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HYDROTHERMAL DETERMINATION OF TEMPERATURE AND WATER PRESSURE OF THE MAGMA OF AIRA CALDERA, JAPAN

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Abstract

A series of hydrothermal runs indicates that pressures and temperatures at which quartz, plagioclase, liquid, and an aqueous gas phase coexist for compositions of pumices from Aira Caldera, southern Japan, range from 700°C to 780°C and 1600 to 1950 bars. These values are thought to approximate the actual conditions of temperature and water pressure of the magma at the time of the eruption.

Introduction

An important aspect of volcanic phenomena is the temperature and pressure of the volatile components within an erupting magma. Although temperature may be determined by direct measurements, the estimate of vapor pressure of volatiles is very difficult to obtain. Estimates of these unknowns may be made by a laboratory study of the quenched magmatic material (volcanic glass) at high temperature and pressure in an attempt to simulate the original magmatic conditions.

Such a set of experiments has been made using glasses collected from the Aira caldera in southern Kyushu, Japan. This structure was formed about 30,000 years ago by subsidence immediately after the eruption of a large volume (~40 Km^3) of felsic magma. The erupted material formed pyroclastic flows consisting of pumice lumps, ash, and xenoliths from the walls of the conduit and magma reservoir. The transparent glass contains phenocrysts of plagioclase, quartz, hypersthene, and magnetite.

This glass is thought to represent the nonvoltatile components of the liquid magma at the time of eruption. The phenocyrsts are considered to be in equilibrium with the liquid, so that the magmatic liquid coincided with the composition of the quartz-plagioclase boundary curve. The volatile pressure and temperature of the eruption may be estimated if a set of conditions can be found where quartz, plagioclase, liquid, and perhaps gas are in equilibrium.

Experimental Techniques

Starting Materials. Four glasses (Table 1) were separated from the coexisting phenocrysts by use of an isodynamic separator and heavy liquids. Less than 0.5 weight percent crystals

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Table 1 Chemical composition and CIPW norm of the glasses

Chemical Composition

No.	1	2	3	4
Sample	Ito, matrix	Ito, pumice	Osumi, pumice	Kamewarizaka, pumice
SiO_2	75.06	74.26	73.67	74.12
TiO_2	0.05	0.08	0.11	0.12
Al_2O_3	12.21	12.37	12.12	12.14
Fe_2O_3	0.82	0.82	0.79	0.75
FeO	0.40	0.49	0.79	1.01
MnO	0.02	0.01	0.02	0.02
MgO	0.20	0.20	0.31	0.35
CaO	0.87	1.12	1.12	1.06
Na_2O	3.44	3.56	3.48	3.62
K_2O	3.42	3.30	3.26	3.35
$H_2O(+)$	3.18	4.09	4.21	3.73
$H_2O(-)$	0.09	0.17	0.10	0.09
P_2O_5	0.01	0.01	0.01	0.02
Cl	0.050	0.060	0.088	0.084
F	0.026	0.038	0.037	0.037
	99.846	100.578	100.115	100.501
$O \equiv Cl, F$	0.022	0.030	0.034	0.034
Total	99.82	100.55	100.08	100.47

CIPW norm

	1	2	3	4
Q	39.84	38.25	37.86	36.98
C	1.30	0.95	0.87	0.66
Or	20.21	19.48	19.26	19.81
Ab	29.10	30.09	29.41	30.62
An	4.23	5.48	5.48	5.17
En	0.50	0.50	0.77	0.87
Fs	0.03	0.11	0.65	1.08
Mt	1.18	1.18	1.16	1.09
Il	0.09	0.15	0.21	0.23
Ap	0.03	0.03	0.03	0.05

Analyst: Hiroshi ASARI

Sample localities:

1. Ito, matrix. Quarry of the welded deposit of the Ito pyroclastic flow. Ito, north of Kokubu, Kagoshima Prefecture.
2. Ito, pumice. Same locality as No. 1.
3. Osumi, pumice. Road cut, north of Fukue, Kagoshima Prefecture.
4. Kamewarizaka, pumice. Quarry, top of Kamewarizaka, Kagoshima Prefecture.

(mainly plagioclase and quartz) remained in the final concentrates. The glasses were then ground under acetone for 30 minutes.

Hydrothermal Runs. Standard "cold seal" apparatus was employed using Rene 41 pressure vessels. Runs were of 4 days through 2 weeks duration and the results were independent of run length in these time intervals.

