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Experimental Geothermal Loop:

I, 295°C Study

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EXPERIMENTAL GEOTHERMAL LOOP: I, 295°C STUDY

by

Robert W. Charles

ABSTRACT

Reaction of granodiorite from the Fenton Hill Hot Dry Rock Geothermal Site with distilled water at 300°C and 345 bars total pressure for 8 months has produced many morphological and chemical effects. Eight polished rock disks were mounted on a tantalum pedestal inside a 500-ml autoclave. The autoclave is part of a circulation system designed for operation to 400°C and 345 bars. Solution samples were taken at 32, 56, 176, 368, 752, 1544, 3104, and 5816 h. Rock disks were removed also at the latter four times.

The reactivity of phases was shown to be quartz>>microcline> plagioclase>mafic, opaques, and trace phases. Quartz was removed congruently. The albite component of the plagioclase was dissolved essentially congruently changing plagioclase from oligoclase (fresh) to bytownite (8 mo.). Microcline showed congruent dissolution. Other phases were inert. Secondary mineralization included phillipsite, thomsonite, and vermiculite.

I. INTRODUCTION AND SCOPE

The Hot Dry Rock field program at Los Alamos Scientific Laboratory (LASL) entails circulation of water through hot rock at several kilometers depth and extraction of heat from the water by surface heat exchangers. The aqueous working fluid, originally taken from a local well, passes repeatedly through deep hot rock and surface heat exchangers. The presence of temperature and pressure gradients within the system, coupled with the fact that the rock is out of equilibrium with its present-day environment, causes both chemical reaction between rock and working solution and transport of materials such as silica into the surface heat exchanger.

The laboratory program is designed to permit direct observation of: 1) the alteration taking place within hot rock, 2) changes in chemical composition of aqueous working fluid, and 3) deposition of scale in a heat exchanger. The experimental loop used for this study circulates aqueous solution repeatedly past hot rock at 295°C and through a heat exchanger at 26°C. It is run at a constant pressure of 345 bars whereas the pressure in the field varies from 90 bars at the surface (imposed to prevent boiling) to 350 bars at 3-km depth. The major differences between field and laboratory experiments are that the laboratory loop lacks the pressure gradients and the flow characteristics of the field loop.

The current hot dry rock field experiment is being run at 3-km depth, where rock temperature is 185°C. The next stage of the field experiment is planned for greater depth and higher temperature to increase the efficiency of power production. The first laboratory study was planned and carried out at 295°C to maximize the rate of rock-water interaction during the 8-month-run period. A second study is currently being conducted at 200°C.

II. EXPERIMENTAL SYSTEM

The experimental system consisted of a loop in which the aqueous solution moved slowly (2.5 cm³ per minute) through a heated chamber containing rock samples, through a cooling column, through a circulating pump, and back to the heated chamber. Pressure within the system was maintained by a second pump. Temperature of the sample chamber was controlled by a tube furnace. Temperature of the loop between the sample chamber and the cooling column was maintained by heating tapes. The cooling column had a central core of platinum gauze on a tantalum rod for collection of scale. All heated parts of the system were gold-plated.

For the eight-month run, circulation was maintained continuously during the week and stopped at pressure and temperature during the weekend. The whole system was cooled five times, for one day each time, for sample removal and maintenance.

Figure 1 illustrates the circulation loop; flow was counterclockwise. Polished rock disks 3 mm thick and 19 mm in diameter were mounted vertically on a carousel made of tantalum (Plate 1). The tantalum pedestal was at the center of the vertically mounted pressure vessel. The pressure vessel was a 500-ml

autoclave with a modified Bridgeman closure constructed of 316 ss. Its interior, as well as other heated portions of the system, were gold plated to help prevent spurious reaction of the fluid media with vessel walls.

Temperature was maintained by an Ohio Thermal tube furnace regulated by a Love Instruments controller to $\pm 10^{\circ}\text{C}$. The fluid circulated over the rock samples was maintained just above reactor temperature upon exit from the reactor by heat tapes and monitored with Chromel-Alumel thermocouples. Thermocouple 5 is the most accurate measure of line temperature, because it is inserted directly into the line. Thermocouples 2, 3, and 4 were placed under the heat tapes. Temperature was dropped to 26°C in the cooling column between thermocouples 6 and 8 (T_6 and T_8). The cooling column contained platinum mesh wrapped around a tantalum rod, which provided a large surface area to permit scale deposition. Temperature was monitored continuously with a Honeywell 12-channel recorder.

Tubing and valves were Autoclave Engineers 3/8-in. slim line design. Two fluid taps were installed for sampling, one at high temperature and one at room temperature. All high-temperature valves employed graphite packings with heat sink extended valve stems. The Ashcroft gauge was isolated from the experimental solution by a 1-to-1 piston gauge protector. A line filter with a 5- μm stainless steel mesh element was used to prevent particulate material from entering the capillary connecting the circulating pump to the system.

Circulation was provided by a Scientific Systems circulating pump with maximum pressure rating of 345 bars. The pistons were redesigned of 440C stainless steel heat treated to Rockwell 68C. These were mated with graphite-impregnated Teflon packings to give a reliable moving seal for up to 345 bars. A Haskel air-driven pump was inserted in the line to maintain run pressure to ± 10 bars. Fluid that slowly leaked from the circulating pump was reinserted into the line via the reservoir to maintain a constant fluid volume. Pressure oscillated between 310 and 345 bars. Total system volume was 561 cm^3 . During the eight-month-run period, 478 liters circulated past the rock sample.

III. ROCK ALTERATION

A. Introduction

Physical and chemical changes in the experimental rock samples indicate how the natural rock reservoir may be expected to behave. Removal of large amounts of material may be a problem; deposition of material may constrict the

circulation loop below or above ground. Important questions are: How are the original minerals attacked: along grain boundaries, along fractures, or along compositional zones? Which minerals are attacked? Where do the secondary phases grow and why? This section will present and analyze the data gathered on rock alteration; a later section concerns scaling in the rest of the circulation system.

Eight circular disks of rock 3 mm thick and 19 mm in diameter were polished through 600 grit, supersonically cleaned, and placed in a carousel-like holder (Plate 1) in the heated reaction vessel. An identically prepared ninth disk was used as an unreacted control. Disks 1 through 4 were removed successively at 1, 2, 4, and 8 months.

