

A CRYSTALLIZATION STUDY OF A THOLEIITIC BASALT FROM THE INDIAN HEAVEN LAVA FIELD, SOUTHERN WASHINGTON CASCADE RANGE

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Introduction

The Indian Heaven Lava Field is located in the Cascade range of southern Washington, between Mount St. Helens and Mt. Adams. There are more than twenty vents within a thirty kilometer (north to south) area. Periods of eruption began around 730,000 years ago and have occurred as recently as less than 10,000 years ago. The lavas extruded from the vents are mostly mafic. There are four dominant types of lava that define the Indian Heaven area: a calcalkaline basalt and a basaltic andesite (olivine, plagioclase and rare clinopyroxene), a porphyritic basalt intermediate in composition between the previous (olivine and plagioclase), a high potassium calcalkaline basaltic andesite (clinopyroxene, olivine and relict amphibole), and a tholeiitic basalt (Smith and Leeman, 1989).

The goal of this study was to find the path of crystallization of one of the rocks, a tholeiitic basalt, in the laboratory. The main areas of investigation were: what temperatures minerals formed at, the chemical compositions of each mineral, whether the chemical compositions changed as temperature decreased and the proportions of minerals to glass at a particular temperature.

Procedures

The procedures described by Donaldson (1975) were used as a basis for preparing the samples used in this study. These techniques were the most efficient for minimum contact with the sample holder and maximum contact with the gases. The procedures were modified to accommodate the available equipment.

A 4 mm diameter loop was made from 1.5 cm of platinum wire and placed at the bottom of a small graphite crucible. Two hundred mg of tholeiitic basalt powder were placed on top of the platinum loop. The crucible was placed in a 1 atm bulk furnace and heated for two minutes at about 1350°C. The powder melted into a bead and adhered to the platinum wire. After the crucible was taken out and allowed to cool, the bead and wire were removed.

Once cooled, the bead was ready to be hung from the sample assembly and lowered into a 1 atm gas mixing, vertical tube furnace. A problem often encountered in experiments of this nature is the sample hitting the sides of the furnace when it is lowered into or removed from the furnace. This was solved by hanging the basalt bead inside a platinum wire cage, and attaching the cage to the platinum wires coming through the bottom of the alumina tube with a loop of thin platinum wire.

To begin, the temperature inside the column was raised to 1300°C. The oxygen fugacity (fO_2) was controlled by flushing the furnace tube with a measured mixture of CO and CO₂. The ratio of CO:CO₂ was determined by using a chart relating fO_2 and temperature to CO:CO₂ (Kozak, 1994). The sample was then lowered into the hot spot of the furnace (determined by experiment). Samples 201-204 were run at $-\log fO_2=9$; the rest were run at $-\log fO_2=10$. In the first few experiments, the temperature was lowered manually, because the computer had a tendency to undershoot the desired temperature if it was brought down too quickly. Once the appropriate rate of cooling had been found, a program was run to decrease the temperature. Initially, the temperature was decreased at a rate of three degrees per minute, then one degree per minute when the temperature was within thirty to forty degrees of the ending temperature. Throughout the runs, the CO:CO₂ levels were adjusted to maintain the same fO_2 . When the desired temperature was reached, the sample was kept in the furnace for various lengths of time so that it could reach equilibrium. The times varied from one hour to almost sixty-seven hours.

