


Senior Thesis

A ESTIMATION OF THE PHYSICAL PARAMETERS OF MAGMA
CRYSTALLIZATION FOR SANTORINI LAVA USING
THERMODYNAMIC METHODS

Presented in Partial Fulfillment of the Requirements for the Degree of Bachelor of
Science in the Department of Geological Sciences

by
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1996

Approved by:

A handwritten signature in black ink, appearing to read "MBarton", written over a horizontal line.

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Department of Geological Sciences

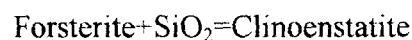
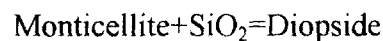
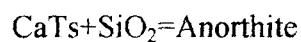
Introduction

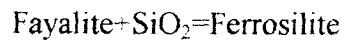
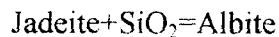
Accurate procedures now exist that can estimate the pressure and temperature at which magmas crystallize. Knowing these conditions are important for a number of reasons. First, the path of magma evolution can be determined by knowing the pressure and temperature. Furthermore, accurate calculation of pressure and temperature of magma crystallization can give important insight into the depth of magma crystallization at or below the Earth's crust. Finally, knowledge of pressure and temperature of magmas is necessary in order to calculate assorted physical properties of magmas, which in turn, are indispensable for modelling of eruptions and magma flow.

Typically, pressure and temperature of magma crystallization can be determined through experiments. However, predicting the pressure and temperature parameters can also be determined by the use of thermodynamic calculations. There are advantages to this method. Thermodynamic calculations are relatively fast and inexpensive when compared with experiments. Furthermore, when compared to the laborious methods involved in experimental techniques, thermodynamic calculations provide an easy alternative to finding the pressure and temperature parameters of magma crystallization. Finally, thermodynamic calculations are faster than experimentation methods. The scope of this thesis is concerned with the theory and application of these thermodynamic principles and how they relate to a sample basalt from the Santorini volcano located in the Hellenic arc, Greece.

Objectives

The sample basalt that was analyzed for this thesis, originated from a volcanic center on Santorini known as, Micro Profitas Ilias. This is one of four volcanic centers on Santorini that has been studied intensively. Earlier findings have determined that these centers have erupted at different times in Santorini's history, as well as being geochemically distinct from one another (Huijismans and Barton, 1989). To determine whether the sample studied (hereafter, to be referred as slide 138) evolved under the same physical conditions and depth as the other samples taken from different Santorini volcanic centers, methods employing thermodynamic techniques were utilized. These techniques for calculating crystallization conditions are based on chemical compositions of the basalts analyzed. Basalts typically contain phenocrysts with the following components; clinopyroxene (cpx), olivene (ol) and plagioclase (plag). From these chemical components, equilibrium equations can be established. By deriving these equations and then plotting them graphically against each other, the resulting intersection will provide the pressure and temperature of crystallization of that given basalt. The five equilibrium used are as follows:





(CaTs= the Ca-Tschermak's component of clinopyroxene.)

Applying these equations to the other volcanos studied (Patmos, Greece) crystallization temperatures ranged from 1173 to 920° C. Also pressures were determined to range from 2 to 4 kilobars (Barton and Wyers 1991) By interpreting these results, an estimated depth of the magma chambers for these volcanic centers has been determined to range from approximately 6 to 9 kilometers depth. Earlier research of lavas from the Micro Profitas Ilias volcanic center, has shown them to contain Bronzite. Bronzite is pyroxene phenocrysts with cores containing high amounts of aluminum. The high aluminum content in these magmas has been found to be the result of the magma crystallizing in a high pressure environment (Huijsmans and Barton, 1989). Initial analysis of slide 138 has produced results indicating aluminum-rich pyroxene cores. Research performed on other Santorini basalts utilizing the thermodynamic techniques described above, have revealed pressure and temperature of crystallization to be in the range of 2 to 3 kilobars pressure and temperature ranging from 1020-1050°c respectively.

These values are consistent with data from earlier measurements as stated above (Barton, unpublished). Variables for silica in a melt are included in each of the above equilibrium. At this time, there is no known method of calculating the variable composition, or activity of silica. Therefore, three or more of the equilibrium must be

must be solved simultaneously for pressure, temperature, and silica activity in order to get accurate results for the conditions of crystallization of a magma. It should be noted however, that the thermodynamic techniques that have been applied towards the Santorini basalts, can also be applied towards any igneous sample.

Electron Microprobe Methodology

The first step in determining the pressures and temperatures of magma crystallization, is to obtain the exact chemical content. This is achieved through the use of an electron microprobe. The chemical composition of slide 138 was determined in this way. The microprobe used was a Cameca SX-50 microprobe equipped with four wavelength-dispersive and one energy dispersive spectrometers. The analysis that comprises the data in this thesis was performed on August 1, 1995. Approximately, 20 hours were spent working with the microprobe, when considering calibrations necessary for accurate analysis. Analysis focused on obtaining data from pyroxene phenocrysts in the basalt sample (slide 138). One technique employed to maximize the value of the data, was to analyze both the edges and the cores of pyroxene phenocrysts, in order to differentiate compositional differences within each phenocryst. These compositional differences can be attributed the cores of the phenocrysts being formed under different physical conditions than the rims. This may be due to the fact that the cores of the

phenocrysts were crystallized at different depths than the rims. During analysis, the electron beam was set at one micron and an accelerating voltage of 15kV. Current for the probe was set to 20nA. Earlier work on this basalt sample by Dr. Barton, included analysis for plagioclase, pyroxene, magnetite, as well as, olivene analysis. The pyroxene data obtained from this basalt was subsequently added to the earlier pyroxene data. Figure 1., below, is a spreadsheet data set showing the combined pyroxene data from these analyses.

