Experimental Investigation of Garnet Nucleation from Chlorite + Quartz Mixtures at 8kbar Pressure

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Submitted to the Department of Geosciences of
Smith College
in partial fulfillment of the requirements of a degree of
Bachelor of Arts

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May 3, 2013

Abstract

Nucleation describes the process of when a mineral first begins to form on the microscopic level and the atoms align into the particular orientations of its crystal lattice. The volume of the crystal nucleus must also reach a critical size so that the decrease in Gibbs free energy from phase change is greater than the increase in Gibbs free energy due to surface energy of a small crystal. Minerals begin to grow because of chemical reactions that occur during metamorphism of a metamorphic rock or during the cooling of an igneous rock. For nucleation to occur, specific conditions must be in place. All of the elements necessary to create a mineral can be present in a rock, but unless the conditions are productive for nucleation, the mineral will not form. In the experiments described in this paper, I sought to discover specific experimental conditions that would promote nucleation of garnet.

Chlorite, quartz, biotite, muscovite, and garnet were ground into powders and subjected to temperatures ranging from 610˚C to 750˚C and 8kbar pressure in a piston cylinder press for lengths of time ranging from 4 to 18 days. Water was added to half of the samples in order to determine if it would promote garnet nucleation. Products were analyzed on a Scanning Electron Microscope (SEM). Garnet nucleation only occurred for the longest experiment at the highest temperature (750˚C, 8kbar, 17 days and 20 hours). This temperature is 160˚C higher than the calculated minimum temperature for garnet nucleation and growth from chlorite + quartz at 8kbar. Perhaps if the lower temperature experiments were run for longer periods of time, garnet would have nucleated. Cordierite nucleation, gedrite nucleation, garnet overgrowth, and grain coarsening occurred in several of the experiments.

Acknowledgements

First, I would like to thank Prof. John Brady for being my advisor and mentor on this project. He was always willing to help and give guidance, and I thank him for all of the experimental petrology wisdom he shared with me.

Additionally, I would like to thank Mark Brandris for being my second reader. I also thank Michael Vollinger for teaching me how to use the equipment in the rock room and for helping me to lift equipment in the lab. Marc Anderson also assisted me with lifting equipment.

I would also like to thank Prof. Wendy Panero at the Ohio State University for allowing me access into her lab and library resources, and Prof. Carey for inviting me to participate in Ohio State undergraduate research activities this past summer.

Lastly, I would like to thank Smith College for providing me the opportunity to complete an honors thesis; Tomelson funding for partially funding my project; and the Mellon Mays Foundation for their mentorship, support, and funding.

This work was supported by the National Science Foundation Major Research Instrumentation Program grant EAR-1039707.

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Previous Work

Vocabulary

Garnet nucleation and growth are two interconnected topics, and it is difficult to explore nucleation without also discussing growth. In order to discuss both nucleation and growth, one must first present some vocabulary. Nucleation refers to when a mineral first begins to form on the microscopic level and the crystals first align into the particular structure of the crystal lattice. Continuous nucleation refers to nucleation that occurs for solid solution minerals that nucleate with a range of chemical compositions at a range of temperatures. Prograde nucleation occurs during prograde metamorphism; this type of nucleation occurs because of increasing pressure or temperature. Growth describes when atoms attach onto a preexisting crystal lattice.

Methods for Analyzing Nucleation and Growth

Several studies have explored the nucleation of large garnet crystals, garnet porphyroblasts, in rocks from a wide range of locations (Daniel and Spear 1998). The data were collected in a variety of ways. Initially, geologists had either to extract each grain or to create two-dimensional compositional maps by serial cross cuts (Kretz 1973; Daniel and Spear 1998, 1999). X-Ray tomography allowed geologists to analyze large numbers of grains without using these tedious methods (e.g. Carlson and Denison 1992; Ketcham et al. 2005). Now geologists can also use thin sections to project a 3D image using a digital imaging system (Zeh 2004).

Rate-Limiting Step

Many of these experiments sought to discover the rate-limiting step for garnet nucleation and growth. The rate-limiting step refers to the slowest step in the process of nucleation because the slowest step limits the rate of the entire reaction. Heat flow, diffusion, and attachment of atoms were candidates for this limiting step.

Diffusion Gradient

Spear and Daniel studied metamorphic rocks from Harpswell Neck and the Casco Bay areas in Maine, USA, and they report that diffusion cannot be the rate limiting step for continuous nucleation on large scales (distances at least twice the length of the garnet radius) because they found that garnet can nucleate next to preexisting garnet crystals within this range (1998). If diffusion were the rate limiting step, then garnet would not nucleate next to preexisting crystals because the area around these crystals would be depleted of the nutrients necessary to nucleate garnet. There reports did not rule out that diffusion could be rate limiting for continuous nucleation on shorter scales.

Daniel and Spear (1999) examined garnet porphyroblasts in garnet schists from the Everett Formation in northwestern Connecticut. Chlorite + quartz = garnet + water was the reaction that caused these garnet porphyroblasts to nucleate and grow. They examined how, as a garnet crystal grows, a diffusion gradient forms around the crystal. Since the surrounding area is depleted of the necessary reactants to make the crystal, nucleation does not occur within the diffusion gradient. This research also suggests that as the garnet crystal grows larger, the depleted surrounding area grows larger, and therefore, the larger garnet crystals would have a longer distance to its nearest garnet neighbor. In the rocks that they studied, nucleation and growth were not affected by diffusion gradients on length scales of less than 2mm. They also suggest that diffusion controlled nucleation would promote large crystals because the diffusing material would go toward growing the existing garnet as opposed to nucleating new garnet. It is important to note that both of the papers mentioned in this section are written by the same authors.

Diffusion Along Grain Boundaries

Spear and Daniel further examined the metamorphic rocks from Harpswell Neck Maine (2001). Their calculations indicated that the diffusion of silicon and aluminum was the rate limiting step for the growth of garnet along double grain boundaries. A double grain boundary refers to the contact between two crystal grains.

Heat Flow

Daniel and Spear (1999) rejected the idea that heat flow was the limiting step for garnet porphyroblast growth. They determined that heat flow controlled the total amount of garnet produced in a rock, but that the rates at which new material reaches and becomes incorporated into the nucleus was rate limiting for garnet porphyroblast growth.

Observable Texture in Rock

Zeh (2004) asserts that, generally, increased nucleation caused increased number of crystals in the rock. This statement does not seem to be in line with Spear's (1998) assertion that garnet crystals do not form from one nucleation cite expanding radially outward, but instead, occur when several nuclei coaless. If garnet crystals do not form when one nucleus grows radially outward, then increased nucleation does not directly imply an increased number of garnet crystals in the rock.

Grain Coarsening

Zeh (2004) examined a garnet–epidote–biotite gneiss from the Moine Supergroup in Scotland that had three texturally distinct regions. He found that the accessory minerals (apatite, titanite and allanite) nucleated just before the first garnet region began to overgrow (Zeh 2004). The matrix coarsened as the accessory phases grew (2004).

Replacement of Minerals

Spear and Daniel (2001) researched garnet crystals in rocks from Harpswell Neck, Maine, USA. They found that garnet nucleates in crenulations of chlorite or mica before it nucleates elsewhere within the rock. After it nucleates in the crenulation, the garnet then overgrows the entire crenulaiton. The garnet crystals had zoning of different elements. If the garnet experienced calcium zoning, they determined that there was diffusive transport between the crystal and the matrix. If the garnet experienced iron, magnesium, or manganese zoning, they determined that the crystal was at equilibrium with the matrix. They also found that garnet grows slower along double grain boundaries than it does along triple grain boundaries. Garnet growth along double grain boundaries shows a preference for the order in which garnet replaces other minerals; that order is as follows: muscovite**>**chlorite **>**plagioclase**>**quartz.

Methods

The reaction chlorite + quartz = garnet + water was used to nucleate garnet. This reaction was used because it is a common reaction that produces garnet in metamorphosed mud rock. Garnet was added to some of the experiments. Garnet nuclei were added in order to determine if the rate-limiting step was related to nucleation or growth. If the rate-limiting step were related to growth, there would be no overgrowth rims on the garnet crystals, and this would mean that any nucleated garnet would most likely not be able to grow to a size that was visible on the scanning electron microscope. Biotite and muscovite were added to some of the experiments. The addition of these minerals promoted partial melting, and therefore, it could be determined whether the presence of melt promoted garnet nucleation and growth. Water was added to some of the experiments in order to determine if the addition of water promoted nucleation and growth.

All experiments were performed in a nickel container with four holes that are each approximately 2.6mm in diameter and 8.36mm in depth. Each hole was lined with gold. A variety of different mineral mixtures were added to these holes for each experiment (Table 1). The experimental procedures were developed from the procedures of Morse et al. (2004) and Ayers et al. (1992). Experiments 1-3 were either not successfully completed or not able to be analyzed, and therefore, data from these experiments were not used for this research.

Chlorite and quartz were weighed in roughly a 3:2 mass ratio (Tables 2-3). Excess quartz was used for this reaction. The quartz and the chlorite were ground together using a mortar and pestle and ethyl alcohol to prevent losing material. The mixture was dried under a lamp and a fan. For some experiments, a portion of the chlorite + quartz mixture was mixed with garnet from central Massachusetts near Ware, MA in metamorphic Zone VI of Tracy et al. (1976) (MAK 98-4). Chlorite, quartz, muscovite, biotite, and garnet were mixed together using the same method in roughly a 6:1:1:1:2 mass ratio (Tables 2-3).

These mineral mixtures were added to the various holes in the nickel container (Table 1). The minerals in each hole were compressed with a rod as they were added to the hole. Before the minerals were added, distilled water (2μL) was added with a syringe to some of the holes (Table 1). For experiment 8, the chlorite + quartz mixture and the chlorite + quartz + muscovite + biotite mixtures were sieved to 75μm. The garnet was not sieved to 75μm for any experiment. After the mineral mixtures were added to the nickel container, a sample assembly was prepared (Figure 1).

Each sample assembly was placed into the piston cylinder press and was run at 8kbar at temperatures ranging from 610˚C to 750˚C and for times ranging from 4 to 11 days (Table 4). The first temperature used in an experiment was 610˚C because, according to Theriak Domino calculations, this temperature was just above the tipping point for garnet to nucleate from chlorite and quartz (Appendix III). After the experiment, the top portion of the nickel container was sawed off using a Buehler Isomet low-speed saw. Sawing the nickel container allowed a surface of the sample to be exposed so that that surface could be coated with epoxy, polished to 1μm, and analyzed on the SEM.

	Experiment 4	Experiment 5	Experiment 6	Experiment 7	Experiment 8
Hole 1	Chl+Qz	Chl+Qz	Chl+Qz	Chl+Qz+Grt+ water	Chl+Qz+Grt+ water
Hole 2	Chl+Qz+ water	Chl+Qz+ water	Chl+Qz+ water	Chl+Qz+ water	Chl+Qz+ water
Hole 3	Chl+Qz+Grt	Chl+Qz+Grt	Chl+Qz+Grt	Chl+Qz+Grt	Chl+Qz+Grt
Hole 4	Chl+Qz+Grt+ water	Chl+Qz+Grt+ water	Chl+Qz+Mus +Bio+Grt	Chl+Qz+Bio+ Mus+Grt	Chl+Qz+Bio+ Mus+Grt

Table 1: Mineral mixtures for experiments 4-8.

	Mass (g)				
	Experiment 4	**Experiment 5**	**Experiment 6**	**Experiment 7**	**Experiment 8**
Hole 1	0.0283	0.0304	0.0239	0.0375	0.0290
Hole 2	0.0304	0.0322	0.0305	0.0279	0.0219
Hole 3	0.0312	0.0297	0.0313	0.0234	0.0209
Hole 4	0.0319	0.0261	0.0229	0.0252	0.0226

Table 2 Mass in grams of mineral mixtures for each experiments 4-8. Error is ±0.001g. Refer to Table 1 for mineral mixtures in each hole.

	Mass Ratios		
	Chl:Qz	**Chl:Qz:Grt**	**Chl+Qz+Mus+Bio+Grt**
Experiment 4	487 : 372	24.4 : 18.6 : 1	N/A
Experiment 5	13890 : 9330	24.4 : 18.6 : 1	N/A
Experiment 6	13890 : 9330	24.4 : 18.6 : 1	6 : 1 : 1 : 1 : 2.3
Experiment 7	13890 : 9330	24.4 : 18.6 : 1	6 : 1 : 1 : 1 : 2.3
Experiment 8	13890 : 9330	529 : 355 : 884	6 : 1 : 1 : 1 : 2.3

Table 3 Mass ratios of mineral mixtures for experiments 4-8.

	Temp (˚C)	Length of Reaction
Experiment 4	610	7 days 23 hours
Experiment 5	650	6 days 22 hours
Experiment 6	750	10 days 20 hours
Experiment 7	750	4 days
Experiment 8	750	17 days 22 hours

Table 4 Temperature and length of each experiment. All experiments were performed at 8kbar.

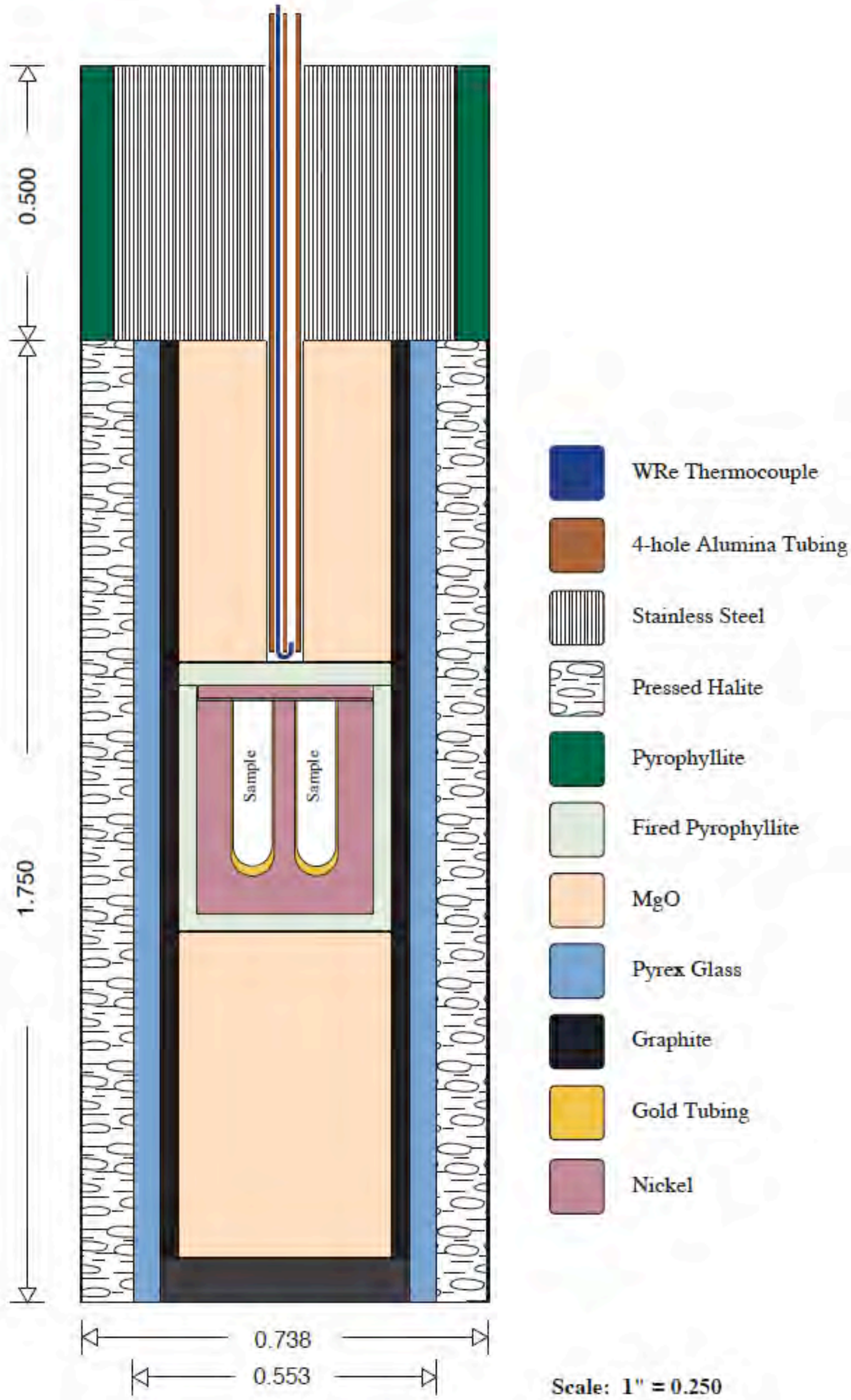


Figure 1 Sample assembly for all experiments.

Starting Materials

Composition of Chlorite Sample

Four chlorite samples were analyzed on the Scanning Electron Microscope to discover which one had elements in the correct proportions to form garnet. This was a standardless analysis. The samples were not coated with carbon, therefore the analysis was run under low vacuum. Each chlorite sample came from a rock which contained another mineral. In the following tables, the chlorite samples are identified by the accessory mineral (Tables 5-8).

	Weight % of Element	
	Spot	**Whole Area**
Oxygen	46.67	46.52
Magnesium	22.96	23.20
Aluminum	11.01	10.98
Silicon	15.55	15.54
Chromium	1.34	1.41
Iron	2.47	2.35

Table 5 Elemental composition of chlorite with ripidolite

	Weight % of Element	
	Spot	**Whole Area**
Oxygen	46.86	46.66
Magnesium	22.12	22.05
Aluminum	11.17	10.95
Silicon	16.16	16.06
Chromium	0.68	0.94
Iron	3.01	3.35

Table 6 Elemental composition of chlorite with penninite

	Weight % of Element	
	Spot	**Whole Area**
Oxygen	49.06	48.96
Magnesium	21.86	21.89
Aluminum	10.44	10.39
Silicon	14.55	14.60
Iron	4.09	4.16

Table 7 Elemental composition of chlinochlorite

	Weight % of Element	
	Spot	**Whole Area**
Oxygen	50.45	50.01
Magnesium	14.32	14.28
Aluminum	13.73	13.78
Silicon	11.40	11.39
Iron	10.10	10.55

Table 8 Elemental composition of chlorite with margarite

All of the chlorite samples, except the chlorite with margarite, were deficient in Al (Tables 5-8). The samples that were deficient in aluminum had significantly less aluminum than magnesium. A low aluminum to magnesium ratio would not promote garnet growth. The chlorite with margarite contained Mg and Al in nearly a 1:1 ratio, therefore, this chlorite sample was used in order to grow garnet in all of the experiments (Table 8).

Chlorite + Quartz Mixture

Chlorite +Quartz mixture, which was the starting material for all experiments, was analyzed on the SEM to obtain average crystal sizes and quantitative chemical analysis for the different minerals. The starting material contained chlorite, quartz, margarite, and iron titanium oxides (Table 9 and Figure 2).

		Chlorite	Quartz	Margarite	FeTiO
Average Width (μM)	**Max**	249	247	142	29.1
	Min	60.7	90.3	7.38	7.56

Table 9 Average maximum and minimum width for crystals in the starting material. To obtain this average, larger quartz crystals were measured. Since these numbers represent the average of the largest crystals in the starting material, if a larger quartz grain is found in the results of one of the experiments, it is assumed that that quartz grain experienced grain coarsening.

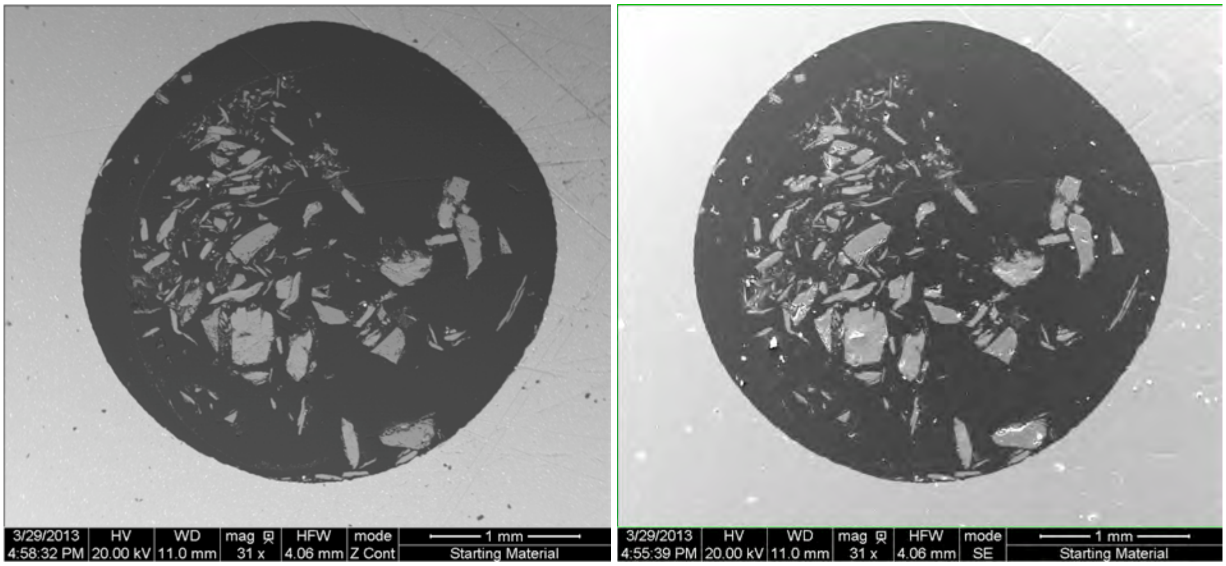


Figure 2 Starting material for all experiments. The image on the left is BSED, and the image on the right is ETD. (See the section later in the methods section which is titled, "Scanning Electron Microscope (SEM): Electron Detectors" for an explanation of BSED and ETD.) The crystals in this image are very loosely packed. The platy grains are chlorite. All of the dark grey area within the hole is epoxy.

Piston Cylinder Press

Sample Assembly

In the piston cylinder press, the sample is placed inside a nickel container with four holes that have a gold lining and a gold lid. This gold acts as an inert lining to prevent the sample from reacting with the nickel container. During pressurization of the sample in the piston cylinder press, the gold lid seals and does not allow water to escape from the sample. The nickel container also has a nickel lid which goes on top of the gold lid (Figure 1).

The nickel container is inside a fired pyrophillyte container with a lid. Pyrophillyte insulates the sample from the electric current that is flowing through the graphite furnace to generate the high temperatures. This pyrophillyte container is bound on either side with magnesium oxide which acts to insulate the sample from the electric current. The top piece of MgO contains a hole through which the thermocouple can enter. The thermocouple rests on top of the fired pyrophillyte lid and measures the temperature at the top of the lid (Figure 1).

The setup discussed above is inside a graphite furnace. The graphite furnace is encased by a glass sleeve which is encased by a salt sleeve. The salt sleeve converts the uniaxial pressure of the piston cylinder press into hydrostatic pressure, and the glass sleeve prevents the salt sleeve from compressing into the graphite furnace and deforming it. If the graphite furnace were deformed it might affect how the electrical current flows through, and this, in turn, may affect the temperature of the experiment. The salt sleeve is wrapped with lead foil (not seen in Figure 1). Lead foil reduces friction. If the friction is too high, the actual pressure of the experiment might be lower than expected. On top of this assembly is a stainless steel base plug which is encased by a pyrophillyte sleeve that has not been fired. The base plug is used to hold the thermocouple in place, and the pyrophillyte insulates the base plug so that the electrical current will flow toward the sample (Figure 1).

Salt Sleeve Preparation

For each experiment, two 22mm-long salt sleeves were prepared. The two sleeves were stacked on top of each other and glued to the glass sleeve to make a 44mm-long salt sleeve. The sleeves were prepared by putting 7.0 ± 0.1g of table salt into a salt mold and applying 1500lbs of pressure for 3-5min. To prevent the salt from hydrating, these sleeves were stored in a 110˚C oven until the experiment started.

Mechanics of the Piston Cylinder Press

The piston cylinder press has a series of metal pieces that are stacked on top of each other. On top of the lower ram, there is a spacer. The spacer is made of steel and provides a level base for the pusher. The Bridge goes on top of the spacer, and the piston is inside of the bridge. The bridge is made of steel, and it supports the piston as it is pushed by the lower ram. The Pressure vessel is on top of the bridge, and the sample is inside of this vessel. The pressure vessel is composed of concentric, steel rings with increasing hardness toward the center. The innermost ring is made of tungsten carbide. A punched mylar sheet is on top of the pressure vessel. The hole in this mylar sheet is centered around the sample assembly in order to guarantee that the current flows directly into the sample assembly. A thermocouple is threaded through a hole in the top plate, and this steel plate is placed on top of the punched mylar sheet with the thermocouple centered over the sample assembly. While the experiment is running, water flows in through the bridge and out through the top plate. This water is used to keep the experiment from overheating (Figures 3 and 4).

A slotted plate rests on top of the top plate, and a spacer is placed on top of this slotted plate. The top spacer has wires attached to it which provide the current for the experiment. A mylar sheet is placed between the top spacer and the upper ram in order to prevent current from flowing up to the upper ram instead of down toward the sample (Figures 3 and 4).

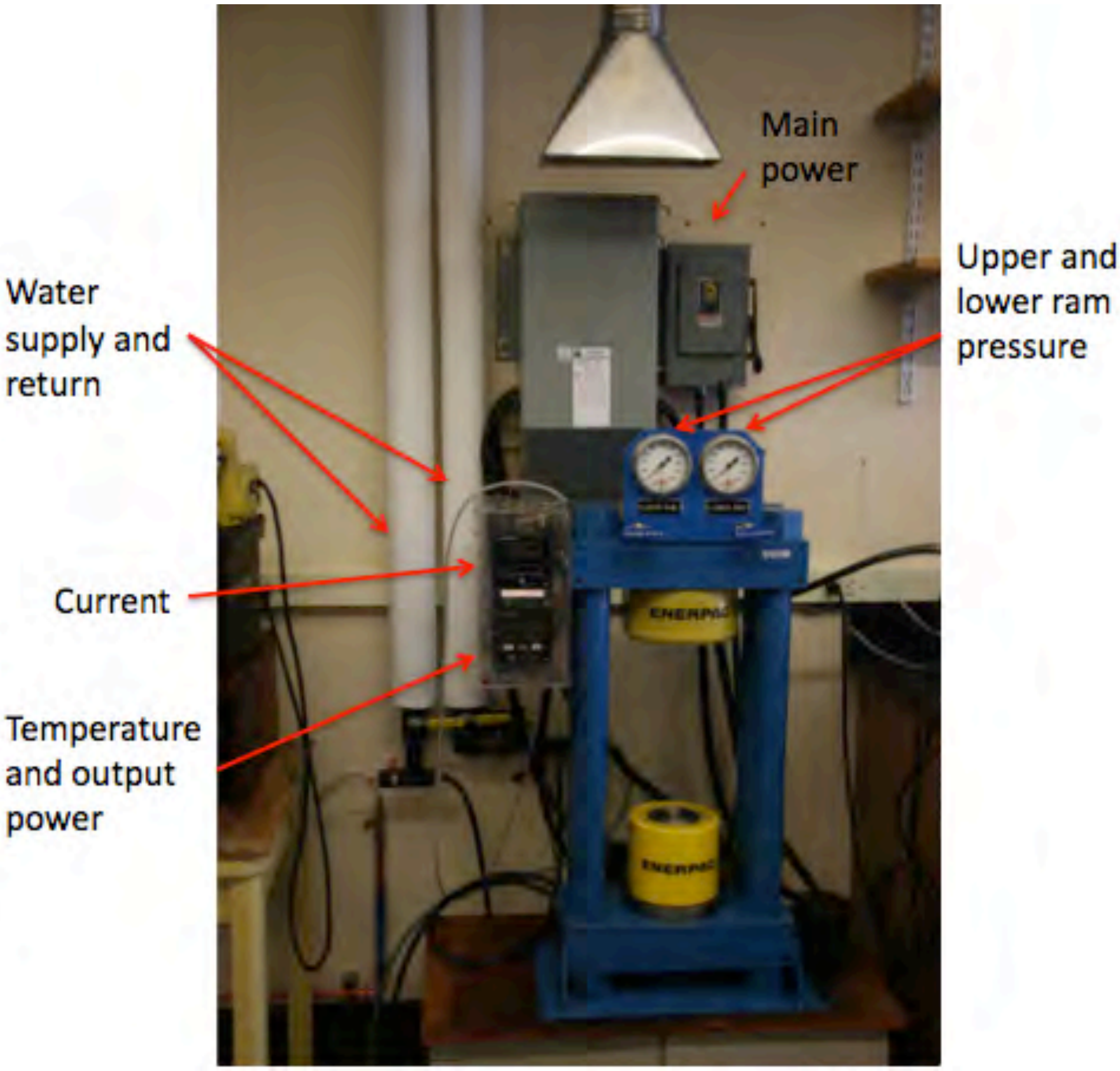


Figure 3 Image of piston cylinder press when it is not assembled for an experiment.