Some runs were buffered with wüstite-magnetite or quartz-fayalite-magnetite buffers. It was found that buffers only influenced the formation of very small amounts of hematite and/or magnetite, so that many runs were made using the wall of the reactor as buffer. The oxidation state of Rene 41 varies with age, but most of the runs correspond to a region between Ni-NiO and quartz-fayalite-magnetite buffers (Eugster and Wones, 1962; Wones, personal communication).

The powdered glasses were sealed in platinum capsules with an excess of triply distilled water. In most cases four different, separately encapsulated, glasses were placed in the same run. Runs with samples undersaturated with H_2O were not feasible because of the sharp rise of the liquidus temperature.

Results. The results of selected runs are listed in Table 2 and plotted in Figure 1. The glass powder is welded into a bead containing round bubbles. The identification of incipient crystallization is straightforward, as the small crystals are easily identified in glass fragments. Plagioclase occurs as euhredal plates and laths, and in some cases as stout paral-

TABLE 2. RESULTS OF SELECTED HYDROTHERMAL RUNS[1]

Temperature °C	Pressure bars	Duration days	Result 1	2	3	4
829±3	1000±50	8	P	P	P	P
814±3	1090±50	7½	P	P	P	P
820±3	980±50	6	—	P	—	P
804±3	1530±50	8	G	G	G	P
795±2	1510±50	6½	G	G	P≫Q	P
770±3	1500±50	8	P≫Q	P	P≫Q	P>Q
760±2	1730±50	10	P≫Q	P>Q	P>Q	P≫Q
759±3	1800±50	8	P>Q	Q≈P	Q>P	P>Q
752±2	1900±50	14½	Q<P	Q>P	—	P>Q
748±2	2020±50	10	Q≫P	G	Q>P	Q>P
767±3	2150±70	6½	G	G	—	G
762±2	2300±50	8	G	G	G	Q≫P
758±3	2080±70	7	Q>P	Q≈P(?)	Q>P	Q>P
740±4	2240±50	8	Q	Q	Q>P	P>Q

1. Ito, matrix, 2. Ito, pumice, 3. Osumi, pumice, 4. Kamewarizaka, pumice.

[1] Temperature and pressure given are mean values; the range (instrumental error +actual fluctuation) is indicated as the sizes of the rectangles in Figs. 1 and 2. Symbols:— run failure, G glass only, P plagioclase, Q quartz. All runs contain abundant glass, and crystals are always in a very small amount. All runs in this table were held at a fixed temperature and pressure throughout, and there is no overshooting in either temperature or pressure at the beginning.

lelepipeds. Quartz bipyramids are characteristic, and even when they resemble the plagioclase parallelepipeds, they are identified by their higher refractive index.

No hypersthene was detected in any run for the *P-T* range investigated. In runs with sealed gold capsules, the higher oxidation conditions cause abundent small plates of hematite or granules of magnetite to appear as the initial crystalline phase. In runs with the pressure vessel acting as a buffer hematite or magnetite appear at temperatures below that for plagioclase and quartz.

The effect of seeding the glasses was studied by annealing the charges at 30°C above the liquidus for a given pressure. This treatment apparently dissolves the abundant crystals of plagioclase and quartz which remained after mechanical separation, and decreases the number of available nuclei. The results, plotted in Figure 2, for the Aira glass (Fig. 1A), yield a liquidus some 30°C lower than the unannealed glasses. The interpretations are based only on those runs which were not annealed. The position of the liquidus was placed at the highest temperature (at a given pressure) at which euhedral crystals were detected.

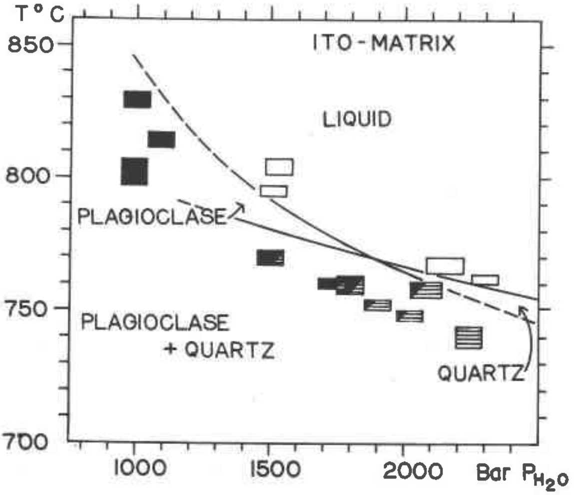
The pressure at which the relative abundance of plagioclase and quartz is reversed may be determined with confidence from Figure 1, but the liquidus temperature is more difficult to place. The pressures and temperatures have been fixed as follows:

