

Anhydrous Melting Experiment of a Wannienta Basalt in the Kuanyinshan Area, Northern Taiwan, at Atmospheric Pressure

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ABSTRACT

A Wannienta basalt from Kuanyinshan, northern Taiwan, is studied using a high temperature furnace at atmospheric pressure. The purpose of this study is to investigate the crystallization sequence of the phenocrysts, to analyze the chemical compositions of the phenocrysts, and to estimate the evolution trend of the magma in the Kuanyinshan area.

Fifteen runs are made to locate the liquidus temperature, the solidus temperature, and the melting interval of the Wannienta basaltic magma. The experimental temperatures range from 1087 °C to 1281 °C. The duration is from five hours to nineteen hours. Compositions of glasses and phenocrysts are analyzed with an electron microprobe.

The experimental results show that the liquidus temperature is located at 1270 °C and the solidus temperature is estimated to be close to 1080 °C. The melting interval is about 190 °C. The liquidus minerals are oxides with compositions in spinel series. The following crystallized phase is olivine at about 1217 °C. Plagioclase and clinopyroxene appear, respectively, at about 1178 °C and 1137 °C. The evolution of the residual magma shows the chemical trend as: enrichment in silicon, aluminum, and alkalis; and depletion in calcium, iron, and magnesium with the decreasing temperature. The fractionation trend of the Kuanyinshan volcanic series is similar to the variation trend of the residual magmas. It implies that the depth for the fractional crystallization of the Wannienta basaltic magma to produce andesites could be modeled at low pressure. The fractionates to produce biotite hornblende andesitic magma could be oxides, olivine, plagioclase, and clinopyroxene.

(Key words: Basalt, Kuanyinshan, Fractional crystallization, Magma)

1. INTRODUCTION

Taiwan is situated at the junction of the Ryukyu arc and the Luzon arc (Yen, 1958).

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According to seismic studies, the Coastal Range in eastern Taiwan is on the Philippine Sea plate, whereas western Taiwan is on the Eurasian plate (*e.g.* Tsai *et al.*, 1977; Kao and Wu, 1996). The Philippine Sea plate subducts along an E-W hinge line located at a latitude of about 24° N with an angle of 45°-50° dipping northward to a depth of about 300 km (*e.g.* Kao and Wu, 1996). Depth of the Benioff Zone near the Kuanyinshan area is about 150 km (Tsai *et al.*, 1977). The study of the Kuanyinshan rock series is significant in the research of magma genesis near the lateral edge of the subducted plate.

Kuanyinshan volcano is located in Taipei County, northern Taiwan. This composite volcano is mainly composed of three successive lava flows and agglomerates covering an area of about 30 square kilometers. Ichimura (1950) classified all the volcanics in the area into one type of basalt and five types of andesites based on the proportion of mafic minerals in the rocks. A caldera structure in the Kuanyinshan area was recognized. The eruptive sequence of the lava flows was successively constructed by Wang (1958), Chen and Hwang (1982), and Hwang and Lo (1986).

Most of the volcanic rocks in the Kuanyinshan area are porphyritic. The most abundant phenocryst is zoned plagioclase (30-40 percent in mode); other minerals are olivine, augite, hypersthene, amphibole, and biotite. Based on the content of mafic minerals, Chen (1982) classified the volcanic rocks into two types of basalt and six types of andesite. Three major lava flows are made of augite andesite at the bottom, two-pyroxene andesite in the middle, and hypersthene hornblende andesite on the top (Huang and Lo, 1986; Chen, 1987).

Yen (1958) inferred that the activity of Kuanyinshan volcanism started in the Plio-Pleistocene and ended in the early or middle Pleistocene. The volcanic activity was dated with K-Ar dating by Juang and Chen (1989) at between 0.63 and 0.20 Ma. Wang (1989) traced the earliest volcanic activity in this province back to 1.1 Ma by the fission track dating method.

Fractional crystallization has been proposed as one of the mechanisms to derive andesites and dacites from basaltic magmas. Fractionation involves separation of magnetite (*e. g.* Osborn, 1969), olivine (*e. g.* Nicholls, 1974), amphibole (*e. g.* Allen and Boettcher, 1978), or assemblage of these or other mineral phases (*e. g.* Sarkar *et al.*, 1989). Several authors (*e. g.* Singer *et al.*, 1992) have expanded the single differentiation trend to multiple differentiation trends.

From a geochemical study of the Kuanyinshan shoshonitic series, Chen (1982) proposed that Kuanyinshan andesites are most likely derived from Kuanyinshan basalts with the separation of an amphibole-plagioclase-magnetite assemblage. Hwang and Lo (1986) suggested that there are three differentiation trends with different fractionates made up of amphibole, plagioclase or magnetite. The fractionation mechanism was well certified by the trace element distributions described by Chen (1990). The similar strontium, neodymium, and oxygen isotopes of the basalt (K-64) and the andesite (K-99) showed that they are strongly related (Chen, 1989). The Kuanyinshan area is the best candidate for the experimental petrological study on Taiwan to start.

To decipher the mechanism involved in the petrogenesis of the Kuanyinshan shoshonitic series, the crystallization sequence of Wannienta basalt was investigated at atmospheric pressure in this study. The differentiation trend of the basaltic magma near the surface was constrained by the compositions of the residual magmas analyzed in the study.

2. EXPERIMENTAL METHOD

2.1 Starting Material

In order to model the fractionation of the magmas in the Kuanyinshan area, the rock with the highest Mg value in the area, Wannienta basalt, was chosen for experiments. The Wannienta basalt is fine-grained and grayish-black with small vesicles. The phenocrysts are olivine (with diameters of between 1.25 and 3.25 mm), augite (with diameters of between 0.25 and 1 mm), and plagioclase (with diameters of between 0.5 and 1.75 mm). Some plagioclase phenocrysts show clear zoning. The disequilibrium between the plagioclase and the magma was implied. The groundmass is also made up of these same phases with glass. Plagioclase shows euhedral, tabular to lath-shaped crystals. The plagioclase twinning are Carlsbad twin and albite twin.

