GEOTHERMAL SYSTEMS:

ROCKS, FLUIDS, FRACTURES

by

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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 and environment, and their dependence on structure - particularly fractures. Reactions between fluids and rocks depend on fractures for fluid conduction and reaction surfaces. The morphology 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 three to five orders of magnitude. On the other hand, fluid flow is restricted by sealed fractures. The sealed fractures are occasionally the boundary 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 conduction paths. All the studied areas show repeated episodes of fracturing and sealing. Thus, fractures act as both a 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 and rocks then join in alteration reactions which modify or seal fractures. The reaction products that remain in the rocks can be used to limit the models of past fluid properties. Sealing and cementing, in turn, make the rock more susceptible to brittle fracturing.

Figure 1 is an index map of sample locations. Some locations, such as the Dunes and Raft River areas, have been studied in detail. For other areas, such as Marysville, samples have just recently been obtained. Samples were generally chosen on the basis of their fracture content and indurated nature rather than for stratigraphic completeness. The five areas are regions of detrital alluvial sedimentation. Usually, the stratigraphy consists of interbedded sands, silts, clays, and conglomerates. In the Raft River, Marysville, and Roosevelt Hot Springs areas, drilling penetrated fractured igneous intrusive rocks. These igneous rocks may play a significant role in the system.

In many ways, geothermal systems are not typical of the crust. By definition, they possess higher temperature gradients. Because of high temperatures and 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 environment are often different from those that commonly occur in sedimentary basins; 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 often exist (Elders and Bird, 1974; Bird, 1975). Often the first diagenetic reactions involve cementing the sediments which makes fluid circulation dependent upon open fractures.

In several aspects, geothermal systems are typical of the upper crust. These systems involve several common water-rock interactions. Typical diagenetic reactions occur which include cementation, compaction, and alteration.

In this presentation, we will concentrate on the role 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 briefly be summarized here.

FRACTURE RELATIONSHIPS

The five geothermal systems studied all show repeated fracturing superimposed on varying fluid chemistry. One excellent example of repeated fracturing is demonstrated in figure 2 by a Dunes sample from 403.9 meters. 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 remains calcite. The dark wavy bands match almost perfectly with the surface of the clay grain. These dark bands, numbered 1 to 5, oldest to youngest, are probably due to small particles of clay left behind when the calcite and clay fragment separated during fracturing.

A more complicated history is shown in the Heber sample from 1187 meters (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 allow us to determine that 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 and the previous sample show repeated fracturing events followed by fracture sealing.

Fractures can also serve as conduits for reactive fluids. This property is demonstrated by the Roosevelt Hot Springs sample from a depth of 608.7 meters shown in figure 4. A zone of alteration surrounds the fracture through this granodiorite. Here again, multiple fracturing events are indicated (numbers '1' and '2' in figure 4). The relative ages of these events has not yet been determined. The fluid chemistry has changed between the separate fracturing events. The zone marked '1' is quartz and feldspar rich. Zone '2' is predominately hematite. The biotite grains along the fracture (at 'A') are being altered to hematite. Further from the fracture, the mafic grains remain unaltered. At 'B', an alteration rim has formed on the plagioclase grain (albitization?). Future electron microprobe work will help determine exactly which reactions are taking place.

Several variations of fluid chemistry with time are indicated in figure 5. This sample is an argillaceous sandstone from a depth of 345 meters in the Raft River area. The first fracturing to occur, 'f1', is now sealed with calcite 'C'. The next two fracturing events, marked 'f2a' and 'f3a', are now partially sealed with analcime. A well-developed analcime crystal is shown at 'D'. Another set of fracturing 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.

PHYSICAL PROPERTIES

In a self-sealing geothermal system, many physical properties are largely determined 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 geologic environment is strongly dependent on the properties of the local fluids, the environment is indirectly dependent on fractures.

