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Temporal and Spatial Variations of Magnetic Susceptibility of Cretaceous to Neogene Igneous Rocks from the Central and Western Chugoku Province, Japan

By

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with 3 Tables, 15 Text-figures

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Abstract: Magnetic susceptibility is measured on powdered specimens of about 1100 volcanic rocks and 600 related plutonic rocks of the titled area. The results show systematic variation in magnetic susceptibility with age, geographic location of the rocks, and geologic units. When volcanic and plutonic rocks of the same cycle of activity are compared, their magnetic susceptibility resemble each other. The most prominent temporal change in magnetic susceptibility of igneous rocks occurred between Cretaceous and Paleogene. Cretaceous igneous rocks comprise both the magnetite-series (magnetic susceptibility, higher than 50×10^{-6} emu/g) and ilmenite-series (lower than 50×10^{-6} emu/g), the latter is predominant in volume, while the Paleogene and Neogene igneous activities are characterized by the rocks of only magnetite-series. As for the geographic distribution, the ilmenite-series rocks are developed throughout the studied area, whereas the magnetite-series rocks are restricted to the Sea of Japan side, overlapping over the area of the older ilmenite-series rocks.

The two series of igneous rocks are considered to have resulted from the different oxygen fugacities during evolution of the magma. The oxygen fugacity must have been controlled directly or indirectly by many factors such as differences in source material, the effect of buffering agents such as water and crustal carbon, mode of magma emplacement and tectonic setting. Based on the comparison of the tectonic history of this area and the measured magnetic susceptibility, it is argued that the conspicuous temporal change in magnetic susceptibility between the Cretaceous and Paleogene along the Sea of Japan was probably due to the temporal change in tectonic environment related to the formation of the Sea of Japan. It is also suggested that the classification of igneous rocks based on the magnetic susceptibility provides essential information in considering tectonic environment, for it is known that igneous rocks of the two series exhibit systematic distributions in time and space in the circum-Pacific regions.

Contents

I. INTRODUCTION

Cretaceous to Neogene plutonic rocks in Japan have been examined from various points of view, such as isotope age, whole-rock and constituent mineral chemistry, stable isotopes, magnetic susceptibility, and related ore deposits (e.g., KATADA et al., 1971; ISHIHARA, 1971; MURAKAMI, 1974). These studies have revealed distinct zonal distributions of the plutonic rocks in many respects, not only in Northeast Japan but in Southwest Japan.

Recently, ISHIHARA (1975, 1977, 1979b, 1981) proposed a new scheme of classification for granitoids based on the type of the opaque mineral assemblage; that is, he distinguished magnetite-series and ilmenite-series granitoids. The magnetite-series granitoids are characterized by the presence of magnetite, ilmenite, hematite and pyrite, while the ilmenite-series granitoids are practically free from opaque oxide minerals although they contain a small amount of ilmenite and locally pyrrhotite. These two series can be distinguished simply by measuring their magnetic susceptibility χ, since the magnetite-series and ilmenite-series rocks commonly exhibit χ values higher and lower than 50×10^{-6} emu/g, respectively (ISHIHARA, 1979b).

ISHIHARA (1979b) recognized an empirical relationship, $\chi=0.001$ V, between magnetic susceptibility χ in emu/g and volume percent of magnetite V. In general, magnetite content decreases from quartz diorite or andesite to granite or rhyolite. KANAYA and ISHIHARA (1973) and ISHIHARA (1979b) revealed that magnetic susceptibility (or magnetite content) of the granitoids in the Inner zone of Southwest Japan increases gradually toward the Sea of Japan (hereinafter called the Japan Sea). ISHIHARA (1979b) regarded this variation as a fundamental pattern of an island arc magmatism related to major subduction and accompanying back arc spreading.

Those plutonic rocks are closely associated with the intermediate to felsic volcanic rocks, constituting typical volcano-plutonic association. The whole-rock chemistry and silicate mineralogy of these volcanic rocks have been studied recently by IMAOKA and MURAKAMI (1979) and MURAKAMI and IMAOKA (1980). In the course of these studies, it was recognized that different volcanic formations show somewhat different assemblage and chemistry of opaque minerals (IMAOKA et al., 1982). Thus, we felt that the magnetic susceptibility might have changed considerably with time even for volcanic and plutonic rocks of the same area. This was the direct motivation of this study. Based on about 1100 measurements on volcanic rocks and about 600 measurements on plutonic rocks, this paper describes not only temporal variations of the magnetic susceptibility but also its spatial variations for the igneous rocks and discusses possible causes for the variations.

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II. GEOLOGICAL OUTLINE

The Inner zone of Southwest Japan is characterized by an enormous distribution of late Mesozoic to Neogene igneous rocks showing a typical volcano-plutonic association. The igneous activity of this zone was summarized by ICHIKAWA et al. (1969) and MURAKAMI, (1974). Available data to date indicate that the volcanism and plutonism of the studied area can be divided into nine and seven stages, respectively, on the basis of stratigraphy, lithology, radiometric dating and fossil data (Table 1). Note that there are several cycles of volcanism and plutonism.

The Mesozoic igneous activity is widespread throughout the Chugoku province, but the Tertiary activity is restricted to the San-in zone (northern part along the Japan Sea). In the western and central Chugoku, the volcanism began with andesite eruption and changed into the eruption of dacite-rhyolite ignimbrite in the main stages. The volcanism is generally associated with plutonism although the plutonic rocks are often more felsic than the volcanic rocks.

In the central San-in area, rhyolite-dacite eruption is predominant in the early stage and andesite eruption occurred in the later stages. Some shallow intrusives of fine-grained, granophyric facies are the associates of these volcanic rocks. Tertiary igneous activity of this district is characterized by the cauldron subsidence forming several volcano-plutonic complexes (e.g., MURAKAMI, 1973; SAWADA, 1978a, b).

III. EXPERIMENTAL PROCEDURES

Magnetic susceptibility is measured on powdered specimens (less than 0.15 mm) of the late Cretaceous to Neogene igneous rocks in the central and western Chugoku province, Southwest Japan (Tables 2 and 3). In collecting samples, special attention is paid to: 1) no signs of weathering and alteration, 2) representatives of each of the stratigraphic units, 3) uniform sampling to avoid an overestimate of the data from small exposures. The samples are crushed with stainless-steel bowl or stump mill. The magnetic measurements are all conducted by using a magnetic balance with an automatic recording system, MB-2 Type, at the Faculty of Science, Yamaguchi University in collaboration with Prof. G. SHIBUYA. Mohr salt ($(NH_4)_2Fe(SO_4)_26H_2O$) is used as a standard, and the temperature dependence of magnetic susceptibility of this salt is corrected by using the following equation;

$$\chi=32.0\times\frac{290.4}{273.16+T}\times10^{-6}$$

where χ is magnetic susceptibility in c.g.s. emu/g and T is temperature in degree Centigrade. The measurements are performed in the magnetic field of 2000–14000 Oe.

TABLE 1. CORRELATION AND MAJOR CONSTITUENT ROCK TYPE OF THE CRETACEOUS TO NEOGENE IGNEOUS ROCKS IN THE CENTRAL AND WESTERN CHUGOKU PROVINCE, SOUTHWEST JAPAN.

	Stage	Western Chugoku	Central Chugoku	Central San'in	
				Ōda-Kawamoto area	Southern Izumo City
Neogene	V-9			Omori F. andesite lava & pyroclastic rocks Kuri F. mudstone, acidic tuff Kawai F. sandstone, conglomerate Hata F. andesite lava & pyroclastic rocks, dacite-rhyolite lava & pyroclastic rocks	Iwami Group(Hikawa S.g.) Omori F. basalt, plagio-rhyolite, andesite lava & pyroclastic r., dacite lava & pyroclastic r. Kuri F. mudstone, acidic tuff Kawai F. conglomerate, sandstone, volcanic conglomerate Oro F. andesite-dacite lava & pyroclastic r., conglomerate, sandstone, plagio-rhyolite
	P-7				V-P complex: Yoshida, South Mindani, East Mindani, Nodayama complex gabbro, qtz-gabbro, diorite, granodiorite-granophyre
	V-8				V-P complex: Iwami Group(Hata S.g.) Anami F. andesite lava & pyroclastic r., rhyolite lava & pyroclastic r. Irima F. andesite lava & pyroclastic r., dacite pyroclastic r., rhyolite lava
Paleogene	P-6	V-P complex: Tamagawa-type plutonic rocks (38**, 24-36***) qtz-gabbro, qtz-diorite, granodiorite, granite		V-P complex: Tamagawa-type plutonic rocks Sojiki diorite Kawamoto granodiorite	
	V-7	V-P complex: Tamagawa Group plagio-rhyolite, dacite-rhyolite pyroclastic rocks andesite lava & pyroclastic rocks		V-P complex: Kawauchi Group dacite-rhyodacite pyroclastic rocks, andesite lava	
	P-5		Tadokoro granite(38***) V-P complex: Sakugi plutonic rocks qtz-diorite,granodiorite, granite	Izimi granite	Younger granite,Izumo
	V-6		V-P complex: Sakugi volcanic rocks plagio-rhyolite, dacite pyroclastic r., andesite lava & pyroclastic r.	Takayama Group andesite lava & pyroclastic rocks dacite-rhyolite pyroclastic rocks	Hakami Group dacite-rhyolite pyroclastic rocks andesite lava & pyroclastic rocks basalt lava
	P-4			Onbara granite(64***) Uogiridani granodiorite	Older granites,Izumo
	V-5			Sakurae Group dacite-rhyolite pyroclastic rocks	Oyorogi-yama Group dacite-rhyolite pyroclastic rocks andesite lava & pyroclastic rocks
Cretaceous	P-3	Hiroshima granite(batholith)(80-90***) granite, granodiorite Hoben-zan pluton(zoned pluton)(91***,102**) granite, granodiorite		Takahata granite	
	V-4	Abu Group(82***,112**) Efune F. dacite-rhyolite pyroclastic rocks Fukuga F. andesite lava, rhyolite pyroclastic rocks Maitani F. rhyodacite-rhyolite pyroclastic rocks Shinome F. dacite-rhyolite pyroclastic rocks	Takada Rhyolite rhyolite-dacite pyroclastic rocks rhyolite lava	Ouchi Group rhyodacite-rhyolite pyroclastic rocks	
	V-3	Hikimi Group Upper rhyolite F. Lucustrine sediments Lower rhyolite F. Upper dacite F. Middle dacite F. Lower dacite F. Lowermost rhyolite F.			
	P-2	Niho-dainoki plutonic rocks V-P complex: Kibe plutonic rocks(94**) granite, qtz-monzodiorite qtz-monzogabbro			
	V-2	V-P complex: Shunan Group III.dacite-rhyodacite pyroclastic rocks II.dacite-rhyolite pyroclastic rocks I.andesite lava & pyroclastic rocks	Kisa Group dacite-rhyolite pyroclastic rocks andesite lava & pyroclastic rocks		
	P-1	Izuruha plutonic rocks(99**) granodiorite, plagiophyre			
	V-1	Kanmon Group(Shimonoseki S.g.)(101*) Fukue F. basaltic andesite lava & pyroclastic rocks Sujigahama F. dacite-rhyolite pyroclastic rocks, sandstone, shale Kitahikoshima F. andesite lava & pyroclastic rocks Shiohama F. volcanic conglomerate, sandstone, shale			

Stratigraphic data from Hase(1958), Higashimoto(1975), Iizumi & Sawada(1980), Matsuda & Oda(1982), Ministry of International Trade and Industry (1970), Murakami(1973), Murakami & Hase(1967), Murakami & Matsusato(1970), Research Group for the San'in Late Mesozoic Igneous Activity(1979), Sawada(1978a,b), Tai(1973), Yoshida(1961).
( ): radiometric age data from Kawano & Ueda(1966), Seki(1978), Shibata & Ishihara(1974, 1979a), Shibata & Kamitani(1974), Ueda & Nishimura(1982), Wakizaka(1982).
* : Fission track age, **: Rb-Sr whole rock age, ***: K-Ar mineral age.
V-P complex: volcano-plutonic complex, S.g.: Subgroup.

Specimens of 200–500 mg in weight are used. The results are all expressed in χ ($\times 10^{-6}$ emu/g).

