



HOKKAIDO UNIVERSITY

Title	Petrology of the Pankenushi gabbroic intrusion, Hidaka metamorphic belt, Hokkaido
Author(s)	Maeda, Jinichirou
Degree Grantor	北海道大学
Degree Name	博士(理学)
Dissertation Number	甲第1598号
Issue Date	1981-03-25
Doc URL	https://hdl.handle.net/2115/80563
Type	doctoral thesis
File Information	Maeda_81_PhD_600.pdf



PETROLOGY OF THE PANKENUSHI GABBROIC INTRUSION,
HIDAKA METAMORPHIC BELT, HOKKAIDO

by

Jin'ichirou MAEDA

January, 1981

Department of Geology and Mineralogy,
Faculty of Science, Hokkaido University.

CONTENTS

Abstract	1
Chapter 1 INTRODUCTION	4
Chapter 2 FIELD OBSERVATION	5
Chapter 3 PETROGRAPHIC DESCRIPTION	12
Chapter 4 MINERALOGY	21
Chapter 5 CRYSTALLIZATION OF OLIVINE	62
Chapter 6 PETROCHEMISTRY OF THE PANKENUSHI INTRUSION AND THE MEMURODAKE COMPLEX	68
Chapter 7 EVOLUTION OF THE PANKENUSHI MAGMA	86
Chapter 8 EFFECT OF PLAGIOCLASE FRACTIONATION ON THE EVOLUTION OF NON-ALKALINE BASALT MAGMA	121
Chapter 9 COMPARISON OF THE PANKENUSHI INTRUSION WITH THE COMMON STRATIFORM TYPE INTRUSION	133
Acknowledgements	137
References	138

ABSTRACT

The Pankenushi gabbroic intrusion, situated at the northern part in the Main zone of the Hidaka metamorphic belt, is a layered differentiated body. Major rock types and the assemblage of cumulus phases are troctolite (Cr-spinel + plagioclase + olivine), olivine gabbro (plagioclase + olivine + clinopyroxene + orthopyroxene) and ferrogabbro (plagioclase + olivine + clinopyroxene + orthopyroxene + ilmenite + apatite $\pm$ amphibole). The compositions of major minerals vary from troctolite to ferrogabbro via olivine gabbro: olivine, from Fo₈₇ to Fo₂₆; plagioclase, from An₈₆ to An₃₆; clinopyroxene, from diopside to ferroaugite; and orthopyroxene, from bronzite to ferrohypersthene. In consideration of the petrographical features, the Pankenushi intrusion is clearly non-alkaline.

There is no compositional break of olivine, though the reaction relation between olivine and orthopyroxene is observed. Only orthopyroxene is found as Ca-poor pyroxene and pigeonite is lacking. The occurrence of hydrous silicates such as amphibole and biotite is relatively abundant. Only ilmenite is found as Fe-Ti oxide and magnetite is absent.

It is difficult, in general, to estimate accurately the composition of successive liquid in the layered gabbro. Because the bulk chemical composition of cumulate does not correspond to that of liquid fraction in the fractionated process but that of solid fraction with some pore liquid. One method for estimation of the composition of the successive magma is proposed in this paper. The method is essentially based on the concept of the average rock proposed by Wager

and Mg-Fe partition between olivine and liquid. If one composition in the successive magma series is given, the composition of olivine coexisting with the magma is defined. When the compositional change of average rocks is represented as a function of the olivine composition, the full compositional change of successive magma is estimated by the subtraction or the addition of the average rock that has olivine coexisting with the magma.

As a result of the application to the Pankenushi intrusion, it is clearly shown that the intrusion belongs to tholeiitic suite. The Memurodake plutonic complex, situated side by side to the east of the Pankenushi intrusion, shows the calc-alkalic trend and never correspond with the composition of successive magma of the Pankenushi intrusion.

The effect of plagioclase fractionation on the evolution of non-alkalic basalt magma is discussed by using the simple model. Plagioclase plays a role of diluting the total iron content in fractionated solid material. While mafic silicates such as olivine have a role of concentrating the total iron content. Plagioclase fractionation is indispensable for the production of the tholeiitic trend. Non-total iron enrichment observed in calc-alkalic series may be partly due to the non fractionation of plagioclase.

The petrographical, mineralogical and geological features of the Pankenushi intrusion are quite different from those of tholeiitic stratiform intrusion, such as the Skaergaard, Bushveld and Stillwater intrusions occurred in the stable continent crust. Accordingly the Pankenushi gabbroic intrusion gives a unique and unreported example of the tholeiitic

differentiated intrusion. The presence of the troctolite fractionation in the earlier stage of the differentiation is the only one sameness between the Pankenushi intrusion and other tholeiitic stratiform intrusions. A large amount of plagioclase is contained in troctolite. It is suggested that the plagioclase fractionation has a important role to produce the tholeiitic trend. The ultimate difference between the Pankenushi intrusion and tholeiitic stratiform intrusions is the difference in the tectonical environment. Tholeiitic stratiform intrusions were emplaced in the stable continental crust. On the other hand, the Pankenushi intrusion was emplaced in the mobile belt.

Chapter 1

INTRODUCTION

The Hidaka metamorphic belt is composed of two distinct zones: the Western zone having a characteristic of oceanic crust, and the Main zone regarded as crust of island arc or of continental margin (Komatsu et al., 1979). In the Main zone, the plutonic rocks ranging in composition from basic to intermediate are second to meta-sedimentary rocks including biotite hornfels, biotite gneiss and biotite migmatite in abundance. The plutonic rocks occupy the one-third of the Main zone and have two main areas of activity: at the area around the Pankenushi river in the northern part of the metamorphic belt (the Pankenushi gabbroic intrusion, the Memurodake plutonic complex, etc.), and at the area around the upper stream of the Horoman river (the Horoman plutonic complex; Motoyoshi, 1980). In this paper, the petrographical and mineralogical features of the Pankenushi gabbroic intrusion are described and the magma evolution is discussed. The author also discusses the genetical relationship between the Pankenushi gabbroic intrusion and the Memurodake dioritic complex. Lastly the effect of the plagioclase fractionation on the evolution of non-alkaline basaltic magma is preliminary discussed.

Chapter 2

FIELD OBSERVATION

The Pankenushi gabbroic intrusion outcropping in an area of about 30 km long and 4 km wide is situated in the northern part of the Main zone (Fig. 2-1). It is bordered by the metamorphic rocks which belong to the granulite facies to the west, and by the Memurodake plutonic complex to the east. The relation between the Pankenushi intrusion and the Memurodake complex is not distinct due to the poor outcropping. The relation between the Pankenushi intrusion and the metamorphic rocks is obscure by the later mylonitization originated in the thrust fault between the Western zone and the Main zone. In the south of the Memurodake complex, around the Pipairo river, the complex consisting of the biotite gneiss and the biotite migmatite is exposed. Several xenoliths of the biotite gneiss are found in the eastern part of the Pankenushi intrusion.

The layered structure observed in the intrusion trends north - north-northwest and dips eastward. From west to east, three lithostratigraphic zones, Zones I, II and III, are recognized (Fig. 2-2). In Zone I and Zone III, olivine gabbro and ferrogabbro are mainly found. Troctolite occurs in Zone I. It is characteristic that the earliest rock, i.e. troctolite occupies the central part and the most differentiated rock, i.e. ferrogabbro occupies the both sides.

The occurrence of the layered structure observed in Zone II is slightly different from those in Zones I and III.

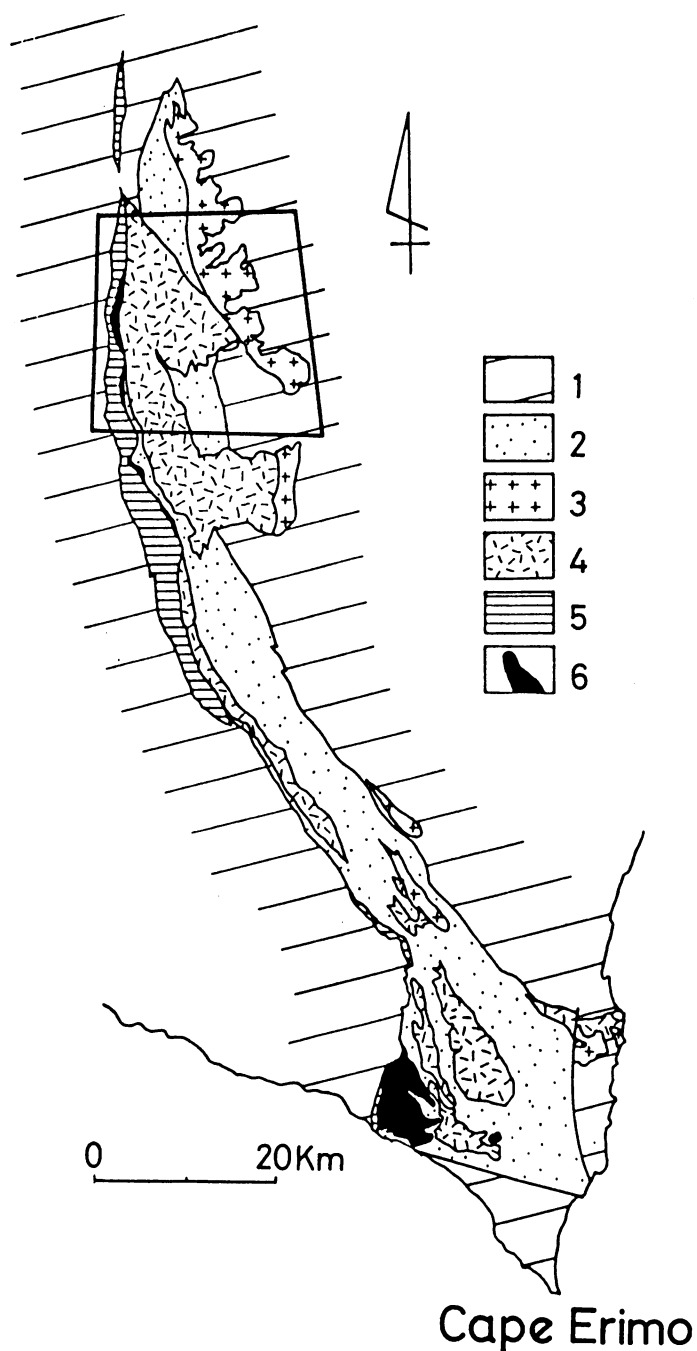


Fig. 2-1

Geologic sketch map of the Hidaka metamorphic belt and adjacent region (simplified from Yamaguchi et al., 1978). Enclosed area is corresponding to Fig. 2-2. 1, Hidaka Supergroup, 2, Biotite schist, schistose biotite hornfels, biotite gneiss and migmatites, 3, Granitic rock. 4, Gabbroic rock of the Main zone. 5, Basic rock of the Western zone. 6, Ultramafic rock.

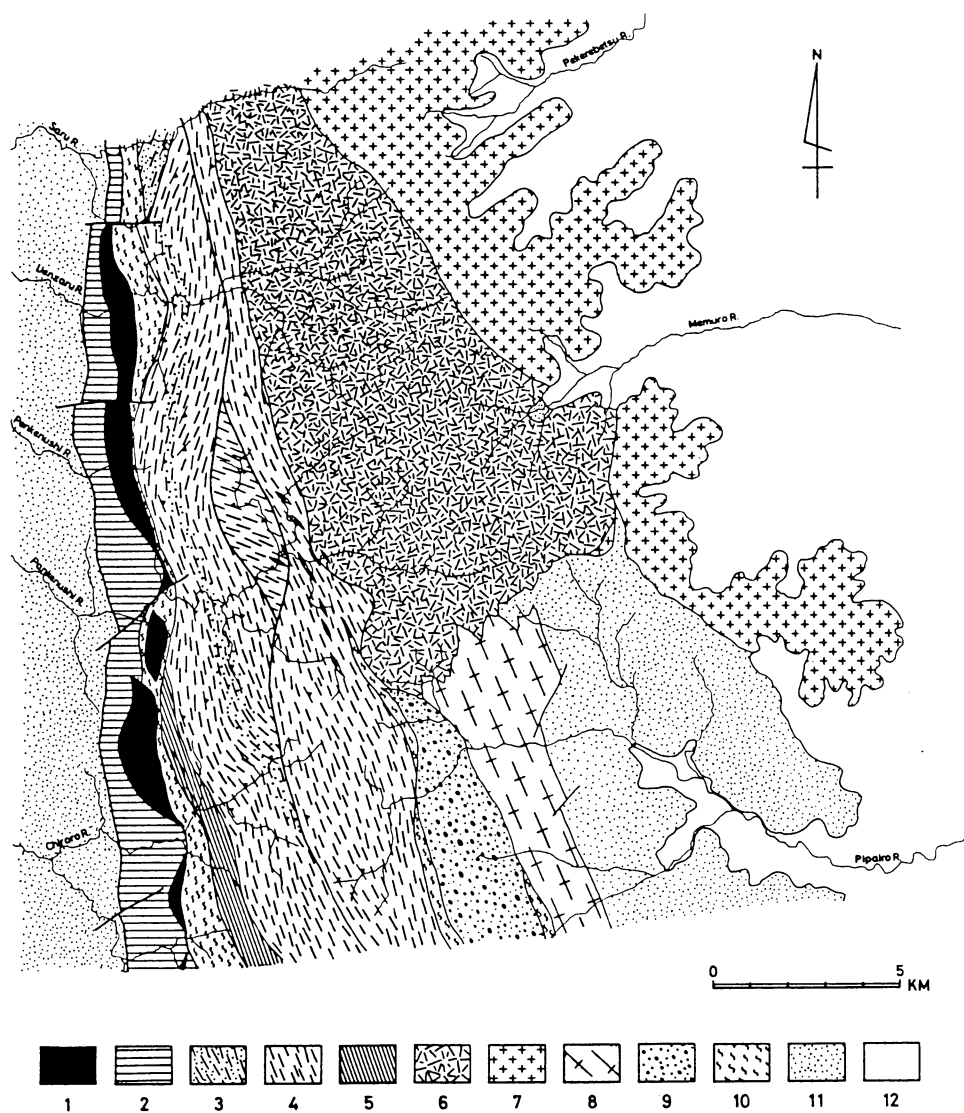


Fig. 2-2

Geologic map of the northern Hidaka metamorphic belt.

- 1, Ultramafic rock. 2, Basic rock of the Western zone.
- 3, Troctolite. 4, Olivine gabbro and ferrogabbro (3 and 4, Pankenushi gabbroic intrusion). 5, Brown hornblende amphibolite. 6, Memurodake plutonic complex. 7, Biotite granite. 8, Biotite gneissose granite. 9, Biotite migamite. 10, Biotite gneiss and allied rocks. 11, Hidaka Supergroup. 12, Quaternary sediment.

Remarkable rhythmic layering is often found in Zones I and III (Figs. 2-3, and 2-4). On the other hand uniform layering is observed in Zone II (Fig. 2-5). Such a difference suggests that magmatic currents are stronger in the marginal part than in the central part.

Graded layering found very rarely in the intrusion is observed at three localities along the Pankenushi river (Figs. 2-6 and 2-7). Judging from the occurrence of the graded layering, the sequence is lowered to the eastward in Zone I, to the westward in Zone III and the eastern part of Zone II. It suggests that the crystallization proceeds from the central part to the both sides. Mechanism of the fractionation may be due to the flowage differentiation rather than the gravity settling.

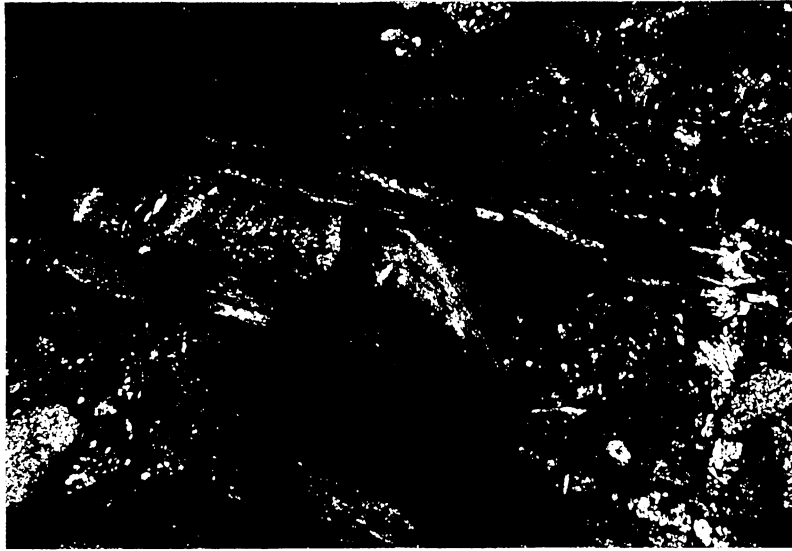


Fig. 2-3

Rhythmic layering observed in Zone I. Anorthosite layer is shown.



Fig. 2-4

Occurrence of rhythmic layering in Zone III.



Fig. 2-5

Occurrence of uniform layering in Zone II.

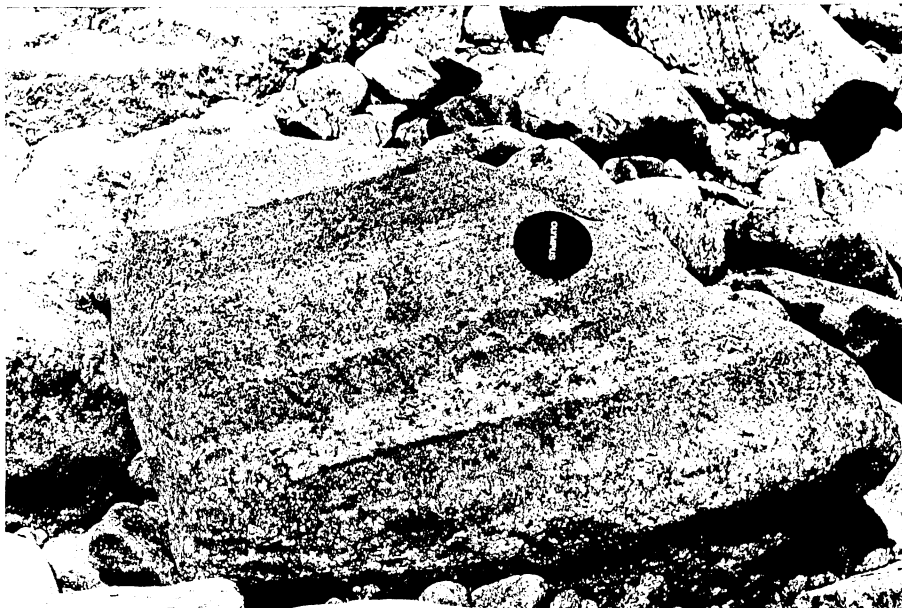


Fig. 2-6
Occurrence of graded layering.

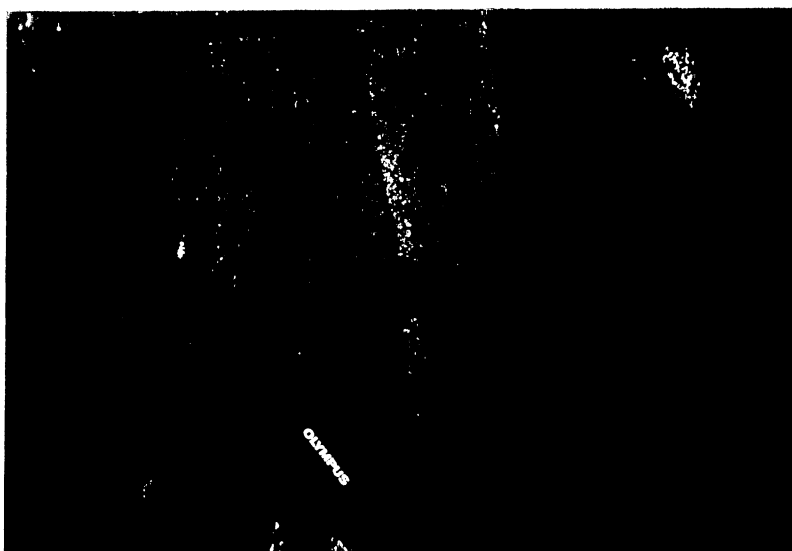


Fig. 2-7
Graded layering observed in Zone I.

Chapter 3

PETROGRAPHIC DESCRIPTION

A. The Pankenushi gabbroic intrusion

Major rock types of the Pankenushi intrusion are troctolite, olivine gabbro and ferrogabbro. Anorthosite and olivine-plagioclase bearing websterite are observed very rarely.

Troctolite contains magnesian olivine, calcic plagioclase and spinel (Fig. 3-1). In general, igneous lamination due to the parallel arrangement of plagioclase and olivine is observed (Fig. 3-2). Small amounts of clinopyroxene, orthopyroxene and amphibole are observed as a reaction rim to olivine (Fig. 3-3). Grains of sulphide are also included as accessory phase. Representative analysis of modal composition is shown in Table 3-1.

Olivine gabbro contains olivine, plagioclase, clinopyroxene and orthopyroxene as cumulus phase (Fig. 3-4). Amphibole occurs as reaction rim to both olivine and pyroxenes. Sulphide minerals are included as accessory phase. Igneous lamination is frequently observed (Fig. 3-5). Representative analysis of modal composition is given in Table 3-1. Rarely a small amount of ilmenite is also found as cumulus phase.

The term "ferrogabbro" is used in this paper for the rocks containing iron rich olivine and abundant ilmenite about 10 percent in modal composition (Fig. 3-6). In the ferrogabbro, plagioclase, clinopyroxene, orthopyroxene, ilmenite and apatite are cumulus phase. Olivine is generally found as cumulus phase. Amphibole occurs as intercumulus phase (Fig. 3-7).



Fig. 3-1

Troctolite of Zone II. Ol, olivine. Pl, plagioclase. Sp, spinel. Olivine is partly serpentinized.

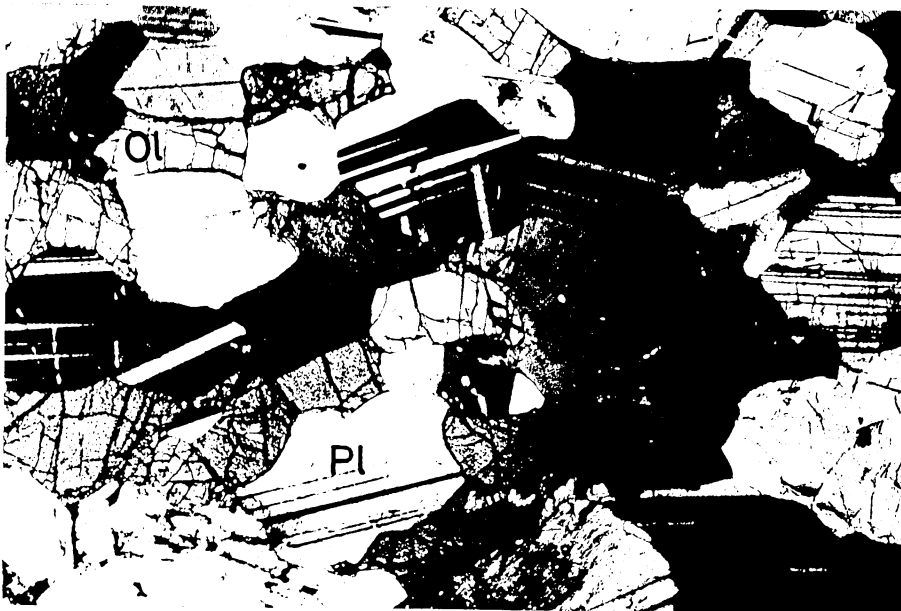


Fig. 3-2

Igneous lamination observed in troctolite. Parallel arrangement of plagioclase and olivine is shown.



Fig. 3-3

Occurrence of reaction rim. Opx, Ca-poor orthopyroxene.
Hb, amphibole.



Fig. 3-4

Olivine gabbro of Zone I. Cpx, Ca-rich clinopyroxene.

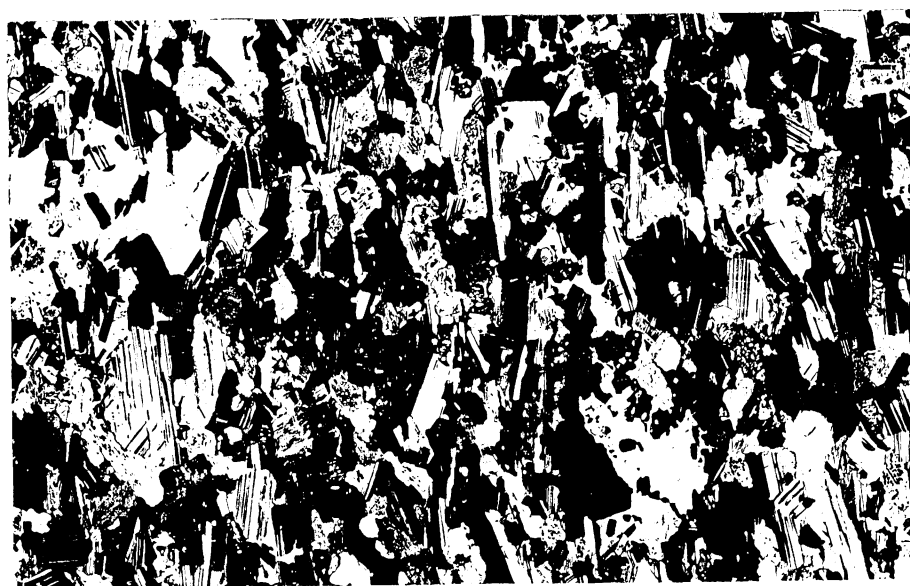


Fig. 3-5 Olivine gabbro

	1	2	3
plagioclase	61.5	65.2	42.9
olivine	24.6	19.2	rare
clinopyroxene	rare	11.0	12.6
orthopyroxene	6.6	1.2	14.5
amphibole	0.1	2.7	18.8
biotite	0.1	0.0	1.8
opaque	0.5*	0.3**	7.8***
apatite	0.0	0.0	1.6

Table 3-1 Representative analyses of modal composition of the Pankenushi gabbro. 1; troctolite. 2; olivine gabbro. 3; ferrogabbro. * spinel plus sulphide. ** sulphide. *** ilmenite plus sulphide.

plagioclase	61.0	53.1	51.1	44.6
K-feldspar	0.0	0.6	2.2	7.1
quartz	1.1	6.3	8.6	10.7
clinopyroxene	4.5	1.1	0.0	0.0
orthopyroxene	3.6	0.0	0.0	0.0
amphibole	23.6	29.7	14.0	20.0
biotite	2.5	6.9	23.7	17.1
opaque	} 3.8	1.2	0.2	0.3
apatite sphene		0.3	0.1	0.1
sphene		0.6	0.1	0.1
others		0.1*		

Table 3-2 Representative analyses of modal composition of the Memurodake rock. * zircon.

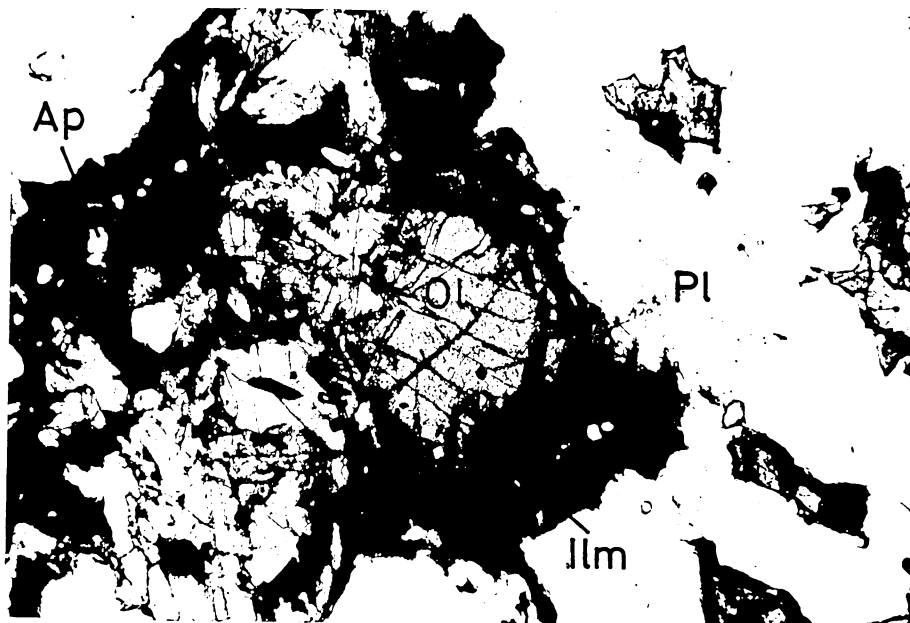


Fig. 3-6

Ferrogabbro of Zone III. Ilm, ilmenite. Ap, apatite. Ilm, ilmenite. Composition of the olivine is $\text{Fo}_{25.5}$.

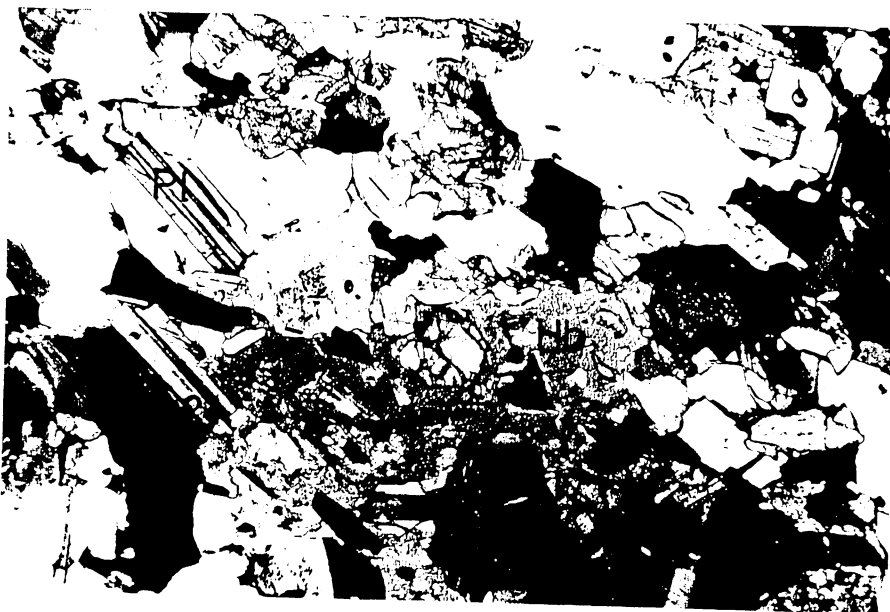


Fig. 3-7

Occurrence of intercumulus amphibole.

Rarely cumulus amphibole is found in the considerably differentiated ferrogabbro. A small amount of biotite is also included. Intercumulus quartz is observed rarely (Fig. 3-8). Representative analysis of modal composition is shown in Table 3-1.

Summary on the Pankenushi petrography is shown in Table 3-3. Because of the appearance of orthopyroxene, it is concluded that the Pankenushi intrusion belongs to non-alkalic suite.

B. The Memurodake plutonic complex

The Memurodake complex mainly consists of diorite. A small amount of tonalite is observed as the leucocratic part of the heterogeneous diorite. More basic rock than the diorite, pyroxene-hornblende gabbro is found. The Memurodake rocks show, in general, fine-grained texture. It suggests, therefore, that the composition of the bulk rock matches that of magma. In the Memurodake rocks, euhedral to subhedral plagioclase, amphibole and biotite, are usually included (Fig. 3-9). Interstitial quartz is generally observed with some exception. Euhedral clinopyroxene and orthopyroxene are observed in comparatively mafic rock (Fig. 3-10). Interstitial K-feldspar is observed in relatively differentiated diorite and in tonalite (Fig. 3-11). Small amounts of ilmenite and sphene are also included. Representative analyses of modal composition are given in Table 3-2.



Fig. 3-8

Occurrence of intercumulus quartz. Qz, quartz.

rock type	cumulus	intercumulus
Troctolite	Sp+Ol+Pl	Cpx+Opx+Hb
Ol. Gabbro	Ol+Pl+Cpx+Opx+Ilm	Hb
Ferrogabbro	Ol+Pl+Cpx+Opx+Ilm+Ap	Hb+Bio+Qz

Table 3-3

Constituent minerals observed in each rock type.

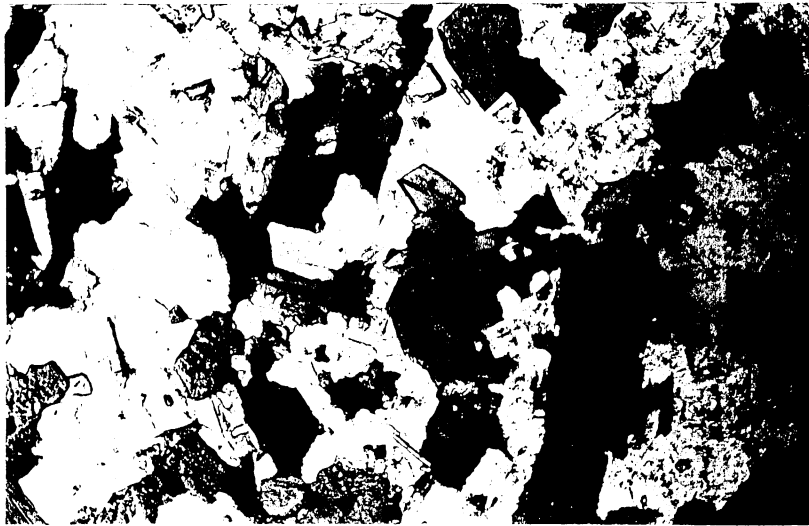


Fig. 3-9 Memurodake diorite



Fig. 3-10
Pyroxene-hornblende gabbro of the Memurodake complex.

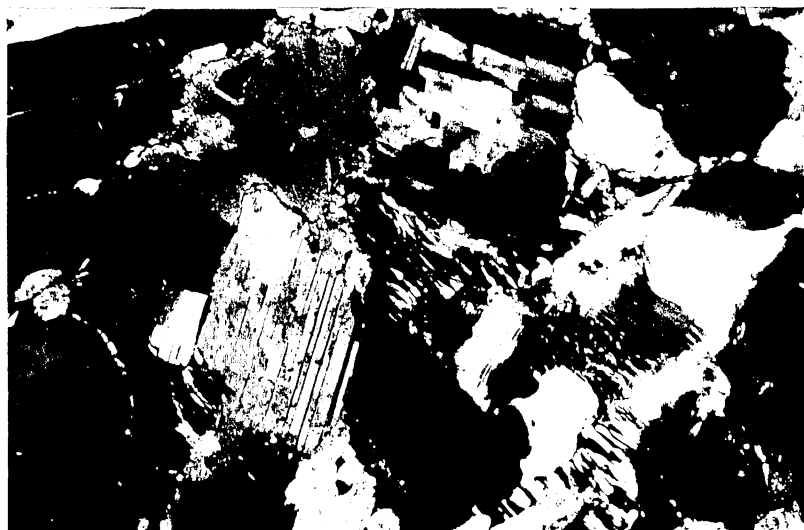


Fig. 3-11
Tonalitic rock of the Memurodake complex.

Chapter 4

MINERALOGY

Analyses of the constituent minerals were carried out by using the electron probe microanalyser of Niigata University (JEOL JXA-5A), Akita University (JEOL JXA-5) and Hokkaido University (JEOL JXA-50A). The correction was made by the method of Bence and Albee (1968). Selected chemical compositions together with cation ratios are given in Table 4-1 - 4-8.