	T, °C	*P*, bars
Ito matrix	770±20	1850±100
Ito pumice	770±20	1800±100
Osumi pumice	780±20	1600±150
Kamewarizaka pumice	770±20	1950±100

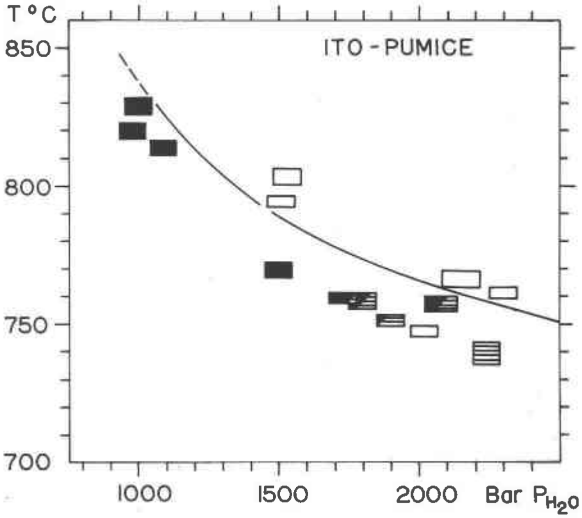
DISCUSSION

Previous Investigations. Luth *et al.* (1964) summarized the liquidus data for the system SiO_2-$KAlSi_3O_8$-$NaAlSi_3O_8$-H_2O between 500 and 10,000 bars, extending the earlier work of Tuttle and Bowen (1958). Stewart (1957, 1967), Shaw (1963), and von Platen (1965) have provided data which permits the construction of a phase diagram for the system SiO_2-$KAlSi_3O_8$-$NaAlSi_3O_8$-$CaAl_2Si_2O_8$-H_2O. Figure 3 shows the general shape of the boundary surfaces within this system and has been discussed by Carmichael (1963), and Bateman *et al.* (1963). An increase in H_2O pressure causes the quartz-plagioclase boundary to move away from the SiO_2 apex.

Pressure and Temperature of the Liquidus of the Aira Glasses. As the amount of normative Q+Or+Ab+An in these glasses is 95 weight percent, their phase relations should be approximated by the system Q-Or-Ab-An. The projection of the four glasses on the SiO_2-$KAlSi_3O_8$-$NaAlSi_3O_8$ surface are given in Figure 4. In Figure 5, a cross section containing the SiO_2 and $CaAl_2Si_2O_3$ apices and the point $Or_{40}Ab_{60}$ is shown. The four glasses fall very nearly on this section. Figure 5 also contains the boundary curves for quartz and plagioclase at H_2O pressures of 1000 and 2000 bars. The curves are derived from the data given by Tuttle and Bowen (1958) and Stewart (1957). The four points representing the Aira glasses fall near and

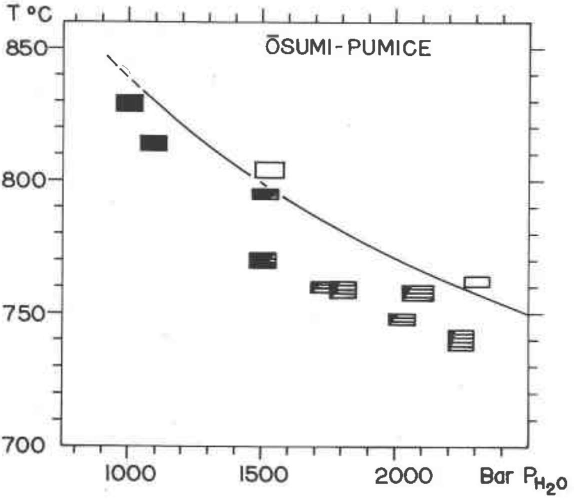


1A

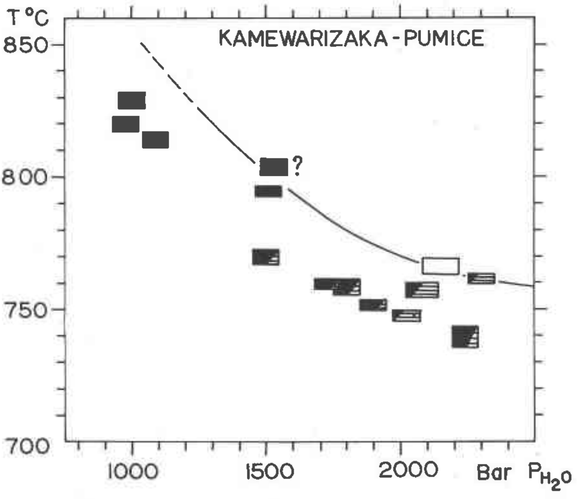


1B

FIG. 1. Pressure-temperature diagrams for glasses separated from Aira pyroclastic flows. Rectangles indicate uncertainties. All runs in presence of gas: white, liquid only; black, liquid and euhedral plagioclase; ruled, liquid with euhedral quartz. A, Ito matrix; B, Ito pumice; C, Osumi pumice; and D, Kamewarizaka pumice. See Table 1 for description of starting materials.



