MICROCRACK TECHNOLOGY

**Progress Report
for Period 1 October 1978 - 31 March 1979**

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TABLE OF CONTENTS

Title page	1
Table of contents	2
1.0 What we have done (1 October 78-31 March 79)	3
1.1 Introduction	3
1.2 Coso and Raft River samples	3
1.2.1 Locations	3
1.2.2 Unique characteristics of microcracks from geothermal areas	11
1.3 Physical properties - hydraulic permeability and electrical conductivity	25
1.3.1 Measurements	25
1.3.2 Models	31
1.3.3 A future application: waste isolation	37
1.4 Collection of samples	37
2.0 References	39

1.0 WHAT WE HAVE DONE (1 OCTOBER 78-31 MARCH 79)

- A. Examined the microcracks in core samples from Coso and Raft River Geothermal Areas.
- B. Discovered a set of observable characteristics of microcracks in rocks from geothermal regions that appears to be unique and to have considerable potential for exploration for geothermal regions.
- C. Measured both permeability and electrical conductivity for a suite of samples with a range of microcrack characteristics. (We are using the data to develop general relationships.)
- D. Collected a partial set of samples to study migration of radioactive elements.

1.1 Introduction

This study of microfractures in rocks from geothermal areas began in October 1978 and had the benefit of a previous study which had been supported by NSF. The techniques that we use, as well as other applications, are described in the publications listed in Table 1.

During the current period (1 October 1978-31 March 1979), we examined in detail samples from two geothermal areas, measured physical properties on a suite of samples, and collected several samples for study during the next contract year.

1.2 Coso and Raft River Samples

1.2.1 Locations

We have added specimens to the suites of samples already in hand from the Raft River, Idaho and Coso, California geothermal areas. They consist of cores from the Raft River Geothermal Injection Wells #4 and #6 and outcrop samples of cataclastic rocks from a fault zone at Coso Hot Springs. The locations of these new specimens are shown in Figures 1, 2, and 3. We have

Table 1.

Manuscripts on Microcracks

Authors	Title	Year	Where Published
Simmons, Siegfried, and Feves	Differential strain analysis: a new method for examining cracks in rocks	1974	Journal of Geophysical Research, <u>79</u> , 4383-4385.
Simmons, Todd, and Baldrige	Toward a quantitative relationship between elastic properties and cracks in low porosity rocks	1975	American Journal of Science, <u>275</u> , 318-345.
Simmons, Siegfried, and Richter	Characteristics of microcracks in lunar rocks	1975	Proceedings Sixth Lunar Science Conference, <u>3</u> , 3227-3254.
Batzle and Simmons	Microfractures in rocks from two geothermal areas	1976	Earth and Planetary Science Letters, <u>30</u> , 71-93.
Simmons and Richter	Microcracks in rocks	1976	<u>The Physics and Chemistry of Minerals and Rocks</u> , Wiley-Interscience, 105-137.
Feves and Simmons	Effects of stress on cracks in Westerly granite	1976	Bulletin of the Seismological Society of America, <u>66</u> , 1755-1765.
Richter, Simmons, and Siegfried	Microcracks, micropores, and their petrological interpretation for 72415 and 15418	1976	Proceedings Seventh Lunar Science Conference, <u>2</u> , 1901-1923.
Simmons and Cooper	DSA of the microcracks in GT-2 core: interpretation and implications	1976	Final Technical Report: Los Alamos Scientific Laboratory

Table 1 (continued).

Authors	Title	Year	Where Published
Richter and Simmons	Microscopic tubes in igneous rocks	1977	Earth and Planetary Science Letters, <u>34</u> , 1-12.
Batzle and Simmons	Assessing geothermal areas <u>during</u> drilling	1977	Geothermal: <u>State of the Art</u> , Trans. Geothermal Resources Council Annual Meeting, 13-15.
Batzle and Simmons	Geothermal systems: rocks, fluids, fractures	1977	<u>The Earth's Crust: Its Nature and Physical Properties</u> , AGU, 233-242.
Feves, Simmons, and Siegfried	Microcracks in crustal igneous rocks: physical properties	1977	<u>The Earth's Crust: Its Nature and Physical Properties</u> , AGU, 95-117.
Richter and Simmons	Microcracks in crustal igneous rocks: microscopy	1977	<u>The Earth's Crust: Its Nature and Physical Properties</u> , AGU, 149-180.
Simmons and Cooper	DSA of the microcracks in more GT-2 core: interpretation and implications	1977	Final Technical Report: Los Alamos Scientific Laboratory.
Batzle and Simmons	Fracturing and sealing in geothermal systems	1978	Proceedings volume, NSF-RANN Geothermal Conference, 1976, submitted.
Siegfried and Simmons	Characterization of oriented cracks with differential strain analysis	1978	Journal of Geophysical Research, <u>83</u> , 1269-1278.