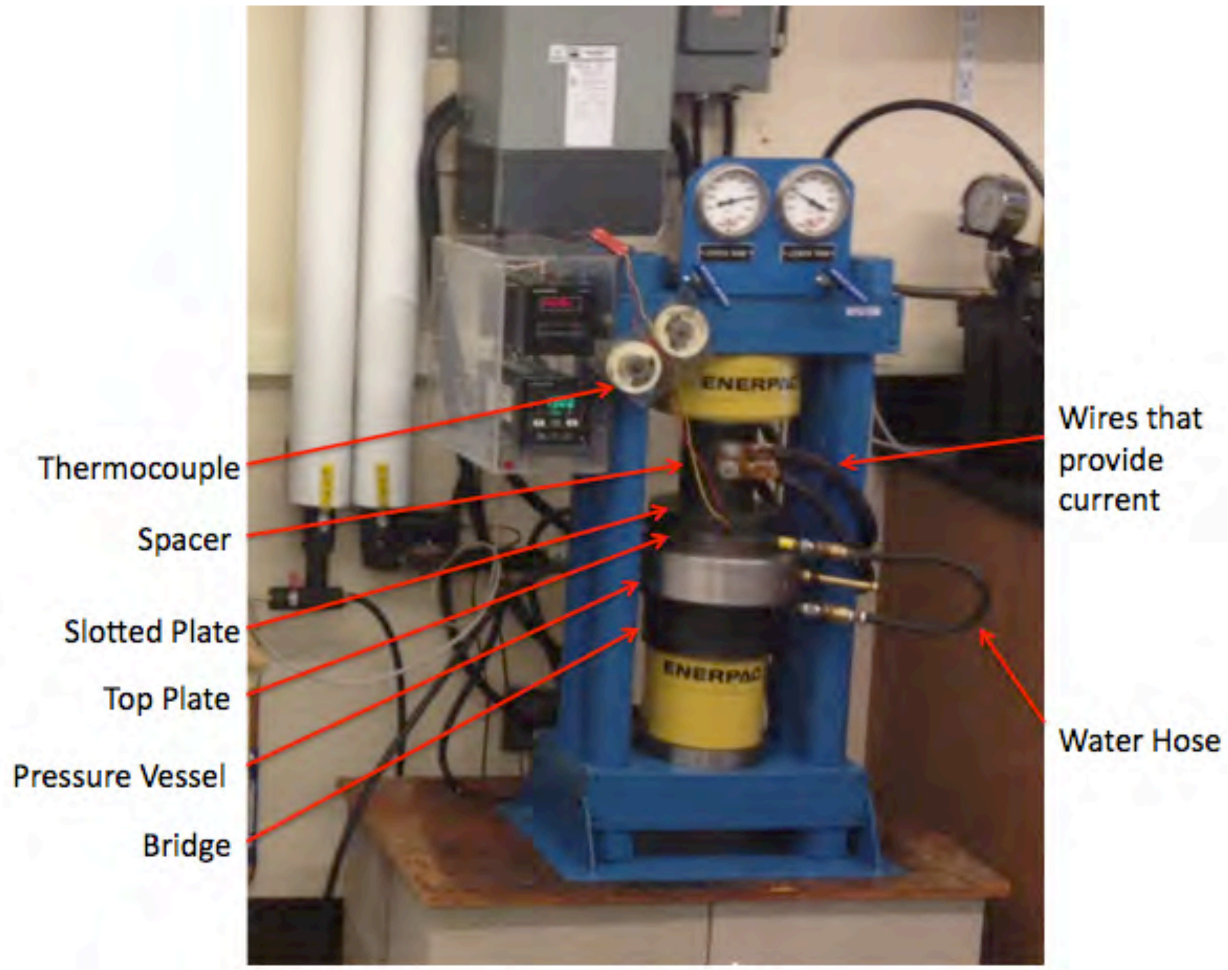


Figure 4 Image of piston cylinder press when it is assembled for an experiment.

Thermocouple Assembly

Thermocouple assembly required two wires; one wire was Type D W97Re3 and one was Type D W75Re25. These wires were threaded through two, four-hole thermocouple sleeves which are made of aluminum oxide. The wires were then bent, crossed, and tucked back into the thermocouple sleeve. The wires were only permitted to cross at this point. This is the point at which the temperature of the sample is measured.

Pre-Analysis Preparation

Epoxy and Polishing

After an experiment is complete, the nickel container is removed from the piston cylinder press and from the sample assembly. The top of the nickel container is sawed off so that the sample is exposed. Epoxy is prepared by mixing epoxy and hardner in a 3:1 volumetric ratio. This epoxy and hardner is manufactured by Epoxy Technology.

Epoxy is then placed on the side of the nickel container with the exposed sample. The nickel container is then placed in a vacuum at -25~-30 P.S.I. for 3-5min. The vacuum sucks the air out of the holes within the sample and allows epoxy to enter into these empty spaces and ensure that the sample will stick together as one cohesive piece. After the nickel container is removed from the vacuum, it is placed into a 60°C oven for 24hr. Once the nickel container is removed from the oven, the side that is covered with epoxy is polished in preparation for SEM analysis.

During this step, the sample is polished on a series of diamond wheels. First, it is successively polished on a 74μm, 40μm, and 30μm wheel with water as the lubricant. Then it is successively polished on a 6μm, 3μm, and 1μm wheel with polycrystalline diamond suspension as the lubricant. Between polishing on each of the last three wheels, the sample was placed into a sonicator for 1-2min to remove the remaining diamond suspension.

Carbon Coating

All samples were coated with carbon before SEM analysis. When the sample is in the SEM, an electron beam hits the sample, and the carbon coating conducts the electrons away from the site where they initially hit the sample. If there were no carbon coating, the electrons would build-up on the surface of the sample, and the SEM would not obtain a clear image.

Scanning Electron Microscope (SEM)

Vacuum

The samples were placed into the SEM and placed under high vacuum. If the sample were not under high vacuum, the electron beam would hit air molecules, and fewer electrons would contact the sample. When nearly all of the electrons hit the sample, this helps the SEM to obtain a clear image of the sample and give accurate quantitative analysis.

Electron Detectors

When the electron beam contacts the sample, the electron transmitting detector (ETD) detects and creates an image from the electrons that hit the sample. The back scattered electron detector (BSED) detects and creates an image from the electrons that bounce from the sample back to the source where the beam came from. In BSED, minerals with high atomic weight appear bright, and in EDT, areas of high topography appear bright.

EDAX Genesis

EDAX Genesis was used to obtain quantitative analysis of each sample. For quantitative chemical analysis, one must insure that the same number of electrons is hitting each sample that is being analyzed. To ensure that this was the case, the electron beam was aimed into an aluminum Faraday cup with a platinum aperture before each analysis to make certain that there was the same current reading.

After the current reading was checked, chemical analysis was performed on the minerals within each sample. During chemical analysis, the electron beam hits a particular part of the sample, the electrons from the beam knock some of the 1s electrons in the sample out of their shell (Skoog 2007). Higher energy electrons, specifically 2p electrons, have to move down to fill the vacancy in the lower energy orbital (Skoog 2007). EDAX Genesis can detect the X-rays that are emitted during this K-alpha energy shift and provide an elemental spectrum. In this spectrum, K-alpha shift is on the x-axis and amplitude is on the y-axis. The K-alpha shift identifies the element, and the amplitude shows how many electrons experienced that particular K-alpha shift. Since the same number of electrons is hitting each sample, one can use mineral standards to directly compare the relative quantities of each element within different samples.

Results

Results and comparisons of each successful experiment are presented in this section. For each experiment, Tables 10 and 11 show the average crystal size for cordierite, gedrite, quartz, and garnet. Each experiment also contains accessory minerals such as margarite, iron oxides and iron titanium oxides. Chemical analysis and crystal sizes for the accessory minerals are not presented in this paper.

		Average Width (µm)					
		Cordierite		**Gedrite**		**Quartz**	
		Max	**Min**	**Max**	**Min**	**Max**	**Min**
Exp 4	**Hole 1**	*N/A*	*N/A*	*N/A*	*N/A*	288	119
	Hole 2	*N/A*	*N/A*	*N/A*	*N/A*	177	112
	Hole 3	*N/A*	*N/A*	*N/A*	*N/A*	129	46
	Hole 4	*N/A*	*N/A*	*N/A*	*N/A*	196	45
Exp 5	**Hole 1**	84	21	9	1	404	72
	Hole 2	124	43	*U/M*	*U/M*	195	57
	Hole 3	136	37	*U/M*	*U/M*	120	30
	Hole 4	139	89	*U/M*	*U/M*	106	46
Exp 6	**Hole 1**	45	25	*U/M*	*U/M*	185	46
	Hole 2	63	19	*U/M*	*U/M*	555	102
	Hole 3	33	13	*U/M*	*U/M*	63	25
	Hole 4	58	23	*U/M*	*U/M*	185	47
Exp 7	**Hole 1**	65	18	*U/M*	*U/M*	148	40
	Hole 2	59	29	*U/M*	*U/M*	105	33
	Hole 3	29	2	*U/M*	*U/M*	89	11
	Hole 4	55	10	23	13	*N/A*	*N/A*
Exp 8	**Hole 1**	*N/A*	*N/A*	*U/M*	*U/M*	128	89
	Hole 2	21	5	*U/M*	*U/M*	66	31
	Hole 3	22	8	12	2	71	25
	Hole 4	24	6	12	2	72	31

Table 10 Average maximum and minimum width, in µm, of cordierite, gedrite, and quartz crystals in experiments 4-8. *N/A* indicates that that mineral was not found in the experiment. *U/M* indicates that that mineral was found in the experiment, but a crystal size was unable to be measured. The error is higher for all gendrite measurements because gendrite crystals were fine, closely packed, overlapping, and difficult to measure.

		Average Width (μm)					
		Garnet		Garnet Core		Garnet Rim	
		Max	Min	Max	Min	Max	Min
Exp 4	**Hole 1**	*N/A*	*N/A*	*N/A*	*N/A*	*N/A*	*N/A*
	Hole 2	*N/A*	*N/A*	*N/A*	*N/A*	*N/A*	*N/A*
	Hole 3	117	46	*N/A*	*N/A*	*N/A*	*N/A*
	Hole 4	70	12	*N/A*	*N/A*	*N/A*	*N/A*
Exp 5	**Hole 1**	*N/A*	*N/A*	*N/A*	*N/A*	*N/A*	*N/A*
	Hole 2	*N/A*	*N/A*	*N/A*	*N/A*	*N/A*	*N/A*
	Hole 3	76	36	*N/A*	*N/A*	*N/A*	*N/A*
	Hole 4	67	30	*N/A*	*N/A*	*N/A*	*N/A*
Exp 6	**Hole 1**	*N/A*	*N/A*	*N/A*	*N/A*	*N/A*	*N/A*
	Hole 2	*N/A*	*N/A*	*N/A*	*N/A*	*N/A*	*N/A*
	Hole 3	29	10	19	7	3	0.31
	Hole 4	41	20	89	26	9	2
Exp 7	**Hole 1**	42	17	22	8	5	1
	Hole 2	*N/A*	*N/A*	*N/A*	*N/A*	*N/A*	*N/A*
	Hole 3	849	189	45	18	4	0.90
	Hole 4	132	13	21	7	4	0.90
Exp 8	**Hole 1**	69	20	86	45	3	1
	Hole 2	*N/A*	*N/A*	*N/A*	*N/A*	*N/A*	*N/A*
	Hole 3	13	4	67	13	1	0.6
	Hole 4	74	24	9	3	2	0.87

Table 11 Average maximum and minimum width, in μm, of garnet crystals with no rim "garnet", garnet cores, and garnet rims for experiments 4-8. *N/A* indicates that that form of garnet was not found in the experiment. The maximum and minimum width for "garnet Exp 7 Hole 3" is based on the measurement of one crystal because there was only one garnet crystal without a rim.

***Experiment 4** (610˚C, 8kbar, 7 days and 23hr)*

A dry and a wet sample of both chlorite + quartz and chlorite + quartz + garnet were prepared. These samples were run at 610˚C, 8kbar for 7 days and 23 hours. For each hole of experiment 4, chlorite is present, but the crystals were very fine grained and closely packed, so a crystal size is unable to be obtained. Angular iron oxide crystals and iron titanium oxide crystals are found in all holes. Very little margarite is found in holes 1-4 of experiment 4 (Figure 5).

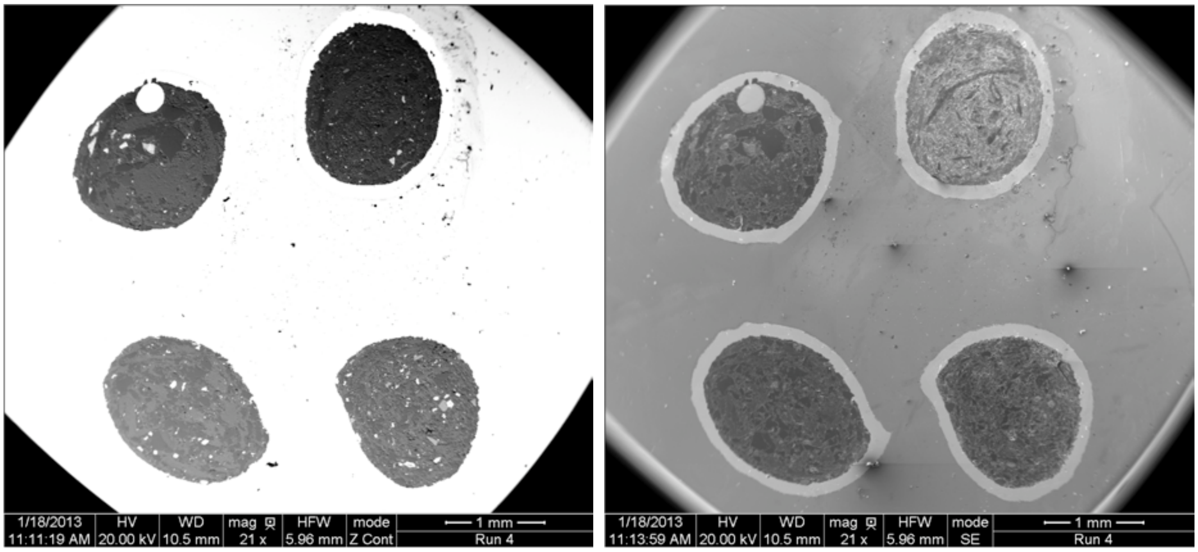


Figure 5 Experiment 4 (610°C, 8kbar, 7 days and 23 hours). The image on the left is BSED and the image on the right is ETD. Hole 1 (chlorite + quartz) is the top left. Hole 2 (chlorite + quartz + water) is the bottom left. Hole 3 (chlorite + quartz + garnet) is the bottom right, and hole 4 (chlorite + quartz + garnet + water) is the top right.

Hole 1 (Chl+Qz)

Chlorite and quartz were mixed together for hole 1 of experiment 4. Large, angular quartz crystals are found in this sample (Figures 6 and 7). Quartz crystals have an average maximum width of 288μm and an average minimum width of 119μm (Table 10). This size is slightly larger than the average quartz crystal size in the starting material (maximum: 247μm, minimum: 90μm), therefore these quartz grains may have experienced grain coarsening (Table 9).

Chlorite is the most abundant (~70%) followed by quartz (~20%), iron and titanium oxides (~9%), and margarite (~1%). Minerals of the same kind are clustered together, especially chlorite and quartz (Figure 6). The chemical formula of chlorite in experiment 4, hole 1 is presented in Table 12.

Garnet nucleation did not occur for experiment 4, hole 1.

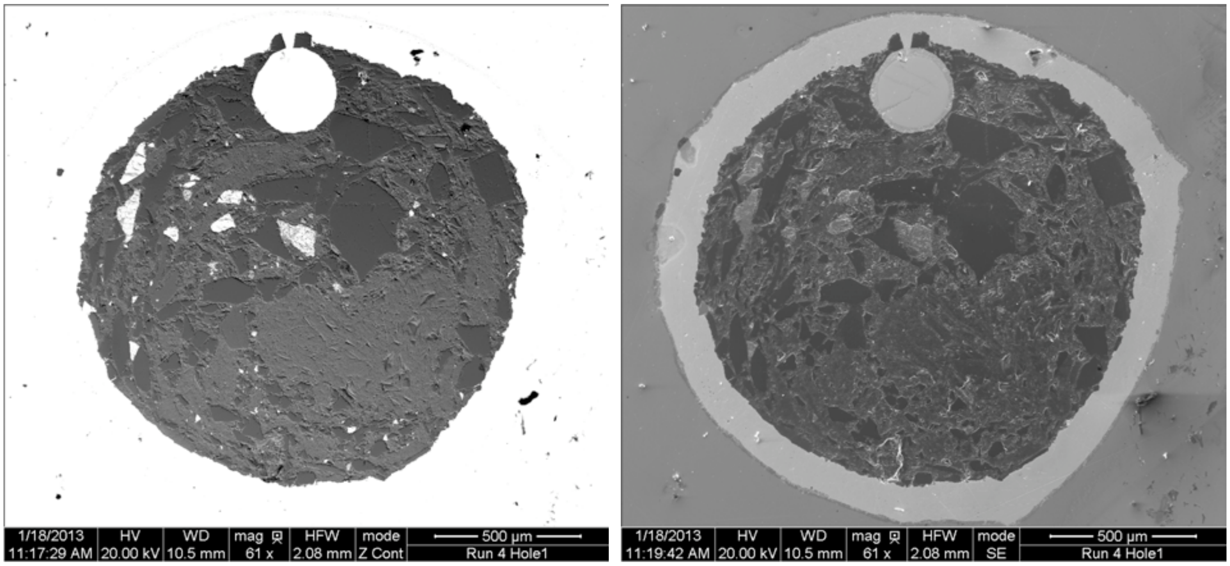


Figure 6 Experiment 4 (610˚C, 7 days and 23 hours) hole 1 (chlorite + quartz). The image on the left is BSED and the image on the right is ETD. Quartz crystals are angular, dark grey in BSED. Chlorite crystals are lighter grey in BSED and most abundant. Iron oxides and iron titanium oxides are the brightest crystals in BSED. The bright circle is a tungsten wire used to identify the hole.

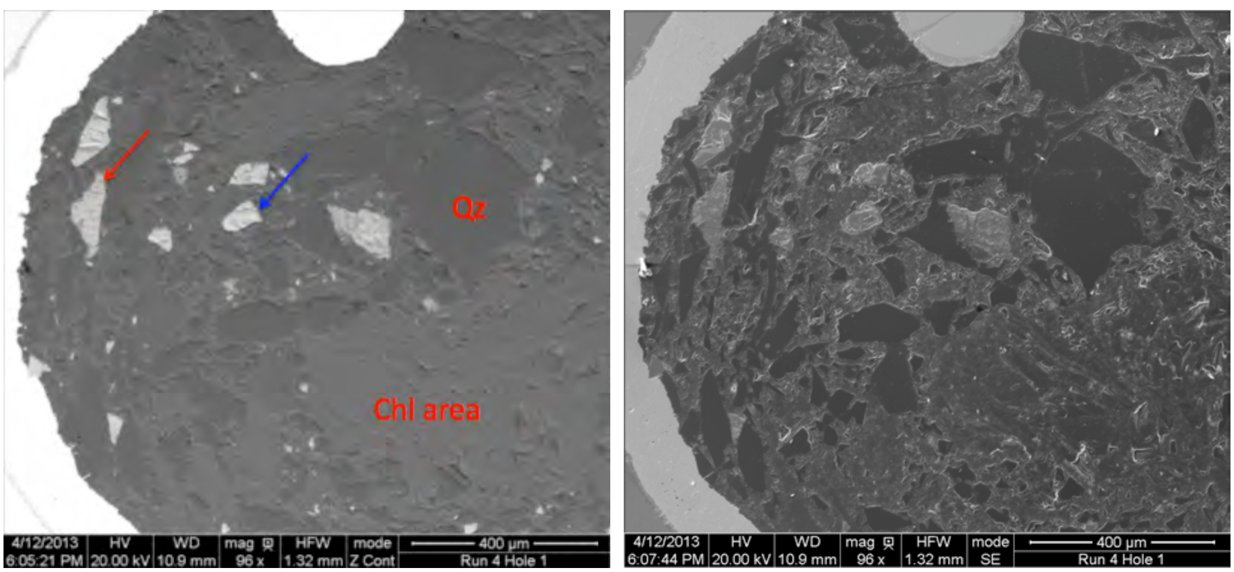


Figure 7 Various minerals found within the experiments. The image on the left is BSED, and the image on the right is ETD of experiment 4 (610˚C, 8kbar, 7 days and 23 hours), hole 1 (chlorite + quartz). For all experiments, quartz is angular and dark grey in BSED as shown here. Chlorite is lighter grey than quartz and difficult to measure a crystal size. The red arrow points to an iron titanium oxide, and the blue arrow points to an iron oxide. For all experiments, iron and titanium oxides are bright in BSED.

	Average Chlorite Wt%
MgO	23.8
Al_2O_3	30.8
SiO_2	30.8
FeO	14.7

Table 12 Average weight percent of each oxide in the chlorite in experiment 4 (610˚C, 7 days and 23 hours), hole 1 (chlorite + quartz). The average formula for this chlorite is $Mg_{3.03}Fe_{1.05}Si_{2.63}Al_{3.10}O_{10}(OH)_8$

Hole 2 (Chl+Qz+water)

Chlorite, quartz, and water (2µL) were mixed together for hole 2 of experiment 4. Angular quartz crystals are found in this sample (Figure 8). Quartz crystals have an average maximum width of 177µm and an average minimum width of 112µm (Table 10). This size is smaller than the average quartz crystal size in the starting material (maximum: 247µm, minimum: 90µm) (Table 9), therefore this wet sample did not experience grain coarsening.

Chlorite is the most abundant (~50%) followed by quartz (~40%), iron and titanium oxides (~9%), and margarite (~1%) (Figure 8). Minerals of the same kind are more evenly dispersed through out hole 2 than they were in hole 1 (Figures 6 and 8). The chemical formula of chlorite in experiment 4, hole 2 is presented in Table 13.

Garnet nucleation did not occur for experiment 4, hole 2.

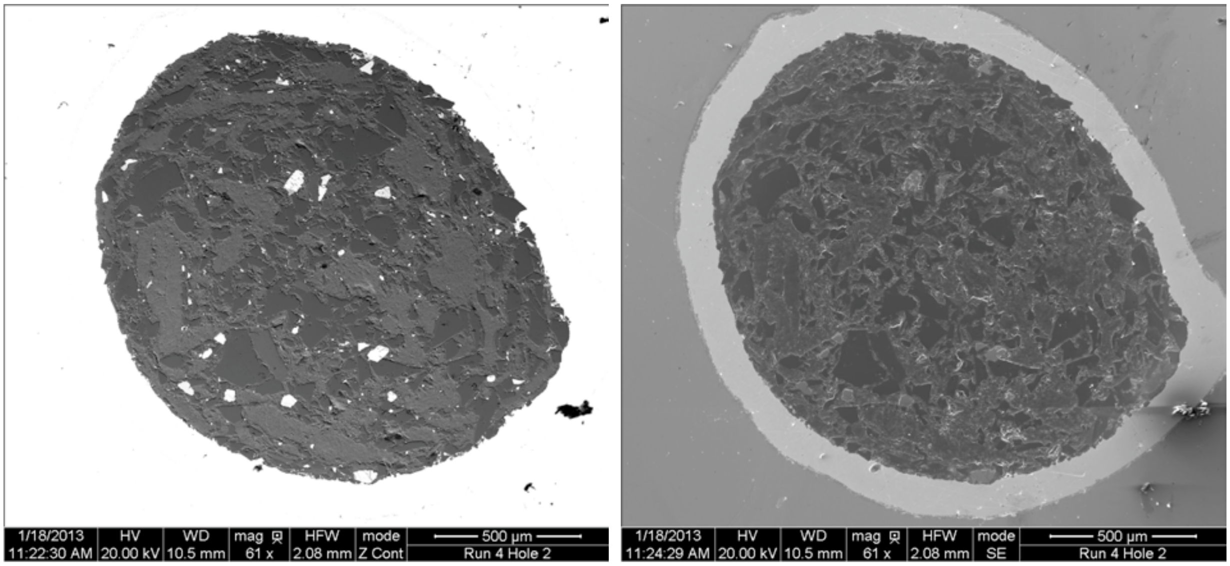


Figure 8 Experiment 4 (610˚C, 7 days and 23 hours) hole 2 (chlorite + quartz + water). The image on the left is BSED and the image on the right is ETD. Quartz crystals are angular, dark grey in BSED. Chlorite crystals are lighter grey in BSED and most abundant. Iron oxides and iron titanium oxides are the brightest crystals in BSED.

	Average Chlorite Wt%
MgO	24.2
Al_2O_3	29.9
SiO_2	31.7
FeO	14.1

Table 13 Average weight percent of each oxide in the chlorite in experiment 4 (610˚C, 7 days and 23 hours), hole 2 (chlorite + quartz + water). The average formula for this chlorite is $Mg_{3.07}Fe_{1.01}Si_{2.71}Al_{3.00}O_{10}(OH)_2$

Hole 3 (Chl+Qz+Grt)

Chlorite, quartz, and garnet (MAK-98) were mixed together for hole 3 of experiment 4. Angular quartz crystals are found in this sample (Figure 9a). Quartz crystals have an average maximum width of 129μm and an average minimum width of 46μm (Table 10). This size is smaller than the average quartz crystal size in the starting material (maximum: 247μm, minimum: 90μm) (Table 9), therefore the quartz grains of this dry sample did not undergo grain coarsening.

Chlorite is the most abundant (~70%) followed by quartz (~15%), iron and titanium oxides (~9%), garnet (~5%), and margarite (~1%). Minerals of the same kind are evenly dispersed through out the hole (Figure 9a). The chemical formula of chlorite and garnet (MAK-98) in experiment 4, hole 3 are presented in Table 14.

Garnet crystals in experiment 4, hole 3 did not experience overgrowth. Garnet nucleation did not occur for experiment 4, hole 3.