Biotite granodiorite sample 9522 from drill hole GT-2 was reacted with distilled water at 330 ± 10 bars and $295 \pm 10^\circ\text{C}$ for 8 months. Table I gives the granodiorite composition in volume per cent. Potassium feldspar was of the structural variety microcline with a composition of $\text{Or}_{95}\text{Ab}_5$. Plagioclase feldspar was compositionally zoned and commonly showed hydrothermal alteration to illitic mica. Plagioclase composition was bimodal with a core of $\text{Ab}_{75}\text{An}_{24}\text{Or}_1$ and a rim of $\text{Ab}_{90}\text{An}_9\text{Or}_1$. Fresh biotite was aluminous and deficient in potassium. Many of the biotites had undergone natural chloritization with removal of potassium and titanium. Epidote gave a constant composition near $\text{Ca}_2\text{Al}_2\text{Fe}^{+3}\text{Si}_3\text{O}_{12}(\text{OH})$. Sphene was quite common and showed some substitution of aluminum for silicon.

B. Morphological Changes

Plate 2 is a scanning electron photomicrograph showing a portion of an initially unreacted rock disk. Superimposed are labels identifying the mineral phases, their grain boundaries, and fractures. Abbreviations are listed in Table II. The disk is smooth showing some natural fracturing but no voids or open areas. Plates 3, 5, 6, and 9 show four rock disks removed from the circulation system after 1, 2, 4, and 8 months.

Many physical changes are apparent after 1 month (see Plate 3). Quartz is removed much more quickly than the other phases. The quartz etching is shown as white patches on the overlay. It seems to follow natural or manmade fractures in the quartz crystals. Microcline is removed in a similar manner to a lesser extent. Plagioclase shows a great deal of surface reaction. Almost all of the plagioclase is covered with a filmy secondary phase near phillipsite composition,

which will be discussed later. Etching of plagioclase commonly yields a pockmarked surface. Magnetite shows some surface frosting indicating secondary precipitation. Other phases appear physically resistant to etching. Another secondary phase, OG-1, identified as vermiculite appears in spongy black masses which stand up from the surface like small buttes. It commonly grows on or adjacent to the mafic minerals.

Plate 4 shows an enlargement of the vermiculite found in Plate 3 near the center at 7 o'clock. The spongy mass is vermiculite. The relative reactivity of plagioclase is clearly illustrated as is the resistance of sphene, biotite, epidote, apatite, and chlorite.

Plate 5 shows a portion of a rock disk removed from the circulation system after 2 months of reaction time. Observations are similar to those reported above, only more pronounced. The secondary phases show a change in character. More vermiculite is present (4 o'clock) and much of the phillipsite has been resorbed. A new secondary mineral, OG-3, a Ca-Al silicate, closely approximating thomsonsite appears growing primarily on plagioclases but occasionally on other phases. An example of OG-3 is at 12 o'clock. It has a sugary texture and appears in distinct irregular masses. The mafic phases remain resistant.

After 4 mo. (Plate 6), some new morphological changes are apparent. Almost all of the quartz has been removed from the surface, leaving many large voids. In the upper left one can see three resistant rods of apatite, which were once surrounded by a quartz grain protruding from the underlying plagioclase. A close-up is shown in Plate 7. Microcline shows deeper etching than previously noted. The patchy material along fractures in the microcline suggests incongruent reaction of microcline, leaving an aluminum and silica-rich residue. Plagioclase shows a number of irregularly spaced striations that are compositionally controlled. These will be discussed quantitatively later. Natural alterations of plagioclase to phengitic moscovite are more resistant to alteration than the parent plagioclase. A number of overgrowths are present. These have the same texture as on the previous disks. The amount of phillipsite present is continuing to decline but is still detectable. Both the thomsonite and vermiculite are more abundant. An enlargement of the OG-3 found at 4 o'clock is shown in Plate 8. The mafic minerals remain resistant.

Plate 9 shows a portion of a rock disk at the conclusion of the experiment (8 mo.). Quartz has been dissolved to an even greater depth, up to 2 or 3 mm. Microcline and plagioclase show continued etching. Many of the biotites show a deposit of silica on their surfaces (labeled Alt B). These appear as shaded patches in the SEM micrograph and were not seen on previous disks. The striking relationship between thomsonite and plagioclase is shown. All thomsonite in this photomosaic is entirely surrounded by plagioclase. Note particularly the growths at 8:30 and 10 o'clock. A very large patch of vermiculite is present at 4 o'clock. The mafic phases remain resistant through 8 months.

Summarizing these morphological changes, quartz is much more reactive than microcline, which is more reactive than plagioclase. The mafic minerals and apatite remain physically the same although some show different chemistry which will be dealt with later. Reaction initially follows fractures; raised overgrowths of phillipsite, thomsonite, and vermiculite appear soon after reaction begins. Phillipsite reaches a maximum amount after about one month, is resorbed rapidly, then remains at a constant low level after 2-4 months. Vermiculite and thomsonite increase in amount throughout the experiment. Thomsonite is almost nonexistent after 1 month and rapidly increases in amount. Vermiculite patches appear in one month and increase steadily in size and number.

The rock disks show a net weight loss (Table II). Figure 2 shows this change. After 8 months the disks show a net loss of about 14%. The loss curve is very nearly parabolic, a function of the square root of time. Material removed from the disks was deposited elsewhere in the system or remained in solution.

C. Chemical Alteration

Resistance to chemical attack varied from phase to phase. Change in composition of the major and minor phases is presented in Table III. Trace phases (<1%) were not analyzed extensively. These are not presented in the table but were resistant to chemical attack.

Quartz showed the most attack, being congruently dissolved. Quench fibers of SiO_2 were frequently observed on remaining substrate quartz and occasionally on other phases. Plate 10 shows some of these quench fibers to the left of the spongy overgrowth.

The etched microcline, while remaining nearly stoichiometric, did show a small silica deficiency after 4 and 8 mo. if analyses were based on 8 oxygens.

Calcium and iron also showed a steady rise. One explanation is precipitation of a thin layer of calcium iron silicate with less silica than microcline. Whether the CaFeSi phase is crystalline and a single homogeneous phase is unknown. Another CaFeSi overgrowth is discussed in detail later.

Plagioclase shows a large change in chemistry. Initial plagioclase had a An_{26} core. Even analyses of "fresh" plagioclase are not perfectly stoichiometric feldspar. Natural sericitization was extensively observed in both core and rim. Plagioclase analyses remained bimodal (core and rim) after 1 month. These are the analyses presented in Table IV. Rim analyses remain about An_{10} . After 1 month no more high sodium plagioclase was encountered, suggesting the high Ab rims were covered with An-rich plagioclase. Plate 11 shows the preferential dissolution of sodic plagioclase. The schematic diagram shown in Fig. 3 is based on Plate 11. Areas of high relief were more calcic and more resistant (An_{76}). Areas of lower relief were more albitic (An_{48}). Portions of the sample not showing banding were of intermediate composition (An_{61}).