Table 1 (continued).

Authors	Title	Year	Where Published
Simmons and Cooper	Thermal cycling cracks in three igneous rocks	1978	International Journal of Rock Mechanics and Mining Science, <u>15</u> , 145-148.
Siegfried, Simmons, Richter, and Hörz	Microfractures produced by a laboratory scale hypervelocity impact into granite	1977	Proceedings Eighth Lunar Science Conference, <u>1</u> , 1249-1270.
Cooper and Simmons	The effect of cracks on the thermal expansion of rocks	1977	Earth and Planetary Science Letters, <u>36</u> , 404-412.
Wang and Simmons	Microcracks in crystalline rock from 5.3-km depth in the Michigan Basin	1978	Journal of Geophysical Research, <u>83</u> , 5849-5856.
Fehler and Simmons	Effects of depth on microcracks in granitic rock from Casco, Maine	1979	in preparation.
Siegfried, McQueen, and Simmons	Shock-induced microfractures in six terrestrial igneous rocks characterized with differential strain analysis	1978	Journal of Geophysical Research, submitted.
Siegfried, Simmons, McQueen, and Hörz	Are the microcracks in lunar samples representative of those <u>in situ</u> in the lunar crust?	1979	in preparation.
Padovani, Batzle, and Simmons	Characteristics of microcracks in samples from the drill hole Nördlingen 1973 in the Ries Crater, Germany	1979	Proceedings Ninth Lunar Science Conference, in press.

Table 1 (continued).

Authors	Title	Year	Where Published
Simmons, Batzle, and Cooper	The characteristics of micro-cracks in several igneous rocks from the Chalk River site: a preliminary report	1978	Department of Energy, Mines, and Resources, Canada.
Hall, Miller, and Simmons	A technique for the precise measurement of acoustic velocity in, and between, boreholes with a sparker source	1979	Geoexploration, submitted.
Hall and Simmons	Seismic velocities of Lewisian metamorphic rocks at pressures to 8 kbar: relationship to crustal layering in N. Britain	1979	Geophys. J. Roy. Astron. Soc., in press.

STRUCTURE & HEAT FLOW MAP, COSO GEOTHERMAL AREA, CALIFORNIA

- Volcanic cone
- Alteration areas with or without active geothermal emissions (Smaller areas noted by triangles)
- Mapped faults from literature (Bar and ball on down thrown side)
- Photo-interpreted fault
- Fault interpreted from geophysics
- Heat flow contours (Values in mFU, dashed where approximate)
- Shallow heat flow holes
- Deep hole drill site
- Samples collected in outcrop

Figure 1. Structure and heat flow map, Coso geothermal area, California. Previous samples were obtained from the shallow holes identified by circled numbers and the deep hole drill site. New samples have been collected in outcrop at L2 and L3. (After Combs, 1976; Furgerson, 1973; and Lanphere et al., 1975).

Figure 2. Geology, structure, and well locations for the Raft River area (after Williams *et al.*, 1974 and Williams *et al.*, 1976). See Figure 3 for legend. New samples are from wells RRG1#4 and RRG1#6.

LEGEND

- MAP SYMBOLS

CONTACT

FAULT Bar and ball on downthrown side.
Dotted where concealed.

NARROWS STRUCTURE

ANTICLINAL TREND

WELLS

Raft River Geothermal Exploration (RRGE)

Intermediate depth well (INT)

Raft River Geothermal Injection (RRGI)

Figure 3. Cross-section of Raft River area from A to A' (see Figure 2). Note closely-spaced normal faulting continues at depth. RRGE#1 and Int#3 are projected onto plane of cross-section. Same source as Figure 2.

also obtained downhole information from the Raft River area in the form of Compensated Densilog, BMC Acoustilog, Dual Induction Focused Log with Linear Correlation and Compensated Neutron Logs.