A basalt rock sample of about 10 cm in diameter was crushed to be smaller than one centimeter in diameter. The rock chips were ground into powders to pass through a 200 mesh sieve. The analysis for major elements of the whole rock was carried out by X-ray fluorescence (XRF) spectrometry on fused $\text{Li}_2\text{B}_4\text{O}_7$ glassy disks at the Institute of Geology, National Taiwan University. The analytical settings, standards, and mass absorption corrections for the analysis were the same as described by Lee *et al.* (1997). The IGPET computer program was used to calculate the CIPW norm of the basalt.

2.2 Apparatus and Procedures

The experimental techniques were mostly similar to those reported in a previous study (Liu *et al.*, 1997). The rock powders were loaded into platinum envelopes, suspended in a one atmosphere vertical-quenched furnace and quenched in water. All temperatures were measured with a Pt-Pt₃₇Rh₁₃ thermocouple with a precision of $\pm 1^\circ\text{C}$. All temperatures were corrected to be on the International Practical Temperature Scale of 1968 (Anonymous, 1969) based on the calibrations with the liquidus temperature of synthetic diopside ($\text{CaMgSi}_2\text{O}_6$) (Liu *et al.*, 1997). Duration of the experiments ranged from 5 to 19 hours.

2.3 Identification and Analysis of Phases

Phases were identified in polished sections by reflected-light microscopy. Characteristic relief, reflectivity, and crystal habit were used for phase identification, along with electron microprobe analysis and back-scattered electron imaging in questionable cases. The compositions of oxides, plagioclase, clinopyroxene, olivine, and glass were determined using the automated JEOL JXA-8900R electron microprobe at the Institute of Earth Sciences, Academia Sinica.

Analyses were obtained using an accelerating potential of 15kV, a beam current of 10 nA, and a beam diameter of 1 μm . A synthetic spinel was used as a standard for the analysis of Al and Mg. A synthetic glass was used as a standard for the other elements. Grains of plagioclase, clinopyroxene, and olivine in the quenching products chosen for analysis were usually larger than 10 μm in diameter and the diameter of analyzed glass pools was usually larger than 30

μm . Matrix corrections were made with a ZAF procedure.

Several workers have pointed out that glass composition can be significantly altered by the formation of quench crystals (*e. g.* Jaques and Green, 1979, 1980). In this study, no quench crystals were found. All the spots for the glass analyses are at least 10 μm off the crystallized phases. The glass compositions are considered to represent the compositions of the melt coexisting with the crystallized assemblage in that run.

3. RESULTS AND DISCUSSIONS

3.1 Whole Rock Chemistry

The whole rock compositions analyzed by XRF are listed in Table 1. Compared to the basalt analysis by Chen (1990), the calcium content of the basalt in this study is low. The loss

Table 1. Whole rock composition of Wannienta Basalt .

	Present study	Chen (1990)
Wt. (%)		
SiO ₂	50.47	50.10
TiO ₂	0.84	---
Al ₂ O ₃	16.37	16.30
tFeO	8.12	7.43
MnO	0.16	0.17
MgO	7.99	7.50
CaO	8.86	11.07
Na ₂ O	2.37	2.83
K ₂ O	1.60	1.89
P ₂ O ₅	0.46	0.94
L. O. L.	1.99	0.94
Total	99.23	99.17
CIPW Norm		
Il	1.52	1.78
Or	9.46	11.17
Ab	20.05	18.20
An	29.31	26.19
Di	11.98	23.46
Hy	15.01	0.00
Ol	9.37	14.31
Ne	0.00	3.14
Mg#¹	63.7	64.3

¹ Mg# = (100Mg)/(Mg+Fe), where
Fe/(Fe⁺²+Fe⁺³)=1.

on ignition of the basalt in this study is, however, higher than that of Chen (1990). Other than these, the content of other major elements of the two analyses are pretty close. From the CIPW norm calculation, the basalt in this study is olivine normative and the basalt of Chen (1990) is, however, nepheline normative. Sampling of different lava flows or inconsistency between the two laboratories may be the cause of the differences between the two analyses. Both the basalt compositions in this study and those by Chen (1990) will be used as the reference points for the differentiation. If the fractionation mechanisms for the two differentiation trends are the same, they will be subparallel to each other in the variation diagrams.

3.2 Chemistry of the Constituent Minerals in Wannienta Basalt

The compositions of the minerals in the Wannienta basalt are significant in the petrogenesis of volcanics in the Kuanyinshan area. The composition of olivine, as phenocryst in the basalt thin section of this study, is with a forsterite (Fo) value of 85% (Table 2). It is close to the Fo value (84.0 %) of olivine core composition analyzed by Chen (1982). They are all in the compositional ranges of the olivine core of Mona Loa tholeiites (80.4 to 90.7 mole % of Fo) and Mona Kea tholeiites (76.3 to 90.5 mole % of Fo) (Baker *et al.*, 1996). The composition of olivine in the groundmass of Wannienta basalt is with a Fo value of 59% (Table 2). This is lower than that of olivine's rim composition (72.2%) in the analysis by Chen (1982). It is consistently shown that the forsterite content of olivine decreases with the decreasing temperature of crystallization.

Chemical compositions of clinopyroxene as phenocryst and in the groundmass of basalt for this study are also listed in Table 2, and are plotted in Figure 1. The wollastonite (Wo) component of the clinopyroxene as phenocryst (Wo=46) in nature is higher than that of clinopyroxene in the groundmass (Wo=40). The analyses are consistent with data obtained by Chen (1982, Table 3, K-41). The plagioclases in the thin section were also analyzed. The results are listed in Table 2 and plotted in Figure 2. In thin section, the compositions of plagioclase vary from An₃₀ (80% of anorthite; 20% of albite) as phenocryst to An₆₃ in the groundmass with the consideration of the plagioclase zoning. The anorthite (An) content (80%) of plagioclase phenocryst is close to the An content (83.0%) in Chen's study (1982, Table 6, K-41).