IV. Magnetic Susceptibility

A. Magnetic Susceptibility of Igneous Rocks at Each Area

This chapter describes results from susceptibility measurement for volcanic rocks of nine stages and for plutonic rocks of seven stages at their type localities (see Fig. 1). The results will be compiled later to delineate temporal and spatial variations of the magnetic susceptibility in the titled area. The stages are numbered in the younging order with V and P designating volcanic and plutonic rocks, respectively.

1. *Stage V–1*

The volcanism of this stage is represented by the volcanic rocks of the Shimonoseki Subgroup which corresponds to the upper half of the lower Cretaceous Kanmon Group distributed broadly from northern Kyushu to western Chugoku. This subgroup is divided into four formations in the ascending order; that is, Shiohama, Kitahikoshima, Sujigahama and Fukue Formations (Fig. 2; Hase, 1958). They are composed mainly

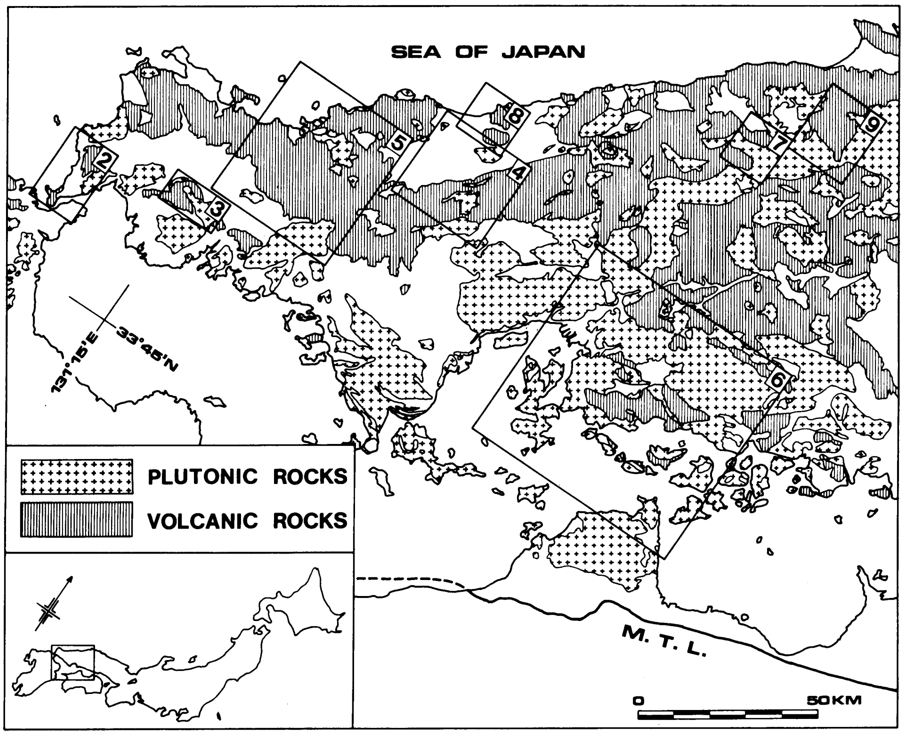

Fig. 1. Distribution of late Mesozoic to Neogene volcanic rocks and related plutonic rocks. Rectangular areas are examined in detail in this paper: numbers correspond to the figure numbers below.

of basaltic andesite, andesite lava and pyroclastic rocks, and a small amount of rhyolitic pyroclastic rocks. Fig. 2 shows magnetic susceptibility of the volcanic rocks of this stage

TABLE 2. MAGNETIC SUSCEPTIBILITY OF THE LATE MESOZOIC TO NEOGENE VOLCANIC ROCKS IN THE CHUGOKU PROVINCE, SHOWN BY NUMBER OF THE MEASUREMENT.

Stage	Volcanic unit	Rock type	Magnetic susceptibility (x 10^{-6}emu/g)			
			0-50	50-100	100-500	500 and more
V-8,9	Iwami Group	Rh-Dac	7	7	10	1
		And	0	3	25	13
V-7	Tamagawa Group	Rh-Dac	34	30	32	1
		And	7	7	44	59
V-6	Sakugi volcanic rocks	Rh-Dac	3	0	0	0
		And	0	1	5	8
	Takayama Group	Rh	0	1	0	0
		And	1	3	3	1
	Hakami Group	Rh-Dac	4	0	3	3
		And	1	1	4	4
V-5	Sakurae Group	Rh-Dac	5	2	6	1
	Oyorogi-yama Group	Rh-Dac	3	4	4	0
		And	0	0	2	4
V-4	Ouchi Group	Rh	16	3	2	0
	Abu Group	Rh-Dac	119	4	7	0
		And	5	0	0	5
	Takada Rhyolite	Rh-Dac	221	37	36	1
V-3		And	6	0	0	0
	Hikimi Group	Rh-Dac	82	3	1	0
V-2	Kisa Group	Rh-Dac	12	2	2	0
		And	68	13	6	2
	Shunan Group	Rh-Dac	33	8	1	2
		And	15	13	12	5
V-1	Kanmon Group	Rh	4	0	0	0
		And	12	4	5	15

TABLE 3. MAGNETIC SUSCEPTIBILITY OF THE LATE MESOZOIC TO NEOGENE PLUTONIC ROCKS IN THE CHUGOKU PROVINCE, SHOWN BY NUMBER OF THE MEASUREMENT.

Stage	Plutonic unit	Rock type	Magnetic susceptibility (x 10^{-6}emu/g)			
			0-50	50-100	100-500	500 and more
P-7	Yoshida complex	Gr-Gd	0	0	1	1
		Qd-Gb	0	0	4	12
P-6	Tamagawa-type plutonic rocks	Gr-Gd	13	11	106	21
		Qd-Gb	0	0	4	29
	Tadokoro granite	Gr	1	4	9	6
	Izimi granite	Gr	7	4	4	3
	Younger granites, Izumo	Gr	0	1	6	0
P-5	Sakugi plutonic rocks	Gr-Gd	2	2	3	4
		Qd	0	0	1	4
P-4	Onbara granite	Gr	1	9	1	1
	Uogiridani granodiorite	Gd	0	2	6	4
	Older granites, Izumo	Gr	4	10	9	1
		Qd	0	0	1	0
P-3	Takahata granite	Gr	1	6	6	0
	Hiroshima granite	Gr-Gd	121	7	8	0
	Hoben-zan pluton	Gr-Gd	28	13	9	0
P-2	Niho-dainoki plutonic rocks	Gr-Qd	0	1	2	5
	Kibe plutonic rocks	Gr	10	2	5	0
		Gb	6	4	7	3
P-1	Yuzuriha plutonic rocks	Gd	18	1	0	0

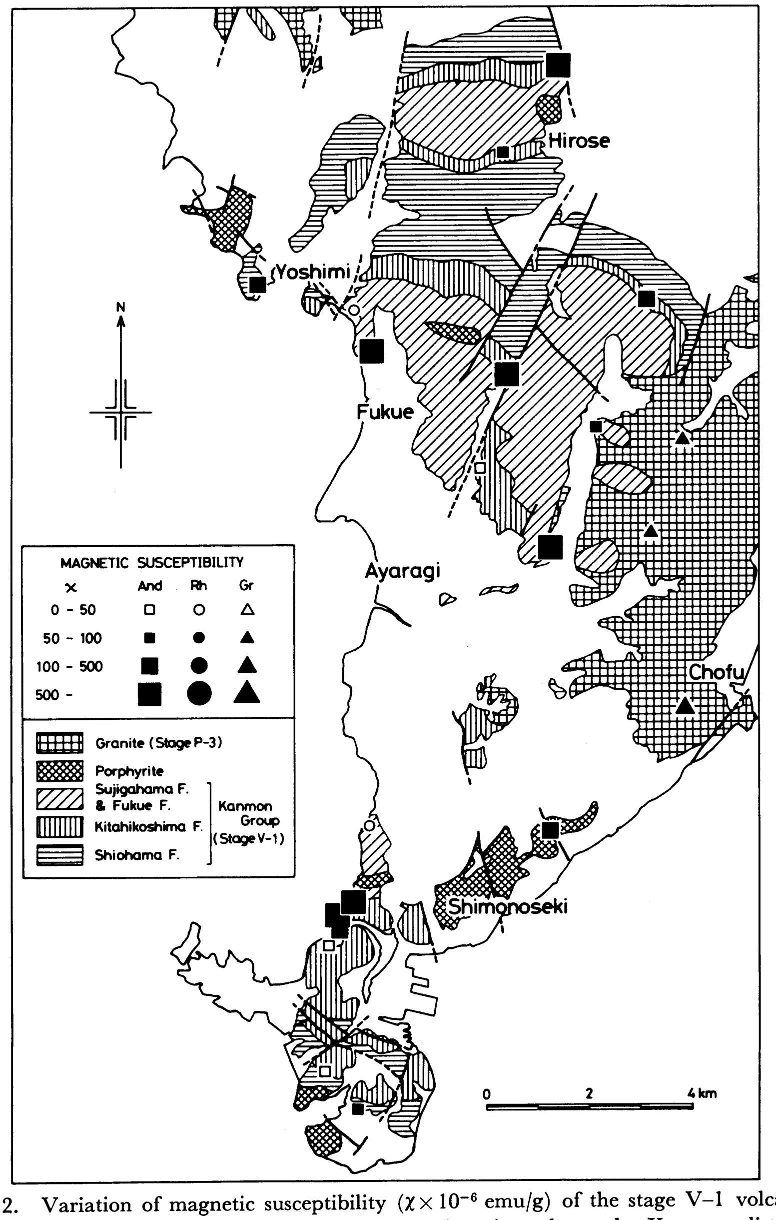

FIG. 2. Variation of magnetic susceptibility ($\chi \times 10^{-6}$ emu/g) of the stage V–1 volcanic rocks (Kanmon Group) and stage P–3 plutonic rocks at the Kanmon district, Yamaguchi Prefecture. Geologic map is simplified from YAMAGUCHI PREFECTURE (1968).

at Kanmon district. χ-values of andesitic rocks are high ($\chi = (250\text{–}1300) \times 10^{-6}$ emu/g), and thus the rocks belong to the magnetite-series regardless of their stratigraphic horizons. On the other hand, two samples of garnet-bearing rhyolite tuff have χ-values lower than 50×10^{-6} emu/g, and they belong to the ilmenite-series (Table 2).

2. *Stages V–2, P–1 and P–2*

The Shunan Group in the western Chugoku and the Kisa Group in the central Chugoku, volcanic rocks of this stage, are sporadically distributed, but there is no systematic spatial variation of magnetic susceptibility in the volcanic rocks of this stage.

Fig. 3 shows the magnetic susceptibility of the Kibe mass in the Shunan Group. The succession of the volcanic rocks of this mass is considered to have been in the following order: andesite lava and pyroclastic rocks, dacite-rhyolite pyroclastic rocks, dacite-rhyodacite pyroclastic rocks, and associated plutonic rocks (Table 1; MURAKAMI and MATSUSATO, 1970). These volcanic rocks exhibit magnetic susceptibility of considerable variation, i.e., (10–400) $\times 10^{-6}$ emu/g, and hence rocks of the ilmenite-series and magnetite-series coexist here.

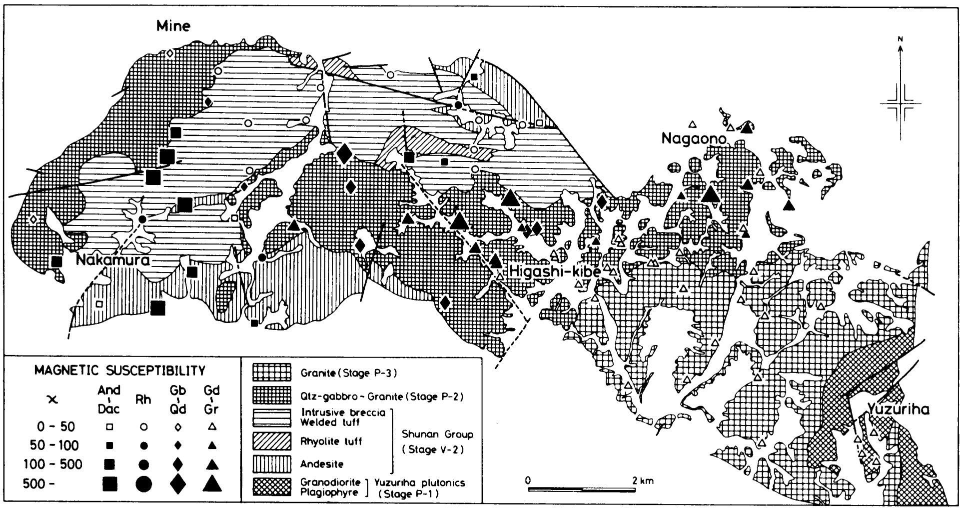

FIG. 3. Variation of magnetic susceptibility ($\chi \times 10^{-6}$ emu/g) of the stage V–2 volcanic rocks (Shunan Group) and stages P–1, P–2, and P–3 plutonic rocks at Kibe district, Yamaguchi Prefecture. Geologic map is simplified from YAMAGUCHI PREFECTURE (1968) and SEO (1976).