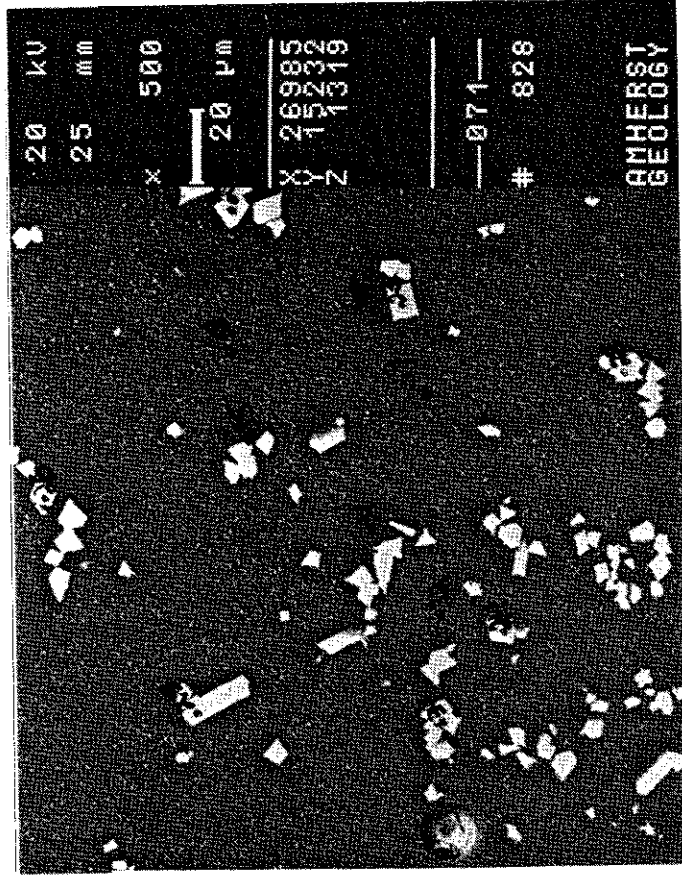
The sample was quenched by dropping the bead into a 800 mL beaker of tap water. This was accomplished by running an electrical current through the wires holding the sample in the furnace. The current burned through the thin platinum wire, detaching the wire cage from the alumina tube assembly.

To prepare the beads for microanalysis, approximately half of each individual sample was placed in a hollow plastic cylinder (three to six samples per cylinder) that was then filled with Quikmount epoxy. After hardening, the samples were polished with wet sandpaper discs mounted on a lap, using progressively smaller grit sizes, down to a 1 μ diamond paste. The samples were also polished using a 1/4 μ diamond impregnated cloth covered lap. The cylinders were then coated with a thin film of carbon using a Pelco Advanced Coater 9500.

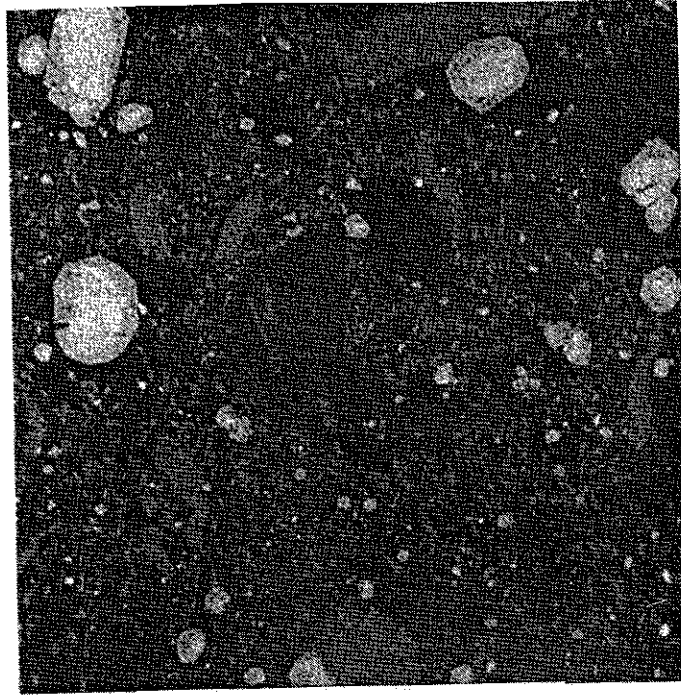
All of the phases present in each sample were analyzed for chemical composition using the JEOL JSM-6400 Scanning Electron Microscope and Quantex VI software on a Kevex Analyst 8000. The electron dispersive mode was used for chemical analysis; the working distance was 39 mm. The Feature II software program was used