3.3 Crystallization Sequence

Fifteen runs are made to locate the liquidus temperature, the solidus temperature, and the melting interval of the basaltic magma. The quenching results are listed in Table 3. The liquidus temperature of the basaltic magma was determined to be 1270 °C. As the experimental temperature decreases, the crystallized phases increase. Image analysis software was tried, but it failed to estimate the percentage of each phase present. The run at 1087 °C is with a trace amount of glass. The solidus temperature of the basaltic magma is, therefore, deduced to be about 1080 °C. The melting interval is about 190 °C.

The crystallization sequence of the basaltic magma at atmospheric pressure is, therefore, constructed and shown in Figure 3. The near-liquidus mineral is oxides which belongs to spinel series in composition. The second mineral, olivine, appears at about 1217 °C. It is

Table 2. Microprobe analyses of minerals as phenocrysts or in groundmass of Wannienta basalt.

Phase ¹	Ol ²	Ol ³	Cpx ²	Cpx ³	Pl ²	Pl ³
Avg. of	4	4	5	4	5	5
Wt. %						
SiO ₂	40.18	36.06	52.20	51.51	48.14	53.22
Al ₂ O ₃	--	--	3.52	2.84	32.58	28.93
Cr ₂ O ₃	--	--	0.30	0.04	0.03	0.04
tFeO	14.74	34.60	5.31	9.26	0.08	0.10
MnO	0.14	1.22	0.21	0.41	0.02	0.03
MgO	46.19	29.05	15.70	15.91	0.92	0.12
CaO	0.13	0.26	22.86	19.81	16.33	12.78
NiO	0.23	0.02	--	--	--	--
Na ₂ O	--	--	0.24	0.23	2.18	4.21
K ₂ O	--	--	0.00	0.02	0.10	0.40
Total	101.58	101.21	100.79	100.87	100.42	100.54
Cations						
O	4	4	6	6	8	8
Si	1.175	0.990	1.908	1.900	2.208	2.408
Al	--	--	0.151	0.123	1.762	1.542
Cr	--	--	0.023	0.001	0.000	0.006
Fe	0.305	0.795	0.162	0.287	0.028	0.038
Mn	0.005	0.029	0.001	0.011	0.001	0.004
Mg	1.518	1.189	0.869	0.874	0.017	0.045
Ca	0.004	0.008	0.893	0.783	0.802	0.620
Ni	0.003	0.011	--	--	0.000	0.000
Na	--	--	0.022	0.017	0.194	0.369
K	--	--	0.000	0.001	0.014	0.045
Total	3.010	3.022	4.019	4.020	5.188	5.074
	Fo=85	Fo=59	Wo=46	Wo=40	An=80	An=63
			En=46	En=45		
			Fs=8	Fs=15		
Mg #⁴	84.8	59.9	84.1	75.4		

¹ Cpx: clinopyroxene; Ol: olivine; Pl: plagioclase.

² phenocrysts in basalt.

³ in groundmass of basalt.

⁴ the same meaning as in Table 1.

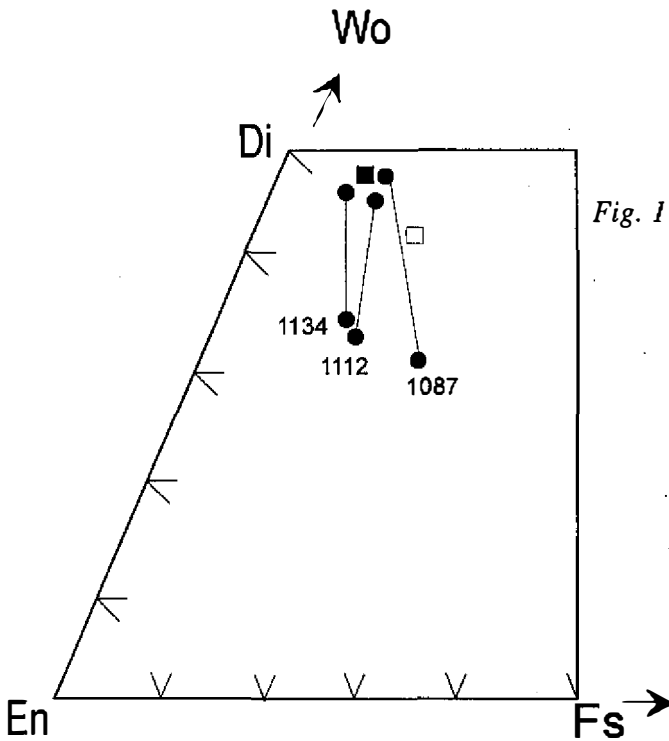


Fig. 1. Compositions of clinopyroxenes in Wannienta basalt in nature and in the quenching products of this study. The numbers in the figure are the temperatures for each run. The tie lines are drawn for the coexisting phases. Symbols: filled square: composition of clinopyroxene in basalt; open square: composition of clinopyroxene in groundmass of basalt; filled circles: compositions of clinopyroxenes in the quenching products.

Table 3. Quenching experiments.

