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# HYDROTHERMAL MINERALOGY AND ISOTOPIC GEOCHEMISTRY IN THE CERRO PRIETO GEOTHERMAL FIELD, MEXICO. III. PRACTICAL APPLICATIONS

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## ABSTRACT

Our studies of rock samples from geothermal boreholes use a combination of mineralogy, light stable isotopes, fluid inclusions and other methods of geothermometry. This approach has proved cost effective and rapid when applied to practical problems of exploration at Cerro Prieto. We were able to predict temperatures and make qualitative statements about permeability during drilling. Our predictions were largely substantiated when the boreholes were subsequently tested. This kind of timely information helps determine final depth and the siting of future wells. We can also identify zones of different permeability, and distinguish between the natural recharge, discharge, and heating regimes of the geothermal system. Thus the effective hydrology and its evolution in the natural state can be described. Although these concepts were developed as a result of our studies in the Salton Trough, we believe that, with suitable modifications, they can be applied to various different types of geothermal fields elsewhere.

## Introduction

This paper and the two accompanying papers on Cerro Prieto (Hoagland and Elders, 1978; Olson and Elders, 1978) illustrate our belief that mineralogical and isotopic studies should be a part of the normal routine of investigation of geothermal boreholes. For modest incremental costs, certainly only a few percent of the cost of drilling, such studies of subsurface samples provide useful and timely information. To be most effective we use a combination of mineralogy, isotope geochemistry, and geothermometry. No one of these methods alone is adequate in our experience, but together they support each other.

These studies investigate the results of water/rock reactions. These results are important for two reasons: firstly, the reactions have a dramatic effect on the porosity, permeability, and other physical properties of the rocks, and secondly, they leave a record in the rocks of the hydrological and thermal regime. We can think of a high intensity hot-water geothermal field simply as being a thermally-driven free convection system. But in addition, we can also think of it as chemical pump transporting various components around the system. Some components are concentrated in the fluid system, others move through the rock system as they are dissolved or precipitated as the fluid moves through a temperature gradient. Precipitation of minerals obviously increases density and reduces porosity and permeability; however, incongruent dissolution at grain to grain contacts usually has the same effect, reducing the permeability. Thus these kinds of water/rock reactions are self-limiting and would come to a stop were it not for the competing effects of hydraulic fracturing and faulting which generate fracture permeability (Elders, 1977). The results of these processes can be traced in the rocks effected.

## Hydrothermal Mineralogy

The most obvious application of mineralogy is to help make correlations between wells, in order to determine the structural relations of the aquifers. Such studies can assist electric log correlations. However, electric logs do not easily reveal the pattern of hydrothermal mineralization.

The first of our three papers at this meeting (Hoagland and Elders, 1978, this volume) shows how specific minerals form in response to water/rock reactions under specific conditions. Some of these mineral assemblages appear to be primarily controlled by temperature. Thus the diagenetic assemblage, the illite/chlorite assemblage, and the calc-aluminum silicate assemblage can be used to determine the temperatures at which they were in equilibrium with brine. As well as being used to predict temperatures from cuttings obtained while drilling, correlation of these mineral assemblages across a geothermal field can reveal the pattern of temperature distribution in three dimensions.

Other mineral assemblages are indicative of the direction of temperature change. When hot brine ascends into colder rocks in a discharge zone, quartz and potassium feldspar precipitate, forming the quartz-adularia assemblage. Similarly, cold water descending into hotter rocks will precipitate carbonate and sulfate, forming the calcite-anhydrite assemblage. Thus we can, in principle, map out the pattern of fluid flow in a geothermal field from the mineralogy.

Rapid identification of mineral assemblages is easily achieved using X-ray diffraction. We use an automated system which produces quantitative modal analyses. However, these analyses are augmented by optical microscopy for several reasons. Firstly, the detection limit for minerals in the microscope is lower. Secondly, textural criteria help to distinguish between detrital and authigenic minerals. Furthermore, we can use the textures to study the sequence of mineral formation in rocks and in mineralized fractures to determine the history of water/rock reactions. Finally, textures give information on the degree of self-sealing by precipitation in pore spaces. Self-sealing is more likely to be associated with discharge than with recharge, because of the higher rates of flow to be expected. Discharge regimes have smaller areas than the broader, more diffuse, recharge regimes which surround them.

## Light Stable Isotopes

Many studies of the stable isotopes of water and gas samples from geothermal wells aim at determining the origins of the fluids and their temperatures of reaction. Whereas fluids tend to be well mixed and therefore give averages over a whole well or even over a whole aquifer, rock samples give information on the detailed variations in a drilled section and on the changes which have occurred within it. For this reason, the second of our three papers in this series (Olson and Elders, 1978, this volume) stresses the isotopic ratios of minerals. The study concentrated on calcite because carbonates can be much more easily prepared for analysis than silicates, and because calcite is ubiquitous, except at the highest temperatures.