The plutonic rocks of this area have been divided into three stages, P–1, P–2 and P–3, on the basis of their field occurrence and petrographic characters (Fig. 3; MURAKAMI, 1960; SEO, 1976). The P–1 plutonic rocks (Yuzuruha plutonic rocks consisting of granodiorite and plagiophyre) intruded into the Kanmon Group and are covered by the Shunan Group. The magnetic susceptibility of the P–1 rocks is below 50×10^{-6} emu/g. The P–2 plutonic rocks composed of quartz gabbro to granite are associated closely with the Shunan Group. They have a wide range of magnetic susceptibility, i.e., $(1\text{–}2000) \times 10^{-6}$ emu/g.

Numerous measurements have revealed no significant difference in the ratio of ilmenite-series/(ilmenite-series + magnetite-series) between V–2 volcanic rocks (Shunan Group) and P–2 plutonic rocks, the ratio being 0.5 and 0.45 for the former and the latters, respectively.

3. *Stage V–3*

Volcanism of this stage is represented by the Hikimi Group which consists mainly of rhyolitic to dacitic pyroclastic rocks. This group is divided into the following seven formations in the ascending order; Lowermost rhyolite, Lower dacite, Middle dacite, Upper dacite, Lower rhyolite, Lucustrine sedimentary rocks, and Upper rhyolite Formations (Table 1).

Rocks of this stage have χ-values generally less than 30×10^{-6} emu/g regardless of their stratigraphic horizons (Fig. 4), indicating that they are virtually free from magnetite. Indeed, microscopic observation has not revealed any magnetite in these rocks (IMAOKA et al., 1982). The V–3 volcanic rocks thus belong to the typical ilmenite-series. A similar feature is recognized also in the associated hornblende-biotite granite porphyry and granites (Fig. 4), and hence they also belong to the ilmenite-series.

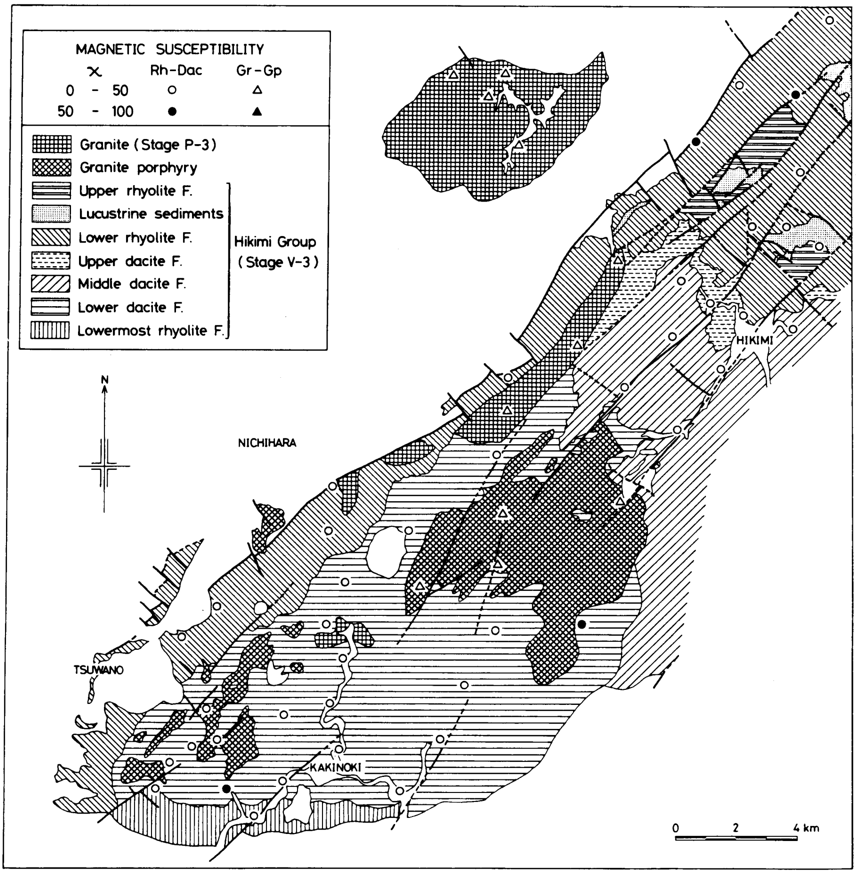

FIG. 4. Variation of magnetic susceptibility ($\chi \times 10^{-6}$emu/g) of the stage V–3 volcanic rocks (Hikimi Group) and stage P–3 plutonic rocks at Hikimi district, Shimane Prefecture. Geologic map is simplified from MINISTRY OF INTERNATIONAL TRADE AND INDUSTRY (1970).

4. *Stages* V–4 *and* P–3

Volcanic rocks of this stage, distributed widely from the San-yo to the San-in districts, are named Abu Group, which can be divided into the Shinome, Maitani, and Efune Formations in the ascending order (Table 1, Fig. 5). The Fukuga Formation is correlated to the Shinome and Maitani Formations (MURAKAMI and HASE, 1967). The constituent rocks of the Abu Group predominate in rhyolite, although they are accompanied by a small amount of andesite and dacite.

Magnetic susceptibility of the rhyolitic rocks is generally low and about 80 percents of measured samples give magnetite-free values. No notable difference in χ-value is recognized among the four formations (Fig. 5). Anormalously high χ-values of some rhyolite samples are apparently due to the formation of minute magnetite grains during opacitization. Andesitic rocks in this group contain rocks of both magnetite-series and ilmenite-series.

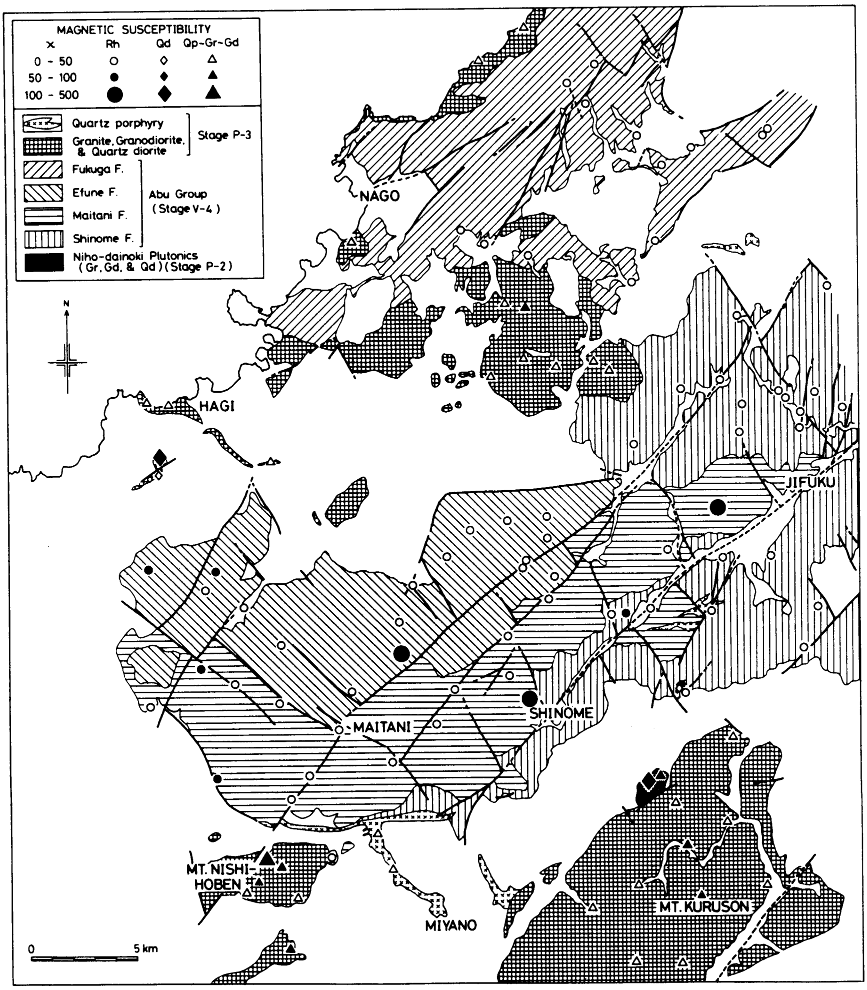

FIG. 5. Variation of magnetic susceptibility ($\chi \times 10^{-6}$emu/g) of the stage V–4 volcanic rocks (Abu Group) and stages P–2 and P–3 plutonic rocks at north of Yamaguchi Prefecture. Geologic map is simplified from YAMAGUCHI PREFECTURE (1968).

The V–3 and V–4 volcanic rocks in the central Chugoku are represented by the Takada rhyolites (Table 1), whose petrographic characters bear many resemblances to those of the Hikimi and Abu Groups. The Takada rhyolites have χ-values lower than 50×10^{-6} emu/g except for a few samples (Fig. 6). A part of the Takada rhyolites in the southern area of the central Shimane Prefecture is named Ouchi Group (RESEARCH GROUP FOR THE SAN-IN LATE MESOZOIC IGNEOUS ACTIVITY, hereafter abbreviated as RGSLMIA, 1979). This group is composed mainly of rhyolitic pyroclastic rocks and about 65 percents of measured samples belong to the ilmenite-series (Table 2, Fig. 7).

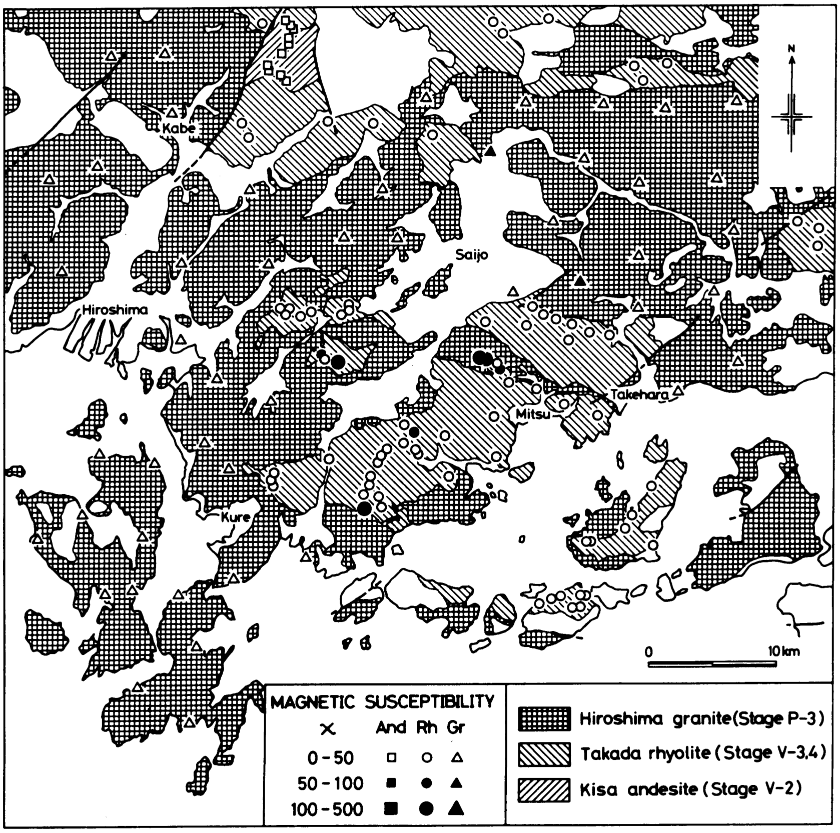

FIG. 6. Variation of magnetic susceptibility ($\chi\times10^{-6}$ emu/g) of the stages V–3 and V–4 volcanic rocks (Takada rhyolite) and stage P–3 plutonic rocks (Hiroshima granite). Geologic map is simplified from HIROSHIMA PREFECTURE (1963).