The biotite is always aluminous, K-deficient, and commonly chloritized. Composition lies between the compositional joins annite-phlogopite and eastonite-siderophyllite. Biotite on the 8-month disk commonly shows shaded areas of high silica content. These are not an alteration of biotite itself but a precipitation of SiO_2 in biotite. The patches seem to be confined to biotite, which argues against a quench phenomena.

Epidote is also resistant. Original epidote is only slightly deficient in ferric iron from the formula $Ca_2Al_2Fe^{+3}Si_3O_{12}(OH)$. Composition remains essentially unchanged after 8-mo. reaction.

Unreacted sphene is aluminous and Ti-deficient. Composition indicates the substitution $CaAl^{+3}Fe^{+3}$ for $2Ti^{+4}$, which is common in nature. Reacted sphene is silica-rich, indicating merely a precipitate of SiO_2 .

Magnetite shows a frosting and may be the source of some of the iron for the vermiculite.

Other minor phases: illite, muscovite, and apatite, were resistant to chemical attack as were the trace phases of calcite, zircon, and iron sulfide.

Three overgrowth phases were observed. Table V presents chemical analyses of these phases along with their identification. Phases were identified by matching their compositions with those of low temperature phases one might expect under these pressure and temperature conditions. The overgrowths showed

constant habit and fairly constant composition from location to location. Because these overgrowths were thin, some effects of the substrate may distort some of the analyses, as would their rough topography. Of the possible low-temperature phases those listed gave the best compositional fit. These overgrowths were observed as discrete phases, not as porous layers.

IV. SCALING IN THE LOOP

A white powdery deposit was observed in nine regions of the experimental system. Figure 4 shows where scale was observed and collected. The samples are tabulated in Table VI. The white powder scraped from areas 1, 2, 3, 7, and 8 was analyzed by microprobe for Na, Mg, Al, Si, K, Ca, and Fe (Table VII). The SEM qualitative analyses were performed upon screen samples removed at points 4, 5, and the line filter. These samples will be discussed in the order in which they occur as one moves downstream from the reaction vessel.

Area 8 was maintained at about 320-330°C, or about 30°C above run temperature to prevent premature crystallization of secondary phases. X-ray examination confirms the presence of wollastonite. Microprobe analyses yield variable results from pure wollastonite to one part wollastonite plus one part silica. There are also 3 to 4 wt% of Al_2O_3 and Fe expressed as FeO and traces (< 1%) of Na_2O and K_2O .

Screen samples from the cooling column show a number of irregular blebs of silica occasionally containing small amounts of sodium and aluminum. Most of the precipitation occurred in the cooler portion of the column. Scaling from areas 1, 2, and 3, all consisting of a white amorphous powder. Microprobe analysis shows this to be almost entirely SiO_2 . Scale from area 7 proved to be of similar composition; however, X-ray powdered diffraction confirms the presence of quartz.

The crystalline phases wollastonite and quartz found in areas 6 and 7, respectively, are thermodynamically stable. The calcium-silicate wollastonite exhibits retrograde solubility and precipitates as the temperature increases from 295° to 330°C. Crystalline quartz forms where the system volume expands from capillary tubing to 0.52-cm(0.204-in.) tubing, locally lowering the pressure.

V. SOLUTION COMPOSITION

Solution was withdrawn from hot and cold parts of the circulation system (high and low T tap, Fig. 1) at run times of 32, 56, 176, 368, 752, 1544, 3104, and 5816 h. Quench pH was 7-7.2. These results are shown in Table VIII.

Analyses were done by atomic absorption by three methods. The results by each method agree. The sampling technique for hot solutions involved expansion of the solution through a high-temperature valve into a capillary and then into a flask cooled by an ice bath. This method of sampling hot solution was found to be unsatisfactory because silica plated out in the capillary and valve during quench. The table shows erratic silica values for hot solution that are lower than those for cold solution. Replicate samples of cool liquid gave satisfactory analyses that showed little scatter. Fluid was pressure-quenched at room temperature to obtain the low-temperature sample.

Because of the erratic changes in hot solution analyses, discussion will be confined to the cool solution analyses. With exception of one sample (1544h) the solution appears to reach a constant concentration after 1 month of about 720 ppm, approximately 680 ppm of which is SiO_2 . Element concentrations are consistent with the reactivity sequence observed on the solid samples, quartz >> K feldspar > plagioclase. Although plagioclase is less reactive than microcline, the albite component of plagioclase is more reactive than microcline although less reactive than quartz. The mineral phases other than quartz are resistant.

Silica concentration fits a logarithmic function developed by J. W. Tester and is shown in Fig. 5.

VI. DISCUSSION

A. Natural Alteration

A number of natural alteration phases occur in the host granodiorite. Epidote, albite, chloritic alteration of biotite, and illitic alteration of the feldspar are present and indicative of low-grade metamorphism. The epidote is iron-rich, approaching the "ideal" composition of $\text{Ca}_2\text{Al}_2\text{Fe}^{+3}\text{Si}_3\text{O}_{12}(\text{OH})$. Miyashiro and Seki (1958) suggest this is an indication of low-temperature origin. Aluminum will substitute for ferric iron in epidotes crystallized at high temperature ($>300^\circ\text{C}$). Low f_{O_2} in the region of the QFM buffer is probably appropriate for this granodiorite and will lower the Fe^{+3} content slightly from unity as is observed. On this basis, Winkler (1974) places this type of alteration in the laumontite facies, indicating pressure below 5 bar and temperature below $300\text{--}350^\circ\text{C}$. Laumontite itself is not present because of the reaction relation: laumontite + magnetite $\rightarrow$ epidote (Seki, 1972). In iron-bearing systems, iron-rich epidote will replace laumontite.

Chlorite, epidote, and illitic mica are resistant in the current study. Albite rims, when not covered by secondary phases, appear quite resistant. Plagioclase of intermediate composition shows strong attack with preferential removal of the albite component. This difference may be due to the structural state of the albite in question. Low albite would be stable in preference to a high-temperature form found in the original granodiorite. In the closed system one would expect secondary albite to be grown experimentally. In the open system albite does not saturate. Silica and sodium are removed from the reaction vessel and another framework silicate, thomsonite, grows instead. The experimentally grown secondary phases such as thomsonite and vermiculite appear to be compatible with the very low grade assemblage of chlorite, albite, epidote, and illite at least on the short term (months to years).

B. Experimental Alteration

Identification of the secondary phases should be explained in more detail. All three secondary phases, vermiculite, phillipsite, and thomsonite, were identified on the basis of composition, habit, and thermal stability. No structural identifications are possible because the samples are too small for standard X-ray techniques.