The isotopic ratios of calcite were used to calculate the temperatures of equilibration between calcite and water. With increasing temperature, the oxygen isotope values of calcites become lighter. However, at any given depth a range of values is found. Invariably the lightest oxygen values are in vein calcite, with progressively heavier values in sandstones, siltstones and shales. This is because of lower water to rock ratios in rocks of lower permeability. Therefore, in addition to getting temperature information, if different isotopic ratios occur in rocks at the same temperatures, we can determine water/rock ratios. This allows study of variations in the effective permeability of aquifers in space and time.

## Geothermometry

At first sight, it may seem redundant to use mineralogical and geochemical geothermometers in an active geothermal system where temperatures can be measured directly. However, at the temperatures encountered at Cerro Prieto, direct measurements in boreholes are time consuming and difficult. Normally weeks or months elapse before the wells return to thermal equilibrium after drilling. Therefore, such indirect temperature estimates are useful to interpolate between actual measurements and to make predictions before temperature logs can be made. In addition to the two methods referred to above, a number of other methods are available. These include the thermal alteration index of carbonaceous materials and the use of fluid inclusions.

At Cerro Prieto we plan to test the applicability of vitrinite reflectance techniques to the carbonaceous materials. We have successfully used fluid inclusion measurements to estimate temperatures. Inclusions of fluid are trapped when crystals grow in contact with fluid. When viewed in the microscope, these inclusions are seen to consist of liquid, vapor, and sometimes daughter crystals, precipitated from the trapped brine. By heating an inclusion, while observing it in the microscope, we can determine the temperature at which the vapor bubble disappears. With an appropriate pressure correction, this is the temperature at which the host crystal grew. The method is simple, rapid, and accurate to a few degrees. It is independent of permeability, water/rock ratios, or of water chemistry. Unlike methods based on analyses of geothermal waters, it gives values valid for volumes smaller than that of a crystal, rather than averaged over a whole aquifer.

## Departures from Equilibrium

In most cases we have found that the results of these different approaches agree with each other and with direct measurements in the wells. This has given us a high degree of confidence in the methods. In certain cases, however, the different data suggest that the samples of rocks are not in equilibrium with the fluid at the temperatures measured in the aquifers. The response rate of these different parameters to temperature changes is different. A downhole temperature recorder measures a temperature at a given instant. A fluid inclusion records the temperature at some time in the past when a crystal grew. Both the mineral assemblages and the isotopic ratios depend on equilibria being established between water and rock, and this requires a sufficiently high ratio of water to rock. This water/rock ratio depends on a combination of the effective permeability and the time elapsed. Therefore, these criteria add another dimension to the study of geothermal systems, the time dimension.

We believe that lack of consistency between the different methods is indicative of a disequilibrium caused by changing conditions. We can, therefore, make qualitative statements about the stage of evolution of a hydrothermal system, its relative age, the direction of temperature change, and about its water/rock ratios and relative permeabilities.

We can, therefore, in principle distinguish systems which are cooling from those that are heating. Furthermore, the temperature information recorded in the rocks may be the best way of determining the initial conditions in an aquifer before the effects of drilling, production-induced draw down and recharge, and reinjection occur.

## Specific Examples

The figure shows the locations of several exploration wells drilled in 1977 and 1978 at Cerro Prieto. Our studies to date have concentrated on these step-out wells rather than wells in the production field because a major exploration program is under way to determine the size of the resource. Based on investigations during the first six months of our study at Cerro Prieto, we made predictions about six wells (Elders et al., 1977). The two which are furthest from the production field appeared to lie outside the geothermal field; two others seemed to be somewhat marginal as production wells; however, the remaining two appeared to be suitable for production. These predictions have been verified in practice. Table 1 compares some of our interpretations with the actual measurements. We initially offered these predictions as a test of our methods and concepts. We feel they have survived the test.