A method modified after Brace et al. (1968) was used to measure permeabilities as small as one nannodarcy (10^{-9} darcy). Water in a closed system under pressure is allowed to pass through the sample. The decrease of pressure in the system as a function of time allows the permeability to be calculated. Errors are likely 50 to 100%. Resistivity, which also depends on fracture parameters, was measured on the same saturated samples as permeability. We used a frequency of 100 Hertz to minimize polarization effects. These measurements have an error of about 10%.

A sandstone from a depth of 609.2 meters 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. The light areas between grains, to the left in the well cemented region, are the calcite cement. This portion has a lower porosity and higher density. The permeability of the poorly cemented region is about 3 millidarcies versus 340 nannodarcies for the well cemented region, a difference of four 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 poorly 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 meters in the Dunes area. The permeability of a sample from a tightly-cemented unfractured area is about 2.8 nannodarcies. The permeability of a sample with a single partially sealed fracture is about 8.2 millidarcies, a change of six orders of magnitude. The resistivity changes one order of magnitude. The difference in the magnitude of change between the permeability and resistivity is due to the differing dependence of these parameters on the width of the fracture. For a plane slit model, 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 20μ. Based on the slit model, the 'effective' width of this partially sealed fracture has been reduced to about 5 microns. 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. (this volume) 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 on only Dunes and Raft River samples. For specific details, see 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, due to the sealing process the total fracture porosities are less than about 0.1% in all samples. For example, the fracture porosity of the 115.8 meter 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 results for this particular sample show that here the fractures do not have a smooth continuous distribution of shapes, but consist of sets of fractures with discrete values of aspect ratio or ratio of width to length.

The samples from geothermal areas are also often anisotropic and inhomogeneous. Strains due to fractures differ by values of 30 to 40% between the axial and radial core directions. In a sample from 337.4 meters in the Raft River area, two portions differ in compressibility by a factor of six. These two regions are separated by a sealed fracture and thus provide further evidence that sealed fractures can act as barriers to the flow of the cement-

ing 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. Repeated cycles of fracturing and sealing have occurred. Fractures provide circulation paths. Sealed fractures can block fluid flow. Reactions between rock and fluids often produce alteration zones along fractures. Mineral precipitation tends to seal fractures and results in low fracture porosity. Fluid properties commonly change with time and these properties can be investigated through their effects on the host rock and specific fracture events.

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FIGURE CAPTIONS

Figure 1. Index map.

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

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

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

Figure 5. Raft River sample from a depth of 345 meters. This mosaic was made from scanning electron micrographs. Features: 'B' - clay rich matrix; 'C' - calcite sealing fracture; 'D' - well formed analcime crystal; 'E' - void; 'F' - void filled with epoxy; 'f1' to 'f4c' - fractures (see text). (After Batzle and Simmons, 1976.)

Figure 6. Dunes sample from a depth of 609.2 meters, photographed in crossed nicols. Poorly cemented portion is to right, well cemented portion is to left.