Vermiculite, Table V, is shown as a ferric iron clay. Actually, the formula should be expressed as:

$$w = 0 \text{ to } 6,$$

$$x = 6 \text{ to } 0,$$

$$y = 7.4 \text{ to } 1.4,$$

$$z = 0.6 \text{ to } 6.6, \text{ and}$$

$$y + z = 8.$$

Because the ferrous - ferric ratio is unknown, only these limits can be placed on the structural formula.

Vermiculite commonly grows on or near the other sheet silicates, biotite and chlorite. Possibly these phases act as a template for clay nucleation. Experimental alteration of chlorite to vermiculite has been observed by Ross (1975). Ross altered a high-iron chlorite in an oxidizing media. He postulates the brittle mica sheets are ruptured by oxidation of iron and subsequent removal of cations.

The other two secondary phases fit the structural formulae for zeolites and have habits common to zeolitic alteration of feldspar. The potassium-rich phase closely corresponds to phillipsite, which has been described by Coombs (1959) as a Ca-K zeolite that can have subordinate Na. Not enough Ca + K + Na are present for the phase to be called ashcroftine. These are the only two zeolites with appropriate Al/Si and K composition. Phillipsite composition ranges from about $(Ca, K_2)_{2.5}Al_5Si_{11}O_{32} \cdot 12H_2O$ to $(Ca, K_2)_{3.5}Al_7Si_9O_{32} \cdot 12H_2O$ (Coombs, 1959). In this study the phillipsite is close to $Ca_{2.5}K_{1.25}Na_{0.75}Al_7Si_9O_{32} \cdot 12H_2O$.

The third secondary phase has a composition near thomsonite. Natural thomsonite shows similar Ca + Na and Al/Si. All other zeolites do not. Coombs proposes a range from $(Ca, Na_2)_{2.1}Al_{4.2}Si_{5.8}O_{32} \cdot 6H_2O$ to $(Ca, Na_2)_{2.56}Al_{5.13}Si_{4.88}O_{32} \cdot 6H_2O$. The composition in this study is near $Ca_2Na_{0.5}Al_{4.5}Si_{5.5}O_{20} \cdot 6H_2O$.

Phillipsite has a low thermal stability (Koizumi and Roy, 1959) but will grow metastably at 300°C and recrystallize to another zeolite or feldspar with time (Wirsching, 1976). Wirsching (1975, 1976) reacted a rhyolite glass with distilled water to 250°C and observed first the growth of high-alkali phillipsite followed by its disappearance and growth of a low-alkali mordenite. The mordenite is probably stable at the temperature of Wirsching's experiment. The present study demonstrates the early evolution of phillipsite, high in K and Na, followed by its resorption and deposition of a Ca-thomsonite. Different bulk composition from the rhyolite mentioned above changes the zeolite variety but gives the same sequence of events.

If the zeolites represent feldspar alteration, the reactions would be,

Taking the molar volumes from Table IX, $\Delta V_{(1)\&(2)}$ are $+90\text{cm}^3$ and $+56\text{cm}^3$, respectively. Normal dehydration is positive. Initially, both feldspars react with solution producing a K-rich, zeolite which grows on plagioclase template. This is supported by the high K observed in the initial hot-solution analysis. This initial rapid reaction (<1 month) may be due to increased reactivity of the sample with high surface free energy due to sample preparation and base change of H^+ for K^+ .

with $\Delta V_{(3)} = +34 \text{ cm}^3$. While this reaction is possible, it was not observed, i.e., no individual patches of overgrowth were part one zeolite and part another nor did any show intermediate composition. Whether Reaction (3) takes place or not, the net effect is eventual reaction of the more anorthite-rich portion of the plagioclase to form a Ca-zeolite. The maximum thermal stability of thomsonite is not known but apparently lies above phillipsite as indicated by Reaction (3), and, therefore, is in excess of 300°C .

Feldspar alteration has been examined extensively in other studies both in single-phase and polyphase systems. Morey and Chen (1955), Adams (1968), Khitarov (1957), and Fyfe and McKay (1962) have noted the preferential removal of the albite component from plagioclase in leaching experiments. Adams (1968) reported reverse zoning as a result. A similar effect is seen here (Table IV). Even the Ab_{90} rims become coated with An_{70} feldspar after 4 months. The net effect appears to be stoichiometric removal of the albite component.

The microcline shows a small silica deficiency after 8 months. Similar compositional changes are noted by Morey and Chen (1955) and Morey and Fournier (1961) in distilled water and Hemley and Jones (1964) and Althaus and Winkler (1962) in acid solutions. Secondary precipitates of aluminum hydrate and aluminum silicate hydrate such as clays and micas will produce this effect although these phases have not been positively identified in the present study.

The reactivity of the feldspar is suppressed in the presence of quartz, as indicated by Khitarov (1957), and Fyfe and McKay (1962). Feldspar should become more reactive once all of the quartz is removed and silica activity is controlled by other silica-bearing minerals. Our experiment of 8-month duration does not yet show this effect.

Commonly silica activities in natural waters are compared with solubilities of silica phases other than quartz in water. These observations are thermodynamically invalid unless the silica species are stable at the pressure and temperature under consideration (Betterman and Liebau, 1975). This study only compares silica activity with the solubility of the stable species, α quartz. Silica concentrations rose smoothly and did not show a high concentration spike due to surface damage (Moore and Rose, 1975). The first sample was tapped after

12

24 h; such an effect may occur at a shorter time interval. Silica content of the solution is less than in the simpler system $\text{SiO}_2(\text{qtz}) - \text{H}_2\text{O}$ (Fournier and Rowe, 1977) by 80 to 100 ppm. This is in agreement with observations made by Khitarov (1957). Reaction of other silica-bearing phases, including alteration products, lowers the silica activity.

C. Mass Balance

Mass balance for this experiment can be estimated from the physical parameters of the system. Table XI lists these parameters. Total material removed is about 11%. The density of the granodiorite was about 2.8 g/cm^3 . Density was measured in two ways. First, the weight may be divided by the calculated volume, yielding 2.83 g/cm^3 . Second, the density of the individual minerals were added in their appropriate proportion (Table X). Data were taken from Robie et al. (1967). In the case of solid solutions linear extrapolation was made between the two end members. Biotite was calculated roughly as annite₅₀phlogopite₅₀, epidote as zoisite₆₇pistacite₃₃, and plagioclase as albite₇₅anorthite₂₅. The trace phases were added in equal proportions to total the remaining 3%. The resulting density of 2.8 is common for ferromagnesian-bearing granodiorite. The similarity of densities calculated by these two methods indicates a lack of much original void space in the granodiorite. Density after reaction dropped to 2.51 g/cm^3 (= net weight/original volume) reflecting the void space caused by the chemical dissolution of quartz. Density of the residue minus void space is still 2.83 g/cm^3 (= net weight/new volume). Low-density secondary phases seem to offset the high-density resistant mafic phases for the net solid density of the reacted sample.