1.2.2 Unique Characteristics of Microcracks from Geothermal Areas

We have learned to recognize in the scanning electron microscope (SEM) a set of characteristic features of microcracks that appear to be unique and also typical for the host rocks of hydrothermal systems (Shirey et al., 1978). If the set continues to be unique after many more samples are examined, then it may prove to be a valuable guide in the exploration for geothermal systems. The set of characteristics consists of (A) bridges in microcracks, (B) modified crack walls, (C) repeated fracturing and sealing of the fractures, (D) existence of a critical crack width, and (E) dominance of transgranular cracks. We shall illustrate our discussion of these features with examples observed in a specimen from Coso.

A. Bridges. Microcracks in rocks from geothermal systems usually have bridging structures that span the distance between the walls on either side of an open microcrack (Figure 4). The presence of bridges is unequivocal evidence that the cracks were open in situ and have not been disturbed during collection or preparation of the specimen. Modification of bridges by cracking during pull-apart or by crumpling during squeezing provides a calibration for changes in crack width. The presence of bridges is an indication that the mechanical closing of a microcrack will be incomplete in the laboratory; some porosity will remain along the microcrack plane even when the microcrack is closed mechanically.

B. Modified Crack Walls. Recent, fresh, open microcracks

Figure 4. Coso sample 1650-1033. The branching system of transgranular cracks (TGC) in center cuts across composite biotite grain (b). TGC is intermittently sealed. Area in box is shown in Figure 5. SEM micrograph, secondary electron image.

such as those produced by shock or unconfined shear stress (thin section making) have walls that appear to be matched perfectly across the microcrack open space. We argue that these fresh surfaces do not last long in contact with hot circulating fluids. Microcracks in rocks from geothermal areas have walls that have been modified from their original, fresh appearance. Evidence for modification consists of mismatched walls and textural relief on the surface of the wall itself. Figures 5 and 6 show both features. Textural relief on the microcrack wall can be of positive or negative type. The positive type is an overgrowth; evidence of incipient crack-sealing by mineral precipitation. The negative type is an etch pit; a signal of incipient crack widening by chemical solution.

C. Repetition of Fracturing and Sealing. Microcracks in rocks from geothermal systems have been sites at which several successive episodes of cracking and sealing have occurred. Close examination of a typical sequence shown in Figures 4-6 reveals a microcrack history of: fracturing, sealing with calcite, refracturing, and modification of calcite-host wall by mineral precipitation. Megascopic models of typical geothermal systems include intermittent refracturing to sustain the connective pathways of the circulatory system. Refracturing offsets the tendency of the system to seal itself by rapid precipitation from saturated solutions. Repeated fracturing on the microscale indicates that dynamic processes essential to the viability of the geothermal system affect even small volumes of rock. Normal megascopic observations often overlook these same small volumes of rock and thus exclude them from the models of the geothermal circulation system.

D. Critical Crack Size. A dependence exists between the size of the microcrack in rocks from a geothermal area and the complexity of the textures developed in the microcrack. Cracks less than 30 μm in width are usually sealed by a

Figure 5. Coso sample 1650-1033. Enlargement of an area in Figure 4. Calcite (c) seals most of volume of microcrack in porous host (h). Refracturing formed partially open microcrack located at lower edge of calcite. The partially open microcrack contains new mineral growth. The area in box is shown in Figure 6. SEM micrograph, secondary electron image.

Figure 6. Coso sample 1650-1033. Enlargement of an area in Figure 5. Numbered spots are locations of energy-dispersive x-ray analyses (EDX). The partially open microcrack between calcite and host is partially spanned by incomplete bridges (see points 6, 9 and 11, 12) and partially filled with new mineral growth (see points 10, 13). Notice bumpy texture of microcrack wall. SEM micrograph mosaic, secondary electron image.

single episode of sealing and the composition of the sealing material approximates the composition of the host. Cracks greater than 100 μm in width are usually sealed with several generations of phases whose composition often differs greatly from that of the host. The existence of this dependence implies that a critical microcrack width exists which is probably different for different fluids and host rocks. Microfractures thinner than the critical width have simple textures because they carry fluids whose equilibria are dominated by the microcrack host. Microcracks wider than the critical width have complex textures because they carry fluids whose equilibria are dominated by fluid chemistry.