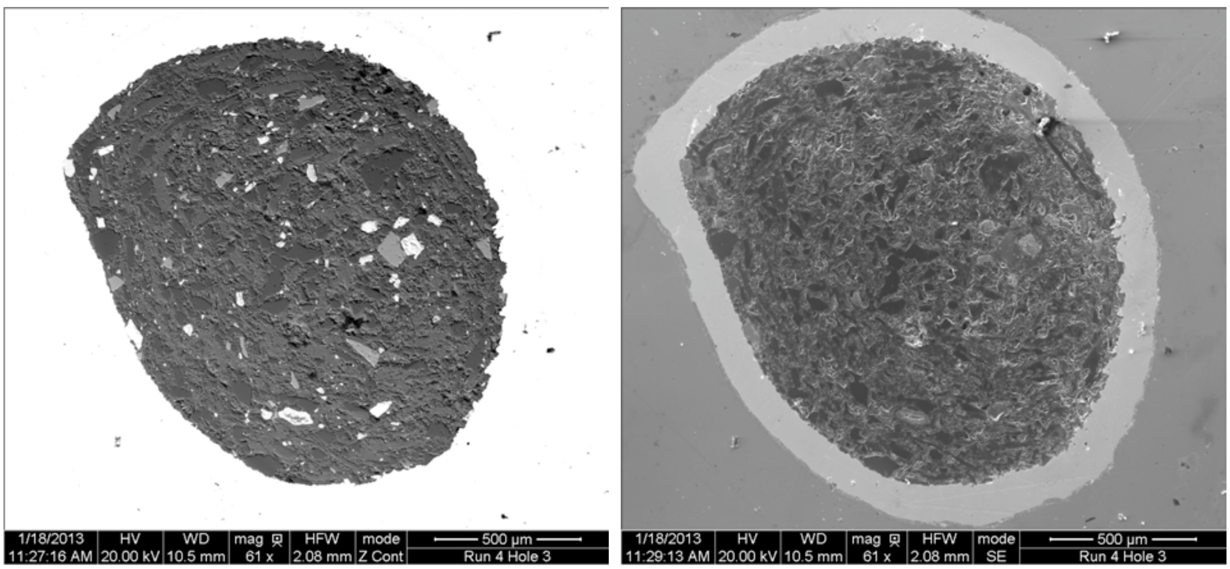


Figure 9a Experiment 4 (610˚C, 7 days and 23 hours) hole 3 (chlorite + quartz + garnet). The image on the left is BSED and the image on the right is ETD. Quartz crystals are angular, dark grey in BSED. Chlorite crystals are lighter grey in BSED and most abundant. The lightest grey crystals are garnet (MAK-98). Iron oxides and iron titanium oxides are the brightest crystals in BSED.

	Average Wt%	
	Chlorite	**Garnet**
MgO	24.6	6.81
Al_2O_3	29.5	22.9
SiO_2	31.9	38.8
CaO	0	0.937
MnO	0	1.14
FeO	14.0	29.5

Table 14 Average weight percent of each oxide in the chlorite and garnet in experiment 4 (610˚C, 7 days and 23 hours), hole 3 (chlorite + quartz + garnet). The average formula for chlorite is $Mg_{3.12}Fe_{1.00}Si_{2.72}Al_{2.96}O_{10}(OH)_8$. The average formula for garnet is $Fe_{1.91}Mg_{0.79}Ca_{0.08}Mn_{0.08}Al_{2.09}Si_{3.01}O_{12}$.

Hole 4 (Chl+Qz+Grt+water)

Chlorite, quartz, garnet (MAK-98), and water (2μL) were mixed together for hole 4 of experiment 4. Angular quartz crystals are found in this sample (Figure 9b). Quartz crystals have an average maximum width of 196μm and an average minimum width of 45μm (Table 10). This size is smaller than the average quartz crystal size in the starting material (maximum: 247μm, minimum: 90μm) (Table 9), therefore the quartz grains of this wet sample did not undergo grain coarsening.

Chlorite is the most abundant (~70%) followed by quartz (~15%), iron and titanium oxides (~9%), garnet (~5%), and margarite (~1%). Minerals of the same kind are evenly dispersed through out the hole (Figure 9b). The chemical formula of chlorite and garnet (MAK-98) in experiment 4, hole 4 are presented in Table 15.

Garnet crystals in experiment 4, hole 4 did not experience overgrowth. Garnet nucleation did not occur for experiment 4, hole 4.

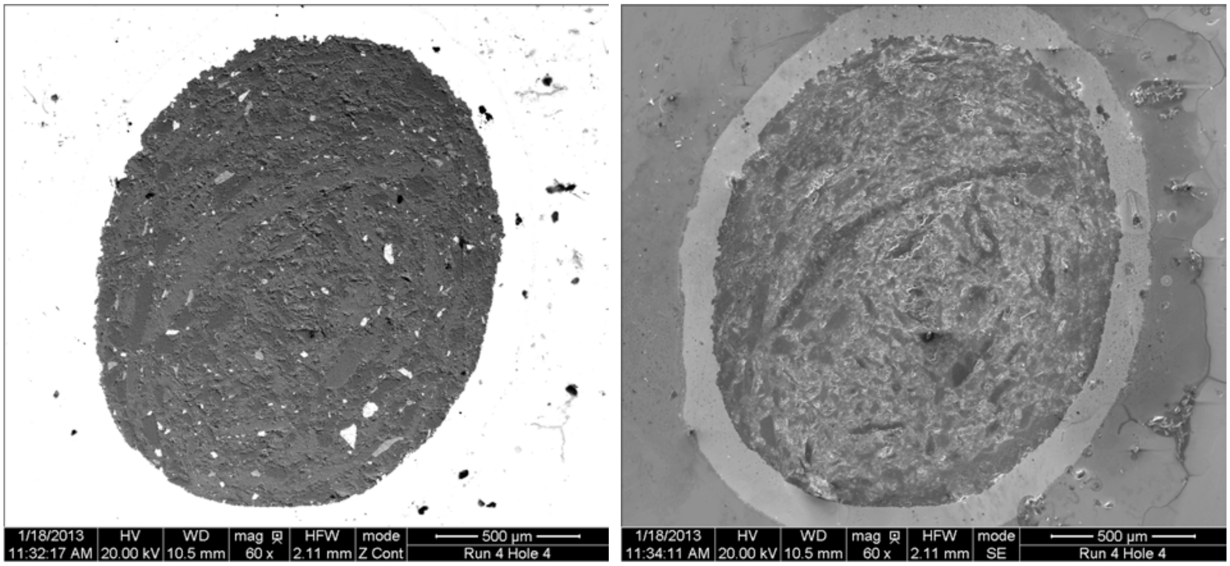


Figure 9b Experiment 4 (610˚C, 7 days and 23 hours) hole 4 (chlorite + quartz + garnet + water). The image on the left is BSED and the image on the right is ETD. Quartz crystals are angular, dark grey in BSED. Chlorite crystals are lighter grey in BSED and most abundant. The lightest grey crystals are garnet (MAK-98). Iron oxides and iron titanium oxides are the brightest crystals in BSED.

	Average Wt%	
	Chlorite	**Garnet**
MgO	24.2	6.55
Al_2O_3	29.8	22.7
SiO_2	31.9	38.9
CaO	0	0.983
MnO	0	1.37
FeO	14.1	29.5

Table 15 Average weight percent of each oxide in the chlorite and garnet in experiment 4 (610˚C, 7 days and 23 hours), hole 4 (chlorite + quartz + garnet + water). The average formula for chlorite is $Mg_{2.72}Fe_{1.01}Si_{2.72}Al_{2.99}O_{10}(OH)_8$. The average formula for garnet is $Fe_{1.92}Mg_{0.76}Ca_{0.08}Mn_{0.09}Al_{2.08}Si_{3.02}O_{12}$.

Experiments 5-8

Chlorite is not found in any of the holes in experiments 5-8. Instead, there is gedrite and cordierite. Chlorite and quartz form cordierite and gedrite via the following reaction:

$$20(Mg_{4.5}Al_3Si_{2.5}O_{10}(OH)_8) + 79SiO_2 \leftrightarrow 9(Mg_2Al_4Si_5O_{18}) + 12(Mg_6Al_2Si_7O_{22}(OH)_2) + 68H_2O$$

Gedrite crystals are thin rods that are closely packed and overlapping, therefore a crystal size is usually unable to be obtained. Cordierite crystals have highly irregular shapes and do not have distinct crystal facies. Many of the garnet crystals in experiments 5-8 have garnet rims (Figure 10).

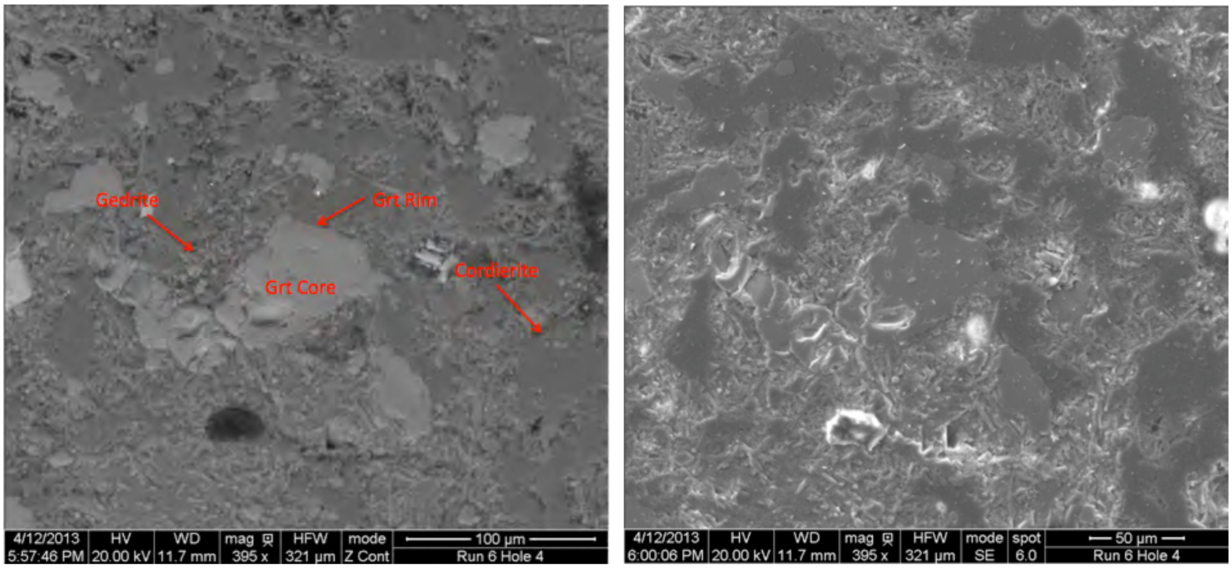


Figure 10 Various minerals found in experiments 5-8. The image on the left is BSED, and the image on the right is ETD. Gedrite and cordierite are labeled as well as a garnet core and a garnet rim.

Experiment 5 *(650˚C, 8kbar, 6 days and 22 hours)*

A dry and a wet sample of both chlorite + quartz and chlorite + quartz + garnet were prepared. These samples were run at 650˚C, 8kbar for 6 days and 22 hours (Figure 11). Angular iron oxide crystals and iron titanium oxide crystals are found in all holes. No margarite is found in holes 1-4 of experiment 5.

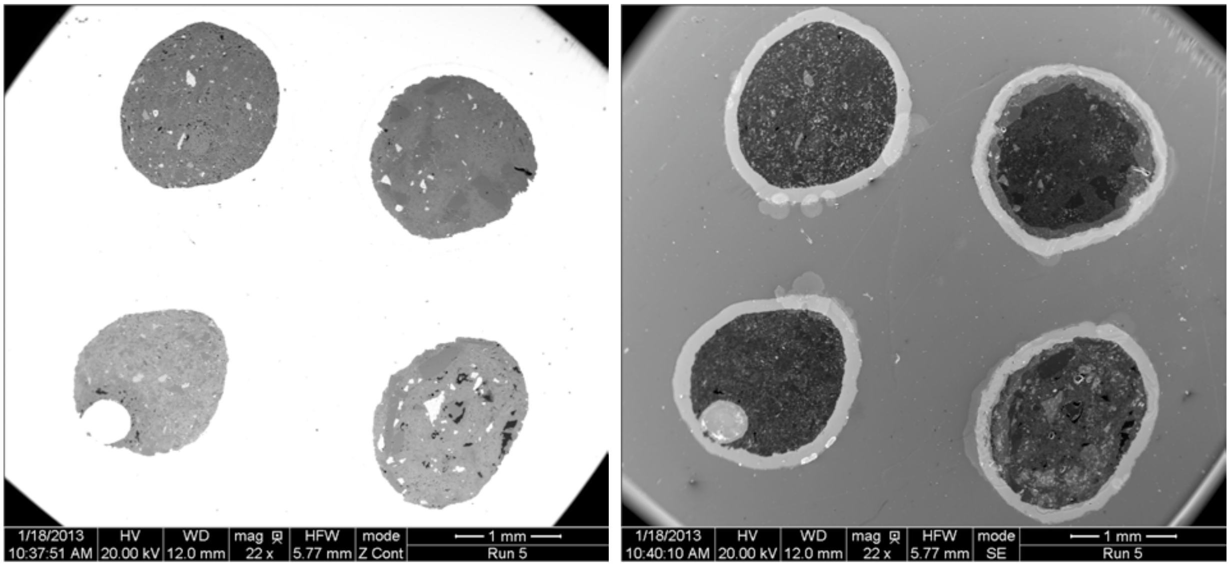


Figure 11 Experiment 5 (650˚C, 8kbar, 6 days and 22 hours). The image on the left is BSED and the image on the right is ETD. Hole 1 (chlorite + quartz) is the bottom right. Hole 2 (chlorite + quartz + water) is the top right. Hole 3 (chlorite + quartz + garnet) is the top left. Hole 4 (chlorite + quartz + garnet + water) is the bottom left.

Hole 1 (Chl+Qz)

Chlorite and quartz were mixed together for hole 1 of experiment 5. Large, angular quartz crystals are found in this sample (Figure 12). Quartz crystals have an average maximum width of 404μm and an average minimum width of 72μm (Table 10). This size is larger than the average quartz crystal size in the starting material (maximum: 247μm, minimum: 90μm) (Table 9), therefore these quartz grains experienced grain coarsening.

Cordierite crystals have an average maximum width of 84μm and an average minimum width of 21μm. Gedrite crystals have an average maximum width of 9μm and an average minimum width of 1μm. The error for the width measurements of the gendrite crystals is high because the crystals are thin rods that are overlapping and difficult to measure (Figure 10).

Gedrite is the most abundant (~65%) followed by iron and titanium oxides (~15%), cordierite (~10%), and iron and quartz (~10%). Minerals of the same kind are clustered together, especially quartz and gedrite (Figure 12). The chemical formulas of the cordierite and gedrite in experiment 5, hole 1 are presented in Table 16.

Garnet nucleation did not occur for experiment 5, hole 1.

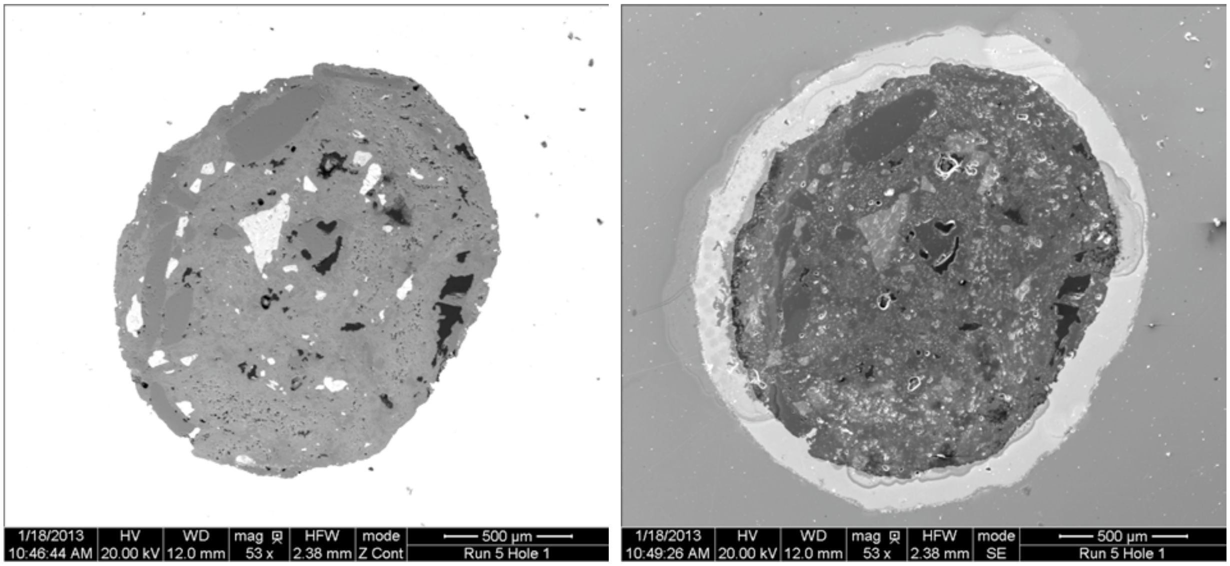


Figure 12 Experiment 5 (650˚C, 8kbar, 6 days and 22 hours) hole 1 (chlorite + quartz). The image on the left is BSED and the image on the right is ETD. Quartz crystals are angular, dark grey in BSED. Cordierite crystals are the same shade of grey as quartz and contain inclusions (Figure 10). Gedrite crystals are lighter grey in BSED. Iron oxides and iron titanium oxides are the brightest crystals in BSED.

	Average Wt%	
	Cordierite	**Gedrite**
MgO	11.9	16.2
Al_2O_3	34.0	18.5
SiO_2	48.5	53.0
CaO	0.747	1.06
FeO	4.68	11.0

Table 16 Average weight % for cordierite and gedrite in experiment 5 (650˚C, 8kbar, 6 days and 22 hours), hole 1 (chlorite + quartz). The average chemical formula of cordierite is $Fe_{0.39}Mg_{1.78}Ca_{0.08}Al_3(Si_{4.86}Al_{1.01}O_{18})$. The average chemical formula of gedrite is $Fe_{1.22}Mg_{3.21}Ca_{0.15}Al_{2.89}Si_{7.03}O_{22}(OH)_2$.

Hole 2 (Chl+Qz+water)

Chlorite, quartz, and water (2µL) were mixed together for hole 2 of experiment 5. Large angular quartz crystals are found in this sample (Figure 13). Quartz crystals have an average maximum width of 195μm and an average minimum width of 57μm (Table 10). Although this average size is smaller than the average quartz crystal size in the starting material (maximum: 247μm, minimum: 90μm), there are some quartz crystals in experiment 5, hole 2 that are considerably larger than the average in the starting material (Table 9). For example, one quartz crystal in hole 2 had a maximum width of 386μm and a minimum width of 114μm, therefore this wet sample experienced grain coarsening.

Cordierite crystals have an average maximum width of 124μm and an average minimum width of 43μm. These crystal sizes are larger than the cordierite crystal sizes found in experiment 5 hole 1 (maximum: 84μm, minimum: 21μm) (Table 10). This evidence indicates that the addition of water increases cordierite growth.

Gedrite crystals have an average maximum width of 9μm and an average minimum width of 1μm. The error for the width measurements of the gendrite crystals is high because the crystals are thin rods that are overlapping and difficult to measure (Figure 10).

Gedrite is the most abundant (~70%) followed by iron and titanium oxides (~15%), quartz (~10%), and cordierite (~5%). Minerals of the same kind are clustered together, especially gedrite and quartz (Figure 13). The chemical formulas of cordierite and gedrite are presented in Table 17.

Garnet nucleation did not occur for experiment 5, hole 2.

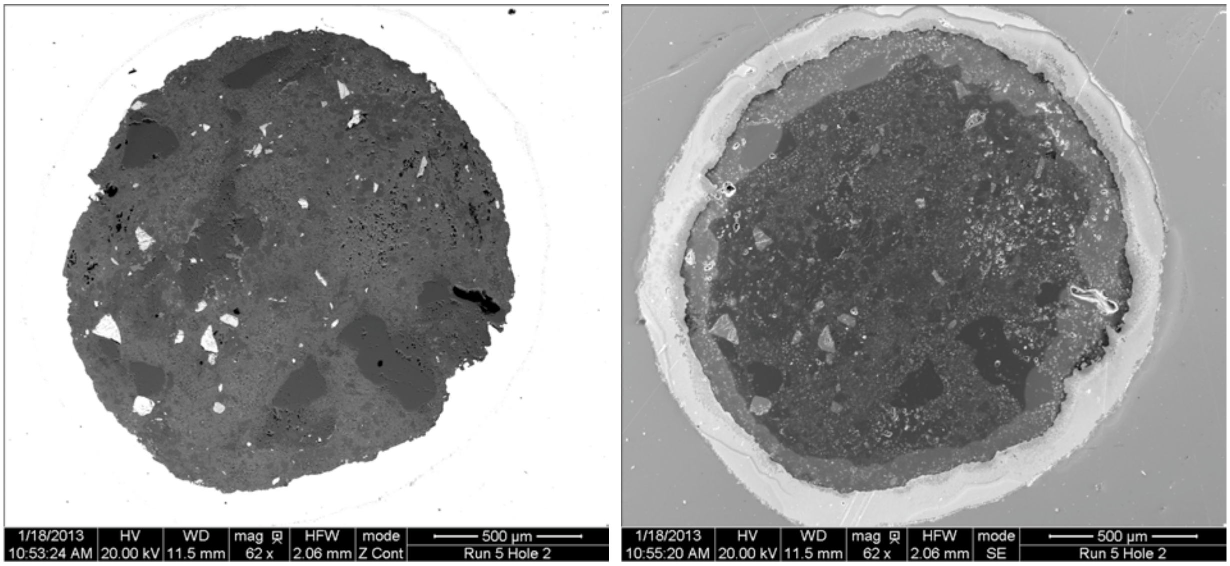


Figure 13 Experiment 5 (650˚C, 8kbar, 6 days and 22 hours) hole 2 (chlorite + quartz + water). The image on the left is BSED and the image on the right is ETD. Quartz crystals are angular, dark grey in BSED. Cordierite crystals are the same shade of grey as quartz and contain inclusions (Figure 10). Gendrite crystals are lighter grey in BSED and most abundant. Iron oxides and iron titanium oxides are the brightest crystals in BSED. The cloudy ring around the ETD image has to do with the carbon coating on the sample and is not related to the contents of the sample.

	Average Wt%	
	Cordierite	**Gedrite**
MgO	11.6	17.6
Al_2O_3	32.4	16.9
SiO_2	51.1	53.3
CaO	0.610	1.03
FeO	4.08	10.8

Table 17 Average weight % for cordierite and gedrite in experiment 5 (650˚C, 8kbar, 6 days and 22 hours), hole 2 (chlorite + quartz + water). The average chemical formula of cordierite is $Fe_{0.34}Mg_{1.72}Ca_{0.07}Al_3(Si_{5.08}Al_{0.80}O_{18})$. The average chemical formula of gedrite is $Fe_{1.20}Mg_{3.48}Ca_{0.15}Al_{2.65}Si_{7.08}O_{22}(OH)_2$.

Hole 3 (Chl+Qz+Grt)

Chlorite, quartz, and garnet (MAK-98) were mixed together for hole 3 of experiment 5. Angular quartz crystals are found in this sample (Figure 14). Quartz crystals have an average maximum width of 120μm and an average minimum width of 30μm (Table 10). This size is smaller than the average quartz crystal size in the starting material (maximum:

247μm, minimum: 90μm) (Table 9), therefore the quartz grains of this dry sample did not undergo grain coarsening.

Cordierite crystals have an average maximum width of 136μm and an average minimum width of 37μm. Gedrite is the most abundant (~60%) followed by cordierite (~20%), quartz (~10%), iron and titanium oxides (~5%), and garnet (~5%). Minerals of the same kind are evenly dispersed through out the hole (Figure 14). The chemical formulas of cordierite and garnet (MAK-98) are presented in Table 18.

Garnet crystals in experiment 5, hole 3 did not experience overgrowth. Garnet nucleation did not occur for experiment 5, hole 3.

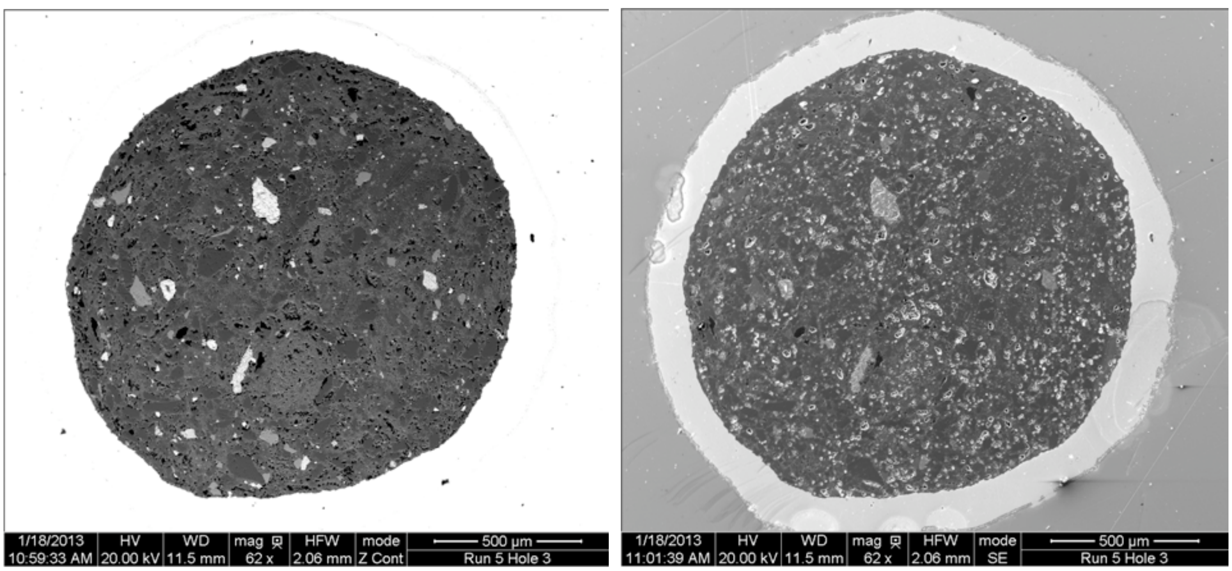


Figure 14 Experiment 5 (650˚C, 8kbar, 6 days and 22 hours) hole 3 (chlorite + quartz + garnet). The image on the left is BSED and the image on the right is ETD. Quartz crystals are angular, dark grey in BSED. Cordierite crystals are the same shade of grey as quartz and contain inclusions (Figure 10). Gedrite crystals are lighter grey in BSED and most abundant. The lightest grey crystals are garnet. Iron oxides and iron titanium oxides are the brightest crystals in BSED.

	Average Wt%		
	Cordierite	**Garnet**	**Gedrite**
MgO	11.1	6.78	15.2
Al_2O_3	33.8	23.3	16.6
SiO_2	48.5	40.6	54.2
CaO	0.920	1.04	1.43
MnO	0	1.33	0
FeO	5.46	27.0	12.1

Table 18 Average weight % for cordierite, garnet and gedrite in experiment 5 (650˚C, 8kbar, 6 days and 22 hours), hole 3 (chlorite + quartz + garnet). The average chemical formula of cordierite is $Fe_{0.46}Mg_{1.66}Ca_{0.10}Al_3(Si_{4.88}Al_{1.00}O_{18})$. The average chemical formula of garnet is $Fe_{2.59}Mg_{1.16}Ca_{0.13}Mn_{0.13}Al_{3.14}Si_{4.64}O_{12}$. The average chemical formula of gedrite is $Fe_{1.35}Mg_{3.03}Ca_{0.20}Al_{2.61}Si_{7.23}O_{22}(OH)_2$.