Material is observed to be deposited throughout the system. Solution burden accounts for only 19% of the total material removed from the rock. The other 81% is deposited in the system. The estimated area for the system is about 1450 cm^2 . This is just an estimate because filter elements and screen in the system have a large and somewhat indefinite area. If deposits are evenly distributed, one would expect to see 1.5 mg/cm^2 of scale. Of course, scale is not deposited uniformly. Material removed from valves and tubing in regions of flow change or pressure loss were in greater concentration than 1.5 mg/cm^2 .

If weight loss is approximated as only silica removal, the results are almost as good as the more detailed analysis. Weight loss of 12% and a volume loss of 1.02 cm^3 are calculated. Counterbalancing the ions other than silica in

the solution burden are secondary precipitates on the rock surface. These effects more or less cancel.

Table XII fits the weight loss data to three mathematical functions. All fit at the 99% confidence level. However, only the power fit yields the correct boundary conditions at $t = 0$. In practice the curve will exhibit a sharp compositional maximum at early times (<1 mo.) due to surface damage during sample preparation. The three-point fit is an attempt to avoid deviations caused by surface damage effects on the first disk removed. The three-point fit would give better estimates at longer reaction times as long as the bulk rock chemistry does not change. For instance, if one phase were eventually removed, the weight loss curve would exhibit a discontinuity. The fitted curves plotted in Fig. 2 are the power fits.

VII. CONCLUSION

The observations made in this study do not favor continuous precipitate layers on the primary phases as postulated by Correns and Von Engelhard (1938) and Helgeson (1971). Overgrowths occur as patches. Some appear to be crystalline; others, such as the aluminum silicate on the microcline and plagioclase may be amorphous. Microprobe analyses show fresh minerals between the patchy secondaries. This observation is similar to the results of Petrovic (1976), LaGache (1965, 1976), and LaGache et al. (1961). No surface analysis techniques were used in the present study; however, Petrovic (1976), reacting sanidine, did not find a continuous precipitate layer using surface techniques. The reactions: feldspar to zeolite, mica to clay, and possibly zeolite to zeolite are fixed by reaction of fluid with the surface of fresh minerals.

The secondary phases produced in this study do not appear to be extensive enough to affect free circulation along fractures as in the LASL Hot Dry Rock Geothermal Project.

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TABLE I

BIOTITE GRANODIORITE MODAL ANALYSIS

Potassium feldspar	15
Plagioclase	38
Quartz	25
Biotite	13
Chlorite	tr.
Opaques	1
Muscovite	tr.
Calcite	tr.
Epidote	3
Apatite	tr.
Sphene	2
Zircon	tr.

Major and Minor Phase Composition

Microcline	K _{0.93±.01}	Na _{0.05±.01}	Ca _{0.00±.01}	Mg _{0.00±.01}	Si _{2.98±.01}	Fe _{0.00±.01}	Al _{1.03±.01}	O ₈
Plagioclase								
Core	K _{0.01±.01}	Na _{0.75±.01}	Ca _{0.26±.01}	Mg _{0.00±.01}	Fe _{0.00±.01}	Si _{2.68±.02}	Al _{1.32±.01}	O ₈
rim	K _{0.02±.02}	Na _{0.90±.01}	Ca _{0.10±.05}	Mg _{0.00±.01}	Fe _{0.00±.01}	Si _{2.87±.05}	Al _{1.12±.05}	O ₈
Biotite	K _{0.78±.02}	Na _{0.01±.01}	Ca _{0.01±.01}	Mg _{1.40±.04}	Fe _{1.16±.01}	Mn _{0.04±.01}	Ti _{0.09±.02}	Al _{0.27±.02}
	Si _{2.82±.02}	Al _{1.18±.02}	O ₁₀ (OH) ₂					
Epidote	K _{0.01±.01}	Na _{0.00±.01}	Ca _{1.99±.02}	Mg _{0.01±.01}	Fe ⁺³ _{0.85±.05}	Mn _{0.02±.01}	Ti _{0.01±.01}	Si _{3.09±.02}
	Al _{2.20±.03}	O ₁₂ (OH)						
Sphene	K _{0.00±.01}	Na _{0.01±.01}	Ca _{1.07±.02}	Mg _{0.00±.01}	Fe _{0.05±.01}	Mn _{0.01±.01}	Ti _{0.82±.01}	Si _{1.01±.01}
	Al _{0.12±.01}	O ₅						

TABLE II

WEIGHT LOSS AND SOME PHYSICAL PROPERTIES OF THE REACTED ROCK DISKS

<i>Disk No.</i>	<i>Time (h)</i>	<i>Wt. Before (g)</i>	<i>Wt. After (g)</i>	<i>% Loss</i>	<i>Initial Volume Surface Area</i>	
					<i>(cm³)</i>	<i>(cm²)</i>
1	752	2.9717	2.8345	4.6	1.02	9.05
2	1544	2.8685	2.6898	6.2	1.06	9.10
3	3104	3.1107	2.8142	9.5	1.09	9.39
4	5816	3.0500	2.6187	14.1	1.04	8.97
5	5816	2.7897	2.3845	14.5	1.02	9.63
6	5816	3.1440	2.7077	13.9	1.08	9.29
7	5816	3.0724	2.6555	13.6	1.09	9.39
8	5816	3.1115	2.7246	12.4	1.13	9.65

TABLE III

PLATE ABBREVIATIONS

<i>Q</i>	<i>Quartz</i>
<i>Pl</i>	<i>Plagioclase</i>
<i>Ks</i>	<i>Microcline</i>
<i>B</i>	<i>Biotite</i>
<i>Ep</i>	<i>Epidote</i>
<i>Sp</i>	<i>Sphene</i>
<i>Ch</i>	<i>Chlorite</i>
<i>Z</i>	<i>Zircon</i>
<i>A</i>	<i>Apatite</i>
<i>C</i>	<i>Calcite</i>
<i>Ser</i>	<i>Sericite</i>
<i>Ms</i>	<i>Muscovite</i>
<i>Mt</i>	<i>Magnetite</i>
<i>Py</i>	<i>Iron Sulphide</i>
<i>O.G. 1</i>	<i>Overgrowth #1 "Vermiculite"</i>
<i>O.G. 2</i>	<i>Overgrowth #2 "Phillipsite"</i>
<i>O.G. 3</i>	<i>Overgrowth #3 "Thomsonite"</i>
<i>V</i>	<i>Void</i>
<i>Alt B</i>	<i>Biotite + quench silica</i>

