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Citation	Journal of science of the Hiroshima University. Series C, Geology and mineralogy , 8 (2) : 149 - 163
Issue Date	1983-11-30
DOI	
Self DOI	10.15027/53104
URL	https://ir.lib.hiroshima-u.ac.jp/00053104
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Contact Metamorphic Effect on Basaltic Rocks by the Koyama Gabbro Complex, Susa Area, Southwest Japan

By

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with 7 Tables, 4 Text-figures and 1 Plate

(Received June 14, 1983)

Abstract: Tertiary basaltic rocks around the Koyama gabbro complex mass, which occurs in the northeastern part of Yamaguchi Prefecture, have undergone intense contact metamorphism by the mass. Radiometric age determinations indicate that the metamorphism is of Miocene age. The contact aureole is rather narrow (a maximum of about 700 m), the metamorphic grade rapidly increasing toward the mass. In the comparatively lower temperature part of the contact aureole, the metamorphic paragenesis is actinolitic hornblende ± hornblende + epidote + biotite + oligoclase + quartz. Meanwhile, the highest-grade rocks are represented by the stable association of orthopyroxene + clinopyroxene ± hornblende + biotite + labradorite + quartz. The metamorphic temperature close to the contact with the mass is estimated to be 800 to 860°C. In the most-intensely metamorphosed basalts, most of such phenocrystic minerals as clinopyroxene and plagioclase can still preserve the essential chemical characteristics in the original rocks, whereas phenocrystic orthopyroxene appears to have been chemically changed its composition during the metamorphism.

Contents

I. Introduction

The Susa area studied is situated in the northeastern part of Yamaguchi Prefecture, southwest Japan (Fig. 1). The area is mainly underlain by Cretaceous volcanic rocks, Miocene sediments, basaltic rocks and gabbro complex. The gabbro complex mass has had intense contact metamorphic effect on the surrounding rocks. In the southern part of the area, Miocene sedimentary rocks have been recrystallized into hornfels showing the progressive zonation of chlorite zone, biotite zone, cordierite-K feldspar zone and orthopyroxene zone (Nishimura et al., 1982 and Suzuki and Nishimura, 1983). The figure of the progressive metamorphism and the metamorphic age will be described in detail in a separate paper (Nishimura et al., in preparation).

In the northern part of the area, basaltic rocks develop and have also been intensely

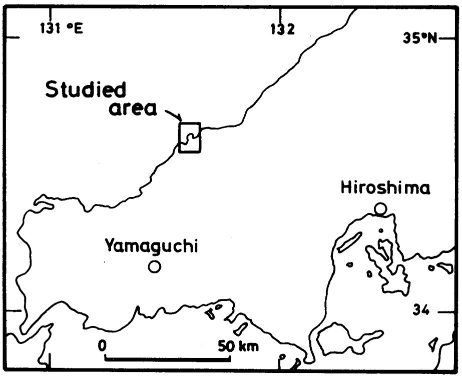

FIG. 1. Index map of the Susa area.

metamorphosed to have the critical association of orthopyroxene and clinopyroxene. Although the lower grade metamorphosed basalts are scattered only on some offshore islets, mineralogical changes from non-metamorphosed basalt toward the highest grade one can roughly be traced.

In this paper, the present authors intend to describe the basaltic rocks to clarify some characteristics of the metamorphism and to estimate the metamorphic temperature close to the contact with the mass.

ACKNOWLEDGMENTS: The authors wish to express their sincere gratitude to Mr. Asao MINAMI of the Hiroshima University for his assistance in EPMA analyses. Their thanks are also due to Messrs. Hideo TAKAHASHI and Akito MAGAI of the same University for preparing polished thin sections. The present study is partly supported by the Grant in Aid for Scientific Researches from the Ministry of Education, Japan.

II. GENERAL GEOLOGY

The geology of the Susa area has been summarized by YAMAZAKI (1967) and OKAMOTO and SUYAMA (1975). Fig. 2 shows the geological map of this area modified on the basis of their results. In the southernmost and northeastern parts of the area, widely develop late Cretaceous volcanic rocks of the Fukuga Formation. It is unconformably overlain by Miocene sedimentary rocks of the Susa Group. Sporadic outcrops of basaltic rocks, contact metamorphism of which is described here, are distributed in the northern part of the area. In the central part, there occurs the intrusive body called the Kayama gabbro complex, which has thermal effect on the above-mentioned rocks.

A. Fukuga Formation

Rhyolitic to dacitic pyroclastic rocks are widely exposed in the southernmost part as well as around Kurosaki. The bed generally trends east-west, and gently dips northward. The rocks are assigned to the upper part of the late Cretaceous Fukuga Formation of the Abu Group, which is widely distributed along the coast from Hagi to Tamagawa through the area now concerned (MURAKAMI and HASE, 1967).