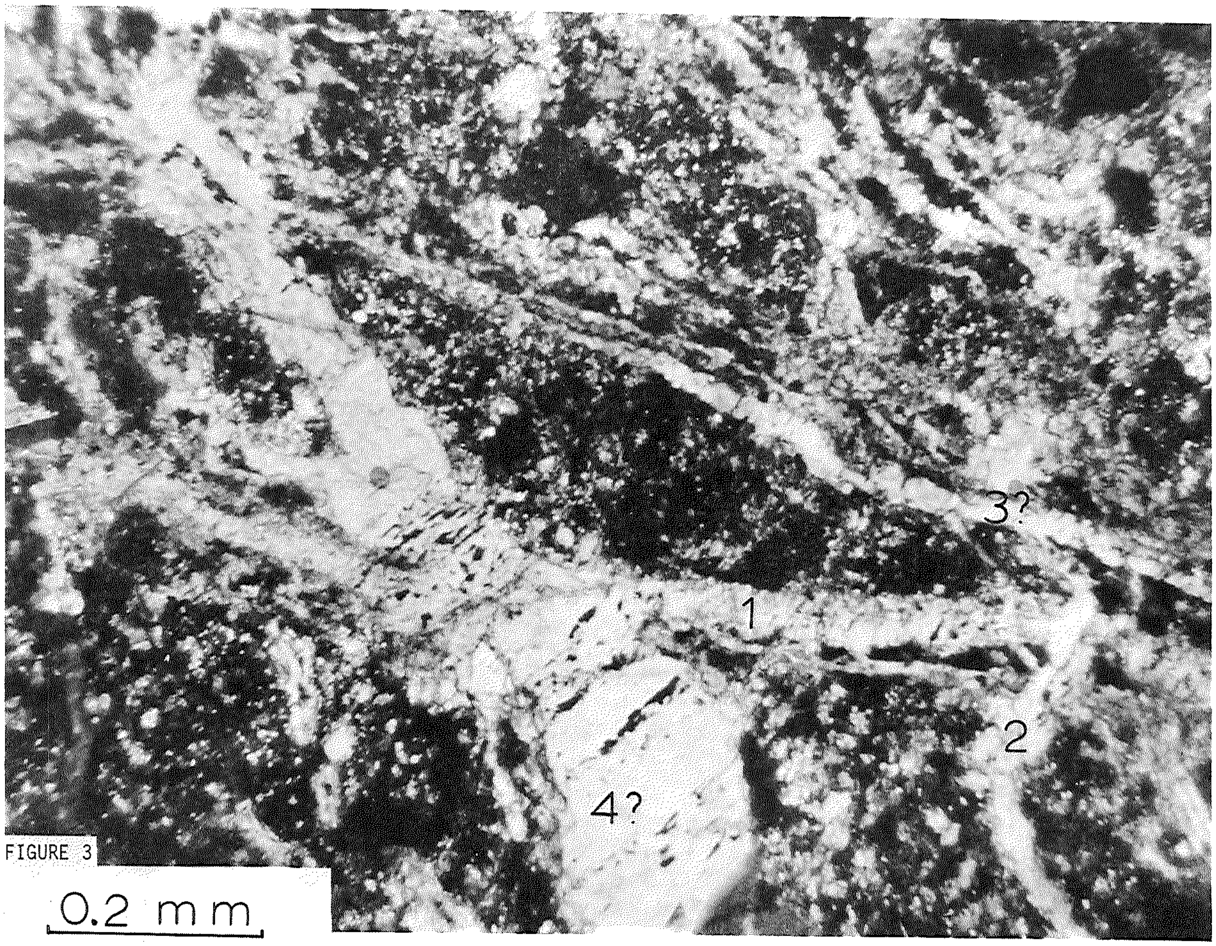


FIGURE 3