TABLE IV

CHANGE IN MAJOR PHASE COMPOSITION VERSUS RUN DURATION

Microcline (8 oxygens)

Fresh	Ca _{0.00}	Na _{0.05±.01}	K _{0.93±.01}	Fe _{0.00}	Ti _{0.00}	Al _{1.02±.01}	Si _{2.96±.01}	O ₈
1 mo	Ca _{0.02±.02}	Na _{0.05±.01}	K _{0.93±.02}	Fe _{0.01±.01}	Ti _{0.01±.01}	Al _{1.02±.01}	Si _{2.96±.02}	O ₈
2 mo	Ca _{0.03±.02}	Na _{0.06±.01}	K _{0.90±.04}	Fe _{0.01±.01}	Ti _{0.01±.01}	Al _{1.04±.02}	Si _{2.94±.02}	O ₈
4 mo	Ca _{0.06±.04}	Na _{0.04±.01}	K _{0.91±.02}	Fe _{0.03±.01}	Ti _{0.02±.01}	Al _{1.07±.06}	Si _{2.90±.03}	O ₈
8 mo	Ca _{0.07±.04}	Na _{0.07±.02}	K _{0.89±.06}	Fe _{0.04±.02}	Ti _{0.01±.01}	Al _{1.09±.02}	Si _{2.86±.02}	O ₈

*Plagioclase (8 oxygens)*Core

Fresh	Ca _{0.26±.02}	Na _{0.75±.01}	K _{0.01±.01}	Al _{1.32±.02}	Si _{2.68±.02}	O ₈
1 mo	Ca _{0.52±.05}	Na _{0.40±.06}	K _{0.05±.02}	Al _{1.48±.06}	Si _{2.51±.06}	O ₈
2 mo	Ca _{0.51±.01}	Na _{0.45±.03}	K _{0.03±.01}	Al _{1.46±.04}	Si _{2.51±.04}	O ₈
4 mo	Ca _{0.70±.03}	Na _{0.28±.03}	K _{0.01±.01}	Al _{1.61±.03}	Si _{2.34±.04}	O ₈
8 mo	Ca _{0.69±.02}	Na _{0.25±.02}	K _{0.06±.02}	Al _{1.67±.02}	Si _{2.35±.02}	O ₈

rim

Fresh	Ca _{0.10±.05}	Na _{0.90±.01}	K _{0.02±.01}	Al _{1.12±.06}	Si _{2.87±.06}	O ₈
1 mo	Ca _{0.12±.03}	Na _{0.83±.03}	K _{0.01±.01}	Al _{1.11±.02}	Si _{2.90±.02}	O ₈

TABLE IV (cont)

Biotite (12 oxygens)

Fresh	K _{0.78±.02}	Na _{0.01±.01}	Ca _{0.01±.00}	Ti _{0.09±.02}	Mn _{0.04±.01}	Mg _{1.40±.04}	Fe _{1.16±.01}	Al _{0.27±.02}	Si _{2.82±.02}	Al _{1.18±.02}	O _{10(OH)₂}
1 mo	K _{0.68±.02}	Na _{0.04±.01}	Ca _{0.02±.01}	Ti _{0.09±.02}	Mn _{0.05±.01}	Mg _{1.42±.08}	Fe _{1.17±.01}	Al _{0.27±.02}	Si _{2.86±.02}	Al _{1.14±.02}	O _{10(OH)₂}
2 mo	K _{0.72±.08}	Na _{0.03±.02}	Ca _{0.03±.02}	Ti _{0.10±.02}	Mn _{0.05±.01}	Mg _{1.45±.10}	Fe _{1.23±.04}	Al _{0.14±.08}	Si _{2.80±.06}	Al _{1.20±.08}	O _{10(OH)₂}
4 mo	K _{0.65±.08}	Na _{0.03±.01}	Ca _{0.03±.02}	Ti _{0.08±.02}	Mn _{0.05±.01}	Mg _{1.42±.08}	Fe _{1.17±.04}	Al _{0.26±.06}	Si _{2.83±.08}	Al _{1.17±.06}	O _{10(OH)₂}
8 mo	K _{0.73±.06}	Na _{0.02±.01}	Ca _{0.03±.01}	Ti _{0.08±.01}	Mn _{0.05±.01}	Mg _{1.39±.04}	Fe _{1.28±.04}	Al _{0.21±.02}	Si _{2.77±.04}	Al _{1.23±.02}	O _{10(OH)₂}

Epidote (12.5 oxygens)

Fresh:	Ca _{2.00±.01}	Mn _{0.02±.01}	Al _{2.20±.04}	Fe ⁺³ _{0.86±.07}	Si _{3.09±.01}	O _{12(OH)}
1 Mo :	Ca _{2.06±.02}	Mn _{0.03±.01}	Al _{2.07±.02}	Fe ⁺³ _{0.89±.02}	Si _{3.17±.07}	O _{12(OH)}
2 Mo :	Ca _{2.11±.06}	Mn _{0.04±.01}	Al _{2.05±.01}	Fe ⁺³ _{0.88±.08}	Si _{3.09±.06}	O _{12(OH)}
4 Mo :	Ca _{2.11±.07}	Mn _{0.02±.01}	Al _{2.01±.10}	Fe ⁺³ _{0.95±.05}	Si _{3.14±.01}	O _{12(OH)}
8 Mo :	Ca _{2.03}	Mn _{0.02}	Al _{2.21}	Fe ⁺³ _{0.88}	Si _{3.07}	O _{12(OH)}

Sphene (5 oxygens)

Fresh:	Ca _{1.07±.02}	Fe _{0.05±.01}	Ti _{0.81±.01}	Al _{0.12±.01}	Si _{1.01±.01}	O ₅
1 Mo :	Ca _{1.04±.01}	Fe _{0.06±.01}	Ti _{0.74±.01}	Al _{0.13±.01}	Si _{1.13±.01}	O ₅
2 Mo :	Ca _{0.95±.02}	Fe _{.07±.01}	Ti _{0.65±.06}	Al _{0.23±.06}	Si _{1.15±.03}	O ₅
4 Mo :	-----					
5 Mo :	Ca _{1.00±.03}	Fe _{.13±.03}	Ti _{.65±.01}	Al _{.19±.01}	Si _{1.13±.01}	O ₅

TABLE V
ANALYSIS OF SECONDARY OVERGROWTHS WITH RUN DURATION

Overgrowth I: "Vermiculite"

1 Mo: Ave. 3 measurements

K.18±.01 Na.11±.01 Ca.62±.02 Mg.12±.01 Mn.03±.01 Ti.01±.01 Fe⁺³ 5.50±.21 Si 5.78±.11 Al 2.26±.04 O₂₀(OH)₄