Run No.	Temp. (°C)	Duration (hrs:mins)	Phase(s)*
KYB14	1281	6:00	Gl
KYB10	1273	17:00	Gl
KYB11	1267	19:00	Gl+Ox
KYB15	1260	16:35	Gl+Ox
KYB1	1254	5:00	Gl+Ox
KYB2	1232	13:30	Gl+Ox
KYB12	1221	7:00	Gl+Ox
KYB3	1212	7:30	Gl+Ox+Ol
KYB4	1183	19:00	Gl+Ox+Ol
KYB5	1173	5:45	Gl+Ox+Ol+Pl
KYB6	1156	6:30	Gl+Ox+Ol+Pl
KYB13	1139	6:00	Gl+Ox+Ol+Pl
KYB7	1134	6:00	Gl+Ox+Ol+Pl+Cpx
KYB8	1112	17:15	Gl+Ox+Ol+Pl+Cpx
KYB9	1087	17:50	Gl+Ox+Ol+Pl+Cpx

* Cpx: clinopyroxene; Gl: glass; Ol: olivine; Ox: oxides; Pl: plagioclase.

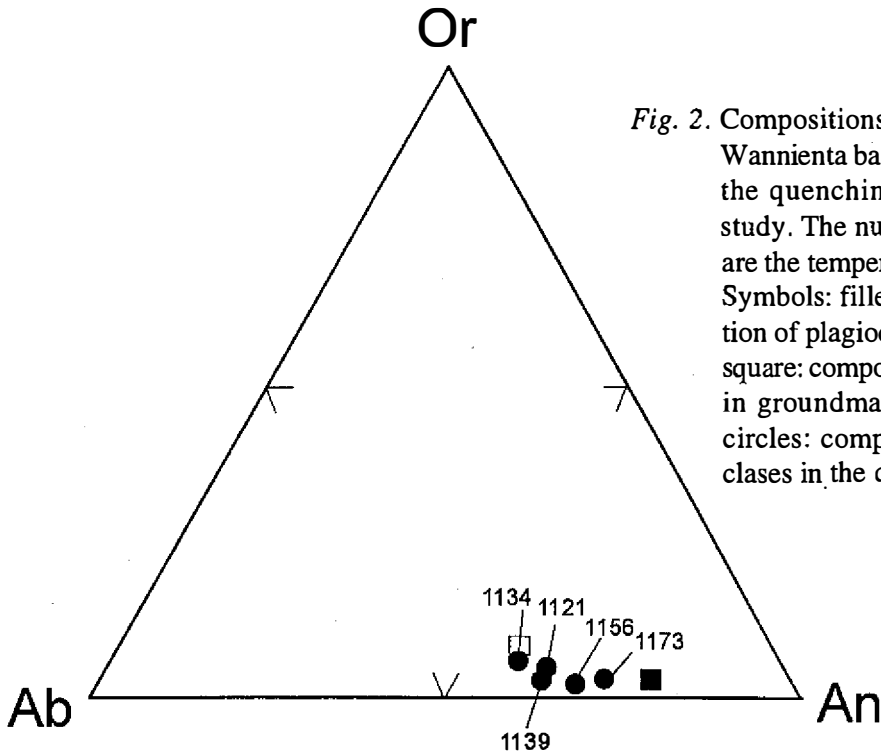


Fig. 2. Compositions of plagioclases in Wannienta basalt in nature and in the quenching products of this study. The numbers in the figure are the temperatures for each run. Symbols: filled square: composition of plagioclase in basalt; open square: composition of plagioclase in groundmass of basalt; filled circles: compositions of plagioclases in the quenching products.

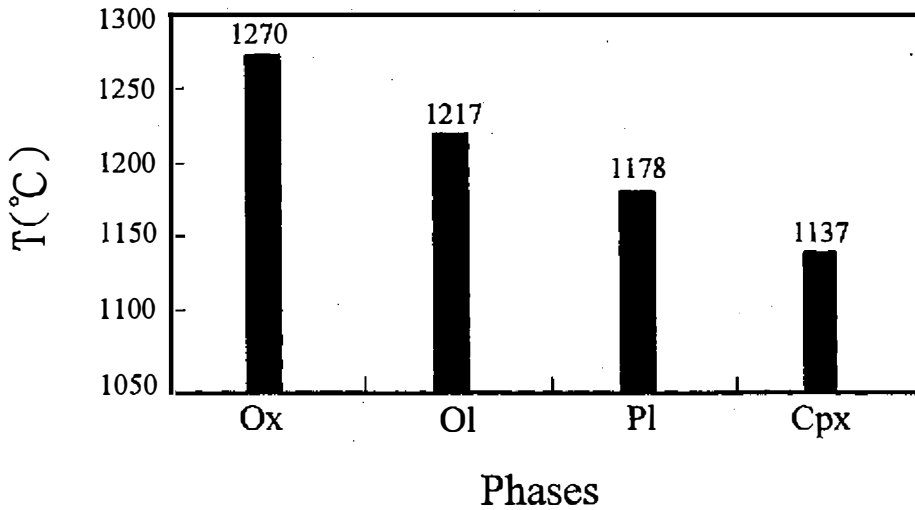


Fig. 3. The crystallization order of the minerals of the Wannienta basalt was constructed by the experiments at atmospheric pressure. The abbreviations for the phases are the same as in Table 3.

followed by plagioclase at about 1178 °C. The last mineral to crystallize, at about 1137 °C, is clinopyroxene. The crystallization sequence at atmospheric pressure is, therefore, established as oxides, olivine, plagioclase, and clinopyroxene.

3.4 Mineral Chemistry of Synthetic Phases

The olivines in Run No. KYB9 were analyzed and are listed in Table 4. The Fo content of olivine is 86%. This is close to the Fo content of olivine as phenocrysts in the Wannienta basalt (Table 2 in this study and Table 2 in Chen (1982)).

