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GEOTHERMAL SYSTEMS: ROCKS, FLUIDS, FRACTURES

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Abstract. Geothermal systems involve the dynamic interaction among rocks, fluids, and fractures. Some aspects of these systems are typical of the upper crust because they involve water-rock reactions resulting in cementation, diagenesis, or even low-grade metamorphism. Other aspects are atypical of the crust because of their speed, specific reactions, environment, and dependence on structure, particularly fractures. Reactions between fluids and rocks depend on fractures for fluid conduction and reaction surfaces. The morphologies of the fractures are dependent on the cementing, sealing, and alteration reactions. Core samples from several geothermal areas show repeated episodes of fracturing and sealing. Fluid flow and electric currents depend on the conduction paths provided by fractures. Cementation and sealing can lower permeability and raise resistivity by 3-5 orders of magnitude. On the other hand, fluid flow is restricted by sealed fractures. The sealed fractures are occasionally the boundaries between regions of significantly different physical characteristics. Despite the many episodes of fracturing, the sealing processes usually result in low fracture porosity.

Introduction

Core samples from several geothermal areas show an interplay among the rocks, fractures, and interstitial and fracture fluids. Fluid flow through the rock column is dependent on the stratigraphy and structure of the area. Geothermal areas commonly occur in fault zones where open fractures provide flow paths. All the studied areas show repeated episodes of fracturing and sealing. Thus fractures act as both cause and effect in these systems. The physical properties of the rock and fluid circulation are dependent in part on the fracture state of the rock. Fluids react with rocks forming alteration products which modify or seal fractures. The reaction products that remain in the rocks can be used to limit the models of temporal variations in fluid chemistry. Sealing and cementing, in turn, make the rock more susceptible to brittle fracturing.

Figure 1 is an index map of sample locations. Samples from some locations, such as the Dunes and Raft River areas, have been studied in detail. For other areas, such as Marysville, samples have only

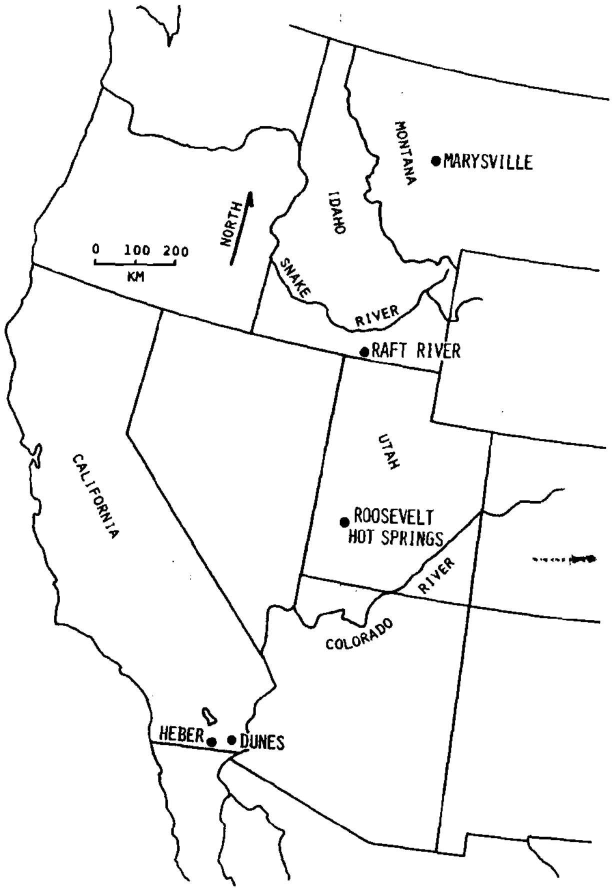

Fig. 1. Index map.

recently been obtained. Samples were generally chosen for high fracture content and indurated nature rather than for stratigraphic completeness. All but the Marysville area are regions of detrital alluvial sedimentation. Usually, the stratigraphy consists of interbedded sands, silts, clays, and conglomerates. In the Raft River and Roosevelt Hot Springs areas, drilling penetrated fractured igneous intrusive rocks. The Marysville well cut metamorphic and granitic plutonic rocks. These igneous rocks may play a significant role in the system. More complete geologic descriptions can be found in Elders and Bird [1974], Bird [1975], Blackwell et al. [1975], and Batzle and Simmons [1976].