MINERAL SUMMARY TABLE

SAMPLE	GARNET	BIOTITE	MUSCOVITE	ALUMINOSILICATE	QUARTZ	SPINEL	ILMENITE	CORUNDUM	STAUROLITE
WET									
750°C-4 DAYS	X	X	X	X	X		X		
850°C-1 DAY		X		X	X	X	X	X	
850°C-2 DAYS	X	X		X	X	X	X		
850°C-4 DAYS	X	X		X	X	X	X		
850°C-14 DAYS	X	X		X	X	X	X		
950°C-2 DAYS	X			X	X	X	X		X
1050°C-1 DAY									
DRY									
750°C-4 DAYS	X	X	X	X	X		X		X
850°C-1 DAY	X	X	X	X	X	X	X		
850°C-2 DAYS	X	X		X	X	X	X		
850°C-4 DAYS	X	X		X	X	X	X		
850°C-14 DAYS	X	X		X	X	X	X		
950°C-2 DAYS	X			X	X	X	X		
1050°C-2.5 DAYS				X	X	X			



1050°C ONE DAY WET



850°C ONE DAY DRY

to determine the mode. The working distance was 8 mm, and the back-scattered electron mode on the SEM was used. The Kevex 4850S Microscope Interface Module was used to transfer the image from the microscope to the Kevex Analyst. Unfortunately, the Feature II software was unable to distinguish between the glass and olivine phases. The plagioclase mode is estimated by the Kevex; the glass and olivine modes are estimated from the photographs.

The remaining portion of the bead was used for x-ray diffraction to confirm the phases present. Each sample was crushed with a mortar and pestle and separated into size fractions using sieves. The fraction between 75 and 150 microns was used for x-ray diffraction. The amount of powder yielded was so small that it would not fill the smallest of the plastic trays used for diffraction. Therefore, it was necessary to mount the sample on a quartz plate that was oriented so that it would not diffract any x-rays. A Scintag XDS 2000 was used to collect x-ray diffraction data. It was operated at 45.0 kV and 40 mA. The sample was scanned from 15 to 70 2θ , at the rate of .5° per minute.

Results

X-Ray Diffraction

The samples that were quenched at the temperatures ranging between 1300°C and 1200°C yielded no diffraction peaks. This meant that there were no phases present other than glass. At 1190°C a few plagioclase peaks began to appear. The sample run at 1185°C exhibited only one identifiable peak, also a plagioclase peak. At 1180°C, plagioclase was still the only phase present. The samples that were run at 1175°C both had plagioclase peaks. The sample which was run for almost nineteen hours, showed strong plagioclase peaks. However, the sample that was run for five hours had only one peak. The samples run at 1160°C, 1150°C and 1140°C showed both plagioclase and olivine peaks.

Chemical Compositions

The chemical compositions of the phases in each sample were determined by converting the oxide percentages reported by the Kevex into atom units. All of the oxide percentages were normalized so the total was 100, and then converted to atom units. Each phase was analyzed in three or more places, and the chemical compositions were averaged. Please see Table A for a summary of average chemical compositions. There was no evident zoning; the crystals were too small to analyze the interior and the margin.

Mode Analysis

The percentage of plagioclase present was computed using the Feature II software package. The software was unable to recognize the olivine phase because it did not differ highly in contrast from the glass phase. Each sample was analyzed in five different places, and the values were averaged. Sample #205 (1160°C) is about 20% plagioclase, 5% olivine and 75% glass. Sample #213 (1150°C) is about 33% plagioclase, 10% olivine and 67% glass, and sample #214 (1140°C) is about 40% plagioclase, 20% olivine and 40% glass.