Figure 1.

	Na	Fe	Ti	Si	Ca	Mn	Al	Ni	Mg	Cr	Sum	Mg#
SI138 GR1 CORE	0.0203	0.4057	0.011758	1.919551	0.78943	0.018793	0.059292	0	0.825372	0	4.049195	0.67045
SI138 GR1 CORE	0.020159	0.426857	0.017034	1.87245	0.807508	0.018345	0.083559	0	0.832874	0	4.078805	0.661147
SI138 GR1 RIM	0.016639	0.396121	0.014925	1.872388	0.732504	0.012806	0.07523	0.003807	0.962171	0.000403	4.063795	0.708368
SI138 GR2 CORE	0.005648	0.777351	0.011397	1.894513	0.210331	0.023602	0.041051	0.001513	1.130981	0.000101	4.096489	0.592654
RIM OF LAST WE	0.022324	0.475748	0.024134	1.876032	0.705397	0.014481	0.112325	0	0.824392	0.000201	4.055035	0.634079
SI 138 PHENO CO	0.022579	0.43727	0.019757	1.860755	0.746381	0.013305	0.10211	0	0.877567	0	4.079723	0.667434
SI138 RIM OF ABO	0.033273	0.300468	0.019359	1.833147	0.82007	0.00857	0.171609	0	0.891829	0.001714	4.08004	0.747992
SI138 RIM OF SAM	0.016441	0.319345	0.016744	1.851001	0.803749	0.012003	0.112255	0.000202	0.952593	0.000705	4.085049	0.74893
MEGA CORE SA	0.026562	0.427501	0.015351	1.844818	0.745282	0.013735	0.119979	0	0.859845	0.002121	4.095294	0.677928
AS ABOVE NEW S	0.026712	0.407228	0.019454	1.857213	0.76018	0.012398	0.134959	0.001008	0.850042	0.004133	4.073337	0.675101
ST138 PYR1 core	0.101	0.262	0.014	1.802	0.717	0.009	0.45	0	0.655	0.001	4.009	0.7144
ST138 PYR2 core	0.057	0.39	0.022	1.85	0.705	0.013	0.2	0	0.801	0.001	4.047	0.6726
ST138 PYR2 rim	0.05	0.382	0.021	1.877	0.697	0.012	0.197	0	0.786	0	4.033	0.6729
ST138 PYR4 core	0.025	0.417	0.02	1.837	0.759	0.013	0.122	0	0.899	0.002	4.054	0.6831
ST138 PYR5 lg edge	0.083	0.64	0.022	1.947	0.572	0.018	0.046	0	0.72	0.001	4.045	0.5291
ST138 PYR5 lg core	0.043	0.404	0.018	1.846	0.739	0.012	0.156	0	0.861	0.001	4.079	0.6808
ST138 PYR6 core	0.024	0.426	0.02	1.835	0.777	0.012	0.097	0	0.915	0.001	4.108	0.6821
ST138 PYR 13 core	0.027	0.541	0.018	2.002	0.406	0.02	0.143	0	0.765	0	3.923	0.5858

Thermodynamic Background

After obtaining probe analyses, the data is processed in a number of computer programs

that calculate the pressure and temperature of magma crystallization. In order to get this result, the computer programs must first calculate the chemical potentials of the separate chemical equilibrium shown previously.

The equation for the chemical potential in an ideal phase is

$$\mu_i = \mu^{\circ} + RT \ln X_i$$

In this equation, R = the gas constant, μ° represents the chemical potential of a pure end member i found at standard pressure and temperature. X_i represents the mole fraction, which in this study is the silica activity. The chemical potential is defined as the energy in one mole of substance available for a reaction, this is also known as Gibb's free energy, G . The equation for the change in Gibb's free energy at equilibrium is:

$$\Delta G_{reaction} = 0 = X_c \mu_c + X_d \mu_d - X_a \mu_a - X_b \mu_b$$

By reworking this equation, the combined mole fractions in this equation can be given a new value known as the equilibrium constant, or K . The equation can then be written in the form:

$$R \ln K = -(\sum X_i \mu_i) / T$$

The change in Gibb's free energy can also be expressed as

$$\Delta G_{reaction} = \sum G_{products} - \sum G_{reactants}$$

To calculate the standard state Gibb's free energy, G° , which refers to the Gibb's free energy for a pure phase, A , this expression is used (Barton, unpublished).

$$G_A^{\circ} = H_A^{\circ} - TS_A^{\circ} + (P-1)V_A^{\circ}$$

In this equation, H =enthalpy, V =volume and S = entropy . However, this equation only

deals with pure phases, which means a temperature of 298K and at a pressure of 0.001
 The equation in this form, is unsuitable for calculating chemical potentials of igneous rocks which crystallize at much higher pressures and temperatures. Therefore, corrections have to be made in order to get free energy equations that work for the basalts analyzed. The following equations correct for elevated temperature and pressure values and their effects on entropy, volume and enthalpy respectively.

$$S^{P,T} - S^{Pr,Tr} = \int_{Tr}^T (C_p/T) dT - \int_{Pr}^P (\partial V/\partial T)_P dP$$

$$V^{P,T} / V^{Pr,Tr} = 1 + v_1 (P - P_r) + v_2 (P - P_r)^2 + v_3 (T - T_r) + v_4 (T - T_r)^2$$

$$\Delta_a H^{P,T} = \Delta_f H^{Pr,Tr} + \int_{Tr}^T C_p dT + \int_{Pr}^P \{V^{Pr,Tr} - T(\partial V/\partial T)_P\} dP$$

Where C_p is the heat capacity (Berman, 1991). The mole fractions in the equations refer to the SiO₂ liquid melt. Therefore, standard-state variables for pure liquid components are calculated. These calculations for standard state entropy and enthalpy for a liquid component are respectively;

$$S^o_{liq}(T_r) = S^o_{THIRDLAW298} + \int_{298}^{T_{fus}} (C_{p, sol}^o/T) dT + \Delta S^o_{fus}(T_{fus}) + \int_{T_{fus}}^T (C_{pliq}^o/T) dT$$

$$H^o_{liq}(T_r) = \Delta_f H^o_{SOL298} + \int_{298}^{T_{fus}} C_{psolid}^o dT + \Delta H^o_{fus}(T_{fus}) + \int_{T_{fus}}^T C_{pliq}^o dT$$

With the last two terms in the equation representing heat of fusion and liquid heat capacity respectively (Lange and Carmichael, 1990).