In many ways, geothermal systems are not typical of the earth's crust. By definition they possess anomalously high temperatures or

heat flow. Because of high temperatures and the availability of reactive fluids, diagenesis, sometimes bordering on low-grade metamorphism, occurs swiftly in some geothermal systems [Muffler and White, 1969]. The reactions and local environments often differ from those that commonly occur in sedimentary basins. These reactions include, for example, the development of adularia and the change from pyrite to hematite stability in the Dunes area. Because of the distribution of fractures and stratified aquifers, successive altered and unaltered zones exist [Elders and Bird, 1974; Bird, 1975]. Typically the first diagenetic reactions involve cementing the sediments, which makes fluid circulation dependent upon open fractures.

In several aspects, geothermal systems have characteristics frequently found in the upper crust. These systems involve several common water-rock interactions. Rocks exhibit authigenesis, replacement, alteration, and breakdown of unstable minerals. Other effects include cementation and compaction.

In this manuscript we will concentrate on the physical aspects of fractures in geothermal systems. This paper is a progress report on our continuing work on numerous core samples from several geothermal areas. A preliminary report on the Dunes and Raft River areas has been published recently by Batzle and Simmons [1976], and the reader is referred to that paper for details on those areas. Material that appears in other publications will only be summarized here.

Fracture Relationships

The five geothermal systems studied all show repeated fracturing superimposed on fluid chemical properties that varied with time. One excellent example of repeated fracturing in a Dunes sample from a depth of 403.9 m is presented in Figure 2. This sample is a sandstone which contains several large clay clasts. At least five episodes of fracturing and resealing have occurred. In this specific case the fracture mineralization remained calcite. The dark wavy bands match almost perfectly with the surface of the clay grain. These dark bands, numbered 1-5, oldest to youngest, are probably due to small particles of clay left behind when the calcite and clay separated during repeated fracturing.

A more complicated history is shown in the Heber sample from 1187 m (Figure 3). This sample is a highly fractured silty sandstone. Probably four or more episodes of fracturing are demonstrated by the figure. Here again calcite remains the sealing material. Cross-cutting relationships are commonly used to determine the relative ages of fracturing events (see, for example, Park and MacDiarmid, 1975, p. 71). In this case, the fracture marked '1' is older than both '2' and '4'. The time relationship between '2' and '4' is ambiguous. Some relative age determinations are hindered by the recrystallization of the calcite which has obscured much of the original texture. The area shown in Figure 3 is actually only a small chip which is surrounded by several more sealed fractures. Hence both this sample and the Dunes (403.9 m) sample show repeated fracturing events followed by fracture sealing.