B. Susa Group

The sedimentary rocks distributed around Mt. Koyama are named the Susa Group

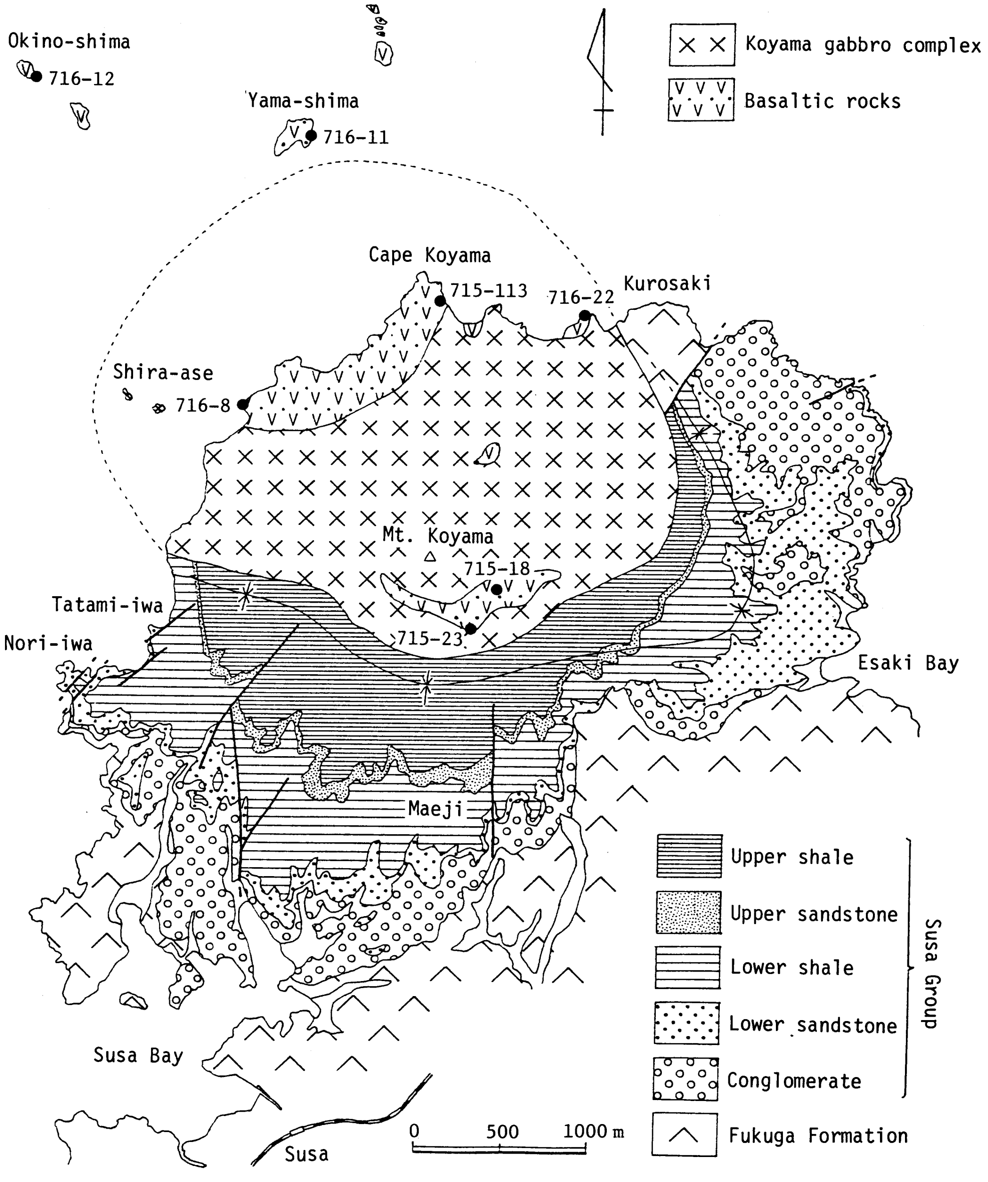

Fig. 2. Geological map of the Susa area, showing the localities of the analysed samples (Modified from Yamazaki, 1967 and Okamoto and Suyama, 1975).

(Okamoto et al., 1973). The Group is composed of regularly alternating beds of conglomerate, sandstone and shale of neritic origin, the total thickness of which exceeds 600 meters (Okamoto, 1983). The Group unconformably overlie the Fukuga Formation described above. Biostratigraphical investigations have revealed that the Group can be correlative with the Yuya-wan Group and the Bihoku Group of early to middle Miocene age (Okamoto, 1974).

Constituent rocks of the Susa Group have been intruded and thermally metamorphosed by the Koyama gabbro complex mass. The contact aureole is formed for about 700 meters or more from the mass. On the basis of mineral associations, the aureole is clearly divided into four progressive zones, namely, chlorite zone, biotite zone, cordierite-K feldspar zone and orthopyroxene zone. Chemical characteristics of the metamorphic minerals change systematically from zone to zone (Nishimura et al., 1982 and Suzuki and Nishimura, 1983).

C. Basaltic rocks

In the northern part of the area, including offshore islets, there crop out basaltic lava and pyroclastic rocks. Nozima (1941) suggested that the basaltic rocks were cognate to the Koyama gabbro complex and had been metamorphosed by it. Oji (1960) and Murakami (1975), however, considered that they belonged to the tholeiitic rock series and could be correlated with Paleogene basaltic rocks in the Yuya-wan area. On the other hand, another ideas that the basaltic rocks correspond to the calc-alkaline rock series and are assigned to those of the Oomori Formation have been put forward (Takamura, 1973 and Okamoto and Suyama, 1975). Recently, Tenpaku et al. (1974 and 1975) has been clarified by means of petrological investigations on basic and ultrabasic xenoliths in the basaltic rocks that the xenoliths were equivalent to basic and ultrabasic phases of the Koyama gabbro complex and represented the early-stage crystalline phase of basaltic magma which was petrogenetically connected with the gabbro complex.