Hole 4 (Chl+Qz+Grt+water)

Chlorite, quartz, garnet (MAK-98), and water (2µL) were mixed together for hole 4 of experiment 5. Angular quartz crystals are found in this sample (Figure 15). Quartz crystals have an average maximum width of 106µm and an average minimum width of 46µm (Table 10). This size is smaller than the average quartz crystal size in the starting material (maximum: 247µm, minimum: 90µm) (Table 9), therefore the quartz grains of this wet sample did not undergo grain coarsening.

Cordierite crystals have an average maximum width of 139µm and an average minimum width of 89µm. These crystal sizes are larger than the cordierite crystal sizes found in experiment 5 hole 1 (maximum: 84µm, minimum: 21µm) (Table 10). This evidence indicates that the addition of garnet and or water to a sample increases cordierite growth.

Gedrite is the most abundant (~59%) followed by cordierite (~20%), quartz (~10%), garnet (~9%), and iron and titanium oxides (~2%). Minerals of the same kind are evenly dispersed through out the hole (Figure 15). The chemical formulas of cordierite and garnet (MAK-98) are presented in Table 19.

Garnet crystals in experiment 5, hole 4 did not experience overgrowth. Garnet nucleation did not occur for experiment 5, hole 4.

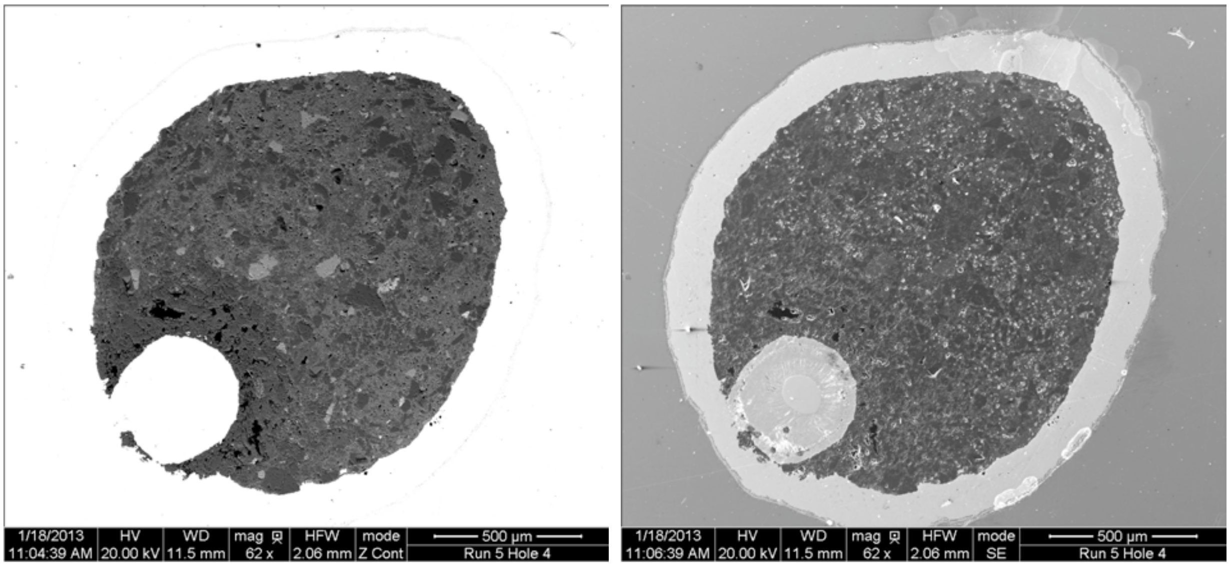


Figure 15 Experiment 5 (650˚C, 8kbar, 6 days 22 hours) hole 4 (chlorite + quartz + garnet + water). The image on the left is BSED and the image on the right is ETD. Quartz crystals are angular, dark grey in BSED. Cordierite crystals are the same shade of grey as quartz and contain inclusions (Figure 10). Gedrite crystals are lighter grey in BSED and most abundant. The lightest grey crystals are garnet. Iron oxides and iron titanium oxides are the brightest crystals in BSED. The bright circle is a wire used to identify the hole.

	Average Wt%		
	Cordierite	**Garnet**	**Gedrite**
MgO	10.0	6.60	16.7
Al_2O_3	32.6	23.3	20.9
SiO_2	51.1	40.7	49.2
CaO	0.853	1.02	1.02
MnO	0	1.27	0
FeO	5.23	27.1	11.8

Table 19 Average weight % for cordierite, garnet and gedrite in experiment 5 (650˚C, 8kbar, 6 days and 22 hours), hole 4 (chlorite + quartz + garnet + water). The average chemical formula of cordierite is $Fe_{0.44}Mg_{1.49}Ca_{0.09}Al_3(Si_{5.10}Al_{0.84}O_{18})$. The average chemical formula of garnet is $Fe_{2.59}Mg_{1.13}Ca_{0.13}Mn_{0.12}Al_{3.14}Si_{4.66}O_{12}$. The average chemical formula of gedrite is $Fe_{1.33}Mg_{3.33}Ca_{0.15}Al_{3.31}Si_{6.60}O_{22}(OH)_2$.

***Experiment 6** (750˚C, 8kbar, 10 days and 20 hours)*

A dry and a wet sample of chlorite + quartz mixture were prepared. A chlorite + quartz + garnet and a chlorite + quartz + muscovite + biotite + garnet sample were prepared. These samples were run at 750˚C and 8kbar for 10 days and 20 hours. Angular iron oxide crystals and iron titanium oxide crystals are found in all holes. No margarite is found in holes 1-4 of experiment 6 (Figure 16).

Garnet overgrowth occurred in holes 3 and 4 of experiment 6. These overgrowth rims are magnesium rich. A potassium melt formed in experiment 6 hole 4, but it is not discussed extensively in this paper.

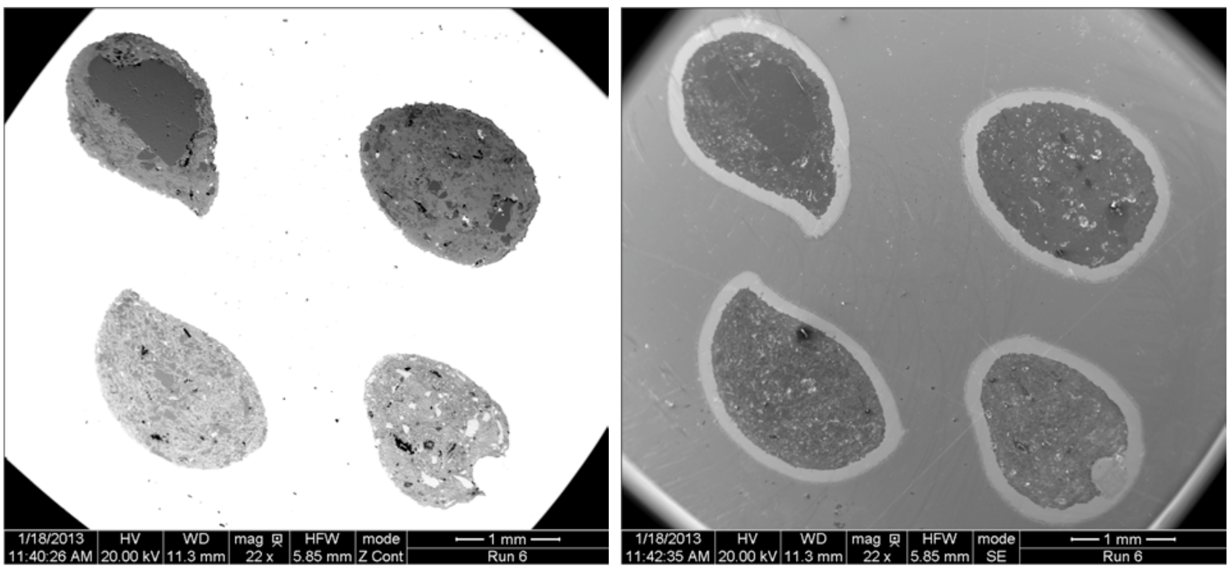


Figure 16 Experiment 6 (750˚C, 10 days and 20 hours). The image on the left is BSED and the image on the right is ETD. Hole 1 (chlorite + quartz) is the top right. Hole 2 (chlorite + quartz + water) is the top left. Hole 3 (chlorite + quartz + garnet) is the bottom left. Hole 4 (chlorite + quartz + biotite + muscovite + garnet) is the bottom right.

Hole 1 (Chl+Qz)

Chlorite and quartz were mixed together for hole 1 of experiment 6. Angular quartz crystals are found in this sample (Figure 17). Quartz crystals have an average maximum width of 185μm and an average minimum width of 46μm (Table 10). Although this average is smaller than the average quartz crystal size in the starting material (maximum: 247μm, minimum: 90μm), there is a quartz crystal in hole 1 with a maximum width of

324μm and a minimum width of 77μm, therefore this dry sample experienced grain coarsening (Table 9).

Cordierite crystals have an average maximum width of 45μm and an average minimum width of 25μm. These crystal sizes are smaller than the cordierite crystal sizes found in experiment 5 hole 1 (maximum: 84μm, minimum: 21μm). Since there are many cordierite crystals throughout the sample, and these crystals are smaller than those in the shorter experiment at lower temperature, this evidence indicates that increase in temperature and duration of the experiment increases nucleation rate of cordierite.

Gedrite is the most abundant (~63%) followed by cordierite (~30%) quartz (~5%), and iron and titanium oxides (~2%). Quartz crystals are clustered together, but other minerals of the same kind are evenly dispersed through out the hole (Figure 17). The chemical formulas of cordierite and gedrite are presented in Table 20.

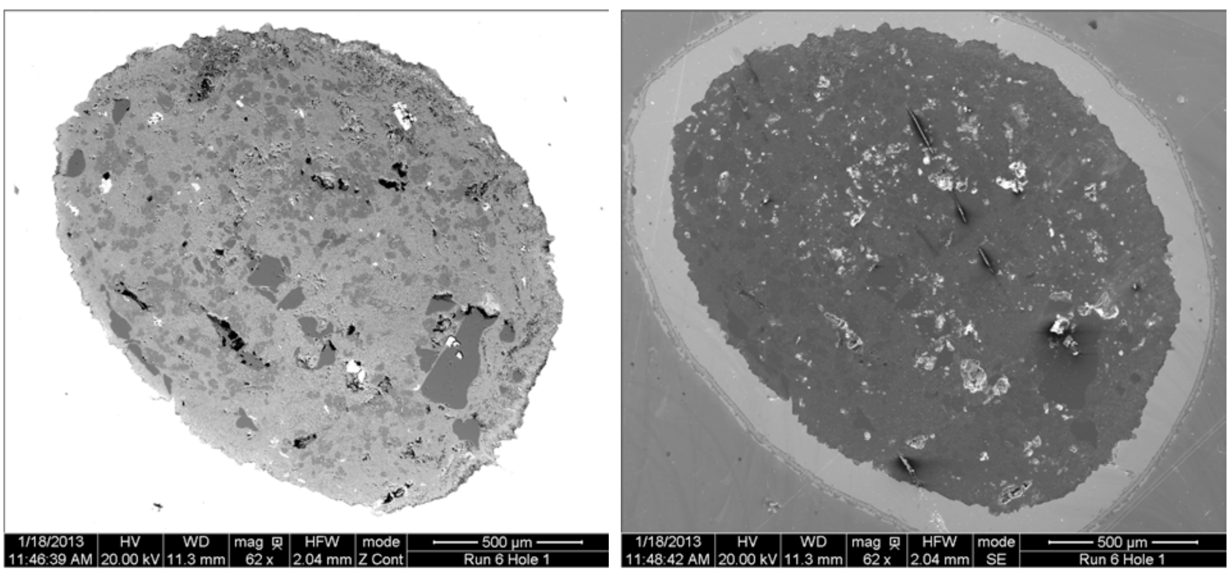


Figure 17 Experiment 6 (750˚C, 8kbar, 10 days and 20 hours) hole 1 (chlorite + quartz). The image on the left is BSED and the image on the right is ETD. Quartz crystals are angular, dark grey in BSED. Cordierite crystals are a slightly lighter shade of grey than the quartz and contain inclusions (Figure 10). Gedrite crystals are lighter grey in BSED. Iron oxides and iron titanium oxides are the brightest crystals in BSED.

	Average Wt%	
	Cordierite	**Gedrite**
MgO	10.6	13.1
Al_2O_3	35.2	18.3
SiO_2	47.5	50.9
CaO	1.08	1.65
FeO	5.48	15.8

Table 20 Average weight % for cordierite and gedrite in experiment 6 (750˚C, 8kbar, 10 days and 20 hours), hole 1 (chlorite + quartz). The average chemical formula of cordierite is $Fe_{0.46}Mg_{1.59}Ca_{1.08}Al_{3.00}(Si_{4.78}Al_{1.17}O_{18})$. The average chemical formula of gedrite is $Fe_{1.80}Mg_{2.66}Ca_{0.24}Al_{2.93}Si_{6.94}O_{22}(OH)_2$.

Hole 2 (Chl+Qz+water)

Chlorite, quartz, and water (2µL) were mixed together for hole 2 of experiment 6. Large angular quartz crystals are found in this sample (Figure 18). Quartz crystals have an average maximum width of 555µm and an average minimum width of 102µm (Table 10). One exceptionally large quartz crystal has a maximum width of 1368µm and a minimum width of 181µm (Figure 18). The quartz crystals in experiment 6 hole 2 are much larger than those in the starting material (maximum: 247µm, minimum: 90µm), therefore this wet sample experienced grain coarsening (Table 9).

Cordierite crystals have an average maximum width of 63µm and an average minimum width of 18µm (Table 10). These crystal sizes are larger than the cordierite crystal sizes found in experiment 6 hole 1 (maximum: 45.0µm, minimum: 24.9µm). This evidence indicates that the addition of water increases cordierite growth. The cordierite crystals are smaller than those found in experiment 5 hole 2 (maximum: 124µm, minimum: 43µm). This evidence indicates that in increase in temperature and duration of the experiment increases cordierite nucleation rate.

Gedrite (~45%) and quartz (~45%) are the most abundant followed by cordierite (~8%), and iron and titanium oxides (~2%). Minerals of the same kind are clustered together, especially gedrite and quartz (Figure 18). The chemical formulas of cordierite and gedrite are presented in Table 21.

Garnet nucleation did not occur for experiment 6, hole 2.

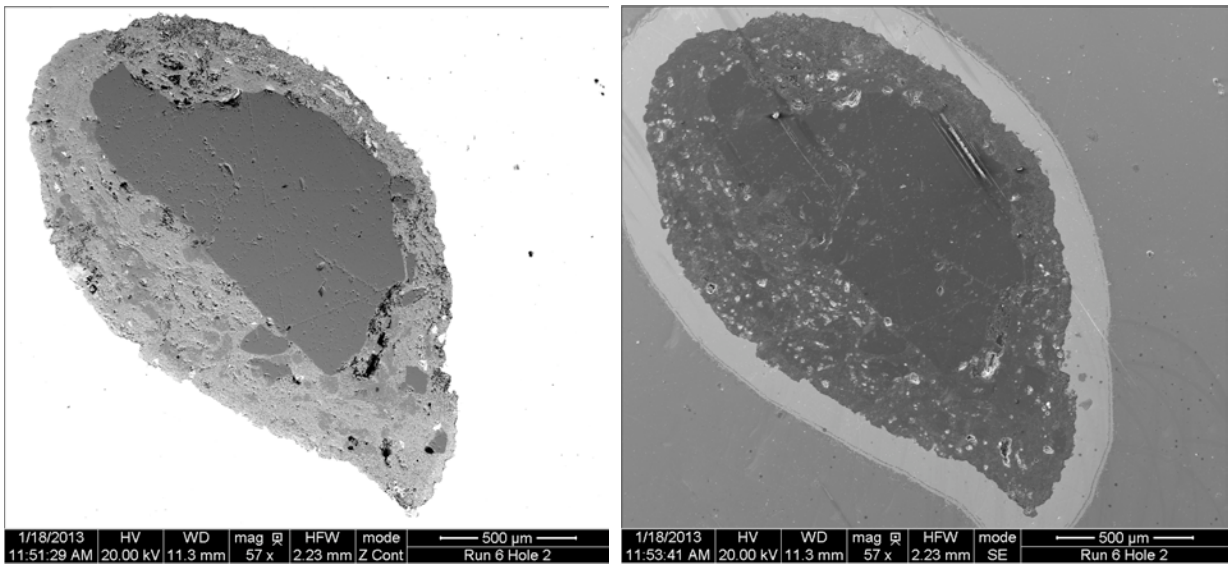


Figure 18 Experiment 6 (750˚C, 8kbar, 10 days and 20 hours) hole 2 (chlorite + quartz + water). The image on the left is BSED and the image on the right is ETD. Quartz crystals are angular, dark grey in BSED. Cordierite crystals are the same shade of grey as quartz and contain inclusions (Figure 10). Gendrite crystals are lighter grey in BSED and most abundant. Iron oxides and iron titanium oxides are the brightest crystals in BSED.

	Average Wt%	
	Cordierite	**Gedrite**
MgO	10.4	15.3
Al_2O_3	33.6	19.1
SiO_2	49.8	50.1
CaO	0.630	1.28
FeO	5.48	13.9

Table 21 Average weight % for cordierite and gedrite in experiment 6 (750˚C, 8kbar, 10 days and 20 hours), hole 2 (chlorite + quartz + water). The average chemical formula of cordierite is $Fe_{0.46}Mg_{1.55}Ca_{0.63}Al_{3.00}(Si_{4.99}Al_{0.96}O_{18})$. The average chemical formula of gedrite is $Fe_{1.57}Mg_{3.08}Ca_{0.19}Al_{3.05}Si_{6.77}O_{22}(OH)_2$.

Hole 3 (Chl+Qz+Grt)

Chlorite, quartz, and garnet (MAK-98) were mixed together for hole 3 of experiment 6. Angular quartz crystals are found in this sample (Figure 19). Quartz crystals have an average maximum width of 63μm and an average minimum width of 25μm (Table 10). This size is smaller than the average quartz crystal size in the starting material (maximum: 247μm, minimum: 90μm) (Table 9), therefore the quartz grains of this dry sample did not undergo grain coarsening.

Cordierite crystals have an average maximum width of 33μm and an average minimum width of 13μm. These crystal sizes are smaller than those found in experiment 5 hole 3 (maximum: 136μm, minimum: 37μm) (Table 10). This evidence indicates that between 650˚C and 750˚C there is a point at which increase in temperature no longer increases cordierite growth.

Garnet crystals with no rim have an average maximum width of 29μm and an average minimum width of 10μm (Table 10). Garnet cores (garnet crystals with rims) have an average maximum width of 19μm and an average minimum width of 7μm. Garnet rims have an average maximum width of 3μm and an average minimum width of 0.31μm (Table 11).

Gedrite is the most abundant (~70%) followed by quartz (~10%), cordierite (~10%), iron and titanium oxides (~5%), and garnet (~5%). Minerals of the same kind are evenly dispersed through out the hole (Figure 19). The chemical formulas of cordierite, gedrite, and all forms of garnet are presented in Table 22.

Garnet nucleation did not occur for experiment 6, hole 3.

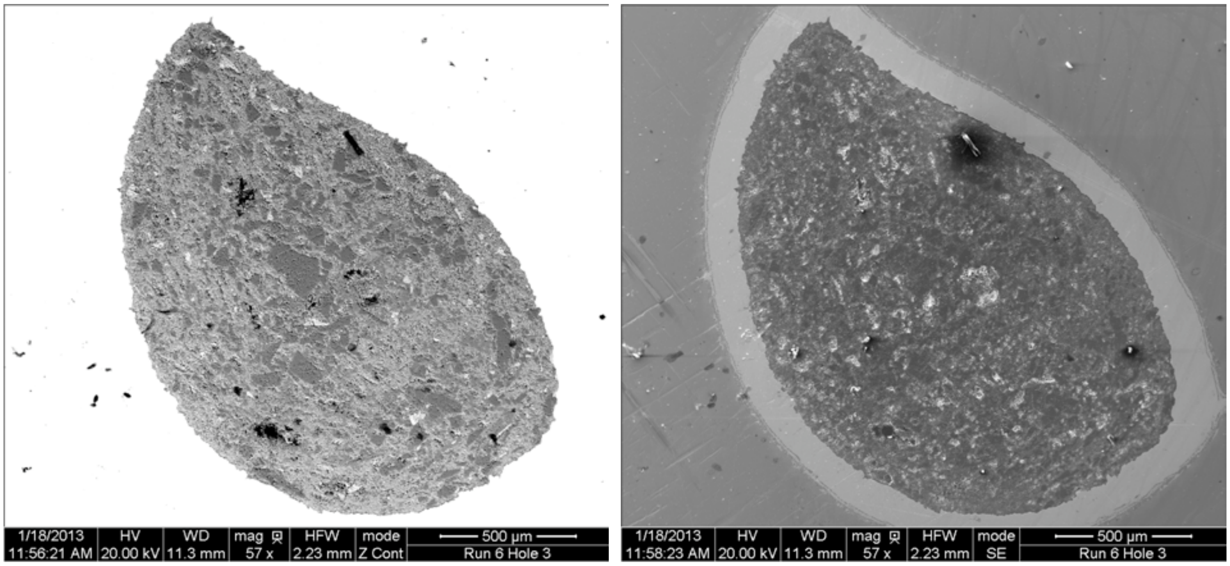


Figure 19 Experiment 6 (750˚C, 8kbar, 10 days and 20 hours) hole 3 (chlorite + quartz + garnet). The image on the left is BSED and the image on the right is ETD. Quartz crystals are angular, dark grey in BSED. Cordierite crystals are the same shade of grey as quartz and contain inclusions (Figure 10). Gedrite crystals are lighter grey in BSED and most abundant. The lightest grey crystals are garnet. Iron oxides and iron titanium oxides are the brightest crystals in BSED.

	Average Wt%				
	Cordierite	**Gedrite**	**Garnet**	**Grt Core**	**Grt Rim**
MgO	11.3	14.7	5.81	6.57	9.89
Al_2O_3	27.6	17.7	21.8	22.7	24.1
SiO_2	51.6	50.9	36.5	38.8	39.9
CaO	0.860	1.35	0.920	0.943	1.66
MnO	0	0	1.45	1.31	1.15
FeO	8.46	15.0	33.5	29.6	23.3

Table 22 Average weight % for cordierite, gedrite, and all forms of garnet in experiment 6 (750˚C, 8kbar, 10 days and 20 hours), hole 3 (chlorite + quartz + garnet). The average chemical formula of cordierite is $Fe_{0.72}Mg_{1.72}Ca_{0.86}Al_{3.00}(Si_{5.25}Al_{0.30}O_{18})$. The average chemical formula of gedrite is $Fe_{1.70}Mg_{2.98}Ca_{0.20}Al_{2.83}Si_{6.92}O_{22}(OH)_2$. The average chemical formula of garnet is $Fe_{2.24}Mg_{0.69}Ca_{0.08}Mn_{0.10}Al_{2.05}Si_{2.91}O_{12}$. The average chemical formula of a garnet core is $Fe_{1.93}Mg_{0.76}Ca_{0.08}Mn_{0.09}Al_{2.08}Si_{3.02}O_{12}$. The average chemical formula of a garnet rim is $Fe_{1.47}Mg_{01.11}Ca_{0.13}Mn_{0.07}Al_{2.14}Si_{3.00}O_{12}$. The garnets without rims are more Fe rich.

Hole 4 (Chl+Qz+Mus+Bio+Grt)

Chlorite, quartz, muscovite, biotite, and garnet were mixed together for hole 4 of experiment 6. Few quartz crystals are in this sample, but there is silica in the melt. All quartz crystals are angular (Figure 20). Quartz crystals have an average maximum width of 185μm and an average minimum width of 47μm (Table 10). This size is smaller than the average quartz crystal size in the starting material (maximum: 247μm, minimum: 90μm) (Table 9), therefore the quartz grains of this dry sample did not undergo grain coarsening. Cordierite crystals have an average maximum width of 58μm and an average minimum width of 23μm (Table 10).

Garnet crystals with no rim have an average maximum width of 41μm and an average minimum width of 20μm. Garnet cores have an average maximum width of 89μm and an average minimum width of 26μm. Garnet rims have an average maximum width of 9μm and an average minimum width of 1.84μm (Table 11). This average rim width is larger than the average width of the rims in hole 3 (maximum: 3μm, minimum: 0.31μm). This evidence indicates that the presence of melt may promote garnet growth.

Gedrite is the most abundant (~50%) followed by melt (~20%), cordierite (~15%), quartz (~5%) iron and titanium oxides (~5%), and garnet (~5%). Minerals of the same kind are evenly dispersed through out the hole (Figure 20). The chemical formulas of cordierite, gedrite, and all forms of garnet are presented in Table 23.

Garnet nucleation did not occur for experiment 6, hole 4.

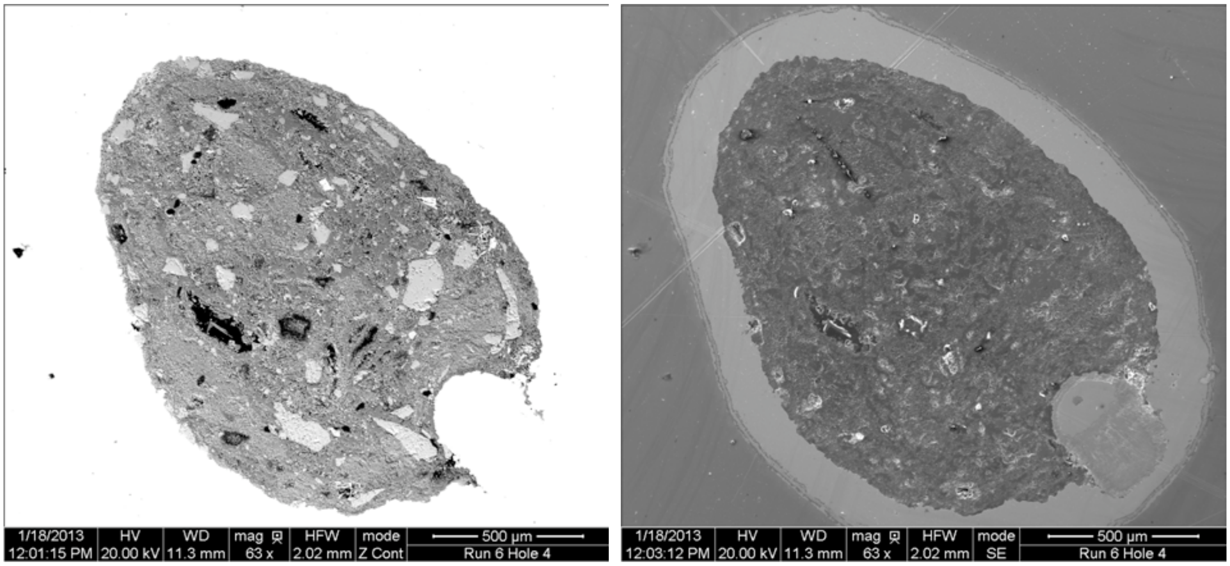


Figure 20 Experiment 6 (750˚C, 8kbar, 10 days and 20 hours) hole 4 (chlorite + quartz + muscovite + biotite + garnet). The image on the left is BSED and the image on the right is ETD. Quartz crystals are angular, dark grey in BSED. Cordierite crystals are the same shade of grey as quartz and contain inclusions (Figure 10). Gedrite crystals are lighter grey in BSED and most abundant. Melt is difficult to distinguish from gedrite. The lightest grey crystals are garnet. Iron oxides and iron titanium oxides are the brightest crystals in BSED.