The clinopyroxenes in the quenching products were probed and are listed in Table 5 and also plotted in Figure 1. The clinopyroxenes in each run contain two groups different in composition. The reason for this is not clear. The clinopyroxenes of the first group are higher in wollastonite (Wo) than the second group. Except for one diopside in KYB9, they are all classified as augite following the classification of Moritomo (1988). The En components range from 55 to 45 mole %. The En components of all the clinopyroxenes decrease with decreasing temperature (Table 5 and Figure 1). The ranges of Wo and Fs components are from 30 to 46 % and 7 to 21 %, respectively. The clinopyroxenes of the first group are in a similar range to the clinopyroxenes in the thin section of this study (Table 2) and in the basalt as reported by Chen (1982) (Figure 1).

Table 4. Mean and standard deviation of microprobe analyses of olivine in this study.

T (°C)	1087
Avg. of	3
Run No.	KYB9
Wt.(%)	
SiO₂	41.25(0.86) ¹
tFeO	12.91(2.32)
MnO	0.43(0.22)
MgO	44.71(1.45)
CaO	0.79(0.26)
Total	100.02
Cations per 4 oxygens	
Si	1.024
Fe	0.263
Mn	0.009
Mg	1.654
Ca	0.021
Total	2.971
	Fo=86

¹ standard deviations in parentheses.

Table 5. Mean and standard deviation of microprobe analyses of clinopyroxene in this study.

Run No.	KYB7	KYB7	KYB8	KYB8	KYB9	KYB9
T (°C)	1134	1134	1112	1112	1087	1087
Avg. of	3	3	3	3	4	4
Wt. (%)						
SiO ₂	50.89(1.24) ¹	48.37(1.25)	52.23(1.70)	49.55(1.45)	52.39(0.98)	48.63(1.21)
TiO ₂	0.36(0.15)	0.23(0.02)	0.57(0.02)	0.24(0.03)	0.47(0.12)	0.45(0.17)
Al ₂ O ₃	2.66(0.27)	2.21(0.04)	3.06(0.21)	3.30(0.05)	2.99(0.65)	2.27(0.67)
Cr ₂ O ₃	0.27(0.01)	0.03(0.01)	0.45(0.02)	0.03(0.01)	0.32(0.28)	0.02(0.04)
tFeO	4.69(1.23)	9.02(1.15)	5.36(1.44)	9.33(1.24)	5.74(1.52)	13.75(1.07)
MnO	0.44(0.02)	0.23(0.01)	0.41(0.05)	0.47(0.02)	0.23(0.09)	0.44(0.28)
MgO	17.60(2.14)	21.47(2.46)	16.21(1.21)	20.11(3.22)	15.90(0.66)	19.07(1.87)
CaO	22.07(2.21)	17.63(1.33)	21.11(1.21)	15.19(3.14)	21.83(0.72)	15.20(2.02)
Na ₂ O	1.06(0.01)	0.66(0.01)	0.30(0.01)	0.89(0.03)	0.24(0.04)	0.23(0.03)
K ₂ O	0.05(0.02)	0.12(0.01)	0.06(0.02)	0.11(0.02)	0.03(0.01)	0.08(0.10)
Total	100.09	99.97	99.75	99.23	99.87	100.14
Cations per 6 oxygens						
Si	1.878	1.810	1.920	1.850	1.925	1.837
Ti	0.010	0.006	0.016	0.007	0.013	0.013
Al	0.116	0.094	0.080	0.145	0.075	0.101
Cr	0.008	0.000	0.013	0.000	0.009	0.001
tFe	0.145	0.281	0.165	0.291	0.168	0.434
Mn	0.014	0.007	0.013	0.015	0.007	0.014
Mg	0.986	1.197	0.888	1.119	0.871	1.074
Ca	0.873	0.707	0.831	0.608	0.860	0.615
Na	0.076	0.048	0.021	0.064	0.017	0.017
K	0.002	0.006	0.003	0.005	0.001	0.004
Total	4.090	4.156	3.950	4.104	3.950	4.109
Wo	44	32	44	31	46	30
En	49	55	47	55	45	49
Fs	7	13	9	14	9	21
Mg #²	87.0	80.9	84.4	79.3	83.2	71.2

¹ standard deviations in parentheses.² the same meaning as in Table 1.

The plagioclases of some runs were analyzed by electron microprobe. Their compositions are listed in Table 6 and plotted in Figure 2. The An content in the plagioclase varies from 71 to 60 mole %. The An contents of the zoning plagioclases in the natural basalt vary from 83% to 63% (data from Chen (1982)). The plagioclase with An higher than 71% in the basalt cannot be reproduced in the laboratory at atmospheric pressure. They may occur at a pressure higher than one atmosphere.

3.5 Evolution of the Magma

The glasses in five runs were analyzed and are listed in Table 7. The reason for choosing these glasses from five runs for analysis is that they coexist with phase assemblages different from each other. As temperature decreased, the phases successively crystallized one after an-

Table 6. Mean and standard deviation of microprobe analyses of plagioclase in this study.

Run No.	KYB5	KYB6	KYB13	KYB7	KYB8	KYB9
T (°C)	1173	1156	1139	1134	1121	1087
Avg. of	4	1	1	4	4	3
Wt.(%)						
SiO ₂	50.05(1.62) ¹	50.55	50.69	50.21(1.22)	52.11(1.23)	52.45(2.39)
Al ₂ O ₃	30.17(1.61)	28.09	28.87	29.10(2.14)	29.69(2.31)	29.56(2.14)
tFeO	1.07(0.07)	2.33	1.98	1.23(0.33)	0.37(0.02)	1.06(0.09)
CaO	14.21(1.45)	14.86	13.45	13.91(2.13)	13.26(2.15)	12.42(1.43)
Na ₂ O	3.04(0.65)	3.60	3.27	4.42(1.27)	3.77(1.55)	3.97(1.41)
K ₂ O	0.26(0.11)	0.23	0.47	0.89(0.02)	0.60(0.01)	0.74(0.73)
Total	98.80	99.66	98.73	99.76	99.80	100.20
Cations per 8 oxygens						
Si	2.314	2.317	2.330	2.312	2.371	2.389
Al	1.644	1.517	1.564	1.586	1.592	1.556
Fe	0.040	0.089	0.075	0.048	0.014	0.040
Ca	0.704	0.730	0.662	0.689	0.646	0.606
Na	0.273	0.320	0.291	0.396	0.332	0.351
K	0.015	0.013	0.028	0.052	0.035	0.043
Total	4.990	4.986	4.910	5.056	4.990	4.982
An	71	69	68	60	64	61
Ab	27	30	30	35	33	35
Or	2	1	2	5	3	4

¹ standard deviations in parentheses.