In any way, the petrogenetic relationship between basaltic rocks and gabbroic rocks has not yet been confirmed. The contact metamorphism now discussed is on these basaltic rocks.

D. Koyama gabbro complex

The Koyama gabbro complex is well-exposed in a small boss (about 3 km diameter) around Mt. Koyama. Since Tsuboi (1926), the complex has been investigated by many authors from the view point of crystallization differentiation. It is mainly composed of medium- to coarse-grained hypersthene-augite-quartz gabbro associated with olivine pyroxenite, anorthositic gabbro, diorite and aplite (Murakami, 1975). The original magma of the complex was considered to belong to the calc-alkaline rock series (Oji and Oji, 1965 and Yamazaki, 1967). Recently, Yamaguchi et al. (1974) has investigated chemically on the zonal structure of pyroxenes in the complex and clarified that the magmatism had evolved from the tholeiitic rock series in the early stage to the calc-alkaline one in the later stage.

The age of the intrusion of the complex is infered to be around 12 Ma (Nishimura et al., 1982).

E. Dykes

Small-scale diabasic dykes are widespread not only in the Susa Group but in the Koyama gabbro complex. It seems that the dykes are radially distributed around and in the complex mass. Some of the dykes have been thermally metamorphosed by the complex and the other shows no sign of the contact effect. Therefore, the activity of the dykes can be divided at least into two stages.

III. PETROGRAPHY OF BASALTIC ROCKS

A. Microscopic characteristics

Basaltic rocks are mainly developed in the northern part of the area including offshore islets as well as on the southern and northern sides of Mt. Koyama as roof remnants.

Near the very contact with the gabbro complex mass, especially on the southern side of Mt. Koyama and west of Kurosaki, basaltic rocks have been most-intensely metamorphosed (Sample Nos. 715–18, 715–23, 716–22). The groundmass shows distinct granoblastic texture, which is mainly composed of very fine-grained (0.05 mm) aggregates of recrystallized orthopyroxene, clinopyroxene, plagioclase and biotite. Medium-grained (1 to 4 mm) crystals of plagioclase and fine- to medium-grained (0.7 to 2.5 mm) crystals of orthopyroxene and clinopyroxene occur sporadically in the groundmass. They seem to retain the phenocrystic appearance of the orignal basaltic rocks. Phenocrystic plagioclase shows distinct zonal structure, the outermost rim of which includes the very fine-grained (0.05 mm) crystals of recrystallized orthopyroxene and clinopyroxene. The width of the rim reaches only 0.1 to 0.2 millimeters. The margin of phenocrystic orthopyroxene has also been changed into very fine-grained (0.05 mm) aggregates of recrystallized orthopyroxene and/or clinopyroxene, each grain of which shows mutually different extinction position. Recrystallized biotite (0.05 to 0.2 mm) is fairly abundant, but recrystallized hornblende exists only in less abundance or not. Typical photomicrograph of the most-intensely metamorphosed basalt is given in Plate 17–1.

Samples near the Cape Koyama (No. 715–113) and from east of Shira-ase (No. 716–8) seem to have been subjected rather lower-grade metamorphic effect, although they contain orthopyroxene and clinopyroxene as metamorphic minerals. The groundmass has perfectly been recrystallized to show distinct granoblastic texture. Recrystallized minerals are rich in hornblende and biotite but are poor in orthopyroxene and clinopyroxene as compared with the highest grade rocks described above. The grain size of the groundmass decreases to the order of 0.02 millimeter. In the groundmass, are scattered glomeroporphyritic aggregates of plagioclase and coarser-grained (0.5 to 1 mm) orthopyroxene and clinopyroxene. The periphery of phenocrystic pyroxenes has always been replaced by platy green hornblende. Quartz pool is sometimes found. The photomicrograph of the sample 715–113 is shown in Plate 17–2.

At Yama-shima islet about 1.1 kilometers northwest of the Cape Koyama, the contact effect seems to further be weakened. The porphyritic texture of the original basaltic rock is well preserved, but minute recrystallized crystals of fibrous amphiboles, flaky biotite, granular quartz and granular plagioclase are found in a groundmass. Phenocrystic plagioclase have partly been recrystallized to show the aggregate of quartz+amphiboles+epidote+sphene. Phenocrystic pyroxenes have been completely replaced by green amphiboles. As will be shown later, such metamorphic amphiboles as actinolitic hornblende and hornblende seem to coexist with each other in one sample (No. 716–11). The photomicrograph of the sample is given in Plate 17–3.

At Okino-shima islet about 3 kilometers northwest of the Cape Koyama, unmetamorphosed basaltic rocks crop out. A typical sample (No. 716–12) of the islet shows porphyritic and hyalopilitic texture (Plate 17–4). The phenocrysts are of orthopyroxene,

TABLE 1. MINERAL PARAGENESES OF BASALTIC ROCKS.