	Average Wt%				
	Cordierite	**Gedrite**	**Garnet**	**Grt Core**	**Grt Rim**
MgO	9.50	16.2	5.87	5.99	9.15
Al_2O_3	38.1	19.9	22.2	22.2	22.7
SiO_2	44.0	46.8	37.2	37.2	38.2
CaO	0.640	0.970	0.870	0.840	2.75
MnO	0	0	1.43	1.34	0.947
FeO	7.54	15.8	32.4	32.5	26.3

Table 23 Average weight % for cordierite, gedrite, and all forms of garnet in experiment 6 (750˚C, 8kbar, 10 days and 20 hours), hole 4 (chlorite + quartz + muscovite + biotite + garnet). The average chemical formula of cordierite is $Fe_{0.64}Mg_{1.44}Ca_{0.07}Al_{3.00}(Si_{4.48}Al_{1.58}O_{18})$. The average chemical formula of gedrite is $Fe_{1.81}Mg_{3.32}Ca_{0.14}Al_{3.22}Si_{6.42}O_{22}(OH)_2$. The average chemical formula of garnet is $Fe_{2.14}Mg_{0.69}Ca_{0.07}Mn_{0.10}Al_{2.07}Si_{2.94}O_{12}$. The average chemical formula of a garnet core is $Fe_{2.15}Mg_{0.71}Ca_{0.07}Mn_{0.09}Al_{2.07}Si_{2.94}O_{12}$. The average chemical formula of a garnet rim is $Fe_{1.69}Mg_{1.05}Ca_{0.23}Mn_{0.06}Al_{2.06}Si_{2.94}O_{12}$.

***Experiment 7** (750˚C, 8kbar, 4 days)*

A dry and a wet sample of chlorite + quartz + garnet was prepared. A dry sample of chlorite + quartz and a dry sample of chlorite + quartz + muscovite + biotite + garnet were prepared as well. These samples were run at 750˚C and 8kbar for 4 days. Angular iron oxide crystals and iron titanium oxide crystals are found in all holes. No margarite is found in holes 1-4 of experiment 7 (Figure 21).

Garnet overgrowth occurred in holes 1, 3 and 4 of experiment 7. These overgrowth rims are magnesium rich. A potassium melt formed in experiment 7 hole 4, but it is not discussed extensively in this paper.

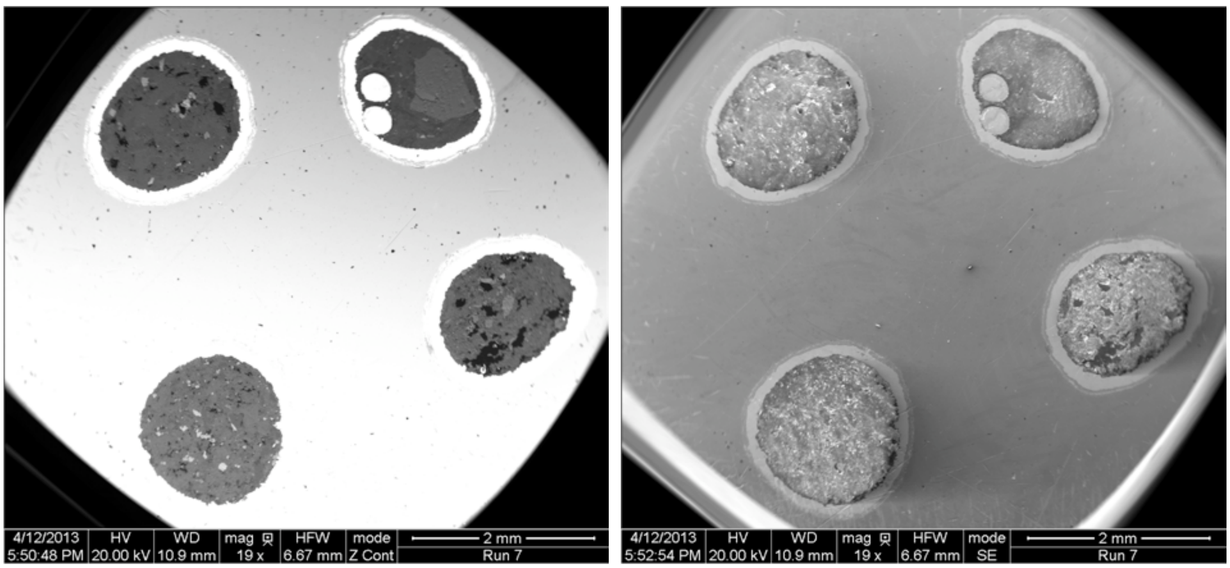


Figure 21 Experiment 7 (750˚C, 8kbar, 4 days). The image on the left is BSED, and the image on the right is ETD. Hole 1 (chlorite + quartz + garnet + water) is the bottom left. Hole 2 (chlorite + quartz + water) is the top left. Hole 3 (chlorite + quartz + garnet) is the top right. Hole 4 (chlorite + quartz + biotite + muscovite + garnet) is the bottom right.

Hole 1 (Chl+Qz+Grt+water)

Chlorite, quartz, garnet (MAK-98), and water (2μL) were mixed together for hole 1 of experiment 7. Angular quartz crystals are found in this sample (Figure 22). Quartz crystals have an average maximum width of 148μm and an average minimum width of 40μm (Table 10). This size is smaller than the average quartz crystal size in the starting material (maximum: 247μm, minimum: 90μm) (Table 9), therefore the quartz grains of this wet sample did not undergo grain coarsening.

Cordierite crystals have an average maximum width of 65μm and an average minimum width of 18μm (Table 10). Garnet crystals with no rim have an average maximum width of 42μm and an average minimum width of 17μm. Garnet cores have an average maximum width of 22μm and an average minimum width of 8μm. Garnet rims have an average maximum width of 5μm and an average minimum width of 1.49μm (Table 11).

Gedrite is the most abundant (~75%) followed by cordierite (~10%), iron and titanium oxides (~5%), quartz (~5%), and garnet (~5%). Minerals of the same kind are evenly dispersed through out the hole (Figure 22). The chemical formulas of cordierite, gedrite, and all forms of garnet are presented in Table 24.

Garnet nucleation did not occur for experiment 7, hole 1.

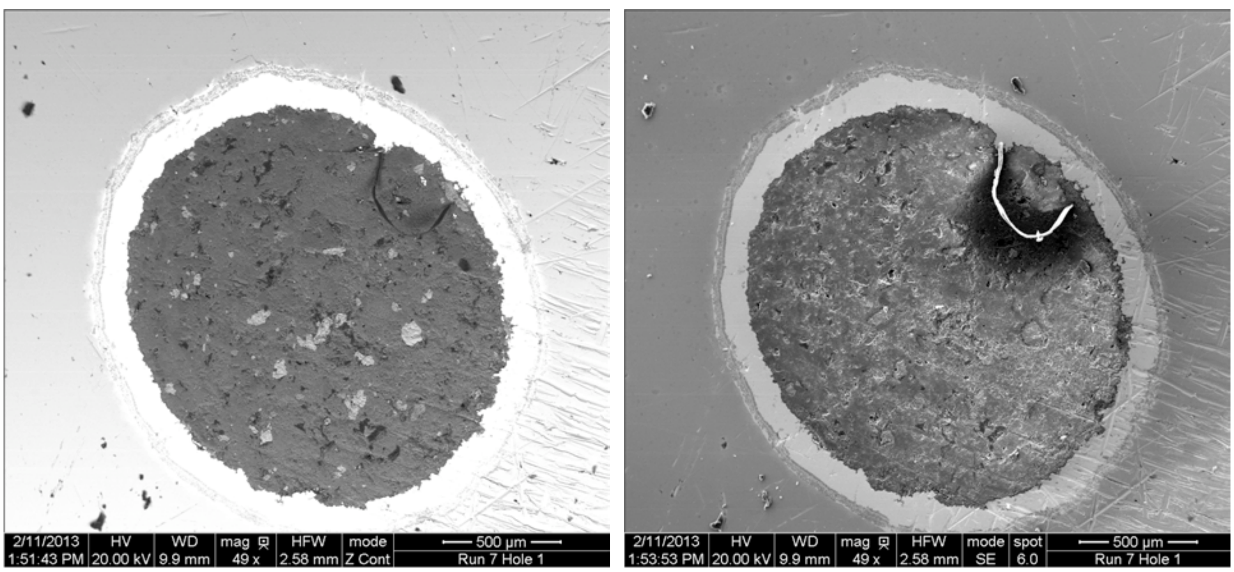


Figure 22 Experiment 7 (750˚C, 8kbar, 4 days) hole 1 (chlorite + quartz + garnet + water). The image on the left is BSED and the image on the right is ETD. Quartz crystals are angular, dark grey in BSED. Cordierite crystals are the same shade of grey as quartz and contain inclusions (Figure 10). Gedrite crystals are lighter grey in BSED and most abundant. The lightest grey crystals are garnet. Iron oxides and iron titanium oxides are the brightest crystals in BSED. The bright string in the top right of the ETD image is on the surface of the sample and is not related to the contents of the sample.

	Average Wt%				
	Cordierite	**Gedrite**	**Garnet**	**Grt Core**	**Grt Rim**
MgO	10.8	11.9	6.26	6.17	10.7
Al_2O_3	33.3	16.5	21.9	22.6	22.0
SiO_2	50.6	56.6	38.5	38.5	42.7
CaO	0.330	1.89	1.05	0.903	1.31
MnO	0	0	1.26	1.48	0.990
FeO	4.83	12.6	31.1	30.3	22.2

Table 24 Average weight % for cordierite, gedrite, and all forms of garnet in experiment 7 (750˚C, 8kbar, 4 days), hole 1 (chlorite + quartz + garnet +water). The average chemical formula of cordierite is $Fe_{0.40}Mg_{1.61}Ca_{0.04}Al_{3.00}(Si_{5.04}Al_{0.91}O_{18})$. The average chemical formula of gedrite is $Fe_{1.40}Mg_{2.35}Ca_{0.27}Al_{2.59}Si_{7.52}O_{22}(OH)_2$. The average chemical formula of garnet is $Fe_{2.04}Mg_{0.73}Ca_{0.09}Mn_{0.08}Al_{2.02}Si_{3.01}O_{12}$. The average chemical formula of a garnet core is $Fe_{1.98}Mg_{0.72}Ca_{0.08}Mn_{0.10}Al_{2.08}Si_{3.00}O_{12}$. The average chemical formula of a garnet rim is $Fe_{1.40}Mg_{1.15}Ca_{0.21}Mn_{0.05}Al_{2.03}Si_{3.08}O_{12}$. Garnet crystals without a rim are more Fe rich.

Hole 2 (Chl+Qz+water)

Chlorite, quartz, and water (2μL) were mixed together for hole 2 of experiment 7. Angular quartz crystals are found in this sample (Figure 23). Quartz crystals have an average maximum width of 105μm and an average minimum width of 33μm (Table 10). These sizes are smaller than the average size of quartz in the starting material (maximum: 247μm, minimum: 90μm), therefore this wet sample did not experience grain coarsening (Table 9). Cordierite crystals have an average maximum width of 59μm and an average minimum width of 29μm (Table 10).

Gedrite is the most abundant (~70%) followed by cordierite (~20%), iron and titanium oxides (~5%), and quartz (~5%). Minerals of the same kind are evenly dispersed through out the sample (Figure 23). The chemical formulas of cordierite and gedrite are presented in Table 25.

Garnet nucleation did not occur for experiment 7, hole 2.

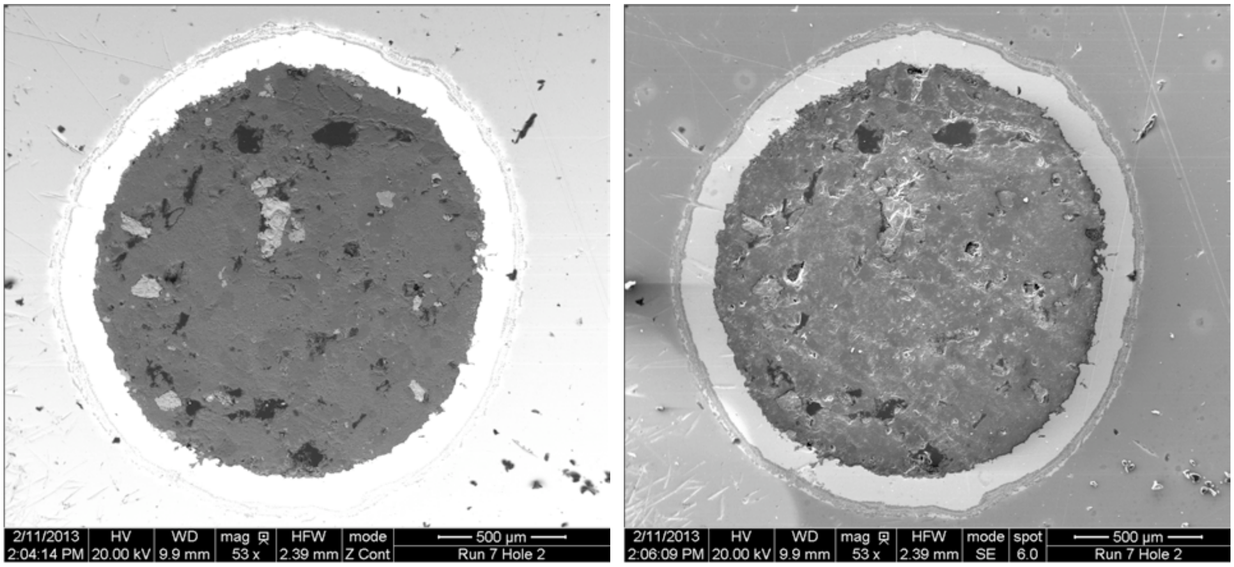


Figure 23 Experiment 7 (750˚C, 8kbar, 4 days) hole 2 (chlorite + quartz +water). The image on the left is BSED and the image on the right is ETD. Quartz crystals are angular, dark grey in BSED. Cordierite crystals are the same shade of grey as quartz and contain inclusions (Figure 10). Gedrite crystals are lighter grey in BSED and most abundant. Iron oxides and iron titanium oxides are the brightest crystals in BSED.

	Average Wt%	
	Cordierite	**Gedrite**
MgO	11.4	14.2
Al_2O_3	32.6	18.2
SiO_2	50.6	54.6
CaO	0.513	1.75
FeO	4.78	10.9

Table 25 Average weight % for cordierite and gedrite in experiment 7 (750˚C, 8kbar, 4 days), hole 2 (chlorite + quartz + water). The average chemical formula of cordierite is $Fe_{0.40}Mg_{1.69}Ca_{0.06}Al_{3.00}(Si_{5.05}Al_{0.83}O_{18})$. The average chemical formula of gedrite is $Fe_{1.21}Mg_{2.81}Ca_{0.25}Al_{2.83}Si_{7.23}O_{22}(OH)_2$.

Hole 3 (Chl+Qz+Grt)

Chlorite, quartz, and garnet (MAK-98) were mixed together for hole 3 of experiment 7. Angular quartz crystals are found in this sample (Figure 24). Quartz crystals have an average maximum width of 89µm and an average minimum width of 11µm (Table 10). This size is smaller than the average quartz crystal size in the starting material (maximum:

247μm, minimum: 90μm) (Table 9), therefore the quartz grains of this dry sample did not undergo grain coarsening.

Cordierite crystals have an average maximum width of 29μm and an average minimum width of 2μm. These sizes are smaller than those in experiment 7 hole 1 (maximum: 65μm, minimum: 18μm) (Table 10). This evidence indicates that the addition of water to a sample increases cordierite growth.

Garnet crystals with no rim have an average maximum width of 849μm and an average minimum width of 189μm. It is uncertain whether a crystal of this size was in the starting material or if this garnet experienced grain coarsening. Garnet cores have an average maximum width of 45μm and an average minimum width of 18μm. Garnet rims have an average maximum width of 4.07μm and an average minimum width of 0.901μm. Larger garnet crystals tend not to have garnet rims (Table 11).

Gedrite is the most abundant (~50%) followed by garnet (~25%), cordierite (~10%), iron and titanium oxides (~5%), quartz (~5%), and garnet (~5%). Most of the garnet present in hole 3 is in one large crystal. It is unclear why there is so much garnet in hole 3. It is also unclear whether this large garnet experienced grain coarsening. Minerals of the same kind are evenly dispersed through out the hole (Figure 24). The chemical formulas of cordierite, gedrite, and all forms of garnet are presented in Table 26.

Garnet nucleation did not occur for experiment 7, hole 3.

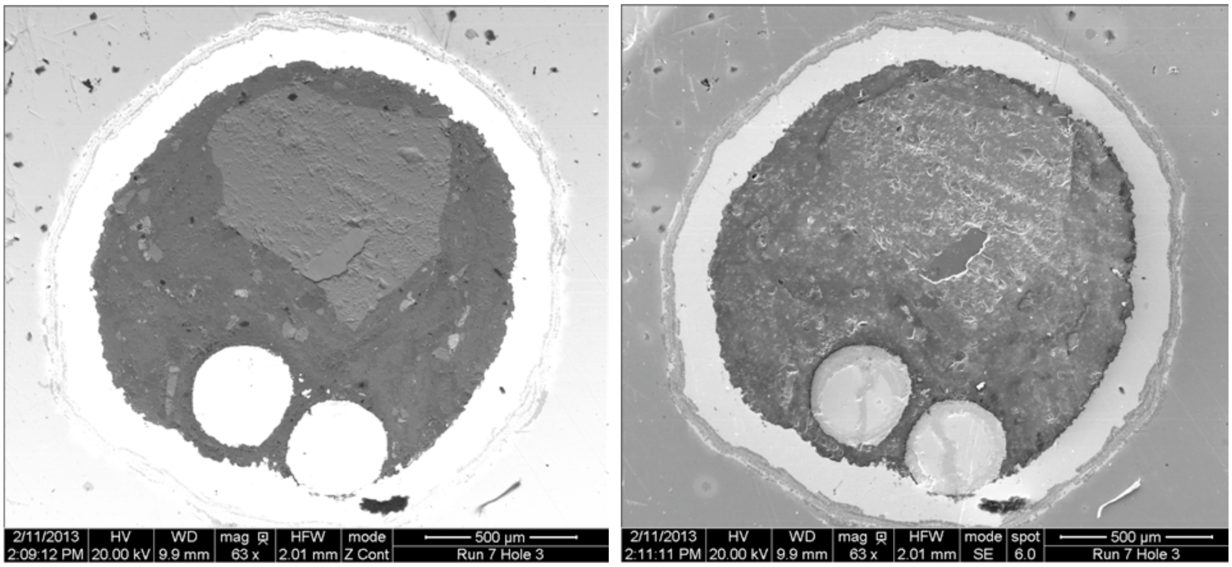


Figure 24 Experiment 7 (750˚C, 8kbar, 4 days) hole 3 (chlorite + quartz + garnet). The image on the left is BSED and the image on the right is ETD. Quartz crystals are angular, dark grey in BSED. Cordierite crystals are the same shade of grey as quartz and contain inclusions (Figure 10). Gedrite crystals are lighter grey in BSED and most abundant. The lightest grey crystals are garnet. The largest crystal in hole 3 is a garnet crystal. Iron oxides and iron titanium oxides are the brightest crystals in BSED.

	Average Wt%				
	Cordierite	**Gedrite**	**Garnet**	**Grt Core**	**Grt Rim**
MgO	10.6	15.7	6.04	6.18	10.3
Al_2O_3	32.8	19.9	22.0	22.7	22.9
SiO_2	50.4	50.3	37.7	39.1	41.0
CaO	0.797	1.64	0.955	1.05	2.64
MnO	0	0	1.50	1.29	0.817
FeO	5.27	12.0	31.8	29.7	22.3

Table 26 Average weight % for cordierite, gedrite, and all forms of garnet in experiment 7 (750˚C, 8kbar, 4 days), hole 3 (chlorite + quartz + garnet). The average chemical formula of cordierite is $Fe_{0.44}Mg_{1.58}Ca_{0.09}Al_{3.00}(Si_{5.04}Al_{0.86}O_{18})$. The average chemical formula of gedrite is $Fe_{1.35}Mg_{3.15}Ca_{0.24}Al_{3.15}Si_{6.75}O_{22}(OH)_2$. The average chemical formula of garnet is $Fe_{2.10}Mg_{0.71}Ca_{0.08}Mn_{0.10}Al_{2.05}Si_{2.97}O_{12}$. The average chemical formula of a garnet core is $Fe_{1.93}Mg_{0.72}Ca_{0.09}Mn_{0.09}Al_{2.07}Si_{3.04}O_{12}$. The average chemical formula of a garnet rim is $Fe_{1.40}Mg_{1.15}Ca_{0.21}Mn_{0.05}Al_{2.03}Si_{3.08}O_{12}$. Garnet crystals without a garnet rim are more Fe rich.

Hole 4 (Chl+Qz+Mus+Bio+Grt)

Chlorite, quartz, muscovite, biotite, and garnet (MAK-98) were mixed together for hole 4 of experiment 7. No quartz crystals are found in this sample (Figure 25). Cordierite crystals have an average maximum width of 55μm and an average minimum width of

10μm. Gedrite crystals have an average maximum width of 23μm and an average minimum width of 13μm (Table 10).

Garnet crystals with no rim have an average maximum width of 132μm and an average minimum width of 13μm. Garnet cores have an average maximum width of 21μm and an average minimum width of 7μm. Garnet rims have an average maximum width of 4μm and an average minimum width of 0.90μm. This average garnet rim width is smaller than those found in hole 1 (maximum: 5μm, minimum: 1μm). This evidence indicates that water promotes garnet growth more effectively than does melt (Table 11).

Gedrite is the most abundant (~55%) followed by melt (~20%), cordierite (~10%), iron and titanium oxides (~5%), quartz (~5%), and garnet (~5%). Minerals of the same kind are evenly dispersed through out the hole (Figure 25). The chemical formulas of cordierite, gedrite, and all forms of garnet are presented in Table 27.

Garnet nucleation did not occur for experiment 7, hole 4.

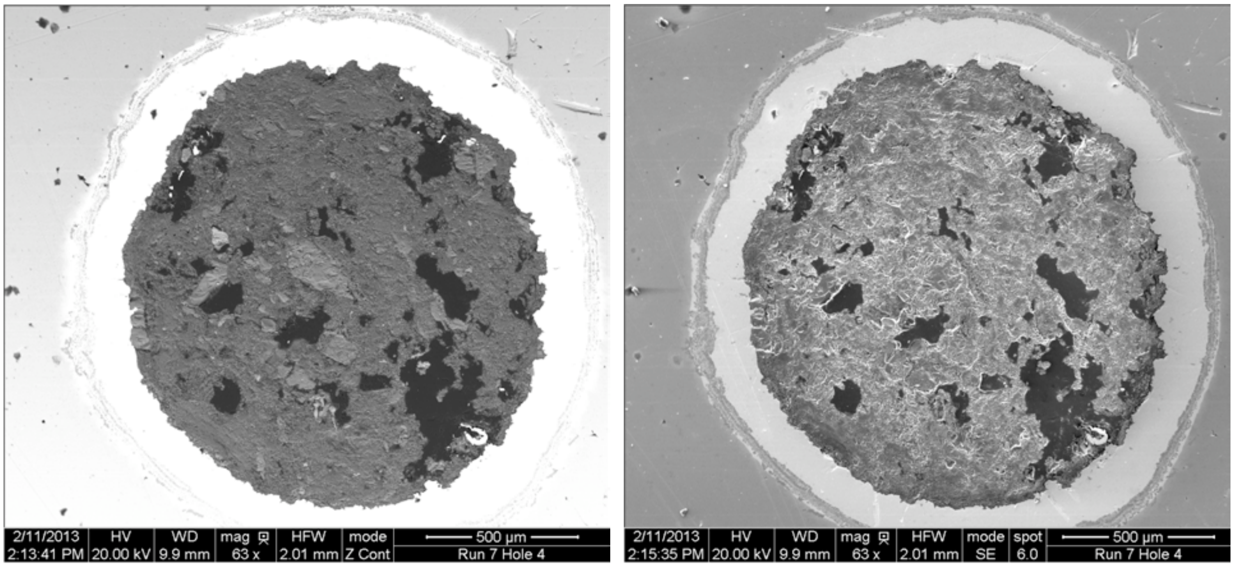


Figure 25 Experiment 7 (750˚C, 8kbar, 4 days), hole 4 (chlorite + quartz + biotite + muscovite + garnet). The image on the left is BSED and the image on the right is ETD. Cordierite crystals are dark grey in BSED and contain inclusions (Figure 10). Gedrite crystals are lighter grey in BSED and most abundant. Melt is difficult to distinguish from gedrite. The lightest grey crystals are garnet. Iron oxides and iron titanium oxides are the brightest crystals in BSED.

	Average Wt%				
	Cordierite	**Gedrite**	**Garnet**	**Grt Core**	**Grt Rim**
MgO	9.99	17.2	6.47	8.11	9.99
Al_2O_3	35.5	17.8	23.0	24.1	23.3
SiO_2	47.9	49.1	39.2	38.9	40.4
CaO	0.607	1.06	0.920	1.81	1.81
MnO	0	0	1.25	0.950	0.900
FeO	5.96	14.5	29.1	26.2	23.6

Table 27 Average weight % for cordierite, gedrite, and all forms of garnet in experiment 7 (750˚C, 8kbar, 4 days), hole 4 (chlorite + quartz + muscovite + biotite + garnet). The average chemical formula of cordierite is $Fe_{0.50}Mg_{1.50}Ca_{0.07}Al_{3.00}(Si_{4.81}Al_{1.20}O_{18})$. The average chemical formula of gedrite is $Fe_{1.65}Mg_{3.49}Ca_{0.15}Al_{2.86}Si_{6.69}O_{22}(OH)_2$. The average chemical formula of garnet is $Fe_{1.88}Mg_{0.75}Ca_{0.08}Mn_{0.08}Al_{2.10}Si_{3.03}O_{12}$. The average chemical formula of a garnet core is $Fe_{1.68}Mg_{0.94}Ca_{0.15}Mn_{0.06}Al_{2.17}Si_{2.97}O_{12}$. The average chemical formula of a garnet rim is $Fe_{1.49}Mg_{1.12}Ca_{0.15}Mn_{0.06}Al_{2.07}Si_{3.04}O_{12}$. Garnet crystals without a rim are more Fe rich.

Experiment 8 *(750˚C, 8kbar, 17 days and 22 hours)*

A dry and a wet sample of chlorite + quartz + garnet was prepared. A dry sample of chlorite + quartz and a dry sample of chlorite + quartz + muscovite + biotite + garnet were prepared as well. These samples were run at 750˚C and 8kbar for 17 days and 22 hours. Angular iron oxide crystals and iron titanium oxide crystals are found in all holes. Very little margarite is found in holes 1-4 of experiment 8 (Figure 26).

Garnet nucleation occurred in hole 4 of experiment 8. Garnet overgrowth occurred in holes 1, 3 and 4 of experiment 8. These overgrowth rims are magnesium rich. A potassium melt formed in experiment 8 hole 4, but it is not discussed extensively in this paper.