A. Spinel

Spinel is commonly found in troctolite and very rarely in olivine gabbro. Spinel is generally about 100-300 μm in diameter and dark brown or opaque under the microscope. They are euhedral or slightly irregular and included in olivine as well as in plagioclase. Selected analyses are given in Table 4-1.

Compositional variations among the grains in one polished section are rather remarkable. For example, in sample 80070305, the range in Al_2O_3 is from 41.68% to 59.63%, that in Cr_2O_3 is from 6.81% to 25.20% and that in MgO is from 13.41% to 18.64%. These analyses are plotted in Cr-Al-Fe³⁺ (Fig. 4-1) and Cr/Cr + Al-Mg/Mg + Fe²⁺ diagrams (Fig. 4-2). The most remarkable feature of the spinel composition is high Al content. It contrasts with those of the chromitic spinel in the tholeiitic layered intrusion, such as in the Bushveld intrusion (Cameron, 1977).

Fig. 4-3 shows the compositional zoning of the spinels in sample 80070305. With one exception, Cr/Cr + Al decreases

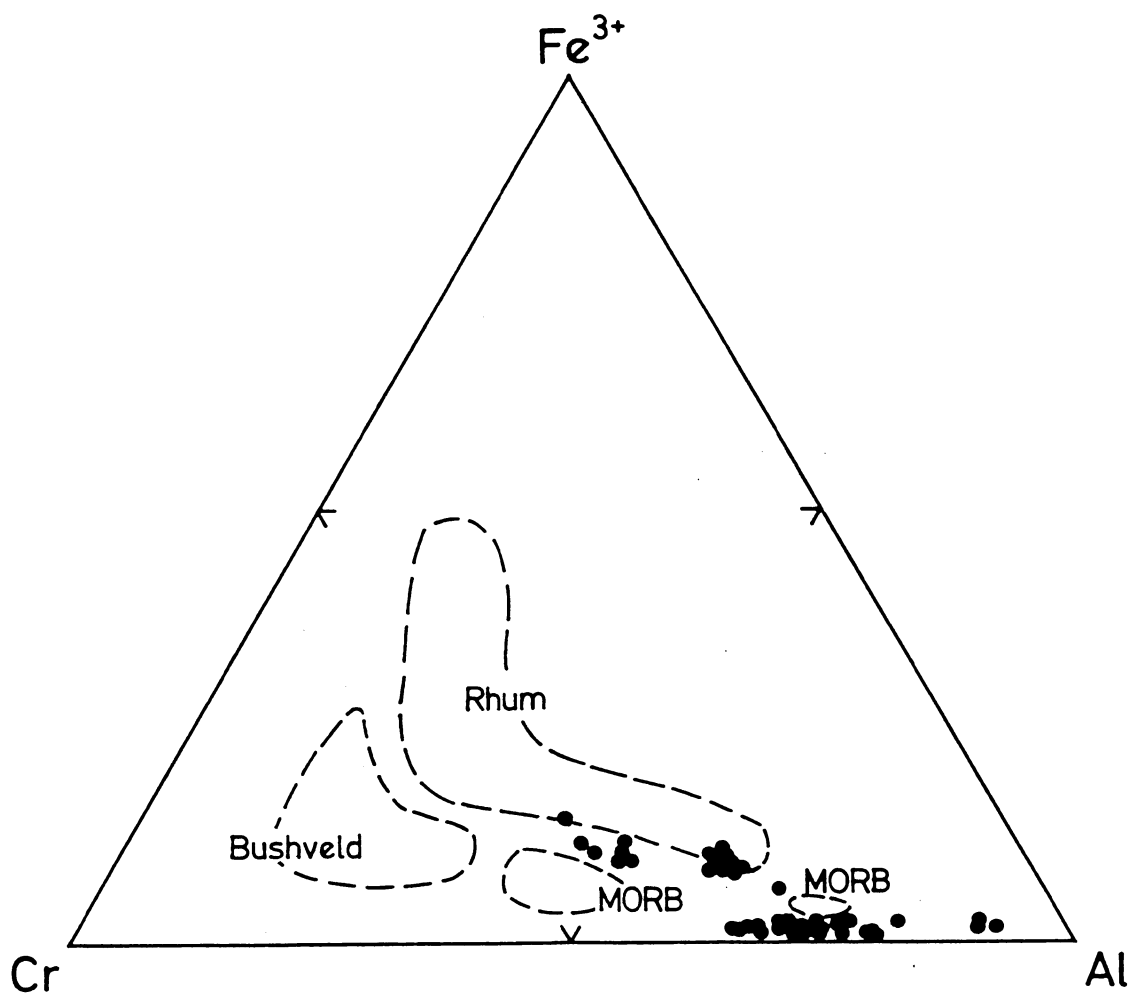


Fig. 4-1

Cr-Al-Fe³⁺ diagram of spinels. Compositional ranges of spinels from the Rhum intrusion (Henderson, 1975; Henderson and Suddaby, 1971), the Bushveld intrusion (Cameron, 1977) and mid-oceanic basalts (Sigurdsson and Schilling, 1976) are also shown.

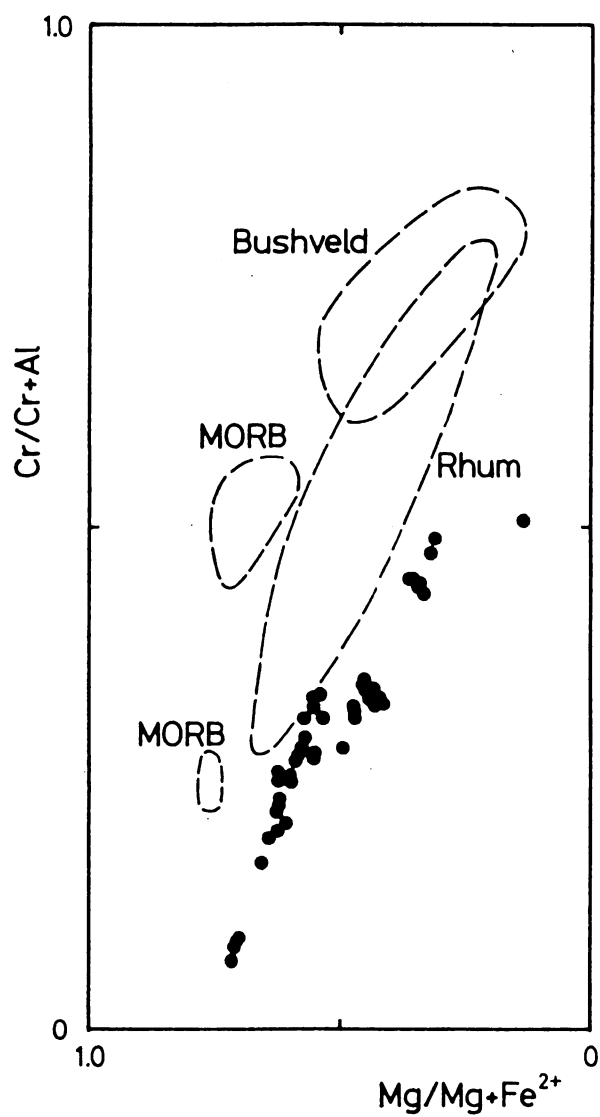


Fig. 4-2

$\text{Cr}/\text{Cr}+\text{Al}-\text{Mg}/\text{Mg}+\text{Fe}^{2+}$ diagram of spinels.

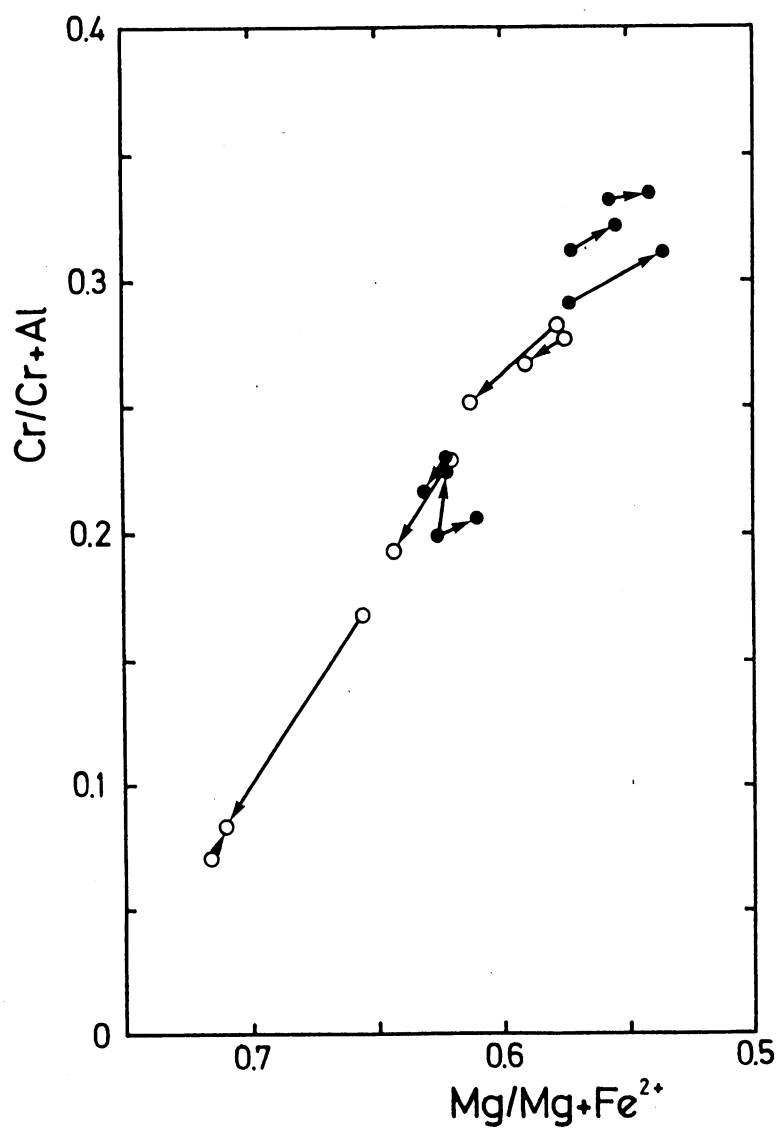


Fig. 4-3

$\text{Cr/Cr+Al-Mg/Mg+Fe}^{2+}$ diagram. Arrows indicate direction of zoning from core to margin. Open circle, 80070305. Closed circle, 80070303.

	1	2	3	4	5	6
TiO ₂	.16	.04	.07	.10	.09	.22
Al ₂ O ₃	59.63	58.00	49.80	41.68	42.38	41.90
Cr ₂ O ₃	6.81	7.93	15.03	24.89	24.47	24.55
Fe ₂ O ₃	1.86	2.74	2.32	1.84	1.87	1.75
FeO	13.09	13.23	14.81	17.94	18.31	17.71
MnO	.04	.17	.24	.26	.37	.37
MgO	18.64	18.24	15.88	13.43	13.32	13.59
Total	100.24	100.35	98.15	100.14	100.82	100.10
Ti	.025	.006	.012	.017	.015	.038
Al	14.546	14.251	12.966	11.174	11.281	11.217
Cr	1.114	1.307	2.625	4.476	4.370	4.409
Fe ³⁺	.290	.430	.385	.316	.318	.300
Fe ²⁺	2.266	2.307	2.737	3.413	3.459	3.365
Mn	.007	.030	.045	.050	.071	.071
Mg	5.751	5.669	5.230	4.554	4.485	4.602
	7	8	9	10	11	12
TiO ₂	.12	.09	.02	.25	.13	.04
Al ₂ O ₃	44.41	46.57	49.52	42.76	42.62	43.39
Cr ₂ O ₃	22.16	20.62	17.71	24.47	23.70	23.97
Fe ₂ O ₃	2.33	.84	.70	.72	1.79	.59
FeO	16.50	16.31	15.49	17.92	17.35	18.69
MnO	.36	.23	.19	.34	.16	.21
MgO	14.68	14.90	15.67	13.58	13.89	13.09
Total	100.56	99.56	99.30	100.03	99.64	99.98
Ti	.020	.015	.003	.043	.022	.007
Al	11.664	12.204	12.806	11.412	11.398	11.591
Cr	3.904	3.625	3.072	4.381	4.252	4.296
Fe ³⁺	.391	.141	.116	.122	.305	.100
Fe ²⁺	3.075	3.033	2.842	3.393	3.293	3.543
Mn	.068	.043	.035	.065	.031	.040
Mg	4.877	4.939	5.126	4.584	4.699	4.423

Table 4-1

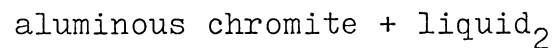
Selected analyses of spinels.

	13	14	15	16	17	18
TiO ₂	.12	.12	.13	.02	.08	.66
Al ₂ O ₃	42.32	38.58	38.45	45.95	46.62	33.33
Cr ₂ O ₃	24.23	28.56	28.89	20.47	19.26	25.73
Fe ₂ O ₃	1.44	1.23	1.32	2.09	2.27	8.12
FeO	18.66	18.18	18.88	16.16	15.82	22.73
MnO	.40	.43	.41	.32	.25	.35
MgO	12.94	12.81	12.50	14.89	15.17	9.76
Total	100.11	99.91	100.58	99.91	99.47	100.68
Ti	.021	.021	.023	.003	.013	.119
Al	11.352	10.520	10.455	12.044	12.211	9.419
Cr	4.360	5.224	5.270	3.599	3.384	4.878
Fe ³⁺	.246	.214	.230	.351	.379	1.465
Fe ²⁺	3.553	3.518	3.643	3.006	2.940	4.559
Mn	.077	.084	.080	.060	.047	.071
Mg	4.391	4.418	4.299	4.937	5.026	3.489
	19	20	21	22	23	24
TiO ₂	.55	.47	.68	.50	.46	1.60
Al ₂ O ₃	33.51	26.46	23.68	35.07	35.66	20.92
Cr ₂ O ₃	24.82	31.91	33.78	24.55	24.24	31.96
Fe ₂ O ₃	7.83	7.96	9.22	8.00	7.93	11.35
FeO	22.69	24.40	25.71	21.12	21.35	32.35
MnO	.33	.48	.50	.50	.26	.30
MgO	9.44	7.44	6.62	10.76	10.86	2.90
Total	99.17	99.13	100.19	100.50	100.76	101.38
Ti	.101	.090	.131	.089	.082	.316
Al	9.598	7.906	7.136	9.796	9.911	6.481
Cr	4.769	6.396	6.829	4.600	4.519	6.642
Fe ³⁺	1.432	1.519	1.774	1.426	1.407	2.245
Fe ²⁺	4.612	5.174	5.498	4.187	4.211	7.112
Mn	.068	.103	.108	.100	.052	.067
Mg	3.420	2.812	2.523	3.802	3.818	1.136

Table 4-1

Selected analyses of spinels.

and $\text{Mg}/\text{Mg} + \text{Fe}^{2+}$ increases from the core to the margin. Such a pattern of zoning is similar to those in Rhum intrusion (Henderson and Suddaby, 1971) and in Panton sill (Hamlyn, 1977). Henderson and Suddaby (1971) proposed the reaction

$$\text{plagioclase} + \text{olivine} + \text{chromite} + \text{liquid}_1 =$$


and explained that the cumulus chromite reacted with postcumulus liquid to form chromite relatively enriched in Al and Mg. Therefore, the aluminous nature of the Pankenushi spinel may partly originate in the reaction of spinel with postcumulus liquid. Compositional range of spinels in Rhum intrusion (Henderson and Suddaby, 1971; Henderson, 1977) are also shown in Figs. 4-1 and 4-2.

B. Plagioclase

Plagioclase in the Pankenushi gabbro is euhedral and regarded as cumulus phase throughout the sequence. The compositional range is from about An_{86} to An_{36} . Selected analyses are given in Table 4-2. Low K_2O content is characteristic.

Pankenushi plagioclase is cloudy, so even an anorthositic rock looks very dark.

C. Olivine

Olivine in the Pankenushi gabbro is euhedral and is regarded as cumulus phase. In some ferrogabbro, olivine is absent and intercumulus quartz is present. In olivine gabbro zone (Zone I and III), there are instances where olivine is not present according to the modal variation in layer by layer. The composition ranges from $\text{Fo}_{86.6}$ to $\text{Fo}_{25.5}$. Although more iron rich olivine ($\text{Fo}_{18.5}$) is found in the ferrogabbro, the

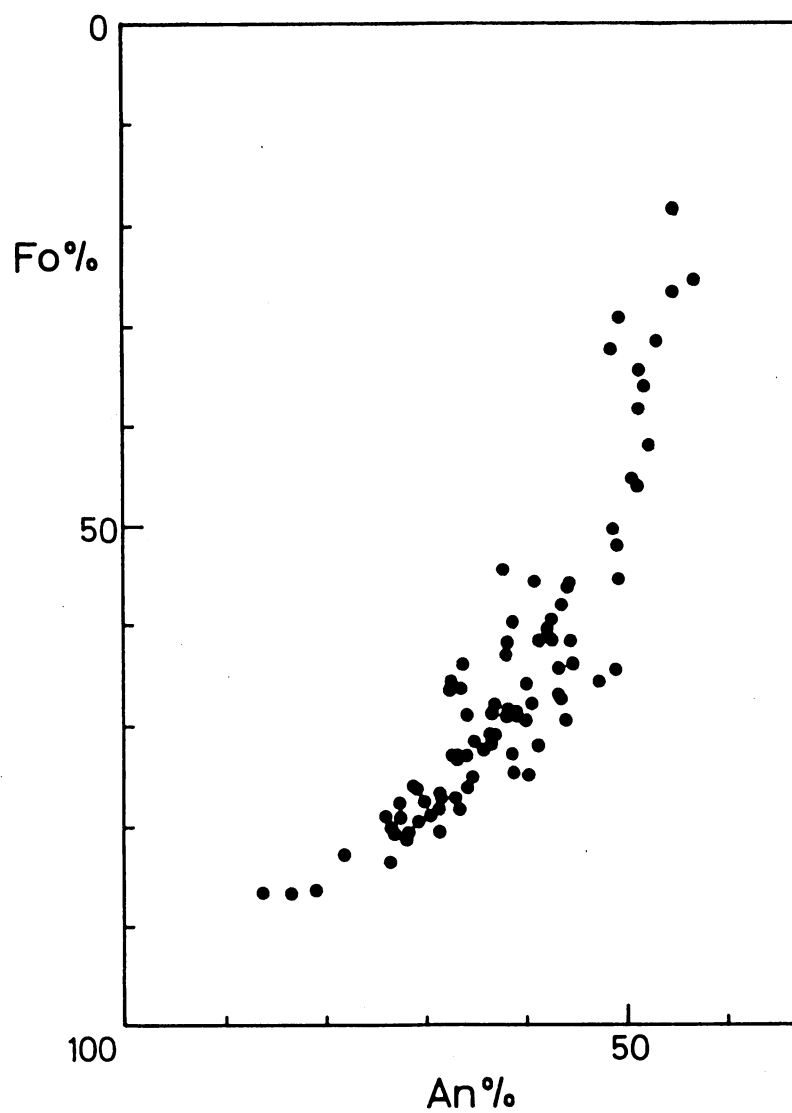


Fig. 4-4

Composition of olivines and plagioclases plotted against each other. Some of them were determined by the method of Yusa (1975).

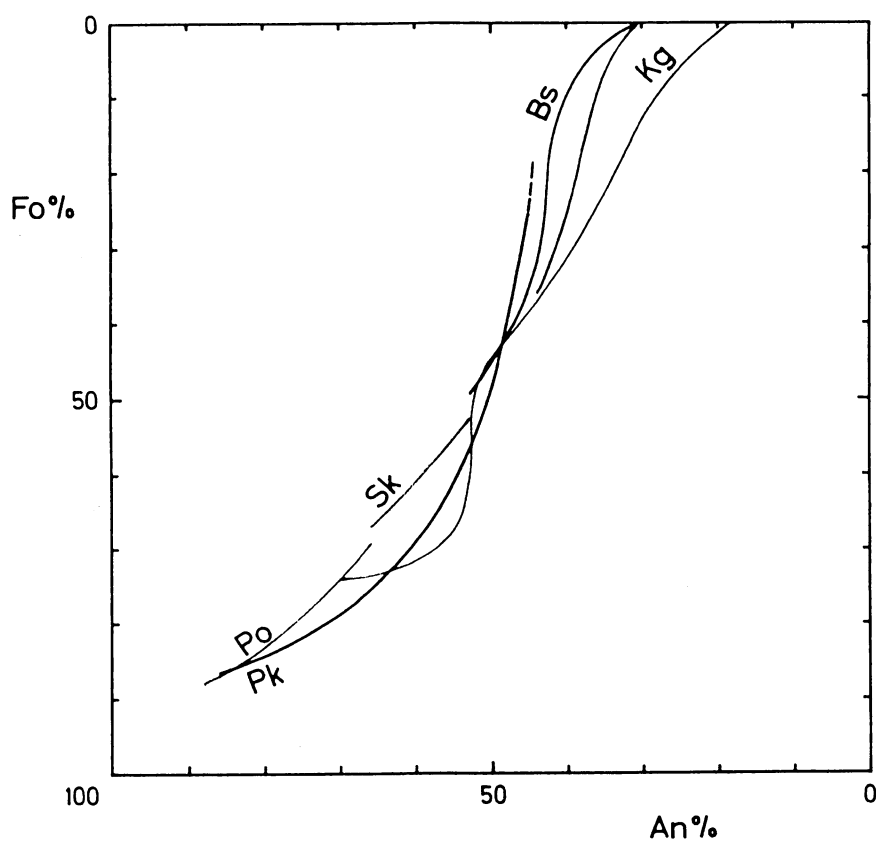


Fig. 4-5

Comparison with other layered intrusions. Po, Mt. Poroshiri complex (Miyashita and Hashimoto, 1975). Sk, Skaergaard intrusion (Wager and Brown, 1967). Bs, Bushveld intrusion (Wager and Brown, 1967). Kg, Kiglapait intrusion (Morse, 1979). Pk, Pankenushi intrusion.

	1	2	3	4	5	6	7	8	9
SiO ₂	49.18	49.61	51.81	52.99	53.32	53.24	54.36	57.75	56.45
TiO ₂	.00	.02	.03	.01	.00	.09	.07	.02	.01
Al ₂ O ₃	32.56	31.79	31.01	29.54	28.97	29.43	28.37	26.39	28.12
Cr ₂ O ₃	.00	.04	.00	.02	.00	.00	.07	.02	.02
FeO	.10	.03	.02	.11	.00	.00	.02	.04	.09
MnO	.02	.00	.00	.00	.00	.00	.02	.02	.00
MgO	.00	.01	.00	.00	.00	.05	.00	.00	.01
CaO	15.53	15.12	13.64	13.28	13.12	12.72	11.68	9.93	9.63
Na ₂ O	2.42	3.22	3.70	4.24	4.63	4.86	5.24	5.76	6.03
K ₂ O	.00	.01	.02	.12	.12	.12	.05	.05	.11
Total	99.81	99.85	100.23	100.31	100.16	100.51	99.88	99.98	100.47
Si	2.248	2.270	2.346	2.399	2.417	2.405	2.462	2.588	2.523
Al	1.754	1.714	1.655	1.576	1.548	1.567	1.514	1.394	1.481
Ti	.000	.001	.001	.000	.000	.003	.002	.001	.000
Cr	.000	.001	.000	.001	.000	.000	.002	.001	.001
Fe	.004	.001	.001	.004	.000	.000	.001	.002	.004
Mn	.001	.000	.000	.000	.000	.000	.001	.001	.000
Mg	.000	.001	.000	.000	.000	.003	.000	.000	.001
Ca	.761	.741	.662	.644	.637	.616	.567	.477	.461
Na	.215	.286	.325	.372	.407	.426	.460	.500	.522
K	.000	.001	.001	.007	.007	.007	.003	.003	.007
Total	4.983	5.016	4.991	5.003	5.016	5.027	5.012	4.967	5.000
An*	78.0	72.2	67.1	63.4	61.0	59.6	55.2	48.4	46.9

Table 4-2.
Representative
analyses
of
plagioclase.

1; 76091903
2; 76091905
3; 76080720
4; 76091906
5; 76091907
6; 76092104
7; 76080802
8; 76080407
9; 7072101

	1	2	3	4	5	6	7
SiO ₂	39.20	38.97	38.06	37.45	37.12	37.25	36.72
TiO ₂	.01	.05	.00	.00	.03	.02	.03
Al ₂ O ₃	.07	.06	.00	.04	.04	.01	.04
Cr ₂ O ₃	.04	.00	.00	.00	.00	.02	.01
FeO	16.27	18.48	24.22	25.51	27.63	28.86	30.39
MnO	.18	.18	.34	.35	.28	.35	.30
MgO	43.73	41.99	37.37	36.12	34.49	33.95	32.36
CaO	.04	.01	.03	.02	.00	.01	.01
Na ₂ O	.02	.02	.00	.00	.00	.03	.00
K ₂ O	.05	.00	.00	.09	.00	.01	.00
Total	99.61	99.76	100.02	99.58	99.59	100.51	99.86
Si	.995	.997	.999	.995	.996	.996	.997
Al	.002	.002	.000	.001	.002	.000	.001
Ti	.000	.001	.000	.000	.001	.000	.001
Cr	.001	.000	.000	.000	.000	.000	.000
Fe	.345	.395	.532	.567	.620	.645	.689
Mn	.004	.004	.008	.008	.006	.008	.007
Mg	1.654	1.601	1.462	1.431	1.380	1.353	1.308
Ca	.001	.000	.001	.000	.000	.000	.000
Na	.001	.001	.000	.000	.000	.001	.000
K	.002	.000	.000	.003	.000	.000	.000
Total	3.005	3.001	3.002	3.005	3.005	3.003	3.002
Mg*	82.7	80.2	73.3	71.6	69.0	67.7	65.5

Table 4-3 Selected analyses of olivine.

1; 76091903. 2; 76091022. 3; 76080720. 4; 76091906. 5; 76091907.
6; 76092104. 7; 76080719.

	8	9	10	11	12	13	14
SiO ₂	35.48	35.58	35.47	33.97	33.85	33.14	32.03
TiO ₂	.02	.00	.01	.01	.03	.02	.00
Al ₂ O ₃	.00	.16	.03	.00	.00	.01	.06
Cr ₂ O ₃	.00	.00	.07	.01	.04	.01	.00
FeO	37.04	37.55	37.80	43.83	44.46	50.69	56.67
MnO	.50	.47	.41	.60	.58	.65	.83
MgO	26.63	26.62	26.35	21.57	21.19	15.69	10.99
CaO	.06	.03	.03	.03	.02	.07	.02
Na ₂ O	.00	.00	.00	.02	.00	.00	.00
K ₂ O	.00	.01	.01	.00	.01	.00	.00
Total	99.73	100.42	100.18	100.04	100.18	100.28	100.60
Si	.999	.995	.997	.989	.988	.999	.996
Al	.000	.005	.001	.000	.000	.000	.002
Ti	.000	.000	.000	.000	.001	.001	.000
Cr	.000	.000	.002	.000	.001	.000	.000
Fe	.872	.879	.888	1.068	1.085	1.277	1.473
Mn	.012	.011	.010	.015	.014	.017	.022
Mg	1.117	1.110	1.104	.937	.922	.705	.509
Ca	.002	.001	.001	.001	.001	.002	.001
Na	.000	.000	.000	.001	.000	.000	.000
K	.000	.000	.000	.000	.000	.000	.000
Total	3.002	3.001	3.003	3.011	3.012	3.001	3.003
Mg*	56.2	55.8	55.4	46.7	45.9	35.6	25.7

Table 4-3 (continued) Selected analyses of olivine.

8, 9; 76080712. 10; 76080802. 11, 12; 76073002. 13; 76080407
14; 76091209

ferrogabbro is completely recrystallized to granule rock. Therefore, in the discussion on igneous petrology, that olivine is neglected. Selected analyses are given in Table 4-3.

Fig. 4-4 shows the Fo content of olivine against the An content of associated plagioclase. This gives a smooth curve and indicates that there is a close correlation in the changing composition of these minerals as the result of crystal fractionation. Fig. 4-5 shows the comparison with other layered intrusions. In the first half the decrease in An content is greater than the decrease in Fo content. On the other hand, in the latter half the decrease in Fo content is greater than that in An content. The fact suggests that the fractionation of plagioclase is prominent in the first half and the fractionation of ferromagnesian minerals is prominent in the latter half.

The notable feature in the Pankenushi olivine is the absence of the compositional break in the middle stage, although the Pankenushi intrusion does not belong to alkalic suite. This problem will be discussed in Chapter 5.

D. Pyroxenes

Throughout the Pankenushi gabbro sequence, both Ca-rich clinopyroxene (hereinafter referred to clinopyroxene) and Ca-poor orthopyroxene (hereinafter referred to orthopyroxene) are present. In the troctolitic rocks, they appear as intercumulus phase or rim to olivine. In the olivine gabbro and the ferrogabbro, pyroxenes are euhedral and considered to be cumulus phase. The range of Mg ratio ($\text{Mg} \times 100 / (\text{Mg} + \text{Fe})$) is from about 83 (86 in intercumulus phase) to 52 in

clinopyroxene and from 77 (85 in intercumulus phase) to 42 in orthopyroxene, respectively. Selected analyses are shown in Tables 4-4 and 4-5.

Fig. 4-6 shows the composition of the pyroxenes in the familiar pyroxene quadrilateral. Characteristic feature of pyroxene mineralogy is essential lacking of pigeonite, though in only two samples inverted pigeonite is found. As compared with the Skaergaard pyroxene, the Pankenushi clinopyroxenes are more calcic and the orthopyroxenes are less calcic. Such feature of the Pankenushi pyroxene mineralogy resembles the Guadalupe pyroxene. The Guadalupe intrusion is believed to be calc-alkalic gabbro (Best, 1963; Best and Mercy, 1967).

Wide range of Wo content in the clinopyroxene composition is shown in Fig. 4-6. Fig. 4-7 shows the intragrain variation observed in the olivine gabbro (sample 76092104). From the core to the margin, Wo content and Mg ratio increase. They suggest that the marginal part, at least, is suffered from subsolidus re-equilibrium. Fig. 4-8 shows the equilibrium temperature estimated by the method of Wood and Banno (1973) using the pair of most Ca-rich orthopyroxene and most Ca-poor clinopyroxene in each polished section. Estimated temperatures, about 800 - 900°C, also suggest the evidence of subsolidus re-equilibration.

The Cr_2O_3 content of clinopyroxene against Mg ratio is shown in Fig. 4-9. High concentration of Cr in the early magnesian clinopyroxene (Mg ratio > 80) and very low concentration in the later iron rich clinopyroxene are clear. Such a behavior is undoubtedly due to the strong partition of Cr between clinopyroxene and liquid favouring the former

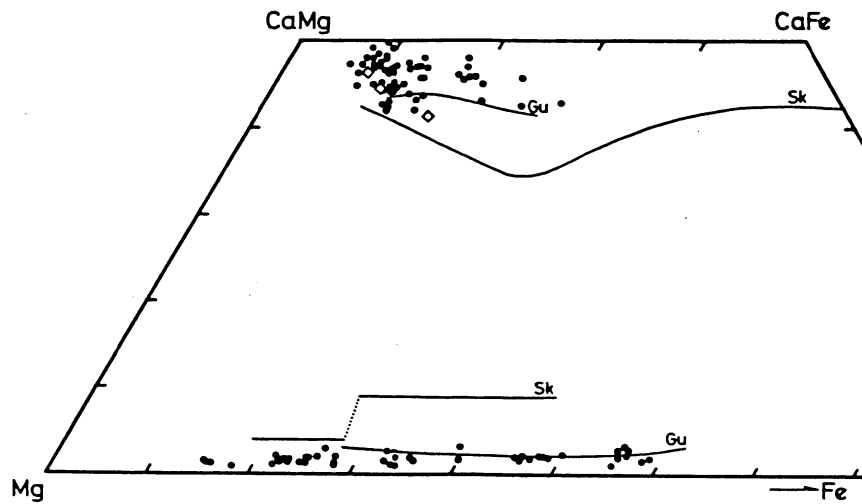


Fig. 4-6

Compositions of pyroxenes plotted in the quadrilateral. Sk, trends of the Skaergaard pyroxenes (Brown, 1957; Brown and Vincent, 1963). Gu, trends of the Guadalupe pyroxenes (Best and Mercy, 1967). Rhombic symbols indicate the wet chemical analyses by Nochi and Komatsu (1967).

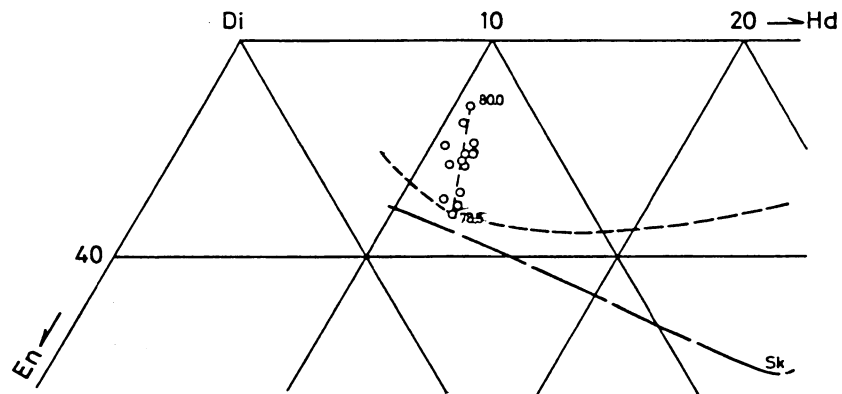


Fig. 4-7

Intragrain variation of clinopyroxene observed in olivine gabbro (76092104). Sk, crystallization trend of the Skaergaard clinopyroxene. Broken line indicates the trend of least calcic clinopyroxene. Numerical value indicates Mg ratio ($100 \times \text{Mg} / (\text{Mg} + \text{Fe})$) of pyroxene.

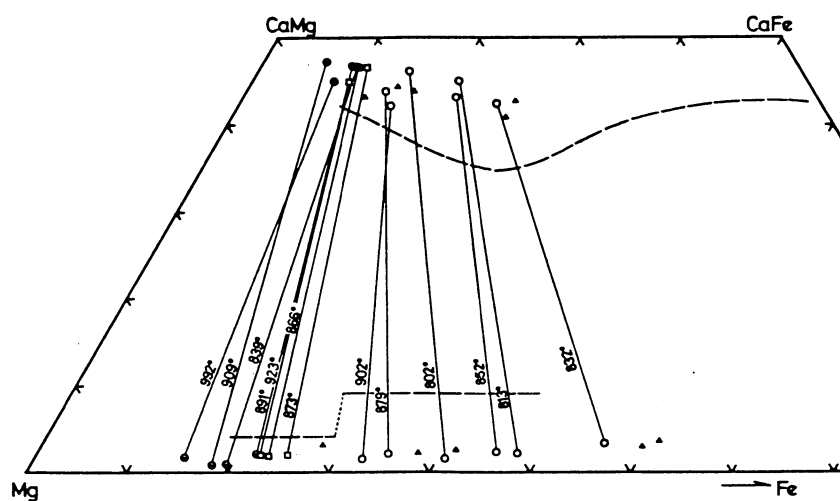


Fig. 4-8

Estimated temperature by the method of Wood and Banno (1973).