The P–3 plutonic rocks occur either as zoned plutons or as batholiths. The Hoben-zan granites, a typical example of the zoned plutons, have χ-values of $(5–200)\times10^{-6}$ emu/g, hence they comprise of both magnetite-series and ilmenite-series (Fig. 5). There is a notable spatial variation in the magnetic susceptibility of batholithic granites of this stage. Granitoids of the southern parts of batholith (represented by the Hiroshima granites, Fig. 6) and similar granites of the Mt. Kuruson area (Fig. 5) have low magnetic susceptibility, whereas those of northern parts of batholiths such as granitoids of the southern area of Ôasa, Hiroshima Prefecture (see Fig. 4.11 of ISHIHARA, 1980) and the Takahata granite (RGSLMIA, 1979; MATSUDA et al., 1981) have χ-values higher than 50×10^{-6} emu/g (Table 3, Fig. 7). Thus the batholithic granites become more magnetic toward the Japan Sea.

5. *Stages V–5 and P–4*

The V–5 volcanic rocks are represented by the Sakurae Group (MATSUDA and ODA, 1982), and by the Ôyorogi-yama Group (IIZUMI and SAWADA, 1980). The former comprises dacitic to rhyolitic pyroclastic rocks, and the latter consists of andesitic to rhyolitic pyroclastic rocks and lava (Table 1). About 70 percents of measured rhyolitic and dacitic volcanic rocks and all of the andesites of this stage belong to the magnetite-series.

The P–4 plutonic rocks, which MURAKAMI (1974) called the Imbi plutonic rocks, are composed of the Onbara granite (RGSLMIA, 1979; Fig. 7), Uogiri-dani granodiorite (RGSLMIA, 1979; Fig. 7), and the Older granites (SAWADA, 1978a; Fig. 9). Most of

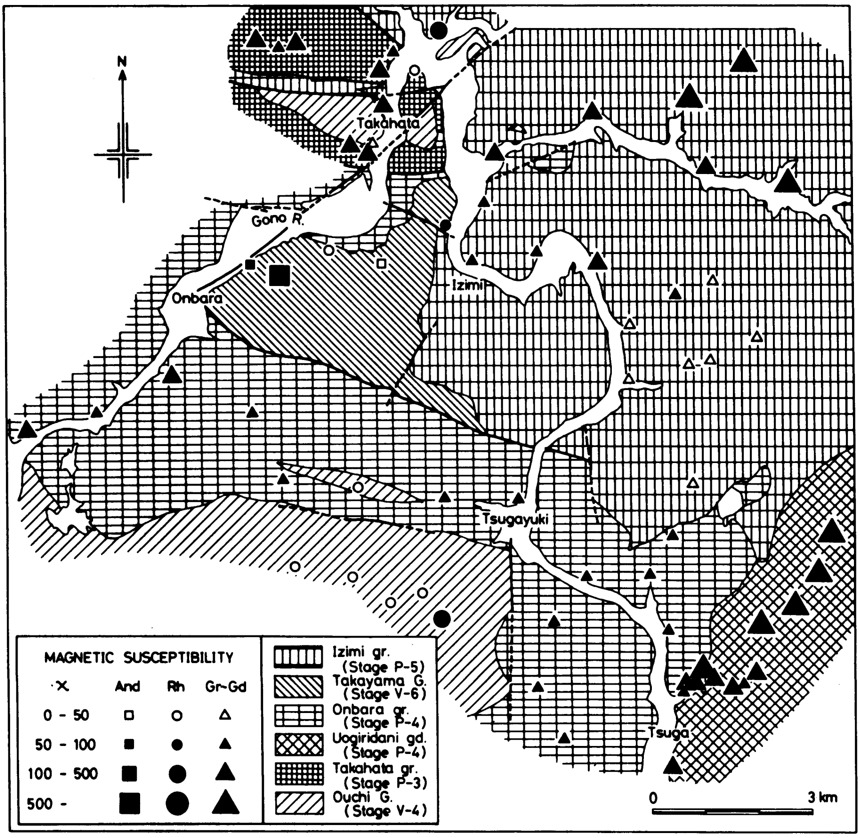

FIG. 7. Variation of magnetic susceptibility ($\chi\times10^{-6}$ emu/g) of the stages V–4 (Ouchi Group) and V–6 (Takayama Group) volcanic rocks and stages P–3, P–4 and P–5 plutonic rocks around the Ouchi-cho, Shimane Prefecture. Geologic map is simplified from RESEARCH GROUP FOR THE SAN-IN LATE MESOZOIC IGNEOUS ACTIVITY (1979).

the measured plutonic rocks (80–95%) show high magnetic susceptibility and belong to the magnetite-series (Fig. 7).

6. *Stages V–6 and P–5*

The volcanism of this stage is represented by the Paleogene Sakugi volcanic rocks, Takayama Group (RGSLMIA, 1979) and the Hakami Group (SAWADA, 1978a) in the central San-in. They are composed mainly of andesitic to rhyolitic pyroclastic rocks and lava and have a high magnetic susceptibility (Table 2, Figs. 7 and 9).

The P–5 plutonic rocks are composed of the Tadokoro granite (HIGASHIMOTO, 1975), Izimi granite (RGSLMIA, 1979; Fig. 7), the Younger granites (SAWADA, 1978a, Fig. 9), and the Sakugi plutonic rocks. They also show high magnetic susceptibility and all belong to the magnetite-series.

7. *Stages V–7 and P–6*

The Paleogene Tamagawa Group and its correlatable formations are distributed in the western San-in district. The volcanic rocks of this stage are intimately associated with gabbroic to granitic rocks of stage P–6, forming a volcano-plutonic complex associated

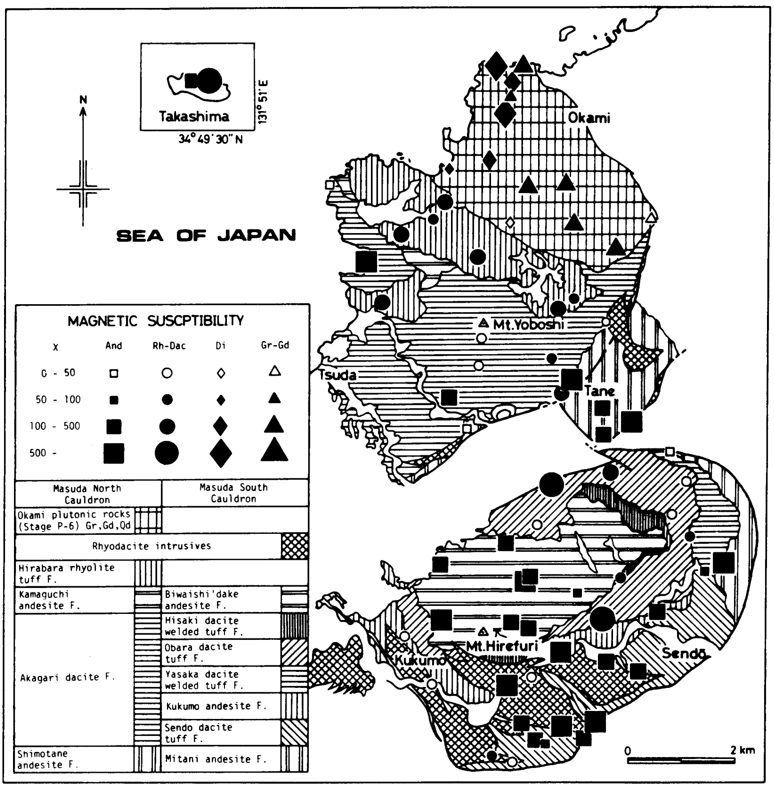

FIG. 8. Variation of magnetic susceptibility ($\chi \times 10^{-6}$ emu/g) of the stage V–6 volcanic rocks (Tamagawa Group) and stage P–5 plutonic rocks of the Masuda cauldrons, Shimane Prefecture. Geologic map is simplified from MASUDA RESEARCH GROUP (1982).

with cauldron subsidence. Those complexes are distributed in a linear arrangement roughly parallel to the coast line of the Japan Sea, spaced at about 20 km interval (IMAOKA and MURAKAMI, 1979). They are named Tamagawa (MURAKAMI, 1973), MASUDA (MASUDA RESEARCH GROUP, 1982), Hamada (IMAOKA, 1978MS), Haza (MURAKAMI et al., 1982), Sakurae (NAKAMURA, 1979), and KAWAUCHI (MATSUDA and ODA, 1982) cauldrons from west to east (Fig. 15). The volcanic rocks in these cauldrons consist of basaltic andesites to rhyolites mostly with high χ-values. Ninety percents of andesitic rocks and 70 percents of rhyolitic rocks belong to the magnetite-series.

The Tamagawa-type plutonic rocks, associated plutonic rocks of the complexes, also

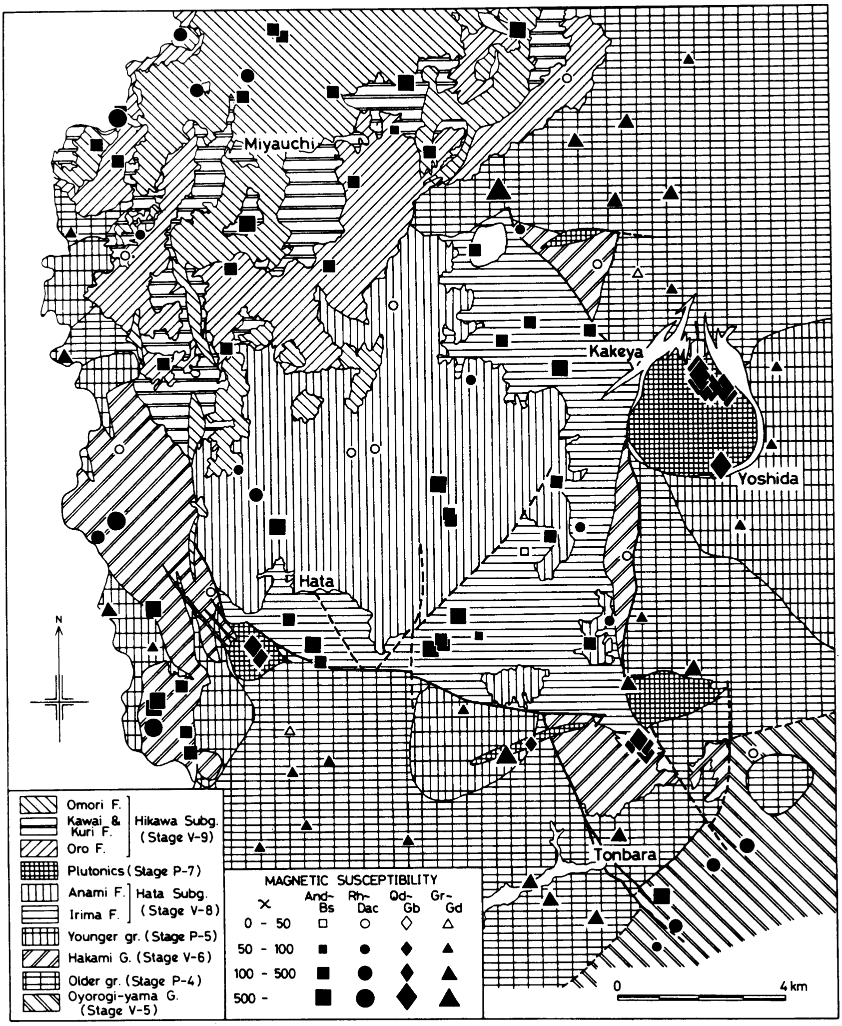

FIG. 9. Variation of magnetic susceptibility ($\chi \times 10^{-6}$ emu/g) of the stages V–5 (Hakami Group), V–8 (Hata Subgroup) and V–9 (Hikawa Subgroup) volcanic rocks and stages P–4, P–5 and P–7 plutonic rocks at south of Izumo city, Shimane Prefecture. Geologic map is simplified from SAWADA (1978a, 1978b AND UNPUBLISHED DATA) and IIZUMI AND SAWADA (1980).

exhibit high magnetic susceptibility, $(100\text{–}4000)\times10^{-6}$ emu/g, in consistent with the microscopic observation that they contain magnetite of 0.1–4% in volume (IMAOKA et al., 1979). Plutonic rocks of this stage have higher χ-value than the Imbi plutonic rocks of the previous stage (Figs. 14a and 14b).