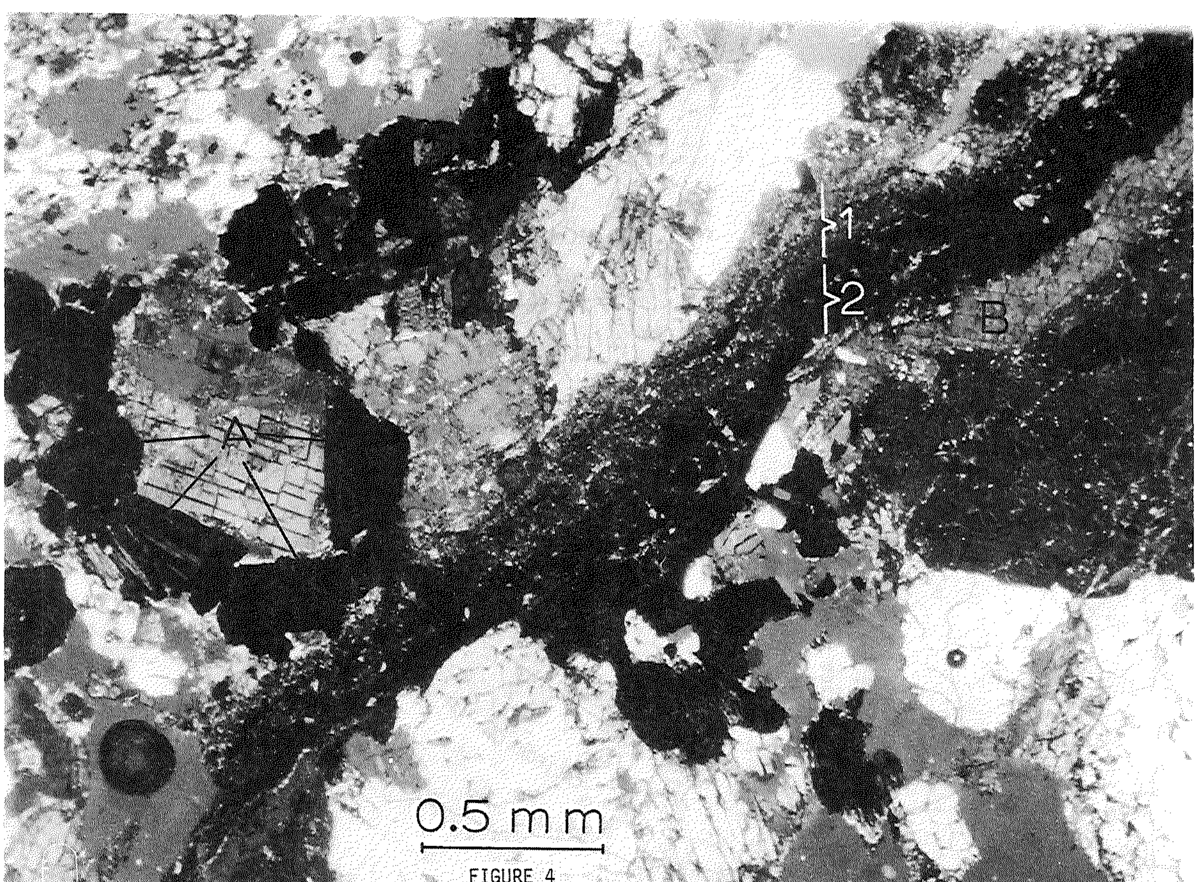


FIGURE 4

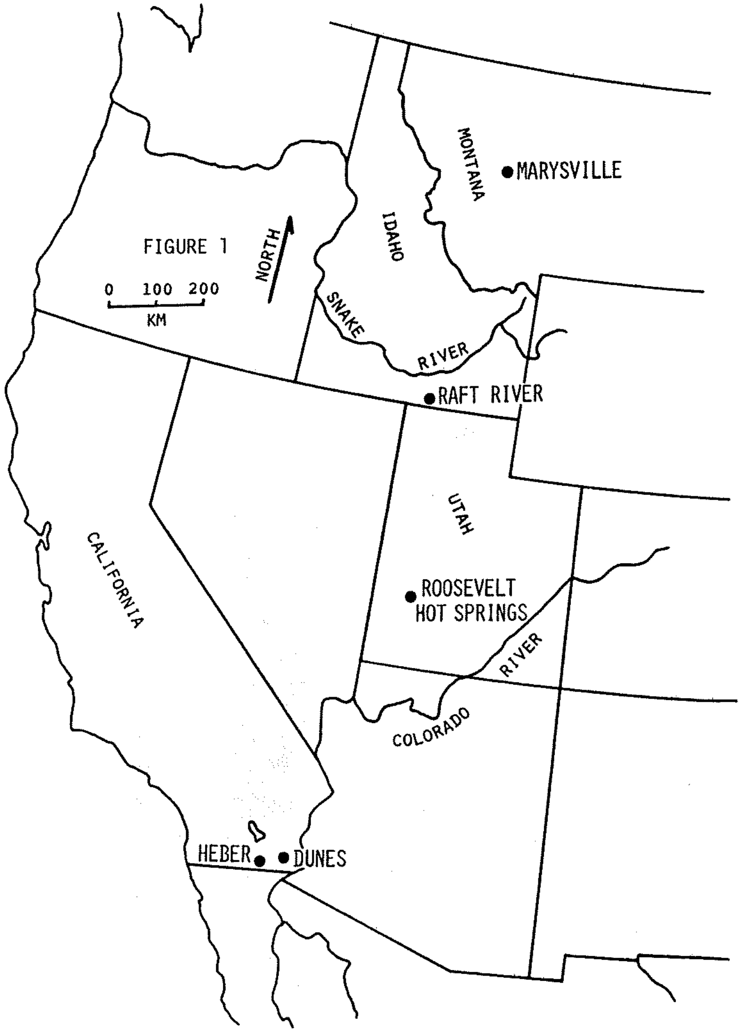