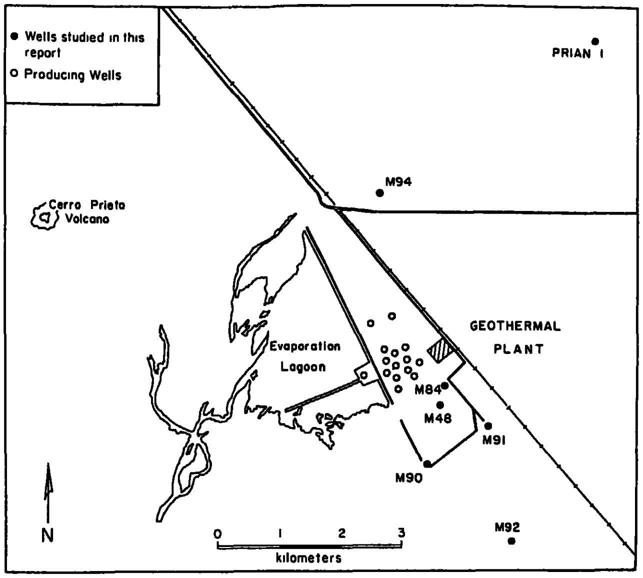

TABLE 1
COMPARISONS BETWEEN INFERENCES FROM LABORATORY MEASUREMENTS OF WELL SAMPLES AND DOWNHOLE MEASUREMENTS

| Well No. | Synopsis of our Predictions | Maximum Downhole Temperature Measured | Depth of Measurement | Date Measured |
|---|---|---|---|---|
| Prian No. 1 | No hydrothermal alteration. Has unusually low geothermal gradient for the Salton Trough. Lies outside geothermal field. | 102°C | 2670 m | 12/4/77 |
| M-92 | Low hydrothermal alteration and permeability. Temperatures less than 210°C at 2100 m. Outside the possible production field. | 84°C* | 1750 m | 2/24/77 |
| M-91 | Moderate to high hydrothermal alteration only below 2000 m. Moderate permeability. Temperatures higher than 300°C below 2100 m, maximum 320°C. | 311°C | 2220 m | 7/10/77 |
| M-90 | Lower portion has good permeability and temperatures. High temperature minerals not fully developed. Producing zones localized and temperature reversals present. Hot water may have recently entered this area. Temperature 302°C at 1341 m. | 302°C | 1385 m | 1/21/78 |
| M-48 | Good permeability and moderate to high degree of alteration. Some zones of low permeability occur in the hot zone. Temperatures higher than 300°C at well bottom. | 327°C | 1251 m | 12/15/77 |
| M-84 | Good permeability and high temperatures probably up to 350°C. Should be successful both from the point of view of temperature and permeability. | 347°C | 1700 m | 2/15/78 |

*Measured during drilling, not an equilibrium temperature. No data available below 1800 m.

A limited study made on well M-94 exemplifies the use of these techniques to assist decision-making while drilling. When this well reached 2100 m depth we were asked to make a rapid examination of the well products. Two working days after receiving the samples, we reported on X-ray analyses of 12 shales, thin section studies of 12 sandstones, fluid inclusion measurements of 18 crystals of vein calcite, and 6 isotope temperatures. We predicted temperatures of about 230°C at 1300 m and about 200°C at 2100 m. We also suggested that this well lies on the margin of the field but it had flow of hot water through a fracture system at about 1290 m depth. It was decided to deepen the well. At 2420 m the rocks showed a much higher degree of induration and a field test showed poor permeability. Our laboratory studies of samples from 2505 m gave fluid inclusion temperatures of 250°C. However, both the mineral assemblages and the isotopic measurements suggested temperatures in the range 200-230°C. The well was not continued and the next well site programmed was abandoned.

## Applications to the Imperial Valley

The concepts described above were refined at Cerro Prieto but were developed during our studies of geothermal systems in the Imperial Valley of California, during the past five years (Elders, 1978). For example, the Dunes system is a prime example of a discharge system. Similarly, the interplay between the quartz-adularia assemblage and the calcite assemblages is clearly demonstrated at East Mesa. In that field disequilibrium between water and rock is well seen, as it is evident that the rocks were formerly heated by a discharge system and are now being cooled by recharge as the system progressed from a free to forced convective regime. Earlier studies of the Salton Sea Geothermal Field showing the relation of temperature to mineral assemblages have recently been further elaborated. There are some significant differences from Cerro Prieto. For example, wairakite and prehnite are absent and above 325°C andradite garnet is stable. In this field a similar correspondence between isotopic temperatures and fluid inclusion temperatures is seen. Both document large temporal fluctuations in temperature on the flanks of the system (Elders, 1977b; Freckman, 1978).

## Conclusions

A combination of mineralogy and isotope geochemistry is proving to be an effective tool to study geothermal fields and to assist in exploration. At Cerro Prieto we are currently mapping mineral assembleges and isotopic ratios across the production field as a record of its hydrology in the natural state. The model which will emerge should have some bearing on resource assessment and field management. We would also like to attempt the same type of study in a variety of different geothermal fields. It is clear, for example, that the diagnostic minerals in a basaltic terrain would be different. However, they could be identified by a similar approach to the one we have used at Cerro Prieto.

In making assertions about the practicality of our methods we are conscious that X-ray diffractometers and mass spectrometers are not normally found around drilling rigs. At Cerro Prieto the most easily recognized effect of post-depositional alteration is a progressive color change in the shales from brown to tan, through light gray, to dark gray. The change brown to light gray occurs at the diagenetic to illite/chlorite transition. The rocks from the calc-aluminum silicate zone have a decidedly hornfelsic appearance. We hope to develop, as the result of our intensive laboratory study, simple criteria which can be applied to different field situations. Perhaps petrographic microscopes with heating stages will be found around drilling rigs in the future.

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