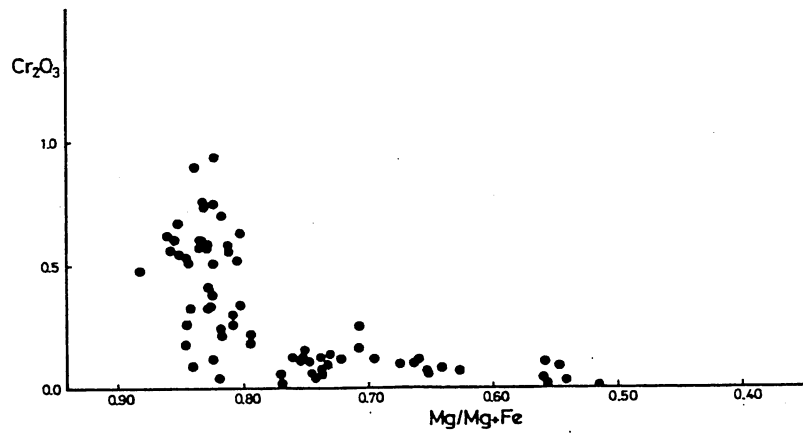


Fig. 4-9

Cr_2O_3 content of clinopyroxene plotted against Mg ratio.

	1	2	3	4	5	6	7
SiO ₂	51.65	52.20	52.38	52.21	50.37	51.15	51.59
TiO ₂	.60	.62	.60	.68	.78	.42	.48
Al ₂ O ₃	3.32	3.54	2.18	2.35	3.11	2.53	2.22
Cr ₂ O ₃	.67	.60	.76	.90	.19	.22	.69
FeO	5.07	4.54	5.55	5.28	6.97	6.82	7.84
MnO	.08	.14	.16	.16	.17	.20	.26
MgO	16.60	15.11	15.47	15.29	15.18	14.79	16.09
CaO	22.08	22.63	22.81	22.68	22.94	23.07	20.62
Na ₂ O	.45	.42	.46	.46	.47	.45	.44
K ₂ O	—	—	.01	.01	.02	—	—
Total	100.52	99.80	100.38	100.02	100.20	100.01	100.23
Si	1.895	1.922	1.932	1.931	1.881	1.918	1.912
Al	.143	.153	.095	.103	.137	.111	.097
Ti	.017	.017	.017	.019	.022	.012	.013
Cr	.020	.018	.022	.027	.006	.007	.020
Fe	.156	.140	.171	.163	.218	.212	.243
Mn	.003	.004	.005	.005	.005	.006	.008
Mg	.908	.829	.851	.843	.845	.821	.889
Ca	.868	.893	.901	.898	.918	.920	.819
Na	.032	.030	.033	.033	.034	.032	.031
K	—	—	—	—	.001	—	—
Total	4.042	4.006	4.027	4.022	4.067	4.039	4.032
Mg*	85.3	85.6	83.3	83.8	79.5	79.5	78.5
Wo	44.9	48.0	46.9	47.2	46.3	47.1	42.0
En	47.0	44.5	44.3	44.2	42.7	42.0	45.6
Fs	8.1	7.5	8.9	8.6	11.0	10.9	12.5

Table 4-4

Selected analyses of clinopyroxenes.

	8	9	10	11	12	13	14
SiO ₂	51.50	52.47	52.92	52.10	51.68	51.89	52.18
TiO ₂	.70	.62	.41	.38	.58	.52	.23
Al ₂ O ₃	2.26	2.12	1.41	1.46	2.11	2.51	1.71
Cr ₂ O ₃	.71	.45	.06	.06	.14	.06	.12
FeO	7.49	6.62	9.49	7.62	9.41	8.13	9.37
MnO	.22	.19	.28	.24	.20	.23	.23
MgO	15.68	14.86	15.00	14.44	14.32	13.40	13.77
CaO	21.89	22.91	20.57	23.58	21.18	23.08	22.51
Na ₂ O	.39	.40	.33	.29	.39	.43	.34
K ₂ O	—	—	—	—	—	.01	.01
Total	100.84	100.64	100.47	100.17	100.01	100.26	100.47
Si	1.901	1.932	1.965	1.944	1.936	1.936	1.948
Al	.098	.092	.062	.064	.093	.111	.075
Ti	.019	.017	.012	.011	.016	.015	.007
Cr	.021	.013	.002	.002	.004	.002	.004
Fe	.231	.204	.295	.238	.295	.254	.293
Mn	.007	.006	.009	.008	.006	.007	.007
Mg	.863	.816	.830	.803	.800	.745	.766
Ca	.866	.904	.818	.943	.850	.923	.901
Na	.028	.029	.024	.021	.028	.031	.024
K	—	—	—	—	—	.001	—
Total	4.034	4.013	4.017	4.034	4.028	4.025	4.025
Mg*	78.9	80.0	73.8	77.1	73.1	74.6	72.3
Wo	44.2	47.0	42.1	47.5	43.7	48.0	46.0
En	44.0	42.4	42.7	40.5	41.1	38.8	39.1
Fs	11.8	10.6	15.2	12.0	15.2	13.2	14.9

Table 4-4 (continued)

Selected analyses of clinopyroxenes.

	15	16	17	18	19	20	21
SiO ₂	51.21	51.40	52.14	51.25	50.87	50.85	51.68
TiO ₂	.43	.23	.18	.14	.17	.18	.13
Al ₂ O ₃	1.78	1.37	1.18	.82	.83	.83	.92
Cr ₂ O ₃	.25	—	.12	.03	.04	.02	.11
FeO	9.49	13.02	11.17	14.85	13.80	15.93	14.87
MnO	.27	.31	.29	.20	.35	.25	.37
MgO	12.90	12.30	12.19	11.51	11.62	11.25	10.57
CaO	23.74	20.79	22.71	21.06	22.04	20.74	22.02
Na ₂ O	.30	.23	.24	.21	.21	.28	.20
K ₂ O	—	.01	—	—	—	—	—
Total	100.37	99.66	100.22	100.07	99.93	100.33	100.87
Si	1.929	1.959	1.968	1.962	1.950	1.953	1.967
Al	.079	.062	.053	.037	.037	.037	.041
Ti	.012	.007	.005	.004	.005	.005	.004
Cr	.007	—	.004	.001	.001	.001	.003
Fe	.299	.415	.352	.476	.443	.512	.473
Mn	.009	.010	.009	.006	.011	.008	.012
Mg	.725	.699	.686	.657	.664	.644	.600
Ca	.958	.849	.918	.864	.905	.853	.898
Na	.022	.017	.017	.015	.016	.021	.015
K	—	—	—	—	—	—	—
Total	4.040	4.018	4.012	4.022	4.032	4.034	4.013
Mg*	70.8	62.7	66.1	60.0	60.0	55.7	55.9
Wo	48.3	43.2	46.9	43.3	45.0	42.5	45.6
En	36.6	35.6	35.1	32.9	33.0	32.0	30.4
Fs	15.1	21.1	18.0	23.8	22.0	25.5	24.0

Table 4-4 (continued)

Selected analyses of clinopyroxenes.

	1	2	3	4	5	6	7
SiO ₂	54.91	54.85	54.27	53.72	54.34	53.39	53.28
TiO ₂	.15	.20	.27	.28	.21	.25	.18
Al ₂ O ₃	1.90	2.15	1.65	1.94	1.56	1.58	.88
Cr ₂ O ₃	.30	.22	.19	.20	.11	.07	—
FeO	10.16	10.25	14.26	14.81	16.67	17.02	21.03
MnO	.18	.21	.36	.34	.28	.40	.45
MgO	32.05	31.61	27.85	27.42	25.95	25.71	23.76
CaO	.79	.67	1.06	.84	.99	1.48	.75
Na ₂ O	.01	.01	.03	.01	.01	.02	.01
K ₂ O	—	.01	.02	—	.07	.06	.04
Total	100.45	100.18	99.96	99.56	100.19	99.98	100.38
Si	1.928	1.930	1.952	1.944	1.967	1.949	1.967
Al	.078	.089	.070	.083	.066	.068	.038
Ti	.004	.005	.007	.008	.006	.007	.005
Cr	.008	.006	.005	.006	.003	.002	—
Fe	.298	.302	.429	.448	.505	.519	.649
Mn	.005	.006	.011	.010	.009	.012	.014
Mg	1.677	1.658	1.493	1.479	1.401	1.399	1.308
Ca	.030	.025	.041	.033	.038	.058	.030
Na	.001	.001	.002	.001	.001	.001	.001
K	—	—	.001	—	.003	.003	.002
Total	4.029	4.022	4.011	4.011	3.999	4.018	4.014
Mg*	84.9	84.6	77.7	76.8	73.6	72.9	66.8
Wo	1.5	1.3	2.1	1.7	2.0	2.9	1.5
En	83.6	83.5	76.1	75.5	72.1	70.8	65.8
Fs	14.9	15.2	21.9	22.9	26.0	26.3	32.7

Table 4-5 Selected analyses of orthopyroxenes.

	8	9	10	11	12	13	14
SiO ₂	53.45	53.26	52.68	51.27	51.41	51.46	50.37
TiO ₂	.06	.08	.17	.08	.12	.08	.06
Al ₂ O ₃	.47	.77	1.23	.88	.84	.59	.93
Cr ₂ O ₃	—	.03	.01	.04	—	.06	—
FeO	21.60	22.21	22.54	25.79	25.59	28.18	30.45
MnO	.44	.49	.49	.51	.60	.65	.61
MgO	23.20	22.34	22.30	20.52	20.32	18.16	16.29
CaO	.50	.95	.72	.73	.75	.94	1.07
Na ₂ O	—	.01	—	.01	—	—	—
K ₂ O	—	.01	—	.02	.01	.03	—
Total	99.72	100.15	100.14	99.85	99.64	100.15	99.78
Si	1.988	1.981	1.964	1.952	1.960	1.976	1.964
Al	.021	.034	.054	.039	.038	.027	.043
Ti	.002	.002	.005	.002	.004	.002	.002
Cr	—	.001	—	.001	—	.002	—
Fe	.672	.691	.703	.821	.816	.905	.993
Mn	.014	.015	.016	.017	.019	.021	.020
Mg	1.286	1.239	1.239	1.165	1.155	1.039	.947
Ca	.020	.038	.029	.030	.031	.039	.045
Na	—	.001	—	.001	—	—	—
K	—	—	—	.001	—	.001	—
Total	4.003	4.002	4.010	4.029	4.023	4.012	4.014
Mg*	65.7	64.2	63.9	58.7	58.6	53.5	48.8
Wo	1.0	1.9	1.5	1.5	1.5	2.0	2.3
En	65.0	63.0	62.9	57.8	57.7	52.4	47.7
Fs	34.0	35.1	35.7	40.7	40.8	45.6	50.0

Table 4-5 (continued)

	15	16	17
SiO ₂	50.66	50.76	50.82
TiO ₂	.10	.14	.17
Al ₂ O ₃	.40	.39	.48
Cr ₂ O ₃	.02	.03	—
FeO	33.47	33.27	33.38
MnO	.70	.66	.69
MgO	14.74	14.22	13.76
CaO	.78	1.32	1.48
Na ₂ O	—	—	.02
K ₂ O	—	—	—
Total	100.87	100.79	100.80
Si	1.979	1.985	1.988
Al	.019	.017	.022
Ti	.003	.004	.005
Cr	.001	.001	—
Fe	1.093	1.088	1.092
Mn	.023	.022	.023
Mg	.858	.829	.802
Ca	.033	.055	.062
Na	—	—	.002
K	—	—	—
Total	4.009	4.001	3.996
Mg*	44.0	43.2	42.4
Wo	1.7	2.8	3.2
En	43.2	42.0	41.0
Fs	55.1	55.2	55.8

Table 4-5 (continued)

(Seward, 1971; Gibb, 1973; etc), and therefore is characteristic for igneous crystallization. As already mentioned, Pankenushi pyroxene may be suffered from subsolidus reequilibration, however the behavior of Cr is typical of igneous crystallization. So it seems that the chemical change by the subsolidus reaction is not so remarkable.

E. Amphibole

Amphibole occurs as intercumulus phase in most of the rocks and rims to other mafic minerals. In some ferrogabbro, discrete cumulus-like amphibole is present. Pankenushi amphibole is dark brown or pale brown under the microscope.

Pankenushi amphibole is Si-poor and pargasitic in composition (Fig. 4-10). Crystallization trend from pargasite to ferro-edenitic hornblende through ferroan pargasitic hornblende (Leake, 1968) is shown in Fig. 4-11. Selected analyses are given in Table 4-6.

One of the characteristic features is high Cr_2O_3 content in the magnesian amphibole. Fig. 4-12 shows the Cr_2O_3 content against Mg ratio of amphibole. In the magnesian amphibole (Mg ratio 75), high concentration of Cr is clear. Cr_2O_3 attains a maximum content of about 1.6%. The pattern shown in Fig. 4-12 is very similar to that of clinopyroxene, and can be explained by the crystal chemical character of Cr as well as in clinopyroxene.

F. Biotite

Analyses of biotite are too limited for mineralogical discussion. Representative analyses are shown in Table 4-7.

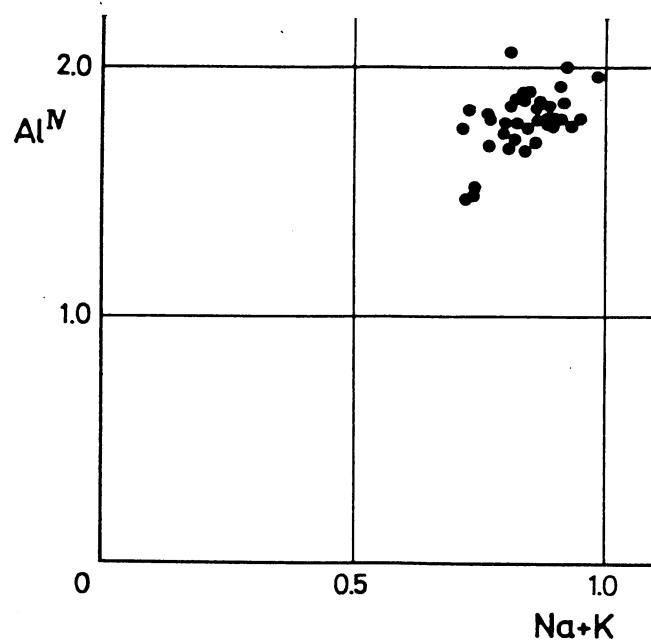


Fig. 4-10
 Al^{IV} - $Na+K$ diagram of amphiboles.

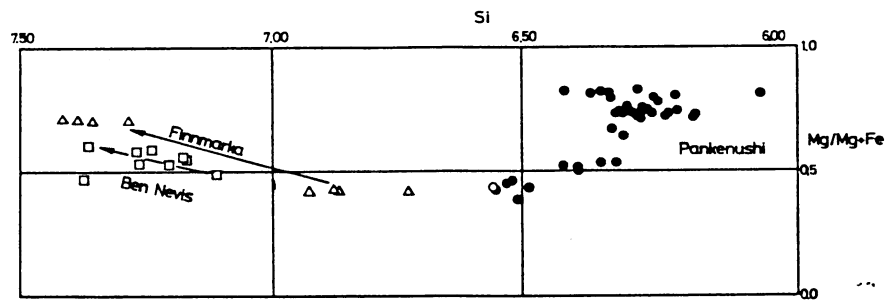


Fig. 4-11

Si-Mg/Mg+Fe diagram of amphibole. Circle, Pankenushiy amphibole. Solid, $\text{Ca}+\text{Na}+\text{K} > 2.5$. Open, $\text{Ca}+\text{Na}+\text{K} < 2.5$. Finnmarka amphibole (Czamanske and Wones, 1973) and Ben Nevis amphibole (Haslam, 1968) are also plotted.

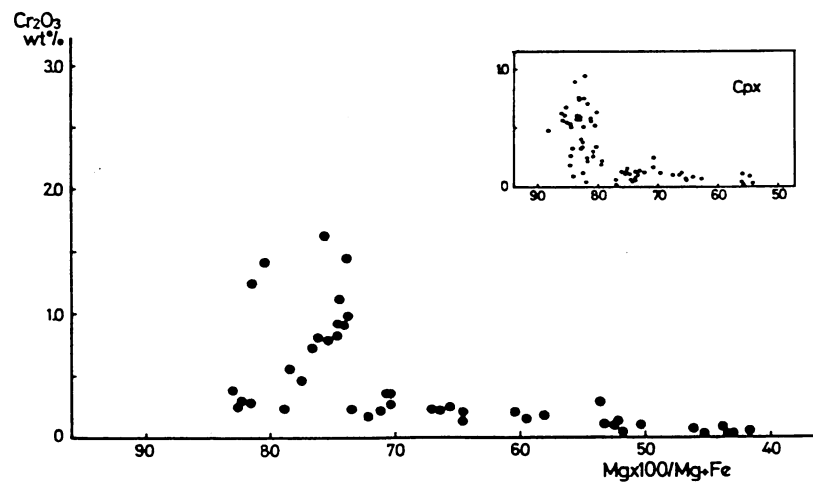


Fig. 4-12

Cr_2O_3 content of amphibole plotted against Mg ratio.
The inset graph shows Cr_2O_3 content of Pankenushi
clinopyroxene.

	1	2	3	4	5	6	7
SiO ₂	41.61	42.51	43.58	44.42	44.62	44.14	42.50
TiO ₂	2.96	2.86	1.43	1.16	2.71	3.00	3.19
Al ₂ O ₃	16.43	14.14	13.92	13.05	12.69	13.28	13.01
Cr ₂ O ₃	1.24	1.41	.38	.30	.25	.28	1.62
FeO	6.06	6.63	6.26	6.63	6.10	6.31	8.34
MnO	.06	.00	.06	.06	.07	.07	.02
MgO	14.90	15.24	17.12	17.34	16.23	15.66	14.53
CaO	11.91	11.94	11.84	12.59	12.82	12.82	12.31
Na ₂ O	2.44	2.62	2.90	2.80	2.56	2.48	2.74
K ₂ O	.73	.64	.43	.49	.57	.58	.39
Total	98.34	97.99	97.92	98.84	98.62	98.62	98.65
Si	5.940	6.111	6.228	6.308	6.335	6.275	6.130
Al	2.765	2.396	2.345	2.184	2.124	2.225	2.212
Ti	.318	.309	.154	.124	.289	.321	.346
Cr	.140	.160	.043	.034	.028	.031	.185
Fe	.724	.797	.748	.797	.724	.750	1.006
Mn	.007	.000	.007	.007	.008	.008	.002
Mg	3.171	3.266	3.647	3.670	3.435	3.318	3.124
Ca	1.822	1.839	1.813	1.916	1.950	1.953	1.902
Na	.675	.730	.804	.771	.705	.684	.766
K	.133	.117	.078	.089	.103	.105	.072
Total	15.694	15.726	15.866	15.890	15.703	15.671	15.745
Mg*	81.4	80.4	83.0	82.3	82.6	81.6	75.6

Table 4-6.

Selected analyses of amphiboles.

	8	9	10	11	12	13	14
SiO ₂	42.47	42.65	42.15	42.07	41.91	42.31	41.73
TiO ₂	3.40	2.66	3.60	2.75	1.90	3.64	4.10
Al ₂ O ₃	12.87	13.11	13.02	13.06	14.91	12.53	12.42
Cr ₂ O ₃	1.44	.23	.22	.29	.20	.22	.20
FeO	8.76	9.35	9.94	9.50	9.57	11.16	11.88
MnO	.07	.13	.11	.10	.14	.12	.16
MgO	13.82	14.55	13.73	14.29	13.68	12.76	12.15
CaO	11.97	11.91	11.99	11.99	12.42	12.18	11.99
Na ₂ O	2.82	2.19	2.44	2.51	2.81	2.26	2.17
K ₂ O	.37	.81	.64	.74	.29	.75	.86
Total	97.99	97.59	97.84	97.30	97.83	97.93	97.66
Si	6.171	6.217	6.156	6.171	6.100	6.211	6.172
Al	2.204	2.253	2.241	2.258	2.558	2.168	2.165
Ti	.372	.292	.395	.303	.208	.402	.456
Cr	.165	.027	.025	.034	.023	.026	.023
Fe	1.064	1.140	1.214	1.165	1.165	1.370	1.470
Mn	.009	.016	.014	.012	.017	.015	.020
Mg	2.993	3.162	2.989	3.125	2.968	2.792	2.679
Ca	1.864	1.860	1.876	1.885	1.937	1.916	1.900
Na	.794	.619	.691	.714	.793	.643	.622
K	.069	.151	.119	.138	.054	.140	.162
Total	15.705	15.736	15.721	15.806	15.824	15.683	15.670
Mg*	73.8	73.5	71.1	72.8	71.8	67.1	64.6

Table 4-6 (continued)

Selected analyses of amphiboles.

	15	16	17	18	19	20	21
SiO ₂	41.14	41.73	41.19	42.57	41.83	42.85	42.84
TiO ₂	3.41	3.89	3.27	2.63	2.02	3.03	2.73
Al ₂ O ₃	13.63	12.39	13.11	11.85	11.62	9.26	9.27
Cr ₂ O ₃	.21	.12	.14	.12	.04	.06	.02
FeO	11.07	12.45	13.03	16.63	17.52	18.91	19.47
MnO	.11	.09	.11	.22	.12	.16	.21
MgO	12.29	12.74	10.72	10.19	10.58	9.06	9.06
CaO	12.34	11.77	11.15	11.56	11.04	11.79	11.56
Na ₂ O	2.61	2.61	2.46	2.31	2.07	1.94	1.89
K ₂ O	.86	.66	1.02	.74	.85	.85	.85
Total	97.67	98.45	96.20	98.82	97.69	97.91	97.90
Si	6.076	6.137	6.209	6.334	6.321	6.518	6.528
Al	2.373	2.148	2.328	2.078	2.070	1.660	1.665
Ti	.379	.430	.370	.294	.230	.347	.313
Cr	.025	.014	.017	.014	.005	.007	.002
Fe	1.367	1.531	1.643	2.069	2.214	2.406	2.481
Mn	.014	.011	.015	.028	.015	.021	.027
Mg	2.706	2.793	2.409	2.260	2.383	2.054	2.058
Ca	1.953	1.855	1.801	1.843	1.788	1.922	1.888
Na	.747	.744	.718	.666	.607	.572	.558
K	.162	.124	.195	.140	.164	.165	.165
Total	15.801	15.786	15.705	15.729	15.797	15.671	15.687
Mg*	66.4	64.6	59.5	52.2	51.8	46.1	45.3

Table 4-6 (continued)

Selected analyses of amphiboles.

	1	2	3	4	5	6	7	8
SiO ₂	37.65	37.62	38.11	36.50	36.25	40.10	39.99	35.96
TiO ₂	2.45	1.79	3.84	1.83	3.65	4.17	5.30	5.11
Al ₂ O ₃	16.09	17.61	16.16	16.69	16.17	15.59	15.03	15.05
Cr ₂ O ₃	.26	.07	.24	.25	.21	.04	.22	.01
FeO	7.03	9.00	9.31	9.89	10.68	12.19	13.10	19.04
MnO	.07	.02	.01	.10	.04	.07	.03	.06
MgO	20.98	19.22	17.97	18.79	16.85	15.60	14.38	11.55
CaO	.03	.02	.01	.10	.07	.06	.02	.08
Na ₂ O	.34	.50	.56	.13	.16	.31	.38	.19
K ₂ O	8.70	8.08	8.28	9.03	8.77	7.82	7.94	8.00
Total	93.61	93.93	94.51	93.31	92.83	95.98	96.31	95.05
Si	5.490	5.481	5.542	5.428	5.435	5.767	5.763	5.464
Al	2.766	3.024	2.769	2.926	2.857	2.643	2.553	2.695
Ti	.269	.196	.420	.205	.412	.451	.574	.584
Cr	.030	.008	.027	.030	.025	.004	.025	.001
Fe	.857	1.097	1.132	1.231	1.340	1.466	1.579	2.419
Mn	.008	.002	.002	.009	.004	.008	.003	.008
Mg	4.562	4.174	3.895	4.166	3.766	3.344	3.090	2.616
Ca	.005	.003	.002	.016	.011	.009	.004	.013
Na	.096	.141	.157	.038	.045	.088	.107	.056
K	1.619	1.502	1.537	1.713	1.678	1.435	1.460	1.551
Total	15.701	15.629	15.486	15.764	15.573	15.220	15.158	15.407
Mg*	84.2	79.2	77.5	77.2	73.8	69.5	66.2	52.0

Table 4-7 Representative analyses of biotite.
1; 76092112. 2; 76080719. 3; 76080113. 4, 5; 76081419.
6; 7; 76092106. 8; 76080407.

G. Ilmenite

Fe-Ti oxide observed in the Pankenushi gabbro is ilmenite alone and magnetite is not found. Selective analyses are shown in Table 4-8.

Fig. 4-13 shows the MgO and MnO contents of ilmenite against the Fo content of the associated olivine. Maximum content of MgO and the geikielite molecule attains up to 5.4 % and 20 %, respectively. MnO content is low and ranges from about 0.4 % to 0.7 %. In some grains, the marginal part has rather high MnO, more than 1 % (Table 4-8, 6). That is explained by the secondary oxidation. Low concentration of MnO and the lack of magnetite show the comparatively reduced condition at the time of crystallization. Even in Skaergaard intrusion, magnetite is present as well as ilmenite (Vincent and Phillips, 1954).

H. Summary on the mineralogy

Fig. 4-14 shows the crystallization sequence of the Pankenushi gabbroic intrusion. Significant features of the Pankenushi mineralogy are as follows.

1. Nevertheless the existence of the reaction relation between olivine and orthopyroxene and of the wide compositional range of olivine (from Fo₈₇ to Fo₂₆), there is no compositional break of olivine in its middle stage of crystallization.

Only orthopyroxene is found as Ca-poor pyroxene, and pigeonite is essentially lacking.

3. The amount of hydrous silicates such as amphibole and biotite is comparatively abundant. Fig. 4-15 shows the proportion of the hydrous mafic silicates within the total mafic silicates.

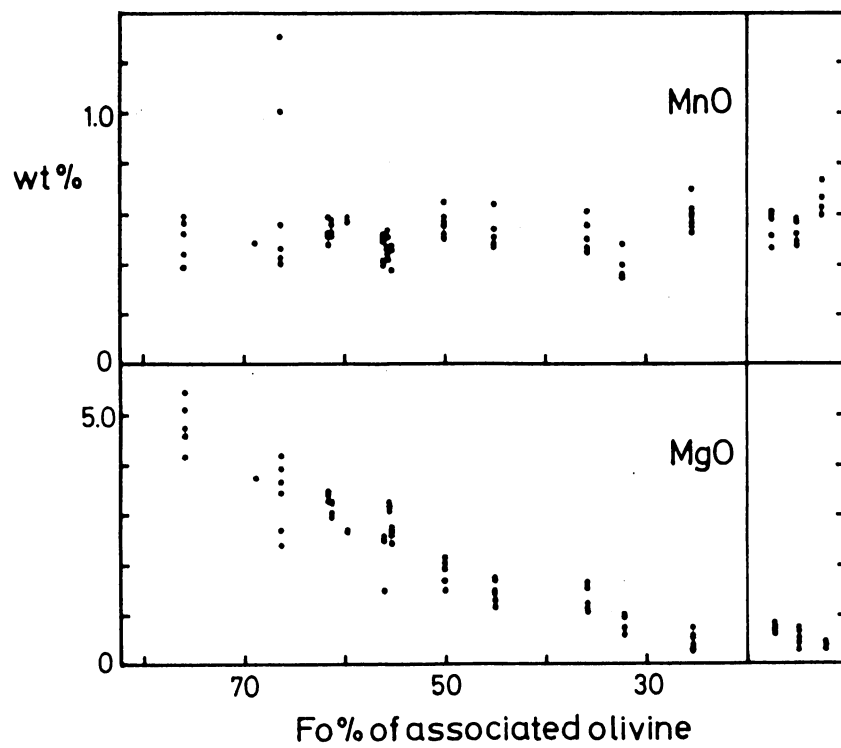


Fig. 4-13

Composition of ilmenite (MnO and MgO) plotted against Fo content of associated olivine. Ilmenite in olivine free rock is shown separately in the right.

	1	2	3	4	5	6
TiO ₂	53.83	53.97	53.14	53.44	54.21	53.31
Al ₂ O ₃	.16	.02	.00	.05	.06	.00
Cr ₂ O ₃	.15	.25	.09	.02	.12	.05
Fe ₂ O ₃	1.86	1.86	2.02	1.38	.30	1.51
FeO	38.32	39.07	39.87	41.53	41.74	41.82
MnO	.43	.43	.42	.42	.46	1.30
MgO	5.41	5.06	4.20	3.42	3.67	2.69
Total	100.17	100.67	99.74	100.26	100.56	100.68
Ti	1.959	1.961	1.961	1.973	1.990	1.971
Al	.009	.001	.000	.003	.003	.000
Cr	.006	.010	.003	.001	.005	.002
Fe ³⁺	.068	.068	.075	.051	.011	.056
Fe ²⁺	1.551	1.579	1.636	1.705	1.704	1.720
Mn	.018	.018	.017	.017	.019	.054
Mg	.390	.364	.307	.250	.267	.197
	7	8	9	10	11	12
TiO ₂	52.34	53.09	52.66	51.94	52.43	51.94
Al ₂ O ₃	.06	.07	.02	.07	.19	.13
Cr ₂ O ₃	.11	.16	.08	.07	.11	.09
Fe ₂ O ₃	2.04	1.07	1.29	3.25	2.31	2.87
FeO	40.65	41.45	42.31	41.68	42.04	42.01
MnO	.58	.56	.49	.40	.48	.38
MgO	3.27	3.21	2.55	2.59	2.59	2.42
Total	99.04	99.61	99.40	100.01	100.15	99.84
Ti	1.958	1.975	1.974	1.936	1.949	1.941
Al	.004	.004	.001	.004	.011	.008
Cr	.004	.006	.003	.003	.004	.004
Fe ³⁺	.076	.040	.048	.121	.086	.107
Fe ²⁺	1.691	1.715	1.764	1.728	1.738	1.745
Mn	.024	.023	.021	.017	.020	.016
Mg	.243	.237	.189	.191	.191	.179

Table 4-8

Selected analyses of ilmenite.

	13	14	15	16	17	18
TiO ₂	52.05	52.87	53.24	53.01	52.61	52.01
Al ₂ O ₃	.08	.00	.18	.13	.00	.03
Cr ₂ O ₃	.05	.07	.12	.10	.00	.02
Fe ₂ O ₃	2.26	2.03	.49	.64	1.37	2.29
FeO	43.18	43.34	44.26	44.05	43.84	43.33
MnO	.57	.59	.51	.47	.45	.60
MgO	1.71	2.02	1.74	1.76	1.69	1.59
Total	99.90	100.92	100.54	100.16	99.96	99.87
Ti	1.954	1.961	1.983	1.982	1.974	1.956
Al	.005	.000	.011	.008	.000	.002
Cr	.002	.003	.005	.004	.000	.001
Fe ³⁺	.085	.075	.018	.024	.051	.086
Fe ²⁺	1.803	1.788	1.833	1.832	1.830	1.812
Mn	.024	.025	.021	.020	.019	.025
Mg	.127	.149	.128	.130	.126	.119
	19	20	21	22	23	24
TiO ₂	50.81	51.75	52.29	51.94	51.94	52.30
Al ₂ O ₃	.00	.06	.12	.06	.00	.06
Cr ₂ O ₃	.04	.00	.00	.00	.00	.00
Fe ₂ O ₃	3.66	1.94	.66	2.08	2.18	2.09
FeO	44.05	44.78	45.11	45.42	45.11	45.47
MnO	.58	.59	.62	.60	.57	.55
MgO	.59	.65	.72	.38	.57	.56
Total	99.73	99.76	99.52	100.48	100.37	101.03
Ti	1.930	1.962	1.984	1.959	1.959	1.959
Al	.000	.004	.007	.004	.000	.004
Cr	.002	.000	.000	.000	.000	.000
Fe ³⁺	.139	.073	.025	.078	.082	.078
Fe ²⁺	1.860	1.887	1.903	1.905	1.892	1.894
Mn	.025	.025	.026	.025	.024	.023
Mg	.044	.049	.054	.028	.043	.042

Table 4-8 (continued)

Selected analyses of ilmenite.

	25	26
TiO ₂	51.65	51.77
Al ₂ O ₃	.00	.09
Cr ₂ O ₃	.03	.03
Fe ₂ O ₃	2.23	2.70
FeO	45.25	44.96
MnO	.63	.74
MgO	.31	.47
Total	100.10	100.76
Ti	1.957	1.946
Al	.000	.005
Cr	.001	.001
Fe ³⁺	.085	.101
Fe ²⁺	1.907	1.880
Mn	.027	.031
Mg	.023	.035

Table 4-8 (continued)

Selected analyses of ilmenite.

It is usually said that, in the above mentioned three features, 2 and 3 are typical of calc-alkalic gabbro (e.g. Miyashiro and Kushiro, 1975). However, the Pankenushi gabbro does not belong to calc-alkalic suite but to tholeiitic suite as discussed in Chapter 7.

Fig. 4-16 shows the compositional change of major minerals along the Pankenushi river. From Zone II to both Zones I and III, mafic minerals show the iron enrichment and plagioclase shows the Na enrichment, although the examination in zone I is restricted by the effect of later mylonitization.

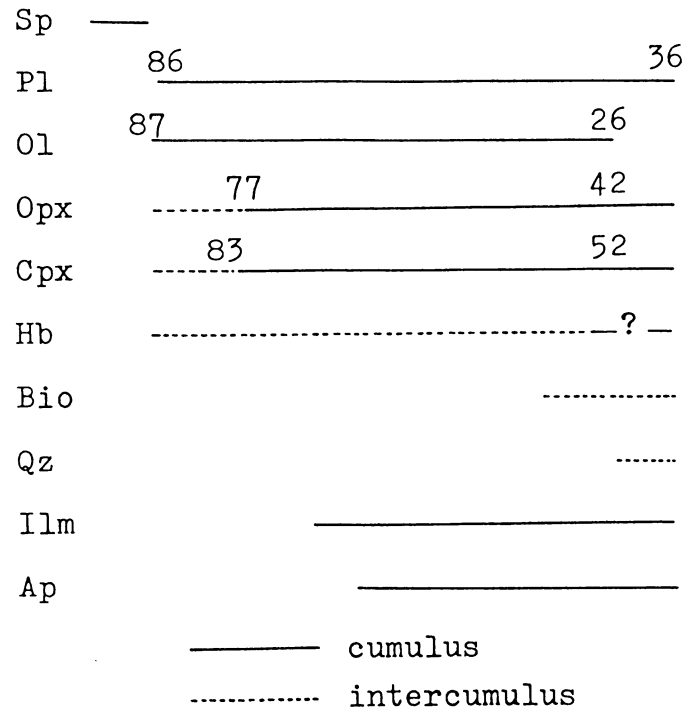


Fig. 4-14

Crystallization order of the main constituent minerals from the Pankenushi intrusion. Numerical values for plagioclase show An content and those for mafic silicates show Mg ratio.