E. Dominance of Transgranular Cracks. Transgranular cracks (TGC) are the dominant microcrack type found in geothermal systems. This particular crack morphology is interpreted by us to be evidence against a mechanism of microcrack formation related to properties of individual constituent minerals such as differential thermal expansion or cleavage. The TGC morphology suggests a microfracture mechanism such as corrosion fracture, hydrofracture or tectonic stress fracture akin to the mechanism of fracture in the megascopic system.

All five characteristics of microcracks in geothermal rocks are seldom developed in a single crack-section. However, they are all present in suites of samples located close enough together to be within the volumetric confines of an active geothermal circulation system. The set of characteristics of microcracks in geothermal rocks is unique when compared with the characteristics of microcracks in rocks from non-hydrothermal regions that we have investigated: rhyolite, quartz-monzonite, gabbro, granite, diabase (Richter and Simmons, 1977); granulite and amphibolite (Padovani et al., 1979a); quartz arenite, orthoquartzite, arkose

(Simmons, 1979); lunar dunite and lunar breccia (Richter et al., 1976); lunar basalts (Simmons et al., 1975); shocked aplite, amphibolite and flasergneiss (Padovani et al., 1979b); and stressed granite (Feves and Simmons, 1976). We conclude that microcracks in geothermal rocks have a unique set of features that result from episodic stress buildup and the interaction of hot reactive fluids in the circulation system with the rocks.

Detailed examination of microcracks in a drill core sample from the Raft River Geothermal Injection Well #6 at 3005' depth, provides a good example of the application of geothermal microfracture characteristics to the analysis of a small volume of rock. We know our sample has been collected proximal to the Raft River area. The central question is: Does the morphology of the microcrack allow us to connect this small parcel of rock to the geothermal circulation system? A firm answer to this question will help define the limits of the system. The capability to answer this question is necessary to construct an exploration tool for geothermal energy resources based on microcracks.

In hand specimen, the sample is a grey-green silty sandstone. In thin-section it is texturally immature with angular, poorly sorted quartz as the dominant detrital mineral and orthoclase, muscovite, biotite, chlorite, plagioclase, and apatite as detrital minerals of lesser abundance. Authigenic pyrite granules in aggregates shaped like cauliflowers are dispersed at random in the rock. The detrital minerals are supported by a matrix of microcrystalline material that contains spotty concentrations of calcite or microcrystalline silica. Analcime and calcite occur

in a 2 mm wide microfault visible at one side of the section.

The porous and microcrystalline-amorphous nature of the matrix is evident in the SEM images (Figure 7). At higher magnification (Figure 8), the matrix is seen to be a complex mass of relatively impermeable clay that changes to airy aggregates of discrete grains near detrital grain boundaries. Energy dispersive x-ray analyses indicate that the clay is near illite in composition, but contains some Ti. The microfault and analcime along it are readily visible at low magnifications on the SEM (Figure 9). However, of special interest for the assessment of the geothermal system, is a series of small cracks that parallel bedding and appear to be connected to the microfault. An SEM micrograph mosaic (Figure 10a) along the fracture at the center of Figure 9 reveals 100 μm long open crack segments $\sim 10 \mu\text{m}$ in width which provide considerable porosity along the bedding plane. Analcime similar in composition to the analcime near the microfault grows in patches along the bedding plane microcrack. Analcime bridges are well developed (Figures 10a and 10b) and span the microcrack without breaks at several spots. The microcrack thus displays an original in situ width that has remained unchanged through drilling, removal of the core to surface and sample preparation. However, the microcrack wall has been altered in width by fluids in situ and now has variations of at least 5 to 12 μm along it (Figure 10a). The microcrack walls have been modified also by spiky analcime overgrowths into open fracture space (Figure 10b). Multiple sealing textures are absent; an observation consistent with the narrow width ($< 20 \mu\text{m}$) of the microcrack

Figure 7. Silty sandstone from Raft River Geothermal Injection Well #6, 3005'. Detrital grains (d) are smooth surfaced and matrix (m) is irregular porous material. Note areas of matrix separate most detrital grains. SEM micrograph, secondary electron image.

Figure 8. Detailed view of silty sandstone matrix from Raft River Geothermal Injection Well #6, 3005'. The compact material in center is clay. Note the dessication cracks (Δ). EDX analyses were taken at white circles. The matrix changes to airy aggregates of discrete grains near contact with some detrital materials (d). SEM micrograph, secondary electron image.