Discussion

Above 1200°C, the rock exists entirely in the liquid phase. Between 1190°C and 1200°C, the liquidus was reached and plagioclase began to crystallize. At 1180°C, large plagioclase crystals began to crystallize on the margin of the sample. This suggests that the platinum wire used to hold the sample probably acted as a nucleation site (Berkebile and Dowty, 1982).

Two samples were run at 1175°C, one for five hours and one for nineteen hours. Both samples had crystals on the margin. The nineteen hour sample had a few large plagioclase crystals that were h-shaped ("hopper crystals"). However, the five hour run crystallized both olivine and plagioclase. This may have been due to the short period of time it was in the furnace; perhaps the sample was not run for long enough for the sample to reach equilibrium. In other studies similar to this one, the seventeen hours to twenty-three hours was the minimum time necessary to reach equilibrium (Thy, 1991 and Thy, Lofgren & Imsland, 1991). Figure A shows the relationship between time, temperature, and the minerals that were crystallized.

At 1160°C, randomly oriented plagioclase hopper crystals and olivine crystals intergrown with plagioclase were growing (see Figure 3). The dark crystals are plagioclase; the gray, mottled crystals intergrown with the plagioclase are olivine; the gray background is basalt glass. At 1150°, the intergrown crystals outnumbered and were larger than the hopper crystals (see Figure 1). Again, the dark crystals are plagioclase, the olivine crystals are white. The large black fissure in the upper right corner is a crack in the sample. Also, a few olivines began to crystallize independent of the plagioclase. In the sample run at 1140°C, there was a dendritic growth pattern (see Figure 2). The intergrown crystals are quite large, and there are many independent olivine crystals. Figure 4 is the same sample as Figure 2, magnified 600x. The olivine crystals appear to be zoned, but chemical analyses in different areas of the same crystal showed that they were not. The apparent zoning is actually a back scattered electron edge effect.

The chemical composition of the plagioclase crystals near the margin of the sample remained nearly the same, about An₇₀. However, when olivine began to crystallize, the composition changed. In the sample run at

1160°C, the independent hopper crystals were also about An₇₀, but the plagioclase intergrown with olivine was about An₆₆. The composition of the intergrown plagioclase remained about the same as temperature was reduced; at 1150°C and 1140°C, the intergrown plagioclase was about An₆₇.

The composition of olivine, although dominantly forsteritic, moved towards fayalite as temperature dropped. The intergrown olivine crystals in the sample run at 1160°C had a chemical composition of about Fo₇₅. At 1150°C, the intergrown olivine was approximately Fo₇₃. The sample run at 1140°C was Fo₇₁. The lone olivine crystals in the same sample were Fo₇₂.