Fractures can also serve as conduits for reactive fluids. This

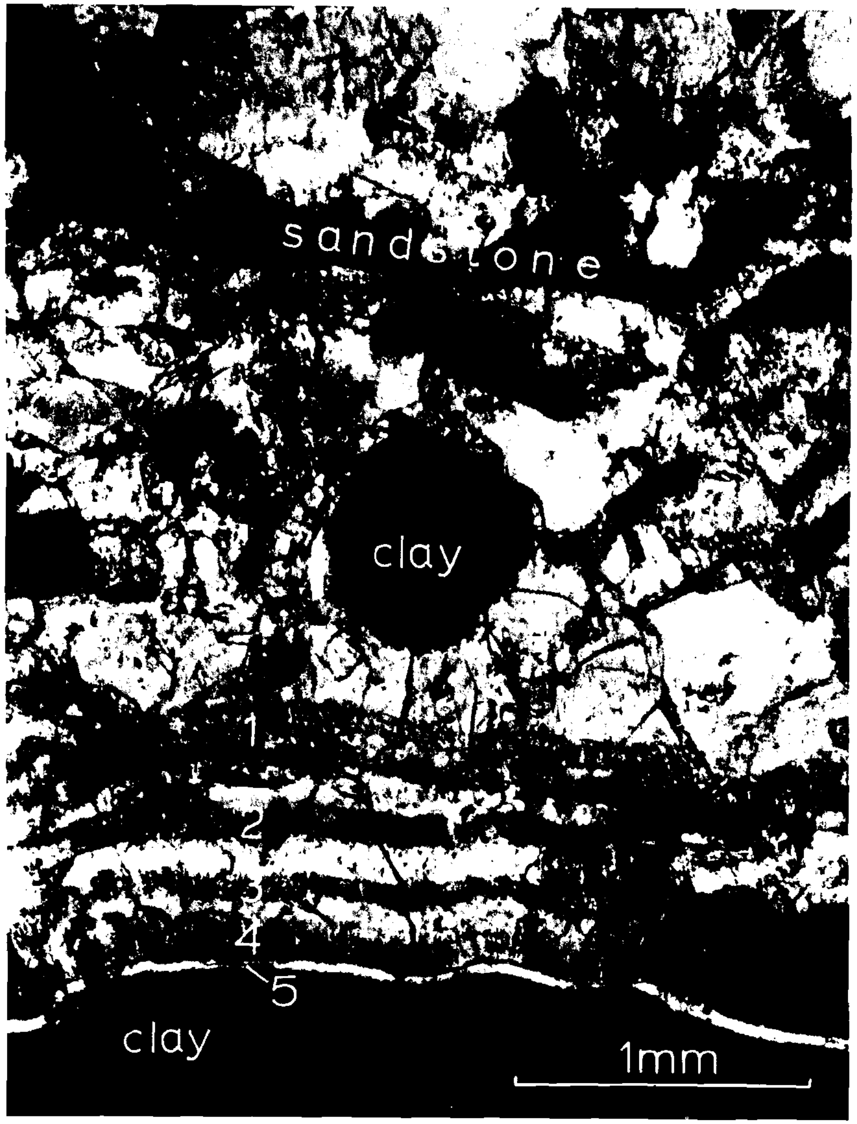

Fig. 2. Dunes sample from a depth of 403.9 m, photographed in transmitted light. The material between the 'sandstone' and the bottom clay fragment is the calcite sealed fracture. Numbers indicate successive fracture boundaries.

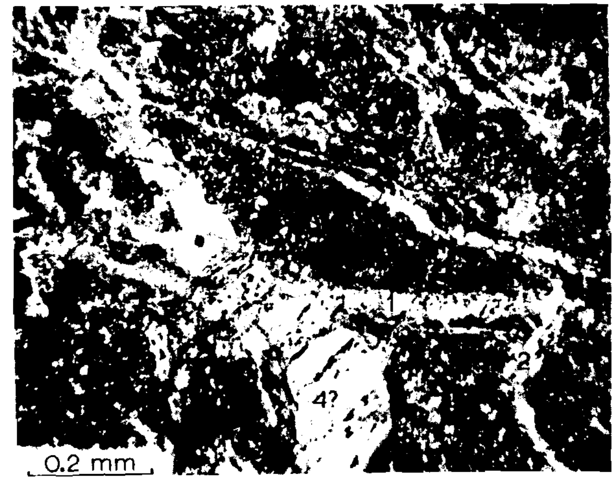

Fig. 3. Heber sample from a depth of 1187 m, photographed with crossed nicols. Dark areas are siltstone. Light areas are calcite sealed fractures.

property is demonstrated by the Roosevelt Hot Springs sample from a depth of 608.7 m. See Figure 4. A zone of alteration surrounds the fracture through this granodiorite. Here again multiple fracturing events may have occurred (numbers '1' and '2' in Figure 4). The relative ages of these 'events' have not yet been determined. Both x-ray diffraction and electron microprobe analysis indicates that hematite is the major fracture sealant. The zone marked '1' is enriched in calcite, feldspar, and quartz. The biotite grains along the fracture (at 'A') are being altered to hematite. Farther from the fracture the mafic grains remain unaltered. At 'B' a replacement rim of potassium feldspar has formed on the plagioclase grain.

Several variations of fluid chemistry with time are indicated in Figure 5. This sample is an argillaceous sandstone from a depth of 345 m in the Raft River area. The first fracture, 'f1,' is now sealed with calcite 'C.' The next two fractures, marked 'f2a' and 'f3a,' are now partially sealed with analcime. A well-developed analcime crystal is shown at 'D.' Another set of fractures is indicated by 'f4a,' 'f4b,' and 'f4c' in the figure. Here the fractures have apparently been widened by etching out the clayey matrix. Analcime remains unetched. The fracture fluids have therefore changed from calcite supersaturation to analcime supersaturation to undersaturation with respect to the clay matrix. This sample is also divided into a well-indurated portion at the top of the figure and a poorly indurated portion at the bottom. The boundary is the calcite sealed fracture f1. This sealed fracture has blocked the circulation of the fluids responsible for the cementation.