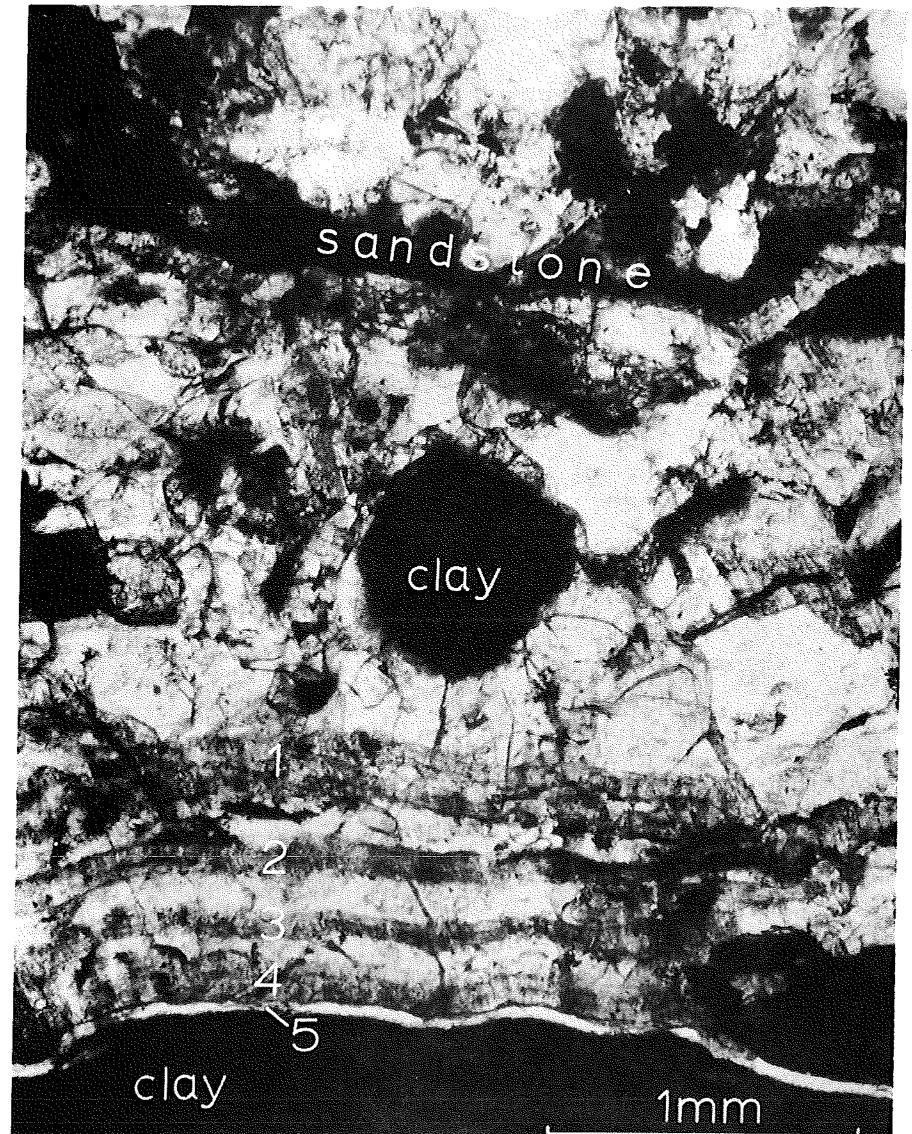