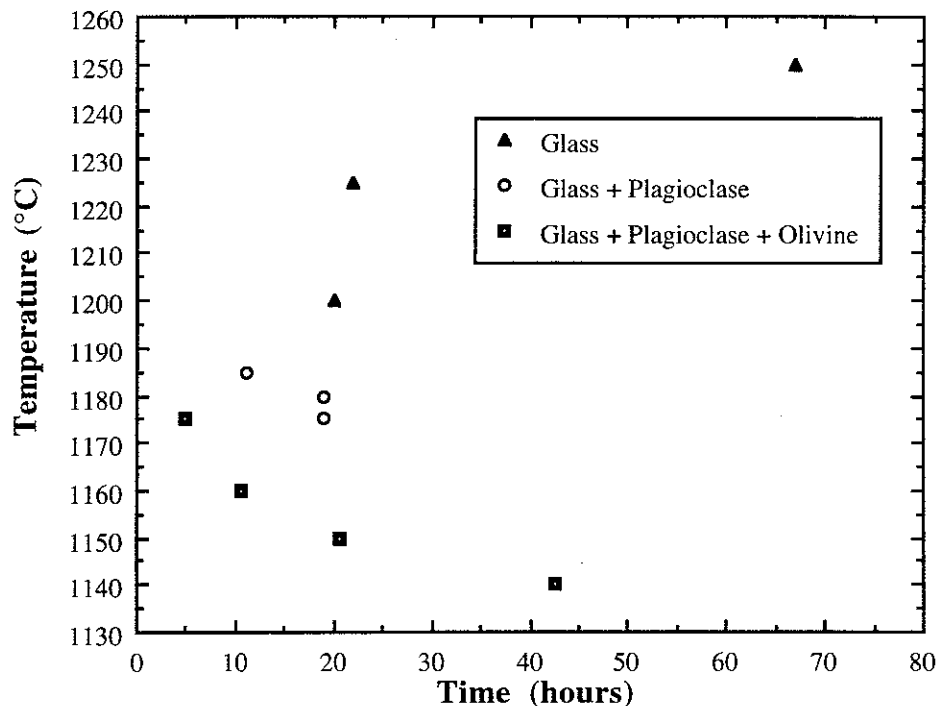
Acknowledgements

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Figure A



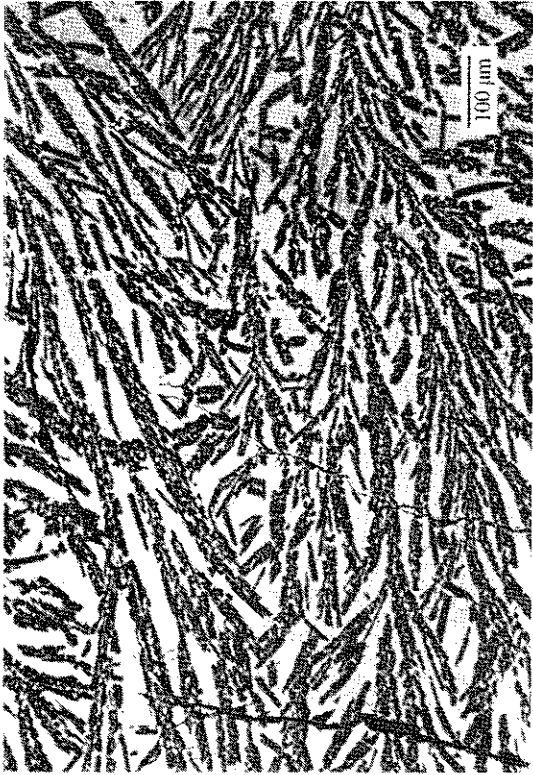


Figure 2. Sample #214, 1140°C, 42 hrs.

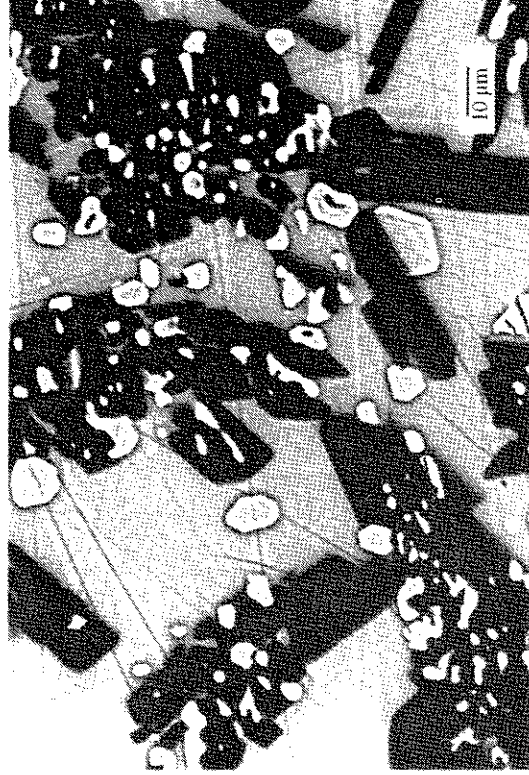


Figure 4. Sample #214, 1140°C, 42 hrs.