1C



1D

slightly above the 1 kilobar line, and the experimentally determined values are in fair agreement with these values. The simple five component system is a good approximation of the natural system.

The experimental determination is thought to be more accurate because of the errors in chemical analysis and the unknown effect of minor components.

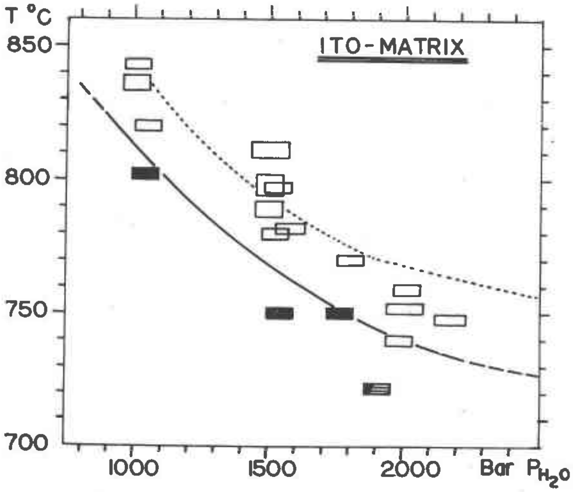


FIG. 2. Pressure-temperature diagrams for glass from matrix of Ito pyroclastic flow, Aira, Japan. Starting material annealed at 30°C above liquidus of figure 1A (dotted line) for 24 hours. Contrast with figure 1A.

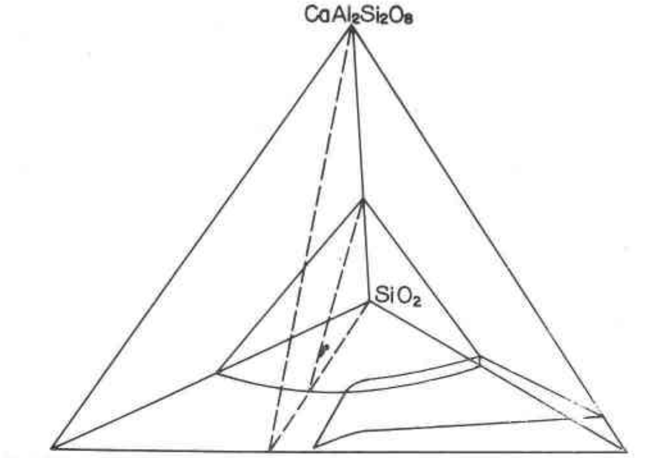


FIG. 3. SiO_2-$KAlSi_3O_8$-$NaAlSi_3O_8$-$CaAl_2Si_2O_8$ tetrahedron showing approximate locations of primary volumes of quartz (including SiO_2 apex), K-feldspar (including $KAlSi_3O_8$ apex) and plagioclase. Dashed lines define the plane SiO_2-$CaAl_2Si_{12}O_8$-$Or_{40}Ab_{60}$. Dots represent composition of glass from Aira pyroclastic flows.

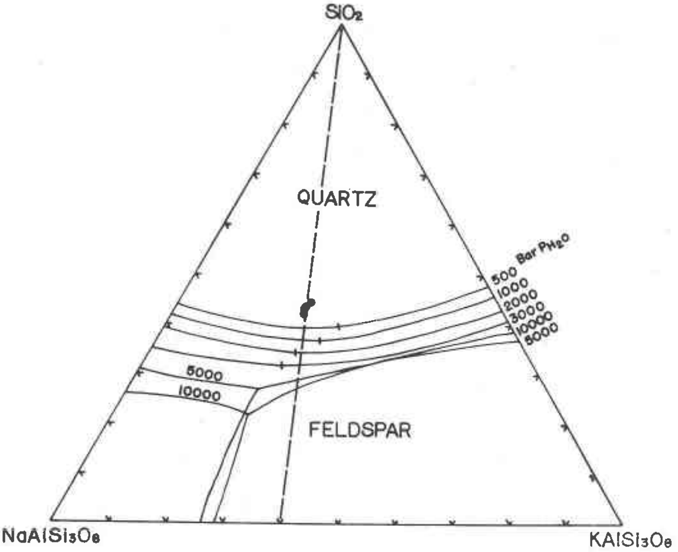


FIG. 4. Projection of the four glasses from Aira caldera on the SiO_2-$KAlSi_3O_8$-$NaAlSi_3O_8$ plane. Boundary line between quartz and feldspar are after Tuttle and Bowen (1958) and Luth *et al.* (1964).