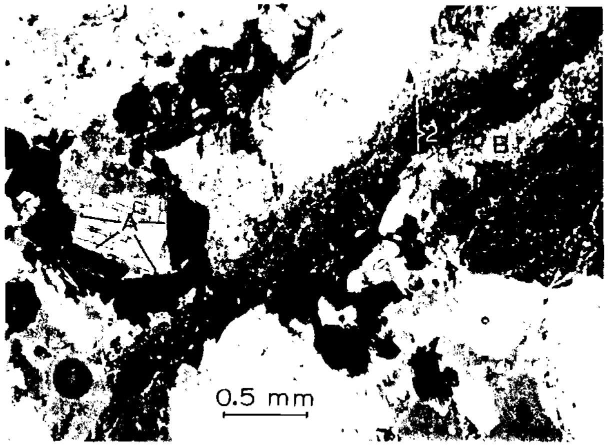

Fig. 4. Roosevelt Hot Springs sample from a depth of 608.7 m, photographed with crossed nicols. The dark band marked '1' and '2' is a sealed fracture. 'A' and 'B' are alteration zones (see text).

Physical Properties

In a self-sealing geothermal system, many physical properties are determined largely by the fracture state of the rock. Such parameters as permeability and electrical resistivity depend on the conduction paths provided by fractures. If a rock is tightly cemented, the only route for significant fluid movement is through fractures. Since the local physical and chemical environment is strongly dependent on the properties of the local fluids and fractures control the distribution of fluids, the environment is indirectly dependent on fractures.

A method modified after Brace et al. [1968] was used to measure permeabilities as small as 1 nanodarcy (10^{-9} darcy). Water in a closed system under pressure is passed through the sample. The decrease of pressure in the system as a function of time allows the permeability to be calculated. Errors in the permeability determinations are probably about 50 to 100% due to the exponential dependence on the several measured factors. Resistivity, which also depends on fracture parameters, was measured on the same saturated samples as permeability. We used a frequency of 100 Hz to minimize polarization effects. These measurements have an error of about 10%.

A sandstone from a depth of 609.2 m from the Dunes area shows the effect of cementation. Figure 6 is a photomicrograph of the boundary between well-cemented and poorly cemented portions. To the right in the poorly cemented region the dark areas between the grains are voids. This region is highly porous and permeable. To the left, in the well-cemented region, the light areas between grains are the calcite cement. This portion has a lower porosity and higher density. The permeability of the poorly cemented region is about 3 milli-

Fig. 5. Raft River sample from a depth of 345 m. This mosaic was made from scanning electron micrographs. The features are as follows: 'B' is a clay rich matrix, 'C' is a calcite sealing fracture, 'D' is a well-formed analcime crystal, 'E' is a void, 'F' is a void filled with epoxy, 'f1'-'f4c' are fractures (see text) [after Batzle and Simmons, 1976].

Fig. 6. Dunes sample from a depth of 609.2 m, photographed with crossed nicols. The poorly cemented portion is to right, the well-cemented portion is to left.

darcies versus 340 nanodarcies for the well-cemented region, a difference of 4 orders of magnitude. The resistivity of the well-cemented region is about double that of the poorly cemented portion. This relatively small change in resistivity is probably due to the presence of clays in the well-cemented region which provide a large surface conduction contribution. New fracturing will be required for any significant fluid movement through the well-cemented region.

The effect of a single fracture is demonstrated by a sample from a depth of 115.8 m in the Dunes area. The permeability of a sample from a tightly cemented unfractured area is about 2.8 nanodarcies. The permeability of a sample of the same size and with a single partially sealed fracture cutting the sample in the direction of fluid flow is about 8.2 millidarcies, a change of 6 orders of magnitude. The resistivity changes by 1 order of magnitude. The difference in the magnitude of change between the permeability and the resistivity is due to the differing dependence of these parameters on the width of the fracture. For a plane slit model, a model well-suited to this single fracture, the permeability depends on the width or aperture to the third power, but the resistivity depends on the width to the first power only. The original unsealed width of the fracture was about 20 μ. Based on the slit model, the 'effective' width of this partially sealed fracture has been reduced to about 5 μ. Hence even a single small fracture is extremely important to the physical properties of the rock.