Table 7. Mean and standard deviation of microprobe analyses of glasses in this study.

Run No.	KYB10	KYB11	KYB3	KYB5	KYB9
T (°C)	1273	1267	1212	1173	1087
No. of analyses	6	6	5	6	6
Wt. (%)					
SiO ₂	53.48(0.80) ²	52.40(0.73)	53.79(0.35)	55.80(0.39)	58.66(1.33)
TiO ₂	0.83(0.02)	0.86(0.01)	0.95(0.28)	0.86(0.06)	0.99(0.31)
Al ₂ O ₃	16.42(0.25)	17.54(0.26)	16.57(0.56)	15.66(0.57)	20.51(1.54)
Cr ₂ O ₃	0.01(0.01)	0.02(0.05)	0.06(0.03)	0.02(0.03)	0.03(0.08)
tFeO	7.77(0.12)	7.62(0.21)	7.42(0.06)	6.89(0.20)	4.26(1.77)
MnO	0.01(0.01)	0.01(0.01)	0.01(0.13)	0.01(0.06)	0.00(0.05)
MgO	7.84(0.12)	8.16(0.15)	8.29(0.45)	6.94(0.29)	1.76(0.90)
CaO	9.31(0.12)	8.87(0.23)	8.80(0.77)	8.85(0.28)	6.87(1.71)
Na ₂ O	2.70(0.14)	2.84(0.05)	2.40(0.25)	2.96(0.07)	4.10(0.55)
K ₂ O	1.63(0.04)	1.68(0.01)	1.71(0.55)	1.99(0.08)	2.89(0.63)
Total ¹	100.00	100.00	100.00	100.00	100.00
CIPW Norm					
Il	1.60	1.56	1.60	1.86	1.81
Or	9.69	9.57	9.75	11.64	17.08
Ab	22.85	22.93	22.93	24.79	34.78
An	27.95	28.26	28.15	24.52	29.01
Di	14.99	12.32	12.40	15.45	3.89
Hy	19.02	18.92	22.07	20.77	9.26
Q	0.00	0.00	0.00	0.58	4.45
Cm	0.18	0.07	0.07	0.03	0.10
Ol	6.24	7.05	2.75	0.00	0.00
Mg # ³	64.26	65.68	65.64	63.60	42.42

¹ normalized to 100%.² standard deviations in parentheses.³ the same meaning as in Table 1.

other in each run. The glass compositions, therefore, imply the fractional crystallization trend of the Wannienta basaltic magma.

The compositions of glasses, in Table 7, were plotted versus temperature in Figure 4. The fractionation trends (reading from high temperature, right, to low temperature, left) show enrichment in silicon, aluminum, and alkalis. The residual magmas become depleted in calcium, iron, and magnesium. Six rock type compositions from Chen (1990) were plotted with the compositions of residual liquids for comparison in Harker's variation diagrams (Figure 5).

The chemical variations of the trends were shown to be subparallel for all the major elements of Kuanyinshan volcanics in nature and of the residual magmas in this study with the available data. The fractionation trend in nature can, therefore, be modeled by the variation of the residual magmas in the quenching products. It implies that the fractional crystallization of the Wannienta basaltic magma could not have occurred at a great depth. The basaltic magma can be modeled as producing, by fractional crystallization, augite andesitic magma (No. 4 in