Sample No.	Locality	Metamorphic minerals (M)							Phenocrystic minerals (P)		
		Opx	Cpx	Amph	Biot	Ep	Plag	Q	Opx	Cpx	Plag
715–18	Southern side of Mt. Koyama	1, 3	2, 4	5	6	–	+	+	+	+	+
715–23	ditto	7	8	–	11	–	+	+	9	10	+
716–22	West of Kurosaki	12	13	–	16	–	+	+	14	15	+
715–113	Cape Koyama	17	18	21	22	–	+	+	19	20	+
716–8	East of Shira-ase	+	+	24	25	–	+	+	23	+	+
716–11	Yama-shima islet	–	–	26, 27	+	28	+	+	+	+	+
716–12	Okino-shima islet	–	–	–	–	–	–	–	+	29	+

This table shows the mineral assemblages of basaltic rocks discussed in the text. The numerals in the table refer to the column numbers in other tables where the chemical compositions of minerals are given. The symbols plus and bar mean present and absent, respectively. Abbreviations of minerals are as follows: Opx; orthopyroxene, Cpx; clinopyroxene, Amph; amphiboles, Biot; biotite, Ep; epidote, Plag; plagioclase, Q; quartz

TABLE 2. CHEMICAL COMPOSITIONS OF MAIN CONSTITUENT MINERALS OF THE METAMORPHOSED BASALTS (SAMPLE NO. 715–18).

	1	2	3	4	5	6
	Opx-1	Cpx-1	Opx-2	Cpx-2	Amph	Biot
SiO_2	51.4	51.6	52.1	52.1	46.1	36.2
TiO_2	0.27	0.43	0.39	0.27	0.76	4.36
Al_2O_3	0.45	1.10	0.54	0.77	6.33	13.2
FeO	30.2	15.2	29.0	13.4	18.7	20.6
MnO	0.77	0.35	0.71	0.26	0.20	0.06
MgO	15.2	11.8	15.7	12.1	11.3	10.2
CaO	1.18	18.5	1.62	20.7	11.2	0.05
Na_2O	0.02	0.20	0.03	0.17	0.86	0.13
K_2O	0.02	0.02	0.03	0.02	0.71	9.09
Total	99.51	99.20	100.12	99.79	96.16	93.89
			Numbers of ions			
O	6.000	6.000	6.000	6.000	23.000	22.000
Si	2.005	1.979	2.006	1.982	7.049	5.664
Ti	0.008	0.012	0.011	0.008	0.087	0.512
Al	0.021	0.050	0.025	0.035	1.141	2.428
Fe	0.984	0.488	0.933	0.425	2.398	2.694
Mn	0.025	0.011	0.023	0.009	0.026	0.008
Mg	0.881	0.675	0.903	0.687	2.565	2.371
Ca	0.049	0.761	0.067	0.842	1.830	0.008
Na	0.002	0.015	0.002	0.013	0.256	0.038
K	0.001	0.001	0.001	0.001	0.139	1.812

All Fe as FeO.

Abbreviations of minerals as in Table 1.

clinopyroxene and plagioclase. Plagioclase occurs often as glomeroporphyritic aggregate of medium-grained (1 to 2 mm) crystals. Each grain commonly shows distinct oscillatory zoning. Orthopyroxene and clinopyroxene are fine-grained (0.5 to 1 mm). The former has been intensely altered to chlorite, while the latter shows a fresh appearance. The groundmass is composed of very fine-grained lath-shaped plagioclase, opaque minerals and glass.

B. Mineralogy

The mineral associations of basaltic rocks now discussed are summarized in Table 1. Metamorphosed basaltic rocks are mainly composed of such kinds of metamorphic minerals as orthopyroxene, clinopyroxene, amphiboles, epidote, biotite, plagioclase and quartz. Especially in weakly- and non-metamorphosed rocks, are preserved essential minerals of orthopyroxene, clinopyroxene and plagioclase of igneous origin.

Main constituent minerals are analysed by the use of JEOL JXA–5A. Operation

Table 3. Chemical Compositions of Main Constituent Minerals of the Metamorphosed Basalt (Sample No. 715–23).

	7	8	9	10	11
	Opx-1	Cpx-1	Opx-P*	Cpx-P*	Biot
SiO_2	51.5	51.2	51.6	52.8	35.7
TiO_2	0.22	0.31	0.30	0.39	4.04
Al_2O_3	0.37	1.04	1.09	1.96	13.0
FeO	31.0	14.6	27.7	12.0	22.0
MnO	0.82	0.37	0.66	0.26	0.07
MgO	14.6	11.1	17.4	13.6	9.92
CaO	0.92	20.3	1.70	19.1	0.16
Na_2O	0.02	0.19	0.03	0.16	0.06
K_2O	0.01	0.03	0.02	0.03	9.47
Total	99.46	99.14	100.50	100.30	94.42
		Numbers of ions			
O	6.000	6.000	6.000	6.000	22.000
Si	2.015	1.972	1.971	1.970	5.608
Ti	0.006	0.009	0.009	0.011	0.478
Al	0.017	0.047	0.049	0.086	2.407
Fe	1.014	0.470	0.883	0.375	2.895
Mn	0.027	0.012	0.021	0.008	0.010
Mg	0.851	0.639	0.991	0.754	2.326
Ca	0.038	0.838	0.070	0.764	0.026
Na	0.002	0.014	0.002	0.011	0.018
K	0.001	0.002	0.001	0.001	1.901

All Fe as FeO.

Abbreviations of minerals as in Table 1.

* P means "phenocrystic" crystal, see text.

conditions are 15 kilovolts accelerating voltage, 0.01 to 0.02 microamperes sample current and about 2 to 3 microns spot size. The results are given in Tables 2 to 6.