Absence of Hypersthene. No mafic minerals, except iron oxides, were detected on the liquidus in these experiments. In contrast, the natural samples contained fairly large amounts of hypersthene phenocrysts. The presence of hypersthene and absence of biotite could give maximum limits for the fugacity of water of the magma (Wones and Eugster, 1965;

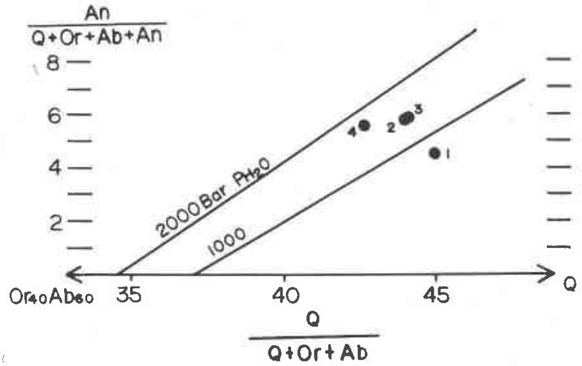


FIG. 5. Plane of SiO_2-$CaAl_2Si_2O_8$-$Or_{40}Ab_{60}$ from Figure 3. Numbers refer to glasses given in Table 1. Boundary between quartz and plagioclase fields are at water pressures of 1000 and 2000 bars.

Wones and Dodge, 1966). The large size of the hypersthene phenocryst and lack of small hypersthene crystals indicate that hypersthene had ceased crystallizing and was being resorbed when the magmas were erupted.

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REFERENCES

ARAMAKI, S., AND T. UI (1966) The Aira and Ata pyroclastic flows and related caldera and depressions in southern Kyushu, Japan. *Bull. Volcanol.* **29,** 29–47.

BATEMAN, P. C., L. D. CLARK, N. K. HUBER, J. G. MOORE, AND C. D. RINEHART (1963) The Sierra Nevada batholith, a synthesis of recent work across the central part. *U. S. Geol. Surv. Prof.* Pap. **414-D.**

CARMICHAEL, I. S. E. (1963) The crystallization of feldspar in volcanic acid liquids. *Quart. J. Geol. Soc. London* **119,** 95–131.

EUGSTER, H. P., AND D. R. WONES (1962) Stability relations of the ferruginous biotite, annite. *J. Petrology* **3,** 82–125.

LUTH, W. C. (1969) The systems $NaAlSi_3O_8$-SiO_2 and $KAlSi_3O_8$-SiO_2 to 20 kb and the relationship between H_2O content, P_{H_2O}, and P_{total} in granitic magmas. *Amer. J. Sci.,* **267-A,** 325–341.

———, R. H. JAHNS, AND O. F. TUTTLE (1964) The granite system at pressures of 4 to 10 kilobars. *J. Geophys. Res.* **69,** 759–773.

PLATEN, H. VON (1965) Kristallisation granitischer Schmelzen. *Beitr. Mineral. Petrog.* **11,** 334–381.

SHAW, H. R. (1963) The four-phase curve sanidine-quartz-liquid-gas between 500 and 4000 bars. *Amer. Mineral.* **48,** 883–896.

STEWART, D. B. (1957) The system $CaAl_2Si_2O_8$-SiO_2H_2O. *Carnegie Inst. Wash. Year Book* **56,** 214–216.

——— (1967) Four phase-curve in the system $CaAl_2Si_2O_8$-SiO_2-H_2O between 1 and 10 kilobars. *Schweiz. Mineral. Petrogr. Mitt.* **47/1,** 35–59.

TUTTLE, O. F., AND N. L. BOWEN (1958) Origin of granite in the light of experimental studies in the system $NaAlSi_3O_8$-$KAlSi_3O_8$-SiO_2-H_2O. *Geol. Soc. Amer. Mem.* **74.**

WONES, D. R., AND F. C. W. DODGE, (1966) On the stability of phlogopite (abstr.). *Geol. Soc. Amer., Spec. Pap.* **101,** 242.

———., AND H. P. EUGSTER (1965) Stability of biotite: experiment, theory, and application. *Amer. Mineral.* **50,** 1228–1272.

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