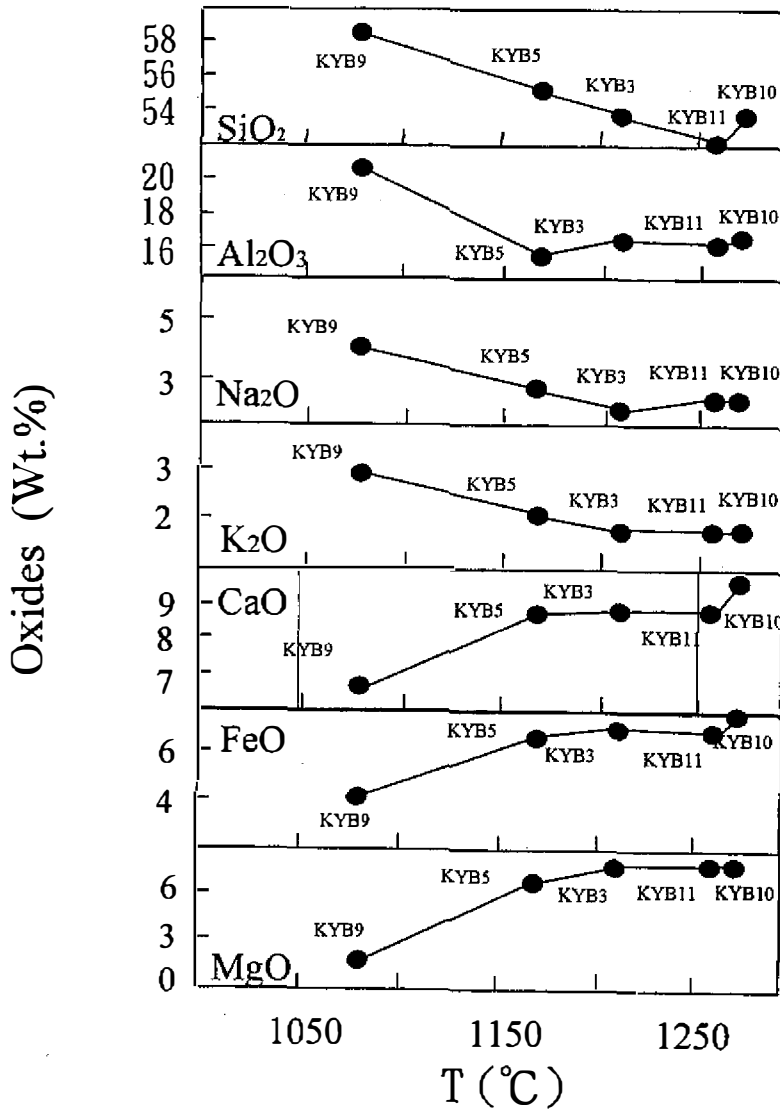


Fig. 4. Variations of SiO₂, Al₂O₃, Na₂O, K₂O, CaO, total Fe as FeO, and MgO of residual glasses versus temperature. KYB numbers are the run numbers listed in Table 3.

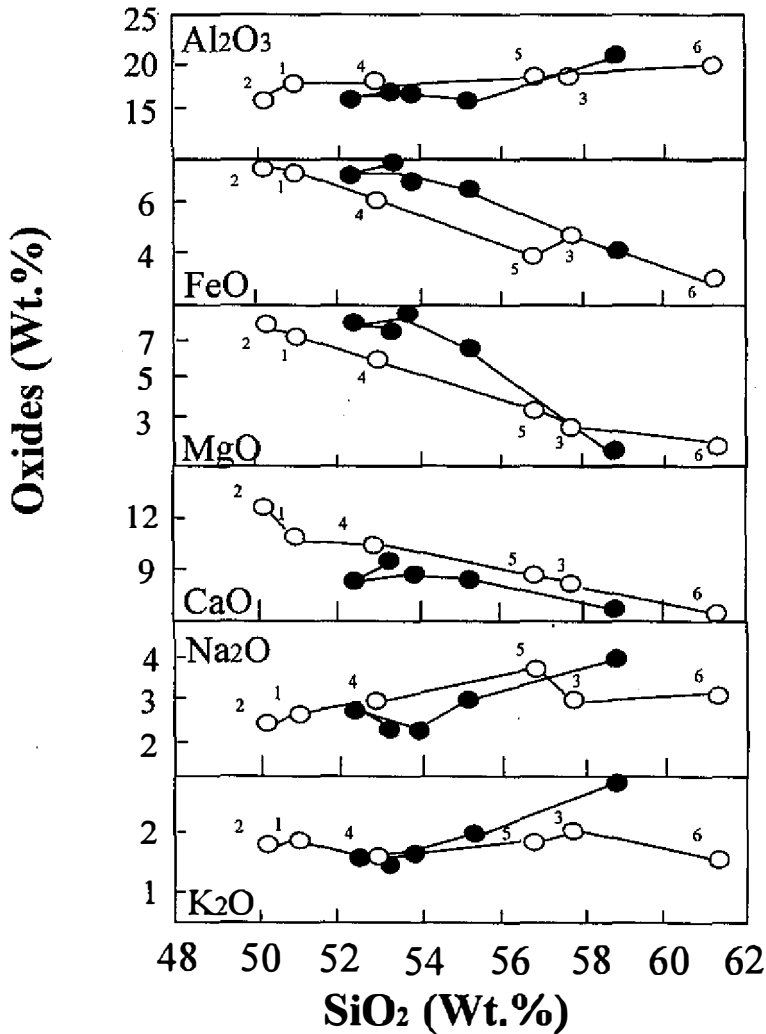


Fig. 5. Harker variation diagrams for the residual glasses in the quenching products and Kuanyinshan volcanics (Chen, 1990). Symbols: solid dots: the residual glasses in this study; open circles: average compositions of each rock type from Chen (1990): 1: augite olivine basalt; 2: augite basalt; 3: biotite hornblende andesite; 4: augite andesite; 5: hornblende bearing two pyroxene andesite; 6: hypersthene hornblende andesite.

Figure 5); hornblende bearing two pyroxene andesitic magma (No. 5 in Figure 5); and biotite hornblende andesitic magma (No. 3 in Figure 5). The fractionates for the differentiation include oxides, olivine, plagioclase, or clinopyroxene.

The glass compositions in Table 7 and the rock type compositions from Chen (1990) are

also plotted in an AMF diagram (Figure 6). They all show a trend similar to that for alkali enrichment. They are also plotted in the Ol-Di-Sil pseudoternary diagram projected from plagioclase in Figure 7 following the methods of Walker *et al.* (1979) and Sack *et al.* (1987). The cotectics of Sack *et al.* (1987) are reproduced in Figure 7 for reference. The entire series of Kuanyinshan volcanics analyzed by Chen (1990) forms a trend extending from basalts toward the silica apex close to the cotectics. The residual magmas in this study are plotted in the olivine (and plagioclase) primary phase field. The experiments of Sack *et al.* (1987), however, were undertaken proceeded in the oxygen fugacity of Quartz-Fayalite-Magnetite buffer. The experiments in this study were made in the air. Furthermore, the liquidus boundary surfaces were projected from the plagioclase apex and shown as lines in the diagram for the simplicity. Therefore, the primary phase fields for olivine and high-Ca pyroxene may vary depending on the oxygen fugacity and the section we choose.

The glass composition at 1267 °C seems to move toward the Ol-apex (Figure 7) as temperature decreases to 1212 °C crystallizing olivine. The reason for this is that the real positions of the glass compositions at 1267 °C and 1212 °C are in the tetrahedron of plagioclase (Plag) - diopside (Di) - olivine (Ol) - silica (Sil). They are plotted in the Ol-Di-Sil pseudoternary diagram projected from the plagioclase apex. The dots in Figure 7 were influenced by the paralactic effect.