As a representative complex of this stage, the Masuda complex has been investigated recently in detail. This complex is composed of two isolated cauldrons which are intruded by the Okami plutonic rocks (NUREKI, 1957) and by small stocks of granite to quartz diorite. The volcanic and plutonic rocks in these cauldrons have χ-values mostly larger than 50×10^{-6} emu/g and hence they belong to the magnetite-series (Fig. 8). There is no clear difference in χ-value among formations.

8. *Stages V–8, V–9 and P–7*

The volcanic formation of this stage is known as the Iwami Group (so-called Green Tuff volcanism) distributed to the north of the Paleogene basin (Fig. 13). Volcanic rocks exposed from Izumo to Hamada are all strongly magnetic and belong to the magnetite-series.

As a representative area, the variation of magnetic susceptibility of the Izumo basin, recently described in detail by SAWADA (1978a, 1978b), is shown in Fig. 9. The Iwami Group consists of the Hata and Hikawa Subgroups (Table 1). The Hata Subgroup occurs in volcano-tectonic depression (Kakeya cauldron) and constitutes the main volcano-plutonic complex of this stage. The constituent volcanic rocks have a wide range of composition from basaltic andesite to rhyolite. Eighty percents of rhyolitic to dacitic rocks and all of the andesitic volcanic rocks have the χ-values larger than 50×10^{-6} emu/g.

A similar result is obtained also for the P–7 plutonic rocks consisting of gabbro, quartz diorite and granodiorite. They are closely associated with the Kakeya cauldron and are all strongly magnetic with the χ-values of $(150\text{–}3000)\times10^{-6}$ emu/g (Table 3, Fig. 9).

B. MAGNETIC SUSCEPTIBILITY AND CHEMICAL COMPOSITION OF ROCKS

Measured magnetic susceptibility of volcanic and plutonic rocks ranges from 0 to 1×10^{-3} emu/g. It is now well established that the magnetic properties of rocks are principally attributable to those of the ferromagnetic minerals contained in the rocks, such as iron-titanium oxides and iron-sulfides. Relationships between the susceptibility and the volume percent of magnetite in the rock are proposed by MOONEY and BLEIFUES (1953), BALSLEY and BUDDINGTON (1964), SAUCK (1972) and ISHIHARA (1979b). ISHIHARA (1979b) proposed a simple relation, $\chi=0.001$ V, where χ is magnetic susceptibility and V is volume percent of magnetite. These empirical relationships were established for plutonic rocks. Ore-microscopic observations of our volcanic rocks suggest that magnetic susceptibility of the volcanic rocks is also related to the content of magnetite.

The relationship between magnetic susceptibility and SiO_2 content (wt.%) of the volcanic rocks is represented in Fig. 10. The boundary line dividing magnetite-series and ilmenite-series fields is drawn following the definition by ISHIHARA (1979b). Measured magnetic susceptibility of the volcanic rocks range from 0 to 6000×10^{-6} emu/g. The rocks of each stage exhibit characteristic distribution in the diagram. The typical magnetite-series volcanic rocks (55–75% SiO_2) of the Tamagawa (stage V–7) and Iwami (stage V–8, 9) Groups have values 100 to 6000×10^{-6} emu/g, while the typical ilmenite-series volcanic rocks (65–75% SiO_2) of the Hikimi Group (stage V–3) have values below 50×10^{-6} emu/g. Magnetic susceptibility of the magnetite-series volcanic rocks slightly decreases as the silica content increases, possibly due to the gradual decrease of magnetite content. Magnetites in the volcanic rocks of the Kanmon (stage V–1) and Tamagawa (stage V–7) were more or less martitized (IMAOKA et al., 1982). Therefore, the modal amount of magnetite estimated from the magnetic susceptibility of rock should be regarded as the possible minimum value of the conceivable original mode. Magnetic susceptibility of the volcanic rocks of the Hikimi Group (stage V–3) also slightly decreases as the silica content increases. The volcanic rocks of the Shunan Group (stage V–2) have magnetic susceptibility ($(10–400)\times10^{-6}$ emu/g) that is assigned to both the ilmenite-series and the magnetite-series.

Fig. 11 illustrates the relationship between the magnetic susceptibility and SiO_2 wt. percent of plutonic rocks. Magnetic susceptibility of the typical magnetite-series plutonic rocks of stages P–6 and P–7 is higher than 100×10^{-6} emu/g, and the value gradually decreases as the silica content increases. As stated by KANAYA and ISHIHARA (1973), typical ilmenite-series plutonic rocks in the Ryoke and San-yo zones have the value below 50×10^{-6} emu/g. Similarly to the case of the ilmenite-series volcanic rocks, magnetic susceptibility of ilmenite-series plutonic rocks of the Ryoke zone slightly decreases as the silica content increases, although not clear below 60% SiO_2. From these data, the most prominent difference in magnetic susceptibility is observed between Cretaceous and Tertiary in comparison with same basicity (SiO_2=65–75%) of rocks.

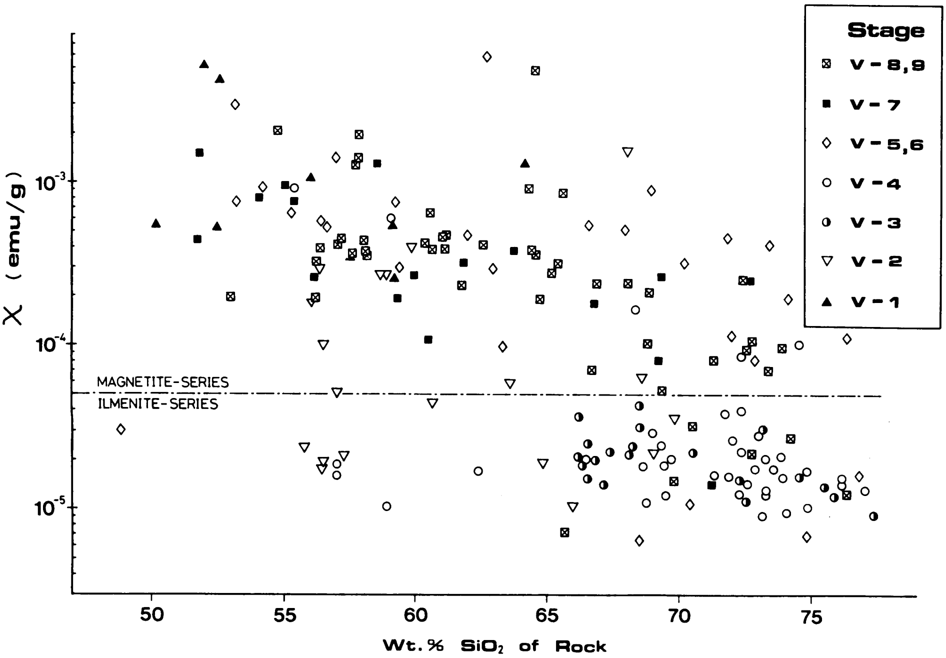

FIG. 10. Relationship between magnetic susceptibility and SiO_2 (wt. %) content of volcanic rocks.

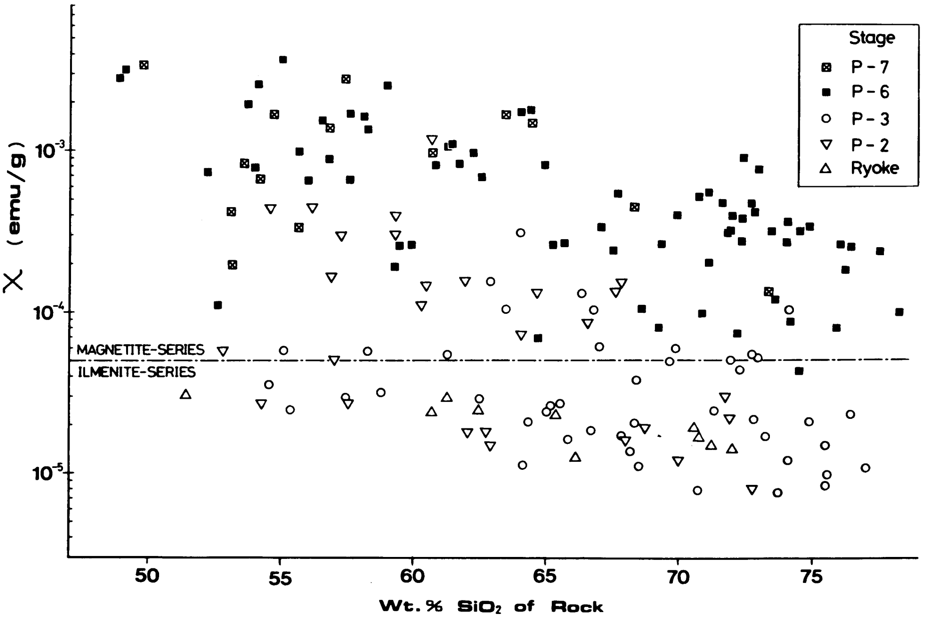

FIG. 11. Relationship between magnetic susceptibility and SiO_2 (wt. %) content of plutonic rocks.

V. TEMPORAL AND SPATIAL VARIATIONS OF MAGNETIC SUSCEPTIBILITY

A. TEMPORAL VARIATION

Magnetic susceptibility of Cretaceous to Neogene igneous rocks has been described at their type localities in the preceding chapter. These results will now be summarized with special reference to the temporal change in the magnetic susceptibility (Fig. 12).

The late Mesozoic volcanism of the titled area was initiated by the extrusion of the magnetite-series andesites of the Kanmon Group, and succeeded by the intrusion of the stage P–1 plutonic rocks of the ilmenite-series. Subsequent V–2 volcanism and associated P–2 plutonism comprise of both magnetite-series and ilmenite-series. Voluminous amounts of the felsic volcanic rocks of stages V–3 and V–4, and batholithic granites of stage P–3 are mostly of the ilmenite-series, although some granites of this stage in the San-in zone definitely belong to the magnetite-series. The volcanic rocks of stage V–3 and V–4 are correlated to the Nohi rhyolite in Central Japan which as well as other felsic volcanic rocks there belong to the ilmenite-series (HARAYAMA, 1979). These results strongly suggest that the enormous-scale felsic volcanism of the Cretaceous age in Japan are characterized by the ilmenite-series.

On the other hand, the Paleogene to Neogene volcanic rocks (stages V–5~V–9) and their associated plutonic rocks (stages P–4~P–7) have high magnetic susceptibility regardless of their rock types. Hence, the most prominent temporal change in magnetic susceptibility of volcanic rocks occurred between Cretaceous and Paleogene.

There is a marked similarity in magnetic susceptibility between volcanic rocks and their associated plutonic rocks; that is, stage V–2 volcanics and stage P–2 plutonics, stages

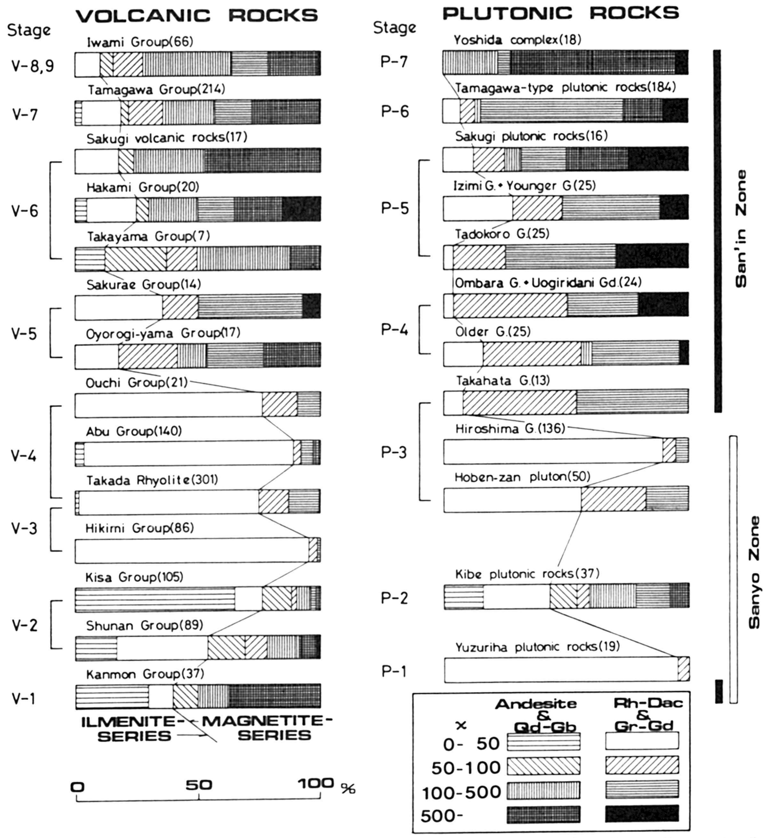

FIG. 12. Relative abundances of late Mesozoic to Neogene volcanic rocks and plutonic rocks on the basis of their magnetic susceptibility.