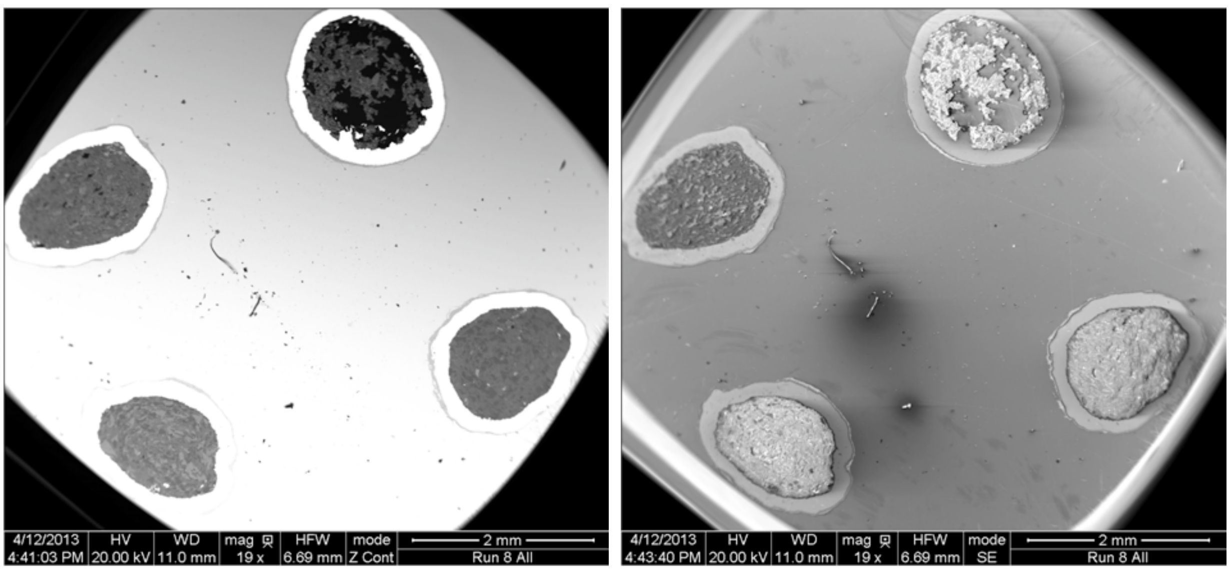


Figure 26 Experiment 8 (750˚C, 8kbar, 17 days and 22 hours). The image on the left is BSED, and the image on the right is ETD. Hole 1 (chlorite + quartz + garnet + water) is the top right. Hole 2 (chlorite + quartz + water) is the bottom right. Hole 3 (chlorite + quartz + garnet) is the bottom left. Hole 4 (chlorite + quartz + biotite + muscovite + garnet) is the top left.

Hole 1 (Ch+Qz+Grt+water)

Chlorite, quartz, garnet (MAK-98), and water (2μL) were mixed together for hole 1 of experiment 8. Many holes are found in this sample. Angular quartz crystals are found in this sample (Figure 27). Quartz crystals have an average maximum width of 128μm and an average minimum width of 89μm (Table 10). This size is smaller than the average quartz crystal size in the starting material (maximum: 247μm, minimum: 90μm) (Table 9), therefore the quartz grains of this wet sample did not undergo grain coarsening.

No cordierite crystals are found in this sample, but cordierite and quartz look similar in experiment 8, therefore, there may be cordierite in hole 1 that was not identified. Also, during polishing, a great deal of material was lost from hole 1. Garnet crystals with no rim have an average maximum width of 69μm and an average minimum width of 20μm. Garnet cores have an average maximum width of 86μm and an average minimum width of 45μm. Garnet rims have an average maximum width of 3μm and an average minimum width of 1μm (Table 11).

Various aluminous minerals are most abundant (~70%) followed by garnet (~10%), cordierite (~7%), gedrite (~5%), quartz (~5%), and iron and titanium oxides (~3%). These aluminous minerals could be kyanite or staurolite. Minerals of the same kind are evenly dispersed through out the hole (Figure 27). The chemical formulas of gedrite and most forms of garnet are presented in Table 28.

Garnet nucleation did not occur for experiment 8, hole 1.

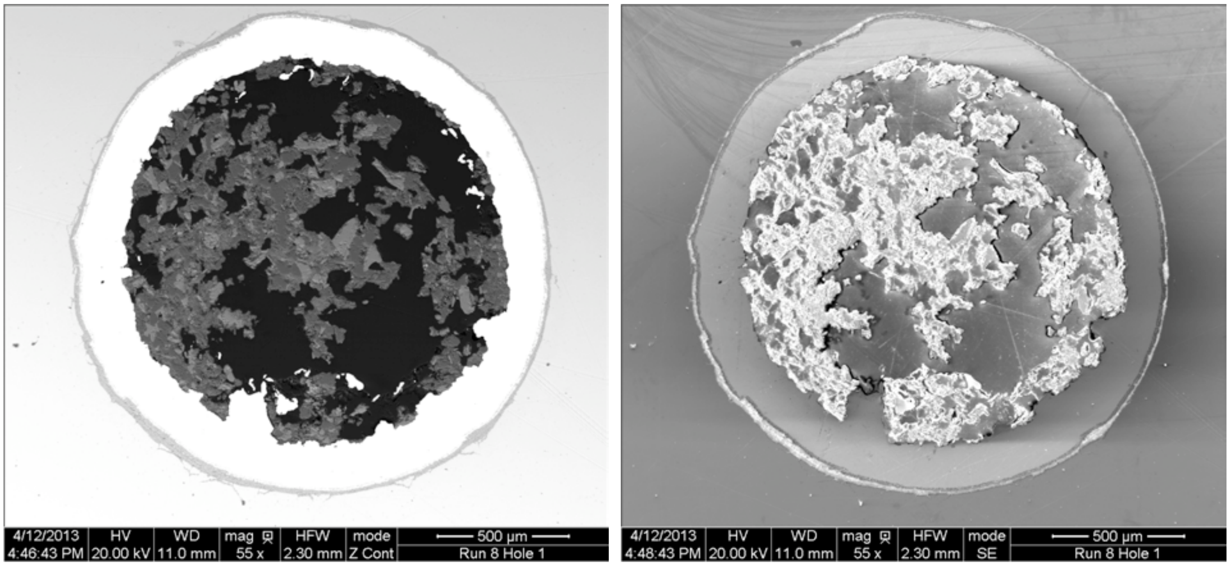


Figure 27 Experiment 8 (750˚C, 8kbar, 17 days and 22 hours) hole 1 (chlorite + quartz + garnet + water). The image on the left is BSED and the image on the right is ETD. Quartz crystals are angular, dark grey in BSED. Cordierite crystals are the same shade of grey as quartz and contain inclusions (Figure 10). Gedrite and the other aluminous minerals are practically indistinguishable. They are both lighter grey in BSED. The lightest grey crystals are garnet. Iron oxides and iron titanium oxides are the brightest crystals in BSED. The large black areas are holes. The bright spots near the edge of the hole are shavings from the gold lining.

	Average Wt%			
	Gedrite	**Garnet**	**Grt Core**	**Grt Rim**
MgO	17.5	5.94	6.25	7.22
Al_2O_3	24.0	21.5	22.4	19.3
SiO_2	36.0	36.4	38.1	47.0
CaO	0.360	1.04	0.943	1.97
MnO	0	1.36	1.21	0.627
FeO	21.9	33.7	31.1	23.8

Table 28 Average weight % for gedrite and all forms of garnet in experiment 8 (750˚C, 8kbar, 17 days and 22 hours), hole 1 (chlorite + quartz + garnet + water). The average chemical formula of gedrite is $Fe_{2.65}Mg_{3.77}Ca_{0.06}Al_{4.08}Si_{5.19}O_{22}(OH)_2$. The average chemical formula of garnet is $Fe_{2.25}Mg_{0.71}Ca_{0.09}Mn_{0.09}Al_{2.03}Si_{2.91}O_{12}$. The average chemical formula of a garnet core is $Fe_{2.04}Mg_{0.73}Ca_{0.08}Mn_{0.08}Al_{2.07}Si_{2.99}O_{12}$. Garnet crystals without a rim are more Fe rich.

Hole 2 (Chl+Qz+water)

Chlorite, quartz, and water (2µL) were mixed together for hole 2 of experiment 8.

Angular quartz crystals are found in this sample (Figure 28). Quartz crystals have an average maximum width of 66μm and an average minimum width of 31μm (Table 10). These sizes are smaller than the average size of quartz in the starting material (maximum: 247μm, minimum: 90μm), therefore this wet sample did not experience grain coarsening (Table 9). Cordierite crystals have an average maximum width of 21μm and an average minimum width of 5μm (Table 10).

Gedrite is the most abundant (~65%) followed by cordierite (~20%), quartz (~10%), and iron and titanium oxides (~5%). Minerals of the same kind are evenly dispersed through out the sample (Figure 28). The chemical formulas of cordierite and gedrite are presented in Table 29.

Garnet nucleation did not occur for experiment 8, hole 2.

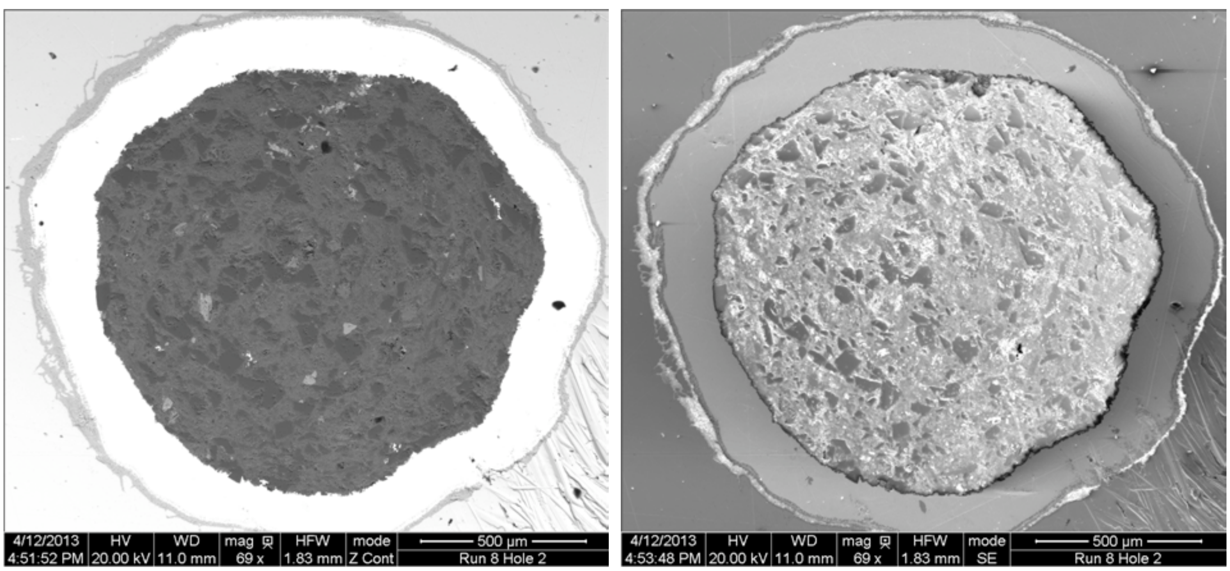


Figure 28 Experiment 8 (750˚C, 8kbar, 17 days and 22 hours) hole 2 (chlorite + quartz +water). The image on the left is BSED and the image on the right is ETD. Quartz crystals are angular, dark grey in BSED. Cordierite crystals are the same shade of grey as quartz and contain inclusions (Figure 10). Gedrite crystals are lighter grey in BSED and most abundant. Iron oxides and iron titanium oxides are the brightest crystals in BSED.

	Average Wt%	
	Cordierite	**Gedrite**
MgO	11.3	14.8
Al_2O_3	30.7	17.7
SiO_2	47.4	45.8
CaO	0.983	0.627
FeO	9.50	20.7

Table 29 Average weight % for cordierite and gedrite in experiment 8 (750˚C, 8kbar, 17 days and 22 hours), hole 2 (chlorite + quartz + water). The average chemical formula of cordierite is $Fe_{0.82}Mg_{1.73}Ca_{0.11}Al_{3.00}(Si_{4.88}Al_{0.72}O_{18})$. The average chemical formula of gedrite is $Fe_{2.44}Mg_{3.11}Ca_{0.10}Al_{2.94}Si_{6.45}O_{22}(OH)_2$.

Hole 3 (Chl+Qz+Grt)

Chlorite, quartz, and garnet (MAK-98) were mixed together for hole 3 of experiment 8. Angular quartz crystals are found in this sample (Figure 29). Quartz crystals have an average maximum width of 71μm and an average minimum width of 25μm (Table 10). This size is smaller than the average quartz crystal size in the starting material (maximum: 247μm, minimum: 90μm) (Table 9), therefore the quartz grains of this dry sample did not undergo grain coarsening.

Cordierite crystals have an average maximum width of 22μm and an average minimum width of 8μm. Gedrite crystals have an average maximum width of 12μm and an average minimum width of 2μm (Table 10). Garnet crystals with no rim have an average maximum width of 13μm and an average minimum width of 4μm. Garnet cores have an average maximum width of 67μm and an average minimum width of 13μm. Garnet rims have an average maximum width of 1μm and an average minimum width of 0.60μm (Table 11).

Gedrite is the most abundant (~45%) followed by garnet (~25%), cordierite (~15%), garnet (~10%), quartz (~5%), and iron and titanium oxides (<1%). Minerals of the same kind are evenly dispersed through out the hole (Figure 29). The chemical formulas of cordierite, gedrite, and all forms of garnet are presented in Table 30.

Garnet nucleation did not occur for experiment 8, hole 3.

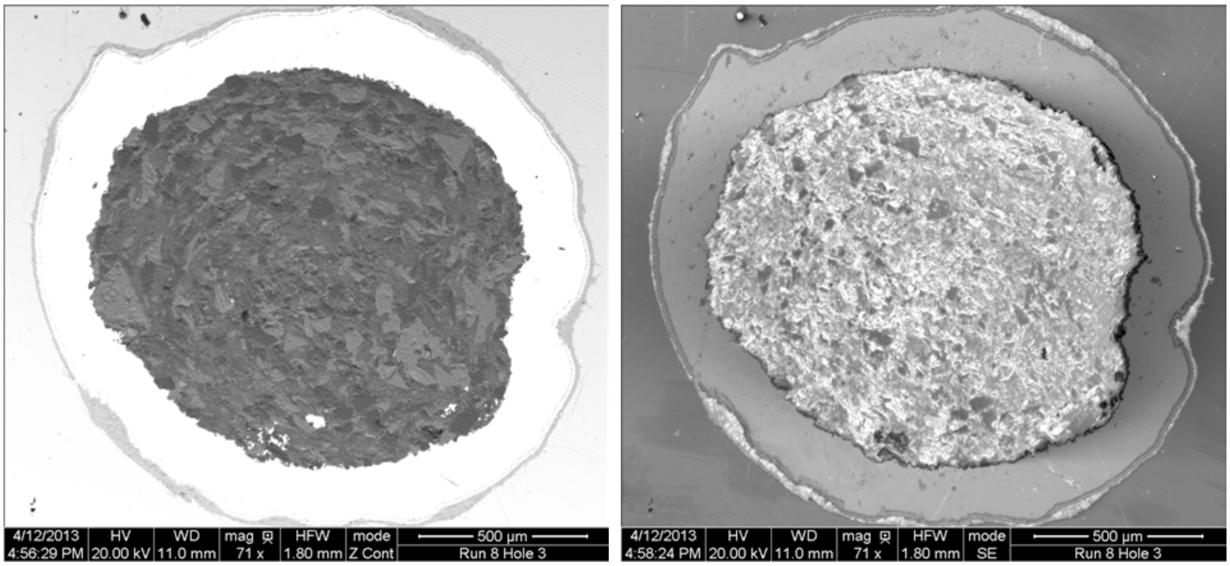


Figure 29 Experiment 8 (750˚C, 8kbar, 17 days and 22 hours) hole 3 (chlorite + quartz + garnet). The image on the left is BSED and the image on the right is ETD. Quartz crystals are angular, dark grey in BSED. Cordierite crystals are the same shade of grey as quartz and contain inclusions (Figure 10). Gedrite crystals are lighter grey in BSED and most abundant. The lightest grey crystals are garnet. Iron oxides and iron titanium oxides are the brightest crystals in BSED. The bright spots near the edge of the hole are shavings from the gold lining.

	Average Wt%				
	Cordierite	**Gedrite**	**Garnet**	**Grt Core**	**Grt Rim**
MgO	11.3	15.7	6.64	6.06	9.06
Al_2O_3	31.7	20.7	22.3	21.7	21.8
SiO_2	47.7	44.0	38.1	37.0	40.7
CaO	0.940	0.777	1.15	0.840	2.16
MnO	0	0	1.28	1.43	0.673
FeO	8.23	18.6	30.5	33.0	25.6

Table 30 Average weight % for cordierite, gedrite, and all forms of garnet in experiment 8 (750˚C, 8kbar, 17 days and 22 hours), hole 3 (chlorite + quartz + garnet). The average chemical formula of cordierite is $Fe_{0.70}Mg_{1.71}Ca_{0.10}Al_{3.00}(Si_{4.87}Al_{0.82}O_{18})$. The average chemical formula of gedrite is $Fe_{2.17}Mg_{3.27}Ca_{0.12}Al_{3.41}Si_{6.15}O_{22}(OH)_2$. The average chemical formula of garnet is $Fe_{2.00}Mg_{0.77}Ca_{0.10}Mn_{0.09}Al_{2.06}Si_{2.98}O_{12}$. The average chemical formula of a garnet core is $Fe_{2.19}Mg_{0.72}Ca_{0.07}Mn_{0.10}Al_{2.03}Si_{2.94}O_{12}$. The average chemical formula of a garnet rim is $Fe_{1.63}Mg_{1.03}Ca_{0.18}Mn_{0.04}Al_{1.95}Si_{3.10}O_{12}$.

Hole 4 (Chl+Qz+Mus+Bio+Grt)

Chlorite, quartz, muscovite, biotite, and garnet (MAK-98) were mixed together for hole 4 of experiment 8. Angular quartz crystals are found in this sample (Figure 30). Quartz crystals have an average maximum width of 72μm and an average minimum width of 31μm (Table 10). This size is smaller than the average quartz crystal size in the starting material (maximum: 247μm, minimum: 90μm) (Table 9), therefore the quartz grains of this dry sample did not undergo grain coarsening.

Cordierite crystals have an average maximum width of 24μm and an average minimum width of 6μm. Gedrite crystals have an average maximum width of 12μm and an average minimum width of 2μm (Table 10).

Garnet crystals with no rim have an average maximum width of 74μm and an average minimum width of 24μm. Garnet cores have an average maximum width of 9μm and an average minimum width of 3μm. Garnet rims have an average maximum width of 2μm and an average minimum width of 0.87μm (Table 11). This average garnet rim width is smaller than those found in hole 1 (maximum: 3μm, minimum: 1μm). This evidence indicates that water promotes garnet growth more effectively than does melt (Table 11).

Gedrite is the most abundant (~55%) followed by melt (~25%), cordierite (~10%), garnet (~5%), quartz (~5%), and iron and titanium oxides (<1%) . Minerals of the same kind are evenly dispersed through out the hole (Figure 30). The chemical formulas of cordierite and gedrite are presented in Table 31. The chemical formulas of all forms of garnet are presented in Table 32.

Garnet nucleation occurred for experiment 8, hole 4. There are small garnet crystals evenly dispersed through out this sample that have the same magnesium-rich chemical composition as a garnet rim (Figure 31).

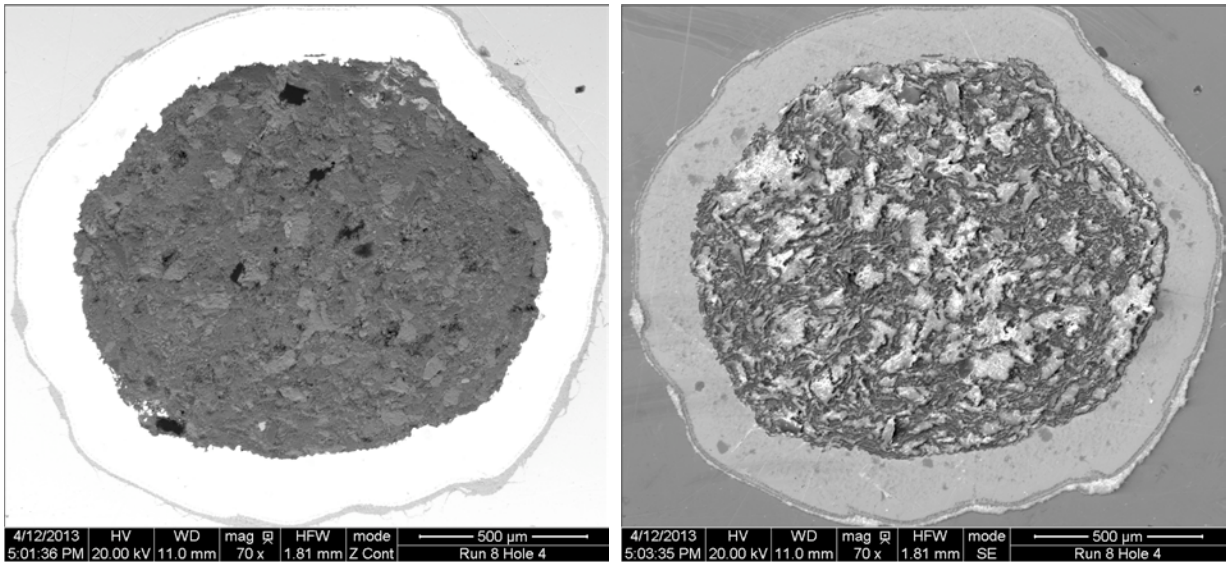
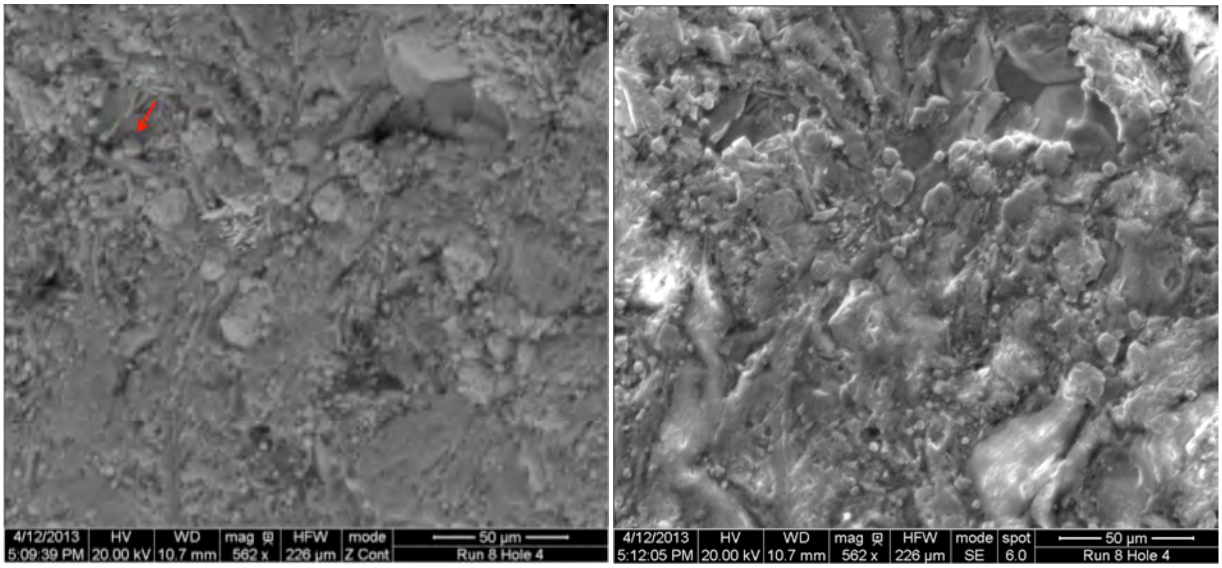
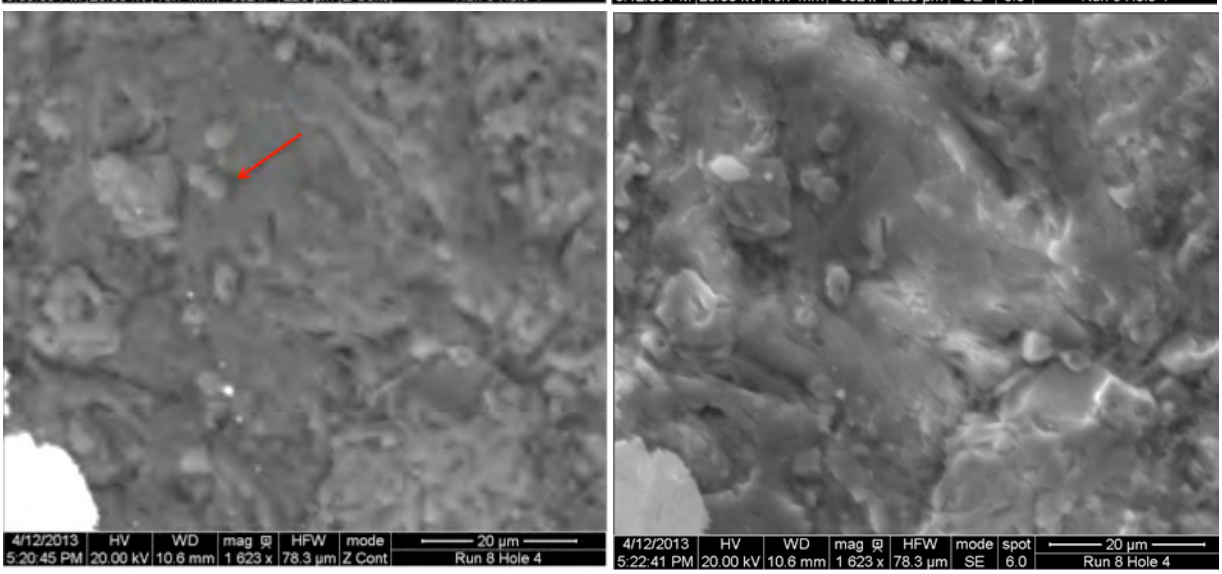


Figure 30 Experiment 8 (750˚C, 8kbar, 17 days and 22 hours), hole 4 (chlorite + quartz + biotite + muscovite + garnet). The image on the left is BSED and the image on the right is ETD. Quartz crystals are dark grey in BSED. Cordierite crystals are dark grey in BSED and contain inclusions (Figure 10). Gedrite crystals are lighter grey in BSED and most abundant. Melt is difficult to distinguish from gedrite. The lightest grey crystals are garnet. Iron oxides and iron titanium oxides are the brightest crystals in BSED.



a.



b.

Figure 31 Images of nucleated garnet in hole 4 (chlorite + quartz + muscovite + biotite + garnet) of experiment 8 (750˚C, 8kbar, 17 days and 22 hours). For (a) and (b), the image on the left is BSED, and the image on the right is ETD. The red arrow points to the nucleated garnet. Not every spherical, light grey crystal in these images is a nucleated garnet.

	Average Wt%	
	Cordierite	**Gedrite**
MgO	9.36	13.5
Al_2O_3	33.9	16.6
SiO_2	47.6	50.9
CaO	0.680	0.713
FeO	8.35	18.1

Table 31 Average weight % for cordierite and gedrite in experiment 8 (750˚C, 8kbar, 17 days and 22 hours), hole 4 (chlorite + quartz + muscovite + biotite + garnet). The average chemical formula of cordierite is $Fe_{0.71}Mg_{1.42}Ca_{0.07}Al_{3.00}(Si_{4.85}Al_{1.06}O_{18})$. The average chemical formula of gedrite is $Fe_{2.08}Mg_{2.76}Ca_{0.11}Al_{2.69}Si_{7.00}O_{22}(OH)_2$.