As stated previously, the silica activities cannot be determined on their own. This is due to the fact that the amount of silica cannot be precisely determined. This is because repulsive and attractive forces amongst the components in a solution can change the chemical behavior of the components (Barton, unpublished).

The equation for component activity is:

$$a_i = x_i \gamma_i$$

The variable γ , is the activity coefficient and is used to represent the forces that alter the chemical affinities for the given component in the equation. (Barton, unpublished).

This can then be combined to the Gibb's free energy equation for a solution. By introducing this variable, which is non-ideal, the equation changes form to:

$$G_{solution} = \sum_i x_i [\mu_i^{\circ} + RT \ln x_i + RT \ln \gamma_i]$$

The first two terms in this equation represent the ideal components, however, the third term introduces the non-ideal component to the equation. This is known as the **excess Gibb's free energy**.

Results and Discussion

The concepts in this thesis were put to practical use after a microprobe analysis was completed on a Santorini basalt (slide 138, discussed previously). Pyroxenes were the focus of this study. The pyroxene data was subsequently input into a computer

program designed by Dr. Barton that calculated the thermodynamic equations for each of the pyroxene analyses. These results were then input into a data file (Quattro Pro spreadsheet). This new data set was then input into another series of programs that calculated silica activities of the pyroxenes, over a range of pressures and temperatures. This data was then combined with feldspar data from the same sample. As was stated previously, at least three reactions need to be determined simultaneously in order to compensate for the silica activity present in each of the reactions. The specific reactions that were utilized for the data present in this thesis were as follows:

pyroxenes- fosterite+melt=clinoenstatite

 monticellite+melt=diopside

feldspars- CaTs+melt=anorthite

These reactions were then plotted graphically over a range of silica activities and temperatures. These reactions were plotted against each other in order to find intersection points between values at the same pressures. These intersection points from each of the two sets of reactions were then plotted against each other. The intersection point of these two data sets is a graphical representation of the temperature, silica activity and pressure parameters of magma crystallization.

Conclusion

The following plots (figures 2 through 4) pertain to magma crystallization parameters of

slide 138., a sample of a basalt from the Micro Profitas Ilias volcanic center on Santorini.

The results derived from the plots indicate a temperature and pressure of magma crystallization for this basalt to be 1028° C. and approximately 7- 8 k.bars respectively.. If this data is accurate, This implies magma crystallization occurred at a depth of approximately 21 to 24 kilometers. Basalts from other volcanic centers on Santorini, have given evidence of having crystallized at a depth of 6 to 9 kilometers (MacCracken, 1993). The crust beneath Santorini is approximately 21 - 24 kilometers thick. The disparity between the depth of crystallization of Micro Profitas Ilias basalts compared to the magma crystallization depth of other Santorini basalts, could be attributed to the presence of a magma chamber located at the base of the crust, as well as, the presence of a shallower magma chamber within the crust which appears to be the source of the other Santorini basalts. This would indicate two stages of magma evolution. More microprobe analyses on the Santorini basalts are needed in order to verify or refute this conclusion.

