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Preliminary Studies of the Alteration of a Granite by an Artificial Hydrothermal System

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PRELIMINARY STUDIES OF THE ALTERATION OF A GRANITE BY AN ARTIFICIAL HYDROTHERMAL SYSTEM

by

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ABSTRACT

Solution channels in quartz, microcline, and plagioclase of a granite have been produced by exposure of the rock to an artificial hydrothermal system. Electron microprobe analyses, beam-scanning photographs, and element profiles show that the mineral grains are homogeneous and unaltered within a few micrometers of the channels. The channels, which are 3 to 7 μ in diameter, appear to have formed by removal of material in solution. In the sample material, no new minerals produced by alteration or deposition were detected by microprobe analysis. The apparent absence of such alteration products (e.g., clays) may be due to (1) sample preparation which removed fine-grained alteration products during polishing; or (2) concentrations of such minerals in such small amounts that they are below the limits of detectability with the microprobe.

In this section, the granite is seen to be preferentially attacked by the hydrothermal solution along grain boundaries and cracks. Similar solution effects are observed in amphibolites exposed to the artificial hydrothermal system. Plagioclase crystals in the amphibolite are partially dissolved so that delicate porous boxwork structures remain.

INTRODUCTION

The Los Alamos Scientific Laboratory (LASL) is presently engaged in the development of a system for production of electricity from so-called "dry" geothermal energy, that is, the thermal energy stored in dry, impermeable rocks in areas of the earth's crust with abnormally high geothermal gradients. The Laboratory hopes to establish a hot water circulation loop between hot rocks at depth

and a heat-extraction system in a surface power plant.

In order to understand and predict the behavior of a system involving the movement of large quantities of water along artificially induced fractures in hot rocks, the Laboratory has initiated studies of the behavior of rocks from preliminary test holes in artificial hydrothermal systems. This report presents the results of a study of solution effects caused by the exposure of a granite to hot aqueous fluids.

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GRANITE SAMPLE

The rock chosen for study is a piece of core from Granite Test Hole One at the Los Alamos Scientific Laboratory Geothermal Test Site in the Jemez Mountains, New Mexico. The rock is a medium-grained (~1- to 4-mm grain size) granite, variety adamellite, consisting of 20% quartz, 34% plagioclase, 35% microcline, 6% biotite, 1% opaque minerals, and <1% muscovite, chlorite, apatite, calcite, epidote, myrmekite, sphene, and zircon (Ref. 1, sample PD-2-2). A detailed petrographic description of the rock is included in a previous report (Ref. 2, Table I).

Electron microprobe analyses of major minerals are presented in Table I. Two polished thin sections, PD-2-2b and PD-2-2c, were analyzed to characterize the starting material for the hydrothermal experiments. Analytical procedure was the same as that described in Ref. 2; analyses were calculated by a computer program based on techniques of Bence and Albee (1968).²

EXPERIMENTAL CONDITIONS

The sample examined was subjected to hydrothermal alteration in a circulation system designed to simulate the temperature condition found in a geothermal, dry hot rock, heat-extraction system. Pressure in the system was not as high as that which the real circulating system will require, but it is believed that pressure effects are second order. The temperature of the experiment was 260°C. Pressure was 140 kg/cm². The system contained a heated vessel for the rock sample followed by a heat exchanger to drop the temperature of the circulating water to 60°C. A pressure-regulating valve allowed the pressure differential of 140 kg/cm² to be maintained in a dynamic system. Circulation was provided by a diaphragm pump on the low-pressure side. The duration of the experiment was 275 hours.

CHARACTERIZATION OF SOLUTION CHANNELS

The specimen studied in detail is a 17-mm-diam polished thin section (PD-2-2A, Fig. 1) of rock ex-

posed to the experimental hydrothermal system. Along one edge of the section, mineral grains are intricately etched by minute (3- to 7- μ -diam) solution channels (Figs. 2 and 3). These channels are present in quartz, plagioclase, and microcline, but are absent in the associated biotite, sphene, and magnetite.

No such channels have been observed in any of the starting material, or in any other samples of core from Granite Test Hole One. The channels are therefore attributed to the leaching action of the artificial hydrothermal system. The solution channels were studied in three ways: (1) comparison of average compositions of analytical spots close to channels with average compositions of spots farther away from channels; (2) observation of "beam-scan" photographs of elemental abundances in small areas around channels; and (3) analysis of profiles of elemental abundances, taken perpendicular to individual channels.