	Average Wt%			
	Garnet	**Grt Core**	**Grt Rim**	**Grt Nucleated**
MgO	5.83	7.16	9.32	9.98
Al_2O_3	20.7	21.9	23.3	24.1
SiO_2	34.7	37.3	40.3	39.7
CaO	1.65	2.47	2.11	1.99
MnO	1.29	0.713	0.407	0.423
FeO	35.9	30.5	24.6	23.8

Table 32 Average weight % for all forms of garnet in experiment 8 (750˚C, 8kbar, 17 days and 22 hours), hole 4 (chlorite + quartz + muscovite + biotite + garnet). The average chemical formula of garnet is $Fe_{2.45}Mg_{0.71}Ca_{0.14}Mn_{0.09}Al_{1.98}Si_{2.82}O_{12}$. The average chemical formula of a garnet core is $Fe_{2.01}Mg_{0.84}Ca_{0.21}Mn_{0.05}Al_{2.03}Si_{2.93}O_{12}$. The average chemical formula of a garnet rim is $Fe_{1.56}Mg_{1.05}Ca_{0.17}Mn_{0.03}Al_{2.07}Si_{3.04}O_{12}$. The average chemical formula nucleated garnet is $Fe_{1.50}Mg_{1.12}Ca_{0.16}Mn_{0.03}Al_{2.14}Si_{2.99}O_{12}$. Garnet crystals without a rim are more Fe rich.

Discussion

Nucleation of Garnet

These experiments attempted to nucleate garnet at temperatures around 600˚C. According to Theriak Domino calculations, a chlorite + quartz + muscovite + biotite mineral mixture should become unstable relative to garnet at 590˚C and 8kbar (Appendix II). According to Hsu (1968), chlorite + quartz becomes unstable relative to garnet at temperatures ranging from ~550˚C to ~600˚C for a wide range of pressures. Hsu's (1968) results applied to Fe rich chlorite (Figure 32).

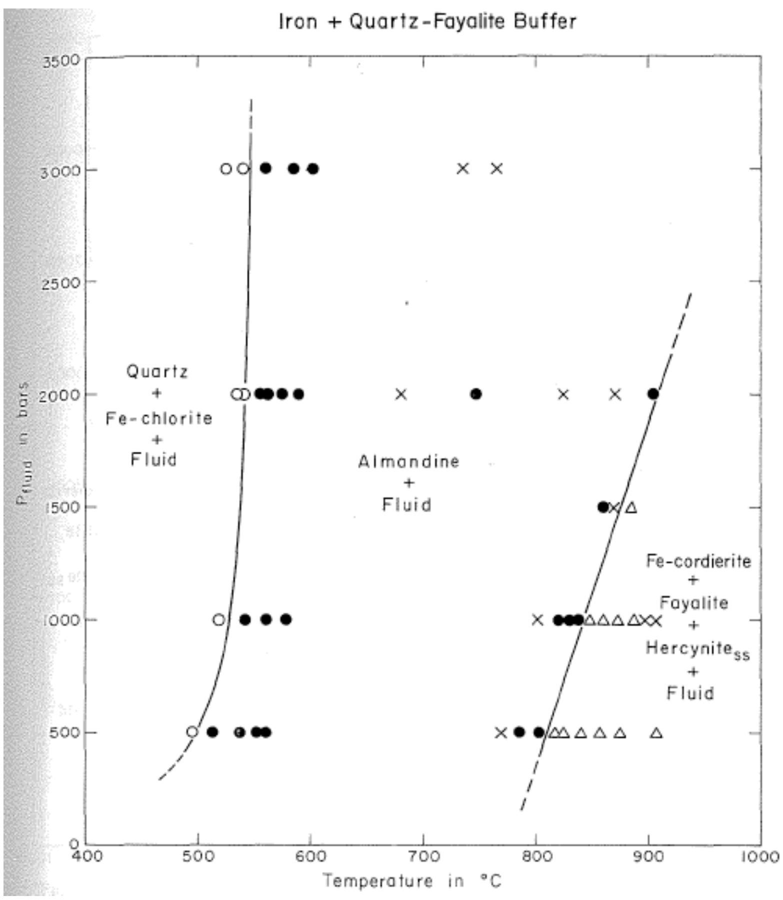


Figure 32 Image from Hsu (1968) showing that garnet becomes stable relative to chlorite + quartz at temperatures between 550˚C and 600˚C for a wide range of pressures. The chlorite must be iron rich.

Nucleation of garnet occurred in experiment 8 (750˚C, 8kbar, 17 days and 20 hours) hole 4 (chlorite + quartz + muscovite + biotite + garnet). This experimental temperature is 160˚C above the temperature at which Theriak Domino calculated garnet would be stable at 8kbar (Appendix II). Length of the experiment is a deciding factor for the nucleation of garnet. At 750˚C and 8kbar for 17 days and 22 hours, garnet nucleates (experiment 8), but if that same sample were run for 10 days and 20 hours garnet does not nucleate (experiment 6). It is surprising that the nucleated garnet crystals are so small because the garnet rims that grew in experiment 8 hole 4 are larger than these nucleated crystals. It is possible that this garnet nucleated in the melt during the rapid temperature decrease in the quench.

Nucleation did not occur for most of the experiments because the temperatures were too high. Because of this high temperature, the nucleation of cordierite and gedrite was more stable than the nucleation of garnet. Garnet was stable in this system as well, but because the bulk composition encouraged cordierite and gedrite nucleation, there was very little motivation to nucleate garnet (Figure 33). That is why the garnet rims formed. Perhaps if experiment 4 (610˚C, 8kbar, 7 days and 23 hours) were run for a longer period of time, garnet would have nucleated.

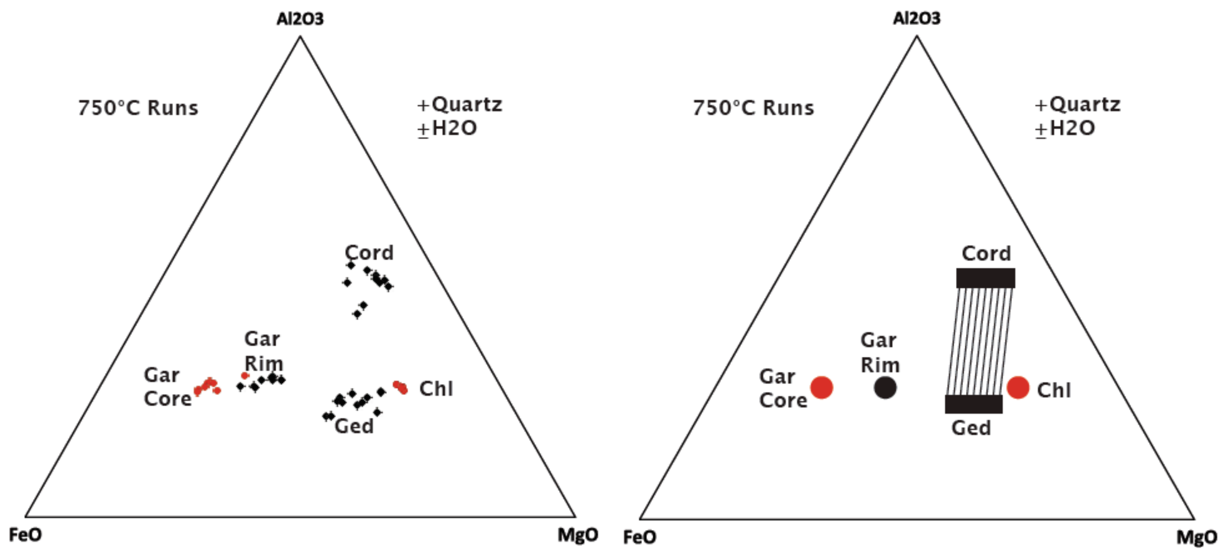


Figure 33 AFM diagrams for the reactants and products in experiments 6-8. The figure on the left shows each sample individually. The figure on the right summarizes the different samples and includes tie lines.

Cordierite and gedrite chemical spectra are similar to chlorite spectra. Because of this similarity, it was not until the last experiment that I realized that the chlorite had been consumed in every reaction. If this had been recognized sooner, I could have developed a different plan to nucleate garnet from chlorite and quartz mixtures.

Garnet Overgrowth

At 8kbar, the tipping point for garnet overgrowth to occur is between 650˚C and 750˚C. There is no clear trend between the size of the garnet rim and the length of the experiment. Generally, the garnet rim becomes more Fe rich as the experiment becomes longer. Water seemed to promote garnet overgrowth. Garnets without a rim tend to be more Fe rich.

Chlorite and Cordierite

Upper Stability of Chlorite

Between 610˚C (experiment 4) and 650˚C (experiment 5) there is a tipping point at which chlorite and quartz become unstable relative to cordierite and gedrite. The cordierite-gedrite-forming reaction proceeds in the following manner:

$20(Mg_{4.5}Al_3Si_{2.5}O_{10}(OH)_8) + 79SiO_2 \leftrightarrow 9(Mg_2Al_4Si_5O_{18}) + 12(Mg_6Al_2Si_7O_{22}(OH)_2) + 68H_2O$

In this reaction, quartz is consumed, so one would expect to see significantly less quartz in all of the experiments which contained cordierite and gedrite. It is uncertain why less quartz was not observed in all experiments at 650˚C and above (experiments 5-8).

In their 2.07kbar experiments, Fleming and Fawcett found that chlorite becomes unstable and cordierite becomes stable above ~590˚C-600˚C (Figure 34). Their experiments were for magnesium rich chlorite. The evidence presented in this paper shows that at higher pressures, the upper stability of chlorite is slightly higher.

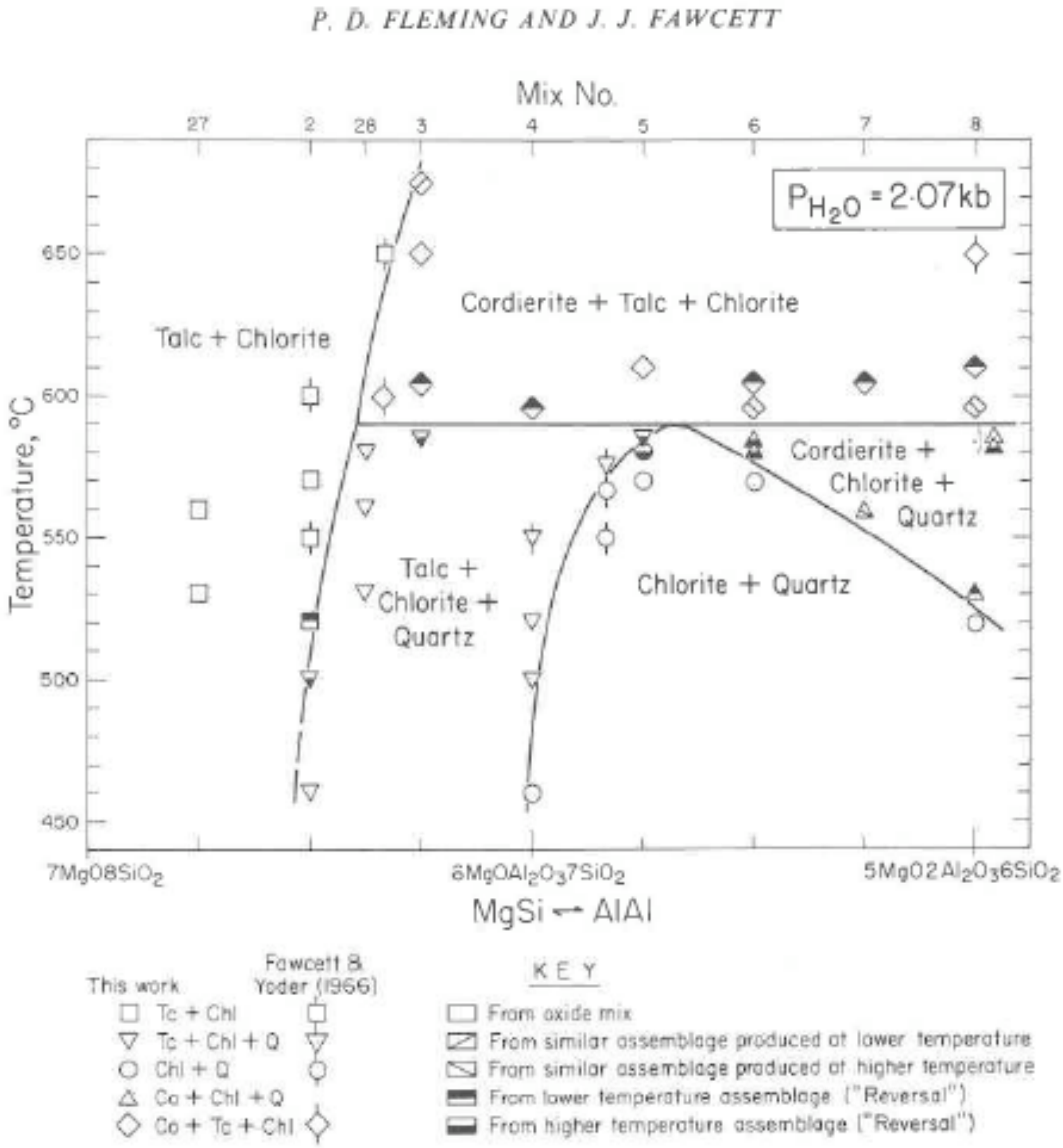


Figure 34 Image from Fleming and Fawcett (1976) showing that chlorite + quartz becomes unstable relative to cordierite + talc + chlorite at ~600˚C at 2.07kbar pressure.

Nucleation of Cordierite

In experiment 5 (650˚C, 8kbar, 6 days and 22 hours) both wet samples have cordierite crystals that are larger than those in the dry samples. The same holds true for experiment 7 (750˚C, 8kbar, 4 days). Once the length of the experiment is increased to 10 days and 20 hours (experiment 6), there is no clear trend for the effect of water on cordierite growth. This evidence indicates that the addition of water decreases cordierite nucleation rates at lower temperatures and for shorter experiments.

Cordierite crystals are smaller and more abundant in shorter experiments and experiments at lower temperatures. This evidence indicates that an increase in temperature and duration of the experiment seems to increase nucleation rates of cordierite. For experiments 5-8, cordierite nucleated homogeneously throughout the sample.

Quartz Grain Coarsening

Garnet seems to inhibit quartz grain coarsening. No samples that contain garnet show signs of coarsening. Quartz grains do not show clear proof of coalescence at 610˚C (experiment 4). Between 610˚C (experiment 4) and 650˚C (experiment 5) there is a tipping point at which coarsening begins. At 750˚C (experiments 6-8), the duration of the experiment becomes a factor. Between 10 days and 20 hours (experiment 6) and 17 days and 22 hours (experiment 8) there is a tipping point at which quartz grain coarsening no longer takes place. There is one outlier to this trend. Hole 2 (chlorite + quartz) in experiment 7 (750˚C, 8kbar, 4 days) does not exhibit quartz grain coarsening.

Conclusions

Garnet nucleation occurs at 750˚C and 8kbar if the experiment is run for 17 days and 22 hours. Perhaps garnet will nucleate at lower temperatures if the experiment is run for a longer period of time. Muscovite and biotite react to form a melt that promotes the nucleation of garnet. Water does not seem to affect the nucleation of garnet.

These experiments promoted the nucleation of cordierite and gedrite. Increase in temperature and duration of the experiment seems to increase nucleation rates of cordierite. Water decreases cordierite nucleation rates at lower temperatures (~650˚C) and for shorter experiments (~4 days).

References

Ayers, J., J. Brenan, B. Watson, D. Wark, and W. Minarik. "A new capsule trechnique for hydrothermal experiments using the piston-cylinder apparatus." American Mineralogist 77 (1992): 1080-1086.

Carlson, William D., 2011. Porphyroblast crystallization: linking processes, kinetics, and microstructures. *International Geology Review*, 53:3-4, 406-445.

Carlson, W.D., and Denison, C., 1992, Mechanisms of porphyroblast crystallization: Results from high-resolution computed X-ray tomography: *Science*, **257**, 1236–1239.

Daniel, C. G. & Spear, F. S., 1998. Three-dimensional patterns of garnet nucleation and growth. *Geology*, **26**, 503–506.

Daniel, C. G. & Spear, F. S., 1999. The clustered nucleation and growth processes of garnet in regional metamorphic rocks from north-west Connecticut, USA. *Journal of Metamorphic Geology*, **17,** 503-520.

Fleming, Peter D. and Fawcett, J. J., 1976. Upper stability of chlorite + quartz in the system MgO-FeO-Al_2O_3-SiO_2-H_2O at 2kbar water pressure. *American Minralogist*, **61**, 1175-1193.

Hsu, L. C., 1968. Selected phase relationships in the system Al-Mn-Fe-Si-O-H: a model for garnet equilibria. *Journal of Petrology*.**9**, 1, 40-83.

Kretz, R., 1973, Kinetics of the crystallization of garnet at two localities near Yellowknife: *Canadian Mineralogist*, **12**, 1–20.

Morse, S., J. Brady, and B. Sporleder. "Experimental Petrology of the Kiglapait Intrusion: Cotectic Trace for the Lower Zone at 5 kbar in Graphite." Journal of Petrology 45, no. 11 (2004): 2225-2259.

Skoog, Douglas A., F. James Holler, Stanley R. Crouch. (2007). *Principles of Chemical Analysis*. 6ed

Spear, F. S. & Daniel, C. G., 1998. 3-dimensional imaging of garnet porphyroblast sizes and chemical zoning. Nucleation and growth history in the garnet zone. *Geological Materials Research*, **1**, 1-43.

Spear, F. S. & Daniel, C. G., 2001. Diffusion control of garnet growth, Harpswell Neck, Maine, USA. . *Journal of Metamorphic Geology*, **19,** 179-195.

Tracy, R. J., 1978, High grade metamorphic reactions and partial melting in pelitic schist, West-central Massachusetts. *American Journal of Science*, **278**, 150-178.

Zeh, A., 2004. Crystal Size Distribution (CSD) and Textural Evolution of Accessory Apatite, Titanite and Allanite during Four Stages of Metamorphism: an Example from the Moine Supergroup, Scotland. *Journal of Petrology*, **45,** 10, 2101–2132.

Appendix I: Piston Cylinder Press Readings

Note for all tables: The phrase, "light was on" indicates that the temperature deviated from within 5˚C of the desired temperature. Unusually high readings are red.

Experiment 4

Date	Time	Temp (˚C)	Output Power	Upper Ram Pressure (P.S.I)	Lower Ram Pressure (P.S.I)
4 Oct	15:10	50	11	6200	2600
	15:11	159	25.4	6200	2600
	15:12	266	32.5	6210	2600
	15:13	365	36.8	6220	2600
	15:14	469	40.4	6250	2550
	15:15	533	41.8	6290	2500
	15:56	584	43.5	6300	2400
	15:18	610	43.8	6350	2400→2500
	15:25	610	43.4	6410	2490→2600
	15:30	610	43.4	6500	2540
	15:35	610	43.7	6550	2540
	18:35	610	43.8	6790	2520
5 Oct	7:20	610	44.5	6800	2450→2600
	11:57	610	44.0	6810	2510
	12:15	610	43.9	6820	2510→2600
	15:29	610	43.8	6820	2550
6 Oct	9:00	610	44.6	6820	2500→2750
	16:38	610	44.9	6820	2690
	19:46	610	44.7	6820	2620
7 Oct	9:45	610	44.8	6810	2600
	12:55	610	44.6	6810	2600
	18:46	610	44.5	6800	2600
8 Oct	13:57	610	44.9	6800	2590
	19:03	610	44.6	6800	2590
9 Oct	12:59	610	44.6	6800	2580
	19:10	610	44.5	6800	2550→2600
10 Oct	8:28	610	44.7	6800	2590
	20:18	610	44.3	6800	2590
11 Oct	10:28	610	44.6	6800	2510→2650
	13:20	610	44.5	6800	2610
12 Oct	12:05	610	45.0	6800	2600
	13:47	610	45.0	6800	2600
	13:47	--	--	--	Quench

Experiment 5

Date	Time	Temp (˚C)	Output Power	Upper Ram Pressure (P.S.I)	Lower Ram Pressure (P.S.I)
12 Nov	15:30	144	16.4	6010	2510
	15:31	258	27.3	6010	2510
	15:32	366	37.6	6010	2490
	15:33	469	47.7	6100	2480
	15:34	560	56.8	6100	2380
	15:35	642	64.3	6120	2280
	15:37	650	65.0	6190	2210
	15:39	649	65.0	6200	2190
	15:45	650	65.0	6290	2150→2590
	15:50	650	65.0	6310	2500
	15:55	650	65.0	6380	2500
	16:00	650	65.0	6400	2500
	16:04	650	65.0	6410	2500
	16:13	650	65.0	6480	2500→2600
	19:48	650	65.0	6620	2500→2610
	22:15	650	46.8	6690	2550→2700
13 Nov	8:22	650	47.3	6700	2510→2600
	10:00	650	46.7	6700	2590
	13:00	650	46.5	6700	2500→2710
	15:55	650	47.2	6700	2680
	18:20	650	47.0	6700	2650
	20:55	650	46.9	6700	2620→2700
14 Nov	9:33	650	47.4	6700	2610
	12:55	650	47.2	6710	2610
	15:30	650	47.4	6705	2610
	17:55	650	47.3	6700	2600→2660
	18:50	650	47.4	6700	2620→2700
15 Nov	8:57	650	48.0	6700	2660
	10:22	650	48.0	6700	2660
	18:40	650	47.6	6700	2610→2710
16 Nov	9:50	650	48.2	6700	2680
	13:43	650	47.9	6700	2700
	22:27	650	47.6	6720	2700
17 Nov	8:24	650	48.1	6700	2680
	11:32	650	48.0	6700	2610→2710
	15:25	650	47.9	6700	2410→2700

	17:10	650	47.7	6700	2700
	19:00	650	47.8	6700	2700
18 Nov	10:04	650	47.9	6700	2700
	17:40	650	50.4	6800	2800→2700
19 Nov	7:19	650	53.6	6910	2690
	11:55	650	54.0	6910	2650
	13:33	650	54.1	6910	2650
	13:33	--	--	--	Quench

Experiment 6

Date	Time	Temp (°C)	Output Power	Upper Ram Pressure (P.S.I.)	Lower Ram Pressure (P.S.I.)
6 Dec	16:59	50	11.7	6020	2400
	17:00	150	24.0	6020	2400
	17:01	250	30.9	6040	2400
	17:02	350	36.7	6080	2410
	17:03	450	40.6	6090	2400
	17:04	550	44.4	6100	2400
	17:05	650	46.7	6110	2200→ 2510
	17:06	712	49.9	6180	2470
	17:07	745	50.0	6200	2310
	17:08	750	50.4	6200	2310→ 2650
	17:10	750	50.6	6280	2580→ 2690
	18:47	750	50.7	6740	2620
	20:43	750	50.8	6810	2620
7 Dec	8:10	750	51.4	6860	2550 light was on
	10:50	750	51.3	6860	2550
	11:57	750	51.2	6860	2550
	15:10	750	51.1	6810	2540
	16:37	750	50.7	6810	2520→ 2700
	17:44	750	50.8	6820	2680
8 Dec	8:25	750	51.1	6810	2610
	10:38	750	50.8	6810	2600
	11:38	750	50.9	6820	2590→ 2620
	13:25	750	51.1	6810	2610
	15:50	750	51.3	6820	2600
	17:27	750	51.0	6820	2580→ 2680
	19:30	750	51.0	6820	2640→ 2720
9 Dec	9:53	750	51.3	6820	2660
	16:00	750	51.0	6790	2620
	18:15	750	50.8	6790	2610→ 2700

10 Dec	8:45	750	51.1	6810	2620
	11:45	750	51.0	6800	2600
	12:10	750	51.0	6800	2560→ 2620
	15:24	750	51.2	6800	2600
	19:15	750	51.0	6800	2560→ 2700
11 Dec	9:45	750	50.7	6790	2600
	12:55	750	50.8	6760	2600
	15:55	750	50.9	6750	2600
	20:50	750	50.5	6780	2600
12 Dec	8:26	750	50.8	6800	2600
	15:00	750	50.5	6800	2610
	15:55	750	50.4	6800	2600
	18:15	750	50.4	6790	2590→ 2690
13 Dec	10:18	750	50.8	6800	2620
	11:57	750	51.0	6800	2620
	16:00	750	50.8	6780	2600
	19:55	750	50.2	6780	2600→ 2700
14 Dec	9:45	750	51.0	6820	2620
	10:38	750	50.9	6830	2620
	15:27	750	50.9	6800	2600
	22:40	750	50.5	6800	2590→ 2700
15 Dec	9:04	750	51.2	6840	2520→ 2650
	13:50	750	51.3	6840	2640
	17:17	750	50.9	6800	2610
	20:40	750	50.6	6800	2640→ 2730
16 Dec	9:37	750	50.9	6840	2580→ 2700
	13:50	750	51.9	6830	2680 light was on
	17:55	750	51.4	6800	2640→ 2700
17 Dec	7:27	750	51.8	6800	2560→ 2610
	11:55	750	51.7	6790	2540→ 2620
	12:55	750	51.7	6790	2550 Quench

Experiment 7

Date	Time	Temp (°C)	Output Power	Upper Ram Pressure (P.S.I.)	Lower Ram Pressure (P.S.I.)
1 Feb	18:16	25	10.3	6020	2500
	18:17	125	21.8	6020	2500
	18:18	225	30.4	6030	2510
	18:19	325	35.8	6090	2520
	18:20	425	40.7	6090	2520
	18:21	525	45.1	6100	2490

	18:22	625	49.0	6120	2360
	18:23	690	50.7	6140	2250 →2500
	18:24	749	52.6	6200	2330
	18:25	750	52.5	6210	2300
	18:28	750	52.6	6260	2240→2650
	18:36	750	53.0	6400	2510→ 2700
	21:20	750	53.1	6800	2600→2700
2 Feb	8:38	750	53.2	6810	2520→2690
	12:00	750	53.1	6810	2600
	14:05	750	53.0	6810	2600
	14:40	750	52.9	6810	2600
	21:20	750	52.6	6810	2550→2720
3 Feb	8:30	750	52.7	6800	2580→2700
	12:38	750	52.6	6800	2640
4 Feb	7:53	750	52.8	6790	2580
	8:36	750	53.8	6770	2590→2700
	10:07	750	52.7	6780	2650
	13:27	750	52.8	6760	2640
	14:34	750	52.9	6760	2630
	18:22	750	52.4	6760	2610→2700
5 Feb	10:06	750	52.4	6750	2610
	15:14	750	52.3	6750	2610
	18:41	750	52.4	6750	2605
	18:41	--	--	--	Quench

Experiment 8

Date	Time	Temp (°C)	Output Power	Upper Ram Pressure (P.S.I.)	Lower Ram Pressure (P.S.I.)
25 Feb	15:55	69	9.2	6000	2450
	15:16	188	22.5	6000	2450
	15:57	292	30.7	6000	2460
	15:58	39.2	40.6	6020	2470
	15:59	494	50.8	6040	2420
	16:00	598	60.6	6060	2260
	16:01	668	67.3	6090	2140→2500
	16:02	718	72.4	6120	2400
	16:03	746	74.6	6140	2310→2510
	16:04	750	75.0	6190	2460
	16:15	750	75.0	6350	2350→2540
	17:16	750	75.0	6650	2450→2570
	21:55	750	75.0	6750	2450→2700
26 Feb	7:37	750	75.0	6790	2500→2620
	8:33	750	53.7	6780	2560→2700

	12:47	750	53.7	6800	2560→2700
	14:47	750	53.7	6800	2620→2700
	17:25	750	53.5	6800	2650
	19:37	750	53.5	6780	2640→2710
27 Feb	8:34	750	46.1	6500	2140→2700
	10:32	750	44.0	6690	2620
	11:51	750	43.7	6670	2610
	13:05	750	43.6	6670	2610
	17:20	750	42.7	6610	2520→2750
	17:41	750	42.6	6630	2700
	20:57	750	42.4	6600	2690→2750
28 Feb	7:39	751	42.2	6600	2700
	8:04	750	42.3	6600	2700
	10:07	750	42.3	6600	2690
	13:34	750	41.9	6600	2680
	14:52	750	42.1	6600	2680
	16:24	750	42.0	6600	2680
	17:08	750	42.1	6590	2660
	21:00	750	41.5	6580	2660→2760
1 Mar	7:19	750	41.4	6570	2690
	8:45	750	41.4	6570	2690
	10:03	750	41.2	6560	2670
	13:57	750	40.9	6550	2650→2720
	14:24	750	41.0	6560	2700
	17:13	750	41.0	6520	2690→2780
2 Mar	9:07	750	40.7	6550	2610
	10:41	750	40.7	6540	2610
	13:40	750	40.7	6550	2610
	16:30	750	40.6	6540	2610→2710
	17:25	750	40.4	6540	2700
3 Mar	9:15	750	40.4	6530	2650
	13:05	750	40.5	6520	2650
	17:22	750	40.2	6540	2650
4 Mar	8:25	750	40.5	6540	2650
	10:51	750	40.6	6530	2650
	13:45	750	40.6	6530	2650
	14:15	750	40.7	6540	2650
	16:16	750	40.6	6540	2660
	17:15	750	40.6	6540	2660
	19:19	750	40.6	6540	2660
5 Mar	7:38	751	40.3	6540	2650
	10:21	750	40.5	6540	2660
	17:19	750	40.5	6550	2660
	19:52	750	40.4	6540	2660

6 Mar	8:55	750	40.4	6540	2660
	9:55	750	40.4	6540	2660
	12:10	750	40.5	6540	2650
	18:17	750	40.3	6540	2650
7 Mar	10:15	750	40.4	6540	2650
	15:00	750	40.5	6540	2650
	16:37	750	40.5	6540	2650
8 Mar	7:49	751	40.1	6550	2650
	9:51	750	40.2	6550	2650
	17:20	750	40.4	6540	2650
	19:32	750	40.3	6540	2650
9 Mar	8:49	750	40.3	6540	2640
	11:24	750	40.3	6530	2640
	19:50	750	40.0	6540	2650
10 Mar	9:25	750	40.2	6530	2630
	14:22	750	40.1	6330	2640
11 Mar	12:20	750	40.3	6530	2640
12 Mar	8:30	750	40.2	6530	2630
	8:45	750	40.3	6530	2640
	10:50	750	40.2	6530	2630
	12:00	750	40.0	6520	2630
	15:05	750	40.2	6530	2630
	18:10	750	40.0	6530	2630
13 Mar	8:54	750	40.2	6530	2630 light was on
	9:55	750	40.3	6530	2620
	11:50	750	40.2	6530	2620
	16:55	750	40.4	6530	2630
	18:37	750	40.0	6530	2630
14 Mar	8:34	750	40.3	6520	2620
	10:55	750	40.2	6520	2610
15 Mar	7:20	750	39.9	6505	2580
	8:50	750	39.9	6505	2580
	11:55	750	39.8	6510	2580
	13:43	750	39.9	6510	2590
	13:44	--	--	--	Quench

Appendix II
Theriak Domino Calculaitons

The following bulk composition was used for all calculations:
K(2) Mg(14.64) Fe(13.37) Al(14) Si(26) H(144) o(?)