Figure 9. Silty sandstone from Raft River Geothermal Injection Well #6. Note epoxy-filled (e) microfault at lower right. Parallel to it is an analcime-filled vein (Δ). Smaller, bedding-plane fractures (∇) are connected to microfault. SEM micrograph, secondary electron image.

Figure 10a. Open bedding-plane microcrack in silty sandstone. Note the supports provided by analcime bridges (a).

Figure 10b. Analcime (a) growths in open bedding-plane microcrack. They form spikes, bridges, and irregular masses. Microcrack walls are located entirely in the detrital feldspar grain (d). Note that the wall near the illite-rich matrix (m) consists entirely of new mineral growth. Both 10a and 10b are SEM micrograph mosaics, secondary electron image.

and the previously observed size dependence of multiple sealing textures. The bedding plane microcrack is transgranular.

Four of the five textural characteristics typical of 'geothermal microcracks' are present in this one bedding plane microcrack, suggesting the microcrack was connected to the periphery of a hydrothermal circulation system. It is clear from textures along the bedding plane microcrack that analcime was the last phase to grow in equilibrium with fluid. The upper limit of analcime stability in H₂O-rich siliceous environments is defined by the reaction: Analcime + Quartz $\rightleftharpoons$ Albite + Fluid (Liou, 1971). The sample was retrieved as drill core from a depth of 3005' where the pressure would be approximately 90 to 270 bars. Over this pressure range, analcime can grow in equilibrium with fluid only at temperatures below 200°C. This observation agrees with well-water temperatures of 150°C determined by Na-Ca-K geothermometry (Kunze et al., 1976; Williams et al., 1976) and measured downhole hot water temperatures of 147°C (Kunze et al., 1976; Stoker et al., 1976, 1977; and Kunze, 1977).

We have specifically chosen a rock for this example whose relationship to the geothermal system is ambiguous after megascopic or standard petrographic examination. With the SEM, we have observed features in microcracks that indicate a physical-chemical connection between a small volume of rock and a geothermal circulation system. By using the SEM to image microcracks and by applying our microcrack characteristics as a set of criteria, we can test small volumes of unknown rock for participation in a hydrothermal circulation system.

1.3 Physical Properties - Hydraulic Permeability and Electrical Conductivity

1.3.1 Measurements

Hydraulic permeability and electrical conductivity were measured as a function of confining pressure. Samples consisted of Westerly granite, both virgin and preheated to 300 and 500°C, and of Frederick diabase preheated to 700°C. The samples were heated and cooled at rates of less than 1°C per minute to prevent spatial thermal gradient effects. Figure 11 shows the experimental set-up. The methods used were almost identical to those described in Chapter 3 of the RANN/ERDA final report. The only variation was that the fluid flowed from the sample to a container exposed to the atmosphere rather than to a low pressure reservoir. Conductivities were measured in similar experimental apparatus, but without input and outlet fluid ports. Conductivities and permeabilities were measured on separate samples. The technique is similar to that used by Brace et al. (1968). The results are shown in Figures 12, 13, 14, and 15.

Consistent and significant variations can be observed in the curves going from virgin Westerly granite to preheated Frederick diabase. Virgin Westerly granite is filled with natural fractures. The fracture walls, as observed with the SEM, are rough, pitted, and mismatched. Crack closure is largely incomplete even at high pressures. As the crack porosity increases due to heating (Figures 13 and 14), note the change not only in the shapes of the curves but also in the relative separation of conductivity and permeability as confining pressure increases. The cracks have changed from all natural in virgin granite to all

Figure 11. Permeability assembly. Fluid flows in through the bottom tube, up through the sample, and out to atmospheric pressure through the upper tube. Electrical conductivities were measured with similar assemblies that lacked input and output tubes.

Figure 12. Permeability and conductivity versus confining pressure for virgin Westerly granite. Note: For the permeability data, the vertical bars represent the spread of measured values, the solid or open symbols are the mean values.

Figure 13. Permeability and conductivity versus confining pressure for Westerly granite preheated to 300°C (see note for Figure 12).

Figure 14. Permeability and conductivity versus confining pressure for Westerly granite preheated to 500°C (see note for Figure 12).

Figure 15. Permeability and conductivity versus confining pressure for Frederick diabase preheated to 700°C (see note for Figure 12).

newly created in the preheated diabase. The new cracks have smooth and well-matched walls, as observed with the SEM, and close more efficiently. This closure effect has also been observed recently (Batzle et al., 1979) with similar rock samples stressed uniaxially in the scanning electron microscope.