FIGURE 1
0 100 200
KM
NORTH
MONTANA
MARYSVILLE
IDAHO
SNAKE
RIVER
RAFT RIVER
UTAH
ROOSEVELT
HOT SPRINGS
RIVER
COLORADO
CALIFORNIA
HEBER
DUNES



sandstone
clay
1
2
3
4
5
clay
1mm

FIGURE 2

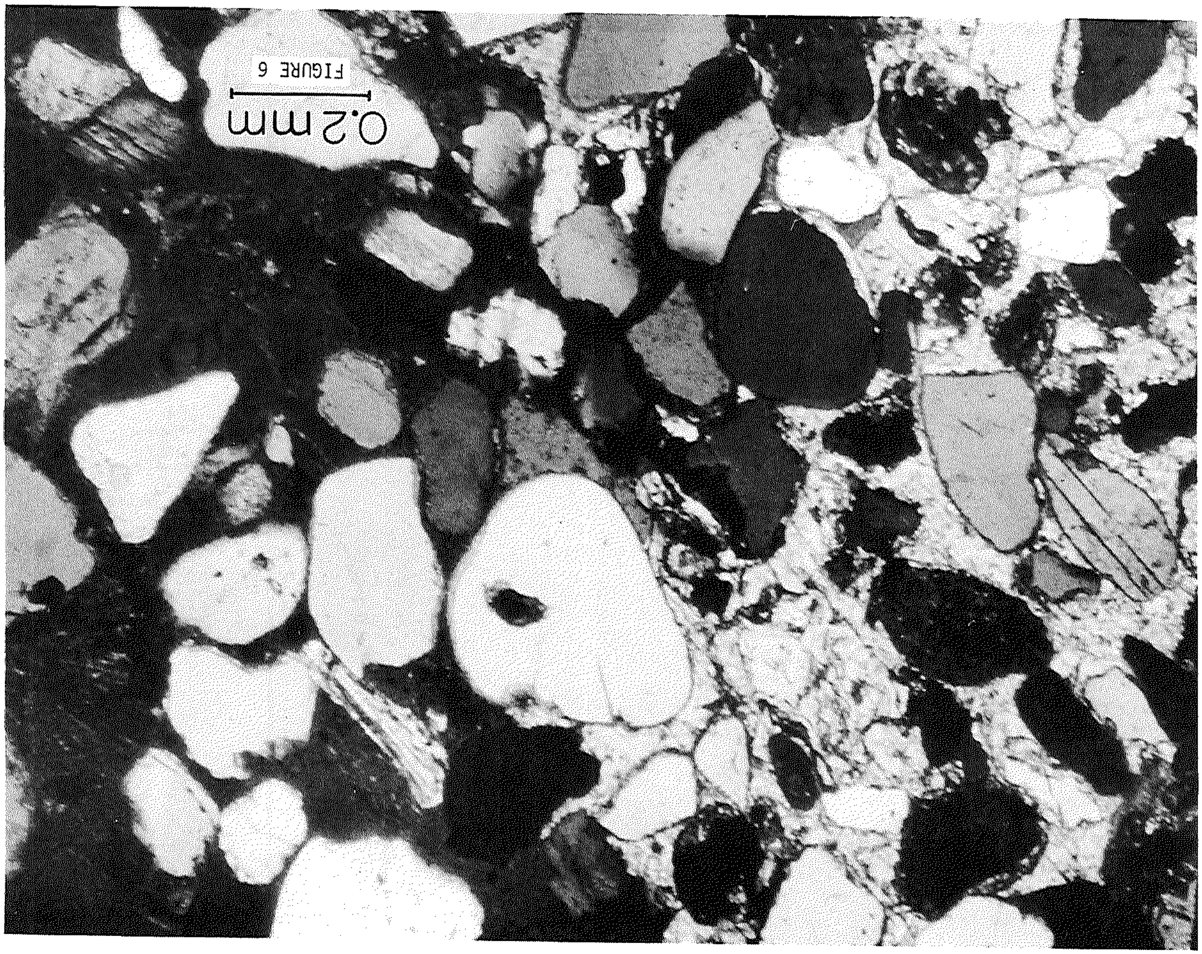


FIGURE 6

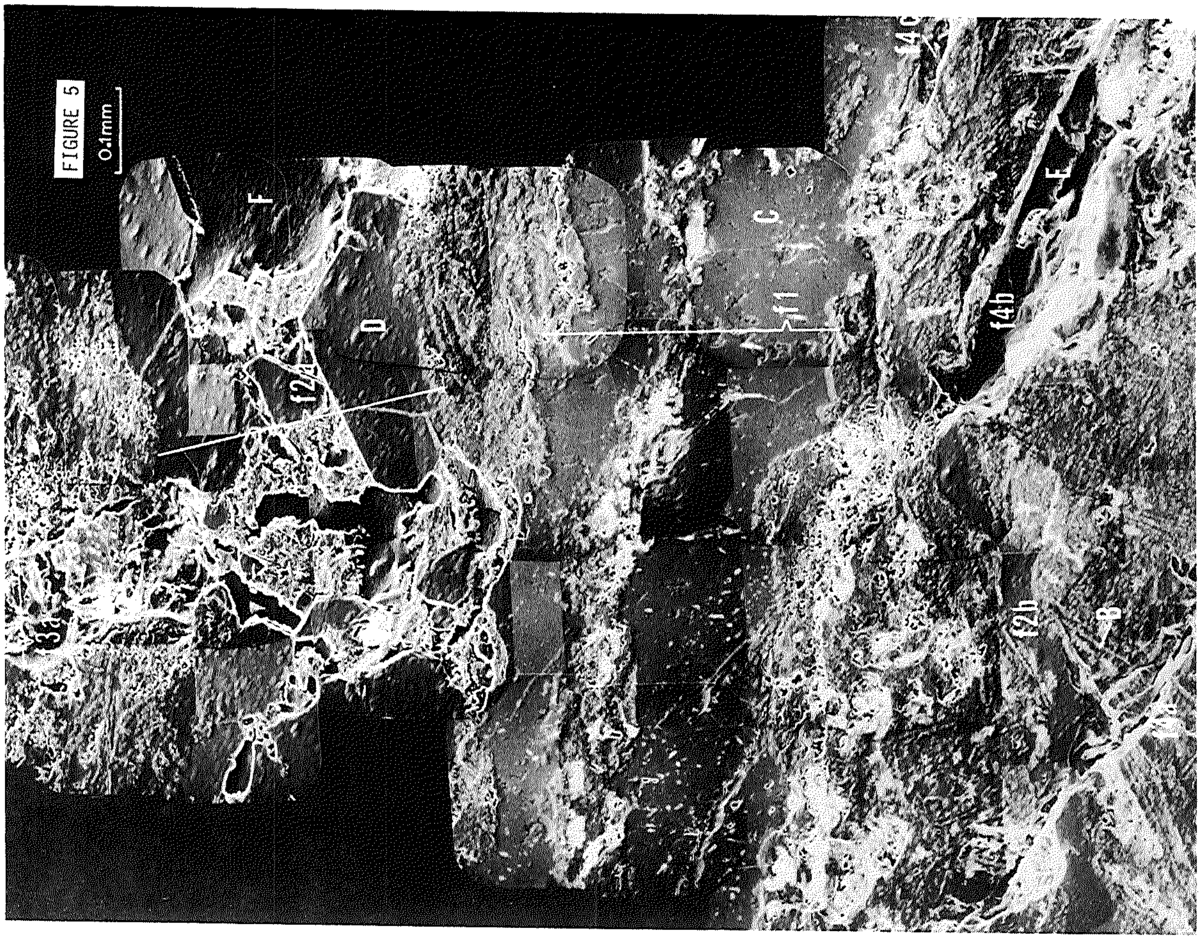


FIGURE 5