1. *Orthopyroxene*

Fine-grained recrystallized orthopyroxenes have the compositional range of $Wo_{2.0-3.5}En_{44.1-57.7}Fs_{38.9-53.9}$. Comparatively coarser-grained ones seem to preserve the original phenocrystic characters. Therefore, they are conveniently called "phenocrystic" orthopyroxenes in the following. They have wide compositional range of $Wo_{3.5-4.1}En_{45.1-69.5}Fs_{27.0-50.8}$. As comparing with the metamorphic ones mentioned above, phenocrystic orthopyroxenes are, in general, slightly rich in Ca, Mg and Al. The above-mentioned chemical discrepancy can easily been visualized from Fig. 4 and Tables 3 to 6. From this it can be pointed out that some of the phenocrystic orthopyroxenes may preserve the chemical characteristics of original basaltic orthopyroxene. Especially in the highly metamorphosed samples of Nos. 715–23 and 716–22, phenocrystic orthopyroxenes must have intensely been affected by the chemical rearrangement during the contact metamo-

TABLE 4. CHEMICAL COMPOSITIONS OF MAIN CONSTITUENT MINERALS OF METAMORPHOSED BASALT (SAMPLE NO. 716–22).

	12	13	14	15	16
	Opx-1	Cpx-1	Opx-P	Cpx-P	Biot
SiO_2	50.7	51.7	50.6	52.2	36.5
TiO_2	0.27	0.33	0.28	0.45	4.62
Al_2O_3	0.44	0.82	0.78	2.15	13.1
FeO	30.9	14.2	29.9	11.2	19.8
MnO	0.95	0.44	0.81	0.34	0.18
MgO	15.2	11.7	15.3	14.5	11.3
CaO	1.25	19.9	1.93	19.1	0.02
Na_2O	0.04	0.23	0.02	0.18	0.08
K_2O	0.03	0.02	0.03	0.02	9.15
Total	99.78	99.34	99.65	100.14	94.75
			Numbers of ions		
O	6.000	6.000	6.000	6.000	22.000
Si	1.984	1.980	1.978	1.949	5.634
Ti	0.008	0.010	0.008	0.013	0.537
Al	0.020	0.037	0.036	0.095	2.377
Fe	1.013	0.455	0.976	0.349	2.554
Mn	0.032	0.014	0.027	0.011	0.024
Mg	0.885	0.669	0.889	0.805	2.598
Ca	0.053	0.817	0.081	0.764	0.003
Na	0.003	0.017	0.001	0.013	0.024
K	0.001	0.001	0.001	0.001	1.803

All Fe as FeO.

Abbreviations of minerals as in Table 3.

rphism in spite of their phenocrystic appearance. In the samples of Nos. 715–113 and 716–8 which have abundant hornblende and biotite as metamorphic minerals, however, phenocrystic orthopyroxenes have rather high content of Mg and Al. Thus, they must highly retain the original chemical characteristics.

2. *Clinopyroxene*

The chemical discrepancy between recrystallized clinopyroxene and phenocrystic (see orthopyroxene in the above section) one seems to be more distinct than that in the case of orthopyroxene. Very fine-grained metamorphic clinopyroxenes have the compositional range of $Wo_{39.3-42.9}En_{32.6-39.1}Fs_{18.1-25.8}$, whereas phenocrystic clinopyroxenes are rich in Mg and Al and poor in Ca and then show the restricted compositional range of $Wo_{39.3-40.2}En_{39.7-43.9}Fs_{16.8-20.1}$.

From this it may be inferred that phenocrystic clinopyroxene can retain the original chemical characteristics of igneous clinopyroxene, and that the contact effect by the gabbro complex is rather undistinct as compared with that on orthopyroxene, even in

TABLE 5. CHEMICAL COMPOSITIONS OF MAIN CONSTITUENT MINERALS OF THE METAMORPHOSED BASALT (SAMPLE NO. 715–113).

	17	18	19	20	21	22
	Opx-1	Cpx-1	Opx-P	Cpx-P	Amph	Biot
SiO_2	50.5	50.3	53.0	51.2	49.1	36.3
TiO_2	0.25	0.38	0.19	0.36	1.11	2.70
Al_2O_3	1.11	1.22	1.00	2.07	5.38	16.4
FeO	24.3	11.1	19.3	10.3	15.8	19.8
MnO	0.94	0.53	0.77	0.36	0.41	0.27
MgO	21.0	14.1	23.5	15.5	14.0	11.7
CaO	1.75	21.5	1.83	19.3	11.3	0.14
Na_2O	0.03	0.29	0.02	0.21	1.10	0.09
K_2O	0.03	0.02	0.01	0.02	0.43	9.26
Total	99.91	99.44	99.62	99.32	98.63	96.66
			Numbers of ions			
O	6.000	6.000	6.000	6.000	23.000	22.000
Si	1.921	1.918	1.964	1.926	7.187	5.468
Ti	0.007	0.001	0.005	0.010	0.122	0.306
Al	0.050	0.055	0.044	0.092	0.927	2.912
Fe	0.774	0.353	0.598	0.323	1.929	2.493
Mn	0.030	0.017	0.024	0.011	0.051	0.035
Mg	1.192	0.802	1.300	0.870	3.047	2.632
Ca	0.071	0.877	0.073	0.778	1.767	0.023
Na	0.003	0.022	0.001	0.016	0.313	0.028
K	0.001	0.001	0.001	0.001	0.081	1.778

All Fe as FeO.