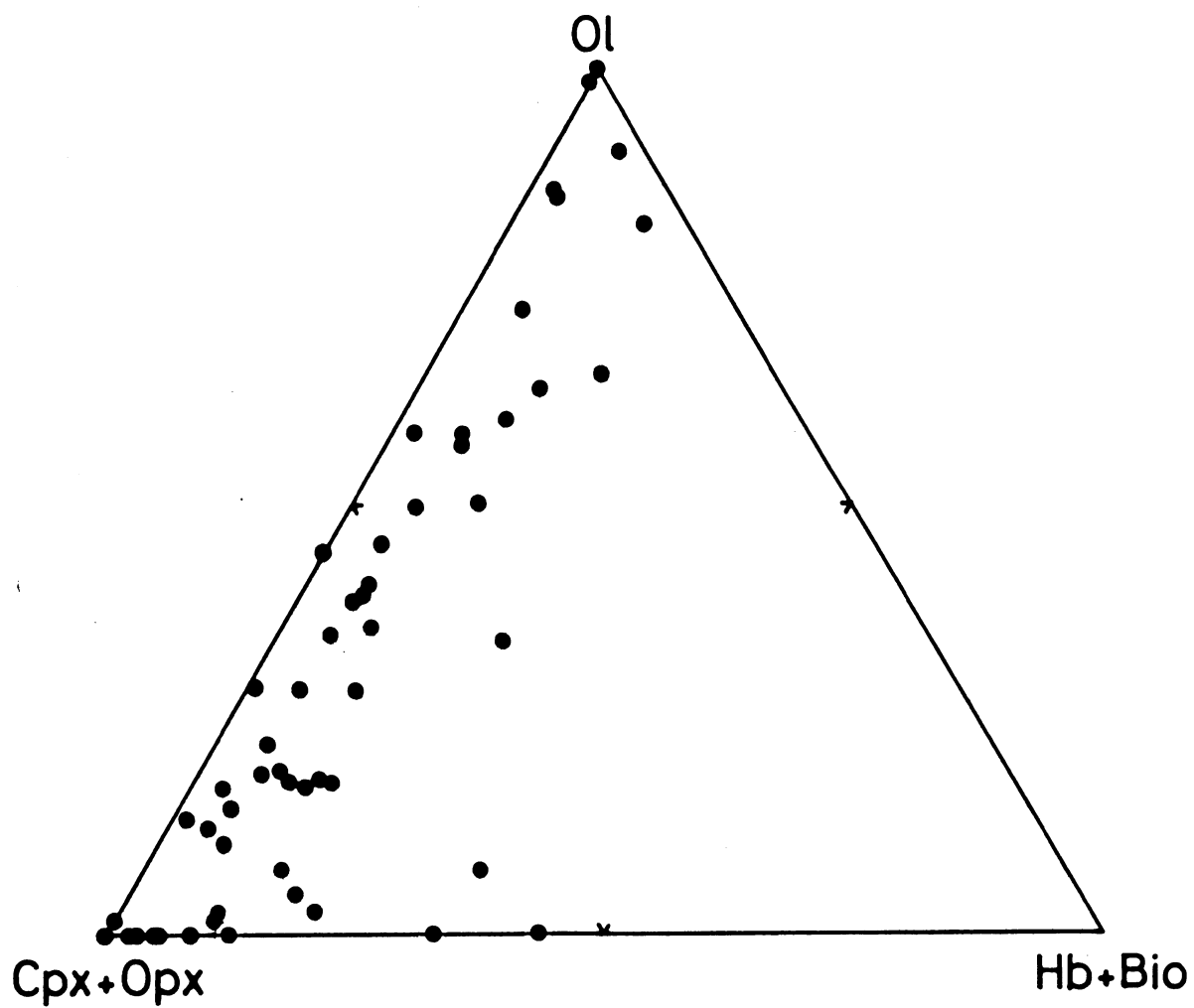


Fig. 4-15

Modal proportion among olivine, clinopyroxene+orthopyroxene,
and amphibole+biotite.

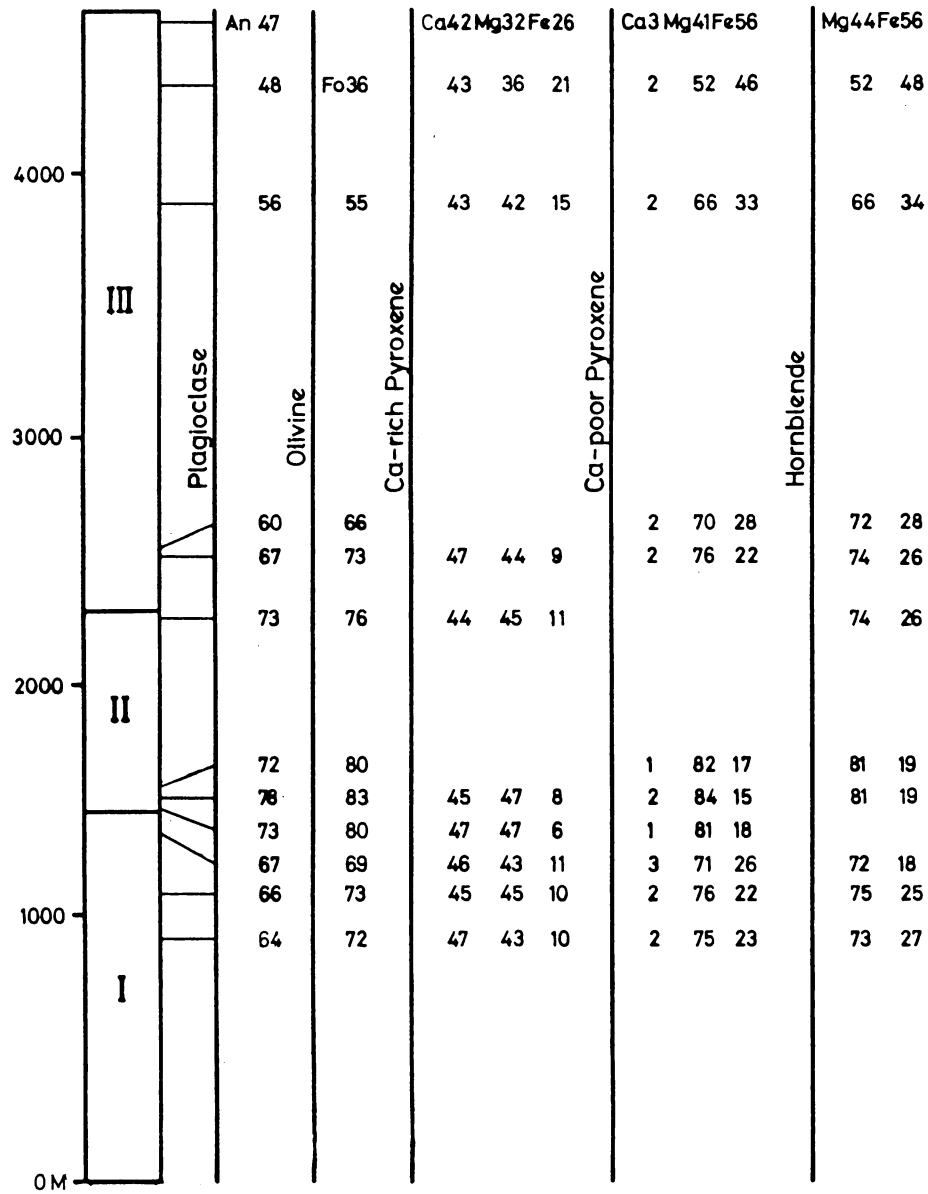


Fig. 4-16
Compositional change of the main constituent minerals
from Zone I to III along the Pankenushi river.

Chapter 5

CRYSTALLIZATION OF OLIVINE

In calc-alkalic rock series, compositional range of olivine is rather narrow and only magnesian olivine appears. In tholeiitic and alkalic rock series, on the other hand, extreme differentiation results in strong iron enrichment that iron rich olivines crystallize from the residual magma. However, in differentiates of tholeiitic suite a distinct gap in the compositional range is always found (Fig. 5-1). Compositional gap in the Skaergaard olivine ranges from about Fo₅₂ to Fo₃₆. Though the Pankenushi gabbroic intrusion belongs to tholeiitic series as discussed later (in Chapter 7), no break of olivine composition is found. That is a very unique fact because such a behavior of the olivine composition has not been reported yet in the tholeiitic suite. All of the olivine in the Pankenushi intrusion do show neither the reaction rim between iron ore and pyroxene nor the mantle to the ore where against plagioclase such as reported in the Skaergaard intrusion (Wager and Brown, 1967).

The presence of the compositional break is explained by the elegant discussion of Bowen and Schairer (1935). They also showed that the absence of the break was explained by the difference in initial magma composition using equilibrium crystallization theory (Fig. 5-2). But in the case of the Pankenushi intrusion, the application of the equilibrium crystallization theory is unsuitable because that is an accumulative body.

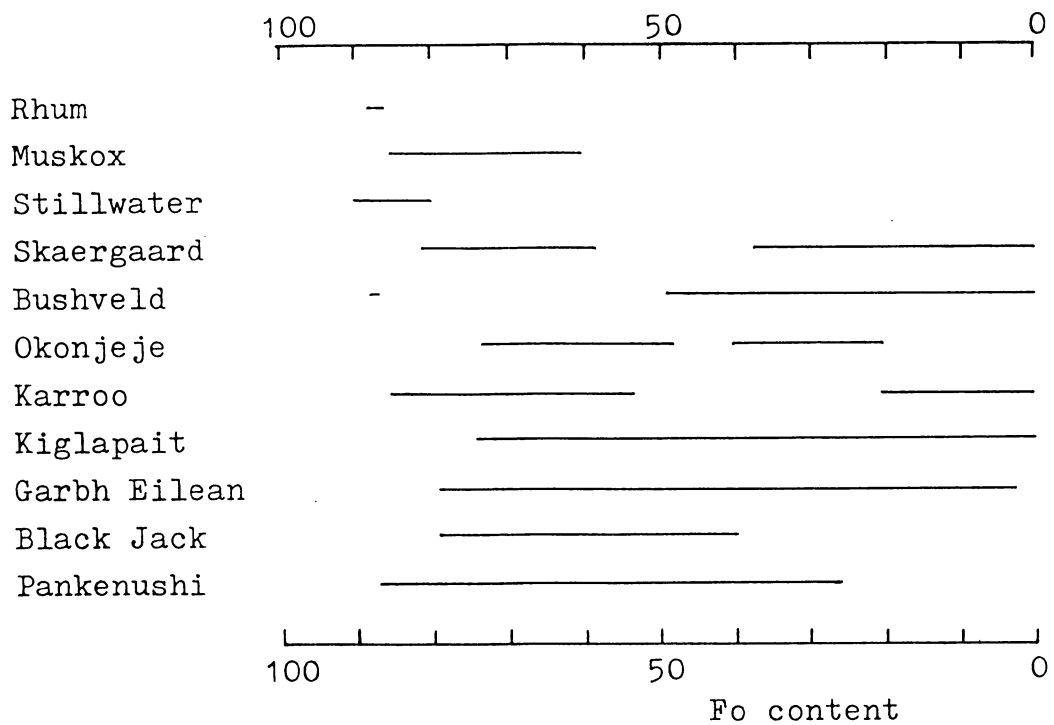


Fig. 5-1

Compositions of olivines from various differentiated intrusions.

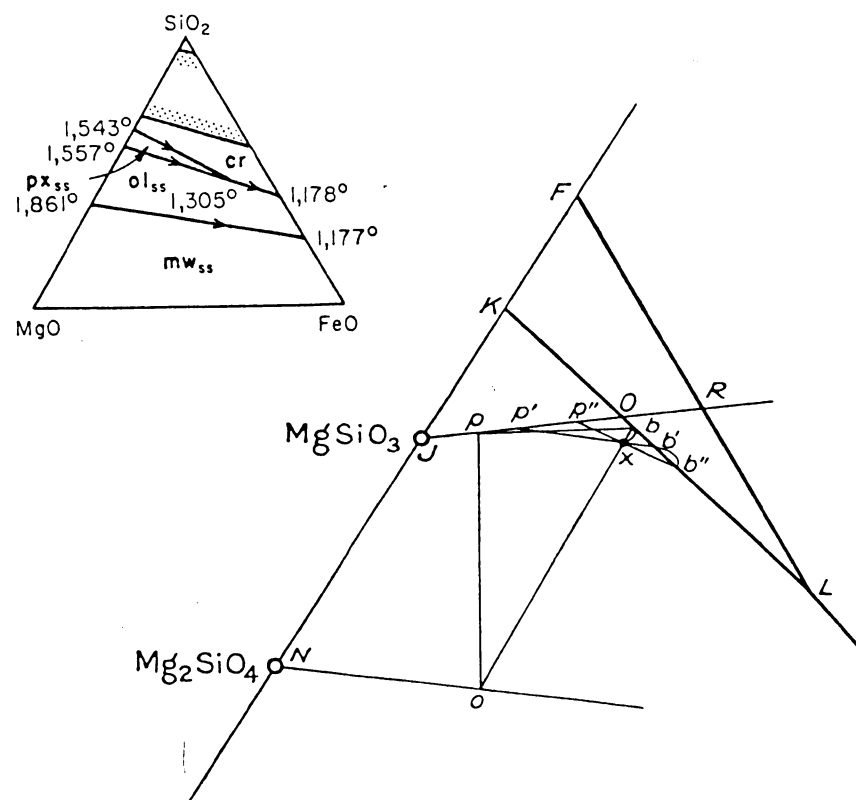


Fig. 5-2

Distorted diagram for the part of the system
 MgO-FeO-SiO_2 (given by Bowen and Schairer, 1935).

Fig. 5-3 shows the $\text{SiO}_2\text{-Mg}_2\text{SiO}_4\text{-Fe}_2\text{SiO}_4$ system (shown in terms of mole percent) at 1atm dry. The composition of most magnesian olivine found in the Pankenushi intrusion is $\text{Fo}_{86.6}$ (0). The olivine coexisting with the first cumulus orthopyroxene (P1, En_{77}) is $\text{Fo}_{73.4}$ (01) and most iron rich olivine coexisting orthopyroxene (P3, En_{42}) is $\text{Fo}_{25.6}$ (03). Liquid compositions are estimated by using the distribution coefficient of Fe-Mg between olivine and liquid (Roeder and Emslie, 1970). The liquid of the most iron rich three phase triangle is on the boundary curve between olivine and silica mineral at 1atm. If the boundary curve is adequate to the Pankenushi intrusion, such liquid (3) can not coexist with orthopyroxene. Because the pressure during the crystallization of the Pankenushi gabbro is estimated to be rather high, it is easily considered that the boundary curve at 1atm (a-a') is not adequate. It is elucidated from the experimental results that the olivine field is reduced with increasing pressure. So hypothetical boundary curve (b-b') is drawn as the first cumulus orthopyroxene has a reaction relation with olivine. Olivine crystallization of the Pankenushi intrusion is explained on the basis of the hypothetical boundary curve at comparatively higher pressure and the assumption of slightly imperfect fractional crystallization. When the fractional crystallization is not perfect, i.e. olivine is not perfectly separated, the liquid does not immediately cross the orthopyroxene field after the arrival at the boundary curve. With further cooling the liquid changes along the boundary curve, orthopyroxene precipitating and olivine being resorbed and both being changed continuously in iron rich composition. After the composition of orthopyroxene

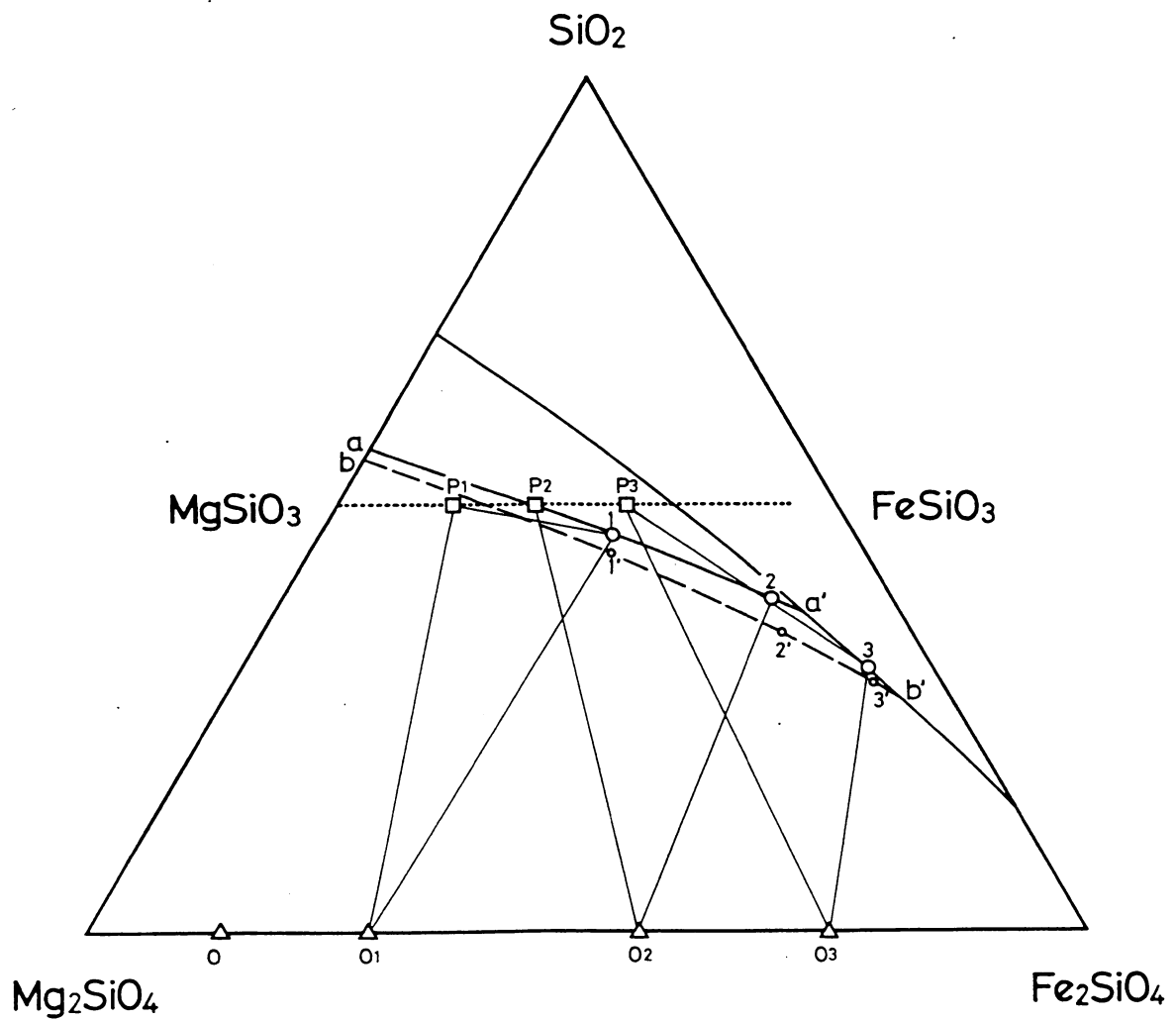


Fig. 5-3

One atmosphere isobaric phase diagram for the system $\text{Mg}_2\text{SiO}_4\text{-Fe}_2\text{SiO}_4\text{-SiO}_2$ in terms of mole per cent.

becomes P2, the reaction relation between olivine and orthopyroxene disappears, so olivine and orthopyroxene can crystallize cotectically. After the cotectic crystallization becomes a reality, the liquid follows the cotectic boundary curve independent of whether equilibrium crystallization proceeds or fractional crystallization proceeds. As a result, no break of olivine crystallization occurs. It is also suggested that the presence of the compositional break observed in many tholeiitic intrusion implies the crystallization under the comparatively low pressure unless the water content is high, because higher pressure removes the reaction relation between olivine and orthopyroxene.

Chapter 6

PETROCHEMISTRY

OF

THE PANKENUSHI INTRUSION AND THE MEMURODAKE COMPLEX

Twenty six samples from the Pankenushi gabbroic intrusion, one sample of the pegmatite intruded into the Pankenushi intrusion and fourteen samples from the Memurodake plutonic complex were analyzed. SiO_2 , TiO_2 , Al_2O_3 , Fe_2O_3 (total Fe as Fe_2O_3), CaO , K_2O and P_2O_5 were analyzed by X-ray emission spectrometer (AFV-777, Toshiba), MnO , Na_2O and MgO by atomic absorption spectrophotometer (AA-457, Varian Techtron). FeO was determined by titration using potassium permanganate. The analytical procedures and conditions using the X-ray emission spectrometer followed those of Yamasaki (1979) and Yamasaki et al. (1980). The chemical compositions and C.I.P.W. norms are given in Tables 6-1 and 6-2. Localities of the analyzed samples are shown in Fig. 6-1. In following discussion, previously published data by Nochi and Komatsu (1967), Hashimoto (1975) and Miyashita and Maeda (1978) are also included.

All of the compositions are plotted on the AFM diagram ($\text{Na}_2\text{O} + \text{K}_2\text{O}-\text{FeO} + 0.9\text{Fe}_2\text{O}_3-\text{MgO}$ diagram in weight percent, Fig. 6-2). The distribution of the Pankenushi gabbros is nearly parallel to the Skaergaard liquid trend, while that of the Memurodake rocks is similar to the calc-alkalic trend. The composition of the pegmatite is plotted near A corner and is calc-alkaline granitic in composition. The same kind of

	1	2	3	4	5	6	7
SiO ₂	40.77	39.92	44.39	48.01	48.87	50.67	50.78
TiO ₂	.10	.10	.10	.19	.21	.55	.33
Al ₂ O ₃	9.23	10.42	18.52	20.83	18.95	17.34	17.86
Fe ₂ O ₃	3.27	2.98	.58	.83	.42	1.10	.97
FeO	5.10	5.14	6.02	4.72	5.90	5.77	5.74
MnO	.14	.14	.11	.10	.12	.15	.16
MgO	29.31	27.91	17.22	10.56	10.15	9.79	8.57
CaO	5.67	5.84	8.97	10.97	11.60	11.68	12.49
Na ₂ O	.06	.06	1.61	2.24	2.24	2.38	2.35
K ₂ O	.04	.02	.05	.08	.12	.21	.15
P ₂ O ₅	.02	.02	.03	.03	.03	.08	.03
H ₂ O(+)	6.32	7.09	1.97	1.47	1.28	1.31	.88
Total	100.02	99.64	99.57	100.03	99.89	101.03	100.32

	8	9	10	11	12	13	14
SiO ₂	52.80	46.35	47.91	50.24	53.65	49.99	45.20
TiO ₂	.49	5.10	4.70	1.27	.50	.66	5.96
Al ₂ O ₃	17.53	17.64	16.87	14.87	19.05	16.59	12.04
Fe ₂ O ₃	1.10	.75	1.44	.89	.88	1.44	1.90
FeO	4.60	9.41	8.95	7.92	5.48	8.42	15.16
MnO	.15	.17	.19	.19	.17	.20	.28
MgO	7.64	6.15	6.46	7.31	6.08	7.87	9.31
CaO	12.77	9.54	10.24	12.43	10.66	11.75	7.59
Na ₂ O	2.70	3.12	3.05	2.61	3.15	2.35	2.17
K ₂ O	.19	.19	.22	.11	.20	.13	.20
P ₂ O ₅	.05	.05	.06	.05	.04	.03	.11
H ₂ O(+)	.80	.93	.81	1.21	.75	.94	1.22
Total	100.80	99.40	100.93	99.10	100.60	100.38	101.14

Table 6-1 Bulk chemical composition.

Pankenushi gabbroic intrusion (1-27)

1-4: troctolite

5-8: olivine gabbro

9-24: ferrogabbro

25, 26: fine-grained olivine gabbro dike

27: pegmatite dike

Memurodake plutonic complex (28-41)

	15	16	17	18	19	20	21
SiO ₂	48.85	46.91	46.00	46.56	50.04	51.63	48.91
TiO ₂	3.19	3.83	3.18	4.85	3.37	3.48	3.38
Al ₂ O ₃	16.81	10.99	16.71	12.32	16.01	14.99	17.14
Fe ₂ O ₃	1.42	.98	1.53	1.65	.39	1.11	.62
FeO	9.85	16.59	14.69	15.53	11.94	11.85	12.30
MnO	.24	.32	.24	.29	.25	.25	.25
MgO	4.93	8.63	4.73	6.10	4.42	4.45	3.95
CaO	9.06	7.74	8.40	8.00	8.36	7.33	8.23
Na ₂ O	3.34	2.20	3.23	2.75	3.64	3.46	3.70
K ₂ O	.23	.33	.24	.54	.32	.74	.25
P ₂ O ₅	1.26	.09	.95	.58	.37	.39	.54
H ₂ O(±)	.58	1.37	.47	1.27	.92	.63	.90
Total	99.76	99.98	100.37	100.44	100.03	100.31	100.17

	22	23	24	25	26	27
SiO ₂	47.95	50.23	46.59	47.23	47.82	77.10
TiO ₂	3.59	2.51	4.67	1.16	1.11	.10
Al ₂ O ₃	16.19	18.38	12.98	15.86	15.37	13.05
Fe ₂ O ₃	.86	1.10	1.29	1.74	1.57	.26
FeO	12.34	9.59	15.71	7.77	7.18	.16
MnO	.24	.19	.30	.19	.16	.01
MgO	3.68	3.63	4.51	14.47	14.77	.14
CaO	9.52	8.90	8.34	9.77	9.59	2.23
Na ₂ O	3.61	3.95	2.93	1.44	2.00	4.23
K ₂ O	.38	.32	.46	.06	.12	2.42
P ₂ O ₅	1.32	.51	.77	.09	.09	.03
H ₂ O(±)	.96	1.00	1.33	.91	.95	.92
Total	100.64	100.31	99.88	100.69	100.72	100.65

Table 6-1 (continued)

	28	29	30	31	32	33	34
SiO ₂	52.55	52.97	51.54	49.33	50.91	52.57	54.15
TiO ₂	.89	.90	.96	1.51	1.15	1.10	1.17
Al ₂ O ₃	17.88	16.45	17.65	16.25	17.22	16.86	16.15
Fe ₂ O ₃	.88	.91	1.07	1.46	1.30	1.11	1.14
FeO	5.47	6.57	5.75	7.32	6.16	5.94	6.15
MnO	.14	.15	.15	.17	.14	.14	.15
MgO	6.78	7.71	6.70	7.45	6.57	6.75	6.21
CaO	10.33	10.14	10.38	10.76	10.32	8.60	8.97
Na ₂ O	3.09	2.91	3.13	2.79	2.58	3.39	3.06
K ₂ O	.63	1.28	.57	.49	1.10	1.40	1.01
P ₂ O ₅	.12	.09	.16	.18	.13	.17	.16
H ₂ O(+)	1.06	1.44	1.70	1.70	1.86	1.60	1.49
Total	99.82	101.52	99.77	99.42	99.44	99.63	99.81

	35	36	37	38	39	40	41
SiO ₂	51.75	53.77	52.70	58.16	56.91	61.92	71.55
TiO ₂	1.17	1.26	1.41	1.31	1.26	1.14	.53
Al ₂ O ₃	17.20	15.81	16.68	15.52	15.59	15.85	14.01
Fe ₂ O ₃	1.49	1.43	1.33	.64	.95	1.17	.65
FeO	6.63	6.83	6.72	6.37	6.43	5.05	1.81
MnO	.14	.16	.15	.16	.14	.12	.03
MgO	6.02	5.82	5.75	4.00	3.93	3.44	1.24
CaO	10.02	8.52	9.19	6.85	7.39	4.47	2.37
Na ₂ O	3.36	3.36	3.59	3.93	3.85	3.61	3.83
K ₂ O	.62	.77	.93	1.14	1.29	1.74	2.20
P ₂ O ₅	.10	.15	.20	.20	.18	.22	.04
H ₂ O(+)	1.18	1.15	1.59	1.56	1.31	1.35	.75
Total	99.68	99.02	100.24	99.84	99.23	100.07	99.02

Table 6-1 (continued)

	1	2	3	4	5	6	7
SiO ₂	43.51	43.13	45.48	48.71	49.56	50.81	51.07
TiO ₂	.11	.11	.10	.19	.21	.55	.33
Al ₂ O ₃	9.85	11.26	18.98	21.13	19.22	17.39	17.96
Fe ₂ O ₃	3.49	3.22	.59	.84	.43	1.10	.98
FeO	5.44	5.55	6.17	4.79	5.98	5.79	5.77
MnO	.15	.15	.11	.10	.12	.15	.16
MgO	31.28	30.16	17.64	10.71	10.29	9.82	8.62
CaO	6.05	6.31	9.19	11.13	11.76	11.71	12.56
Na ₂ O	.06	.06	1.65	2.27	2.27	2.39	2.36
K ₂ O	.04	.02	.05	.08	.12	.21	.15
P ₂ O ₅	.02	.02	.03	.03	.03	.08	.03
Q	—	—	—	—	—	—	—
C	—	—	—	—	—	—	—
or	.24	.12	.30	.47	.71	1.24	.89
ab	.51	.51	13.96	19.21	19.21	20.22	19.97
an	26.49	30.40	44.23	47.23	41.90	36.10	37.97
wo	—	—	—	—	—	—	—
di	2.67	.61	.92	6.23	13.08	17.25	19.49
hy	18.79	17.44	2.03	8.76	8.88	14.88	14.24
ol	45.99	45.99	37.42	16.44	15.11	7.48	5.32
mt	5.06	4.67	.86	1.22	.62	1.59	1.42
hm	—	—	—	—	—	—	—
il	.21	.21	.19	.36	.40	1.04	.63
ap	.05	.05	.07	.07	.07	.19	.07

Table 6-2 Chemical analyses and C.I.P.W. norm values on anhydrous basis. Numbers are the same as those in Table 6-1.

	8	9	10	11	12	13	14
SiO ₂	52.79	47.07	47.85	51.32	53.73	50.28	45.24
TiO ₂	.49	5.18	4.69	1.30	.50	.66	5.96
Al ₂ O ₃	17.53	17.91	16.85	15.19	19.08	16.69	12.05
Fe ₂ O ₃	1.10	.76	1.44	.91	.88	1.45	1.90
FeO	4.60	9.56	8.94	8.09	5.49	8.47	15.17
MnO	.15	.17	.19	.19	.17	.20	.28
MgO	7.64	6.25	6.45	7.47	6.09	7.92	9.32
CaO	12.77	9.69	10.26	12.70	10.67	11.82	7.60
Na ₂ O	2.70	3.17	3.05	2.67	3.15	2.36	2.17
K ₂ O	.19	.19	.22	.11	.20	.13	.20
P ₂ O ₅	.05	.05	.06	.05	.04	.03	.11
Q	.57	—	—	—	2.10	—	—
C	—	—	—	—	—	—	—
or	1.12	1.12	1.30	.65	1.18	.77	1.18
ab	22.85	26.82	25.81	22.59	26.65	19.97	18.36
an	35.15	34.08	31.64	29.14	37.33	34.56	22.55
wo	—	—	—	—	—	— ⁿ	—
di	22.39	11.10	15.27	27.38	12.48	19.52	11.82
hy	15.29	7.74	10.50	13.09	17.94	16.22	24.62
ol	—	8.08	4.35	33.24	—	5.54	7.13
mt	1.59	1.10	2.09	1.32	1.28	2.10	2.75
hm	—	—	—	—	—	—	—
il	.93	9.84	8.91	2.47	.95	1.25	11.32
ap	.12	.12	.14	.12	.09	.07	.25

Table 6-2 (continued)

	15	16	17	18	19	20	21
SiO ₂	49.25	47.57	46.05	46.95	50.49	51.80	49.27
TiO ₂	3.22	3.88	3.18	4.89	3.40	3.49	3.40
Al ₂ O ₃	16.95	11.14	16.73	12.42	16.15	15.04	17.27
Fe ₂ O ₃	1.43	.99	1.53	1.66	.39	1.11	.62
FeO	9.93	16.82	14.70	15.66	12.05	11.89	12.39
MnO	.24	.32	.24	.29	.25	.25	.25
MgO	4.97	8.75	4.73	6.15	4.46	4.46	3.98
CaO	9.13	7.85	8.41	8.07	8.44	7.35	8.29
Na ₂ O	3.37	2.23	3.23	2.77	3.67	3.47	3.73
K ₂ O	.23	.33	.23	.54	.32	.74	.25
P ₂ O ₅	1.27	.09	.95	.58	.37	.39	.54
Q	1.25	—	—	—	—	2.67	—
C	—	—	—	—	—	—	—
or	1.36	1.95	1.42	3.19	1.89	4.37	1.48
ab	28.52	18.87	27.33	23.44	31.05	29.36	31.56
an	30.44	19.41	30.44	19.86	26.65	23.38	29.64
wo	—	—	—	—	—	—	—
di	5.42	15.73	4.28	13.68	10.74	8.90	6.71
hy	21.88	25.87	12.86	22.33	20.06	22.26	17.23
ol	—	9.12	13.20	4.45	1.72	—	4.76
mt	2.07	1.44	2.20	2.41	.57	1.61	.90
hm	—	—	—	—	—	—	—
il	6.11	7.37	6.04	9.29	6.46	6.63	6.46
ap	2.94	.21	2.20	1.34	.86	.90	1.25

Table 6-2 (continued)

	22	23	24	25	26	27
SiO ₂	48.10	50.58	47.28	47.33	47.93	77.31
TiO ₂	3.60	2.53	4.74	1.16	1.11	.10
Al ₂ O ₃	16.24	18.51	13.17	15.89	15.40	13.09
Fe ₂ O ₃	.86	1.11	1.31	1.74	1.57	.26
FeO	12.38	9.66	15.94	7.79	7.20	.16
MnO	.24	.19	.30	.19	.16	.01
MgO	3.69	3.66	4.58	14.50	14.80	.14
CaO	9.55	8.96	8.46	9.79	9.61	2.24
Na ₂ O	3.62	3.98	2.97	1.44	2.00	4.24
K ₂ O	.38	.32	.47	.06	.12	2.43
P ₂ O ₅	1.32	.51	.78	.09	.09	.03
Q	—	—	—	—	—	38.73
C	—	—	—	—	—	—
or	2.25	1.89	2.78	.35	.71	14.36
ab	30.63	33.68	25.13	12.18	16.92	35.88
an	26.94	31.70	21.22	36.72	32.69	9.51
wo	—	—	—	—	—	.18
di	9.97	7.89	13.22	9.01	11.50	.75
hy	14.26	14.67	22.89	20.67	12.89	—
ol	4.79	2.59	2.05	16.11	20.69	—
mt	1.25	1.61	1.90	2.52	2.28	.26
hm	—	—	—	—	—	.08
il	6.84	4.80	9.00	2.20	2.11	.19
ap	3.06	1.18	1.81	.21	.21	.07

Table 6-2 (continued)

	28	29	30	31	32	33	34
SiO ₂	53.21	52.93	52.56	50.49	52.17	53.63	55.08
TiO ₂	.90	.90	.98	1.55	1.18	1.12	1.19
Al ₂ O ₃	18.10	16.44	18.00	16.63	17.65	17.20	16.43
Fe ₂ O ₃	.89	.91	1.09	1.49	1.33	1.13	1.16
FeO	5.54	6.56	5.86	7.49	6.31	6.06	6.26
MnO	.14	.15	.15	.17	.14	.14	.15
MgO	6.87	7.70	6.83	7.62	6.73	6.89	6.32
CaO	10.46	10.13	10.59	11.01	10.58	8.77	9.12
Na ₂ O	3.13	2.91	3.19	2.86	2.64	3.46	3.11
K ₂ O	.64	1.28	.58	.50	1.13	1.43	1.03
P ₂ O ₅	.12	.09	.16	.18	.13	.17	.16
Q	.31	—	—	—	.18	—	4.04
C	—	—	—	—	—	—	—
or	3.78	7.56	3.43	2.95	6.68	8.45	6.09
ab	26.49	24.62	26.99	24.20	22.34	29.28	26.32
an	33.45	28.02	33.08	31.06	32.97	27.18	27.83
wo	—	—	—	—	—	—	—
di	14.28	17.54	14.91	18.16	15.13	12.32	13.30
hy	18.41	14.39	16.34	11.86	18.22	15.49	18.13
ol	—	4.61	1.43	6.23	—	3.12	—
mt	1.29	1.32	1.58	2.16	1.93	1.64	1.68
il	1.71	1.71	1.86	2.94	2.24	2.13	2.26
ap	.28	.21	.37	.42	.30	.39	.37

Table 6-2 (continued)

	35	36	37	38	39	40	41
SiO ₂	52.54	54.93	53.42	59.18	58.12	62.72	72.82
TiO ₂	1.19	1.29	1.43	1.33	1.29	1.15	.54
Al ₂ O ₃	17.46	16.15	16.91	15.79	15.92	16.05	14.26
Fe ₂ O ₃	1.51	1.46	1.35	.65	.97	1.19	.66
FeO	6.73	6.98	6.81	6.48	6.57	5.11	1.84
MnO	.14	.16	.15	.16	.14	.12	.03
MgO	6.11	5.95	5.83	4.07	4.01	3.48	1.26
CaO	10.17	8.70	9.32	6.97	7.55	4.53	2.41
Na ₂ O	3.41	3.43	3.64	4.00	3.93	3.66	3.90
K ₂ O	.63	.79	.94	1.16	1.32	1.76	2.24
P ₂ O ₅	.10	.15	.20	.20	.18	.22	.04
Q	—	3.83	.18	9.22	7.39	17.36	33.72
C	—	—	—	—	—	.41	1.13
or	3.72	4.67	5.56	6.86	7.80	10.40	13.24
ab	28.85	29.04	30.80	33.85	33.25	30.97	33.00
an	30.47	26.34	27.03	21.70	21.90	21.04	11.69
wo	—	—	—	—	—	—	—
di	15.74	12.93	14.60	9.55	11.87	—	—
hy	15.35	18.28	16.70	14.88	13.51	15.39	5.14
ol	1.17	—	—	—	—	—	—
mt	2.19	2.12	1.96	.94	1.41	1.73	.96
il	2.26	2.45	2.72	2.53	2.45	2.18	1.03
ap	.23	.35	.46	.46	.42	.51	.09

Table 6-2 (continued)

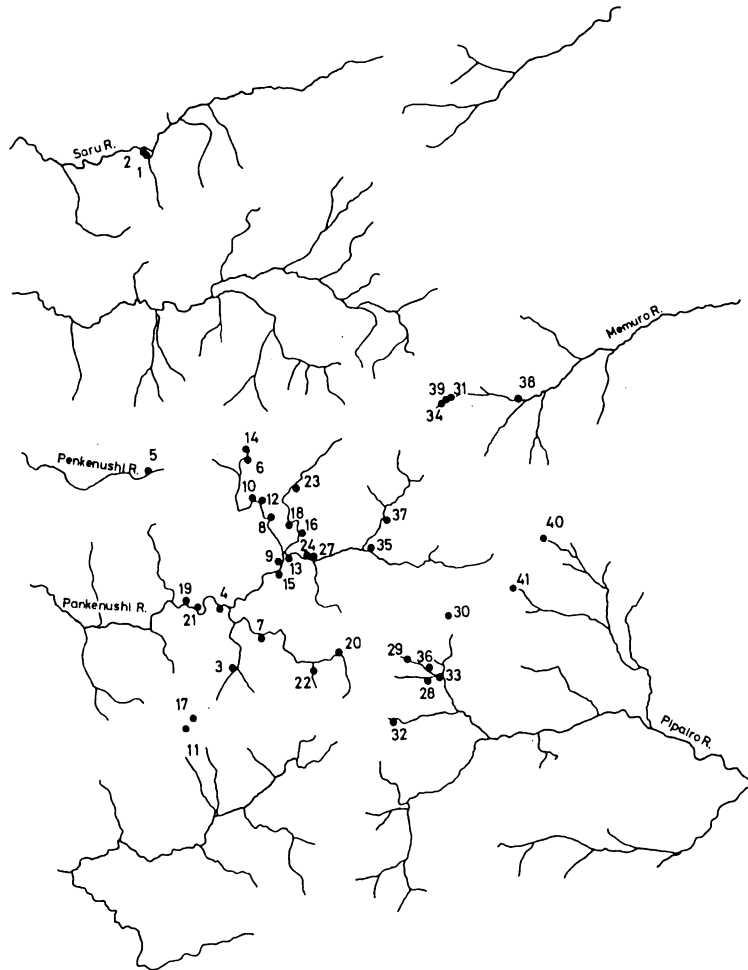


Fig. 6-1

Map showing localities of the examined specimens.

Numbers are corresponding to those in Table 6-1.

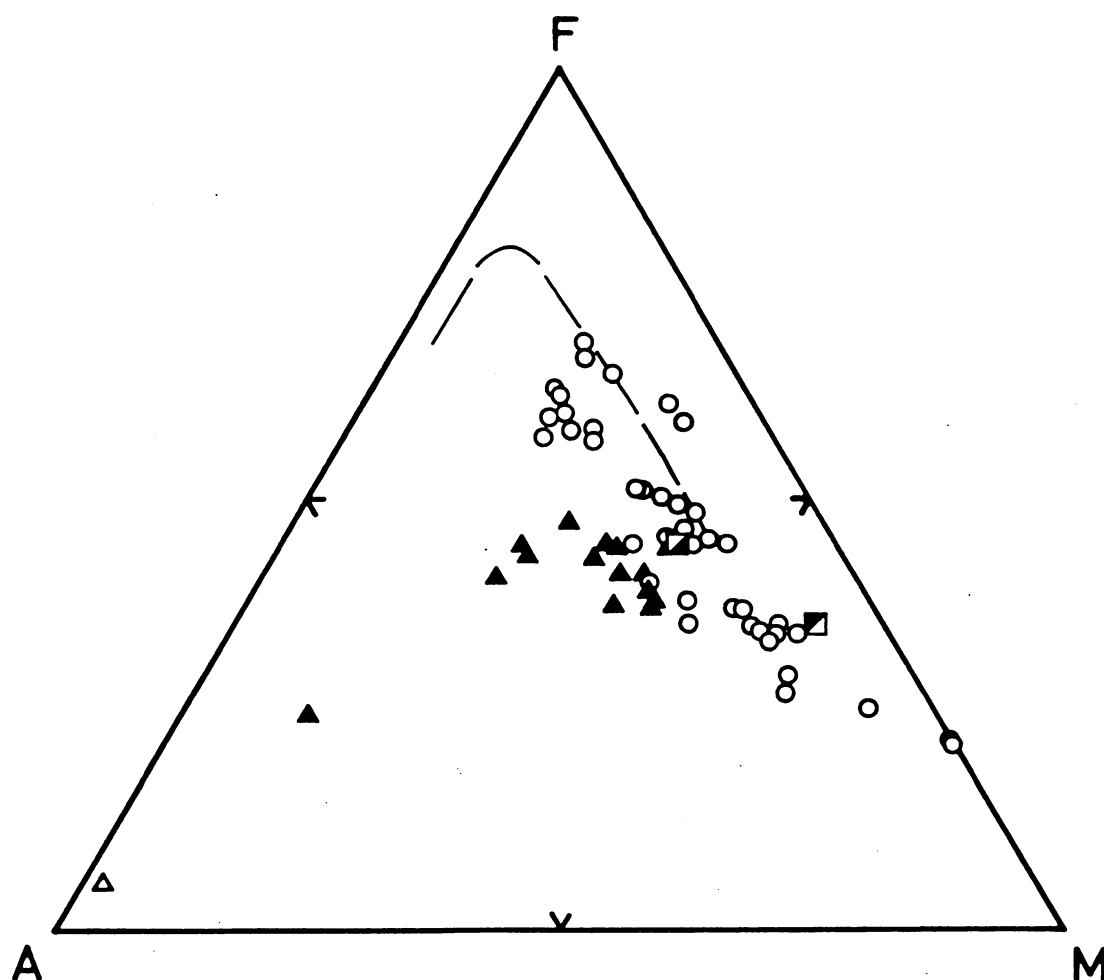


Fig. 6-2

AFM ($\text{Na}_2\text{O}+\text{K}_2\text{O}-\text{FeO}+0.9\text{Fe}_2\text{O}_3-\text{MgO}$) diagram. Open triangle, pegmatite intruding into the Pankenushi intrusion. Square, the magma composition used in Chapter 7. Open circle, Pankenushi gabbro. Solid triangle, Memurodake rock. Broken line indicates the trend of the Skaergaard liquid (Wager and Brown, 1967). Analyses reported by Nochi and Komatsu (1967), Hashimoto (1975) and Miyashita and Maeda (1978) are also plotted.

pegmatite dikes is oftenly observed in the Memurodake complex, it is not necessarily therefore, that the pegmatite is a residual liquid of the Pankenushi gabbro.

Before the petrochemical treatment, the meaning of the bulk composition of the Pankenushi gabbro is discussed. If the composition of the bulk rock shows that of magma, included olivine (at least, the composition of the core) and the bulk rock (i.e. magma) must be coexisting in equilibrium and the $K_D = (\text{Mg/Fe})_{\text{bulk rock}} / (\text{Mg/Fe})_{\text{olivine}}$ must be about 0.3 (Roeder and Emslie, 1970). Distributional relation of Mg-Fe between olivine and liquid is not seriously affected by pressure, temperature and the liquid composition (Roeder and Emslie, 1970; Longhi et al., 1978). In general, olivine is the first ferromagnesian minerals crystallized from basaltic liquid unless the pressure is very high. If spinel is the first phase such as in the Pankenushi intrusion, it is generally a very little, and its influence is maybe neglected. If plagioclase is the earlier phase than olivine, its separation does not change the Mg/Fe of liquid. By these reasons, the distribution of Mg-Fe between olivine and basaltic magma is very profitable for the elucidating whether the composition of rock shows that of liquid or not.

Fig. 6-3 shows the Mg/Fe of the Pankenushi gabbro against that of included olivine. Because K_D are not 0.3 but about 1.0 in all of the examined samples, it is shown that the Pankenushi gabbros do not show the liquid composition but the composition of accumulated minerals. Magma evolution of the Pankenushi intrusion is discussed in Chapter 7.

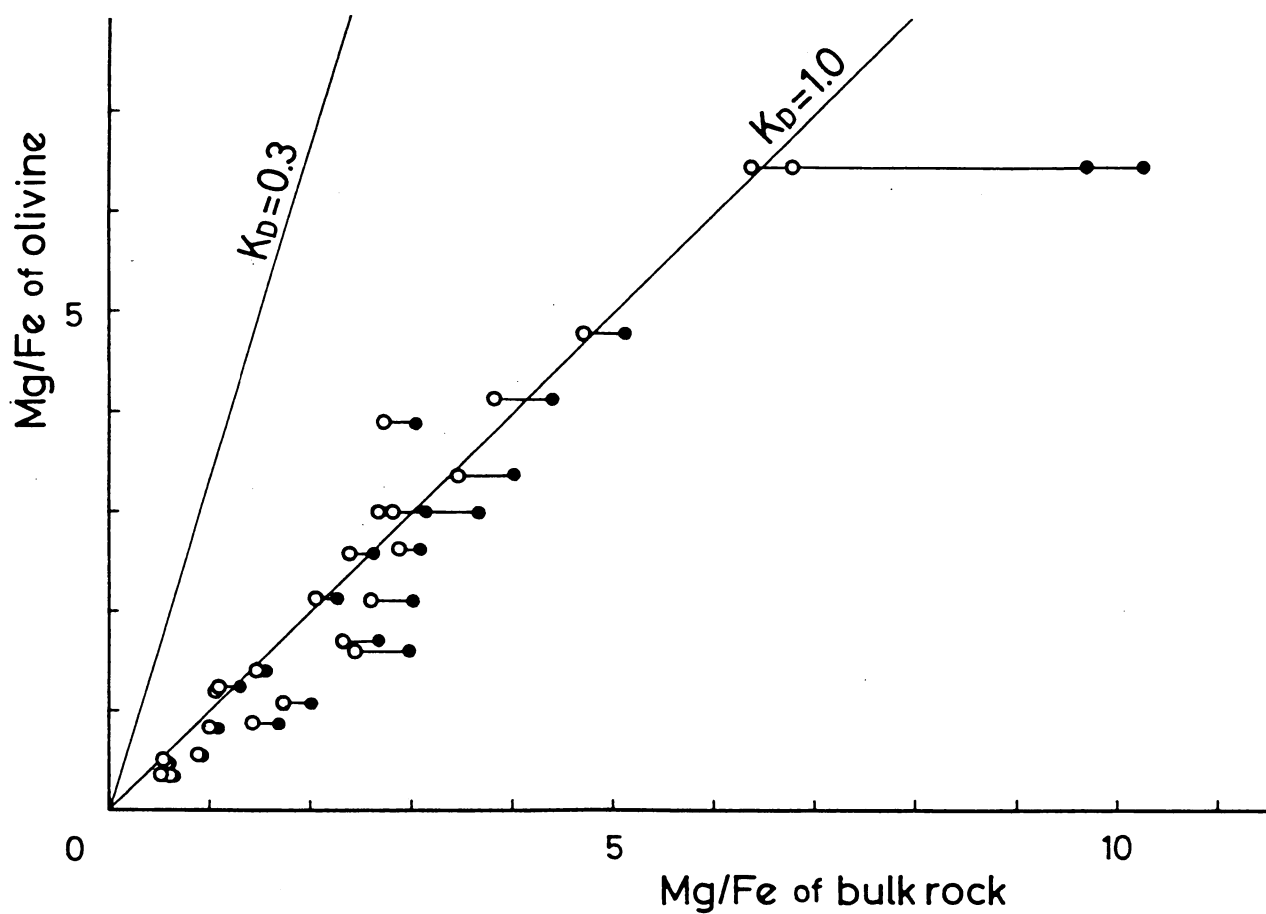


Fig. 6-3

Mg/Fe of olivine and that of bulk rock plotted against each other. K_D means $(\text{Mg/Fe})_{\text{bulk rock}} / (\text{Mg/Fe})_{\text{olivine}}$. Open circle indicates Mg/total Fe of bulk rock. Solid circle indicates Mg/Fe^{2+} of bulk rock.

It is thought that the analyses of the Memurodake rocks represent the composition of magma because of their fine-grained texture. The analyses of the Memurodake complex are plotted in the $\text{SiO}_2\text{-Na}_2\text{O} + \text{K}_2\text{O}$ diagram (Fig. 6-4). All of the Memurodake rocks belong to the non-alkaline suite. The amount of SiO_2 , total iron as FeO , and TiO_2 are shown against FeO/MgO (Fig. 6-5). Although the pattern of iron enrichment is observed, the analyses are plotted in the field of calc-alkalic suite defined by Miyashiro (1974). In the $\text{SiO}_2\text{-FeO}$ diagram, calc-alkalic character is clearly shown (Fig. 6-6).

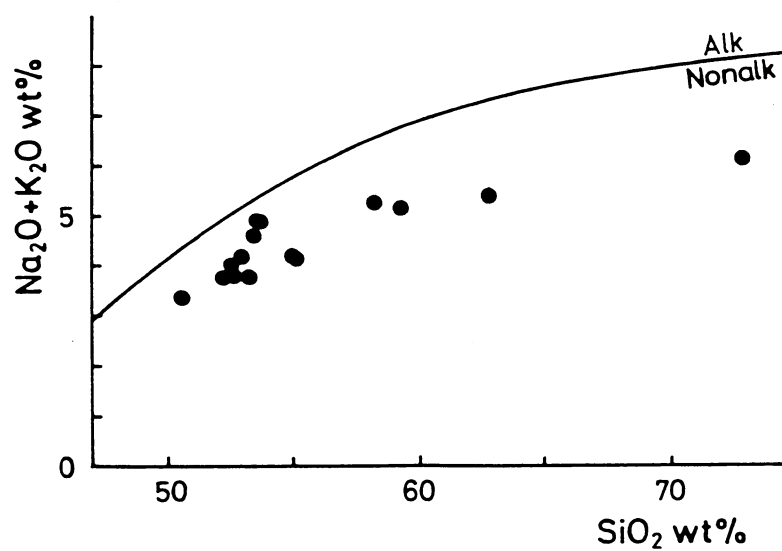


Fig. 6-4

SiO₂-Na₂O+K₂O diagram. Solid circle indicates the bulk composition of the Memurodake rock. Boundary curve between alkalic rock and non-alkalic rock is taken from Miyashiro (1978).

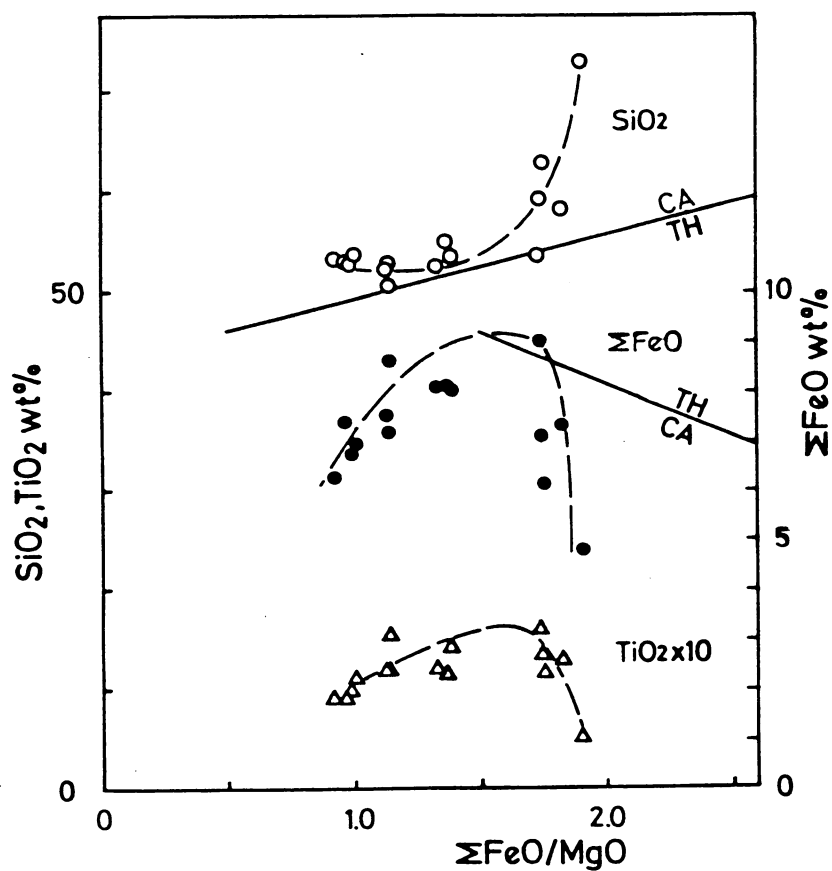


Fig. 6-5

Analyses of the Memurodake rocks (SiO_2 , total iron as FeO and TiO_2) are plotted against $\text{FeO}(\text{total iron})/\text{MgO}$. The boundary curves between calc-alkalic rock series and tholeiitic rock series are taken from Miyashiro (1974).

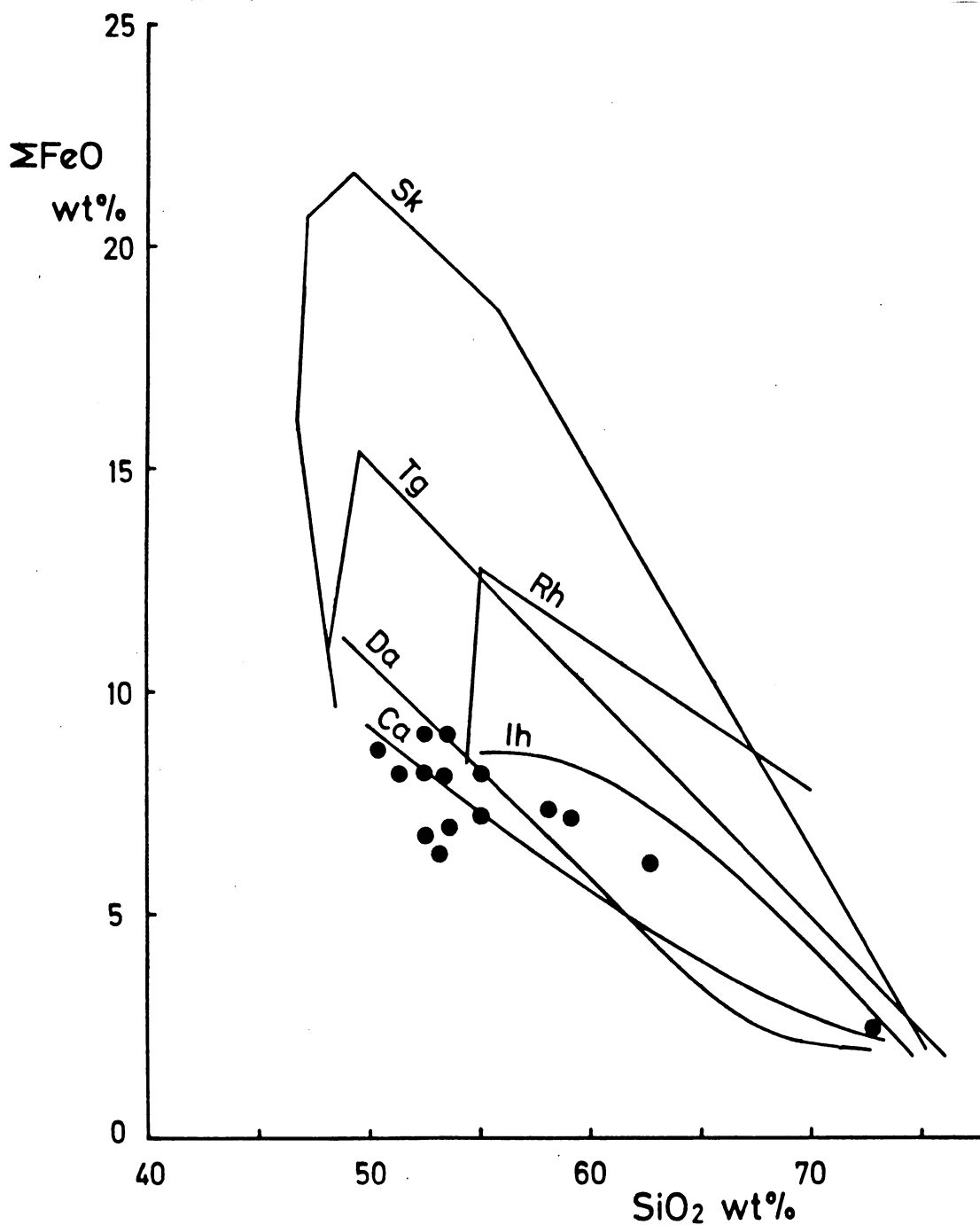


Fig. 6-6

Analyses of the Memurodake rocks plotted in SiO_2 -FeO (total iron) variation diagram. Some differentiation trends are also plotted. Sk, Skaergaard intrusion (Wager and Deer, 1939). Tg, Thingmuli volcano (Carmichael, 1964). Rh, Red Hill dolerite (McDougall, 1962). Da, average compositions of calc-alkalic rock series (Daly, 1914). Ih, average compositions of hypersthene rock series in Izu-Hakone (Kuno, 1954). Ca, average analyses of the Cascade lava (Carmichael, 1964).

Chapter 7

EVOLUTION OF THE PANKENUSHI MAGMA

A. Introduction

In the accumulative intrusion, it is generally difficult to estimate the composition of the successive magma, because the bulk chemical composition of a cumulate is, in contrast to the case of volcanic rock, unlikely to match that of successive liquid. But the cumulate gives the composition of solid material fractionated from magma. If the compositional change of magma is estimated by some method, the study of accumulative intrusion will make a large contribution to the elucidation of crystallization differentiation. The classic study at the Skaergaard intrusion by Wager and Deer (1939) is the typical case.

Magmatic differentiation is a process of elemental distribution between magma and minerals. When the phase relation of common rock-forming minerals in magmatic composition and elemental distribution between rock-forming minerals and liquid are analyzed perfectly, magmatic differentiation will be described by the initial composition of the magma, physical conditions at the time of crystallization and the degree of equilibrium in the crystallization process. But at the present, informations about them are not enough. Main theme in this study, therefore, is to estimate the compositional change of successive magma in the Pankenushi gabbroic intrusion.

B. The method of estimation of successive magma composition

Fig. 7-1 shows the variation of P_2O_5 , TiO_2 , FeO (total

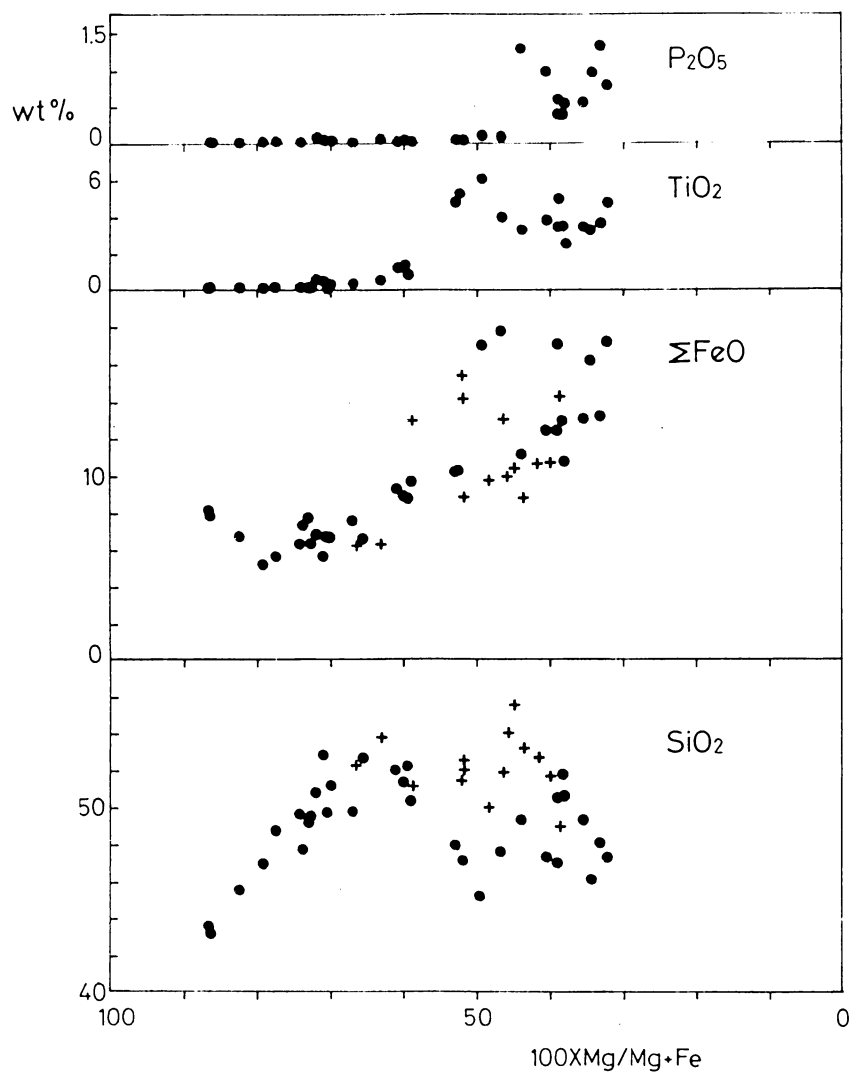


Fig. 7-1

Analyses of the Pankenushi gabbros (P_2O_5 , TiO_2 , total iron as FeO , and SiO_2) are plotted against Mg ratio.

Fe as FeO) and SiO_2 against Mg ratio of bulk rock composition. Mg ratio decreases regularly with proceeding of crystallization until some mineral rich in iron and poor in magnesium, such as magnetite, begins to precipitate. Because the amount of Fe oxide and/or Fe-Ti oxide is not so abundant, Mg ratio is useful for illustrating the degree of crystallization. P_2O_5 content increases abruptly at Mg ratio 40 and TiO_2 content increases abruptly at Mg ratio 60. They correspond with the accumulation of apatite and ilmenite, respectively. FeO and SiO_2 contents show the smooth increase until Mg ratio comes to 60, that is to say until the accumulation of ilmenite commences. After the commencing of ilmenite precipitation, FeO and SiO_2 contents do not follow the extension of the smooth trend. Discontinuously the amount of FeO increases and the amount of SiO_2 decreases. The slight break in Mg ratio around 60 is observed. Rock type of Mg ratio less than 60 is ferrogabbro, that has generally modal ilmenite content close to 10 % and has about 5 % TiO_2 content. Most of TiO_2 in bulk rock composition are included as ilmenite. By the deduction of TiO_2 and equivalent FeO as molecular value from bulk rock composition, the composition of the ferrogabbro without ilmenite is given. The hypothetical compositions follow the extension of the trends obtained from the rock compositions of Mg ratio more than 60 and fill the compositional break. Therefore it is possible to explain that both the abrupt change in TiO_2 , FeO, and SiO_2 and the compositional break are due to the accumulation of a large amount of ilmenite.

In general, the compositions of cumulates in the layered intrusions do not show the smooth variation against Mg ratio.

but show the wide dispersion, because the compositional difference in layer by layer are remarkable. The smooth trend with good correlation observed in the Pankenushi gabbro is very unique and it is shown that the smooth trend roughly match the compositional change of subtracted cumulate, i.e. that of average rock. Definition of the average rock was given by Wager and Brown (1967) as under. "A rock with cumulus crystals corresponding in proportions to those of the total primocryst assemblage precipitating from the liquid at the particular time is to be regarded as giving the average rock."

In the following discussion on magmatic differentiation, total Fe is assumed to be FeO, because the phase that has much Fe^{3+} such as magnetite is lacking in the Pankenushi intrusion. Normative compositions are also calculated under the same assumption.

The method for estimation of successive composition of magma is shown in Fig. 7-2. Dashed line indicates the composition of the solid material i.e. the average rock subtracted from magme. Composition P indicates the initial composition of the parental magma. Fe/Mg of the parental magma defines the Fo content of coexisting olivine*. Olivine which is able to coexist with liquid P is Fo_{90} . Liquid P coexists with the average rock which includes the olivine of Fo_{90} . By the subtraction of such average rock from the liquid P, the composition of the second liquid is estimated. Repeated subtractions give the successive magma compositions.

* A value of 0.3 was used as K_D (Roeder and Emslie, 1970).

K_D means $(\text{Mg/Fe})_{\text{liquid}}/(\text{Mg/Fe})_{\text{olivine}}$.

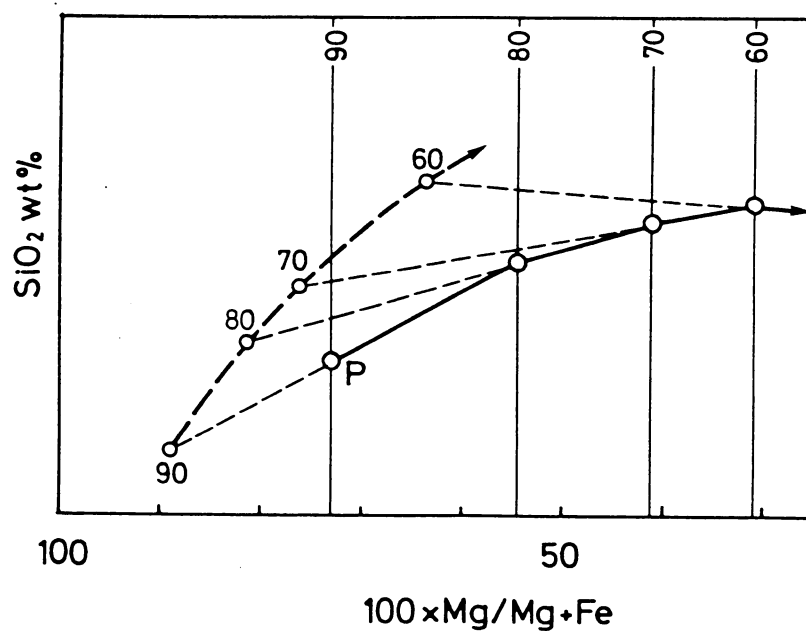


Fig. 7-2

Hypothetical SiO_2 variation diagram plotted against Mg ratio.

Cumulate rock generally consists of the primocryst directly crystallized from magma and intercumulus material crystallized from the trapped liquid. The composition of the trapped liquid is equal to that of the liquid coexisting with the primocryst. The composition of the primocryst only is, therefore, on the extension from the composition of the liquid to that of the average cumulate (Fig. 7-3). When the estimation is done using the subtraction diagram, the presence of pore liquid is not worth due consideration.

C. Rocks that may match the magma composition in the Pankenushi intrusion

Although the most of the Pankenushi gabbros do not show the composition of the liquid but that of accumulated materials as mentioned in Chapter 6, two kinds of rock samples that may match the composition of the magma are found.

Fine-grained olivine gabbro dike

Fine-grained olivine gabbro dikes which intrude into the troctolitic gabbro (Fig. 7-4) are found as boulders along the Chiroro river. The dikes, ranging in width from several centimeters to several ten centimeters, cuts the layered structure of troctolitic gabbro. Chilled margin against the troctolitic gabbro is absent. It suggests that at the time of intrusion the country rocks were still hot. Under the microscope, the dikes show fine-grained equigranular texture and consist of olivine, plagioclase, clinopyroxene, orthopyroxene, amphibole and opaque mineral (Fig. 7-5).

Average composition of two analyzed dike rocks together with the normative value are given in Table 7-1 on anhydrous basis. Original data are included in Table 6-1. The dikes

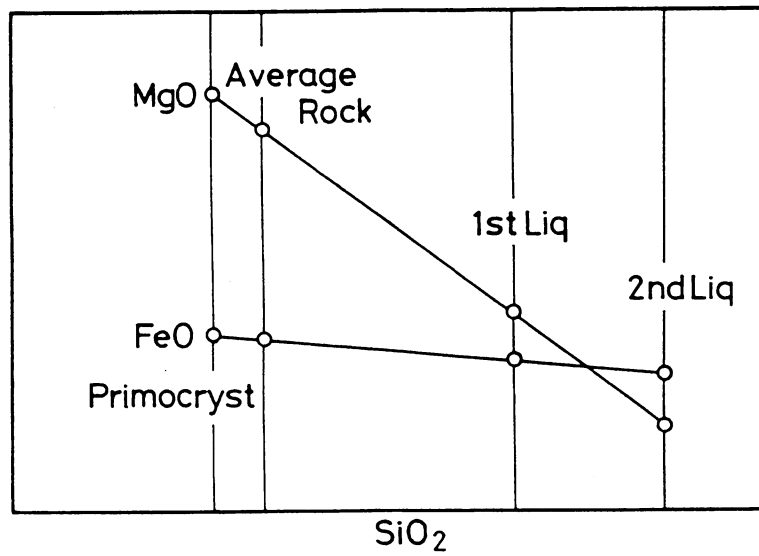


Fig. 7-3
Schematic variation diagram plotted
against SiO_2 .



Fig. 7-4
Occurrence of the fine-
grained olivine gabbro
dike.



Fig. 7-5
Fine-grained olivine gabbro.

are olivine tholeiite in the classification of Yoder and Tilley (1962) and are characterized by high MgO content and high MgO/FeO. The dike composition is very primitive and can coexist with olivine whose composition is about Fo₉₁.

Marginal gabbro (gabbro mylonite) in Zone I

Fig. 7-6 shows the direct contact between the gabbro mylonite in Zone I and the metamorphic rock. Similar relation is observed at other two localities. Original texture of gabbro mylonite is not clear because it suffered from the remarkable mylonitization by the thrusting of the Main zone to the Western zone. The gabbro mylonite might be chilled marginal rock and represent the composition of magma. Fig. 7-7 shows the mylonitic texture. The gabbro mylonites consist of plagioclase, clinopyroxene, orthopyroxene and ilmenite. Sometimes a small amount of amphibole is included.

The composition of the gabbro mylonite is shown in Table 7-1. It belongs to olivine tholeiite according to Yoder and Tilley (1962).

D. Compositional change of average rocks

At B in this chapter, it was noted that the original bulk compositions are roughly equal to the composition of the average rocks. In this section the nature of the bulk composition is examined more carefully.

Bulk rock compositions are plotted on the Ol-Cpx-Pl diagram in weight percent proportion (Fig. 7-8). Ol means the normative olivine plus the olivine component normally into the normative hypersthene. Di is the normative diopside and Pl is the sum of the normative anorthite, albite and orthoclase.

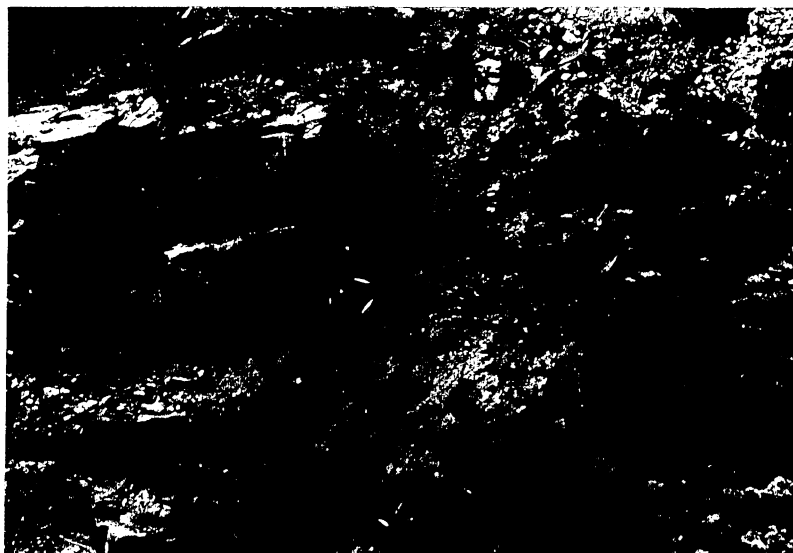


Fig. 7-6

Direct contact between the gabbro mylonite (in the right hand) and metamorphic rock (in the left hand) along the Pankenushi river.

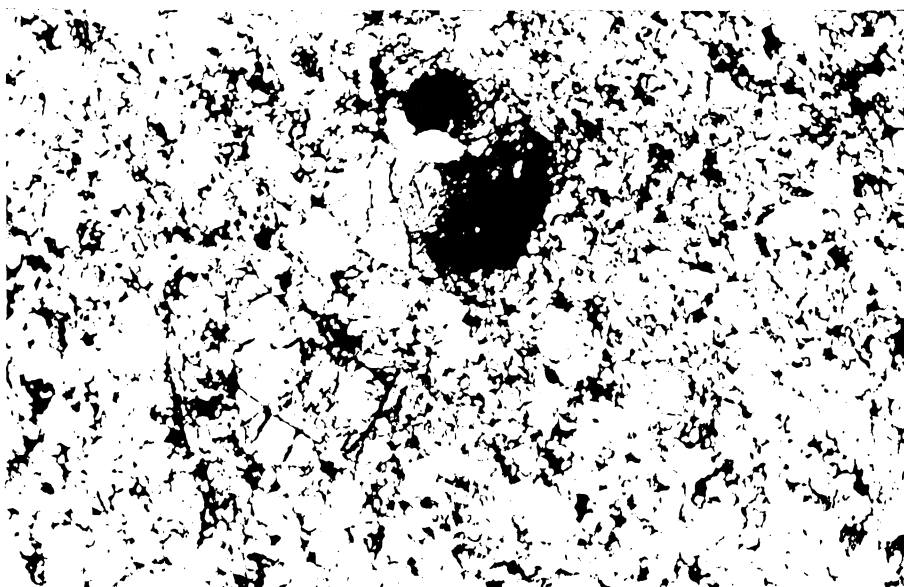


Fig. 7-7

Gabbro mylonite in Zone I.

	1	2		1	2
SiO ₂	47.63	52.01	Q	—	—
TiO ₂	1.14	1.11	or	0.53	1.30
Al ₂ O ₃	15.65	16.11	ab	14.55	26.49
Fe ₂ O ₃	1.66	0.52	an	34.72	29.26
FeO	7.50	8.79	ne	—	—
MnO	0.18	0.16	di	10.25	15.71
MgO	14.65	8.11	hy	16.76	17.89
CaO	9.70	9.81	ol	18.42	6.42
Na ₂ O	1.72	3.13	mt	2.41	0.75
K ₂ O	0.09	0.22	il	2.16	2.11
P ₂ O ₅	0.09	0.03	ap	0.21	0.07
Total	100.00	100.00			

Table 7-1

Bulk analyses and norm values on anhydrous basis.

1, fine-grained olivine gabbro.

2, marginal gabbro.

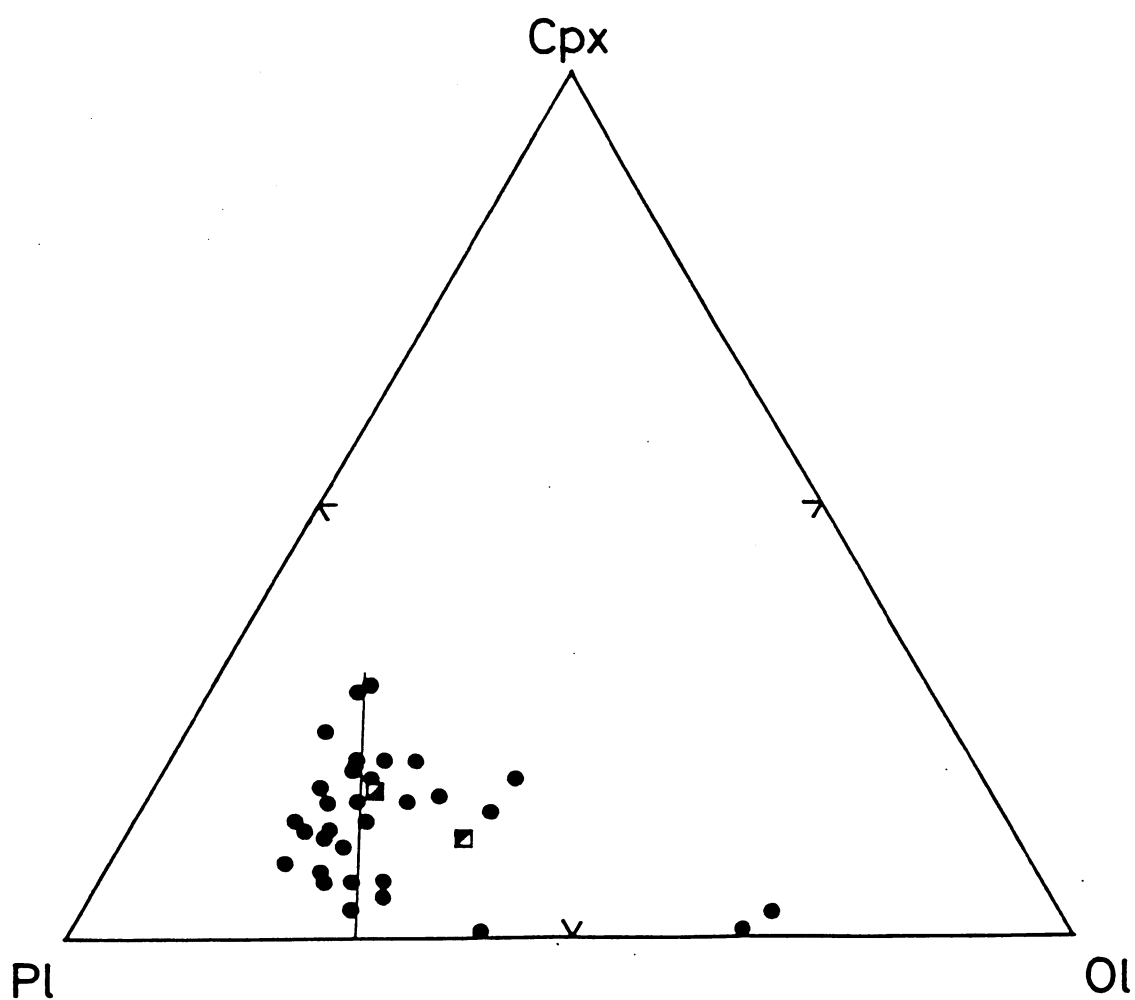


Fig. 7-8

Ol-Pl-Cpx diagram in weight proportions..Solid circles indicate the Pankenushi gabbro. Squares indicate the fine-grained olivine gabbro. Solid line is the hypothetical boundary between the olivine field and plagioclase field.

$$Y = 60.1 - 2.1X$$

$$X = \text{Ol}/\text{Ol} + \text{Pl}, Y = \text{Cpx}/\text{Cpx} + \text{Pl}.$$

When olivine and plagioclase crystallize at the same time, the proportion of them is fixed by the position of the binary eutectic point in the generalized system of olivine and plagioclase. As adding the clinopyroxene to the precipitation assemblage, the proportion among olivine, plagioclase and clinopyroxene is fixed by the position of the ternary eutectic point in the system of olivine-plagioclase-clinopyroxene. In fact, the plots of some troctolites are adjacent to the olivine-plagioclase join. The plots of both olivine gabbro and ferrogabbro show rather scattered area which well corresponds to the boundary curve between forsterite and anorthite in the system of forsterite-diopside-anorthite at 1 atm (Fig. 7-9). It suggests that the ternary eutectic point was not far from the olivine-plagioclase join under the crystallization conditions of the Pankenushi intrusion.

In Fig. 7-8, the assumed boundary curve between olivine and plagioclase is drawn with reference to the boundary curve between forsterite and anorthite in Fig. 7-9. Effect of solid solutions in both olivine and plagioclase is neglected, because olivine and plagioclase in the Pankenushi intrusion change their compositions in a close correlation (Fig. 4-4), and therefore the position is not affected remarkably.

It is impossible to regard the remarkably deviated point from the boundary curve as average rock. Two samples of troctolite which remarkably deviate from the boundary curve toward olivine corner are considered to be olivine-enriched rocks. All of the points are adjusted to be on the boundary curve by changing $Pl/Ol + Cpx$. Because the density of plagioclase is smaller than that of olivine and/or pyroxene, it may be

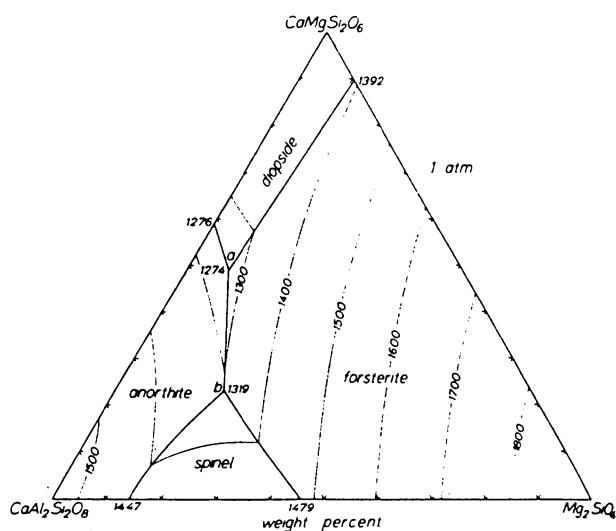


Fig. 7-9

Liquidus phase relations in the join $\text{CaMgSi}_2\text{O}_6$ - Mg_2SiO_4 - $\text{CaAl}_2\text{Si}_2\text{O}_8$, redrawn after Osborn and Tait (1952), Hytönen and Schairer (1961), Kushiro and Schairer (1963), and Kushiro (1972).

very well that the change of Ol/Cpx is much smaller than that of Pl/Ol + Cpx during the accumulation. Modified compositions are given by being multiplied the composition of normative ol, di and pl by the adjusted normative proportion. The amounts of P_2O_5 , TiO_2 and MnO can not be defined, even when the above mentioned method was applied. They are given by using the original analyses independently. Fig. 7-10 shows the original analyses of them against the Fo content of included olivine. The trends of the compositional changes of P_2O_5 , TiO_2 and MnO are obtained by the method of least squares (Fig. 7-13). Because some MnO contents of mafic mineral-enriched rocks are rather high, they are omitted from the calculation. In calculation^s of SiO_2 , Al_2O_3 , FeO, MgO, CaO, Na_2O and K_2O there are two qualifications as follows.

1. In the normative calculation, Mn is added to Fe.

Therefore, Fe equal to Mn is deducted from Fe adjusted in the normative system.

2. Ti is allotted for ilmenite. Therefore, Fe equal to Ti is added to adjusted Fe. P is allotted for apatite, therefore Ca equal to 3.33 P must be added. However, Ca is very little and such a operation is neglected. SiO_2 , Al_2O_3 , FeO, MgO, CaO, Na_2O and K_2O were calculated in order to equal to the difference between 100 percent and the sum of TiO_2 , MnO, P_2O_5 and FeO (equal to TiO_2 in mole proportion) defined independently. The adjusted bulk compositions are given in Table 7-2. Fig. 7-11 shows the calculated MgO, FeO and SiO_2 against the Fo content of olivine. Original analyses are shown by cross symbols. The amounts of SiO_2 and FeO are drastically changed by the precipitation of ilmenite. Calculated amounts of Al_2O_3 ,

	1	2	3	4	5	6	7
SiO ₂	44.83	45.17	46.77	48.78	49.67	51.23	50.91
TiO ₂	.00	.00	.00	.12	.26	.39	.52
Al ₂ O ₃	24.92	24.62	22.99	20.97	19.49	17.99	17.62
FeO	3.34	3.29	4.67	5.63	6.20	6.41	6.97
MnO	.06	.06	.07	.09	.11	.13	.14
MgO	13.01	12.95	12.44	10.98	10.06	9.45	8.84
CaO	13.63	13.63	10.96	11.06	11.76	11.69	12.50
Na ₂ O	.13	.15	2.00	2.25	2.30	2.47	2.31
K ₂ O	.04	.10	.06	.08	.12	.22	.15
P ₂ O ₅	.03	.03	.03	.03	.03	.04	.04
Fo	86.6	86.6	82.7	77.1	72.4	67.7	63.0

	8	9	10	11	12	13	14
SiO ₂	52.52	46.63	47.19	47.86	48.66	46.87	48.75
TiO ₂	.56	5.02	5.00	4.89	4.82	4.53	4.47
Al ₂ O ₃	16.03	16.19	15.42	14.37	15.46	16.30	16.24
FeO	6.42	11.50	11.50	11.47	11.21	11.88	12.24
MnO	.15	.17	.17	.18	.18	.20	.21
MgO	8.74	7.78	7.45	6.83	7.17	6.81	6.65
CaO	12.91	9.64	10.23	11.73	9.74	10.94	8.20
Na ₂ O	2.47	2.87	2.79	2.53	2.55	2.30	2.92
K ₂ O	.17	.17	.20	.10	.16	.13	.27
P ₂ O ₅	.04	.04	.04	.04	.04	.04	.04
Fo	61.5	55.8	55.5	53.3	52.0	46.3	45.3

Table 7-2 Adjusted bulk compositions and olivine compositions.

Numbers from 1 to 24 are the same as those in Table 6-1.

Original analyses of from 25 to 27 are shown in Miyashita and Maeda (1978) and those from 28 to 32 are taken from Nochi and Komatsu (1967).

* determined by the regression equation given in Fig. 7-14.

** determined by Nochi and Komatsu (1967).

	15	16	17	18	19	20	21
SiO ₂	48.68	49.46	46.47	49.64	49.49	51.23	48.38
TiO ₂	4.25	3.99	3.91	3.88	3.84	3.77	3.77
Al ₂ O ₃	16.02	15.35	17.39	14.94	15.04	14.53	16.17
FeO	13.22	12.77	15.63	13.73	13.67	13.64	14.72
MnO	.22	.24	.25	.25	.25	.26	.26
MgO	5.64	5.67	4.34	5.00	5.12	4.70	4.55
CaO	7.30	7.87	7.32	7.50	7.82	6.79	7.42
Na ₂ O	3.19	3.07	3.36	3.33	3.42	3.35	3.49
K ₂ O	.22	.45	.25	.65	.30	.71	.23
P ₂ O ₅	1.26	1.13	1.08	1.07	1.05	1.02	1.01
Fo	41.0*	36.0	34.4	33.8*	33.2*	31.8*	31.7*

	22	23	24	25	26	27	28
SiO ₂	48.76	48.55	50.17	46.93	49.70	47.46	49.67
TiO ₂	3.51	3.44	3.35	.03	.32	3.74	.06
Al ₂ O ₃	15.63	16.07	15.09	22.67	18.89	15.66	18.94
FeO	14.76	14.17	14.53	5.27	7.62	13.57	6.33
MnO	.27	.28	.29	.08	.12	.26	.08
MgO	4.32	4.85	4.11	11.44	8.72	5.40	9.88
CaO	8.01	8.06	7.73	10.93	10.94	8.85	12.39
Na ₂ O	3.48	3.45	4.40	2.55	3.50	3.83	2.53
K ₂ O	.37	.28	.54	.06	.16	.25	.08
P ₂ O ₅	.88	.85	.80	.03	.03	1.00	.03
Fo	26.7	25.5	23.6*	80.5	70.2	31.1*	79.5**

Table 7-2 (continued)

	29	30	31	32
SiO ₂	49.51	47.99	49.49	52.28
TiO ₂	.18	.18	.27	.63
Al ₂ O ₃	18.57	21.19	18.52	15.41
FeO	6.38	6.61	6.92	8.59
MnO	.10	.10	.11	.16
MgO	9.64	10.47	9.23	7.31
CaO	13.01	10.95	13.07	12.45
Na ₂ O	2.54	2.39	2.31	2.94
K ₂ O	.03	.08	.06	.19
P ₂ O ₅	.03	.03	.03	.04
Fo	75.0**	75.0**	72.0**	59.0**

Table 7-2 (continued)

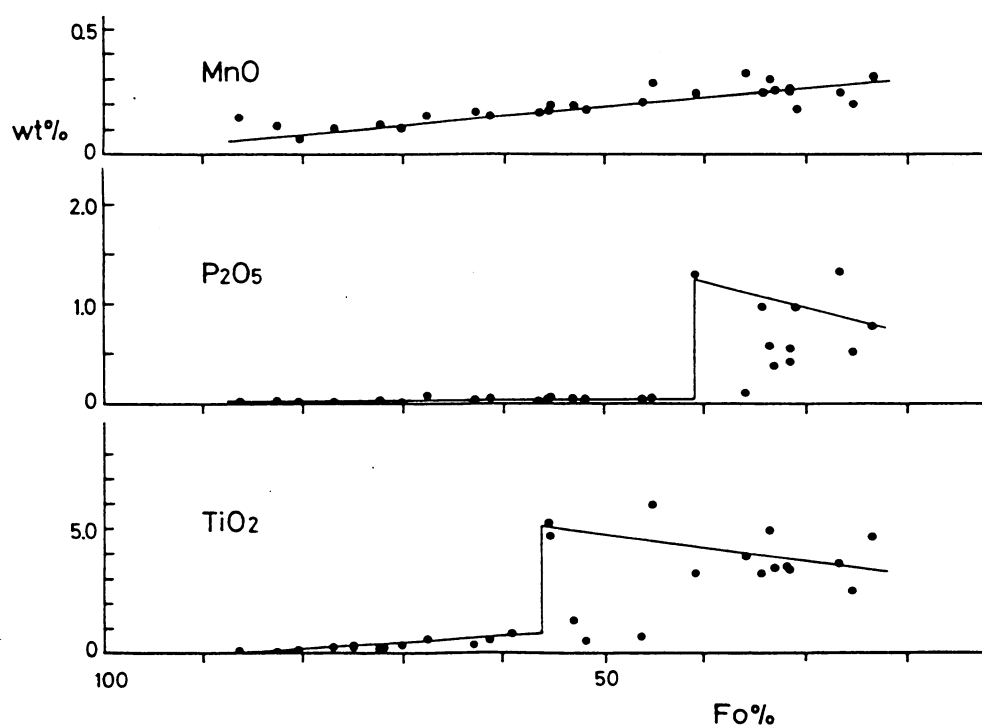


Fig. 7-10

MnO, P₂O₅, and TiO₂ of the Pankenushi gabbros (original data) plotted against Fo content of olivine. Curves show the average trends and the equations are given in Fig. 7-13.

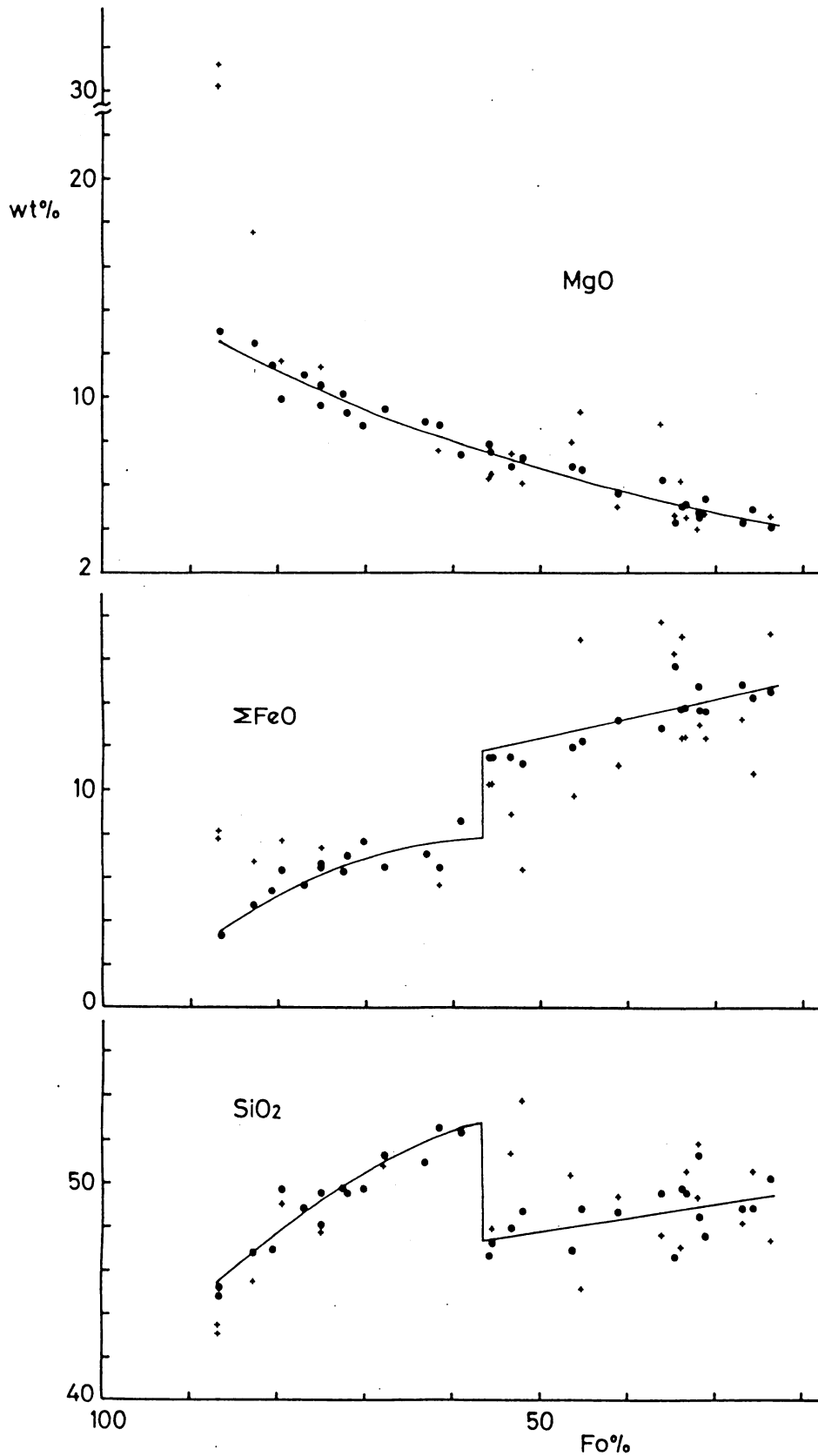


Fig. 7-11

MgO, FeO, and SiO₂ of the adjusted gabbros. Cross indicates the original unadjusted composition. Most of the unadjusted compositions are too close to be plotted.

CaO, Na₂O and K₂O are plotted against the olivine composition (Fig. 7-12). The variation curves of the amount of each component are defined by the method of least squares as a function of the olivine composition (Fig. 7-13). Total amounts of each constituent obtained by the curves were range about 99-101 percent. The total amounts were normalized to 100 percent. Cumulus olivine is lacking in some ferrogabbro. Fo content of hypothetical olivine was determined by using Fig. 7-14.

E. Procedures of simulation

Procedures of practical calculation are shown in Fig. 7-15. At first, the composition of magma was inputted. Secondary, Fo content of olivine in equilibrium with the magma was defined. The amounts of each constituent of the average rock were defined using the equation shown in Fig. 7-13. Subtraction of the average rock from the first liquid gives a next liquid. The second liquid was decided in order to be in equilibrium with the olivine whose Fo content is 1 mole percent lower than that of the first olivine. Repeated subtractions generate the compositions of the successively differentiated magma.

If the true composition of the differentiated magma is known, the compositions of more differentiated magma are estimated by the subtraction method and the composition of the undifferentiated magma, i.e. parental magma is estimated by the repeated additions of the average rocks until the magma becomes to coexist with the average rock which has most magnesian olivine in the intrusive body. As a matter of course, in the procedures of the calculation shown in Fig.

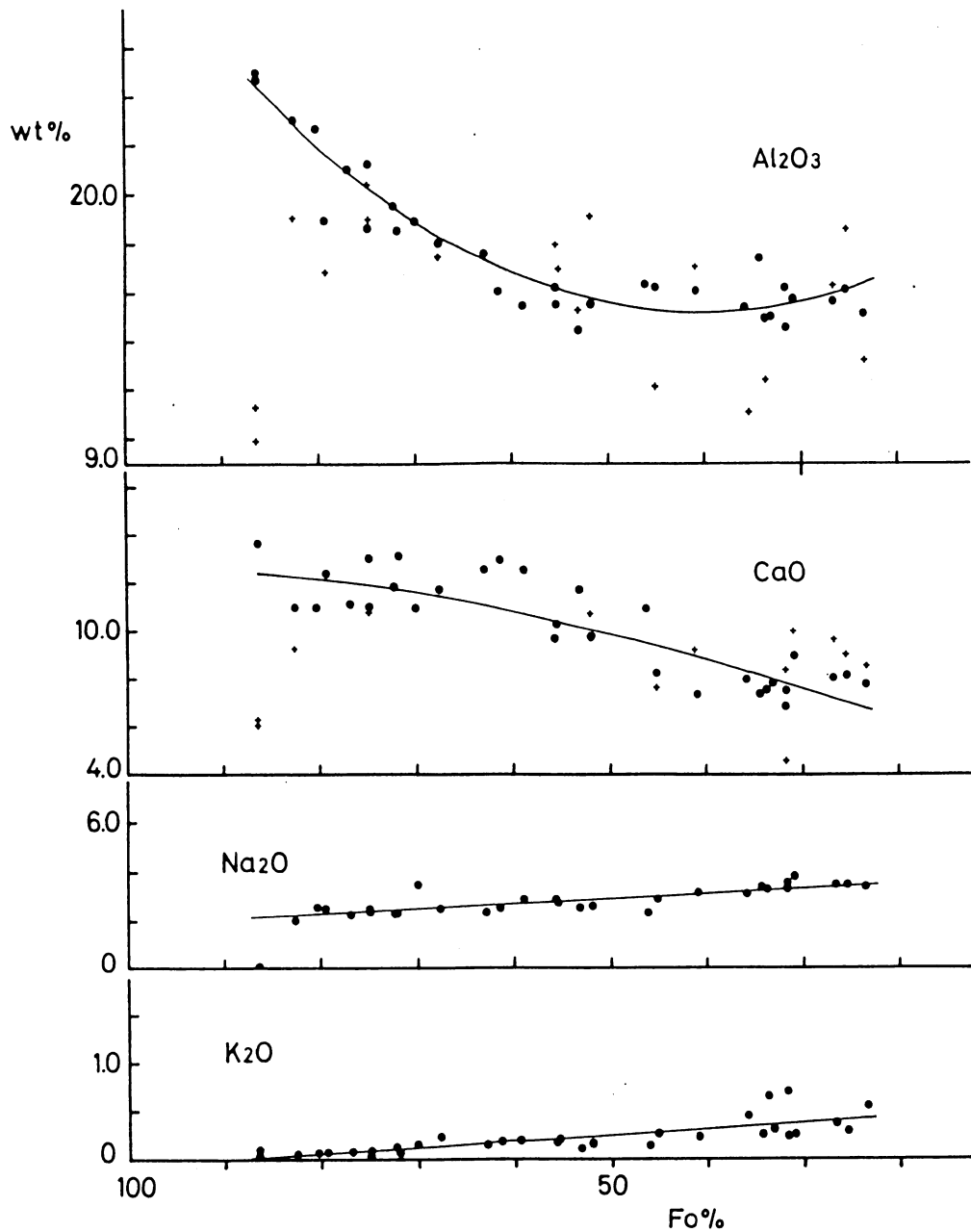


Fig. 7-12

Al₂O₃, CaO, Na₂O, and K₂O of the adjusted gabbros.
 The equations of the curves are given in Fig. 7-13.
 Symbols are the same as those in Fig. 7-11.

$$\begin{aligned}
\text{SiO}_2 &= 44.0666 + 0.4059\text{Fo} - 0.0045\text{Fo}^2 & (86.6 \geq \text{Fo} > 56.6) \\
&= 50.8977 - 0.0624\text{Fo} & (56.6 \geq \text{Fo} \geq 23.6) \\
\text{TiO}_2 &= 2.2682 - 0.0278\text{Fo} & (86.6 \geq \text{Fo} > 56.6) \\
&= 2.1179 + 0.052\text{Fo} & (56.6 \geq \text{Fo} \geq 23.6) \\
\text{Al}_2\text{O}_3 &= 22.4659 - 0.3587\text{Fo} + 0.0044\text{Fo}^2 \\
\text{FeO} &= -5.1122 + 0.4714\text{Fo} - 0.0043\text{Fo}^2 & (86.6 \geq \text{Fo} > 56.6) \\
&= 17.0915 - 0.1039\text{Fo} + 0.0002\text{Fo}^2 & (56.6 \geq \text{Fo} \geq 23.6) \\
\text{MnO} &= 0.3701 - 0.0036\text{Fo} \\
\text{MgO} &= 3.53 + 0.009\text{Fo} + 0.0011\text{Fo}^2 \\
\text{CaO} &= 3.343 + 0.165\text{Fo} - 0.0007\text{Fo}^2 \\
\text{Na}_2\text{O} &= 3.9929 - 0.021\text{Fo} \\
\text{K}_2\text{O} &= 0.5649 - 0.0063\text{Fo} \\
\text{P}_2\text{O}_5 &= 0.0556 - 0.0003\text{Fo} & (86.6 \geq \text{Fo} > 41.0) \\
&= 0.1867 + 0.0278\text{Fo} & (41.0 \geq \text{Fo} \geq 23.6)
\end{aligned}$$

Fig. 7-13

Regression equations of the average rock composition (weight per cent) represented as function of olivine composition (Fo per cent).

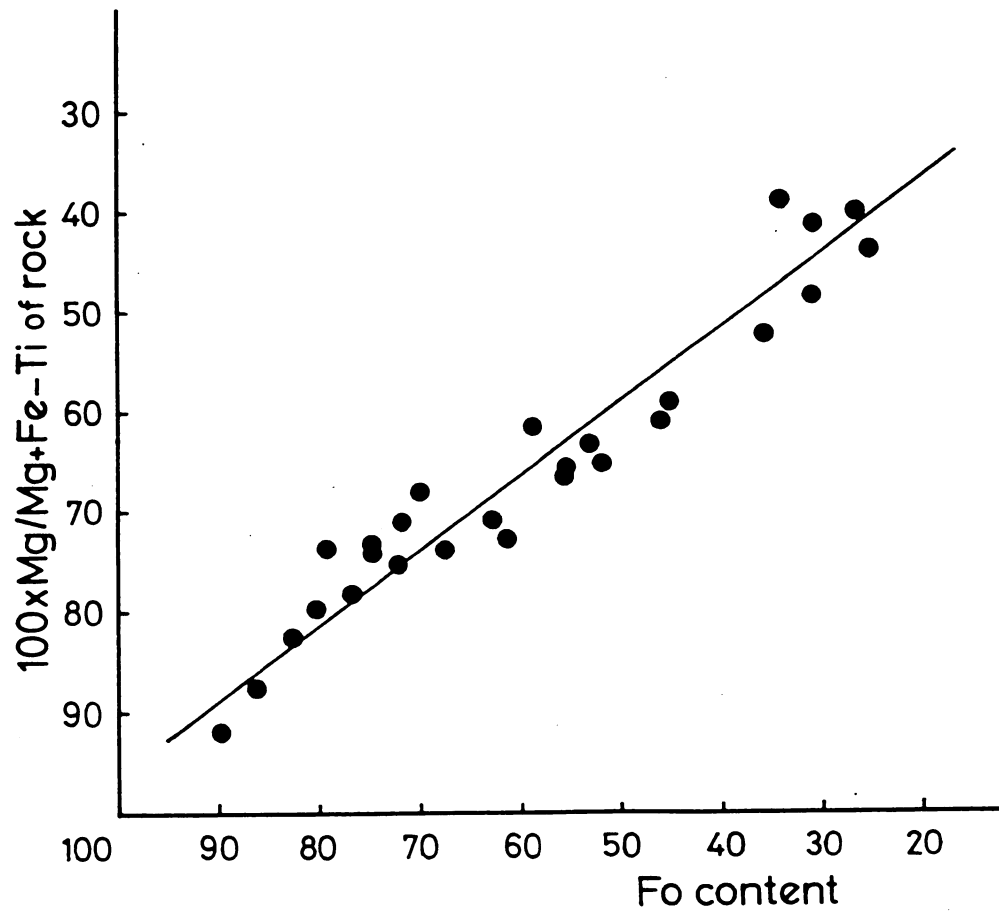


Fig. 7-14

The relation between the bulk rock composition and Fo content of included olivine. $100 \times \text{Mg}/\text{Mg}+\text{Fe}-\text{Ti}$ was used rather than $100 \times \text{Mg}/\text{Mg}+\text{Fe}$ to exclude the effect of ilmenite accumulation. Regression equation is as under.

$$\text{Fo (per cent)} = 1.33 \times 100\text{Mg}/(\text{Mg}+\text{Fe}-\text{Ti})_{\text{rock}} - 28.13.$$

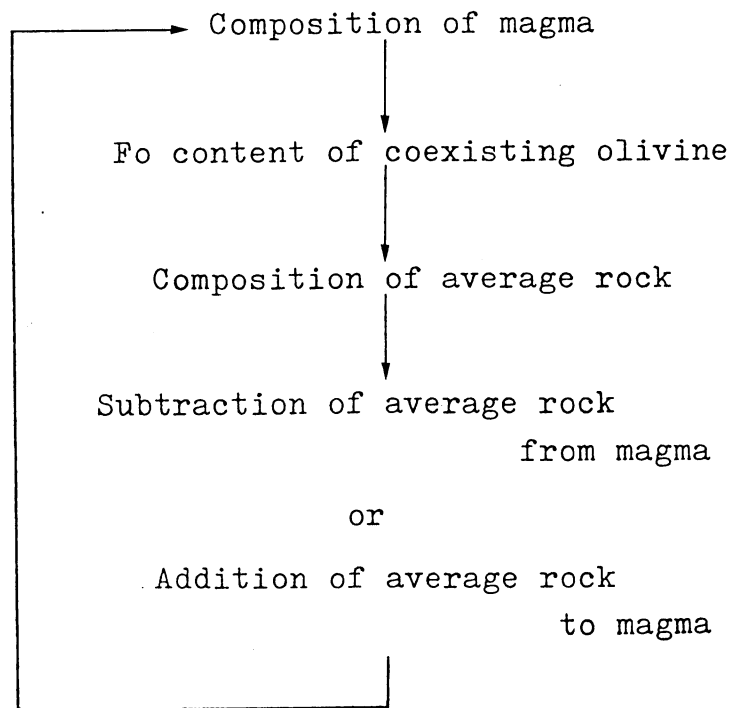


Fig. 7-15
Procedures of simulation.

7-15, crystallization was assumed to be perfectly fractional. Calculation was done using the microcomputer (Olivetti P6040). The program is shown in Fig. 7-16.

F. Result of simulation

Fine-grained olivine gabbro dike

Average composition of fine-grained gabbro, that can coexist with olivine of $\text{Fo}_{90.6}$, is plotted in hypothetical olivine field (Fig. 7-17). For a while, olivine alone must be fractionated. The simple fractionation of olivine from the dike composition is simulated. The liquid just arriving at the boundary curve between olivine and plagioclase can coexist with olivine of about Fo_{84} . Most magnesian olivine of the Pankenushi intrusion is in fact $\text{Fo}_{86.6}$ and that is accompanied by the cumulus plagioclase ($\text{An}_{86.2}$). In the simulation, therefore, olivines alone ranging from $\text{Fo}_{90.6}$ to $\text{Fo}_{86.6}$ in composition were fractionated. When olivine compositions range from $\text{Fo}_{86.6}$ to $\text{Fo}_{26.6}$, fractionation of the average rock calculated previously was simulated. MnO in fractionated olivine ranging from $\text{Fo}_{90.6}$ to $\text{Fo}_{86.6}$ is defined by the method least squares using the composition of Pankenushi olivine. The regression equation is as follows.

$$\text{MnO (wt \%)} = 1.07 - 0.011 \times \text{Fo (\%)}$$

Result of the simulation is shown in Fig. 7-18. The simulation ceased when the amount of Na_2O became to negative.

Marginal gabbro in Zone I

Marginal gabbro can coexist with olivine of $\text{Fo}_{83.9}$. Fractionation of calculated average rock was simulated. The result is shown in Fig. 7-19. Although P_2O_5 content became to negative at 70.2 percent solidified. However, the role

```

10 PRINT "PANKENUSH
I MAGMODEL"
20 INPUT A,B,C,D,E,
F,G,H,I,J
25 FIXED 4
30 PRINT "-----
-----", "TOTAL", A+
B+C+D+E+F+G+H+I+
J, "-----
", "A", (H+I)/(D+F
+H+I), "F", D/(D+F
+H+I), "M", F/(D+F
+H+I), "MG RATIO"
, 71.85*F/(71.85*
F+40.31*D)
40 A=0.99*A
B=0.99*B
C=0.99*C
D=0.99*D
E=0.99*E
F=0.99*F
G=0.99*G
H=0.99*H
I=0.99*I
J=0.99*J
A22=0.01
50 K=F*71.85/(D*40.
31+0.3+F*71.85)
60 FOR L=K TO 0.255
STEP -0.01
65 FIXED 4
70 IF L<0.976 THEN
90
80 O=P=T=U=W=0
R=(1.07-1.1*L)/1
00
85 N=0.745/(1.745+(
1-L)/L*2.5274)/L
*(1-R)
Q=(1-L)*1.7824/(
1.745+(1-L)/L*2.
5274)/L*(1-R)
S=1/(1.745+(1-L)
/L*2.5274)*(1-R)
GOTO 150
90 P=(22.4659-35.97
*L+44*L^2)/100
R=(0.3701-0.35*L
)/100
S=(3.53+0.9*L+11
*L^2)/100
T=(3.343+16.5*L-
7*L^2)/100
U=(3.9929-2.1*L)
/100
V=(0.5649-0.53*L
)/100
100 IF L<0.566 THEN
120
110 N=(44.0868+40.59
*L-45*L^2)/100
Q=(2.2682-2.79*L
)/100
O=(-5.1122+47.14
*L-43*L^2)/100
W=(0.8556-0.03*L
)/100
GOTO 150
120 IF L<0.410 THEN
140
130 N=(50.8977-6.24*
L)/100
O=(2.1179+5.2*L)
/100
Q=(17.0915-10.39
*L+2*L^2)/100
W=(0.8556-0.03*L
)/100
GOTO 150
140 N=(50.8977-6.24*
L)/100
O=(2.1179+5.2*L)
/100
Q=(17.0915-10.39
*L+2*L^2)/100
W=(0.1067+2.61*L
)/100
145 FIXED 4
150 IF O<=0 THEN 170

```

Fig. 7-16

List of the program.

```

160
O=O+
GOTO 169+
170
O=O+
180
A20=N+O+P+Q+R+S+
T+U+V+W+
185
PRINT "CALC TOTA
L",A20+
N=N/A20+
O=O/A20+
P=P/A20+
Q=Q/A20+
R=R/A20+
S=S/A20+
T=T/A20+
U=U/A20+
V=V/A20+
W=W/A20+
190
X=(N*F-A*S)*71.8
5*(1.01-L)-(N*D-
A*Q)*0.3*(L-0.01
)*40.31+
200
X=X/((Q-D)*0.3*(
L-0.01)*40.31-(S
-F)*71.85*(1.01-
L))+
210
Y=((O-B)*X+N*B-A
*Q)/(N-A)+
211
Z=((P-C)*X+N*C-A
*Q)/(N-A)+
212
A9=((Q-D)*X+N*D-
A*Q)/(N-A)+
213
A1=((R-E)*X+N*E-
A*Q)/(N-A)+
214
A2=((S-F)*X+N*F-
A*Q)/(N-A)+
215
A3=((T-G)*X+N*G-
A*Q)/(N-A)+
216
A4=((U-H)*X+N*H-
A*Q)/(N-A)+
217
A5=((V-I)*X+N*I-
A*Q)/(N-A)+
218
A6=((W-J)*X+N*J-
A*Q)/(N-A)+
219
A7=A22*(N-X)/(N-
A)+
220
A8=0.01/A7+
230
A9=X+Y+Z+A8+A1+A
2+A3+A4+A5+A6+
240
A23=X/A9+
A24=Y/A9+
A25=Z/A9+
A26=A8/A9+
A27=A1/A9+
A28=A2/A9+
A29=A3/A9+
A30=A4/A9+
A31=A5/A9+
A32=A6/A9+
250
PRINT "-----
-----", "F0", L, "50
LID", "SID2", N, "T
ID2", Q, "AL203", F
, "FEO", Q, "MNO", R
, "MGO", S, "CAO", T
, "NA2O", U, "K2O",
U, "P2O5", W, "TOTA
L", N+O+P+Q+R+S+T
+U+V+W, "A", (U+V)
/(Q+S+U+V), "F", Q
/(Q+S+U+V), "M", S
/(Q+S+U+V), "MG R
ATIO", 71.85*S/(7
1.85*S+40.31*Q)+

```

Fig. 7-16 (continued)


```

250
PRINT "-----
----", "LIQUID", "
SI02", A23, "TI02"
, A24, "AL203", A25
, "FeO", A26, "MNO"
, A27, "MGO", A28, "
CAO", A29, "MA20",
A30, "K2O", A31, "P
205", A32, "TOTAL"
, A23+A24+A25+A26
+A27+A28+A29+A30
+A31+A32, "R", (A3
0+A31)/(A30+A31+
A26+A28), "F", A26
/(A26+A28+A30+A3
1), "M", A28/(A26+
A28+A30+A31), "MG
RATIO", 71.85*A2
8/(71.85*A28+40.
31*A26), "INCOMPR
TIBLE", A7, "LIO F
RACT", A8, "*****
*****"
270
A=X+
B=Y+
C=Z+
D=A3+
E=A1+
F=A2+
G=A3+
H=A4+
I=A5+
J=A6+
A22=A7+
290
NEXT L+
9400
GOTO 10+

```

Fig. 7-16 (continued)

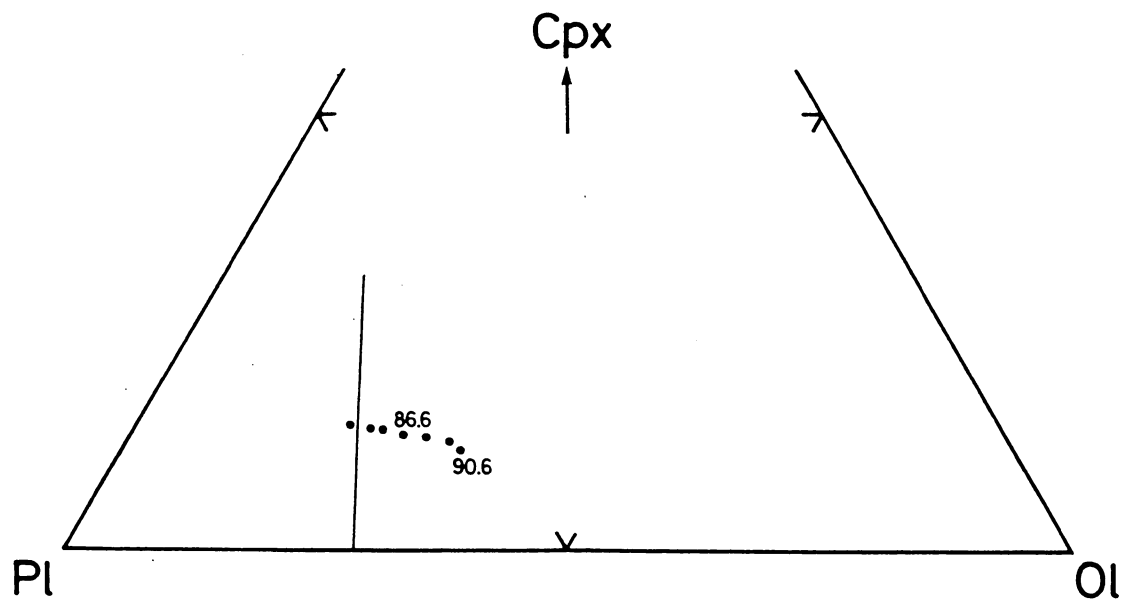


Fig. 7-17

Compositional change of the fine-grained olivine gabbro by the olivine fractionation. Fo content of coexisting olivine is also shown. Solid line is the hypothetical boundary between the fields of olivine and plagioclase.

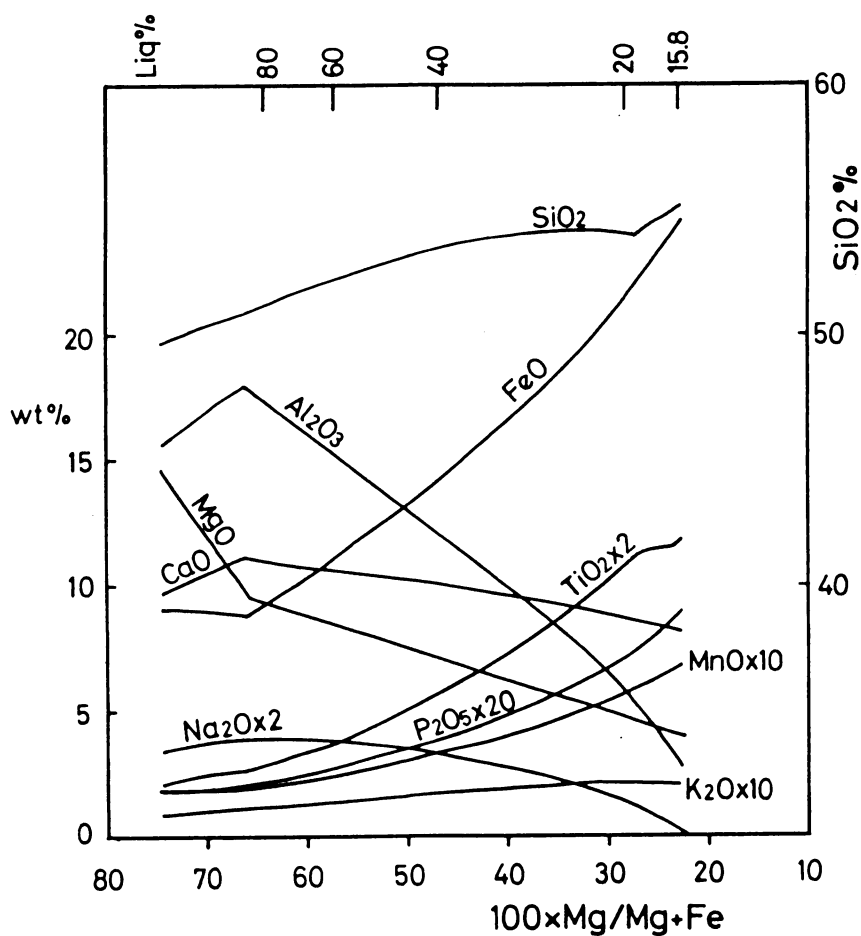


Fig. 7-18

Result of the simulation using the dike composition. Compositional changes are shown against Mg ratio. Proportion of the residual liquid is shown in weight per cent.

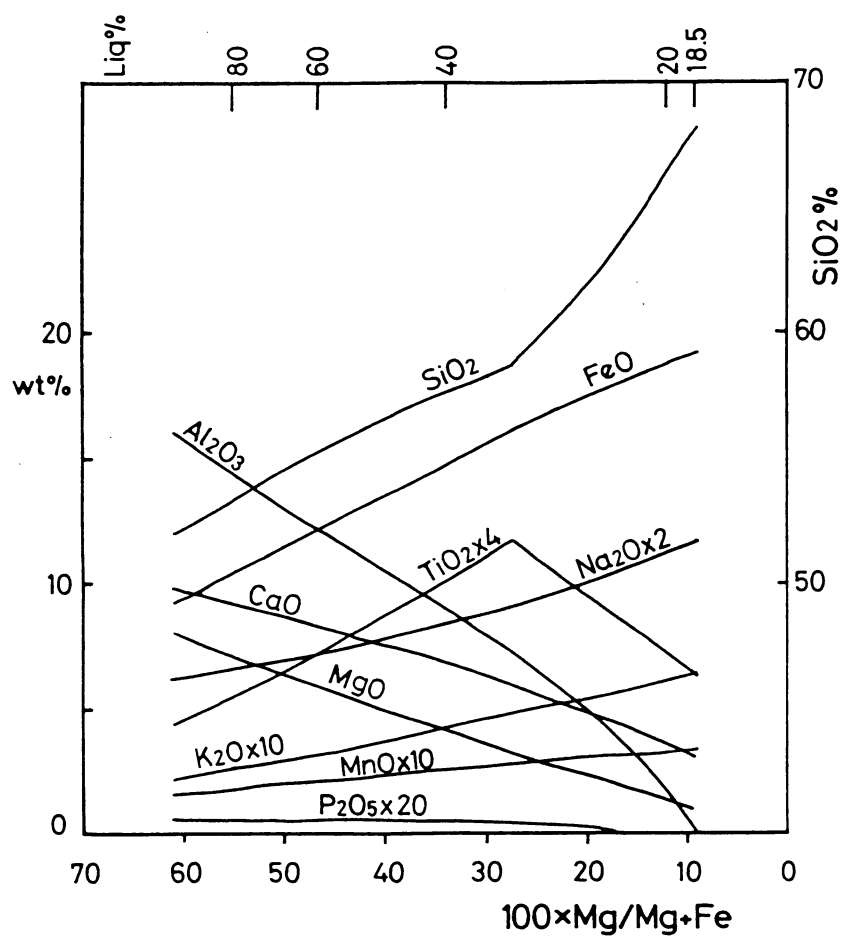


Fig. 7-19

Result of the simulation using the composition of the marginal gabbro.

of P_2O_5 was not so important in the crystallization differentiation process that simulation was continued to the end.

Two results shown in AFM diagram (Fig. 7-20) are corresponding to the tholeiitic trend qualitatively and are remarkably different from the trend of the Memurodake complex which belongs to calc-alkalic series. The relation between FeO and SiO_2 of the two simulated trends are shown in Fig. 7-21. Both trends show the absolute enrichment in iron. Such a change is typically observed in the tholeiitic suite. They also do not match with the trend of the Memurodake complex.

The two results partly show the unrealistic change of magma composition. For example, the FeO contents in the both trends continue to increase as far as simulation is done (Fig. 7-21). Additionally the amount of Na_2O in the result using the fine-grained gabbro decreases and becomes to negative (Fig. 7-18). Accordingly the quantitative discussion on the results is open to question. The cause of the discrepancy between the results of the simulations and the observed facts in the natural occurrences may be partly due to the selection of the liquid composition and partly due to the determination of the average rock composition. The quantitative discussion is left as future problem.

Although the petrographical features of the Pankenushi gabbro are resemblant to that of calc-alkalic gabbro as mentioned in Chapter 4, it is concluded from the result of the simulation that the Pankenushi gabbro belongs to tholeiitic gabbro.

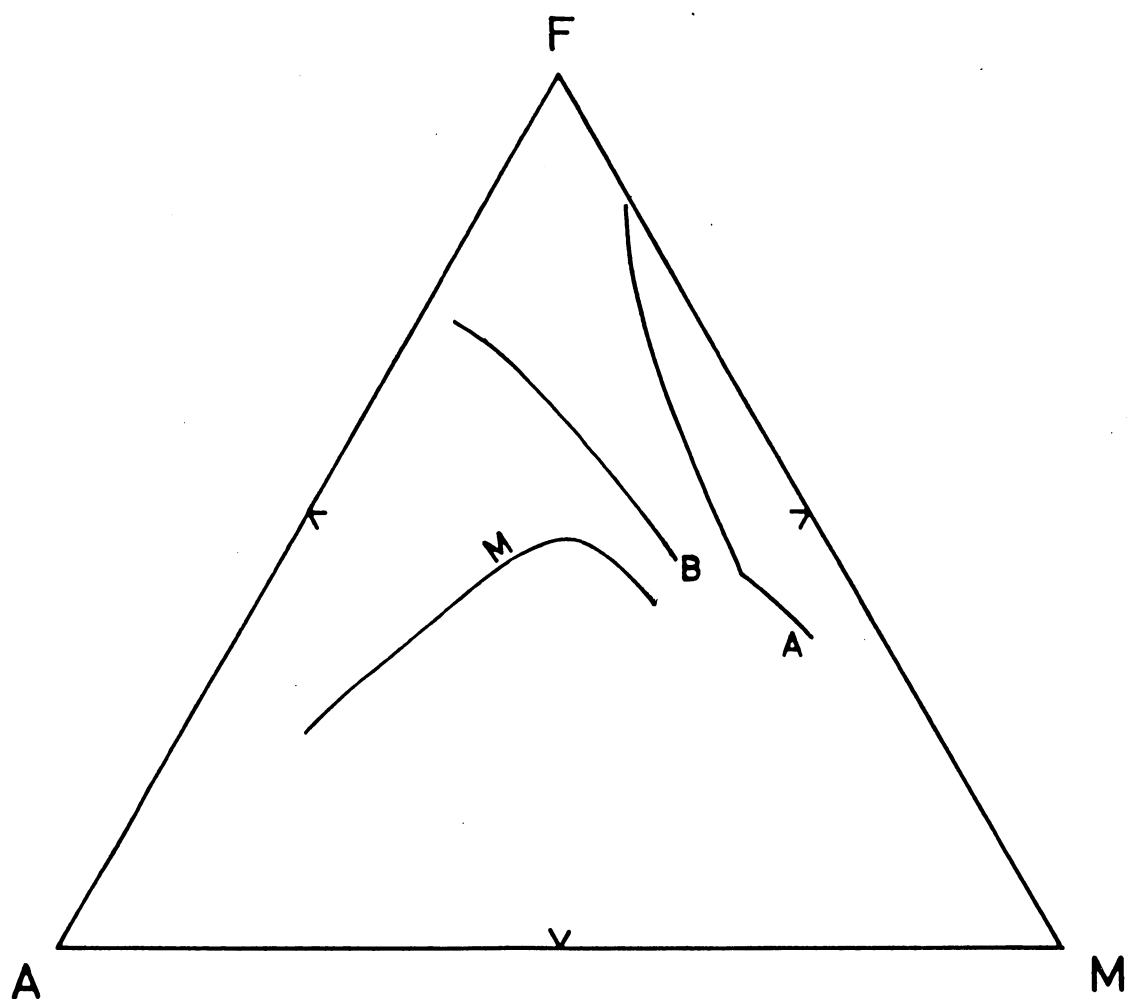


Fig. 7-20

Two results of simulation shown in AFM diagram. A, result using the fine-grained olivine gabbro dike. B, result using the marginal gabbro. Trend of the Memurodake rocks is also shown (M).

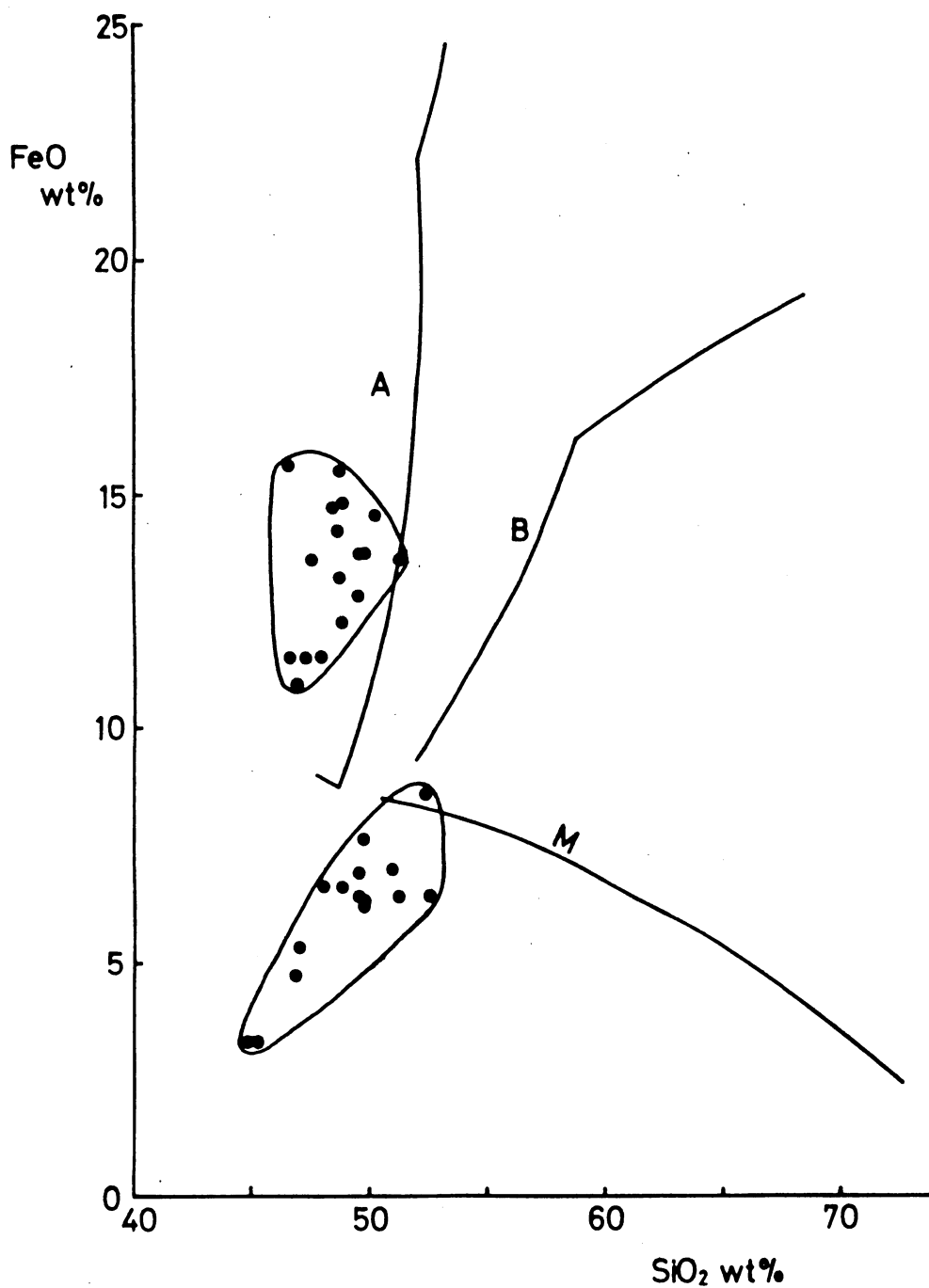


Fig. 7-21

Two results of simulation shown in SiO_2 -FeO diagram. Solid circles within enclosed curves indicate the adjusted composition given in Table 7-3. Symbols are the same as those in Fig. 7-20.

Chapter 8

EFFECT OF PLAGIOCLASE FRACTIONATION
ON
THE EVOLUTION OF NON-ALKALINE BASALT MAGMA

Two series belonging to non-alkaline suite, i.e. tholeiitic and calc-alkalic series, are clearly distinguished in total iron as FeO-SiO₂ diagram. As differentiation proceeds, FeO enrichment is typically observed in the tholeiitic series and a decrease in FeO is typical in the calc-alkalic series (Fig. 8-1). The following discussion about the two distinct trends is based on the assumption that they are derived from basaltic magma by fractional crystallization.

In the earlier stage of the tholeiitic differentiation, strong FeO enrichment and a slight change in SiO₂ content are commonly observed. Such a differentiation must be explained by the subtraction of mineral of which SiO₂ content is nearly the same as basaltic magma and FeO content is very low (Fig. 8-2). In the common rock-forming minerals, only plagioclase satisfies such a limitation. The composition of plagioclase is very unique among the rock-forming minerals contained in common igneous rocks because it has very low FeO content. Accordingly it is expected that the plagioclase fractionation has a very important role to decide the two trends of magmatic differentiation.

As an example of plagioclase non-fractionation, the model of olivine fractionation from some basaltic magma reported as initial magma by some authors was simulated. The trends

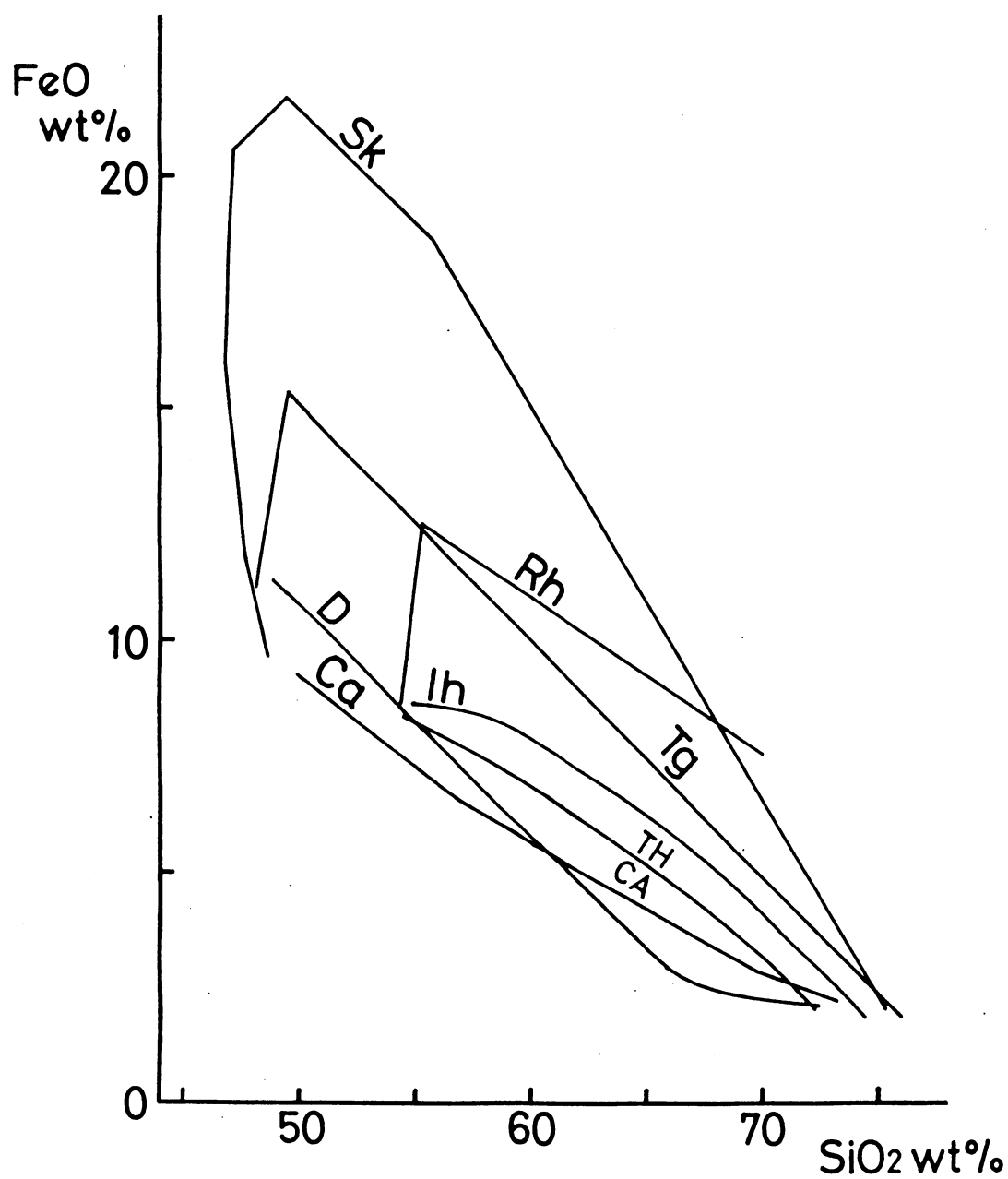


Fig. 8-1

Typical differentiation trends shown in SiO_2 -FeO diagram. Explanations are the same as those in Fig. 6-6.

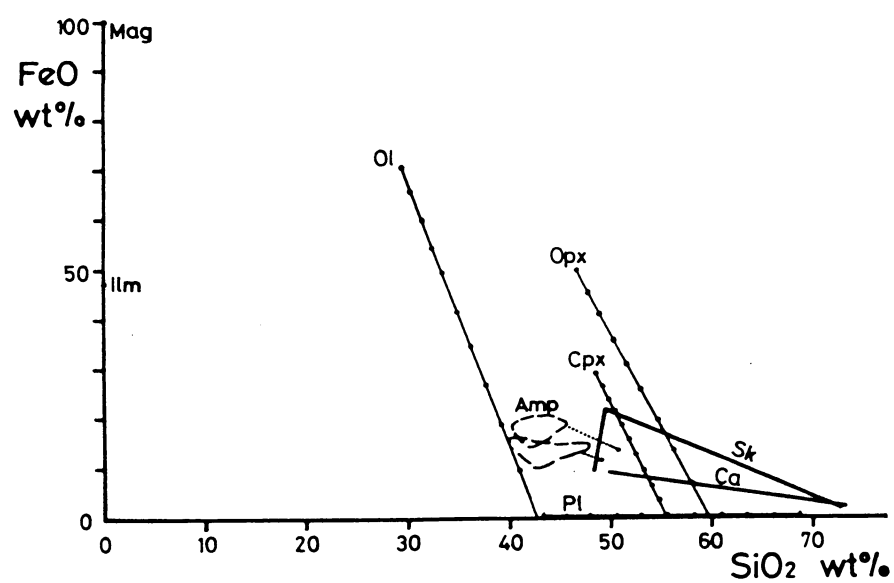


Fig. 8-2

SiO₂-FeO diagram. Compositional ranges of the main rock-forming minerals are plotted.

obtained by the simulations are not typical of tholeiitic such as the Skaergaard liquid but comparatively similar to the calc-alkalic trend (Fig. 8-3).

Next simulations concerning the fractionation of olivine plus plagioclase of varied ratio were done by using the Skaergaard initial magma (Fig. 8-4). The result of olivine 30 % plus plagioclase 70 % fractionation is very similar to the Skaergaard liquid trend. Such a proportion of olivine and plagioclase is in good agreement with the boundary position between forsterite and anorthite (forsterite = 0.3, anorthite = 0.7) in the Fo-An-Di system at 1 atm dry (Fig. 8-5). This suggests that the typically tholeiitic trend is derived from the fractionation of mainly olivine and plagioclase under comparatively low pressure and dry conditions.

The position of the boundary curve between forsterite and anorthite in the Fo-An-Di system is considerably affected by the changes of pressure and P_{H_2O} . It is elucidated that the anorthite field decreases under the high pressure and high P_{H_2O} conditions. Therefore it is concluded that the extent of plagioclase field is maximum at 1 atm dry. When plagioclase and olivine precipitate together, Pl ratio ($Pl/Pl + Ol$) varies only from 1.0 to 0.7 and there exists a wide break in the Pl ratio between 0.7 and 0.0 (fractionation of olivine alone) (Fig. 8-4).

Therefore the intermediate ($0.0 > Pl \text{ ratio} > 0.7$) is not real. The two trends of Pl ratio of 0.7 (A) and that of 0.0 (B) are plotted on the FeO-SiO₂ diagram (Fig. 8-6). They qualitatively correspond to the tholeiitic trend and the calc-alkalic trend, respectively.

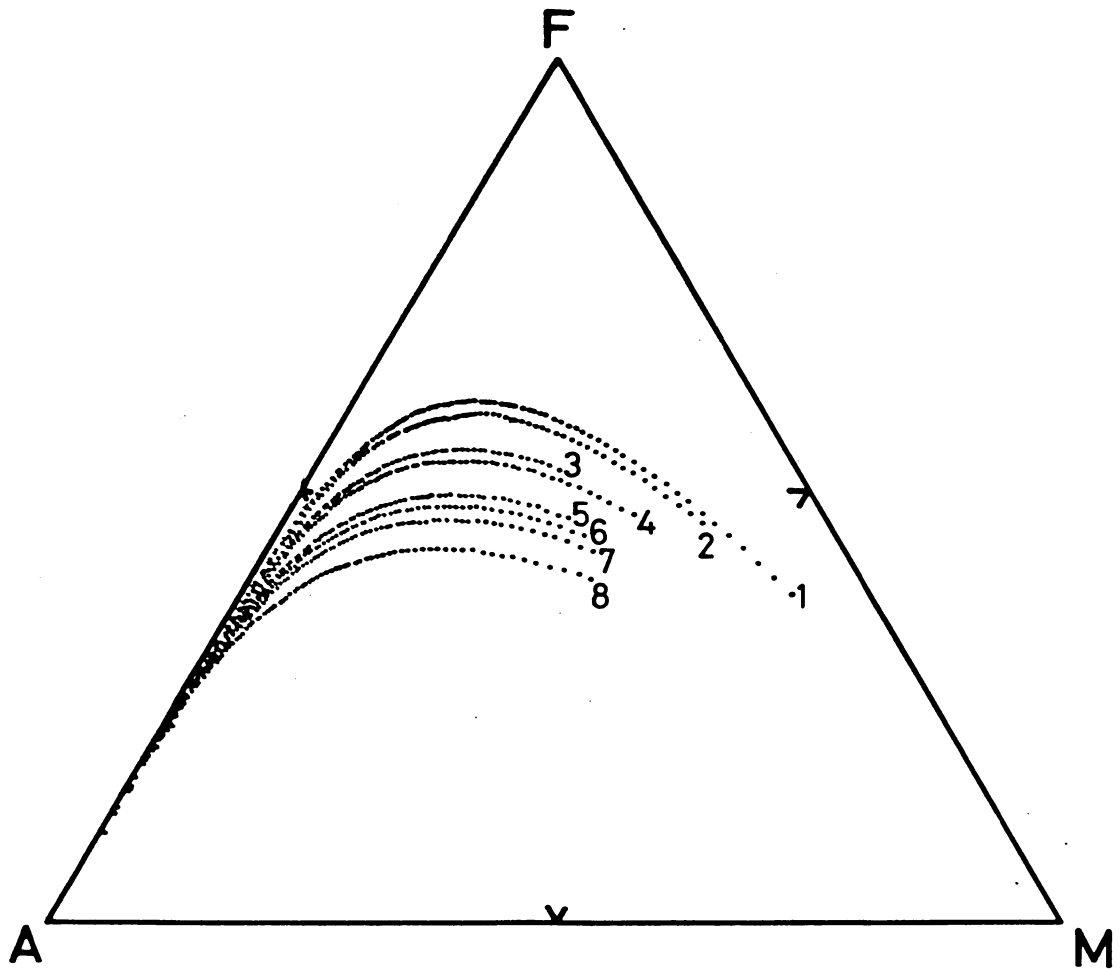


Fig. 8-3

Results of olivine fractionation from eight magmas.

- 1, Muskox intrusion (Irvine, 1979)
- 2, Skaergaard intrusion (Wager and Brown, 1967)
- 3, Lesser Antiles (Best, 1969)
- 4, Cascade (Carmichael, 1964)
- 5, South California batholith (Best, 1969)
- 6, Mt. Lassen (Best, 1969)
- 7, Crater Lake (Best, 1969)
- 8, Caledonide (Best, 1969)

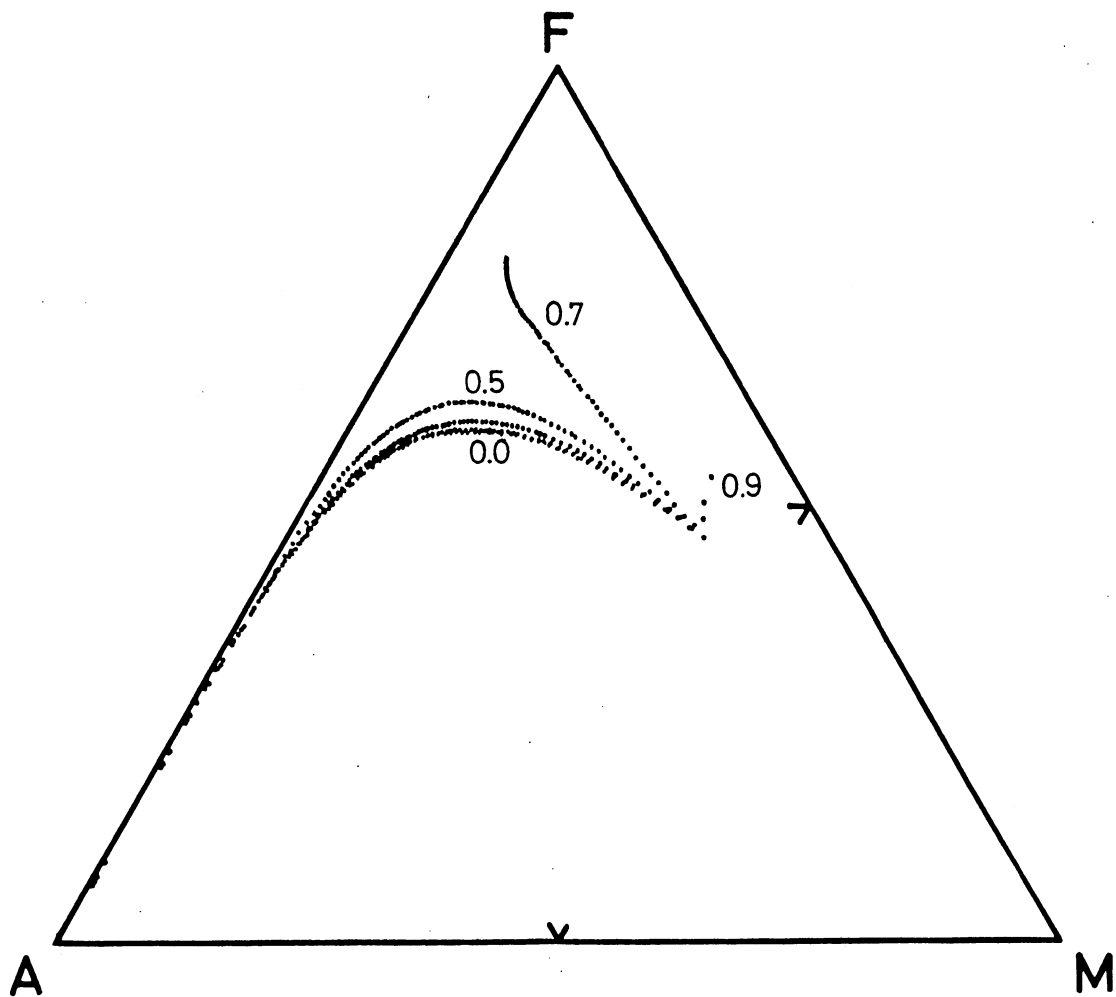


Fig. 8-4

Result of olivine plus plagioclase fractionation from the Skaergaard initial magma. Pl ratio (plagioclase / plagioclase+plivine) is shown near the result.

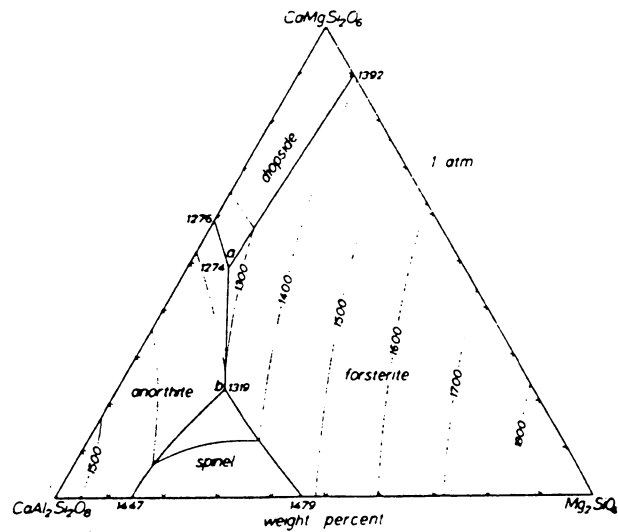


Fig. 8-5

Liquidus phase relations in the join $\text{CaMgSi}_2\text{O}_6$ - Mg_2SiO_4 - $\text{CaAl}_2\text{Si}_2\text{O}_8$, redrawn after Osborn and Tait (1952), Hytönen and Schairer (1961), Kushiro and Schairer (1963), and Kushiro (1972).

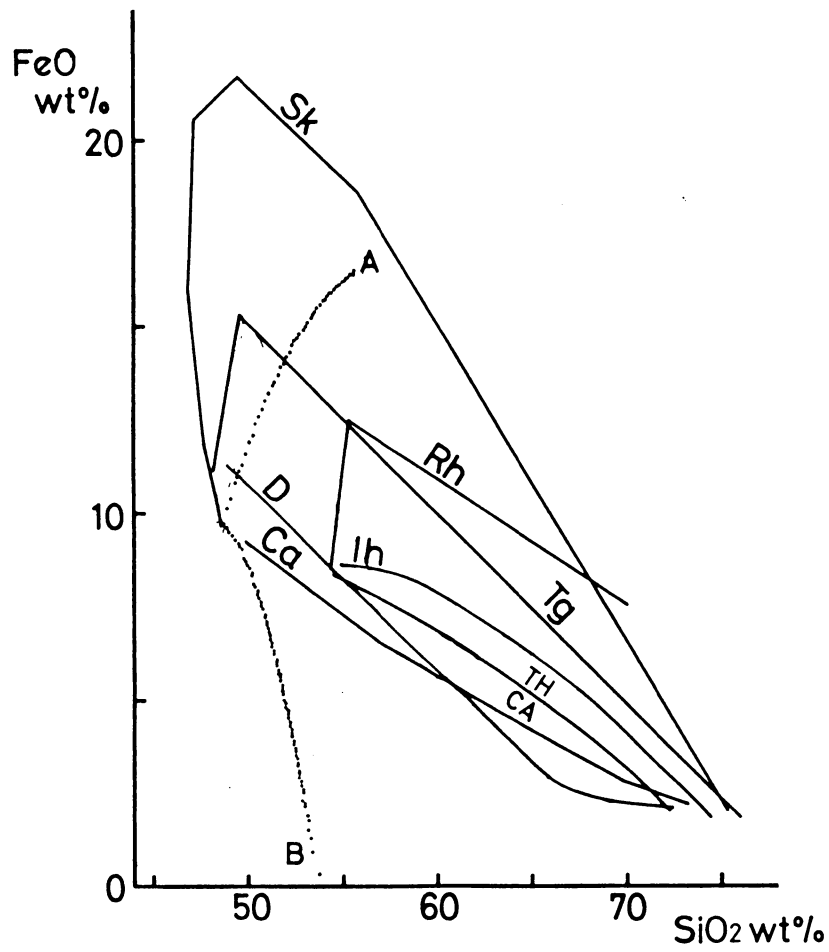


Fig. 8-6

SiO₂-FeO diagram. A, result of fractionation of olivine 30 per cent plus plagioclase 70 per cent. B, result of fractionation of olivine alone.

There is a natural ground that calc-alkalic rocks crystallize under the hydrous conditions and tholeiitic rocks crystallize under the anhydrous conditions. For example, calc-alkalic rocks have hydrous silicates such as hornblende and biotite, while tholeiitic rocks have commonly no hydrous phase. Fig. 8-7 shows that the precipitation temperature of plagioclase is remarkably reduced at high P_{H_2O} ($P_{H_2O} = 5\text{kbar}$) and in fact plagioclase fractionation is not useful at the hydrous conditions.

Fenner (1929) emphasized the enrichment of the residual liquid in iron during the fractional crystallization of basaltic magma by the reason that the mafic silicates have always higher $Mg/Mg + Fe$ ratio than the magma. Since his discussion, many authors thought that the fractionation of common mafic silicate from basaltic magma could not explain the genesis of the calc-alkalic suite. For example, Kushiro (1979) said about the amphibole fractionation, "They (Holloway and Burnham, 1972) also showed that all the amphiboles analyzed have lower Fe/Mg than coexisting glass, indicating that the liquid become iron-rich by separation of amphibole alone is, therefore, not effective in generating a calc-alkalic trend with no iron enrichment.". Fig. 8-8 is $FeO + Fe_2O_3/FeO + Fe_2O_3 + MgO-SiO_2$ diagram for some volcanic suites shown by Osborn (1979). As shown in this diagram, calc-alkalic rock series (A, C and P) show the enrichment in $FeO + Fe_2O_3/FeO + Fe_2O_3 + MgO$ as well as tholeiitic rock series. It is not necessarily accuracy, therefore, that the separation of mafic silicate such as amphibole is not effective in generating the calc-alkalic trend. Significant chemical character of calc-alkalic series is not

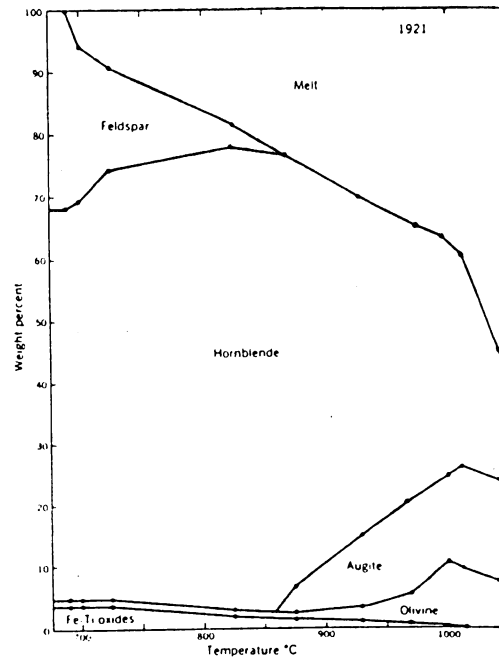


Fig. 8-7

Modal composition (weight per cent) plotted against temperature for the 1921 Kilauea olivine tholeiite melted at $P_{H_2O} = 5\text{ kbar}$ (after Helz, 1976).

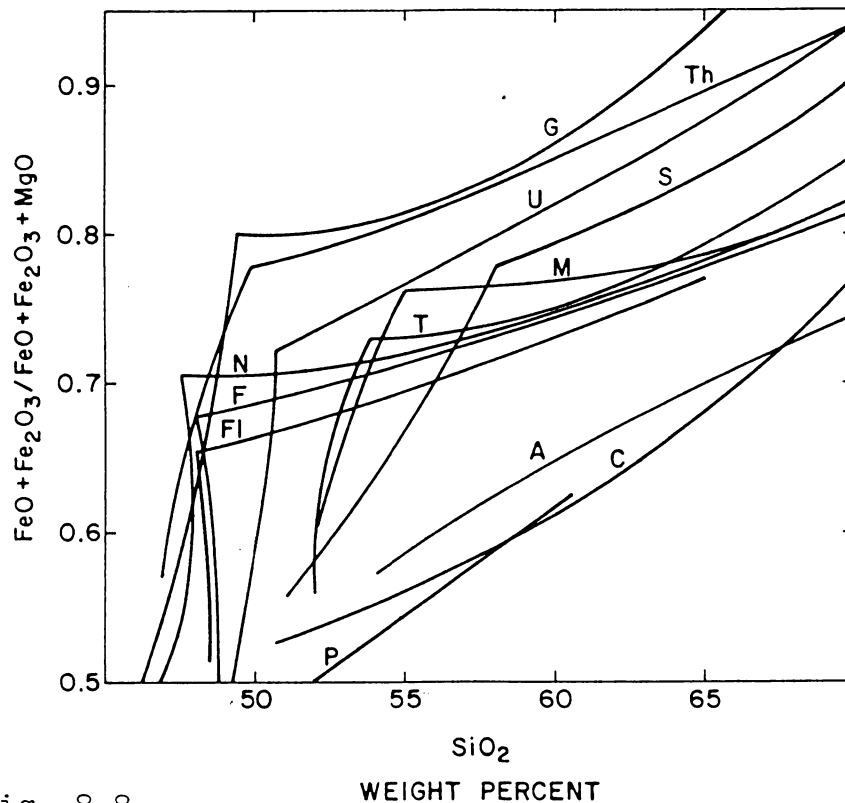


Fig. 8-8 Curves representing $(\text{FeO} + \text{Fe}_2\text{O}_3)/(\text{FeO} + \text{Fe}_2\text{O}_3 + \text{MgO})$ vs. SiO_2 for volcanic rock suites. Abbreviations: *G* = Galápagos Islands [plot of analyses reported by McBirney and Aoki (1966)]; *Th* = Thingmuli volcano, Iceland, after Carmichael (1964); *U* = Northeast Umnak Island, Aleutian Islands, Alaska [plot of analyses reported by Byers (1961)]; *S* = Santorini volcano, Cyclades, Greece [curve for the Main Series, after Nicholls (1971)]; *M* = Mashu volcano, East Hokkaido, Japan, after Katsui, Ando, and Inaba (1975); *T* = Talasea Peninsula, New Britain, Papua New Guinea [plot of analyses reported by Lowder and Carmichael (1970)]; *N* = Nicaragua [plot of analyses reported by Williams (1952), McBirney and Williams (1965), Williams and McBirney (1969) and Ui (1972)]; *F* = Vitu Levu, Fiji [plot of analyses reported by Gill (1970)]; *FI* = Flores Group, Indonesia [plot of analyses reported by Newman van Padang (1951)]; *A* = Aegean [curve for lavas of the western South Aegean Arc, after Nicholls (1971)]; *C* = Cascades, western United States, after Osborn (1959); *P* = Parícutin volcano, Mexico [plot of analyses reported by Wilcox (1954), Foshag and Gonzáles (1956), and Tilley, Yoder, and Schairer (1966)]. Analyses for *G*, *U*, *N*, *F*, *FI*, and *P* were taken from the data base of F. Chayes at the Geophysical Laboratory, by routine application of his information system, RKNFSYS.

(after Osborn, 1979)

decrease in $\text{FeO} + \text{Fe}_2\text{O}_3 / \text{FeO} + \text{Fe}_2\text{O}_3 + \text{MgO}$ but absolute decrease in iron. It is not always necessary for generation of calc-alkalic trend that the fractionated material has higher FeO/MgO than coexisting liquid.

Plagioclase plays a role of diluting the total iron content in fractionated solid material, while mafic silicate such as olivine has a role of concentrating the total iron content (Fig. 8-2). As a result of this brief discussion, it is suggested that anhydrous conditions make the plagioclase fractionation useful and in consequence the total iron content in solid fraction becomes lower than that in basaltic magma, and that hydrous conditions make the plagioclase fractionation unuseful and the total iron content becomes higher than that in basaltic magma. The former may explain the tholeiitic differentiation and the latter may explain the calc-alkalic differentiation.

Chapter 9

COMPARISON OF THE PANKENUSHI INTRUSION WITH
THE COMMON STRATIFORM TYPE INTRUSION

The Skaergaard, Bushveld and Stillwater intrusions are representative examples of tholeiitic layered differentiated body. The Pankenushi intrusion has quite different features from those of them, though that belongs to tholeiitic suite. Table 9-1 shows the contrastive characters between the Pankenushi intrusion and the common stratiform type intrusion.

Parental magma of the stratiform type is, in general, olivine tholeiite and that of the Pankenushi intrusion is estimated to be olivine tholeiite. Crystallization sequence in the stratiform type is observed from the lower part to the upper part in the vertical section. On the other hand, the sequence in the Pankenushi intrusion is observed from the central to the both sides along the horizontal section. Accordingly, the mechanism of the fractionation in the stratiform type is due to gravity settling and that in the Pankenushi intrusion is considered to be the flowage differentiation.

The differences in the petrographical properties are more obvious. Spinel phase in the stratiform type is generally chromitic in composition. On the other hand, that in the Pankenushi intrusion is Al-rich chromian spinel. Olivines in the stratiform type have a wide range of composition and show a compositional break in the middle of the range.

stratiform type		Pankenushi intrusion
magma type	olivine tholeiite	olivine tholeiite
magma series	tholeiitic (troctolite fractionation)	tholeiitic (troctolite fractionation)
crystallization process	from lower to upper	from central to both sides
mechanism of fractionation	gravitational settling	flowage differentiation (?)
mineralogy		
spinel phase	chromitic	Cr-spinel
olivine	strong iron enrichment with compositional break	strong iron enrichment without compositional break
Ca-poor pyroxene	change from orthopyroxene to pigeonite	orthopyroxene
hydrous phase	absent in general	present
Fe-Ti oxide	magnetite+ilmenite	ilmenite
tectonic setting	stable continental crust	mobile belt

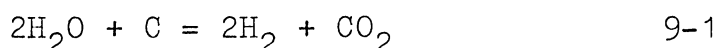
Table 9-1 Comparison between the Pankenushi intrusion and the common stratiform intrusion.

The Pankenushi olivines do not show the break in composition, though they also have a wide range of composition. Both orthopyroxene and pigeonite are found in the stratiform type, on the other hand, in the Pankenushi intrusion Ca-poor pyroxene is orthorhombic only and pigeonite is lacking. The presence of the hydrous phases in the Pankenushi intrusion is in a marked contrast to the absence of them in the stratiform type. Fe-Ti oxide found in the stratiform type is both magnetite and ilmenite. That in the Pankenushi intrusion is ilmenite only.

In consideration of the above mentioned differences, the Pankenushi intrusion gives quite unique and unreported example of the differentiated igneous body belonging to tholeiitic suite.

The lack of the compositional break of olivine is probably explained by the crystallization under the rather high pressure conditions as mentioned in Chapter 5. Presence of hydrous silicates indicates that ~~some amount of~~ water is contained in magma. Relatively low temperature estimated by the presence of orthopyroxene in place of pigeonite may be explained by the presence of water, because the presence of water decreases the crystallization temperature. There is two possibilities to explain the origin of water. One possibility is the addition of crustal water and the other is mantle water. The latter, in other words, means that the water is produced by the partial melting of the hydrous mantle. The solution of the problem on the origin of water will be postponed to a future time.

The absence of magnetite and the composition of ilmenite indicate the relatively reduced condition, in spite of the presence of water. This dilemma is probably solved by only the presence of graphite. Although graphite is not confirmed in the Pankenushi gabbro, if graphite is present, the partial pressure of oxygen does not increase as shown in equation 9-1.



If graphite is lacking, the partial pressure of oxygen is defined in rather high value by the dissociation reaction of water (equation 9-2).



It is possible to assume the presence of graphite, because the Pankenushi intrusion was emplaced in the thick sedimentary rocks.

Tholeiitic Pankenushi intrusion has quite different features from those in the common stratiform type intrusion belonging to tholeiitic suite as mentioned above. However, the presence of troctolite fractionation is only common feature. Therefore fractionation of plagioclase is considered to be indispensable condition in generating the tholeiitic trend as suggested in Chapter 8. Although there may be some factors which result the differences between the two types, the fundamental cause is probably due to the difference in the place of the igneous activity. Stratiform type intrusions were emplaced in the stable crust of continental environment. The Pankenushi intrusion was, on the other hand, emplaced in the mobile belt, i.e. the Hidaka metamorphic belt.

ACKNOWLEDGEMENTS

I would greatly acknowledge my supervisor, Prof. Seiji Hashimoto, for guiding me and encouragement throughout this study.

I would like to thank Drs. Masayuki Komatsu, Sumio Miyashita, Masao Nochi, Kiyooki Niida, Kazunori Arita, Teruo Watanabe and Mr. Yoichi Motoyoshi, for kind suggestions and discussions.

Analyses of bulk rock composition were carried out at Hokkaido National Agricultural Experiment Station. I would like to thank Dr. Sin-ichi Yamasaki for his help and guidance. Analyses of constituent minerals were carried out at Niigata University, Akita University and Hokkaido University. I would like to thank Profs. Mitsuo Shimazu, Kaichi Matsubara, Drs. M. Komatsu, Takahiko Maruyama and Mr. Hiromichi Kuwahata. The members of "Research Group of Mobile Belt in Hokkaido" gave me valuable suggestions in both field survey and laboratory works. Mr. Shigeshi Ohta, Miss Chiaki Sato and Mrs. Emiko Kato gave technical assistance for the present study. I would thank all of these persons.

REFERENCES

- Bence, A. E. and Albee, A. L., 1968. Empirical correction factors for the electron microanalysis of silicates and oxides. *J. Geol.*, 76: 382-403.
- Best, M. G., 1963. Petrology of the Guadalupe igneous complex, south-western Sierra Nevada foothills, California. *J. Petrol.*, 4: 223-259.
- Best, M. G., 1969. Differentiation of calc-alkaline magmas. *Proc. Andesite Conf.*, 65-75.
- Best, M. G. and Mercy, E. L. P., 1967. Composition and crystallization of mafic minerals in the Guadalupe igneous complex, California. *Am. Min.*, 52: 436-474.
- Bowen, N. L. and Schairer, J. F., 1935. The system MgO-FeO-SiO_2 . *Am. J. Sci.*, 29: 151-217.
- Brown, G. M., 1957. Pyroxenes from the early and middle stages of fractionation of the Skaergaard intrusion, west Greenland. *Min. Mag.*, 31: 511-543.
- Brown, G. M., 1967. Mineralogy of basaltic rocks. In: H. H. Hess and A. Poldervaart (ed.), *Basalts*. Interscience, 1: 103-162.
- Brown, G. M. and Vincent, E. A., 1963. Pyroxenes from the late stage of fractionation of the Skaergaard intrusion, east Greenland. *J. Petr.*, 4: 175-197.
- Byers, F. M., 1961. Volcanic suite, Umnak and Bogoslof Islands, Aleutian Islands, Alaska. *Geol. Soc. Am. Bull.*, 72: 93-128.
- Cameron, E. N., 1977. Chromite in the central sector of the Eastern Bushveld complex, south Africa. *Am. Min.*, 62:

1082-1096.

- Carmichael, I. S. E., 1964. The petrology of Thingmuli, a Tertiary volcano in eastern Iceland. *J. Petr.*, 5: 435-460.
- Czamanske, G. K. and Wones, D. R., 1973. Oxidation during magmatic differentiation, Finnmarka, Oslo area, Norway: Part 2. The mafic minerals. *J. Petr.*, 14: 349-380.
- Daly, R. A., 1914. *Igneous Rocks and Their Origin*. McGraw Hill.
- Foshag, W. F. and Gonzáles, J., 1956. Birth and development of Parícutin volcano, Mexico. *U. S. Geol. Surv. Bull.*, 965-D: 355-489.
- Gibb, F. G. F., 1973. The zoned clinopyroxenes of the Shiant Isles sill, Scotland. *J. Petr.*, 14: 203-230.
- Gill, J. B., 1970. Geochemistry of Vitu Levu, Fiji, and its evolution as an island arc. *Contrib. Min. Petr.*, 27: 179-203.
- Hamlyn, P. R., 1975. Chromite alteration in the Panton sill, east Kimberley region, western Australia. *Min. Mag.*, 40: 181-192.
- Hashimoto, S., 1975. The basic plutonic rocks of the Hidaka metamorphic belt, Hokkaido. Part 1. *J. Fac. Sci., Hokkaido Univ.*, ser 4, 16: 367-420.
- Haslam, H. W., 1968. The crystallization of intermediate and acid magma at Ben Nevis, Scotland. *J. Petr.*, 9: 84-104.
- Helz, R. T., 1976. Phase relations of basalts in their melting ranges at $P_{H_2O} = 5\text{kb}$. Part II. Melt compositions. *J. Petr.*, 17: 139-193.

- Henderson, P., 1975. Reaction trends shown by chrome-spinels of the Rhum layered intrusion. *Geochim. Cosmochim. Acta*, 39: 1035-1044.
- Henderson, P. and Suddaby, P., 1971. The nature and origin of the chrome-spinel of the Rhum layered intrusion. *Contrib. Min. Petr.*, 33: 21-31.
- Hytönen, K. and Schairer, J. F., 1961. The plane enstatite-anorthite-diopside and its relation to basalts. *Carnegie Inst. Wash., Year Book*, 60: 125-141.
- Irvine, T. N., 1979. Rocks whose composition is determined by crystal accumulation and sorting. In: H. S. Yoder, Jr. (ed.), *The Evolution of the Igneous Rocks*. Princeton Univ. 245-306.
- Katsui, Y., Ando, S., and Inaba, K., 1975. Formation and magmatic evolution of Mashu volcano, east Hokkaido, Japan. *J. Fac. Sci., Hokkaido Univ.*, ser. 4, 16: 533-552.
- Komatsu, M., Arita, K., Miyashita, S., Maeda, J., and Motoyoshi, Y., 1979. The boundary between the Western zone and the Main zone of the Hidaka metamorphic belt. 86th Ann. Meet., *Geol. Soc. Jap. Abstract* 289.
- Kuno, H., 1954. *Kazan oyobi Kazangan*. Iwanami.
- Kushiro, I., 1972. Determination of liquidus relations in synthetic silicate systems with electron microprobe analysis: The system forsterite-diopside-silica at 1 atmosphere. *Am. Min.*, 57: 1260-1271.
- Kushiro, I., 1979. Fractional crystallization of basaltic magma. In: H. S. Yoder, Jr. (ed.), *The Evolution of the Igneous Rocks*. Princeton Univ. 245-306.

- Kushiro, I. and Schairer, J. F., 1963. New data on the system diopside-forsterite-silica. Carnegie Inst. Wash. Year Book 62: 95-103.
- Leake, B. E., 1968. A catalog of analyzed calciferous and subcalciferous amphiboles together with their nomenclature and associated minerals. Geol. Soc. Am., Spec. Papers 98.
- Longhi, J., Walker, D., and Hays, L. F., 1978. The distribution of Fe and Mg between olivine and lunar basaltic liquids. Geochim. Cosmochim. Acta, 42: 1545-1558.
- Lowder, G. G. and Carmichael, I. S. E., 1970. The volcanoes and caldera of Talasea, New Britain: geology and petrology. Geol. Soc. Am. Bull., 81: 17-38.
- McBirney, A. R. and Aoki, K., 1966. Petrology of the Galápagos Islands. Proc. Symp. Galapagos Intern. Sci. Proj., 71-77.
- McBirney, A. R. and Williams, H., 1965. Volcanic history of Nicaragua. Univ. Calif. Publ. Geol. Sci., 55.
- McDougall, I., 1962. Differentiation of the Tasmanian dolerites: Red Hill dolerite-granophyer association. Geol. Soc. Am. Bull., 73: 279-316.
- Miyashiro, A., 1974. Volcanic rock series in island arcs and active continental margins. Am. J. Sci., 274: 321-355.
- Miyashiro, A., 1978. Nature of alkalic rock series. Contrib. Min. Petr., 66: 91-104.
- Miyashiro, A. and Kushiro, I., 1975. Gansekigaku II. Kyoritsu.
- Miyashita, S. and Hashimoto, S., 1975. The layered basic complex of Mt. Poroshiri, Hokkaido, Japan. J. Fac. Sci., Hokkaido Univ., ser. 4, 16: 421-452.

- Miyashita, S. and Maeda, J., 1975. The basic plutonic and metamorphic rocks from the northern Hidaka metamorphic belt, Hokkaido. Monograph Assoc. Geol. Collab., Jap., 21: 43-60.
- Morse, S. A., 1979. Kiglapait geochemistry I: Systematics, sampling, and density. J. Petr., 20: 555-590.
- Motoyoshi, Y., 1980. Petrology of the Horoman plutonic complex of the Hidaka metamorphic belt. Master thesis, Hokkaido Univ.
- Newmann, van Padang, M., 1951. Catalogue of the World, Part I, Indonesia, Intern. Volc. Assoc., 161-213.
- Nicholls, I. A., 1971. Petrology of Santorini volcano, Cyclades, Greece. J. Petr., 12: 67-119.
- Nochi, M. and Komatsu, M., 1967. Ultrabasic rocks in the Hidaka metamorphic belt, Hokkaido, Japan. II. Petrological relationships of the ultrabasic rock and the olivine gabbro in the Wensaru- Pankenushi area. Earth Sci., 21: 11-26.
- Osborn, E. F., 1959. Role of oxygen pressure in the crystallization and differentiation of basaltic magma. Am. J. Sci., 257: 609-647.
- Osborn, E. F., 1979. The reaction principle. In: H. S. Yoder, Jr. (ed.), The Evolution of the Igneous Rocks. Princeton Univ. 133-169.
- Osborn, E. F. and Tait, D. B., 1952. The system diopside-forsterite-anorthite. Am. J. Sci., Bowen vol., 413-423.
- Presnall, D.C., Dixon, S. A., Dixon, J. R., O'Donnel, T. H., Brenner, N. L., Schrock, R. L., and Dycus, D. W., 1978. Liquidus phase relations in the join diopside-forsterite-

- anorthite from 1 atm to 20 kbar: Their bearing on the generation and crystallization of basaltic magma. *Contrib. Min. Petr.*, 66: 203-220.
- Roeder, P. L. and Emslie, R. F., 1970. Olivine-liquid equilibrium. *Contrib. Min. Petr.*, 29: 275-289.
- Seward, T. M., 1971. The distribution of transitional elements in the system $\text{CaMgSi}_2\text{O}_6\text{-Na}_2\text{Si}_2\text{O}_5\text{-H}_2\text{O}$ at 1,000 bars pressure. *Chem. Geol.*, 7: 73-95.
- Sigurdsson, H. and Schilling, J. G., 1976. Spinels in Mid-Atlantic Ridge basalt: Chemistry and occurrence. *Earth Planet. Sci. Lett.*, 29: 7-20.
- Tilley, C. E., Yoder, H. S., Jr., and Schairer, J. F., 1966. Melting relations of volcanic rock series. *Carnegie Inst. Wash. Year Book*, 65: 260-269.
- Ui, T., 1972. Recent volcanism in Masaya-Granada area, Nicaragua. *Bull. Volcanol.*, 36: 174-190.
- Vincent, E. A. and Phillips, R., 1954. Iron-titanium oxide minerals in layered gabbros of the Skaergaard intrusion, east Greenland. *Geochim. Cosmochim. Acta*, 6: 1-26.
- Wager, L. R. and Brown, G. M., 1967. *Layered Igneous Rocks*. Freeman.
- Wager, L. R. and Deer, W. A., 1939. Geological investigations in east Greenland. Part III. The petrology of the Skaergaard intrusion, Kangerdlugssuaq, east Greenland. *Medd. Grönland*, 105.
- Wilcox, R. E., 1954. Petrology of Parícutin volcano, Mexico. *U. S. Geol. Surv. Bull.*, 965-C: 281-353.
- Williams, H., 1952. The great eruption of Coseguina, Nicaragua, in 1935 with notes on the Nicaraguan volcanic chain. *Univ.*

- Calif. Publ. Geol. Sci., 85.
- Williams, H. and McBairney, A. R., 1969. Volcanic history of Honduras. Univ. Calif. Publ. Geol. Sci., 101.
- Wood, B. J. and Banno, S., 1973. Garnet-orthopyroxene and orthopyroxene-clinopyroxene relationships in simple and complex systems. Contrib. Min. Petr., 42: 109-124.
- Yamaguchi, S., Tsushima, K., and Satoh, H., 1978. 1:500,000 geological sheet map, Sheet 2 "Kushiro". Geol. Surv. Jap.
- Yamasaki, S., 1979. Operating instructions for X-ray emission spectrometer, Nodel AFV-777. Misc. Publ. Hokkaido Natl. Agric. Exp. Stn., 18: 39-100.
- Yamasaki, S., Katayama, M., and Sasaki, T., 1980. Total analysis of major constituents in soil by X-ray emission spectrometry with a glass beads technique. Soil Sci. Plant. Nutr., 26: 25-36.
- Yusa, Y., 1975. A rapid method for quantitative microprobe analysis of olivines, pyroxenes and feldspars. J. Jap. Assoc. Min. Petr. Econ. Geol., 70: 141-156.