V–3 and V–4 volcanics and stage P–3 plutonics, stage V–5 volcanics and stage P–4 plutonics, stage V–6 volcanics and stage P–5 plutonics, stage V–7 volcanics and stage P–6 plutonics, stage V–8 volcanics and stage P–7 plutonics. The plutonic rocks have slightly higher ratio of the magnetite-series rocks to those belonging to the ilmenite-series than do the volcanic rocks.

B. SPATIAL VARIATION

One of the most notable features about the spatial variation of magnetic susceptibility is its asymmetrical distribution; that is, less magnetic igneous rocks distribute all over the studied area, but the distribution of highly magnetic igneous rocks is restricted to the side of the Japan Sea (Fig. 13). The asymmetrical distribution was first recognized by KANAYA and ISHIHARA (1973) for plutonic rocks and by ISHIHARA (1979a) for volcanic rocks.

Magnetic susceptibility of both volcanic and plutonic rocks is plotted against their distances from the Median Tectonic Line in Figs. 14a, 14b and 14c, designated by their stage of activity, geologic age, and rock types. The volcanic and plutonic rocks of the titled area exhibit a crude zonal distribution of magnetic susceptibility and tentatively

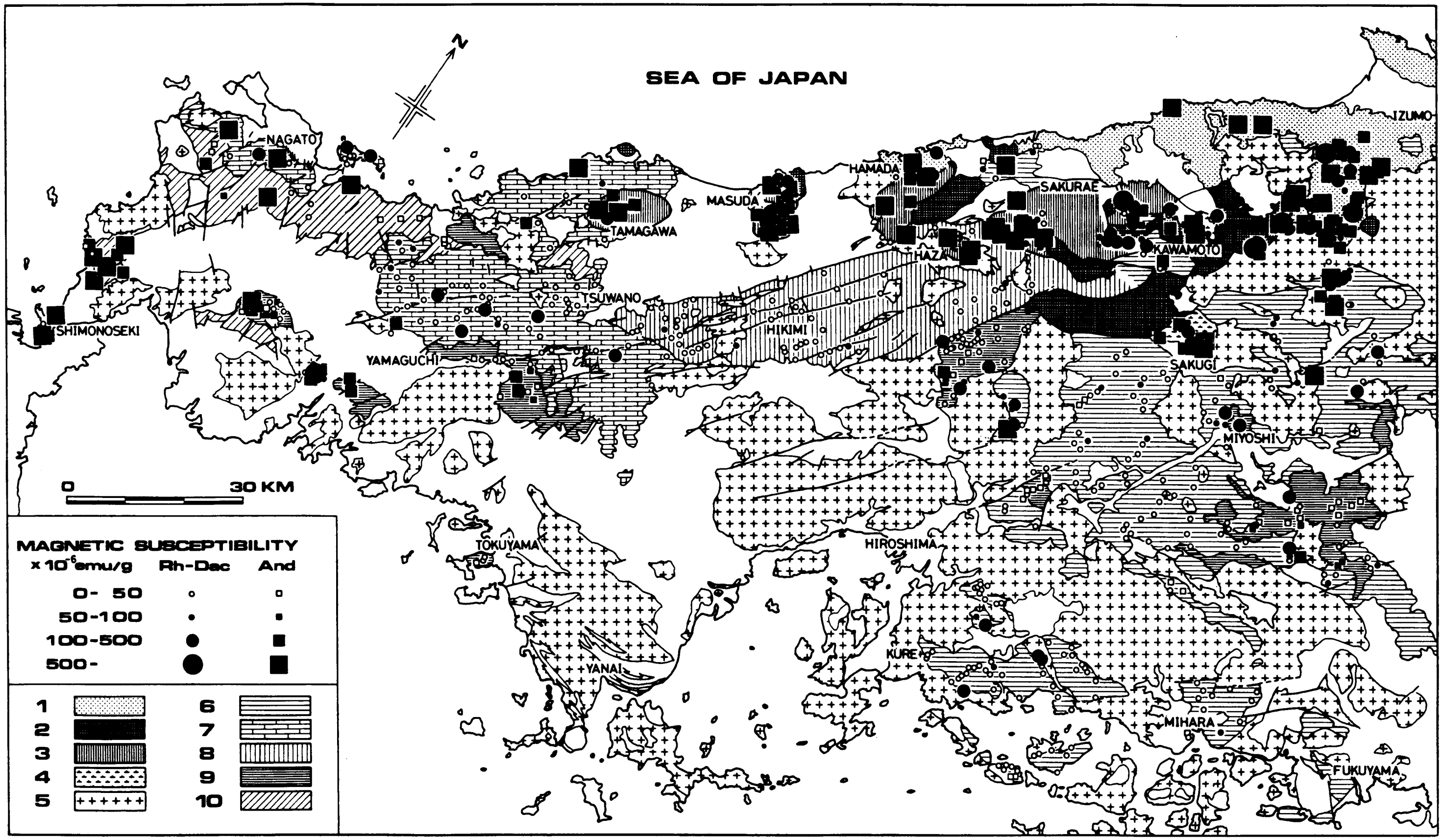

FIG. 13. Variation of magnetic susceptibility of late Mesozoic to Neogene volcanic rocks in the central and western Chugoku province, Southwest Japan. Legend: 1. volcanic rocks of stages V–8 and V–9, 2. plutonic rocks of stages P–5∼P–9, 3. volcanic rocks of stage V–7, 4. volcanic rocks of stage V–6, 5. plutonic rocks of stages P–1∼P–4, 6. volcanic rocks of stages V–3∼V–5, 7. volcanic rocks of stage V–4, 8. volcanic rocks of stage V–3, 9. volcanic rocks of stage V–2, 10. volcanic rocks of stage V–1.

are divided northwestward into three zones; I (low magnetic), II (intermediate magnetic), and III (strongly magnetic). The boundaries between zones I and II and between zones II and III lie approximately 90 km and 110 km apart from the Median Tectonic Line, respectively.

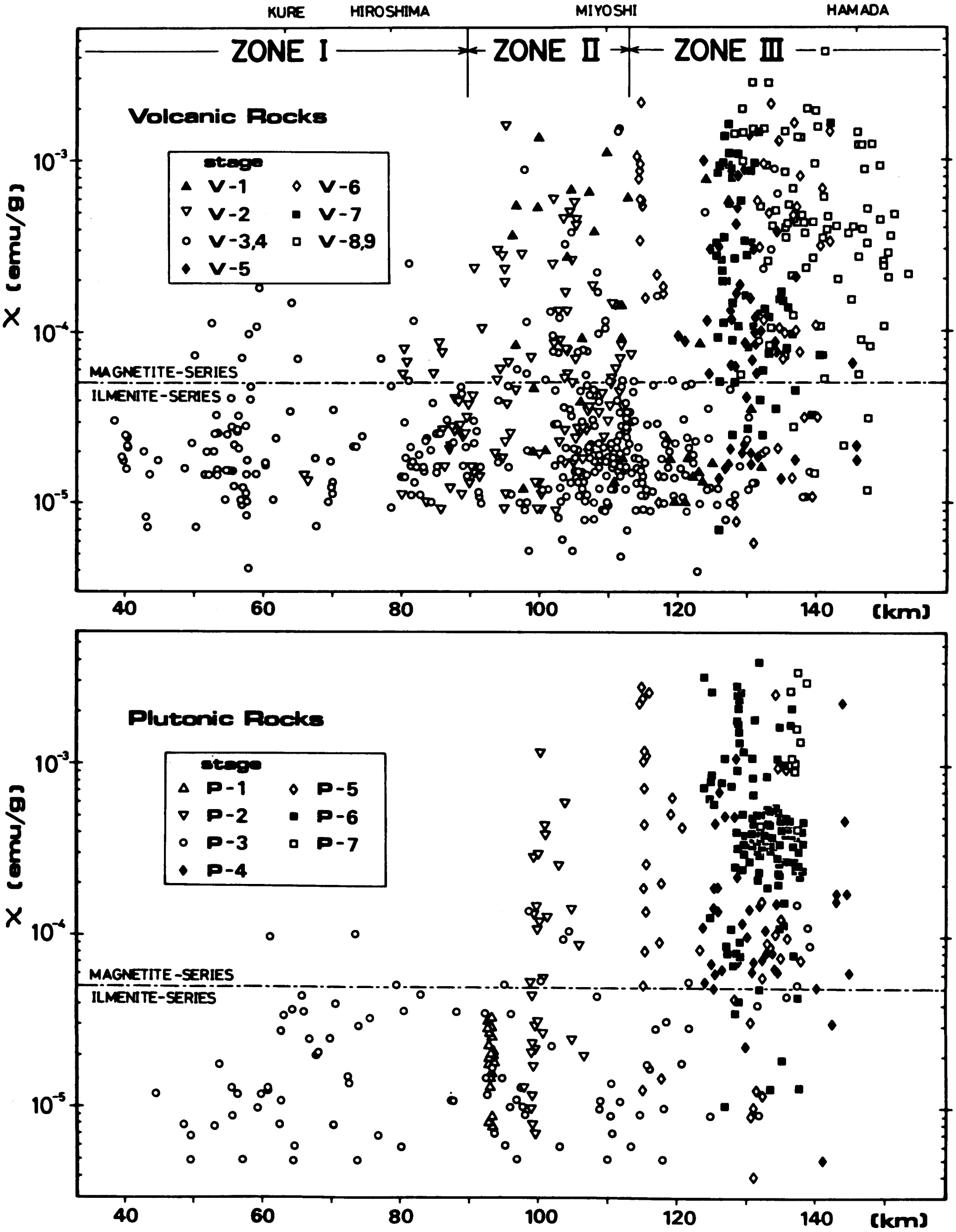

FIG. 14a. Magnetic susceptibility of volcanic rocks and related plutonic rocks in the central and western Chugoku province plotted against their distances from the Median Tectonic Line for different stages.

Zone I consists mainly of V–3 and V–4 rhyolite-dacite ignimbrite and of P–3 batholithic granite of the ilmenite-series (Fig. 14a). Zone II is characterized by the occurrence of the same constituent rocks of zone I and the V–2 and P–2 igneous rocks that form zoned