2 Mo: Ave. 3 measurements

K.05±.01 Na.03±.01 Ca.69±.02 Mg.31±.01 Mn.07±.01 Ti.02±.01 Fe⁺³ 5.93±.21 Si 5.43±.09 Al 2.25±.04 O₂₀(OH)₄

4 Mo: Ave. 2 measurements

K.05±.01 Na.19±.07 Ca.29±.01 Mg.24±.01 Mn.12±.01 Ti.04±.01 Fe⁺³ 6.70±.13 Si 5.27±.05 Al 2.09±.06 O₂₀(OH)₄

8 Mo: Ave. 2 measurements

K.04±.01 Na.08±.01 Ca.61±.02 Mg.10±.01 Mn.10±.01 Ti.02±.01 Fe⁺³ 5.48±.12 Si 5.64±.04 Al 2.53±.08 O₂₀(OH)₄

Ave. 8 measurements:

K.09±.02 Na.09±.02 Ca.56±.05 Mg.19±.03 Mn.07±.01 Ti.02±.01 Fe⁺³ 5.86±.17 Si 5.55±.07 Fe⁺³ 0.17 Al 2.28±.05 O₂₀(OH)₄

Vermiculite: Ca_{0.7} Fe⁺³₆ [(Al, Si)₈O₂₀] (OH)₄ • 8H₂O

Overgrowth II: "Phillipsite"

1 Mo: Ave. 12 measurements

Ca_{2.23±.11} Na.41±.04 K.14±.07 Mg.11±.02 Fe.11±.01 Cr.02±.01 Mn.01±.01 Al 7.09±.06 Si 9.04±.08 O₃₂ • 12H₂O

2 Mo: Ave. 6 measurements

Ca_{2.06±.28} Na.78±.08 K.87±.19 Mg.12±.02 Fe.14±.03 Ti.01±.01 Mn.01±.01 Al 6.91±.11 Si 9.23±.06 O₃₂ • 12H₂O

4 Mo: Ave. 4 measurements

Ca_{2.22±.26} Na.47±.05 D.138±.31 Mg.13±.02 Fe.13±.02 Ti.03±.01 Mn.02±.01 Al 6.25±0.36 Si 9.56±.28 O₃₂ • 12H₂O

8 Mo: Ave. 8 measurements

Ca_{2.42±.20} Na.59±.03 K.101±.21 Mg.12±.01 Fe.20±.02 Ti.01±.01 Mn.03±.01 Al 6.76±.26 Si 9.09±.20 O₃₂ • 12H₂O

Ave. 30 measurements

Ca_{2.25±.09} Na.60±.03 K.109±.19 Mg.12±.01 Fe.14±.02 Ti.01±.01 Mn.02±.01 Al 6.86±.10 Si 9.16±.07 O₃₂ • 12H₂O

TABLE V (cont)

Phillipsite: $(Ca, K)_3.5 Al_7 Si_9 O_{32} \cdot 12H_2O$

Overgrowth III: "Thomsonite"

1 Mo: No measurements

2 Mo: Ave. 3 measurements

Ca_{2.05±.10} Na_{.53±.10} K_{.02±.01} Mg_{.03±.02} Fe_{.10±.02} Al_{4.05±.17} Si_{5.70±.12} O₂₀ • 6H₂O

4 Mo: Ave. 5 measurements

Ca_{2.20±.05} Na_{.38±.02} K_{.05±.02} Mg_{.08±.02} Fe_{.15±.02} Al_{4.05±.07} Si_{5.60±.02} O₂₀ • 6H₂O

8 Mo: Ave. 3 measurements

Ca_{2.55±.15} Na_{.45±.02} K_{.05±.02} Mg_{.07±.02} Fe_{.12±.02} Al_{4.13±.13} Si_{5.38±.02} O₂₀ • 6H₂O

Average 11 measurements

Ca_{2.24±.06} Na_{.44±.02} K_{.04±.01} Mg_{.07±.01} Fe_{.13±.02} Al_{4.07±.01} Si_{5.57±.04} O₂₀ • 6H₂O

Thomsonite: Ca_{2.5} Na_{0.5} Al_{4.5} Si_{5.5} O₂₀ • 6H₂O

TABLE VI

<u>Point</u> (See figure)	<u>Temp.</u> (°C)	<u>Press</u> (bars)	<u>Physical</u>	<u>X Ray</u>	<u>Analysis</u> (microprobe)
1	25	345	White Powder	Amorphous	$Si_{.99}Al_{.01}O_2$
2	"	"	"	"	$Si_{.99}Al_{.01}O_2$
3	"	"	"	"	$Si_{.99}Al_{.01}O_2$
7	"	"	"	Quartz	$Si_{.99}Al_{.01}(trFe)O_2$
8	320-330	"	"	Wollastonite	$CaSiO_3$ to $CaSiO_3 + SiO_2$
4	132	"	Clear Blebs	n.d.	(SEM) (qualitative analysis) SiO_2 , Tr Al, Na
5	40	"	"	n.d.	SiO_2 , Tr Al, Na
6	26	"	"	n.d.	SiO_2 , Tr Al, Na
9	26	"	White Powder & Rods	n.d.	Ca, Si (hydrate?)-rods white powder - SiO_2

TABLE VII

MICROPROBE ANALYSES OF SCALE NORMALIZED TO 100% IN wt%

	<u>#1^a</u>	<u>#2</u>	<u>#3</u>	<u>#7</u>	<u>#8</u>
Na_2O	0.16	0.10	0.16	0.13	0.68
MgO	0.00	0.05	0.05	0.09	0.16
Al_2O_3	0.96	0.47	0.49	0.54	1.42
SiO_2	98.51	99.01	98.97	98.52	64.28
K_2O	0.22	0.14	0.14	0.17	0.41
CaO	0.11	0.10	0.12	0.13	30.64
FeO	0.04	0.13	0.14	0.34	2.50

^aNumbers refer to location in system.

