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Late Mesozoic to Early Tertiary Basic-Acid Dyke Swarms in the Chugoku-Setouchi District, Southwest Japan

By

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with 3 Tables, 11 Text-figures and 1 Plate

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ABSTRACT: Late Mesozoic to Early Tertiary dykes in the Chugoku-Setouchi district, which is geologically placed in the Sanyo and Ryoke belt of the inner zone of Southwest Japan, have been described and discussed with special reference to their petrography, bulk chemical composition, and Fe-Ti oxides and magnetic susceptibility of basic dykes in this paper.

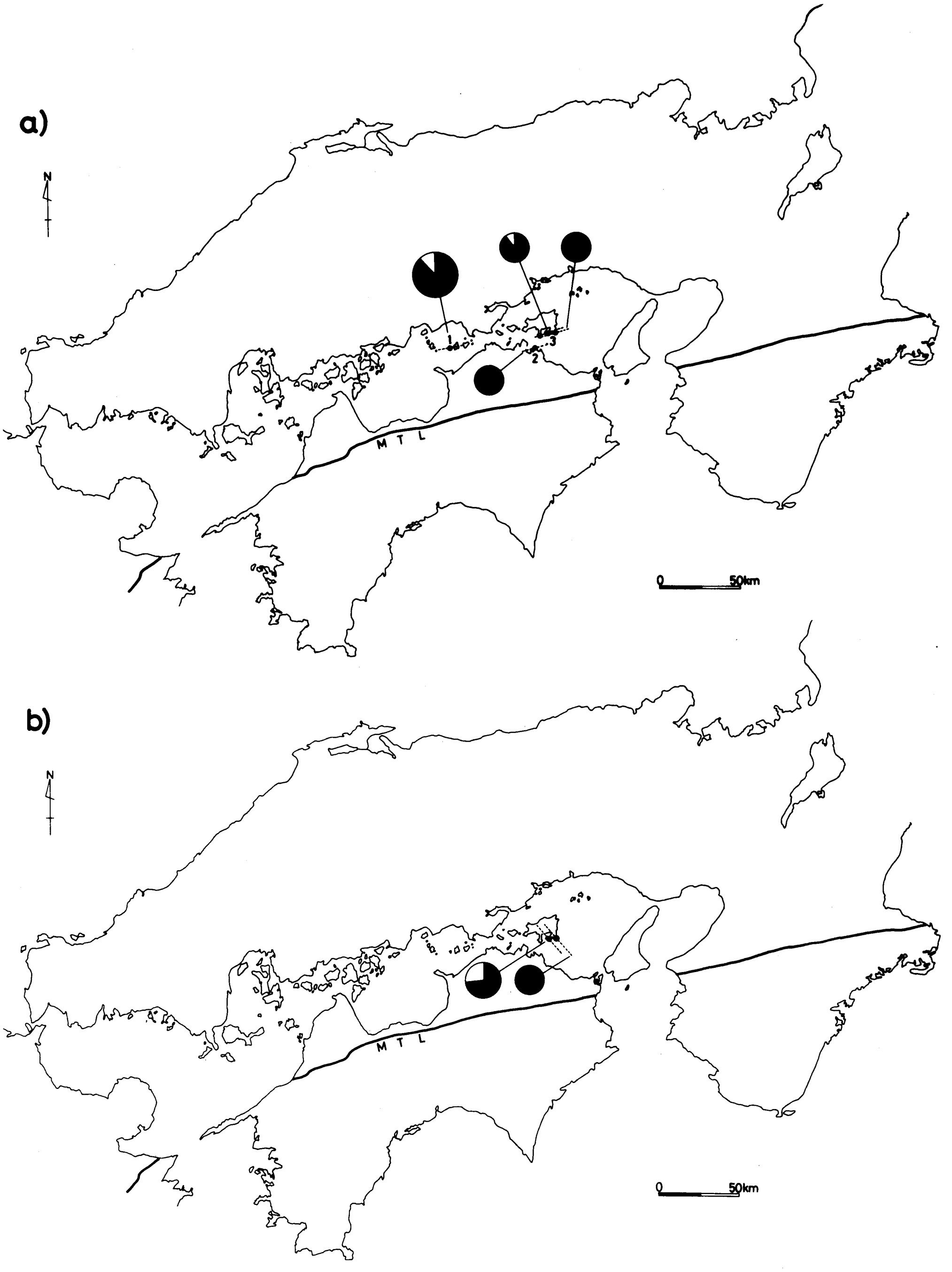
CONTENTS

I. INTRODUCTION AND RESEARCH HISTORY

Late Mesozoic to Early Tertiary violent felsic igneous activities in Circum-Pacific region occur in three modes, eruption of volcanics, emplacement of granites and intrusion of dykes as swarms, which are closely related to each other in space and time and so appear to have some genetic relations to each other. The inner zone of Southwest Japan belongs also to one of the sites of such the regional igenous activities. Late Mesozoic to Early Tertiary volcanic rocks and granites in this zone develop in several cycles, showing typical volcano-plutonic association (e.g. SAKIYAMA and IMAOKA, 1981). Remarkable data such as isotope age, whole rock and mineral chemistry, magnetic susceptibility, stable isotope and so on, have been recently accumulated for those volcanic rocks and granites. Late Mesozoic to Early Tertiary dykes also develop broadly as swarms in the inner zone of Southwest Japan. Those dykes will be studied in this paper.

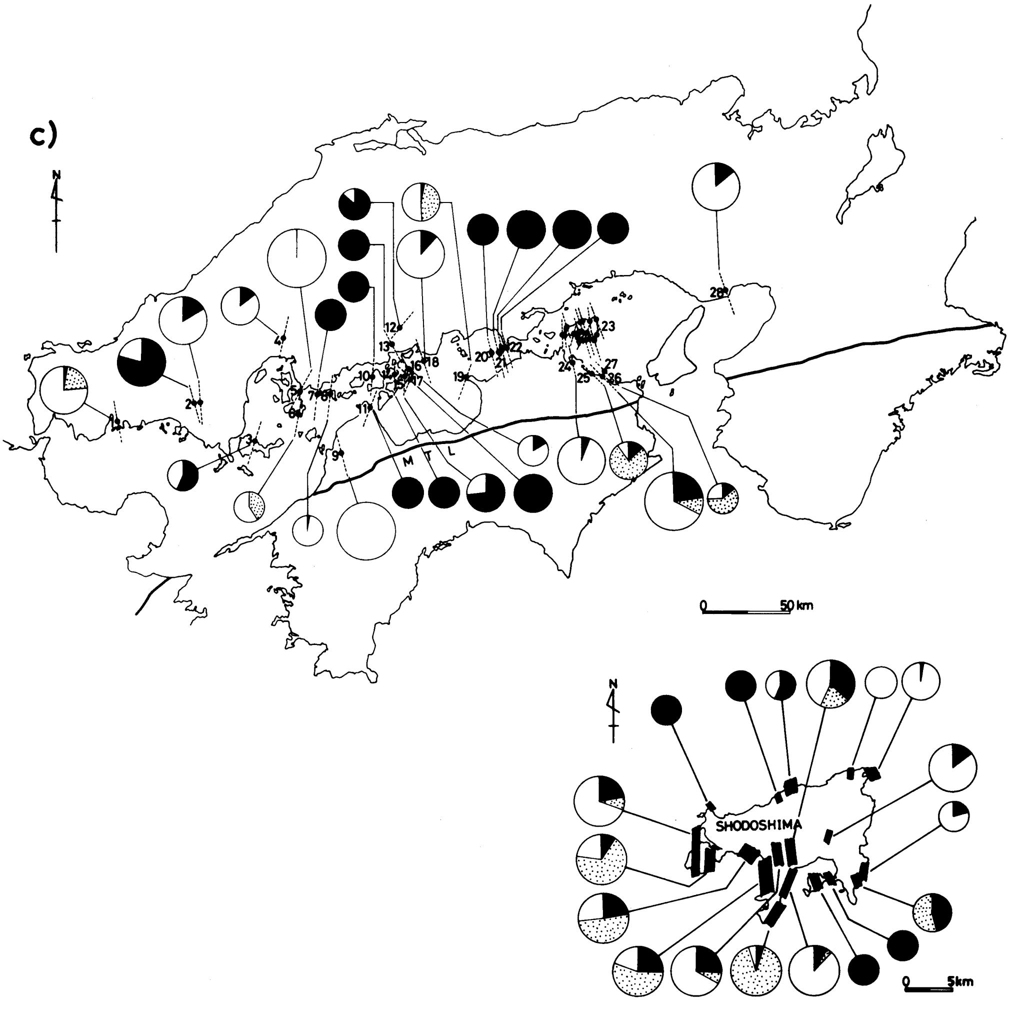
The first systematic study on Late Mesozoic to Early Tertiary dykes in the inner zone of Southwest Japan has been performed by YOKOYAMA *et al.* (1976), clarifying that they tend to occur as swarms in many isolated domains (dyke-domain) and, in individual dyke-domains, they are preferentially oriented parallel to the long axis of the dyke-domain. The area of dyke-domain appears to be between 2 km^2 and several tens km^2 and number of dykes in individual dyke-domains is between some tens and ca. 300, the majority being between 20 and 60 (YOKOYAMA, 1979).

Late Mesozoic to Early Tertiary dykes in the inner zone of Southwest Japan can be divided into five distinguishable populations with reference to intrusion age (YOKOYAMA, 1978, 1983-in press). Those five populations are different from each other in space of



activity (Yokoyama and Hara, 1981). The dyke population of the first generation and that of the second generation develop only in the Ryoke belt (Fig. 1, a) and b)). The distribution of the dyke population of the third generation extends from the Ryoke belt to the southern part of the Sanyo belt: Most of dyke-domains belonging to this population are placed in the Setouchi district (Fig. 1, c)). The dyke population of the fourth generation is poor but develops broadly in the Ryoke — Sanyo belt (Fig. 1, d)). Dykes of the fifth generation are mostly found in the northern part of the Sanyo belt (Fig. 1, e)). Thus, it has been pointed out that the center of dyke magmatism from the first generation to the fifth generation migrated successively toward the north (Yokoyama and Hara, 1981).