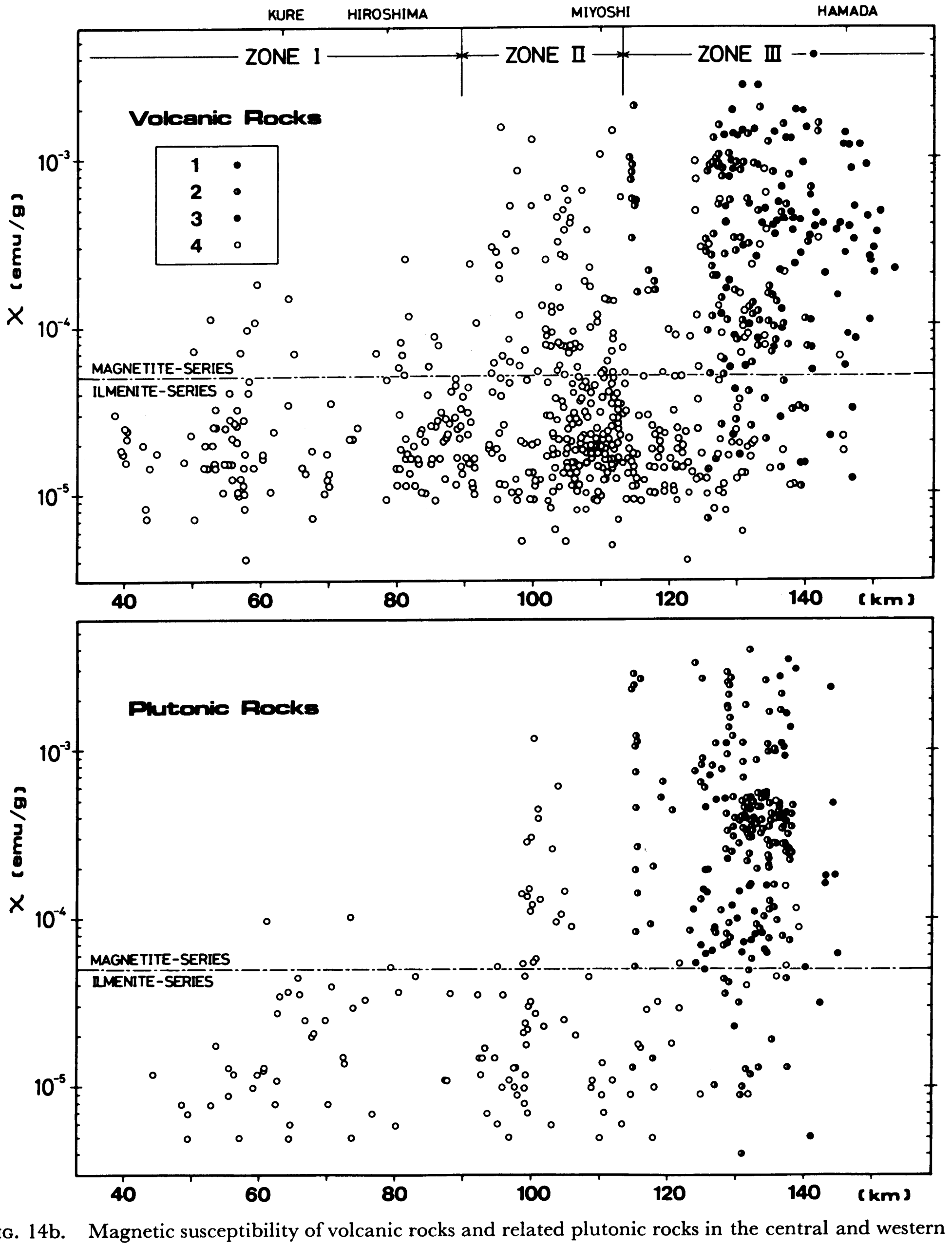

FIG. 14b. Magnetic susceptibility of volcanic rocks and related plutonic rocks in the central and western Chugoku province plotted against their distances from the M. T. L. for different geologic age.
1: Neogene, 2: Late Paleogene, 3: Early Paleogene, 4: Cretaceous

plutons or cauldrons (Fig. 14a). Igneous rocks of this zone show broader compositional variation and basic rocks are more abundant than in zone I (Fig. 14c). They also show a wide range of magnetic susceptibility even within the same rock type and cover both magnetite-series and ilmenite-series. A common feature of zones I and II is that their

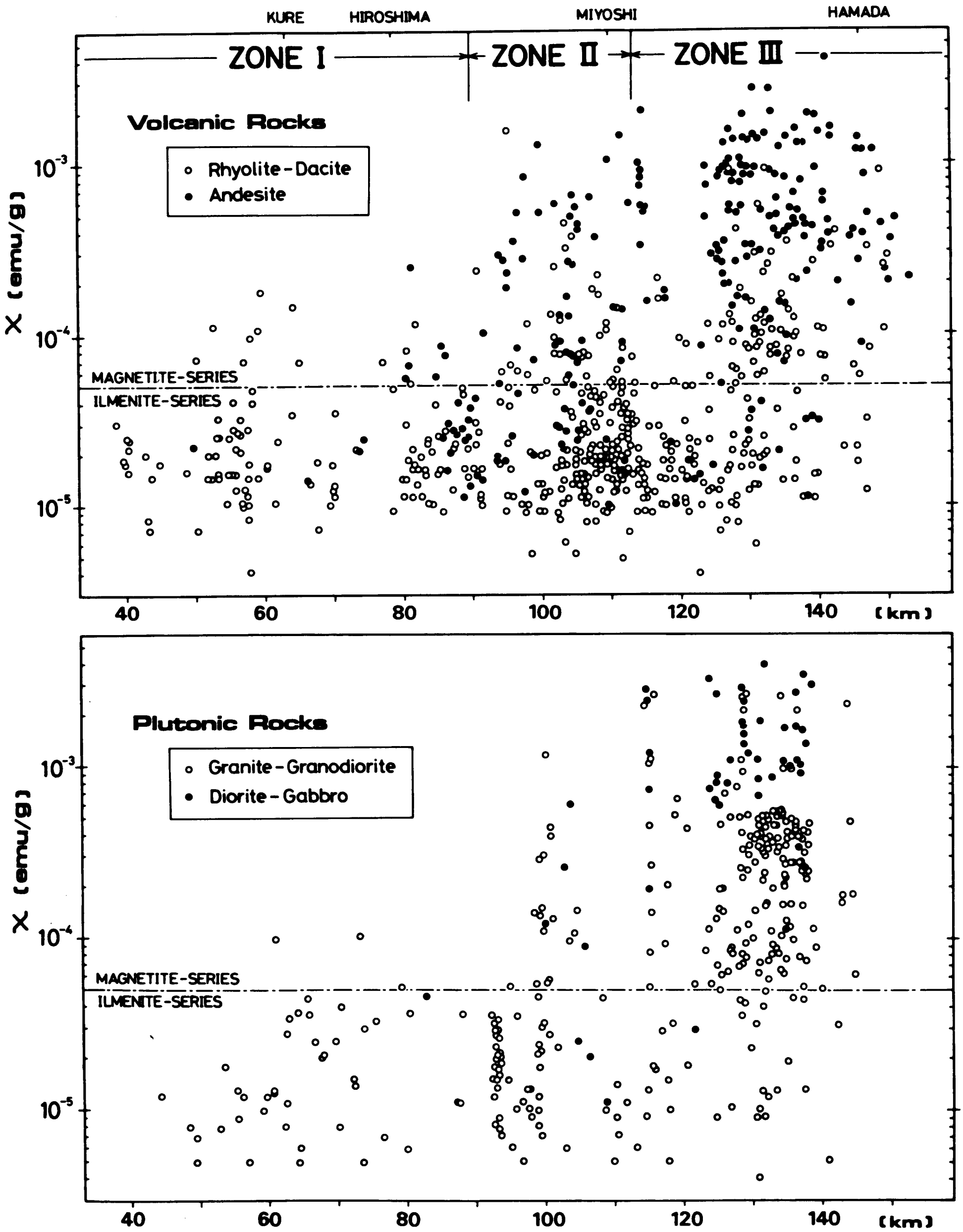

FIG. 14c. Magnetic susceptibility of volcanic rocks and related plutonic rocks in the central and western Chugoku province plotted against their distances from the M. T. L. for different rock types.

constituent rocks are all of Cretaceous age and that the ilmenite-series igneous rocks are more predominant than the magentite-series ones (Fig. 14b).

The Zone III predominates in Tertiary volcanic and plutonic rocks (stages V–5～V–9 and P–5～P–7) of the magnetite-series, although Cretaceous volcanic and plutonic rocks mostly of the ilmenite-series (stages V–3, V–4 and P–3) also coexist here (Fig. 14b). Volcanic rocks of various ages are best developed in this zone, and as noted previous subsection, the nature of volcanism changed from the middle Cretaceous andesite of the magnetite-series, through the late Cretaceous felsic ignimbrite of the ilmenite series, to the Tertiary magnetite-series volcanic rocks.

VI. Discussion

Major results of this study on the relationship between magnetic susceptibility and petrological characters of Cretaceous to Neogene igneous rocks are summarized as follows:

1) Systematic variation in magnetic susceptibility is observed with age, geographic location of the rocks, and geologic units.

2) When volcanic and plutonic rocks of the same cycle of activity are compared, their magnetic susceptibility resemble each other.

3) The most prominent temporal change in magnetic susceptibility of igneous rocks occurred between Cretaceous and Paleogene. Cretaceous igneous rocks are of both the magnetite-series and the ilmenite-series, and the latter being predominant in volume, while the Paleogene and Neogene igneous activities are characterized by only the magnetite-series rocks.

4) The ilmenite-series rocks are developed throughout the studied area, whereas the magnetite-series rocks are restricted to the Japan Sea side, overlapping over the area of older ilmenite-series rocks.

Systematic temporal and spatial changes in the distribution of rocks of the two series have been reported not only in the Japanese islands (Kanaya and Ishihara, 1973; Harayama, 1979; Ishizawa, 1982) but also in other circum-Pacific regions, such as eastern Asia continent (Takahashi et al., 1980), Korea (Ishihara et al., 1981), Thailand (Ishihara et al., 1980), Sierra Nevada (Ishihara, 1979b) and Chile (Ishihara and Ulriksen, 1980). Therefore, the classification into the two series should bear an essential significance in considering the tectonic and geological framework of the circum-Pacific regions.

The variation of the magnetic susceptibility is believed to be controlled by the oxygen fugacity of the igneous rocks. Namely, mineralogical evidences indicate that the oxygen fugacity during crystallization of the magnetite-series rocks is generally higher than that of the ilmenite-series rocks (Tsusue and Ishihara, 1974; Shimazaki, 1976; Murakami, 1977; Kanisawa, 1977). As for the oxidation condition, the boundary between the two series nearly corresponds to the fayalite-magnetite-quartz buffer line (Nakada and Seno, 1980; Seno, 1981; Wones, 1981). Thus the distribution of igneous rocks of the two series should indicate the temporal and spatial variations of the oxygen fugacity.

The oxygen fugacity may be controlled at least by 1) difference in source material as inffered from the initial $^{87}Sr/^{86}Sr$ ratio (Shibata and Ishihara, 1979b), 2) effect of buffering agents such as water as oxidizing medium and crustal carbon as reducing agent (e.g., Miyashiro, 1964; Czamanske and Wones, 1973; Honma, 1974; Ishihara, 1977),

3) modes of magma emplacement and tectonic environments (e.g., SASAKI and ISHIHARA, 1979; ISHIHARA, 1979b). In other words, the oxygen fugacity of a magma can be either intrinsic to the source region, or developed during the history of the magma (WONES, 1981).

Among these factors, the effects of buffering agents may depend on the tectonic environment and the mode of magma emplacement. SASAKI and ISHIHARA (1979) and ISHIHARA (1979b) proposed that the difference in the two series is due to the difference in tectonic environment related to back-arc spreading in an island arc system; that is, inner tensional tectonic environments permit the generation of the magnetite-series magma without much crustal contamination, whereas a large-scale magma-crust interaction under the outer compressional environments favor the generation of the ilmenite-series magma.

Base on available geologic informations, we also consider that the change of tectonic environment related to the tectonic history of the Japan Sea is an important factor for the cause of the variation of the magnetic susceptibility as described below. As is known well, the analyses of dykes provide useful information on the past tectonic stress field, since they tend to propagate in a direction parallel to the maximum compressive stress (e.g., YOKOYAMA et al., 1976; NAKAMURA et al., 1977). Studies on the regional dyke patterns have revealed that the orientation of dykes changed from E–W, then to N–S, and back to E–W again during the Cretaceous time (YOKOYAMA and HARA, 1981). Dykes closely associated with early Paleogene San-in granite batholiths and late Paleogene cauldrons tend to be arranged in NW–SE and WNW–ESE directions, respectively (RESEARCH GROUP FOR THE BATHOLITH IN THE SAN-IN ZONE, 1982; MASUDA RESEARCH GROUP, 1982; YOKOYAMA and HARA, 1981). These data indicate that the stress field changed at least twice during the Cretaceous time and that the San-in area was under N–S extensional stress field during the Paleogene time.

According to ISHIZAWA (1982), igneous rocks of Kashimayarigatake — Eboshidake area, Central Japan changed from ilmenite-series (Cretaceous; E–W or NE–SW structural trend) to magnetite-series (Paleogene; N–S structural trend, parallel to the Itoigawa-Shizuoka Tectonic Line). This temporal change of two series is quite similar to our results at San-in area. From these data, he inferred that the Itoigawa-Shizuoka Tectonic Line could be traced its origin back to the early Paleogene. Above data suggest that the tectonic environment was different between Cretaceous and Paleogene in Central Japan, too, and that it must have been an important controlling factor in determining the types of rock-series in time and space there.