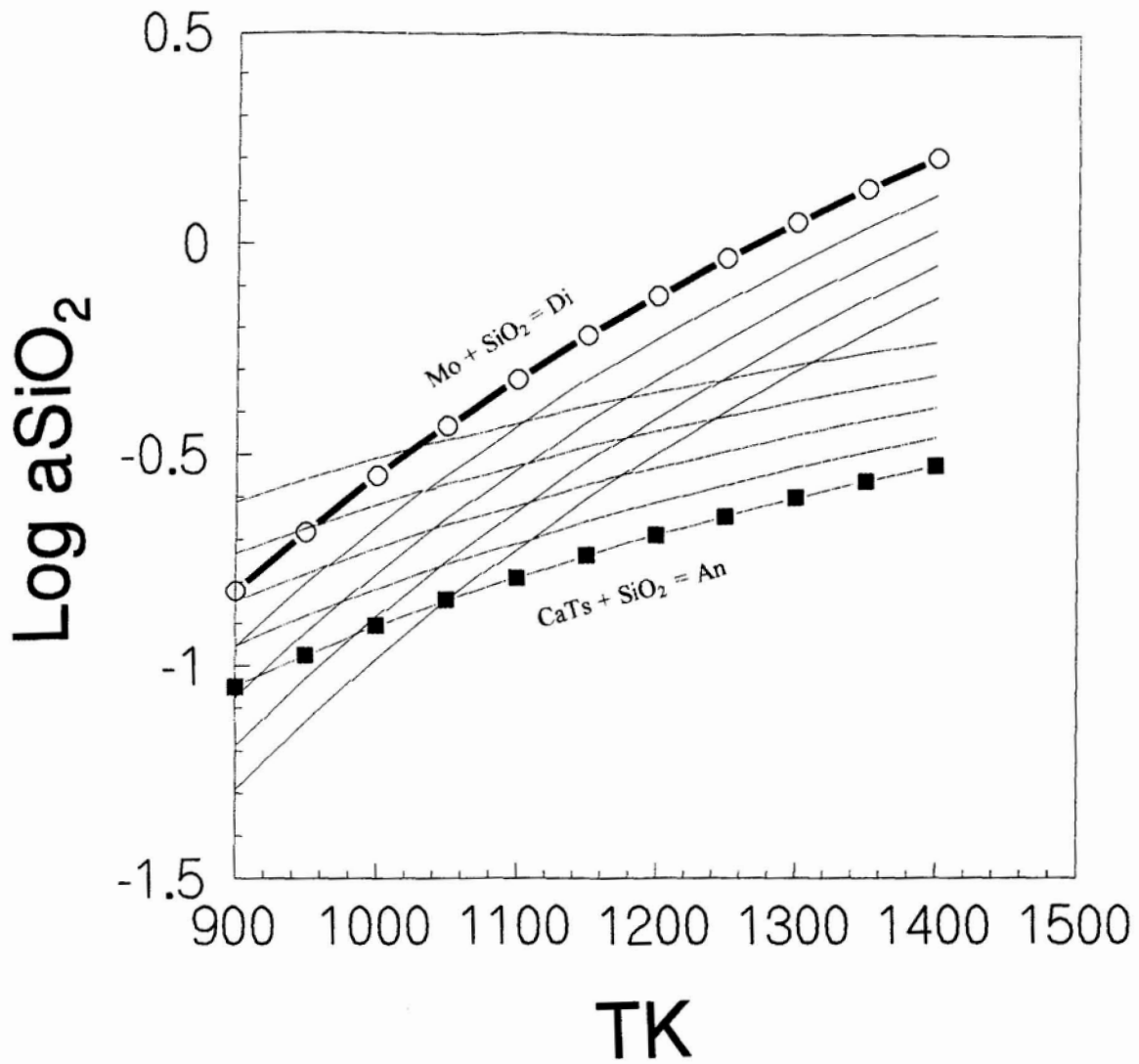


Figure 2 : Plot showing reaction ranges for slide 138 (Micro Profitas Ilias, Santorini)

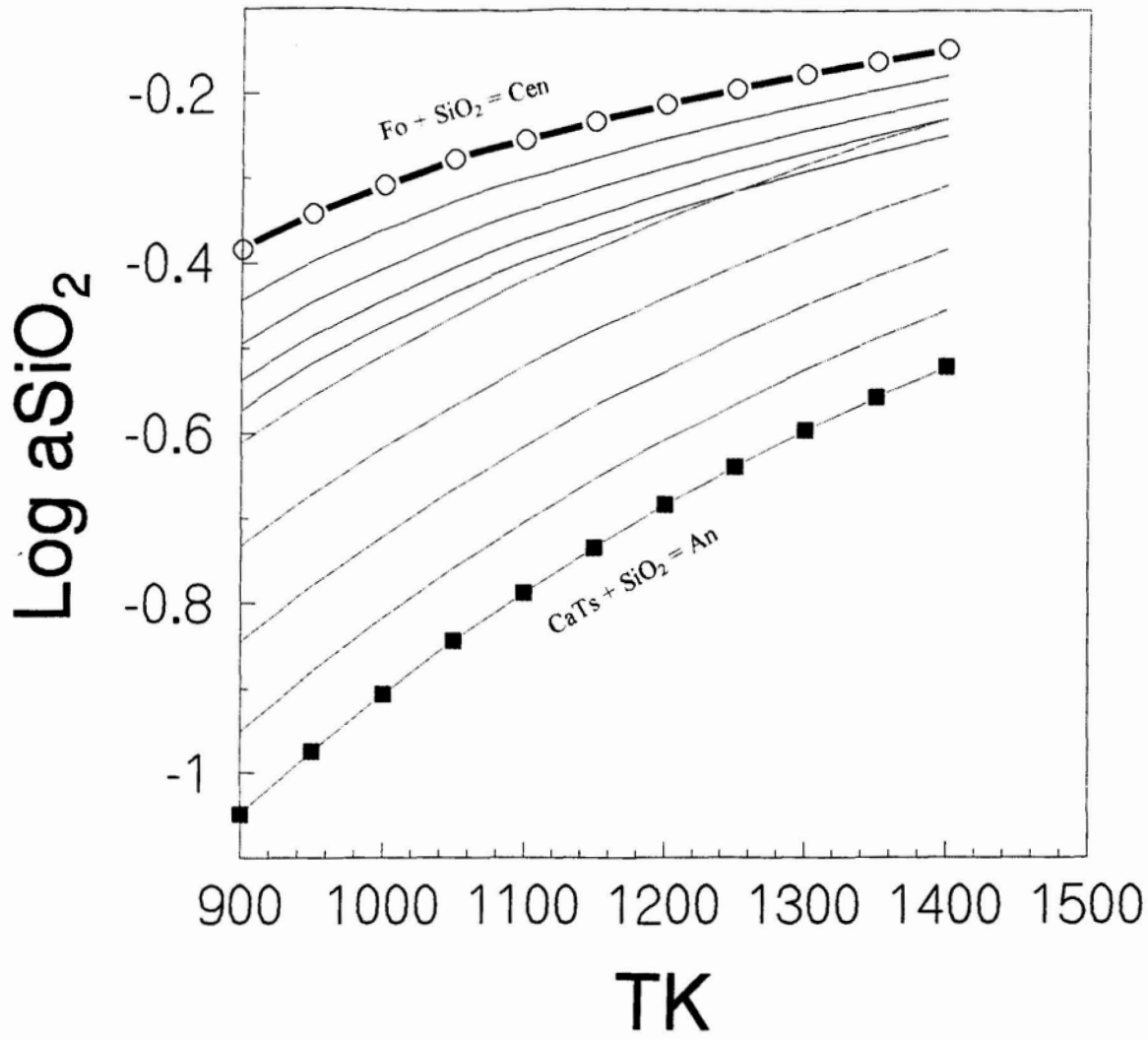


Figure 3: Plot indicating reaction ranges and intersection points for slide138

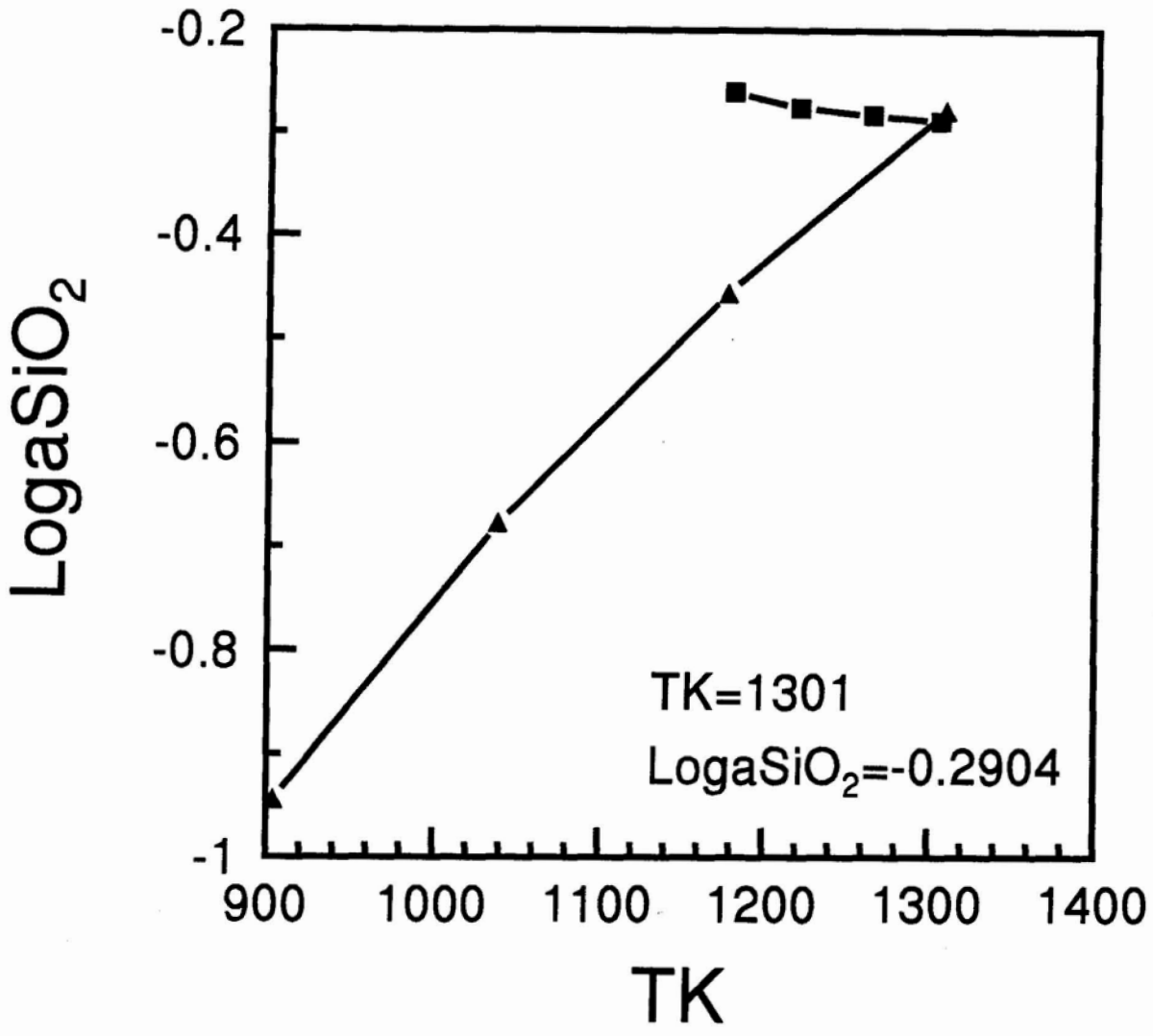


Figure 4: Plot displaying combined data from previous two plots and resulting intersection point indicating final value of crystallization parameters for basalt sample (slide 138).

Acknowledgments

I would like to thank Dr. Barton for his instruction and being my advisor for this thesis. I would also like to thank Michael Comerford for his expertise and patience while instructing me on the use of the microprobe.

Appendix

The following pages contain the data sheets for the preceding graphs. Included are chemical reactions and silica activity values over a range of pressures and temperatures.

ENTHALPY AND ENTROPY OF FUSION CALCULATED FROM DATA OF RICHEL ET AL (GCA, 1982),
 COMBINED WITH DATA FOR B-QTZ FROM BERMAN (1988).
 VOLUMES OF FO, FA, CEN, FS MO, DI, AND EXPANSION AND COMPRESSION TERMS FROM
 BERMAN, J PET, 1988.
 VOLUME OF SILICA MELT, COMPRESSIBILITY AND EXPANSION CALCULATED FROM
 DATA OF KRESS AND CARMICHAEL, CMP, 1991.

ACTIVITY OF FO, FA, MO FROM DAVIDSON AND LINDSLEY, AM MIN, 1989.
 ACTIVITY OF CEN, FS, DI FROM DAVIDSON AND LINDSLEY, AM MIN, 1989.

CA ASSIGNED ONLY TO M2 SITES IN OL AND CEN.

DISTRIBUTION OF MG AND FE OVER M1 AND M2 IN OL AND PYX FOLLOWS
 DAVIDSON AND LINDSLEY (ALSO DAVIDSON AND MUKHOPADHYAY, 1984, CMP, 86, P256).
 THE DISTRIBUTION OF MG AND FE OVER M1 AND M2 SITES IN OL AND CPX IS
 T AND P DEPENDENT AND BASED ON THE MINIMIZATION OF THE CHEMICAL
 POTENTIALS OF DI, HD, EN AND FS IN CPX OR EN.

REACTIONS:

- 1 ----- FORSTERITE+MELT=CLINOENSTATITE
- 2 ----- FAYALITE+MELT=FERROSILITE
- 3 ----- MONTICELLITE+MELT=DIOPSIDE

INPUT CONDITIONS:

INITIAL T(K)	FINAL T(K)	INCREMENTS	INITIAL P(B)	FINAL P(B)	INCREMENTS
1173.2	1673.2	50.0	1.0	10001.0	1000.0

P(B)	T(C)	LOGASIO2		
		(1)	(2)	(3)
1.0	900.0	-0.38484	0.17757	-0.82288
1.0	950.0	-0.34315	0.15484	-0.68064
1.0	1000.0	-0.30837	0.13190	-0.54985
1.0	1050.0	-0.27882	0.10899	-0.42923
1.0	1100.0	-0.25332	0.08633	-0.31760
1.0	1150.0	-0.23095	0.06400	-0.21406
1.0	1200.0	-0.21103	0.04208	-0.11772
1.0	1250.0	-0.19310	0.02063	-0.02791
1.0	1300.0	-0.17673	-0.00037	0.05602
1.0	1350.0	-0.16162	-0.02091	0.13464
1.0	1400.0	-0.14754	-0.04101	0.20842
1001.0	900.0	-0.41535	0.15938	-0.88905
1001.0	950.0	-0.37158	0.13834	-0.74399
1001.0	1000.0	-0.33493	0.11696	-0.61061
1001.0	1050.0	-0.30368	0.09550	-0.48759
1001.0	1100.0	-0.27664	0.07418	-0.37372
1001.0	1150.0	-0.25284	0.05309	-0.26809
1001.0	1200.0	-0.23161	0.03234	-0.16982
1001.0	1250.0	-0.21246	0.01199	-0.07819
1001.0	1300.0	-0.19494	-0.00798	0.00744

1001.0	1350.0	-0.17877	-0.02755	0.08766
1001.0	1400.0	-0.16368	-0.04671	0.16295

2001.0	900.0	-0.44390	0.14301	-0.95301
2001.0	950.0	-0.39818	0.12354	-0.80529
2001.0	1000.0	-0.35977	0.10360	-0.66943
2001.0	1050.0	-0.32695	0.08347	-0.54413
2001.0	1100.0	-0.29845	0.06339	-0.42815
2001.0	1150.0	-0.27334	0.04346	-0.32056
2001.0	1200.0	-0.25088	0.02379	-0.22045
2001.0	1250.0	-0.23060	0.00445	-0.12709
2001.0	1300.0	-0.21202	-0.01457	-0.03984
2001.0	1350.0	-0.19484	-0.03323	0.04189
2001.0	1400.0	-0.17883	-0.05153	0.11861

3001.0	900.0	-0.47047	0.12846	-1.01477
3001.0	950.0	-0.42293	0.11042	-0.86451
3001.0	1000.0	-0.38290	0.09181	-0.72633
3001.0	1050.0	-0.34861	0.07291	-0.59888
3001.0	1100.0	-0.31878	0.05396	-0.48089
3001.0	1150.0	-0.29243	0.03508	-0.37144
3001.0	1200.0	-0.26885	0.01640	-0.26958
3001.0	1250.0	-0.24752	-0.00201	-0.17459
3001.0	1300.0	-0.22795	-0.02014	-0.08582
3001.0	1350.0	-0.20987	-0.03796	-0.00266
3001.0	1400.0	-0.19298	-0.05547	0.07542

4001.0	900.0	-0.49509	0.11573	-1.07433
4001.0	950.0	-0.44586	0.09901	-0.92169
4001.0	1000.0	-0.40432	0.08160	-0.78131
4001.0	1050.0	-0.36866	0.06381	-0.65181
4001.0	1100.0	-0.33761	0.04588	-0.53195
4001.0	1150.0	-0.31014	0.02798	-0.42073
4001.0	1200.0	-0.28551	0.01020	-0.31724
4001.0	1250.0	-0.26320	-0.00735	-0.22071
4001.0	1300.0	-0.24275	-0.02468	-0.13050
4001.0	1350.0	-0.22383	-0.04174	-0.04598
4001.0	1400.0	-0.20615	-0.05854	0.03338

5001.0	900.0	-0.51773	0.10485	-1.13166
5001.0	950.0	-0.46693	0.08930	-0.97679
5001.0	1000.0	-0.42401	0.07297	-0.83436
5001.0	1050.0	-0.38713	0.05616	-0.70295
5001.0	1100.0	-0.35495	0.03919	-0.58131
5001.0	1150.0	-0.32644	0.02214	-0.46844
5001.0	1200.0	-0.30088	0.00519	-0.36341
5001.0	1250.0	-0.27770	-0.01160	-0.26544
5001.0	1300.0	-0.25642	-0.02821	-0.17387
5001.0	1350.0	-0.23672	-0.04458	-0.08808
5001.0	1400.0	-0.21832	-0.06071	-0.00752

6001.0	900.0	-0.53840	0.09577	-1.18680
6001.0	950.0	-0.48619	0.08128	-1.02982
6001.0	1000.0	-0.44201	0.06591	-0.88547
6001.0	1050.0	-0.40398	0.05001	-0.75228

3001.0	1100.0	-0.65051	-1.98399
3001.0	1150.0	-0.60224	-2.00551
3001.0	1200.0	-0.55763	-2.02549
3001.0	1250.0	-0.51631	-2.04415
3001.0	1300.0	-0.47805	-2.06158
3001.0	1350.0	-0.44248	-2.07791
3001.0	1400.0	-0.40947	-2.09321
4001.0	900.0	-0.83551	-1.80778
4001.0	950.0	-0.77037	-1.84005
4001.0	1000.0	-0.71068	-1.86972
4001.0	1050.0	-0.65583	-1.89715
4001.0	1100.0	-0.60538	-1.92253
4001.0	1150.0	-0.55887	-1.94609
4001.0	1200.0	-0.51591	-1.96796
4001.0	1250.0	-0.47615	-1.98837
4001.0	1300.0	-0.43931	-2.00746
4001.0	1350.0	-0.40514	-2.02533
4001.0	1400.0	-0.37337	-2.04205
5001.0	900.0	-0.77981	-1.73482
5001.0	950.0	-0.71720	-1.77001
5001.0	1000.0	-0.65986	-1.80235
5001.0	1050.0	-0.60721	-1.83223
5001.0	1100.0	-0.55877	-1.85989
5001.0	1150.0	-0.51416	-1.88558
5001.0	1200.0	-0.47293	-1.90941
5001.0	1250.0	-0.43479	-1.93168
5001.0	1300.0	-0.39948	-1.95247
5001.0	1350.0	-0.36674	-1.97194
5001.0	1400.0	-0.33633	-1.99018
6001.0	900.0	-0.72215	-1.66024
6001.0	950.0	-0.66224	-1.69843
6001.0	1000.0	-0.60738	-1.73358
6001.0	1050.0	-0.55701	-1.76602
6001.0	1100.0	-0.51069	-1.79606
6001.0	1150.0	-0.46806	-1.82395
6001.0	1200.0	-0.42868	-1.84982
6001.0	1250.0	-0.39225	-1.87400
6001.0	1300.0	-0.35857	-1.89660
6001.0	1350.0	-0.32730	-1.91775
6001.0	1400.0	-0.29830	-1.93755
7001.0	900.0	-0.66255	-1.58405
7001.0	950.0	-0.60546	-1.62536
7001.0	1000.0	-0.55320	-1.66338
7001.0	1050.0	-0.50525	-1.69853
7001.0	1100.0	-0.46118	-1.73103
7001.0	1150.0	-0.42058	-1.76120
7001.0	1200.0	-0.38317	-1.78922
7001.0	1250.0	-0.34852	-1.81538
7001.0	1300.0	-0.31650	-1.83983
7001.0	1350.0	-0.28685	-1.86275
7001.0	1400.0	-0.25934	-1.88420
8001.0	900.0	-0.60099	-1.50619
8001.0	950.0	-0.54687	-1.55077
8001.0	1000.0	-0.49736	-1.59181
8001.0	1050.0	-0.45192	-1.62970

T (IN CELSIUS) = 900.00

FERRIC IRON AND FE3+ CALCULATED FROM CHARGE BALANCE

BERMAN THERMODYNAMIC DATA SET

NON-IDEAL PYROXENE, NON-IDEAL FELDSPAR

(1) ----- CATS + LIQ = AN
(2) ----- JAD + LIQ = ALB

P(B)	T(C)	LOGASIO2	
		(1)	(2)
1.0	900.0	-1.03899	-2.08323
1.0	950.0	-0.96493	-2.10514
1.0	1000.0	-0.89704	-2.12528
1.0	1050.0	-0.83464	-2.14391
1.0	1100.0	-0.77718	-2.16115
1.0	1150.0	-0.72418	-2.17713
1.0	1200.0	-0.67515	-2.19196
1.0	1250.0	-0.62971	-2.20581
1.0	1300.0	-0.58762	-2.21876
1.0	1350.0	-0.54847	-2.23087
1.0	1400.0	-0.51205	-2.24221
1001.0	900.0	-0.99105	-2.01680
1001.0	950.0	-0.91900	-2.04112
1001.0	1000.0	-0.85297	-2.06347
1001.0	1050.0	-0.79227	-2.08415
1001.0	1100.0	-0.73640	-2.10327
1001.0	1150.0	-0.68490	-2.12103
1001.0	1200.0	-0.63724	-2.13749
1001.0	1250.0	-0.59310	-2.15286
1001.0	1300.0	-0.55220	-2.16725
1001.0	1350.0	-0.51417	-2.18068
1001.0	1400.0	-0.47879	-2.19329
2001.0	900.0	-0.94113	-1.94873
2001.0	950.0	-0.87125	-1.97560
2001.0	1000.0	-0.80722	-2.00028
2001.0	1050.0	-0.74837	-2.02310
2001.0	1100.0	-0.69419	-2.04421
2001.0	1150.0	-0.64425	-2.06382
2001.0	1200.0	-0.59807	-2.08200
2001.0	1250.0	-0.55529	-2.09896
2001.0	1300.0	-0.51567	-2.11486
2001.0	1350.0	-0.47885	-2.12970
2001.0	1400.0	-0.44461	-2.14360
3001.0	900.0	-0.88932	-1.87909
3001.0	950.0	-0.82173	-1.90857
3001.0	1000.0	-0.75979	-1.93570
3001.0	1050.0	-0.70289	-1.96078