Many of dyke-domains consist of dykes of plural rock types which frequently show composite and multiple relationships (Fig. 1). The intrusion order changes from basic dykes to acid dykes in individual dyke-domains (Yokoyama, *et al.,* 1976; Yokoyama,

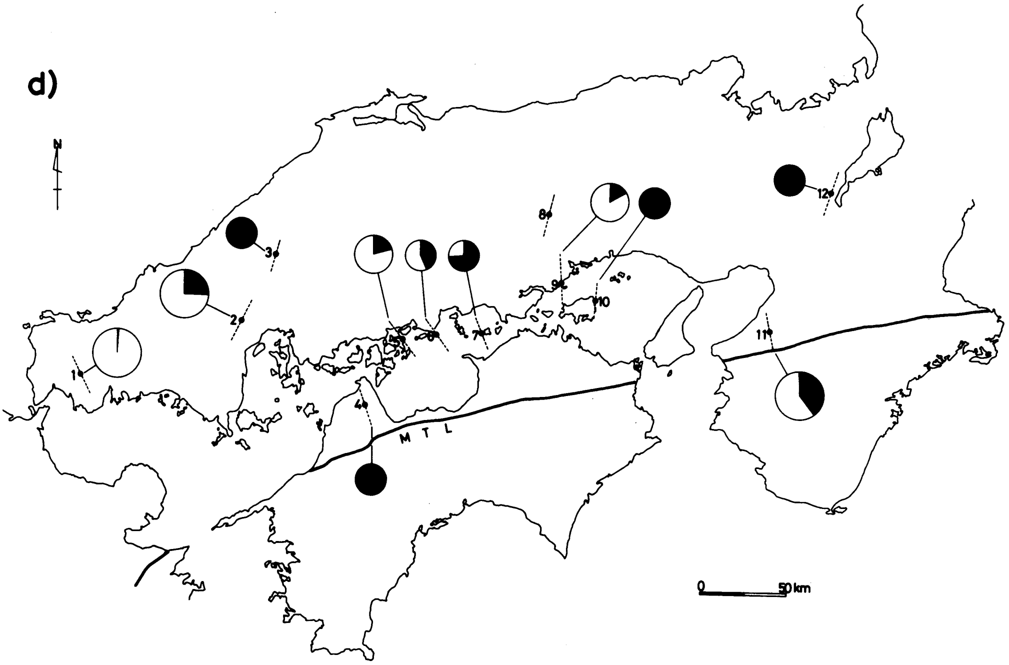


1979; Yokoyama and Hara, 1981). The earliest basic dykes and the latest acid dykes frequently occur as composite dykes in individual dyke-domains, showing that their activity was nearly contemporaneous. Thus, it has been pointed out that the five dyke populations correspond to five cycles of rhythmic magmatism from basic to acid (Yokoyama, 1979; Yokoyama and Hara, 1981).

Yokoyama *et al.* (1976), Yokoyama (1979) and Yokoyama and Hara (1981) have clarified that the widths of dykes in the inner zone of Southwest Japan show a distinct tendency to increase with increase of SiO_2 content and of volume of phenocrysts: Most of basic dykes are smaller in width than 1 m, while many of acid dykes are 50 cm to 10 m in width.

Late Mesozoic to Early Tertiary dykes in the inner zone of Southwest Japan show preferred orientation as clarified by Yokoyama *et al.* (1976), Yokoyama (1979) and Yokoyama and Hara (1981). The results are reproduced in Fig. 1. The dyke population of first generation shows a preferred orientation of ENE-WSW trend. The direction of preferred orientation of the dykes of the second generation is NW-SE. Both dykes of the third generation and of the fourth generation are preferentially oriented in two sets, NNW-SSE and NNE-SSW. The fifth dyke population shows a preferred orientation of ENE-WSW trend. The tectonic stress fields which were responsible for the formation of the five dyke populations have been also discussed by Yokoyama and Hara (1981).

On dykes found in Cretaceous granites in the inner zone of Southwest Japan are sometimes observed evidences indicating that they intruded when the host granites were still hot, i.e. they are synplutonic (Yokoyama, 1978, 1983-in press). All dykes of the first and the second generations are synplutonic, they being subjected to injection of granitic materials from their host, and all dykes of the fourth and the fifth generations have no



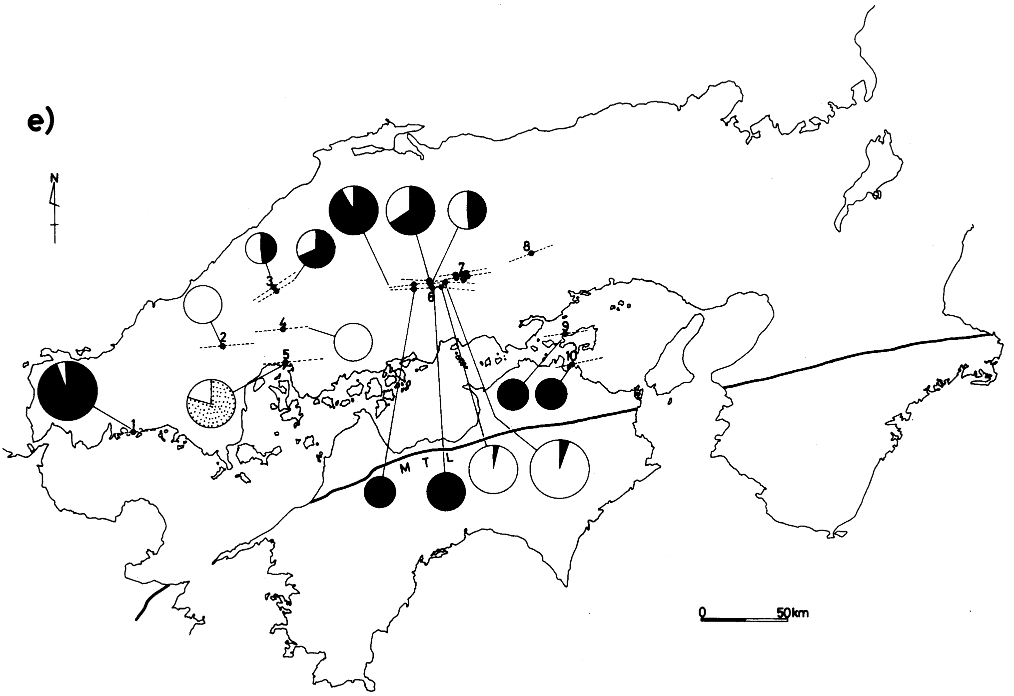


FIG. 1. Diagrams showing the proportion of total width of basic, intermediate and acid dykes in individual dyke-domains.

Dotted lines: dominant direction of dyke swarm [The orientation data of dykes are cited from YOKOYAMA *et al.* (1976), YOKOYAMA (1979) and YOKOYAMA and HARA (1981)], solid areas in circles: basic dykes, stippled areas in circles: intermediate dyke, open areas in circles: acid dyke, MTL: Median Tectonic Line. The sizes of circles indicate total amount of widths of dykes in individual dyke-domains: smallest circles: less than 50×10^2 cm, small circles: $50–100 \times 10^2$ cm, large circles: $100–400 \times 10^2$ cm, largest circles: more than 400×10^2 cm.

a) dykes of the first generation
locality: 1-Teshima & Oteshima, 2-Ookushi, 3-Shodoshima

b) dykes of the second generation
locality: Shodoshima

c) dykes of the third generation
locality: 1-Ogoori, 2-Yashiro, 3-Kuga, 4-Gongensan, 5-Ondo, 6-Kashima, 7-Shimokamagari, 8-Kamikamagari, 9-Matsuyama, 10-Oomishima, 11-Namikata, 12-Mitsugicho, 13-Mihara, 14-Ikuchijima, 15-Ikinajima, 16-Innoshima, 17-Yugejima, 18-Tashima, 19-Misaki, 20-Sanukihiroshima, 21-Mukuchijima & Honjima, 22-Shimotsui, Hitsuishijima & Igurojima, 23-Shodoshima, 24-Ookushi, 25-Sanbonmatsu, 26-Shirotori, 27-Futagojima, 28-Hiyodorigoe

d) dykes of the fourth generation
locality: 1-Kibe, 2-Rakan, 3-Ooasa, 4-Nibukawa, 5-Innoshima, 6-Sensuijima 7-Teshima, 8-Yanahara, 9-Ushimado, 10-Shodoshima, 11-Sennan, 12-Hiei

e) dykes of the fifth generation
locality: 1-Hofu, 2-Inumodorikyo, 3-Ooasa, 4-Nabarakyo, 5-Niho, 6-Yuki, 7-Nariwa, 8-Yanahara, 9-Shodoshima, 10-Ookushi.

evidence of synplutonism. While dykes of the third generation are slightly subjected to injection of granitic materials from the host granites.

In this paper will be described and discussed petrography, bulk chemical composition, chemistry of Fe–Ti oxides and magnetic susceptibility for the dykes of five populations mentioned above.

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II. PETROGRAPY OF DYKES

Late Mesozoic to Early Tertiary dykes in the Chugoku-Setouchi district are divided into three types, which will be named basic type, intermediate type and acid type, respectively, for convenience's sake, in this paper.

In the basic dykes are found two rock types, Hb-dominant type and Cpx-dominant type: Hb-dominant basic dykes consist mainly of hornblende and plagioclase, while Cpx-dominant basic dykes of clinopyroxene and plagioclase.

Basic dykes of the earlier three generations are of Hb-dominant type. Plagioclase phenocrysts (ca. 1–5 mm long) are visible in some of them. Hornblende phenocrysts are rare. A few dykes contain small amount of clinopyroxene as microphenocrysts. The groundmass has a distinctive texture of interlocking slender prisms (ca. 0.2 mm long) of plagioclase and amphibole accompanied with biotite flakes. Modal values of plagioclase are commonly ca. 50%. Though amphibole appears to have initially been brown hornblende, it is partly or completely altered to pale green or colourless amphibole. UJIKE (1977, 1978) described actionlite in basic dykes of Shirotori (Fig. 1, c)–26) and Shodoshima (Fig. 1, c)–23) which belong to the dyke population of the third generation. Biotite flakes occur commonly as euhedral or anhedral crystals replacing brown hornblende and secondary amphibole. The modal values of biotites in the Hb-dominant basic dykes are between 0% and 33%, the majority being between 10% and 17%.

The basic dykes of the first and the second generations are frequently strongly deformed showing development of schistosity in a single set, which is oriented in E–W trend (YOKOYAMA, 1983-in press). In such basic dykes is found preferred orientation of elongated amphibole aggregates.

Basic dykes of Cpx-dominant type are common in the dyke populations of the fourth and the fifth generations. Most of Cpx-dominant basic dykes of those generations show hydrothermal alteration, unlike in the case of the basic dykes of the earlier three generations.

In the Cpx-dominant basic dykes of the fourth and the fifth generations are commonly found relatively large euhedral crystals of plagioclase and clinopyroxene as micropheno-

TABLE 1. MODAL COMPOSITIONS OF BASIC DYKES OF FIVE GENERATIONS.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Clinopyroxene	—	—	1.3	—	—	—	—	—	—	0.4	—	—	19.2	8.5	6.9	13.0	1.6	14.7	1.5	8.6
Hornblende	45.7	39.6	7.5	23.2	18.9	29.2	26.5	38.0	21.9	47.5	27.6	40.8	5.6	6.7	2.0	—	—	—	—	—
Plagioclase	36.7	40.5	46.2	30.5	30.4	52.0	52.7	45.4	49.0	44.5	49.0	44.0	69.7	62.8	52.0	87.0	—	42.7	—	—
Plagioclase (phenocryst)	—	—	28.4	22.1	19.1	—	—	3.5	—	—	—	8.7	—	—	9.6	—	21.6	11.7	—	2.1
Quartz	0.3	3.3	3.0	4.4	tr.	3.1	6.1	0.8	6.5	—	5.4	1.4	3.2	—	tr.	—	—	—	tr.	—
Ilmenite	0.4	tr.	tr.	tr.	tr.	0.7	0.7	0.9	tr.	0.9	0.6	0.6	tr.	1.0	tr.	**	0.1	tr.	—	tr.
Magnetite	—	—	—	—	—	—	—	—	—	—	—	2.2	—	—	1.0	**	—	1.8	tr.	tr.
Biotite	17.0	16.7	9.5	15.4	31.3	15.0	14.0	10.7	22.6	1.5	17.4	—	—	—	—	—	—	—	—	—
Actinolite	—	—	3.8	4.4	—	—	—	—	—	3.7	tr.	—	—	—	—	—	—	—	—	—
Chlorite	—	—	—	—	—	—	—	0.8	—	—	—	2.3	13.9	18.0	31.7	**	5.3	28.7	tr.	16.9
Clinozoisite	—	—	—	—	—	—	—	—	—	—	—	—	tr.	3.0	—	—	—	—	**	—
Epidote	—	—	—	—	—	—	—	tr.	—	—	—	tr.	1.6	—	tr.	**	—	—	**	—
Calcite	—	—	—	—	—	—	—	—	—	—	—	—	—	—	**	—	—	—	—	—
Sericite	—	—	—	—	—	—	—	tr.	—	1.5	—	—	tr.	—	—	—	—	—	**	—
Sphene	—	—	—	—	—	—	—	—	—	—	—	—	tr.	—	—	—	—	—	—	—
groundmass*	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	71.6	—	98.5	72.0

* groundmass impossible to pointcount, ** ubiquitous, dykes of the first generation [1: 5253111 (Shodoshima), 2: 5252410 (Shodoshima), 3: 5252418 (Shodoshima), 4: 4940224 (Teshima)], dykes of the second generation [5: 5351602 (Shodoshima), 6: 5351612 (Shodoshima), 7: 5351906 (Shodoshima)], dykes of the third generation [8: 52402022 (Shodoshima), 9: 5252514 (Shodoshima), 10: 73003 (Shirotori), 11: 5382905 (Mukuchijima), 12: 5372402 (Mitsugicho)], dykes of the fourth generation [13: 5352201 (Shodoshima), 14: 50111505 (Nibukawa), 15: 5372605 (Innoshima), 16: 5150410 (Rakan)], dykes of the fifth generation [17: 5080401 (Hofu), 18: 50120905 (Yanahara), 19: 50110611 (Yuki), 20: 5151502 (Nariwa)].

crysts enclosed in a intersertal groundmass in which granules of clinopyroxene and Fe–Ti oxides and minute particles of chlorite, epidote and sericite fill interstices between unoriented plagioclase laths. Plagioclase phenocrysts (ca. 1–5 mm long) are visible in some dykes. Hornblende phenocrysts are rare. More felsic dykes may contain rounded and partially corroded crystals of quartz as phenocrysts.

The Cpx-dominant basic dykes are usually turbid as a result of hydrothermal alteration: Plagioclase phenocrysts are partly or almost completely clouded with minute grains of sericitic minerals, epidote, calcite and chlorite. Hornblende, if contained, alters commonly to chlorite. The groundmass is dusty with innumerable minute particles of probably sericitic minerals, chlorite and epidote. But, clinopyroxene is commonly flesh, though it is sometimes chloritized.

The distinct difference between the basic dykes of two types is shown by mineral assemblage and modal value of ferromagnesian silicate minerals (Table 1) as mentioned in the preceding paragraphs. The basic dykes of the earlier three generations are generally of Hb-dominant type, while those of the later two generations of Cpx-dominant type. The dykes of the first and the second generations are more or less subjected to injection of granitic materials from the granitic host and biotite is much more abundant in them than in the dykes back-veined by the granitic host are slighly found. While the basic dykes of the later two generations contain commonly clinopyroxene but not biotite. They appear to have intruded after complete consolidation and cooling of the host granites but commonly show hydrothermal alteration giving rise to chlorite in high modal values. A basic dyke of the fourth generation contains modal chlorite of 38%.

Dykes, which have been referred to as the intermediate type, are hornblende-plagioclase-granodiorite porphyry. They develop in the dyke populations of the later three generations. Typical petrographic characteristics of the dykes of this type are summarized as follows: The dykes are grayish white or greenish white and porphyritic under naked eyes. Modal values of phenocrysts are 65–70%. Hornblende phenocrysts are 1–15 mm in size, and plagioclase phenocrysts are 1–10 mm. Clinopyroxene is sometimes found as microphenocrysts. The groundmass is microcrystalline and occasionally spherulitic or micrographic. It consists mainly of plagioclase, quartz and potassium feldspar with apatite and opaque minerals as accessory minerals.

Among dykes, which have been referred to as the acid type, have been distinguished four rock types, plagioclase-tonalitic porphyry, granite-porphyry, plagioclase-granitic porphyry and felsite. The acid dykes of the earlier two generations are of plagioclase-tonalitic porphyry and granite-porphyry, while those of the later three generations are of granite-porphyry, plagioclase-granitic porphyry and felsite. Typical petrographic characteristics of the acid dykes are summarized as follows.

Plagioclase-tonalitic porphyry is grayish white or light gray and porphyritic under naked eyes. Modal values of phenocrysts are ca. 5%. They consist of plagioclase with size of 1–2 mm. The groundmass is hypidiomorphic-granular. It consists mainly of plagioclase, quartz and potassium feldspar with opaque minerals, zircon, apatite, and sphene as accessory minerals.

Granite-porphyry is grayish white or bluish white and porphyritic under naked eyes. Modal values of phenocrysts, which consist commonly of feldspar and quartz (2–15 mm long), though hornblende phenocrysts also occur in less abundance, are 50–70%. The groundmass is micrographic and consists mainly of plagioclase, quartz and potassium feldspar with opaque minerals, allanite and zircon as accessory mineral.

Plagioclase-granitic porphyry is yellowish milky white and porphyritic. There are plagioclase phenocrysts (usually a few milimeters in size) and often quartz microphenocrysts. Modal values of phenocrysts are more than 5%. The groundmass is cryptocrystalline to microcrystalline and sometimes has relatively large spherulites or aggregates of microspherulites. It consists mainly of plagioclase, quartz and potassium feldspar accompanying rarely biotite and hornblende. Its accessory minerals are of apatite and opaque minerals.

Felsite is yellowish milky white or dark bluish black with glassy luster and aphanitic, though sometimes weakly porphyritic. When it is porphyritic (with modal phenocrysts of less than 1%), the commonest phenocrysts are of plagioclase and quartz. The groundmass varies in texture from specimen to specimen or from place to place even within a thin section. It is cryptocrystalline, spherulitic or micrographic. The groundmass consists mainly of plagioclase, quartz and potassium feldspar accompanying sometimes biotite and hornblende. The accessory minerals are apatite, opaque minerals, zircon and allanite.

The intermediate and acid dykes of the later two generations show also hydrothermal alteration of their constituent minerals and usually more or less turbid microscopic appearance, like in the case of the basic dykes. Plagioclase phenocrysts are partly or almost completely clouded with minute flakes of sericitic minerals, epidote, calcite and chlorite, and ferromagnesian minerals such as biotite and hornblende are chloritized. The groundmass is commonly dusty with innumerable minute particles of probably sericitic minerals, chlorite and epidote. The dykes of the third generation, except for dykes back-veined by the granitic host, show also hydrothermal alteration of their constituent minerals. The acid dykes of the earlier two generations all are clear, like in case of the basic dykes.

III. CHEMISTRY OF DYKES

Analysis of bulk chemical compositions of dykes of five populations has been performed by a electron microprobe analyser (JXA–5A) on polished glass chip prepared by direct fusion method (cf. SUZUKI *et al.,* 1977). The results of the major element analysis are shown in Table 2 and Fig. 2.

SiO_2 content ranges from 49% to 64% in basic dykes from 64% to 67% in intermediate dykes and from 68% to 77% in acid dykes, respectively. SiO_2 content of basic dykes of the earlier two generations is much less than 55%, and that of basic dykes of the later two

TABLE 2. CHEMICAL COMPOSITIOMS OF DYKES OF FIVE GENERATIONS.

	SiO_2	TiO_2	Al_2O_3	FeO^*	MnO	MgO	CaO	Na_2O	K_2O	Total
1	48.78	1.48	15.17	11.77	0.37	7.23	10.01	3.02	1.67	99.45
2	52.70	1.93	18.50	10.56	0.29	3.65	8.35	3.57	0.85	100.40
3	53.16	1.73	17.54	10.05	0.26	4.04	8.08	3.10	1.51	99.38
4	50.33	1.17	19.09	8.88	0.22	5.83	10.16	2.95	0.84	99.47
5	50.72	0.91	19.11	8.09	0.24	6.63	10.44	2.22	0.53	98.89
6	53.77	1.14	18.17	8.56	0.29	4.42	8.15	3.44	1.73	99.67
7	55.25	1.03	18.45	7.94	0.31	5.32	8.54	2.30	1.07	100.21

TABLE 2. (Continued)

	SiO_2	TiO_2	Al_2O_3	FeO*	MnO	MgO	CaO	Na_2O	K_2O	Total
8	55.56	1.22	18.06	7.93	0.21	4.81	8.85	3.24	1.15	100.94
9	50.66	1.35	18.43	9.66	0.28	5.97	9.45	2.67	1.81	100.28
10	51.03	1.28	19.12	8.03	0.31	7.03	10.53	2.23	0.83	100.39
11	51.57	1.51	18.24	9.45	0.32	4.98	9.03	2.95	1.41	99.46
12	51.90	1.31	19.41	9.16	0.73	3.79	10.34	2.59	1.19	100.42
13	53.48	0.31	17.18	9.16	0.17	5.31	9.48	3.16	0.97	99.22
14	57.40	1.60	16.17	9.11	0.30	2.82	6.98	3.35	1.53	99.28
15	58.11	1.25	17.78	7.58	0.27	2.86	7.13	2.90	1.65	99.53
16	58.39	1.15	16.93	7.55	0.36	2.55	7.93	2.95	1.26	99.05
17	59.42	1.17	17.85	6.76	0.27	2.42	8.04	2.73	1.43	100.09
18	62.53	1.17	15.16	8.28	0.37	1.46	5.56	3.47	2.00	100.00
19	64.64	0.74	17.00	4.27	0.24	1.80	4.38	2.90	3.33	99.27
20	66.69	0.65	17.00	4.06	0.16	1.45	4.44	3.14	2.25	99.84
21	66.18	0.47	14.62	4.95	0.07	1.36	3.75	4.12	3.13	100.63
22	71.65	0.27	14.84	3.26	0.15	0.34	2.40	3.25	3.21	99.34
23	72.02	0.21	15.55	2.59	0.12	0.28	2.60	2.94	2.99	99.30
24	53.50	1.16	16.93	7.99	0.08	9.29	2.76	2.74	0.74	100*
25	54.56	1.24	17.80	8.30	0.21	5.35	9.03	3.30	0.88	100*
26	54.83	1.19	16.86	7.76	0.13	6.02	9.62	2.55	0.50	100*
27	57.27	1.24	17.39	7.46	0.16	4.02	7.82	2.73	1.79	100*
28	58.77	1.55	17.06	8.01	0.15	3.00	7.28	2.58	1.58	100*
29	72.02	0.36	14.36	2.55	0.07	0.78	2.57	3.73	3.40	100*
30	74.12	0.17	13.52	2.03	0.04	0.36	1.38	3.96	4.29	100*
31	74.35	0.15	13.60	2.28	0.04	0.25	1.61	3.78	4.34	100*
32	75.81	0.15	12.56	1.44	0.03	0.47	1.17	3.94	4.37	100*
33	76.01	0.13	12.73	1.22	0.04	0.32	1.11	4.20	4.12	100*
34	76.98	0.02	12.41	1.15	0.01	0.12	0.86	3.74	4.84	100*
35	48.86	1.22	22.30	9.38	0.13	3.84	11.86	2.52	0.51	100*
36	52.04	1.22	19.55	8.76	0.16	5.43	9.34	2.75	0.40	100*
37	52.08	1.20	18.33	9.60	0.18	5.53	9.09	2.44	1.16	100*
38	52.51	1.20	17.25	9.43	0.20	6.89	8.88	2.47	0.83	100*
39	52.72	1.32	17.31	10.08	0.21	6.21	8.21	2.68	0.77	100*
40	53.60	1.24	18.76	8.66	0.17	4.53	9.06	2.96	0.28	100*
41	53.80	1.14	19.11	8.13	0.16	5.56	8.57	2.52	0.72	100*
42	53.84	1.20	17.52	8.98	0.20	6.61	8.67	2.33	0.71	100*
43	54.32	1.36	17.76	8.82	0.18	4.53	9.35	2.69	0.55	100*
44	56.64	1.10	18.52	8.34	0.18	3.09	7.60	3.07	1.30	100*
45	56.69	1.66	18.05	8.40	0.19	2.97	7.34	3.28	0.79	100*
46	57.42	1.06	17.91	8.91	0.17	2.54	7.16	3.07	1.08	100*
47	57.84	1.48	17.81	8.02	0.16	2.64	6.94	3.24	1.05	100*
48	58.20	1.50	17.81	8.17	0.15	2.43	6.77	3.20	1.17	100*
49	58.31	1.48	17.84	8.23	0.17	2.06	6.96	3.17	1.16	100*
50	61.55	0.95	15.56	8.55	0.14	1.78	4.74	3.71	2.49	100*
51	61.64	0.94	18.12	5.51	0.14	1.49	4.45	3.90	2.22	100*
52	62.90	0.66	17.91	6.15	0.11	1.10	4.28	4.09	2.06	100*
53	65.59	0.57	16.88	4.88	0.11	1.27	4.02	3.97	2.21	100*

TABLE 2. (Continued)

	SiO_2	TiO_2	Al_2O_3	FeO*	MnO	MgO	CaO	Na_2O	K_2O	Total
54	69.34	0.34	15.90	4.39	0.08	0.39	2.70	3.80	2.82	100*
55	70.74	0.29	15.66	2.82	0.08	0.61	2.42	3.92	3.31	100*
56	71.20	0.33	15.30	2.70	0.05	0.55	2.05	4.22	3.39	100*
57	73.19	0.16	15.43	1.95	0.05	0.08	1.61	4.22	3.18	100*
58	73.26	0.12	15.66	1.88	0.04	0.07	1.33	3.79	3.73	100*
59	74.25	0.12	14.96	1.46	0.04	0.08	1.19	3.94	3.85	100*
60	75.41	0.07	13.80	1.46	0.03	0.06	0.76	3.96	4.32	100*
61	75.65	0.04	14.75	1.07	0.03	0.04	0.79	3.44	4.08	100*
62	75.79	0.09	14.25	1.25	0.02	0.05	0.88	3.58	3.99	100*
63	76.72	0.07	13.49	1.12	0.02	0.04	0.64	3.54	4.24	100*
64	49.83	1.03	19.19	8.65	0.19	6.44	10.70	1.86	0.71	100*
65	52.42	1.03	18.91	9.03	0.26	5.23	8.47	2.80	1.53	100*
66	52.69	0.12	18.85	9.25	0.16	4.49	9.82	2.42	0.77	100*
67	52.77	0.14	17.84	9.63	0.18	4.14	8.90	3.52	1.17	100*
68	53.37	1.12	18.73	9.16	0.23	4.82	8.54	2.64	1.05	100*
69	55.92	0.12	18.07	8.69	0.17	3.69	7.66	3.18	1.06	100*
70	60.21	1.12	17.60	7.60	0.14	1.33	6.98	3.32	1.13	100*
71	60.21	0.87	16.83	7.06	0.14	3.14	6.56	2.86	1.94	100*
72	69.35	0.12	16.17	2.23	tr.	1.75	3.60	3.60	3.00	100*
73	54.66	1.18	16.53	8.22	0.23	6.33	6.58	4.07	2.03	99.82
74	54.72	1.87	17.80	10.02	0.31	3.23	6.61	3.09	1.48	99.13
75	56.71	0.96	17.84	7.62	0.28	5.16	8.28	2.35	2.35	100.41
76	57.23	1.25	17.63	8.18	0.23	3.67	7.70	2.74	0.81	99.44
77	57.83	1.07	18.18	8.67	0.12	2.68	5.05	3.08	3.05	99.73
78	63.10	1.11	18.02	7.06	0.15	2.67	1.44	4.04	3.12	100.71
79	75.33	0.13	14.56	1.95	0.11	0.15	2.06	2.34	3.36	99.97
80	55.22	1.26	19.17	7.58	0.18	3.14	8.35	2.91	1.11	99.69
81	56.67	1.09	18.16	7.05	0.48	2.45	9.05	3.42	1.58	99.88
82	57.38	1.13	17.33	8.05	0.22	4.04	6.30	3.26	1.67	99.38
83	57.86	1.33	17.19	8.26	0.21	3.24	7.17	3.04	0.98	99.28
84	64.14	0.70	16.70	5.42	0.20	1.67	4.29	4.30	1.37	98.79
85	68.48	0.76	16.21	4.36	0.24	3.48	3.48	3.56	2.05	100.41
86	70.28	0.49	15.54	3.77	0.11	0.78	4.39	2.87	1.90	100.13

FeO*: all Fe as FeO, 100*: recalculated to 100% volatile free. 1–3: dykes of the first generation, 4–8: dykes of the second generation, 9–72: dykes of the third generation, 73–79: dykes of the fourth generation, 80–86: dykes of the fifth generation. Locality: Hakata: 18, Hiei: 73 & 76, Mihara: 17, Nakamura: 80, 82 & 86, Nibukawa: 74, Ondo: 72, Ooasa: 81 & 85, Sennan: 77–79, Shijihara: 84, Shirotori: 21 & 24–63, Shodoshima: 1–11, 13–16, 19, 20, 22, 23, 64–71 & 75. 24–34 from Oohara (1974), 35–71 from Ujike (1977, 1978), 72 from Yoshida (1964).

Rock types: aphyric basic dyke: 1–4, 6–8, 10–12, 14–16, 18, 24–28, 73–75, 77, 78 & 80–84, porphyritic basic dyke: 5, 13, 17, 76 & 85, 'hybrid' between basic and acid dykes: 21, granite-porphyry: 72, plagioclase-granitic porphyry: 23, felsite: 22, 29–34, 79 & 86, dolerite**: 35 & 64, quartz-diorite-porphyry**: 36–51 & 65–69, granodiorite-porphyry**: 52, 54 & 70–71, granite-porphyry**: 55–63. (**: a rock name classified on the basis of silica content of the bulk by Ujike)

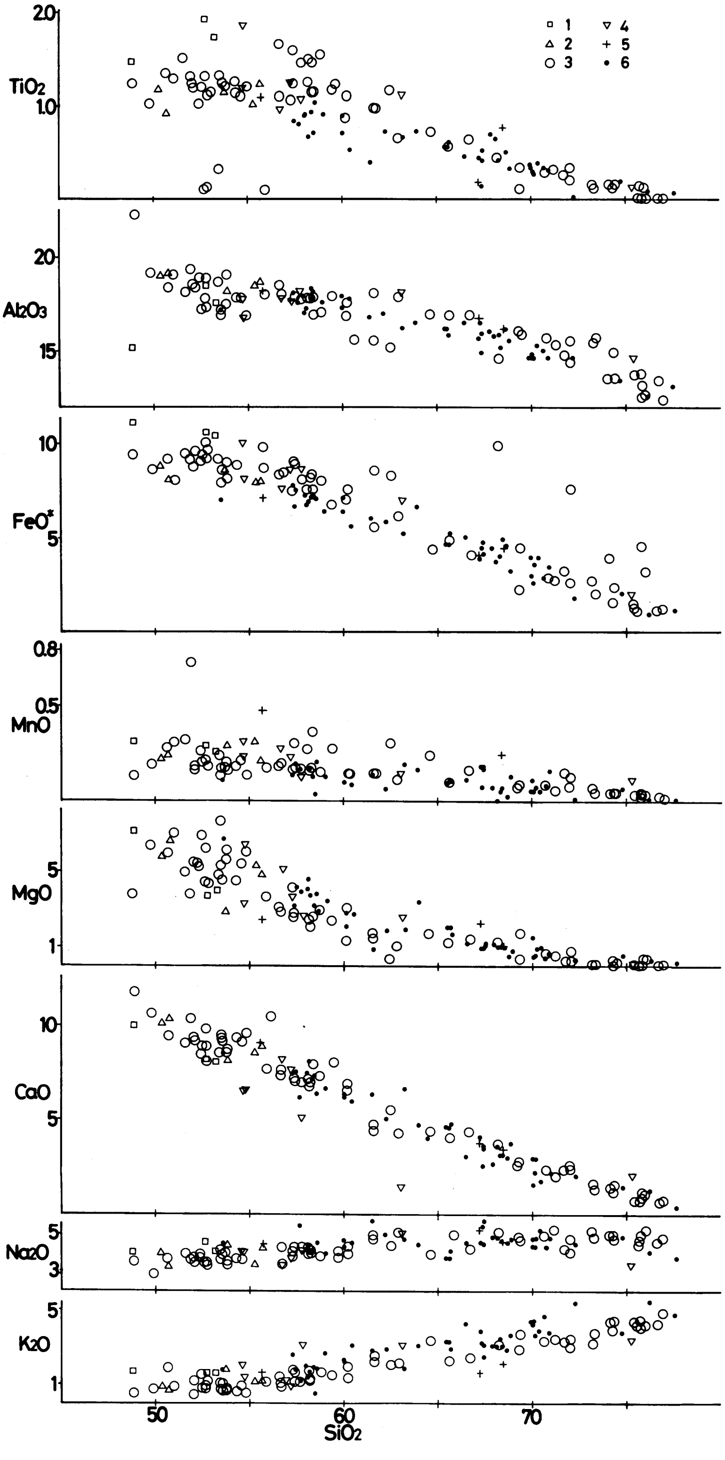

FIG. 2. Variation diagrams of major oxides against silica for the dykes of five generations and Late Mesozoic volcanic rocks in west Japan.

1. dykes of the first generation, 2. dykes of the second generation, 3. dykes of the third generation, 4. dykes of the fourth generation, 5. dykes of the fifth generation, 6. Late Mesozoic volcanic rocks in west Japan (data from MURAKAMI and MATSUSATO (1970) and IMAOKA and MURAKAMI (1979)).

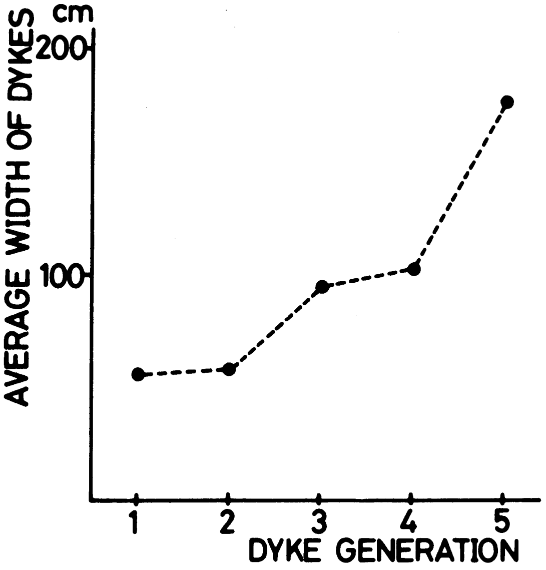

Fig. 3. Diagram showing average width of basic dykes of five generations.

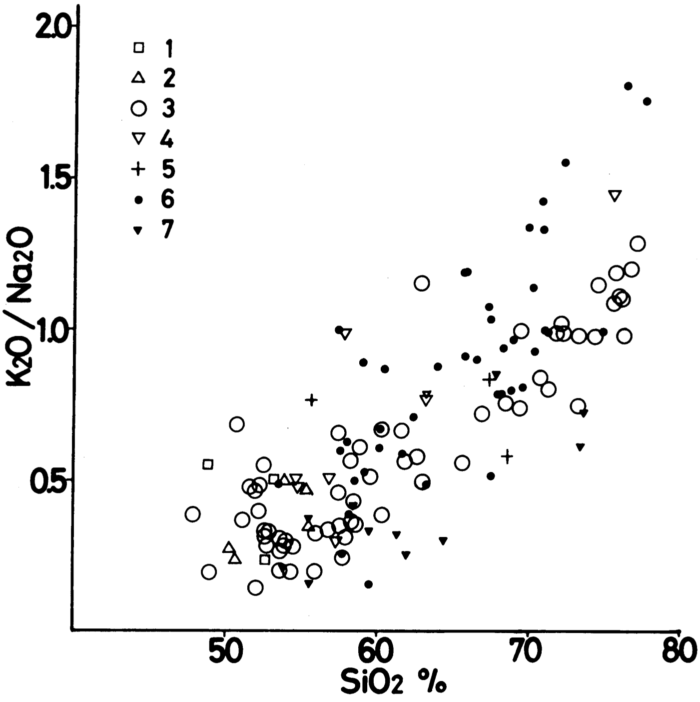

Fig. 4. K_2O/Na_2O ratio versus silica diagram.

1. dykes of the first generation, 2. dykes of the second generation, 3. dykes of the third generation, 4. dykes of the fourth generation, 5. dykes of the fifth generation, 6. Late Mesozoic volcanic rocks in west Japan, 7. Early Tertiary volcanic rocks of the Tamagawa type (data from Imaoka and Murakami (1979)).

generations is much more than 55%, the majority being less than 60%. Basic dykes of the third generation have SiO_2 content ranging from 49% to 62%, the majority being from 51% to 58%. This increasing tendency of SiO_2 content of basic dykes with decreasing age is also indirectly supported by that of the average width of phenocryst-free basic dykes in each dyke population (Fig. 3).

There is little difference in bulk chemical composition between basic dykes of five generations. But the basic dykes of the first generation have TiO_2 and FeO* contents of slightly higher values than those of the later generations (Fig. 2).

Late Mesozoic volcanic rocks in the Chugoku-Setouchi district (e.g. IMAOKA and MURAKAMI, 1979) are in excellent contrast to the dykes of five generations with reference to bulk chemical composition: The former does not contain rocks with SiO_2 content of less than 54%. The dykes with SiO_2 content of less than 65% have TiO_2 and FeO* contents of higher values and MgO and K_2O contents of slightly lower values than Late Mesozoic volcanic rocks with SiO_2 content of less than 65% (Fig. 2). While between the dykes and Late Mesozoic volcanic rocks, which both have SiO_2 content of more than 65%, there is no essential difference in major elements, except for K_2O (Fig. 2). It is interesting that Late Mesozoic volcanic rocks have higher K_2O/Na_2O ratio than Early Tertiary volcanic rocks and the K_2O/Na_2O ratio of the dykes shows intermediate values between that of the former and that of the latter (Fig. 4).

The dykes of five generations have a total width of 11×10^5 cm, so far as the author has

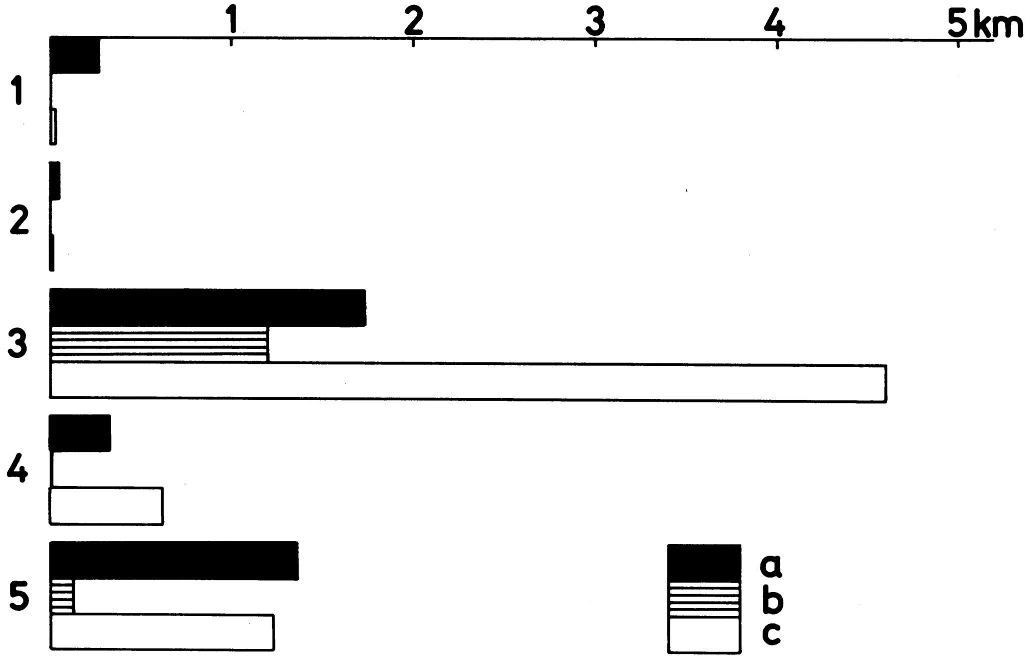

FIG. 5. Diagrams showing total width of basic, intermediate and acid dykes of five generations. 1. dykes of the first generation, 2. dykes of the second generation, 3. dykes of the third generation, 4. dykes of the fourth generation, 5. dykes of the fifth generation; a: basic dyke, b: intermediate dyke, c: acid dyke.

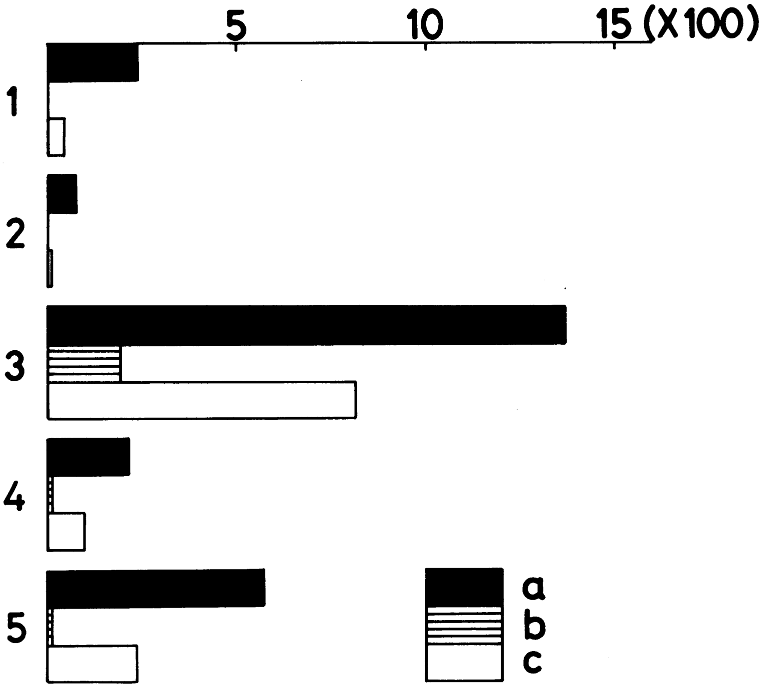

FIG. 6. Diagrams showing number of basic, intermediate and acid dykes of five generations.

1. dykes of the first generation, 2. dykes of the second generation, 3. dykes of the third generation, 4. dykes of the fourth generation, 5. dykes of the fifth generation; a: basic dyke, b: intermediate dyke, c: acid dyke

measured. The total width of dykes of basic, intermediate and acid type in each generation has been separately measured. The results are shown in Fig. 5. In the dyke populations of the earlier two generations are not found intermediate dykes and basic dykes considerably predominate over acid dykes. Amount of acid dykes increases on and after the third generation. The activity of the intermediate dykes occurs in time-span from the third generation to the fifth generation. However, in the dyke populations of the later three generations are quite poor the intermediate dykes. Especially, intermediate dykes are much less in number than basic dykes and acid dykdes (Fig. 6), and moreover their activities are concentrated within some restricted dyke-domains (Fig. 1). Thus, it can be said that the dykes of five generations are bimodal in chemical composition.

IV. FE–TI OXIDES AND MAGNETIC SUSCEPTIBILITY OF BASIC DYKES

This section will be spared for detailed description and discussion on Fe–Ti oxides and magnetic susceptibility of the basic dykes of five generations. Magnetite and ilmenite are commonly present as accessory constituents in basic dykes. Those minerals occur commonly within or are closely associated with ferromagnesian silicate minerals of the groundmass. Most of ilmenite grains occur as slender prisms ranging from 50 to 150 microns in length, but a few grains reach to 250 microns in size. Magentite grains occur as rhombic forms ranging up to 250 microns in size.

Ilmenite is usually fresh. Martitization, hematite replacing magnetite, is often found. Hematite replaces magnetite along grain boundaries and (111) cleavage planes. Decomposition of Fe–Ti oxides is predominant in dykes of dyke-domains in the Sanyo belt far from the Median Tectonic Line, magnetite being often completely converted to hematite and ilmenite being decomposed to mats of hematite and TiO_2 minerals.

The basic dykes are divided into two types with reference to magnetite, magnetite-bearing dykes and magnetite-free dykes. The magnetite-bearing dykes contain only magnetite grains or both magnetite and ilmenite grains. In magnetite grains may or may not be seen ilmenite lamellae. While magnetite-free dykes contain only ilmenite grains.

Magnetite-bearing granites can be clearly distinguished from magnetite-free graintes by the difference in modal values of total opaque minerals (ISHIHARA, 1977): The former have opaque minerals in modal values of 0.2 to 2.0, and most of them, generally more than 90 percent, are magnetite. The latter contain only stubby crystals of ilmenite

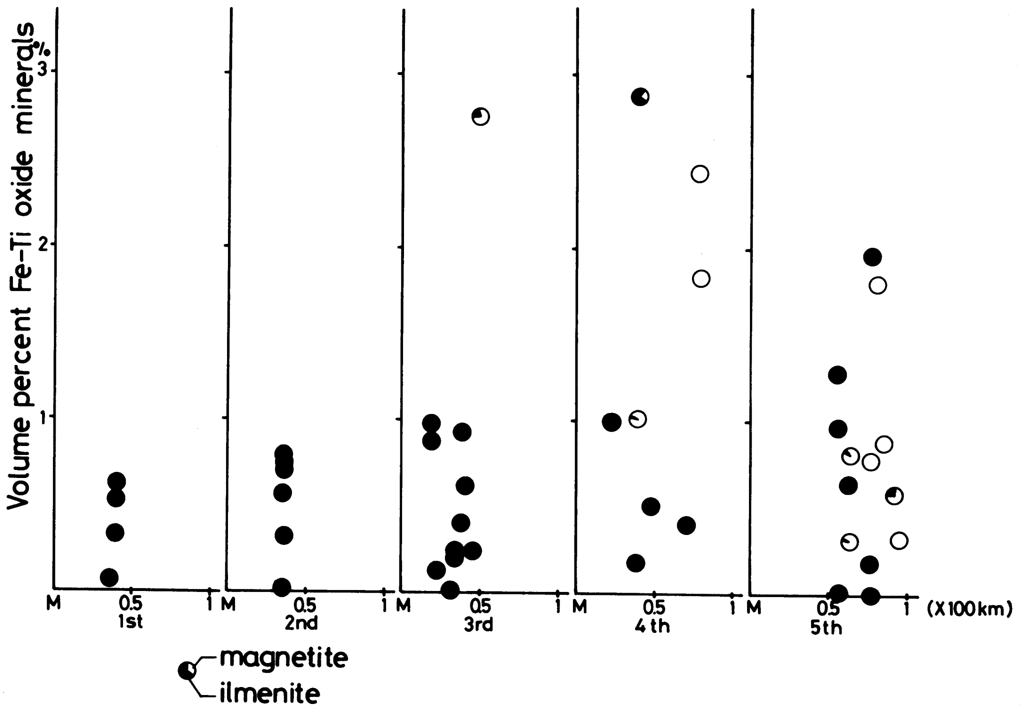

FIG. 7. Diagrams showing variation of volume percentage of Fe–Ti oxides in basic dykes of five generations.

The axes of abscissa: localities of samples shown by distance from the Median Tectonic Line (M), solid areas in circles: volume percentage of ilmenite, white areas in circles: volume percentage of magnetite.

in modal values of less than 0.1. The magnetite-bearing dykes contain Fe–Ti oxides in modal values of 0.3 to 2.9, as determined by pointcounting polished thin sections, and the magnetite-free dykes contain only ilmenite in modal values of 0.1 to 2.0, the majority being less than 1.0 (Fig. 7).

Maximum modal value of ilmenite gradually increases with the younging of dyke generation: The highest modal value of ilmenite for the dyke population of the first generation is 0.6, while that for the dyke population of the fifth generation is 2.0 (Fig. 7).

Magnetic susceptibility was measured on powdered samples by the Naruse automatic recording balance using the Mohr's salt as standard. Magnetic susceptibility of granites and volcanic rocks depends upon content of magnetite, and as observed on ore microscope of ordinary (100X) magnification, magnetite grains can be commonly seen in them when it is more than 50×10^{-6} emu/g (ISHIHARA, 1977; IMAOKA and NAKASHIMA, 1982). Also in the dykes, which have magnetic susceptibility more than 50×10^{-6} emu/g, have been found magnetite grains, and magnetite-free dykes appear to have magnetic susceptibility less than 50×10^{-6} emu/g. The results of measurement of magnetic susceptibility are shown in Figs. 8 and 9.

The dykes of the earlier three generations, except for basic dykes of the third generation in the Mitsugicho dyke-domain (Fig. 1, c)–12), are magnetite-free and have commonly magnetic susceptibility less than 50×10^{-6} emu/g. The dykes of the later two generations may or may not be magnetite-free. Even within individual dyke-domains are found both magnetite-bearing dykes and magnetite-free dykes. Magnetic susceptibility of magnetite-

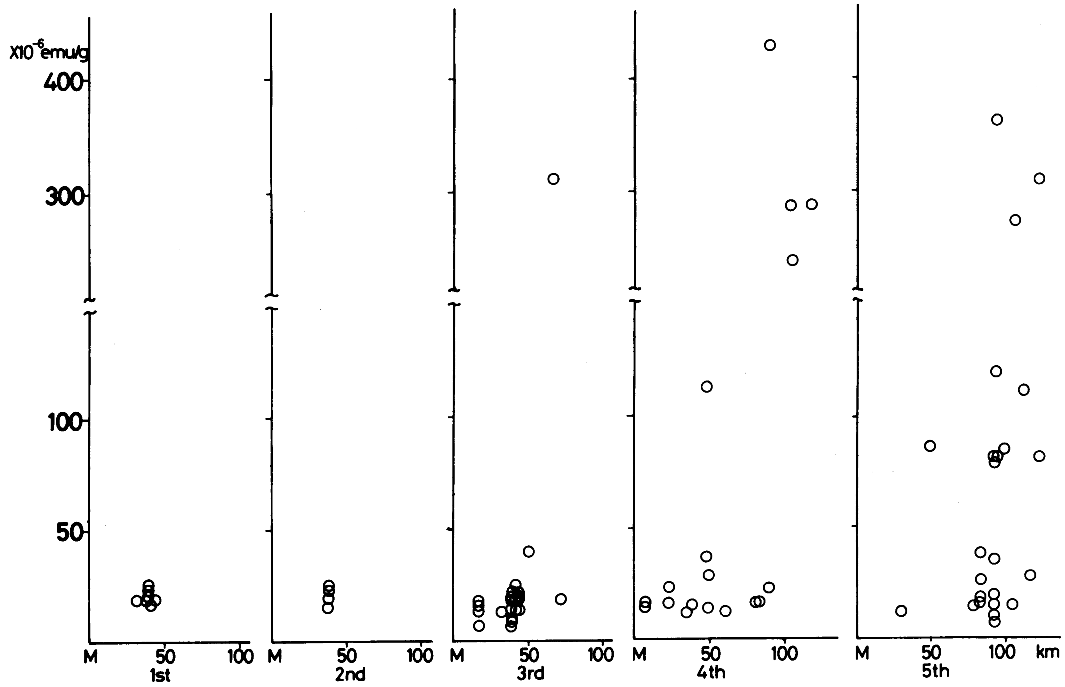

FIG. 8. Diagrams showing magnetic susceptibility of basic dykes of five generations.

The axes of abscissa: localities of samples shown by distance from the Median Tectonic Line (M), the axes of ordinate: values of magnetic susceptibility.

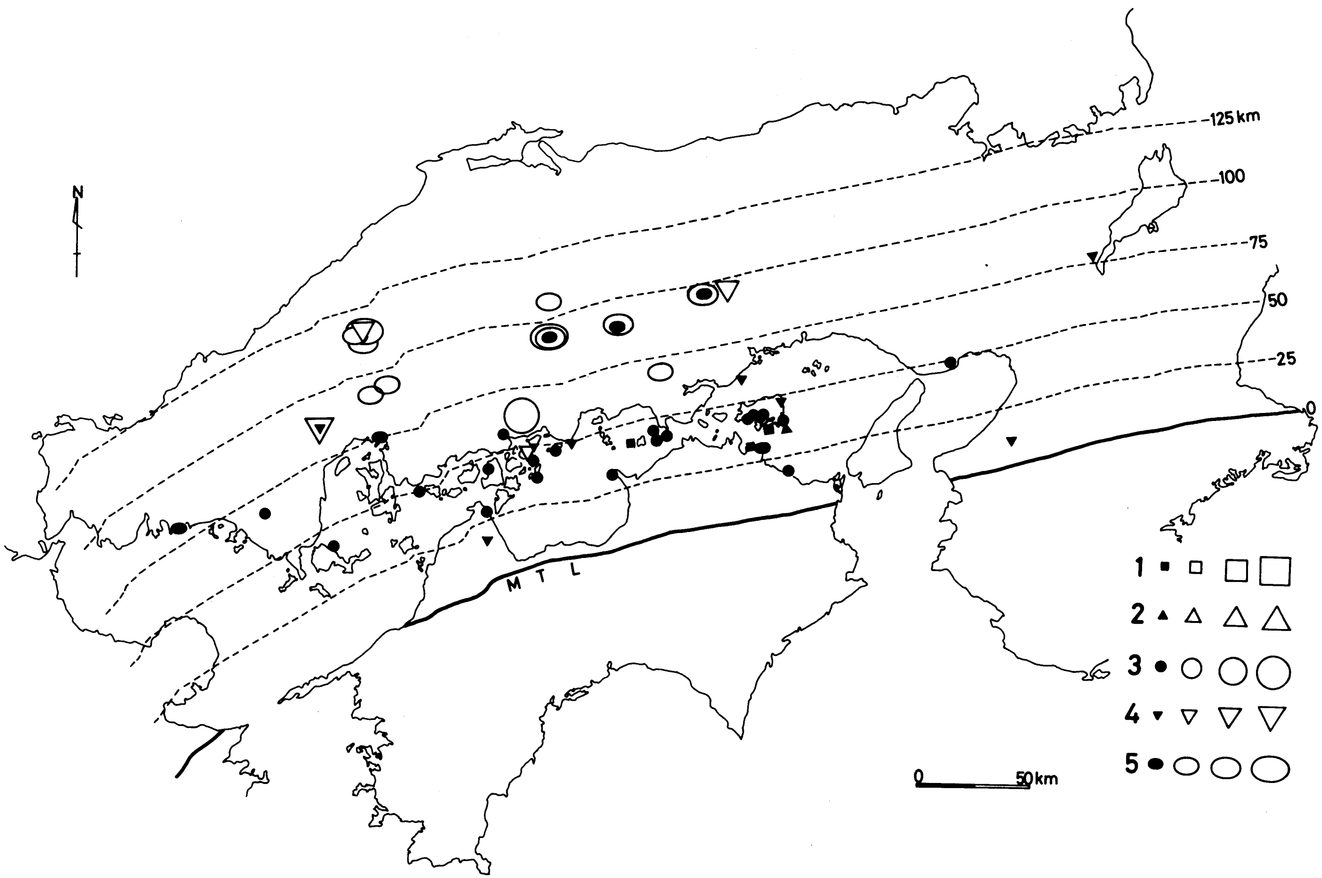

FIG. 9. Map showing the geographical variation of magnetic susceptibility of the basic dykes of Fig. 8.

Solid symboles: magnetite-free dykes, open symboles: magnetite-bearing dykes. The sizes of symboles indicate values of magnetic susceptibility: smallest symboles: magnetic susceptibility less than 50×10^{-6} emu/g, small symboles: magnetic susceptibility of $50\text{–}100 \times 10^{-6}$ emu/g, large symboles: magnetic susceptibility of $100\text{–}300 \times 10^{-6}$ emu/g, largest symboles: magnetic susceptibility more than 300×10^{-6} emu/g. 1. dykes of the first generation, 2. dykes of the second generation, 3. dykes of the third generation, 4. dykes of the fourth generation, 5. dykes of the fifth generation.

bearing dykes ranges from 70 to 360×10^{-6} emu/g. There is a distinct tendency that magnetite-bearing dykes increase in volume toward the north: Magnetite-bearing dykes predominate in the northern part of the Sanyo belt (more than 80 km distance from the Median Tectonic Line) (Fig. 9), whereas in the Ryoke belt and the southern part of the Sanyo belt are predominately developed dyke-domains consisting only of magnetite-free dykes.

ISHIHARA (1977) has pointed out that magnetite-bearing granites were produced under higher oxygen fugacity than magnetite-free granites were. The author considers that it is also possible to apply such the interpretation to the origin of magnetite-bearing dykes and magnetite-free dykes.

TABLE 3. CHEMICAL COMPOSITIONS OF ILMENITES IN BASIC DYKES OF FIVE GENERATIONS.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
TiO_2	52.01	52.49	52.40	52.06	52.42	51.82	51.65	51.39	50.91	48.96	49.21	47.44	50.29	50.63	48.39
FeO*	43.72	43.93	42.88	45.94	45.29	44.82	44.68	45.99	44.38	45.73	47.50	46.36	45.91	46.42	44.48
MnO	3.72	3.68	3.70	1.67	2.14	2.56	2.96	2.09	3.39	4.29	2.37	5.19	2.85	2.77	5.17
MgO	0.12	0.05	0.29	0.06	0.06	0.07	0.10	0.11	0.05	0.04	0.46	0.06	0.08	0.07	0.06
Total	99.57	100.15	99.27	99.73	99.91	99.27	99.39	99.58	98.73	99.02	99.54	99.05	99.13	99.89	98.10
Calculated normative components (Anderson, 1968)															
$MnTiO_3$	7.92	7.83	7.87	3.56	4.56	5.45	6.30	4.44	7.21	9.13	5.04	11.03	6.07	5.89	10.98
$FeTiO_3$	90.35	91.60	90.51	95.07	94.74	92.66	91.39	92.66	89.24	83.65	86.65	78.77	89.11	89.96	80.63
Fe_2O_3	1.04	0.61	0.03	1.03	0.48	1.06	1.56	2.36	2.37	6.80	7.20	10.07	4.13	4.26	7.01
$MgTiO_3$	0.37	0.16	0.86	0.18	0.18	0.22	0.30	0.33	0.15	8.12	1.39	0.19	0.24	0.21	0.18
Total R_2O_3	99.68	100.20	99.27	99.84	99.96	99.38	99.55	99.79	98.97	99.70	100.28	100.06	99.55	100.32	98.80

Dykes of the first generation [1: 523111B Shodoshima, 2: 5253111B Shodoshima, 3: 5252411 Shodoshima], dykes of the second genration [4: 5351613 Shodoshima, 5: 5351904 Shodoshima, 6: 5351905 Shodoshima], dykes of the third generation [7: 5240117 Shirotori, 8: 5383002 Hitsuishijima, 9: 5372402 Mitsugicho], dykes of the fourth generation [10: 5272606 Innoshima, 11: 5272606 Innoshima, 12: 50112409 Ushimado], dykes of the fifth generation [13: 5080205 Hofu, 14: 5080205 Hofu, 15: 5531001 Nariwa]

In the dykes of the earlier two generations, ilmenite commonly occurs as drop-like granules and slender prisms rounded off corners (Plate 18, a)). Some dykes of the third generation also contain ilmenite of slender prisms rounded off corners, but others, as well as the dykes of the later two generations, do ilmenite of angular prisms and/or often of lobate skeltal form (Plate 18, b)) which indicates chilling crystallization (HAGGERTY, 1976). Ilmenite in basic dykes of the third generation in Mukuchijima (Fig. 1, c)–21) and ilmenite and magnetite in those in Mitsugicho (Fig. 1, c)–12) show hopper forms (Plate 18, c)), whose corners appear to be slightly rounded off.

Magnetite in dykes of the third generation in Mitsugicho commonly contains ilmenite lamellae of a few microns wide and in 3–11% of the grain. The development of ilmenite lamellae is not generally found in magnetite of the dykes of the later two generations. Generally, such an intergrowth of ilmenite lamellae in magnetite is considered to be produced by oxidation exsolusion from initial homogeneous, ulvospinel molecule-rich magnetite (BUDDINGTON and LINDSLEY, 1964; CZAMANSKE and MIHALIK, 1972; DUCHENSE, 1972; TSUSUE and ISHIHARA, 1974). The cooling history of the dykes of the third generation appears to have much longer and slower than that of the dykes of the later two

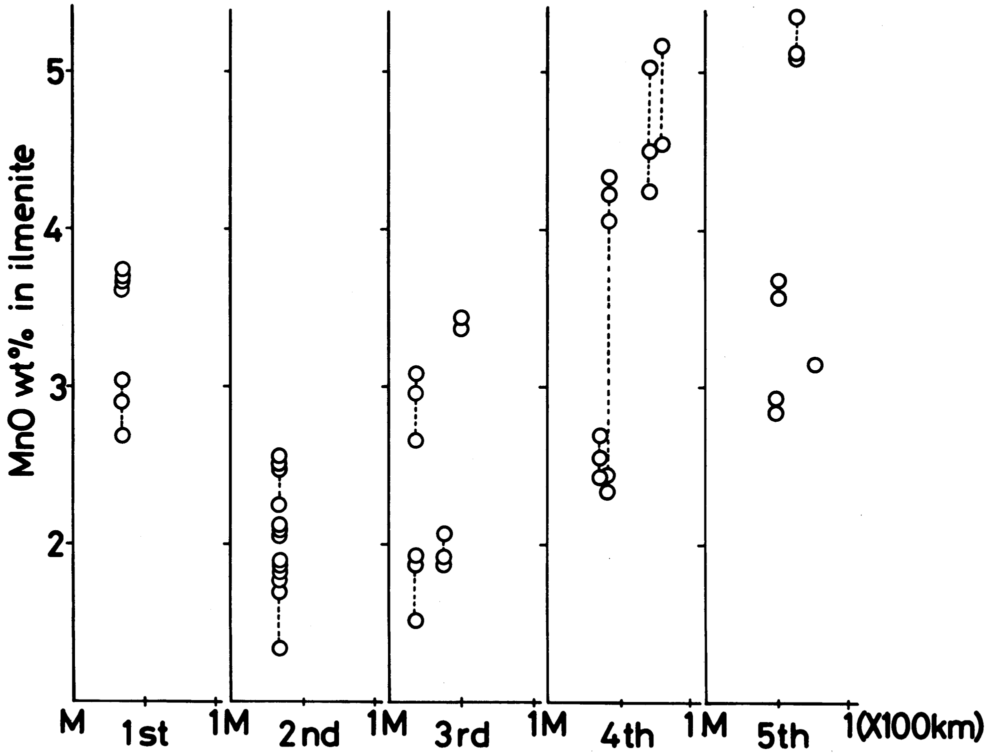

FIG. 10. Diagrams showing MnO content of ilmenites from basic dykes of five generations (The data linked by dotted lines come from the same dyke).

The axes of abscissa: localities of samples shown by distance from the Median Tectonic Line (M). 1st. dykes of the first generation, 2nd. dykes of the second generation, 3rd. dykes of the third generation, 4th. dykes of the fourth generation, 5th. dykes of the fifth generation.

generations. This is because the host granites were still hot when the former intruded but they were already not when the latter intruded as mentioned in the preceding pages. The relatively long slow cooling history of the third generation must have been favorable for the well-development of intergrowth of ilmenite lamellae. The above-described relationship between the generation stages of dykes and the crystal forms of Fe–Ti oxides in them would be also ascribed to difference in cooling rate between them.

Chemical compositions of ilmenite have been also analysed by a JXA–5A. The author tried to irradiate the cores of grains. In Table 3 is only shown chemical compositions of ilmenite grains in some samples.

Fig. 10 indicates that, with the younging of dyke generation from the second to the fifth, MnO content in ilmenite generally increases and the range of MnO content becomes wide. The widest range of MnO content for ilmenites in one polished thin section has been obtained from a basic dyke of the fourth generation in Innoshima: (Fig. 1, d)–5)

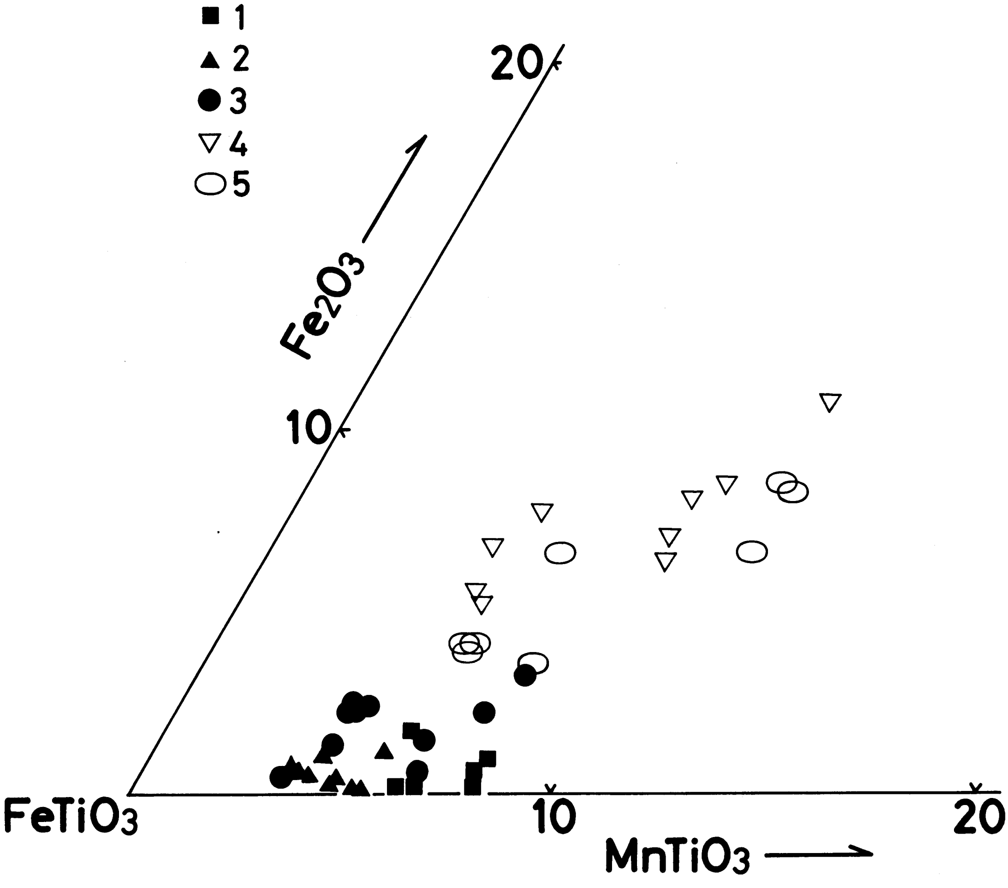

Fig. 11. Fe_2O_3–$FeTiO_3$–$MnTiO_3$ (molecule) triangular diagram from the basic dykes of Fig. 10. 1. dykes of the first generation, 2. dykes of the second generation, 3. dykes of the third generation, 4. dykes of the fourth generation, 5. dykes of the fifth generation.

The lower values of MnO content are ca. 2.4% and the higher values range from 4.1 to 4.5%. In this polished thin section has been observed no considerable variation in size between ilmenite grains. In some other sections, however, higher values of MnO content have been obtained in fine-grained ilmenite rather than in coarse-grained ilmenite.

From Fig. 10, it can be said that, as observed in individual dyke populations (the second to fifth generation), MnO content in ilmenite become higher toward the north. In the dykes of the latter two generations there is no difference in MnO content in ilmenite between the magnetite-bearing dykes and magnetite-free dykes.

The increase of MnO content in ilmenite with the younging of dyke generation corresponds to the of Fe_2O_3 content (Fig. 11). Ilmenite from the dykes of the first generation is richer in MnO or $MnTiO_3$ content than that from the dykes of the second generation, but there appears to be no significant difference in Fe_2O_3 content between them.

As summarized by IMAOKA et al. (1982), the Mn^{2+}/Fe^{2+} ratio of ilmenite depends upon temperature, Mn^{2+}/Fe^{2+} ratio of source magma and oxygen fugacity. BUDDINGTON and LINDSLEY (1964) stated that increase of Fe_2O_3 content in ilmenite is related to increase of oxygen fugacity during crystallization. CZAMANSKE and MIHALIK (1972) reduced that Fe^{2+} in ilmenite is more readly oxidizing than Mn^{2+} and is thus preferentially extracted under the conditions of increasing of oxygen fugacity. Thus, the increase of $MnTiO_3$ content in proportion to that of Fe_2O_3 content in ilmenite in the examined dykes may be convincingly attributed to the ascent of oxygen fugacity. This is consistent with the fact that the magnetite-bearing dykes predominate in the later two generations as mentioned in the preceding pages.

Xenoliths of country rocks are only rarely found in dykes of all generations, but some dykes enclose the rock-fragments derived from the adjacent walls, against that the dykes are chilled. There is no petrographical evidence showing assimilation of xenoliths in the dykes. Graphite is not found even in the magnetite-free dykes. ISHIHARA (1977) has considered that magnetite-free magmas were produced by interaction with pelitic rocks which contain graphite and/or with carbonaceous matter. However, the above-mentioned facts would be inconvenient for such an explanation that the magnetite-free dykes were produced under the conditions of low oxygen fugacity as the result of direct assimilation of carbon-rich sediments during the life of the dyke-magma.

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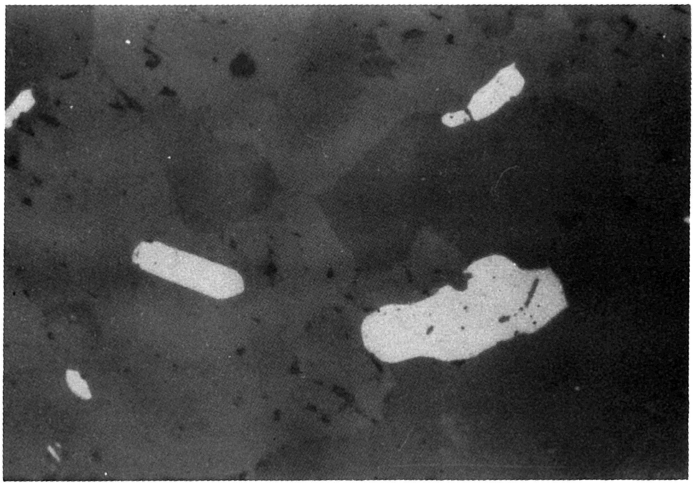
EXPLANATION OF PLATE XVIII

Fig. 1. Photomicrographs showing morphologies of ilmenite crystals in the groundmass of basic dykes.

- a) Ilmenite crystals rounded off corners in basic dyke of the first generation from Shodoshima.
- b) Lobate skeltal ilmenite crystal in basic dyke of the fifth generation from Hofu.
- c) Hopper ilmenite crystal in basic dyke of the third generation from Mukuchijima.

Note: Length of all photographs 167 microns.

a)



b)

c)