Next, what geological event is attributable to the change of regional tectonic environment? Accumulation of marine geological and geophysical data led to the suggestion that the most western Pacific marginal basins were created by crustal extension associated with some unknown tectonic processes operating in an island-arc system (KARIG, 1970, 1971a). The Japan Sea is of no exception, and it is commonly believed to have been created as a result of southward drift of the Japanese islands separated from the Asian continent (e.g. MURAUCHI, 1966, 1971; HURLEY et al., 1973; HILDE and WAGEMAN, 1973). Based on the comparison of geological units between the Japanese islands and Korea Peninsula, Ichikawa (1972) considered that the opening of the Japan Sea occurred between 60 and 20 Ma B.P.. Moreover, weighing various geological and geophysical informations, OTSUKI and EHIRO (1979) concluded that the Japan Sea basins were formed between 50 or 60 and 30 Ma B.P. Although there seem several stages of development of the Japan Sea basin, and the age of the opening of the Japan Sea is still of much debate, it appears that its embryonic stage of opening could trace back to the Paleogene.

Recently, several Paleogene cauldrons circumscribed by ring faults have been found along the side of the Japan Sea in the western San-in district (Fig. 15; e.g., MURAKAMI, 1973; MASUDA RESEARCH GROUP, 1982). Many collapsed basins bounded by normal fault are expected to occur at tensional environment. Indeed, the Basin and Range physiographic province has been recognized as a site of Cenozoic crustal extension and volcanism (e.g., HAMILTON, 1969; COOK, 1969; SCHOLZ et al., 1971).

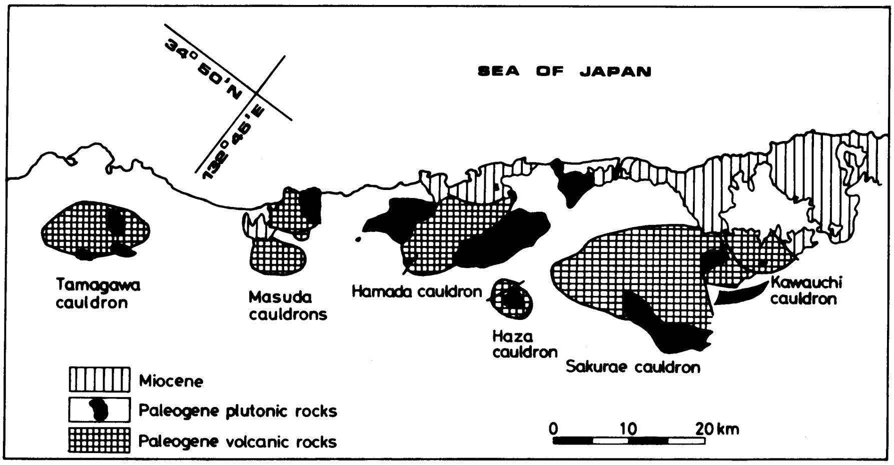

FIG. 15. Distribution of the Paleogene cauldrons at western San-in district, Southwest Japan.

These cauldrons are composed of the magnetite-series igneous rocks showing a linear arrangement parallel to the coast line of the Japan Sea, spaced at about 20 km interval (IMAOKA and MURAKAMI, 1979). Most interestingly, this arrangement of cauldrons is nearly parallel to the lineation of magnetic anomalies in the Japan Sea described by YASUI et al. (1967), ISEZAKI (1973, 1975), ISEZAKI and UYEDA (1973) and KOBAYASHI and ISEZAKI (1976), and to the possible spreading centers identified by ISEZAKI (1975). This suggests that the Paleogene igneous activity in the San-in district took place in close association with the formation of the Japan Sea under the tensional condition.

Taken together, we believe that the conspicuous change in the magnetic susceptibility from Cretaceous to Paleogene is caused by a temporal change in stress field from compressional to tensional and that spatial variation of magnetic susceptibility in Figs. 14a, 14b, 14c is related somehow to the stress gradient in the arc–back arc region as inferred by NAKAMURA and UYEDA (1980). The Paleogene igneous activity which form cauldrons presumably occurred in a back-arc extensional environment nearly contemporaneously with the formation of the Japan Sea or a part of it. Several cycles of Paleogene igneous activity from volcanism to plutonism and basic to felsic may imply that this tectonic activity took place in several pulses as proposed by KARIG (1971a, b) in the light of available data on sedimentary structures and age of basement rocks in Tonga and the Mariana islands.

Finally, if the essential relationship between the magnetic susceptibility and the tectonic environment preliminarily suggested above is established firmly on a global scale by future studies, it will be a very useful tool to infer temporal and spatial changes in tectonic environment from the magnetic susceptibility of igneous rocks.

REFERENCES

BALSLEY, J. R. and BUDDINGTON, T. F. (1964): Iron-titanium oxide minerals, rocks, and aeromagnetic anomalies of the Adirondack area, New York. *Econ. Geol.*, **53**, 777–805.

COOK, K. L. (1969): Active rift system in the Basin and Range province. *Tectonophysics*, **8**, 469–511.

CZAMANSKE, G. K. and WONES, D. R. (1973): Oxidation during magmatic differentiation, Finmarka Complex, Oslo Area, Norway: Part II, The mafic silicates. *Jour. Petrol.*, **14**, 349–380.

HAMILTON, W. (1969): Mesozoic California and the underflow of Pacific mantle. *Geol. Soc. Am. Bull.*, **80**, 2409–2430.

HARAYAMA, S. (1979): Chemical properties of mafic minerals from Cretaceous acid volcanic rocks, Central Japan (in Japanese). *MAGMA*, No. 56, 23–29.

HASE, A. (1958): The stratigraphy and geologic structure of the late Mesozoic formations in western Chugoku and northern Kyushu (in Japanese with English abstract). *Geol. Rept. Hiroshima Univ.*, **6**, 1–50.

HIGASHIMOTO, S. (1975): On the Hiroshima and the San-in granites of the O-asa Area, Central Chugoku Mountainland (in Japanese with English abstract). *Bull. Geol. Surv. Japan*, **26**, 513–518.

HILDE, T. W. C. and WAGEMAN, J. (1973): Structure and origin of the Japan Sea, in *The Western Pacific*, edited by P. J. COLEMAN, 415–434. Crane, Russak and Co., Inc., and University of Western Australia Press, New York.

HIROSHIMA PREFECTURE (1963): Geologic map of Hiroshima Prefecture. 1: 200,000.

HONMA, H. (1974): Chemical features of biotites from metamorphic and granitic rocks of the Yanai district in the Ryoke belt, Japan. *Jour. Japan. Assoc. Min. Pet. Econ. Geol.*, **69**, 390–402.

HURLEY, P. M., FAIRBAIRN, H. W., PINSON, W. H. and LEE, J. H. (1973): Middle Precambrian and older apparent age values in basement gneisses of South Korea, and relation with Southwest Japan. *Geol. Soc. Am. Bull.*, **84**, 2299–2304.

ICHIKAWA, K. (1972): Correlation of geological formations between Japan and Korea in the Mesozoic and Paleozoic (in Japanese). Nihonkai (*Japan Sea*), **8**, 9–13.

———, MURAKAMI, N., HASE, A. and WADATSUMI, K. (1968): Late Mesozoic igneous activity in the inner side of Southwest Japan. *Pacific Geol.*, **1**, 97–118.

IIZUMI, S. and SAWADA, Y. (1980): Late Cretaceous to Early Neogene igneous rocks in the southern region of Matsue, Shimane Prefecture (in Japanese). *87th. Annual Meet. Geol. Soc. Japan, Guidebook for excursion*, **5**, 1–38.

IMAOKA, T. (1978MS): Petrological studies of the Paleogene Hamada cauldrons, Shimane Prefecture, Southwest Japan (in Japanese with English abstract). *Master thesis of Hiroshima University*. 1–160.

——— and MURAKAMI, N. (1979): Petrochemistry of late Mesozoic to early Tertiary volcanic rocks in West Chugoku, Southwest Japan (in Japanese with English abstract). *Mem. Geol. Soc. Japan*, No. 17, 259–272.

———, NAKASHIMA, K. and MURAKAMI, N. (1979): The mode of occurrence and chemistry of Fe–Ti oxide minerals from Paleogene plutonic rocks in San-in zone (in Japanese). *Program* 1979 *Joint Meeting of Miner. Soc. Japan, Soc. Mining Geol. Japan, and Japan. Assoc. Min. Pet. Econ. Geol.*, Shizuoka, p. 100.

———, NAKASHIMA, K. and MURAKAMI, N. (1982): Iron-titanium oxide minerals of Cretaceous to Paleogene volcanic rocks in western Chugoku district, Southwest Japan — Special reference to manganese content of ilmenites — *Jour. Japan. Assoc. Min. Pet. Econ. Geol.*, **77**, 235–255.

ISEZAKI, N. (1973): Geomagnetic anomalies and tectonics around the Japanese Islands. *Oceanogr. Mag.*, **24** (2), 107–158.

ISEZAKI, N. (1975): Possible spreading centers in the Japan Sea. *Jour. Mar. Geophys. Res.*, **4**, 53–65.

——— and UYEDA, S. (1973): Geomagnetic anomaly pattern of the Japan Sea. *Jour. Mar. Geophys. Res.*, **2**, 51–59.

ISHIHARA, S. (1971): Modal and chemical composition of the granitic rocks related to the major molybdenum and tungsten deposits in the inner zone of Southwest Japan. *Jour. Geol. Soc. Japan.*, **77**, 441–452.

——— (1975): Acid magmatism and mineralization — Oxydation status of granitic magma and its relation to mineralization (in Japanese). *Mar. Sci. Monthly* (Tokyo), **7**, 756–759.

——— (1977): The magnetite-series and ilmenite-series granitic rocks. *Mining Geol.*, **27**, 293–305.

——— (1979a): Kappameter KT–3 and its application for some volcanic rocks in Japan. *Geol. Surv. Japan, Bull.*, **30**, 513–520.

——— (1979b): Lateral variation of magnetic susceptibility of the Japanese granitoids. *Jour. Geol. Soc. Japan*, **85**, 509–523.

——— (1980): Granite and rhyolite, in *Chikyu Kagaku* (*Earth Science*) vol. 15, edited by KANMERA, K., HASHIMOTO, M. and MATSUDA, T. 105–141, Iwanami, Tokyo.

——— (1981): The granitoid series and mineralization. *Econ. Geol. 75th Anniversary vol.*, 458–484.

———, SAWATA, H., SHIBATA, K., TERASHIMA, S., ARRYKUL, S. and SATO, K. (1980): Granites and Sn–W deposits of Peninsular Thailand. *Mining Geol. Spec. Issue,* No. 8, 223–241.

——— and ULRIKSEN, C. E. (1980): The magnetite-series and ilmenite-series granitoids in Chile. *Mining Geol.*, **30**, 183–190.

———, LEE, D. S. and KIM. S. Y. (1981): Comparative study of Mesozoic granitoids and related W–Mo mineralization in southern Korea and southeastern Japan. *Ibid.*, **31**, 311–320.

ISHIZAWA, K. (1982): Geology of the igneous rocks in the Mt. Kashimayarigatake — Mt. Eboshidake area, Hida Mountains, Central Japan (in Japanese with English abstract). *Jour. Geol. Soc. Japan,* **88**, 215–230.

KANAYA, H. and ISHIHARA, S. (1973): Regional variation of magnetic susceptibility of the granitic rocks in Japan (in Japanese with English abstract). *Jour. Japan. Assoc. Min. Pet. Econ. Geol.*, **68**, 211–224.

KANISAWA, S. (1977): Chemical characteristics of biotites and hornblendes of the late Mesozoic to early Tertiary granitic rocks in Japan, in *Plutonism in Relation to Volcanism and Metamorphism,* edited by YAMADA, N., Proc. 7th CPPP Meet., Toyama, 194–202.

KARIG, D. E. (1970): Riges and basins of the Tonga-Kermandec island arc system. *Jour. Geophys. Res.*, **75**, 239–255.

——— (1971a): Structural history of the Mariana island arc system. *Geol. Soc. Am. Bull.*, **82**, 323–344.

——— (1971b): Origin and development of marginal basins in the western Pacific. *Jour. Geophys. Res.*, **76**, 2542–2561.

KATADA, M., ONUKI, H., KATO, Y., KANISAWA, S., ONO, C. and YOSHII, M. (1971): Zonal arrangement of the Cretaceous granitic rocks, Kitakami mountainland (in Japanese with English abstract). *Jour. Japan. Assoc. Min. Pet. Econ. