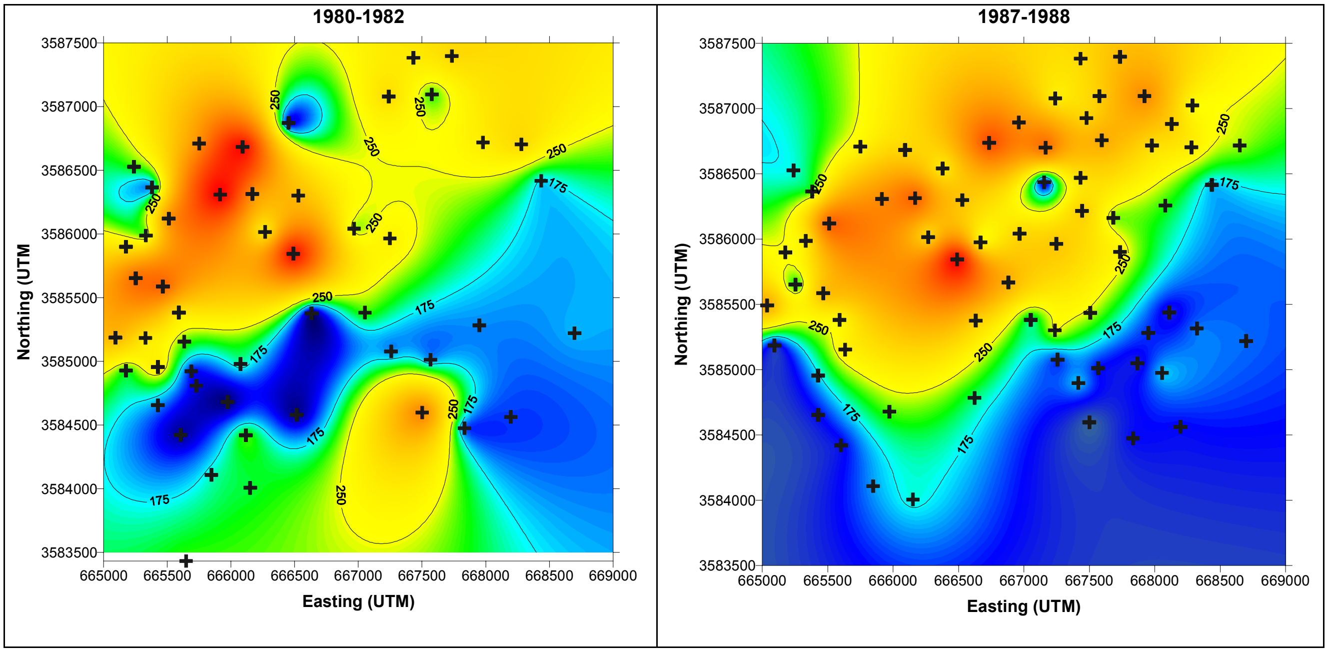


Figure 7. Contour plots of the Cerro Prieto geothermal plume produced by contouring $N_2/Ar + CO_2/N_2$ ratios in gas analyses performed during 1980 to 1982 (left) and 1987-1988 (right). Values below 175 are waters with little or no meteoric component. Values > 250 are fluids with a magmatic component. Gradations of blue to red show the respective proportions of meteoric and magmatic gaseous species. Black crosses locate wells that provided data for the map.

The analyses show that reservoir fluid-flow changes with time, most probably as a result of a changing stress field change. The wells in the red areas on Figure 7 have the highest enthalpies (temperatures), and generally have sustained production for the period 1977-1988. During 1980-1982 there appears to be a NW trending control on magmatic-vapor-rich fluids that coincides with a major NW trending fault. The map for 1986-1988 shows the southern part of the field dominated by meteoric waters, and a shift in the magmatic-vapor-rich waters to a NE trend. Wire frame and shaded image diagrams (Fig. 8) more clearly show the linear features. A vector plot (Fig.9) shows direction of reservoir fluid flow, and should be useful in planning injection well locations.

At Cerro Prieto geophysics and mapping indicates these NE-trending structures (Lippmann 1997). The area of blue-colored meteoric gas-dominated waters that trend NE in the 1980-1982 map (Fig. 7, Left) corresponds to the “H” fault that dips to the SE (Lippmann 1997), which they conclude is an important control on recharge into the reservoir. Contours of Cerro Prieto fluid salinity, enthalpy, and oxygen isotopic compositions (Lippmann 1997) also show a NE trend. Hence, NE-trending structures must be the main controls on Cerro Prieto fluids. Gas data alone (Fig. 8) appear to locate these structures.