Homogeneity of Grains Containing Channels

Figures 2 and 3 show the locations of analytical spots averaged to obtain the partial analyses in Table II. Microcline spots A and C and plagioclase spots A were located as close to the edges of the channels as possible, while still keeping the beam entirely on the mineral grain. No compositional differences of significant magnitude are apparent between spots close to and far from the channels.

Beam-Scan Photographs of Channeled Regions

Photographs of distributions of elemental abundances in small areas of channeled mineral grains are shown in Figs. 4-10. The photographs are time exposures of an oscilloscope screen on which the positions of x-ray counts are projected as the microprobe's electron beam rapidly scans and rescans the rectangular area of the photograph. The x-rays are emitted by excitation of atoms of the particular element indicated, so intensities of light points correspond to elemental abundances. The sinuous dark areas are the solution channels, while the light areas are the undissolved mineral.

TABLE I

ELECTRON MICROPROBE ANALYSES OF MAJOR MINERALS IN GRANITE PD-2-2.
 SAMPLES PD-2-2b AND PD-2-2c ARE POLISHED THIN SECTIONS OF GRANITE
 THAT WAS NOT EXPOSED TO THE ARTIFICIAL HYDROTHERMAL SYSTEM. ANALYST: S. EHRENBERG

	Microcline				Plagioclase		Biotite		Chlorite			Muscovite
	PD-2-2b		PD-2-2c		Pd-2-2b	PD-2-2c	PD-2-2b	PD-2-2c	PD-2-2b ^b	PD-2-2c ^c	PD-2-2c ^b	PD-2-2b ^b
	Rim	Core	Rim	Core	Rim	Rim						
SiO ₂	64.9	64.7	64.6	64.0	61.4	62.7	37.2	37.1	25.4	24.8	25.3	45.7
TiO ₂	----	----	----	----	----	----	2.4	2.2	0.03	0.02	0.05	0.17
Al ₂ O ₃	18.3	17.9	18.0	18.1	23.1	22.8	14.2	14.5	18.1	18.3	18.3	26.9
FeO	0.05	0.02	0.03	0.04	0.14	0.13	19.8	19.7	26.9	26.3	27.3	4.8
MnO	----	----	----	----	----	----	0.89	0.52	1.8	0.74	1.3	0.06
MgO	----	----	----	----	----	----	11.0	11.4	14.3	14.8	14.1	2.2
CaO	0.02	0.01	0.02	BD ^a	5.9	4.9	0.03	BD ^a	0.04	0.06	0.01	0.01
Na ₂ O	0.46	0.52	0.39	0.51	8.2	8.5	0.10	0.08	0.03	0.02	0.02	0.19
K ₂ O	16.0	15.8	16.0	15.8	0.24	0.35	9.7	9.6	0.06	0.05	0.08	10.4
Total Number of ions on the basis of:	99.8	99.0	99.0	98.5	99.0	99.4	95.3	95.1	86.7	85.1	86.5	90.4
	8 oxygens				8 oxygens		[H ₂ O not analyzed or calculated] 24 oxygens		36 oxygens		24 oxygens	
Si	3.004	3.015	3.011	3.001	2.755	2.793	5.548	5.514	5.161	4.912	5.114	5.776
Al	0.998	0.984	0.987	1.001	1.224	1.199	2.496	2.537	4.346	4.270	4.356	4.013
Ti	----	----	----	----	----	----	0.266	0.249	0.005	0.003	0.009	0.016
Mg	----	----	----	----	----	----	2.439	2.518	4.330	4.354	4.244	0.419
Fe	0.002	0.001	0.001	0.001	0.005	0.005	2.475	2.443	4.579	4.357	4.607	0.510
Mn	----	----	----	----	----	----	0.112	0.065	0.308	0.123	0.217	0.006
Ca	0.001	----	0.001	----	0.284	0.283	0.005	----	0.008	0.013	0.001	0.001
Na	0.041	0.047	0.036	0.047	0.713	0.736	0.028	0.022	0.010	0.009	0.006	0.046
K	0.945	0.938	0.954	0.943	0.014	0.020	1.845	1.823	0.015	0.013	0.019	1.674

^aBD = below detection

^binterlayered with biotite

^cmatted masses

Fig. 1.

Photomicrograph of sample PD-2-2A. Area containing solution channels is outlined (plane light). Circle diameter is 1 inch.

Fig. 2.

Analyzed microcline with solution channels. Locations of analytical spots for partial analyses of microcline in Table II. Dots, A; crosses, B; solid squares, C; circles, D (reflected light). Arrows show paths, left to right, of element profiles in Fig. 13A and B. Bar scale is 0.1 mm.