How the various physical properties depend on the fracture state of a rock is a problem yet to be solved completely. Theoretical models exist, but they need to be refined and tested. Permeability and resistivity will depend, for example, on such factors as the size,

shape, distribution, interconnection, and interaction of fractures and pores. Experimental correlations of various other properties with crack parameters are being attempted, and Feves et al. [1977] discuss several.

Fracture State of Rocks

Fractures have a pronounced effect on rock compressibility. From this effect, fracture porosity, effective orientation of cracks in space, and certain aspects of shape can be determined. Differential strain analysis (DSA), a high-precision technique developed by Simmons et al. [1974], was used in this study. This technique reduces error by comparing sample strain with that of a fused silica standard exposed to the same high-pressure environment.

To date, DSA has been used in this particular geothermal study only on Dunes and Raft River samples. For specific details, see the work by Batzle and Simmons [1976]. The samples have a low fracture porosity, and some are strongly anisotropic and inhomogeneous. Although many fractures are apparent to the unaided eye, because of the sealing process the total measured fracture porosities are less than about 0.1% in all samples. For example, the fracture porosity of the 115.8 m sample from the Dunes area is approximately 0.051% (this value was measured on the tightly cemented portion and does not include the open or partially sealed fractures mentioned previously).

The samples from geothermal areas are also often anisotropic and inhomogeneous. Strains due to fractures may differ by values of 30-40% between the axial and radial core directions. Two portions of a single sample from 337.4 m in the Raft River area differ in compressibility by a factor of 6. These two portions are separated by a sealed fracture and thus provide further evidence that sealed fractures can act as barriers to the flow of the cementing fluids. This particular sample is clay rich, and rock compaction obscures the effects of fractures.

Summary

Geothermal systems are a small but interesting part of the earth's crust. These systems involve a dynamic interaction among rocks, fluids, and fractures. The areas studied all showed repeated cycles of fracturing and sealing. Open fractures are important because they provide fluid and electric conduction paths. Sealed fractures however can block fluid flow. Fluid-rock reactions commonly involve mineral precipitation which tends to seal fractures and results in low fracture porosities. Fluid properties commonly change with time and these properties can be investigated through their effects on host rocks and specific fracture events.

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Petroleum Company, through G. Crosby, provided the Roosevelt Hot Springs cores. David Blackwell of Southern Methodist University made the Marysville core samples available. Ann Harlow typed the manuscript. Financial support was provided by NSF-RANN grant AER75-09588.

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COMPLEXITIES OF THE DEEP BASEMENT FROM SEISMIC REFLECTION PROFILING

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Abstract. Observations of continental basement rocks fall into two categories. For rocks at the surface or within drillable depths, observations are primarily geological in nature, and, in general, they indicate great complexity in structure and great spatial variation in composition. Below drillable depths, information comes largely from geophysical observations that, for lack of resolving power, are commonly interpreted in terms of what must be unrealistically simple models of the earth. An attempt to understand the history, or structure, of the crust by relating one kind of information to the other commonly results in an impasse. Seismic reflection profiling offers hope for bridging this gap. Experiments conducted to date in several foreign countries and in the United States under the Consortium for Continental Reflection Profiling (COCORP) program which involves seismic reflection profiling by using VIBROSEIS sources, indicate basement complexities of much smaller scale than is commonly detected by other geophysical methods. The delineation and mapping of such features should greatly enhance our understanding of the basement and, in turn, of the continents. The data from a COCORP test in Hardeman County, Texas, illustrate a variety of features seismically that appear to be geological in nature and that demonstrate the heterogeneity of the basement. Special processing of the data to extend the duration of the time section from 15 s to 18.5 s resulted in the detection of a deep reflector that may correspond to the crust-mantle boundary and the probable detection of still deeper reflectors within the mantle.

Introduction

The deep basement of the continents is one of the major frontiers of modern earth science. The rocks there are known only in sketchy fashion, yet it seems that detailed knowledge of them will surely be of great importance in the study of such fundamental scientific topics as the formation and evolution of the continents. Furthermore, the deep basement rocks are closely related to the near-surface rocks from which man derives much of his livelihood and may hold the key to understanding, for example, the processes that concentrate certain minerals, the causes and history of the sedimentary basins that hold coal and petroleum, the causes of earthquakes, the mechanisms of volcanoes, and the sources of geothermal energy.

Even at drillable depths, information on the basement is sparse and