1.3.2 Models

A parallel plate model has often been used to describe fluid and electrical transport in cracks. Permeability should depend on the width to the third power in a long narrow crack. Conductivity is dependent on the width only to the first power. This simple analogy does not apply well to virgin Westerly granite. The small relative change in conductivity versus permeability as a function of confining pressure requires that crack closure be inefficient with gaps and pockets remaining open. These cracks, in effect, close as much by length as by width. However, as more new cracks are introduced, the relative change in conductivity versus permeability is much larger and more in agreement with the parallel plate model. These new cracks with well-matched walls close much more efficiently.

We are now in the process of developing a model to relate permeability and conductivity to other measured fracture parameters. Crack porosity and crack closure pressure are measured using the differential strain analysis (DSA) technique described in Simmons et al. (1974), Siegfried and Simmons (1978), and our RANN/ERDA final report. For example, the DSA plot for virgin Westerly granite is shown in Figure 16. By plotting the sum of the zero-pressure intercept of the tangents to these curves

Figure 16. Differential strain in three orthogonal directions for virgin Westerly granite. Irregularities at high pressure are due to fluctuations in laboratory temperature.

versus pressure (on a logarithmic scale), the curve of Figure 17 is produced. This curve is a measure of the decrease in crack porosity as a function of confining pressure. By using Walsh's (1965) relationship for the closure of idealized elliptical cracks, the closure pressure can be related to aspect ratio, α (ratio of crack width to length),

$$\alpha = \beta P_c \frac{4(1-\nu^2)}{3\pi(1-2\nu)}$$

where β and ν are the compressibility and Poisson's ratio, respectively, of the fracture-free matrix and P_c is the crack closure pressure. The closure pressures and porosities are then grouped as indicated by the boxes in Figure 17. The resulting graph of porosity versus aspect ratio is shown in Figure 18. The same procedure has been applied to the other samples (Figure 19).

The geometric mean technique (Madden, 1976) is now being used to relate these crack properties to the permeability and conductivity. With this technique, the flow properties of the rock are calculated from the geometric mean of the flow properties from all the contributing cracks. Hence, this technique is a way of calculating megascopic rock properties from the parameters used to describe single cracks. Many parameters must still be assumed, such as absolute crack width. However, other parameters can be defined which describe how the cracks interact. These last parameters include the ratio of crack width closure to length closure and the extent that the cracks of one aspect ratio are actually contained within a different aspect ratio. The results are important for determining how the irregular and

Figure 17. Crack porosity as a function of closure pressure (heave curve). The boxes and numbers within indicate the crack porosity allocated to specific intervals of closure pressure (see text).

Figure 18. Crack porosity versus aspect ratio derived from the groupings in Figure 17. (see text).

Figure 19. Crack porosity versus closure pressure for virgin Westerly granite preheated to 300 and 500°C, and Frederick diabase preheated to 700°C. Arrows indicate where groupings would be centered as in Figure 17.

mismatched natural fractures behave in contrast to, and in relationship with, the well-matched artificial fractures induced by heating.

1.3.3 A Future Application: Waste Isolation

For a radioactive waste disposal site, as an example, such models are needed to predict how permeability will vary as the rocks are heated. The situation is complicated due to the complex stress fields and numerous possible sources of fracturing. Additional cracks will be added to the original fractures due to the temperature increases and stresses related to the excavation of the site. Eventually, however, the modeling will be refined to the point where permeability contours could be drawn around the site as a function of time. The input parameters would come from heat transfer models and a relatively few samples that have been stressed, heated, and had the cracks characterized with DSA.

1.4 Collection of Samples

We visited the NTS in December 1978 to select samples of core for a preliminary study on waste isolation. We obtained samples from test holes UE25A#3, UE17E, and UE25A1. The samples ranged in depth from surface to about 2500 feet and included several rock types. Crack sections, polished thin sections, and DSA blocks are being prepared.

We have obtained a suite of samples of the core from the hole drilled in the Conway granite at Red Stone Quarry, near North Conway, New Hampshire, by Glenn Stewart with ERDA funds. This suite will be used to study the migration of radioactive

elements. Specimens will be prepared for crack-examinations during the next few months.

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