Fig. 3.

Analyzed plagioclase with solution channels. Locations of analytical spots for partial analyses of plagioclase in Table II. Dots, A; crosses, B. Rectangles are areas of beam-scan photographs in Figs. 5 and 6 (plane light). Areas of analytical spots for plagioclase analysis C are shown in Fig. 8B. Arrows show paths, left to right, of element profiles in Figs. 11 and 12. Bar scale is 0.1 mm.

TABLE II

**AVERAGED PARTIAL ELECTRON MICROPROBE ANALYSES OF
MICROCLINE AND PLAGIOCLASE CONTAINING
SOLUTION CHANNELS**

[Analyzed sample is PD-2-2A (Fig. 1) which was exposed to the artificial hydrothermal system.]

Wt%	Microcline ^a				Plagioclase ^b		
	A	B	C	D	A	B	C
SiO ₂	66.2	66.3	66.7	66.3	59.2	59.4	---
Al ₂ O ₃	18.5	18.8	19.0	19.1	24.5	24.5	---
Na ₂ O	0.50	0.47	0.50	0.46	7.5	7.5	7.4
K ₂ O	15.8	15.7	15.4	15.4	0.25	0.26	0.28

^aMicrocline spot locations (A through D) shown in Fig. 2.

^bPlagioclase spot location A and B shown in Fig. 3; Spots C shown in Fig. 8B.

A

B

C

D

E

Fig. 4.

Beam-scan photographs of microcline crystal containing solution channels. (A) Silicon. (B) Potassium. (C) Calcium. (D) Location of calcium concentrations (dots) with respect to solution channels (outlined). (E) Photomicrograph showing location of area scanned (plane light). Length of a side of square on grid is 10 μ .

A

B

C

D

Fig. 5.

Beam-scan photographs of plagioclase crystal containing solution channels. (A) Silicon. (B) Aluminum. (C) Sodium. (D) Calcium. Location of area scanned is shown in Fig. 3. Side of square on grid is 10 μ .

Each of the grid squares in the beam-scan photographs is 10 μ by 10 μ . Locations of the areas scanned are shown in the accompanying photomicrographs. In photomicrographs taken after beam-scanning, the epoxy filling the hollow channels appears darkened due to alteration by the electron beam.

With the possible exception of calcium, no consistent variations in composition related to the solution channels are apparent in the minerals examined. Element abundances appear to be constant

throughout the undissolved parts of the crystals. Sporadic small concentrations of calcium (Figs. 4C, 5D, 6, 7, 8, and 9B) may represent original inhomogeneities in the minerals, such as tiny inclusions of the calcium-rich mineral epidote, common in plagioclase crystals. In microcline (Fig. 4D) and plagioclase (Figs. 5D, 6, 7A, and 7B) the calcium concentrations generally occur along or in channels, although in one plagioclase grain (Fig. 8A), the calcium concentrations do not appear to be strictly related to the channels. Irregular concentrations of

Fig. 6.

Beam-scan photograph of calcium abundance in plagioclase crystal containing solution channels. Location of area scanned is shown in Fig. 3. Side of square on grid is 10 μ .

calcium of unknown origin, are also observed in one channeled quartz grain (Fig. 9C).

Elemental Abundance Profiles

Figures 11, 12, and 13 show profiles of calcium, sodium, and potassium abundances along traverses oriented perpendicular to solution channels in plagioclase and microcline. The profiles were made by mechanically moving the microprobe electron beam across the crystals at a rate of 8 μ per minute and recording intensities of x-rays emitted (which are proportional to the elemental abundances) on a strip-chart recorder. Chart speed was two inches per minute.

A complete analysis would be necessary to convert the data from counts per second to true weight-percentages. (Analyses would have to be corrected for interference of various elements with one another, and the degree of correction would vary with the amounts present.)

On the profiles, solution channels are indicated by sharp drops in x-ray counts per second. Elemental abundances appear constant up to the channel edges, suggesting that dissolution or alteration effects extend no more than 1-2 μ at most into the crystal from the channel walls. The fact that at channel edges x-ray counts per second drop gradually over a distance of 2-4 μ , rather than all at once, is due in part to the 1- to 2- μ -diam of the area under the electron beam which emits x rays. As the electron beam moved off the edge of the crystal into the channel, the area of the crystal excited by the beam diminished gradually to zero. Nonvertical channel walls will also contribute to a gradual drop in x-ray emissions. Integration time for the electronic systems, however, is insignificant (<1 s).