TABLE VIII

SOLUTION ANALYSES FOR SOLUTIONS TAPPED AT THE INDICATED TIME

<i>Hot Solution^a</i>							
<i>Sample Time</i>							
<i>(h)</i>	<i>SiO₂</i>	<i>Al</i>	<i>Fe</i>	<i>Ca</i>	<i>Na</i>	<i>K</i>	<i>Total</i>
32	360±14	6.9±2.1	3.2±.1	0.3±.1	23.2±.6	53.0±1.1	446
56	515±18	6.5±1.4	0.7±.1	0.1±.1	27.7±.7	8.9±.8	560
176	537±16	2.3±.5	0.2±.1	<.1	23.1±.6	6.1±1.0	568
368	627±17	2.7±.5	0.7±.1	0.2±.1	21.3±.6	7.3±1.3	659
752	648±26	4.7±1.2	0.0±1.3	0.2±.1	27.2±.1	6.6±.1	687
1544	516±26	3.3±1.2	0.0±1.3	0.2±.1	18.8±.1	5.7±.1	544
3104	715±12	5.0±.8	0.3±.1.1	0.1±.1	22.5±1.1	8.4±.2	751
5816	854±19	0±2.8	0.7±.3	0±.1	25.9±.1	6.4±.9	890
<i>Cold Solution</i>							
32	429±22	9.2±1.7	0.2±.1	0.4±.1	26.6±.7	9.6±.9	475
56	465±16	6.3±1.5	0.2±.1	0.3±.1	25.3±.7	8.0±.8	504
176	574±19	2.8±.5	0.5±.1	0.4±.1	24.3±.7	8.0±.9	610
368	688±23	5.2±.5	3.6±3.5	1.4±1.4	25.3±.7	7.9±.9	731
752	684±26	4.7±.2	0±1.3	0.1±.1	26.8±.4	6.9±.1	723
1544	590±26	4.3±.2	0±1.3	0.2±.1	19.9±.4	5.7±.1	620
3104	714±12	5±.8	0.2±.2	0.1±.02	22.6±.4	8.2±.2	750
5816	671±29	2.6±.6	0.8±.2	0.6±.1	23.4±.9	6.7±.5	706

^aConcentration is in ppm.

TABLE IX

MOLAR VOLUMES

<u>Phase</u>	<u>Molar Volume (cm³/mole)</u>	<u>References</u>
<i>Phillipsite</i>	616	<i>after Coombs, 1959</i>
<i>Thomsonite</i>	340	<i>after Coombs, 1959</i>
<i>Low Albite</i>	100	<i>Robie & Waldbaum, 1968</i>
<i>Anorthite</i>	101	<i>Robie & Waldbaum, 1968</i>
<i>Microcline</i>	109	<i>Robie & Waldbaum, 1968</i>
α quartz	23	<i>Robie & Waldbaum, 1968</i>
H_2O @ 350 bars @ 300°C	24	<i>U.K. Steam tables, 1970</i>

TABLE X
ESTIMATED ROCK DENSITY

<u>Mineral</u>	<u>Volume (%)</u>	<u>Density (g/cm³)</u>	<u>Column 2 X Column 3 (g/cm³)</u>
microcline	15	2.56 ^a	0.384
plagioclase	38	2.67	1.015
quartz	25	2.65	0.665
biotite	13	3.05	0.400
epidote	3	3.50	0.105
sphene	2	3.52	0.070
magnetite	1	5.20	0.052
muscovite	3	ave. 3.29	0.099
calcite			
chlorite			
apatite			
zircon			
			<hr/> 2.79

^aDensities of minerals are from Robie, Bethke, and Beardsley (1967).

TABLE XI

MASS BALANCE

Total rock weight (8 disks)	24.1185 g	(range 2.7897 to 3.1440)
Total rock volume	8.53 cm ³	(range 1.02 to 1.23)
Rock density:		
by measurement	2.83 g/cm ³	
by mineralogy	2.79 g/cm ³	
Total weight loss	2.6890 g	
Total volume loss	0.96 cm ³	
Percent weight loss	11.2%	
Percent volume loss	11.3%	
Total water volume	1500 cm ³	
Mean solution burden	720 ppm	
Weight loss as solution burden	19%	
Weight loss as deposits	81%	
Estimated system surface area	1450 cm ²	
Deposit thickness if uniform	1.52 mg/cm ³	
Total weight loss as moles of silica	0.0448 moles	
Total volume loss based on silica	1.02 cm ³	
Percent volume loss as moles of silica	12%	

TABLE XII

FIT OF WEIGHT LOSS DATA vs SEVERAL MATHEMATICAL FUNCTIONS

The four-point solution uses all four values. The three-point solution only uses the last three.
r is the confidence of fit.

	<u>Time (h)</u>	<u>Weight loss (%)</u>
	752	4.6
	1544	6.2
	3104	9.5
	5816	13.7 (ave of 5)

	<u>Function</u>								
	<u>$\log (\text{wt loss}) = a\log(t) + b$</u>			<u>$\text{wt loss} = a\sqrt{t} + b$</u>			<u>$\text{wt loss} = at^b$</u>		
	<u>a</u>	<u>b</u>	<u>r</u>	<u>a</u>	<u>b</u>	<u>r</u>	<u>a</u>	<u>b</u>	<u>r</u>
4 point	0.5456	-0.9244	0.9930	0.1892	-0.8977	0.9947	0.1237	0.5405	0.9931
3 point	0.6043	-1.1340	0.9998	0.2028	-1.7772	1.0000	0.0770	0.5981	0.9998

Fig. 1. Second generation circulation system. Note: T_{1-8} are thermocouples.

Fig. 2 Weight loss (%) versus run duration (h).

Fig. 3. Schematic diagram of Plate 11 showing plagioclase compositions.

Fig. 4. Second generation circulation system. Note: T_1 - T_8 are thermocouples. Temperatures are those during system operation. Symbols: SiO_{2A} = amorphous silica, SiO_{2Q} = quartz, wo = wollastonite, and CaHyd = Ca, Si hydrate(?).

Fig. 5. Log SiO_2 (ppm) vs time (h). The fitted exponential curve was generated by J. W. Tester (personal communication).

Plate 1. Tantalum pedestal with eight granodiorite disks placed in experimental configuration.

Plate 2. Scanning electron photomosaic of a portion of an unreacted, polished granodiorite disk. Abbreviations are listed in Table II.

1 mm

Plate 3. SEM photomosaic of a portion of a disk reacted for 752 h.

200 μ

Plate 4. SEM photomosaic of secondary vermiculite near the center of Plate 3.

1 mm

Plate 5. SEM photomosaic of a portion of a second disk reacted for 1544 h.

1 mm

Plate 6. SEM photomosaic of a portion of a third disk reacted for 3104 h.

Plate 7. Apatite projecting from a substrate of plagioclase. The apatite was originally surrounded by quartz and is from the 3104-h disk.

Plate 8. Enlargement of overgrowth near thomsonite in composition growing on plagioclase. The overgrowth was photographed on the 3104-h disk.

Plate 9. SEM photomosaic of a portion of a fourth disk reacted for 5816 h.

200 μ

Plate 10. SEM photomosaic of quench silica fibers to the left of the vermiculites found on the 1544-h disk.

Plate 11. SEM photomosaic of a plagioclase grain from the 3104-h disk. The striations are compositionally controlled; see Fig. 3.