Previous studies (*e. g.* Grove and Baker, 1984; Elthon and Scarfe, 1984; Baker and Eggler, 1987; Liu and Presnall, 1990) have consistently shown that the cotectics shift toward the Ol-apex as pressure increases. It can be concluded that the Kuanyinshan volcanic series can be

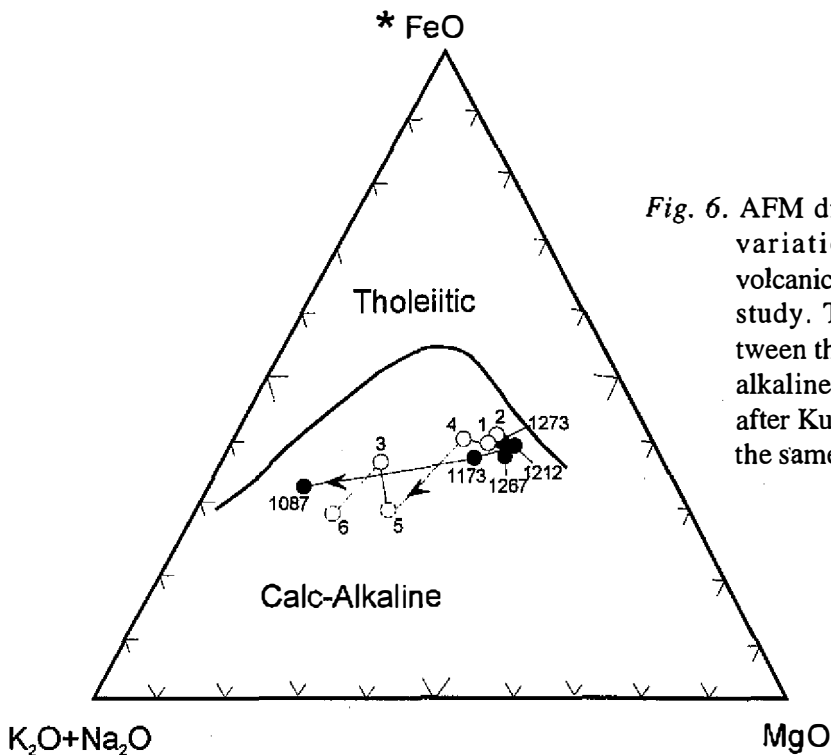
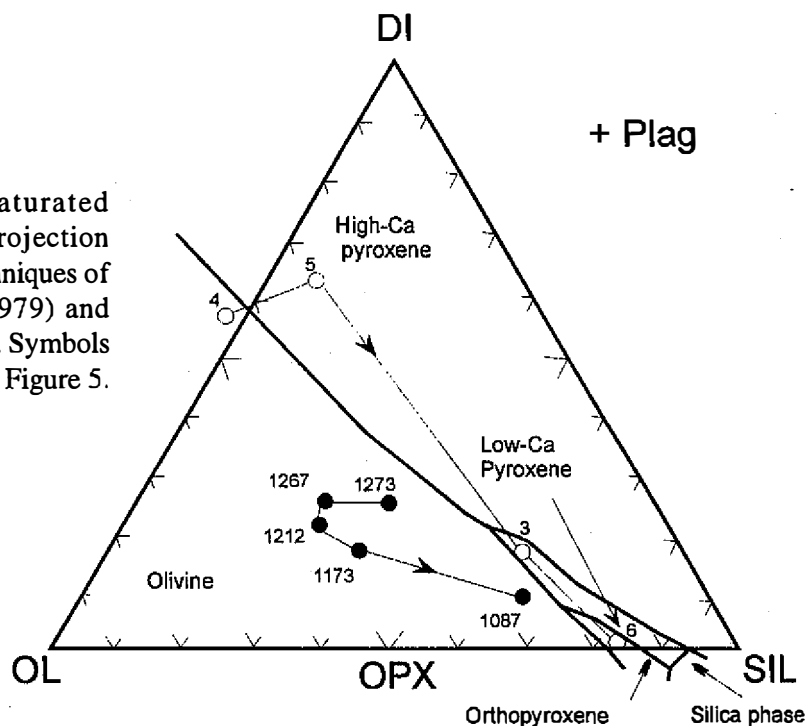


Fig. 6. AFM diagram illustrating the variation of Kuanyinshan volcanics and the glasses in this study. The boundary line between tholeiitic series and calc-alkaline series was reproduced after Kuno (1950). Symbols are the same as in Figure 5.

Fig. 7. Plagioclase saturated pseudoternary projection following the techniques of Walker *et al.* (1979) and Sack *et al.* (1987). Symbols are the same as in Figure 5.



modeled by the fractionation of the Wannienta basaltic magma at a pressure higher than, but close to, one atmosphere. The phenocryst assemblages are inferred as the fractionates for the differentiation trend. The basaltic magma fractionates oxides, olivine, plagioclase, or clinopyroxene to generate many types of magma depending on the degree of fractionation.

4. CONCLUSIONS

The liquidus temperature of the basaltic magma is estimated to be 1270 °C. The solidus temperature of the basaltic magma is close to 1080 °C. The melting interval is about 190 °C. The crystallization sequence of the basaltic magma at atmospheric pressure is constructed as follows: oxides, olivine, plagioclase, and clinopyroxene.

The fractionation trends of the basaltic magma show enrichment in silicon, aluminum, and alkalis, and depletion in calcium, iron, and magnesium in the later stage. The fractionation trend in nature can be modeled by the variation of the residual magmas in this study. It implies that the pressure for the fractional crystallization of the Wannienta basaltic magma is low. Except for hypersthene hornblende andesite, the fractionates producing Kuanyinshan andesites could be oxides, olivine, plagioclase, or clinopyroxene.

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