LOGASIO2

P(B)	T(C)	(1)	(2)
1.0	900.0	-1.04902	-2.05935
1.0	950.0	-0.97494	-2.08163
1.0	1000.0	-0.90702	-2.10212
1.0	1050.0	-0.84459	-2.12106
1.0	1100.0	-0.78710	-2.13860
1.0	1150.0	-0.73408	-2.15486
1.0	1200.0	-0.68503	-2.16994
1.0	1250.0	-0.63958	-2.18403
1.0	1300.0	-0.59746	-2.19721
1.0	1350.0	-0.55829	-2.20952
1.0	1400.0	-0.52186	-2.22106
1001.0	900.0	-1.00111	-1.99290
1001.0	950.0	-0.92903	-2.01760
1001.0	1000.0	-0.86297	-2.04030
1001.0	1050.0	-0.80225	-2.06130
1001.0	1100.0	-0.74634	-2.08071
1001.0	1150.0	-0.69483	-2.09875
1001.0	1200.0	-0.64714	-2.11547
1001.0	1250.0	-0.60298	-2.13107
1001.0	1300.0	-0.56206	-2.14568
1001.0	1350.0	-0.52402	-2.15933
1001.0	1400.0	-0.48862	-2.17213
2001.0	900.0	-0.95122	-1.92484
2001.0	950.0	-0.88130	-1.95208
2001.0	1000.0	-0.81725	-1.97710
2001.0	1050.0	-0.75837	-2.00024
2001.0	1100.0	-0.70416	-2.02165
2001.0	1150.0	-0.65419	-2.04153
2001.0	1200.0	-0.60800	-2.05996
2001.0	1250.0	-0.56519	-2.07717
2001.0	1300.0	-0.52556	-2.09329
2001.0	1350.0	-0.48871	-2.10835
2001.0	1400.0	-0.45445	-2.12244
3001.0	900.0	-0.89944	-1.85519
3001.0	950.0	-0.83181	-1.88504
3001.0	1000.0	-0.76984	-1.91252
3001.0	1050.0	-0.71291	-1.93791
3001.0	1100.0	-0.66050	-1.96142
3001.0	1150.0	-0.61220	-1.98322
3001.0	1200.0	-0.56757	-2.00345
3001.0	1250.0	-0.52623	-2.02236
3001.0	1300.0	-0.48795	-2.04001
3001.0	1350.0	-0.45237	-2.05654
3001.0	1400.0	-0.41933	-2.07204
4001.0	900.0	-0.84565	-1.78387
4001.0	950.0	-0.78048	-1.81651
4001.0	1000.0	-0.72075	-1.84653
4001.0	1050.0	-0.66587	-1.87428
4001.0	1100.0	-0.61539	-1.89996
4001.0	1150.0	-0.56886	-1.92379
4001.0	1200.0	-0.52588	-1.94591

4001.0	1250.0	-0.48609	-1.96657
4001.0	1300.0	-0.44924	-1.98588
4001.0	1350.0	-0.41504	-2.00397
4001.0	1400.0	-0.38325	-2.02088
5001.0	900.0	-0.78997	-1.71090
5001.0	950.0	-0.72733	-1.74647
5001.0	1000.0	-0.66996	-1.77916
5001.0	1050.0	-0.61727	-1.80935
5001.0	1100.0	-0.56881	-1.83732
5001.0	1150.0	-0.52417	-1.86327
5001.0	1200.0	-0.48292	-1.88737
5001.0	1250.0	-0.44475	-1.90987
5001.0	1300.0	-0.40942	-1.93089
5001.0	1350.0	-0.37666	-1.95057
5001.0	1400.0	-0.34623	-1.96900
6001.0	900.0	-0.73234	-1.63631
6001.0	950.0	-0.67239	-1.67488
6001.0	1000.0	-0.61750	-1.71038
6001.0	1050.0	-0.56710	-1.74314
6001.0	1100.0	-0.52075	-1.77347
6001.0	1150.0	-0.47809	-1.80164
6001.0	1200.0	-0.43868	-1.82777
6001.0	1250.0	-0.40223	-1.85218
6001.0	1300.0	-0.36853	-1.87501
6001.0	1350.0	-0.33724	-1.89637
6001.0	1400.0	-0.30822	-1.91638
7001.0	900.0	-0.67276	-1.56012
7001.0	950.0	-0.61564	-1.60181
7001.0	1000.0	-0.56335	-1.64018
7001.0	1050.0	-0.51536	-1.67565
7001.0	1100.0	-0.47126	-1.70844
7001.0	1150.0	-0.43063	-1.73889
7001.0	1200.0	-0.39319	-1.76717
7001.0	1250.0	-0.35852	-1.79357
7001.0	1300.0	-0.32648	-1.81824
7001.0	1350.0	-0.29680	-1.84137
7001.0	1400.0	-0.26927	-1.86301
8001.0	900.0	-0.61123	-1.48226
8001.0	950.0	-0.55707	-1.52721
8001.0	1000.0	-0.50753	-1.56859
8001.0	1050.0	-0.46205	-1.60681
8001.0	1100.0	-0.42027	-1.64220
8001.0	1150.0	-0.38184	-1.67503
8001.0	1200.0	-0.34639	-1.70553
8001.0	1250.0	-0.31365	-1.73401
8001.0	1300.0	-0.28337	-1.76063
8001.0	1350.0	-0.25532	-1.78554
8001.0	1400.0	-0.22934	-1.80889
9001.0	900.0	-0.54774	-1.40275
9001.0	950.0	-0.49669	-1.45110
9001.0	1000.0	-0.44999	-1.49560
9001.0	1050.0	-0.40716	-1.53671
9001.0	1100.0	-0.36783	-1.57473
9001.0	1150.0	-0.33166	-1.61004
9001.0	1200.0	-0.29835	-1.64287

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