Abbreviations of minerals as in Table 3.

the highly metamorphosed samples (Nos. 715–23 and 716–22, see Fig. 4).

3. *Amphiboles*

Amphiboles are very rare in the samples where metamorphic orthopyroxene and clinopyroxene are ubiquitously observable. However, as metamorphism decreases in grade, greenish amphiboles appear as mantling over the phenocystic pyroxenes and as euhedral crystals. When the grade of metamorphism further decreases, colourless to pale greenish amphiboles with fibrous shape also occur.

The chemical compositions of greenish amphiboles are plotted in the area of magnesio-hornblende as defined by LEAKE (1978) with the range of X_{Mg} $(Mg/Mg+Fe)=0.50$ to 0.64 and $Ti=0.024$ to 0.138 $(O=23)$. In a sample (No. 716–11) in which amphiboles and epidote are the main metamorphic mafic minerals lacking of pyroxenes, actinolitic hornblende (LEAKE, op. cit.) appears also.

TABLE 6. CHEMICAL COMPOSITIONS OF MAIN CONSTITUENT MINERALS OF METAMORPHOSED BASALTS (SAMPLE NOS. 716–8 and 716–11) AND NON-METAMORPHOSED ONE (SAMPLE NO. 716–12).

	716–8			716–11			716–12
	23	24	25	26	27	28	29
	Opx-P	Amph	Biot	Amph-1	Amph-2	Ep	Cpx-P
SiO_2	52.4	48.8	36.5	43.6	49.1	36.9	50.9
TiO_2	0.17	1.24	4.62	0.20	0.31	0.16	0.47
Al_2O_3	1.35	5.22	13.3	7.59	4.18	23.7	2.23
FeO	17.6	14.9	17.2	18.3	16.7	14.0	11.2
MnO	0.78	0.55	0.42	0.73	0.66	0.23	0.48
MgO	26.7	14.2	12.8	10.3	12.7	0.07	14.3
CaO	1.88	10.8	0.22	11.4	12.1	22.7	19.3
Na_2O	0.03	1.06	0.08	1.09	0.40	tr.	0.29
K_2O	0.02	0.42	9.05	0.73	0.28	0.03	0.03
Total	100.93	97.19	94.19	93.94	96.43	97.79	99.20
				Numbers of ions			
O	6.000	23.000	22.000	23.000	23.000	12.000	6.000
Si	1.910	7.209	5.601	6.874	7.381	3.027	1.927
Ti	0.005	0.138	0.533	0.024	0.035	0.010	0.013
Al	0.058	0.909	2.405	1.411	0.740	2.295	0.099
Fe	0.537	1.845	2.208	2.418	2.097	0.963	0.355
Mn	0.024	0.069	0.055	0.098	0.084	0.016	0.015
Mg	1.448	3.122	2.929	2.412	2.842	0.009	0.806
Ca	0.073	1.715	0.036	1.918	1.948	1.994	0.783
Na	0.002	0.304	0.025	0.334	0.116	0.001	0.021
K	0.001	0.079	1.770	0.148	0.054	0.004	0.001

All Fe as FeO.

Abbreviations of minerals as in Table 3.

4. *Biotite*

Biotite is always found as recrystallized minerals in the metamorphosed samples now discussed. The TiO_2 content varies from 2.70 to 4.62 weight percent, and X_{Mg} ranges from 0.45 to 0.57.

5. *Plagioclase*

The compositional range of plagioclase is summarized in Fig. 3. In the original basaltic rock from Okino-shima islet, plagioclase shows distinct oscillatory zoning. The anorthite component varies from the core to the rim in the following manner, 88.9→76.5→67.4→64.4, 74.1→80.8→62.3→68.7 and so on.

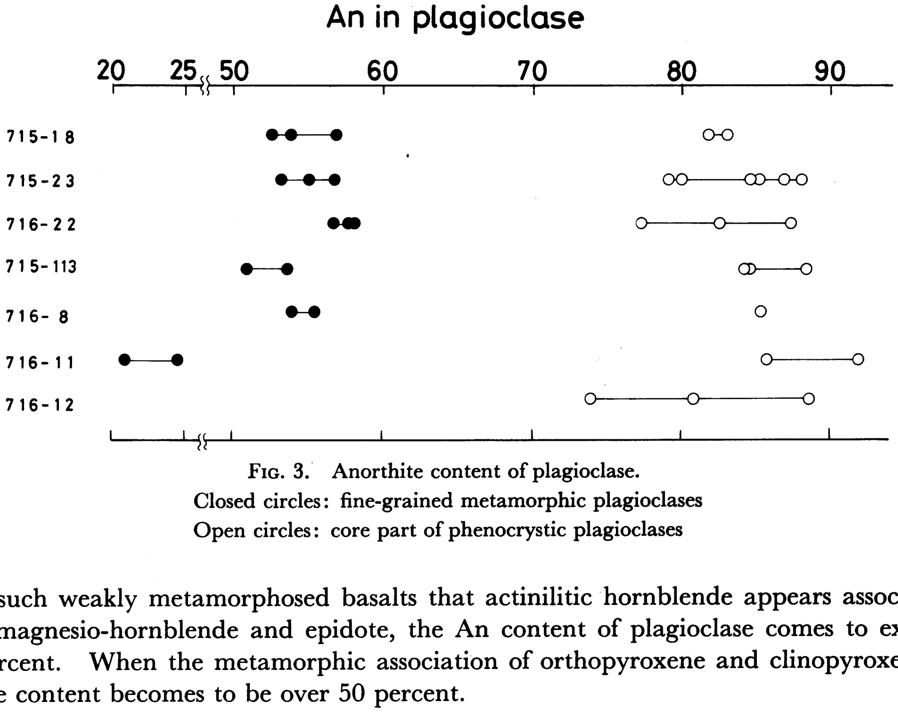

Fig. 3. Anorthite content of plagioclase.
Closed circles: fine-grained metamorphic plagioclases
Open circles: core part of phenocrystic plagioclases

In such weakly metamorphosed basalts that actinilitic hornblende appears associated with magnesio-hornblende and epidote, the An content of plagioclase comes to exceed 20 percent. When the metamorphic association of orthopyroxene and clinopyroxene is in, the content becomes to be over 50 percent.

As can easily be seen in Fig. 3, not to mention in lower-grade basaltic rocks, even in the most intensely metamorphosed ones, the core part of phenocrystic plagioclase contains more than 80 percent An. The compositional range seems to be quite similar to that in the case of non-metamorphosed original rock. Therefore, it can well be said that the essential chemical characteristics of plagioclase are now preserved in the core part of each grain, even in the highest-grade metamorphosed basalts which have the critical association of orthopyroxene and clinopyroxene.

IV. CONTACT METAMORPHISM

In the foregoing chapters, it has been clarified that the basaltic rocks in the Susa area have undergone intense metamorphism by the Koyama gabbro complex mass. The highest grade reaches to the pyroxene hornfels facies, and the lowest grade is as low as the greenschist to the amphibolite transitional facies.

Owing to the lack of continuous outcrops due to the cover of sea water, the total figure of progressive metamorphism from non-metamorphosed original rocks to the most intensely metamorphosed ones can not be systematically traced. Therefore, the metamorphic temperature close to the innermost part of the contact aureole is only discussed here.

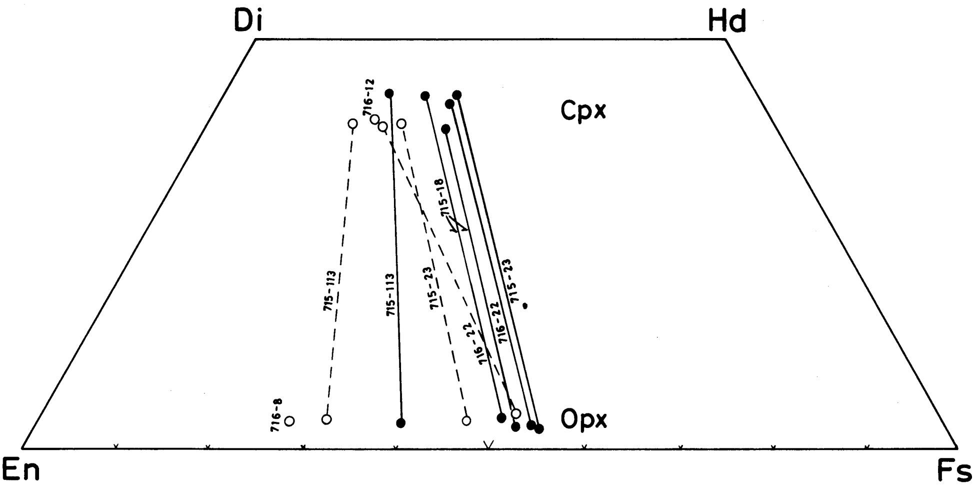

FIG. 4. Two-pyroxene phase relations.
Closed circles: fine-grained metamorphic pyroxenes
Open circles: coarse-grained phenocrystic pyroxenes

Fig. 4 indicates the relationship between two pyroxene phases. As easily visualized from the figure, the tie-line relation for the metamorphic association is compatible with each other, while the pairs of so-called phenocrystic association are incompatible not only with each other but with those of the metamorphic association. From this fact it may also be inferred that phenocrystic clinopyroxene can still preserve its original igneous composition, but phenocrystic orthopyroxene should have been more or less changed its composition during the contact metamorphism.

TABLE 7. TEMPERATURE ESTIMATES BASED ON TWO-PYROXENE PAIRS*.

Sample No.	Pairs	X_{Fe}^{Opx}	$a_{Mg_2Si_2O_6}^{Opx}$	$a_{Mg_2Si_2O_6}^{Cpx}$	T°C
715–18	Opx–1—Cpx–1	0.528	0.200	0.067	857
	Opx–2—Cpx–2	0.508	0.211	0.051	822
715–23	Opx–1—Cpx–1	0.544	0.189	0.044	802
716–22	Opx–1—Cpx–1	0.534	0.196	0.052	823
715–113	Opx–1—Cpx–1	0.394	0.330	0.056	838
	Opx–P—CPx–P	0.315	0.418	0.106	953**

* Calculated after the method by WOOD and BANNO (1973), subtracting 50°C.

** This value is calculated by the use of the phenocrystic pair, while the other values are by the use of recrystallized metamorphic pairs.

By the use of five pairs of the metamorphic two pyroxenes, the metamorphic temperature can be estimated following the method by WOOD and BANNO (1973). As stated by WOOD (1975), the calculation probably includes the overestimation in the order of 50°C. Thus, the values in Table 7 show the results after the subtracting. The metamorphic temperature estimated here ranges from 800 to 860°C. In this connection, it must be noted that a pair (No. 715–113) among the pairs of phenocrystic pyroxenes can preserve the essential equilibrium relationship in the original rock (Fig. 4). The equilibrium temperature calculated in the same manner using the pair gives a value of 953°C, more than 100°C higher than the metamorphic temperature estimated above.

All are concerned, it can be inferred that the basaltic rocks in the discussed area are thermally metamorphosed by the Koyama gabbro complex mass, and that the metamorphic temperature reaches a maximum of more than 800°C.

V. CONCLUSIONS

Based on the petrographical and mineralogical investigations on basaltic rocks in the Susa area, the following conclusions on the thermal effect by the Koyama gabbro complex mass are reached.

1) The basaltic rocks are progressively metamorphosed toward the contact with the mass. As far as we can observe, the lowest-grade metamorphosed basalt is characterized by the association of actinolitic hornblende+magnesio-hornblende+epidote+biotite+oligoclase+quartz.

2) Near the very contact with the gabbro mass, basaltic rocks are recrystallized to have the association of orthopyroxene+clinopyroxene±hornblende+biotite+labradorite+quartz. The highest metamorphic temperature exceeds 800°C.

3) Not to mention in the lower-grade metamorphosed basalts, even in the highly metamorphosed ones, the essential chemical characteristics in the original igneous rocks can still be preserved especially in the phenocrystic crystals such as plagioclase and clinopyroxene. However, phenocrystic orthopyroxene should have been more or less changed its composition during the metamorphism.

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EXPLANATIONS OF PLATE XVII

1. Photomicrograph of the most-intensely metamorphosed basalt (No. 715–18). Phenocrystic crystals of plagioclase, orthopyroxene and clinopyroxene are scattered in the fine-grained granoblastic groundmass constituting of recrystallized orthopyroxene, clinopyroxene and plagioclase.
2. Photomicrograph of intensely metamorphosed basalt (No. 715–113). Phenocrystic crystals of plagioclase, orthopyroxene and clinopyroxene are scattered in the fine-grained recrystallized

groundmass. Phenocrystic pyroxenes are partly changed to hornblende. Groundmass is mainly composed of hornblende, biotite and plagioclase with lesser amounts of pyroxenes.

3. Photomicrograph of weakly-metamorphosed basalt (No. 716–11). Phenocrystic plagioclase (center) is changed to the aggregate of fibrous amphiboles, epidote and sphene. Phenocrystic clinopyroxene (upper left) is also converted chiefly into the aggregate of fibrous amphiboles. In the groundmass, are found fibrous amphiboles, flaky biotite, plagioclase and quartz.
4. Photomicrograph of non-metamorphosed basalt (No. 716–12). Phenocrystic plagioclase (left and lower rihgt-hand corner) and clinopyroxene (right) are mutally aggregated showing the glomeroporphyritic texture in the groundmass of lath-shaped plagioclase, opaque minerals and glass.

Scale bar below each microphotograph is 0.1 millimeter.


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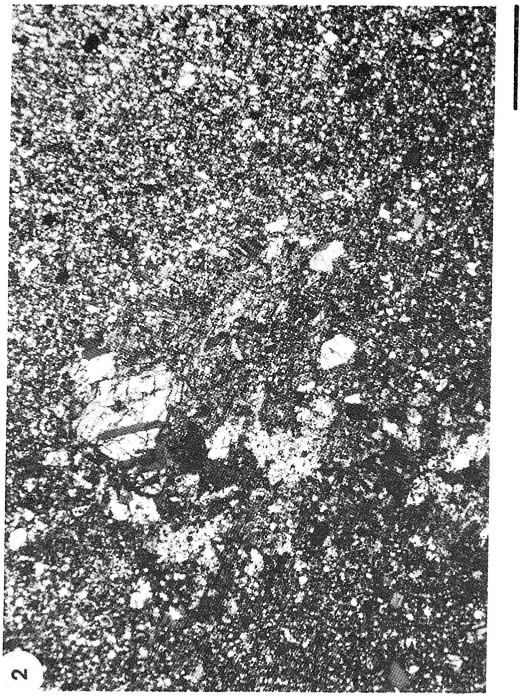
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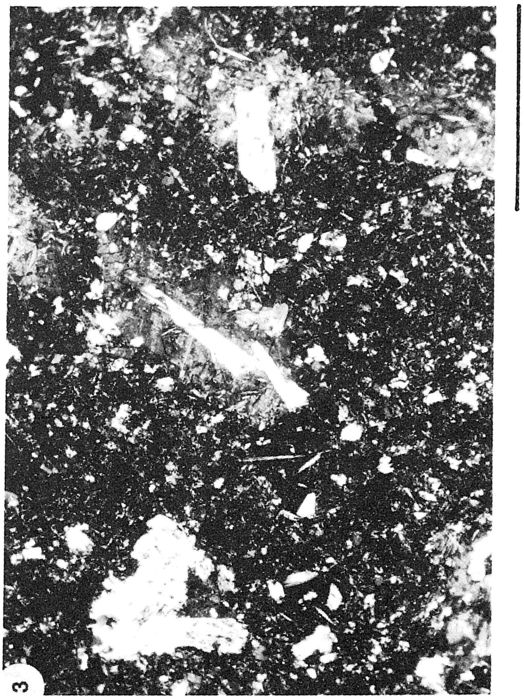
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