Figure 1. Sample #213, 1150°C, 20 hrs.



Figure 3. Sample #205, 1160°C, 10 hrs.

AN EXAMINATION OF THE CHEMICAL OXYGEN DIFFUSION RATES IN THE SYSTEM ANORTHITE₂₀ AND DIOPSIDE₈₀ VIA IRON REDOX EXPERIMENTS

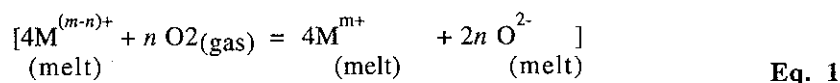
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Introduction

Experiments were performed on melts composed of Anorthite₂₀ Diopsides₈₀ to determine the chemical oxygen diffusion coefficient at one atmosphere pressure at three different temperatures. The experimental temperatures were 1375, 1425, and 1475 degrees C.

Chemical diffusion is defined as the movement of components or constituent species in a melt from point to point within the melt along chemical potential gradients (Dunn, 1986). A chemical potential gradient defines the motion of the chemical from point to point in the melt. Chemical potential is analogous to gravitational systems in that the most stable state is the one of lowest potential. At equilibrium, potentials of neighboring states are equal (Best, 1982).

Oxygen will diffuse from an oxygen rich atmosphere into a sample with a lower oxygen content than the atmosphere. Diffusion rates can be determined by using an iron dopant to monitor changes in the oxygen content. Iron is used because when it is oxidized, it accepts an extra oxygen atom. The redox state of iron changes as oxygen enters or exits the system according to the general redox equation (Eq. 1)



where M is the multivalent element in oxidized M^{m+} , and reduced, $M^{(m-n)+}$, species within the melt and n is the number of electrons transferred in the redox couple (Schreiber et al., 1986).

The experiments used small samples (400 mg) of An₂₀ Di₈₀ doped with %1 iron by weight. Each sample was equilibrated under reducing conditions (CO₂ atmosphere) to minimize the Fe⁺³ content. The reduced samples were remelted at a chosen temperature for varying lengths of time in a more oxidizing environment, air. A modified version of Fick's Second Law of Diffusion (Eq. 2) can be used to calculate the redox ratios at a given depth for a fixed time. The results also allow one to calculate a diffusion coefficient which is the rate of diffusion.

$$\frac{x - x_o}{x_e - x_o} = \sum_{j=0}^{\infty} (-1)^j \times \left[\operatorname{erfc} \frac{(2j+1)L - z}{2\sqrt{Dt}} + \operatorname{erfc} \frac{(2j+1)L + z}{2\sqrt{Dt}} \right] \quad \text{Eq. 2}$$

x_o and x_e "are the initial and equilibrium redox ratios while x is the redox ratio for a particular depth, z, at any given time t. L is the total depth of the sample and D is the diffusion coefficient." (Kozak, 1991)

Experimental Procedures

A glass composed of An₂₀ Di₈₀ was prepared by melting the appropriate elemental materials in a platinum crucible at 1350° C for 24 hours in a Deltec high temperature bulk furnace. After quenching the glass in water, it was removed from the crucible and ground by hand into a fine powder. The powder was then weighed, doped with 1 wt% iron to make a 10g batch and mixed in a mechanical mixer to homogenize the materials. The doped An₂₀-Di₈₀+Fe sample was re-melted, quenched, and ground to a fine powder and separated into 18 400 mg lots. These lots were placed in 5 mm OD round platinum tubes of a constant geometry. Identical sample sizes and small platinum tubes were used to ensure a constant melt depth and minimize convection.

After separating the samples into 3 groups of 6, each sample was equilibrated at a specified temperature above its liquidus (1375° C, 1425° C, or 1475° C) in a reducing atmosphere of CO₂. This was done in a Deltec vertical tube furnace specially equipped to control the atmosphere. One of the reduced