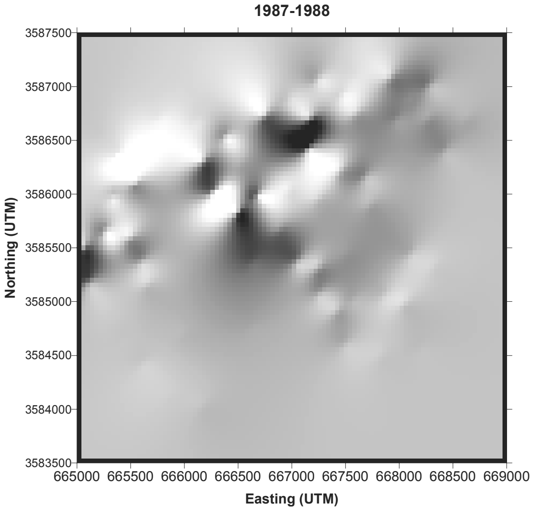


Figure 8. A shaded relief map (upper) produced from 1987-1988 gas analyses using SURFER® software. The map shows the location of structures that control reservoir fluids.

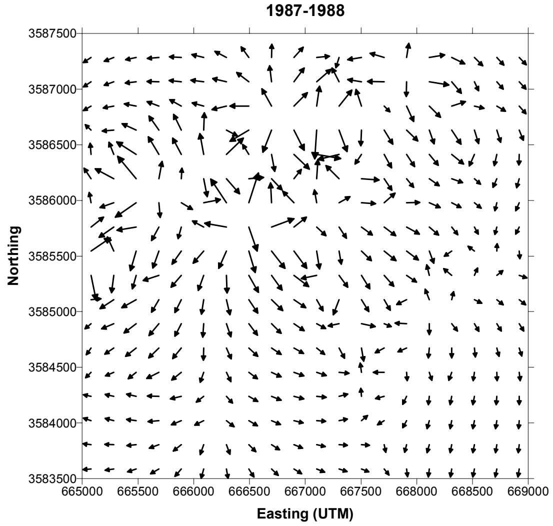


Figure 9. Gas analyses shown in Fig. 7 are shown in a SURFER ® vector plot. It shows the maximum rate of change from fluids with a magmatic gas component to fluids with meteoric and crustal gaseous species. Thus, the vectors should indicate the direction and magnitude of reservoir fluid flow.

Our examination of Cerro Prieto gas analyses indicates that the geothermal system structure is changing with time. Gas data appear to be very useful for monitoring changes of geothermal reservoir fluid flow and identifying controlling structures, which should prove useful in maintaining field production. Gas compositions are basically shown to act as free-of-cost tracers, and should work equally well in monitoring reinjection fluids. Gaseous species are routinely measured in most geothermal fields, hence fluid-flow plots as presented here can be accomplished with little cost. Gas analytical data, therefore, are useful in developing management procedures for geothermal fields characterized by complicated, highly-fractured reservoirs where flow patterns may change with time.

Details

<u>*Who Thinks the Research is Useful*</u>

- Starting May 12, 2002 we are going to work with Lightning Dock Geothermal to do a detailed gas plume map in the same area shown in Fig. 2. The company plans to start a drilling program late summer 2002.

- We will be analyzing chips on the new holes being drilled at Coso by the US Navy. We are planning with Caithness Energy on performing FIS analysis on chips from about 40 Coso boreholes. Analyses will be made by a commercial lab. We will help interpreting the analyses.

- Ridgeway Petroleum Corp. of Calgary, Canada who is drilling in New Mexico for CO_2-He gas wishes to have drill chip analyses made during their drilling program.

Collaborations

Principal collaborations are with Joe Moore, Jeff Hulen, and Sue Lutz at EGI, University of Utah, and the companies mentioned above Lightning Dock Geothermal, US Navy, Caithness Energy, and Ridgeway Petroleum Corp.

Papers Published: Papers published are: (Blamey Nigel J.F. 2001; Moore, Norman et al. 2001; Norman 2001; Norman 2001; Blamey 2002; Lutz 2002; Norman 2002; Norman 2002)

Students Supported: Nigel J.F. Blamey, Postdoc and Penny Oritz, undergraduate Research Assistant

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