Below is the Theriak Domino for finding the threshold temperature at which garnet begins to grow at 8kbar (Garnet begins to grow at 590˚C)

```
-------------------------------
 define Temperature and Pressure
 -------------------------------
 Enter [ "?" | CR | "end" | T(C)  P(bar) ]:
590 8000

 P =  8000.00 bar    P(Gas) =  8000.00 bar    T =  590.00 C    =   863.15 K

 -----------------------
 equilibrium assemblage:
 -----------------------

  P =  8000.00 bar       P(Gas) =  8000.00 bar     T =  590.00 C    =  863.15 K
  stable phases:   6     loop =   8     loop2 =   1     max.phases =    155        gcalc =     18325       blkshift = 1.06581E-14
  G(-) = 3.01270E-12     G(System) =   -77651449.51     stepsize = 0.00000E+00     R =     8.3143000


         phase                   N         mol%                                  x             x         activity       act.(x)
         -----                   -         ----                                  -             -         --------       -------
   0  3  GARNET_Alm            0.529493    0.799841        PYROPE            0.169963     1.69963E-01   6.47206E-03   6.47206E-03
                                                           ALMANDINE         0.830037     8.30037E-01   5.87657E-01   5.87657E-01

                             [Mg(M)]     = 0.169963     [Fe(M)]     = 0.830037
                             Mg/(Fe+Mg)  = 0.169963

   0  4  BIOTITE_Phl           2.000000    3.021156        PHLOGOPITE        0.560442     5.60442E-01   1.76033E-01   1.76033E-01
                                                           ANNITE            0.439558     4.39558E-01   8.49273E-02   8.49273E-02

                             [Fe(M)]     = 0.439558     [Mg(M)]     = 0.560442
                             Mg/(Fe+Mg)  = 0.560442

   0  6  STAU_FSt              0.001852    0.002798        FE-STAUROLITE     0.799846     7.99846E-01   3.66048E-01   3.66048E-01
                                                           MG-STAUROLITE     0.200154     2.00154E-01   2.69864E-04   2.69864E-04

                             [Fe(T)]     = 0.799846     [Mg(T)]     = 0.200154
                             Mg/(Fe+Mg)  = 0.200154

   0  8  CHL4_Ame              4.311325    6.512592        AMESITE           0.279785     2.79785E-01   6.12771E-03   6.12771E-03
                                                           PENNINITE         0.260662     2.60662E-01   4.61651E-03   4.61651E-03
                                                           FEAMESITE         0.230217     2.30217E-01   2.80898E-03   2.80898E-03
                                                           FEPENNINITE       0.229336     2.29336E-01   2.76622E-03   2.76622E-03

                             [AL(T5)]    = 0.632501     [SI(T5)]    = 0.367499
```

```
                         Mg/(Fe+Mg)  = 0.539131
                         Si(pfu)     = 2.734997

 22  0  A-QUARTZ           6.606168    9.979131

 65  0  STEAM             52.750996   79.684483

(Fe/Mg): GARNET - BIOTITE          KD =     6.2267     ln(KD) =    1.8288
(Fe/Mg): GARNET - STAU             KD =     1.2221     ln(KD) =    0.2006
(Fe/Mg): GARNET - CHL4             KD =     5.7129     ln(KD) =    1.7427
(Fe/Mg): BIOTITE - STAU            KD =     0.1963     ln(KD) =   -1.6283
(Fe/Mg): BIOTITE - CHL4            KD =     0.9175     ln(KD) =   -0.0861
(Fe/Mg): STAU - CHL4               KD =     4.6748     ln(KD) =    1.5422

---------------------------------------
volumes and densities of stable phases:
---------------------------------------

 solid phases          N      volume/mol  volume[ccm]    vol%  |   wt/mol      wt [g]     wt %  | density [g/ccm]
 ------------                                                  |                                  |
 GARNET_Alm          0.5295     115.8383     61.3356    4.3023 |  481.6705    255.0413    5.9763 |     4.158126
 BIOTITE_Phl         2.0000     152.8892    305.7784   21.4482 |  458.8536    917.7072   21.5044 |     3.001217
 STAU_FSt            0.0019     448.1427      0.8300    0.0582 | 1666.4469      3.0863    0.0723 |     3.718563
 CHL4_Ame            4.3113     210.7521    908.6209   63.7333 |  625.0454   2694.7740   63.1459 |     2.965785
 A-QUARTZ            6.6062      22.5693    149.0965   10.4581 |   60.0843    396.9270    9.3011 |     2.662215
                                          ----------  -------- |            ----------  -------- |   ----------
 total of solids                           1425.6614  100.0000 |             4267.5357  100.0000 |     2.993373


 gases and fluids      N      volume/mol  volume[ccm]              wt/mol      wt [g]             density [g/ccm]
 ----------------
 STEAM              52.7510      19.2845   1017.2756              18.0153    950.3240                  0.934185


-----------------------------
H2O content of stable phases:
-----------------------------
                                                               |  wt% of     wt% of     wt% of
 solid phases          N     H2O[pfu]    H2O[mol]     H2O [g]  |  phase      solids     H2O.solid
 ------------                                                  |
 BIOTITE_Phl         2.0000    1.000      2.0000      36.0306  |  3.92615    0.84429    10.3901
 STAU_FSt            0.0019    2.000      0.0037       0.0667  |  2.16212    0.00156     0.0192
 CHL4_Ame            4.3113    4.000     17.2453     310.6789  | 11.52894    7.28005    89.5906
                                        --------   ----------  |           --------
 total H2O in solids                     19.2490     346.7762  |            8.12591

                                                               |  wt% of
 gases and fluids      N     H2O[pfu]    H2O[mol]     H2O [g]  |  phase
 ----------------                                              |
 STEAM              52.7510    1.000     52.7510     950.3240  | 100.00000

-------------------------------
```

```
define Temperature and Pressure
-------------------------------
Enter [ "?" | CR | "end" | T(C)  P(bar) ]:
585 8000

P =  8000.00 bar    P(Gas) =  8000.00 bar    T =  585.00 C   =   858.15 K

-----------------------
equilibrium assemblage:
-----------------------

 P =  8000.00 bar       P(Gas) =  8000.00 bar     T =  585.00 C    =  858.15 K
 stable phases:   5     loop =  19     loop2 =   1     max.phases =    185        gcalc =     37395       blkshift = 3.55271E-14
 G(-) = 1.36879E-10     G(System) =   -77574100.01     stepsize = 3.22639E-08     R =     8.3143000


        phase                  N          mol%                                    x              x          activity       act.(x)
        -----                  -          ----                                    -              -          --------       -------
  0  4  BIOTITE_Phl          2.000000    3.063268        PHLOGOPITE          0.543670     5.43670E-01   1.60696E-01   1.60696E-01
                                                         ANNITE              0.456330     4.56330E-01   9.50249E-02   9.50249E-02

                          [Fe(M)]     = 0.456330     [Mg(M)]     = 0.543670
                          Mg/(Fe+Mg)  = 0.543670

  0  6  STAU_FSt             0.013675    0.020945        FE-STAUROLITE       0.810588     8.10588E-01   3.90414E-01   3.90414E-01
                                                         MG-STAUROLITE       0.189412     1.89412E-01   2.04056E-04   2.04055E-04

                          [Fe(T)]     = 0.810588     [Mg(T)]     = 0.189412
                          Mg/(Fe+Mg)  = 0.189412

  0  8  CHL4_Ame             4.638705    7.104797        AMESITE             0.271274     2.71274E-01   5.41544E-03   5.41544E-03
                                                         PENNINITE           0.248274     2.48274E-01   3.79947E-03   3.79947E-03
                                                         FEAMESITE           0.240014     2.40014E-01   3.31856E-03   3.31856E-03
                                                         FEPENNINITE         0.240438     2.40438E-01   3.34203E-03   3.34203E-03

                          [AL(T5)]    = 0.633466     [SI(T5)]    = 0.366534
                          Mg/(Fe+Mg)  = 0.517762
                          Si(pfu)     = 2.733067

 22  0  A-QUARTZ             7.219548   11.057704

 65  0  STEAM               51.417831   78.753287

(Fe/Mg): BIOTITE - STAU             KD =     0.1961     ln(KD) =   -1.6290
(Fe/Mg): BIOTITE - CHL4             KD =     0.9012     ln(KD) =   -0.1040
(Fe/Mg): STAU - CHL4                KD =     4.5947     ln(KD) =    1.5249

---------------------------------------
volumes and densities of stable phases:
---------------------------------------

 solid phases           N       volume/mol  volume[ccm]    vol%  |    wt/mol       wt [g]      wt %   | density [g/ccm]
```

```
 ------------                                              |                                   |
 BIOTITE_Phl          2.0000     152.9484     305.8967   21.0577 |   460.4407     920.8814   21.4580 |      3.010432
 STAU_FSt             0.0137     448.1733       6.1286    0.4219 |  1667.8022      22.8067    0.5314 |      3.721333
 CHL4_Ame             4.6387     210.7733     977.7151   67.3051 |   628.2106    2914.0835   67.9028 |      2.980504
 A-QUARTZ             7.2195      22.5666     162.9205   11.2153 |    60.0843     433.7815   10.1078 |      2.662535
                                            ----------  -------- |               ----------  -------- |   ----------
 total of solids                             1452.6609  100.0000 |               4291.5531  100.0000 |      2.954270


 gases and fluids       N       volume/mol  volume[ccm]              wt/mol       wt [g]              density [g/ccm]
 ----------------
 STEAM               51.4178      19.2355     989.0495               18.0153     926.3066                   0.936562


----------------------------
H2O content of stable phases:
----------------------------
                                                                 |  wt% of     wt% of     wt% of
 solid phases           N      H2O[pfu]    H2O[mol]     H2O [g]  |  phase      solids     H2O.solid
 ------------                                                    |
 BIOTITE_Phl          2.0000     1.000       2.0000     36.0306  |  3.91262    0.83957     9.7171
 STAU_FSt             0.0137     2.000       0.0273      0.4927  |  2.16036    0.01148     0.1329
 CHL4_Ame             4.6387     4.000      18.5548    334.2703  | 11.47085    7.78903    90.1500
                                           ---------   ----------|           --------
 total H2O in solids                        20.5822    370.7935  |            8.64008

                                                                 |  wt% of
 gases and fluids       N      H2O[pfu]    H2O[mol]     H2O [g]  |  phase
 ----------------                                                |
 STEAM               51.4178     1.000      51.4178    926.3066  | 100.00000

------------------------------
define Temperature and Pressure
------------------------------
Enter [ "?" | CR | "end" | T(C)  P(bar) ]:
```

Below is the Theriak Domino for the threshold temperature to make garnet at 600˚C (Garnet begins to grow at 4200bar)

```
------------------------------
 define Temperature and Pressure
 ------------------------------
 Enter [ "?" | CR | "end" | T(C)  P(bar) ]:
600 4200

 P =  4200.00 bar    P(Gas) =  4200.00 bar    T =  600.00 C   =   873.15 K

 ----------------------
 equilibrium assemblage:
 ----------------------

  P =  4200.00 bar       P(Gas) =  4200.00 bar     T =  600.00 C    =  873.15 K
  stable phases:   6     loop =   7     loop2 =   1     max.phases =    156       gcalc =     15290       blkshift = 4.08562E-14
```

```
 G(-) = 2.27374E-13     G(System) =   -78778971.13     stepsize = 1.00000E-09     R =     8.3143000

       phase                   N         mol%                                  x            x          activity       act.(x)
       -----                   -         ----                                  -            -          --------       -------
  0  3  GARNET_Alm           0.047671    0.070899       PYROPE             0.179772     1.79772E-01   7.42137E-03   7.42137E-03
                                                         ALMANDINE          0.820228     8.20228E-01   5.67630E-01   5.67630E-01

                             [Mg(M)]     = 0.179772     [Fe(M)]     = 0.820228
                             Mg/(Fe+Mg)  = 0.179772

  0  4  BIOTITE_Phl          2.000000    2.974487       PHLOGOPITE         0.552909     5.52909E-01   1.69029E-01   1.69029E-01
                                                         ANNITE             0.447091     4.47091E-01   8.93694E-02   8.93694E-02

                             [Fe(M)]     = 0.447091     [Mg(M)]     = 0.552909
                             Mg/(Fe+Mg)  = 0.552909

  0  7  OPX_femg             3.157408    4.695834       ORTHOENSTATITE     0.124452     1.24452E-01   1.24452E-01   1.24452E-01
                                                         FERROSILITE        0.283424     2.83424E-01   2.83424E-01   2.83424E-01
                                                         MG.FE-PYROXENE     0.535507     5.35507E-01   5.35507E-01   5.35507E-01
                                                         FE.MG-PYROXENE     0.034827     3.48268E-02   3.48268E-02   3.48268E-02
                                                         MG.AL-PYROXENE     0.008243     8.24274E-03   8.24274E-03   8.24274E-03
                                                         FE.AL-PYROXENE     0.013547     1.35468E-02   1.35468E-02   1.35468E-02

                             [Mg(M1)]    = 0.668202     [Fe(M1)]    = 0.331798
                             [Mg(M2)]    = 0.159279     [Fe(M2)]    = 0.818932     [Al(M2)]    = 0.021790
                             Mg/(Fe+Mg)  = 0.418298
                             Si(pfu)     = 1.978210

  0  8  CHL4_Ame             2.790519    4.150181       AMESITE            0.280790     2.80790E-01   6.21625E-03   6.21625E-03
                                                         PENNINITE          0.269374     2.69374E-01   5.26530E-03   5.26530E-03
                                                         FEAMESITE          0.222719     2.22719E-01   2.46053E-03   2.46053E-03
                                                         FEPENNINITE        0.227117     2.27117E-01   2.66070E-03   2.66070E-03

                             [AL(T5)]    = 0.627632     [SI(T5)]    = 0.372368
                             Mg/(Fe+Mg)  = 0.548970
                             Si(pfu)     = 2.744736

  0  9  CORD_Cd              1.190346    1.770334       CORDIERITE         0.398465     3.98465E-01   1.58774E-01   1.58774E-01
                                                         HY_CORDIERITE      0.196163     1.96163E-01   3.84800E-02   3.84800E-02
                                                         FE_CORDIERITE      0.271643     2.71643E-01   7.37898E-02   7.37898E-02
                                                         HY_Fe_CORDIERITE   0.133729     1.33729E-01   1.78834E-02   1.78834E-02
                             Mg/(Fe+Mg)  = 0.594628

 65  0  STEAM               58.052552   86.338266

(Fe/Mg): GARNET - BIOTITE           KD =      5.6425     ln(KD) =    1.7303
(Fe/Mg): GARNET - OPX               KD =      3.2809     ln(KD) =    1.1881
(Fe/Mg): GARNET - CHL4              KD =      5.5534     ln(KD) =    1.7144
(Fe/Mg): GARNET - CORD              KD =      6.6928     ln(KD) =    1.9010
(Fe/Mg): BIOTITE - OPX              KD =      0.5815     ln(KD) =   -0.5422
(Fe/Mg): BIOTITE - CHL4             KD =      0.9842     ln(KD) =   -0.0159
```

```
(Fe/Mg): BIOTITE - CORD             KD =     1.1861     ln(KD) =    0.1707
(Fe/Mg): OPX - CHL4                 KD =     1.6926     ln(KD) =    0.5263
(Fe/Mg): OPX - CORD                 KD =     2.0399     ln(KD) =    0.7129
(Fe/Mg): CHL4 - CORD                KD =     1.2052     ln(KD) =    0.1866

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volumes and densities of stable phases:
---------------------------------------

 solid phases           N       volume/mol  volume[ccm]    vol%  |    wt/mol       wt [g]      wt %  | density [g/ccm]
 ------------                                                    |                                   |
 GARNET_Alm           0.0477     116.0965       5.5345    0.3950 |   480.7423      22.9176    0.5493 |      4.140887
 BIOTITE_Phl          2.0000     153.9603     307.9206   21.9793 |   459.5665     919.1330   22.0309 |      2.984968
 OPX_femg             3.1574      65.4929     206.7876   14.7605 |   237.1080     748.6466   17.9444 |      3.620364
 CHL4_Ame             2.7905     212.2947     592.4123   42.2863 |   623.6992    1740.4444   41.7170 |      2.937894
 CORD_Cd              1.1903     242.1992     288.3009   20.5789 |   622.4115     740.8852   17.7584 |      2.569833
                                          ----------  --------- |             ----------  --------- |    ----------
 total of solids                            1400.9559  100.0000 |              4172.0267  100.0000 |      2.977986


 gases and fluids       N       volume/mol  volume[ccm]               wt/mol       wt [g]             density [g/ccm]
 ----------------
 STEAM               58.0526      23.3031    1352.8040                18.0153    1045.8330                  0.773085


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H2O content of stable phases:
-----------------------------
                                                                 |   wt% of     wt% of     wt% of
 solid phases           N      H2O[pfu]    H2O[mol]     H2O [g]  |   phase      solids     H2O.solid
 ------------                                                    |
 BIOTITE_Phl          2.0000     1.000       2.0000      36.0306 |   3.92006    0.86362    14.3395
 CHL4_Ame             2.7905     4.000      11.1621     201.0879 |  11.55383    4.81991    80.0295
 CORD_Cd              1.1903     0.660       0.7854      14.1487 |   1.90970    0.33913     5.6309
                                           ---------  ---------- |             --------
 total H2O in solids                        13.9474     251.2672 |              6.02266

                                                                 |   wt% of
 gases and fluids       N      H2O[pfu]    H2O[mol]     H2O [g]  |   phase
 ----------------                                                |
 STEAM               58.0526     1.000      58.0526    1045.8330 | 100.00000

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define Temperature and Pressure
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Enter [ "?" | CR | "end" | T(C)  P(bar) ]:
600 4150

P =  4150.00 bar    P(Gas) =  4150.00 bar    T =  600.00 C   =   873.15 K

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equilibrium assemblage:
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 P =  4150.00 bar       P(Gas) =  4150.00 bar     T =  600.00 C    =  873.15 K
 stable phases:   5     loop =  17     loop2 =   1     max.phases =    188        gcalc =     26449       blkshift = 5.68434E-14
 G(-) = 2.05773E-11     G(System) =   -78792754.15     stepsize = 1.86333E-08     R =     8.3143000

        phase                   N          mol%                                    x              x          activity       act.(x)
        -----                   -          ----                                    -              -          --------       -------
  0  4  BIOTITE_Phl           2.000000    2.977792        PHLOGOPITE         0.551152     5.51152E-01   1.67423E-01   1.67423E-01
                                                          ANNITE             0.448848     4.48848E-01   9.04270E-02   9.04270E-02

                            [Fe(M)]      = 0.448848     [Mg(M)]     = 0.551152
                            Mg/(Fe+Mg)   = 0.551152

  0  7  OPX_femg              3.175531    4.728036        ORTHOENSTATITE     0.123411     1.23411E-01   1.23411E-01   1.23411E-01
                                                          FERROSILITE        0.285093     2.85093E-01   2.85093E-01   2.85093E-01
                                                          MG.FE-PYROXENE     0.534829     5.34829E-01   5.34829E-01   5.34829E-01
                                                          FE.MG-PYROXENE     0.034783     3.47827E-02   3.47827E-02   3.47827E-02
                                                          MG.AL-PYROXENE     0.008228     8.22807E-03   8.22807E-03   8.22807E-03
                                                          FE.AL-PYROXENE     0.013655     1.36554E-02   1.36554E-02   1.36554E-02

                            [Mg(M1)]     = 0.666468     [Fe(M1)]    = 0.333532
                            [Mg(M2)]     = 0.158194     [Fe(M2)]    = 0.819923     [Al(M2)]    = 0.021883
                            Mg/(Fe+Mg)   = 0.416893
                            Si(pfu)      = 1.978117

  0  8  CHL4_Ame              2.808339    4.181325        AMESITE            0.280115     2.80115E-01   6.15665E-03   6.15665E-03
                                                          PENNINITE          0.268190     2.68190E-01   5.17332E-03   5.17332E-03
                                                          FEAMESITE          0.223596     2.23596E-01   2.49953E-03   2.49953E-03
                                                          FEPENNINITE        0.228099     2.28099E-01   2.70704E-03   2.70704E-03

                            [AL(T5)]     = 0.627783     [SI(T5)]    = 0.372217
                            Mg/(Fe+Mg)   = 0.547063
                            Si(pfu)      = 2.744433

  0  9  CORD_Cd               1.202226    1.789990        CORDIERITE         0.398287     3.98287E-01   1.58633E-01   1.58633E-01
                                                          HY_CORDIERITE      0.194486     1.94486E-01   3.78249E-02   3.78249E-02
                                                          FE_CORDIERITE      0.273617     2.73617E-01   7.48665E-02   7.48665E-02
                                                          HY_Fe_CORDIERITE   0.133609     1.33609E-01   1.78514E-02   1.78514E-02
                            Mg/(Fe+Mg)   = 0.592773

 65  0  STEAM                57.977754   86.322857

(Fe/Mg): BIOTITE - OPX              KD =     0.5822     ln(KD) =   -0.5409
(Fe/Mg): BIOTITE - CHL4             KD =     0.9836     ln(KD) =   -0.0165
(Fe/Mg): BIOTITE - CORD             KD =     1.1854     ln(KD) =    0.1701
(Fe/Mg): OPX - CHL4                 KD =     1.6894     ln(KD) =    0.5244
(Fe/Mg): OPX - CORD                 KD =     2.0360     ln(KD) =    0.7110
(Fe/Mg): CHL4 - CORD                KD =     1.2052     ln(KD) =    0.1866

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volumes and densities of stable phases:
---------------------------------------

 solid phases           N       volume/mol  volume[ccm]    vol%  |    wt/mol       wt [g]      wt %  | density [g/ccm]
 ------------                                                     |                                   |
 BIOTITE_Phl         2.0000     153.9822     307.9644   21.9445 |   459.7327     919.4654   22.0317 |      2.985623
 OPX_femg            3.1755      65.5006     207.9991   14.8213 |   237.1941     753.2171   18.0482 |      3.621252
 CHL4_Ame            2.8083     212.3175     596.2594   42.4874 |   623.9808    1752.3495   41.9888 |      2.938904
 CORD_Cd             1.2022     242.1809     291.1561   20.7468 |   622.4638     748.3422   17.9313 |      2.570244
                                            ----------  -------- |               ----------  -------- |    ----------
 total of solids                             1403.3790  100.0000 |              4173.3742  100.0000 |      2.973804


 gases and fluids       N       volume/mol  volume[ccm]              wt/mol       wt [g]              density [g/ccm]
 ----------------
 STEAM              57.9778      23.3892    1356.0519               18.0153    1044.4855                   0.770240


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H2O content of stable phases:
-----------------------------
                                                                  |   wt% of     wt% of     wt% of
 solid phases           N      H2O[pfu]    H2O[mol]     H2O [g]  |   phase      solids     H2O.solid
 ------------                                                     |
 BIOTITE_Phl         2.0000     1.000       2.0000      36.0306 |   3.91864    0.86334    14.2630
 CHL4_Ame            2.8083     4.000      11.2334     202.3721 |  11.54861    4.84912    80.1110
 CORD_Cd             1.2022     0.656       0.7889      14.2121 |   1.89914    0.34054     5.6260
                                          --------   ---------- |              --------
 total H2O in solids                       14.0222     252.6147 |              6.05301

                                                                  |   wt% of
 gases and fluids       N      H2O[pfu]    H2O[mol]     H2O [g]  |   phase
 ----------------                                                 |
 STEAM              57.9778     1.000      57.9778    1044.4855 | 100.00000

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define Temperature and Pressure
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Enter [ "?" | CR | "end" | T(C)  P(bar) ]:
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