Sodium in the plagioclase profiles (Figs. 11 and 12) appears to drop off faster than calcium at channel edge. However, channel widths, defined by the *beginning* of the drop-off in x-ray counts, are approximately the same for sodium as for calcium. The difference between the sodium and calcium

Fig. 7.

(A) and (B) Beam-scan photographs of calcium abundances in plagioclase crystal containing solution channels. (C) Photomicrograph of areas scanned in (A) and (B) (plane light). Side of square on grid is 10 μ .

profiles, though noticeable, is so small that it is uncertain whether it reflects an actual variation in the rock or an instrumental variation due to differing count rates.

The albite component of feldspar is expected to be more readily attacked than the anorthite component in the hydrothermal experiments.⁴ The irregular channels in microcline shown in Fig. 2 may have been controlled by initial disintegration of albite-rich perthite lamellae. However, the alteration pattern of plagioclase shown in Fig. 3 is not understood at this time. It may have been controlled by initial inhomogeneities in the crystal which were preferentially attacked by the solution.

ALTERATION OF GRANITE AND AMPHIBOLITE ALONG GRAIN BOUNDARIES AND CRACKS

Figures 14 and 15 show thin sections of Precambrian granite (PD-2-4) and amphibolite (PD-2-16a) from the Los Alamos Geothermal Test Site One.¹ These samples were exposed to the artificial hydrothermal system. Subsequently, maps were made of the thin sections to reveal the presence of cracks and grain boundaries along which the samples were attacked by the hydrothermal solutions. The solution of the quartz in the granite, and the alteration of plagioclase in the amphibolite to a

A

B

Fig. 8.

(A) Beam-scan photograph of calcium abundance in plagioclase crystal containing solution channels. (B) Photomicrograph of area scanned (plane light). Dashed outline shows areas of analytical spots for plagioclase analysis C in Table II. Side of square on grid is 10 μ .

porous boxwork, are evidently important in introducing small-scale channels in the samples. Further investigations are needed to determine the possible correlation, suggested by the appearance of the thin sections, between solutions and alteration of quartz and feldspar and the permeability in the test hole rocks under exposure to hydrothermal systems. Presumably, under appropriate conditions, deposition as well as solution could take place in the hydrothermal environment. It was not possible in the present study to confirm the presence of alteration products that might have been deposited at grain boundaries or in cracks.

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A

B

C

D

Fig. 9.

Beam-scan photographs of quartz crystal containing solution channels. (A) Silicon. (B) Calcium. (C) Locations of calcium concentrations (dots) with respect to solution channels (outlined). (D) Photomicrograph showing location of area scanned (plane light). Side of square on grid is 10 μ .

A

B

C

D

Fig. 10.
(A) and (C) Beam-scan photographs of silicon abundances in quartz crystals containing solution channels. (B) and (D) Photomicrographs showing locations of areas scanned in (A) and (C), respectively.

Fig. 11A.

Element profile for calcium in plagioclase. Traverse 11 in Fig. 3; head of arrow shown in Fig. 3 represents right end of profile in Fig. 11. Traverse rate 8μ per min.

Fig. 11B.

Element profile for sodium in plagioclase. Traverse 11 shown in Fig. 3, on which head of arrow represents right end of profile in Fig. 11. Traverse rate 8μ per min.

Fig. 12A.

Element profile for calcium in plagioclase. Traverse 12 in Fig. 3; head of arrow shown in Fig. 3 represents right end of profile. Traverse rate 8 μ per min.

Fig. 12B.

Element profile for sodium in plagioclase. Traverse 12 in Fig. 3; head of arrow shown in Fig. 3 represents right end of profile. Traverse rate 8 μ per min.

Fig. 13.

Element profiles for potassium in microcline. Traverses A and B shown in Fig. 2; heads of arrows in Fig. 2 represent right end of profiles. Traverse rate 8μ per min.

A

B

Fig. 14.

Thin section of Granite Sample Pd-2-4 exposed to artificial hydrothermal system. (A) Photograph of thin section (plane light). (B) Map of thin section showing identity of individual grains. (C) Map of thin section showing location of through-going cracks and grain boundaries along which voids are present. The sample was exposed to the hydrothermal fluid along both sides of its length.

GRANITE
SAMPLE PD-2-4 RUN 9

KEY

- bi BIOTITE
- mi MICROCLINE
- mt MAGNETITE
- q QUARTZ
- pl PLAGIOCLASE
- VOIDS AND CRACKS
- ▨ ETCHED QUARTZ
- ▩ ALTERED FELDSPAR

0 5 10
ONE MILLIMETER

Fig. 14. (cont)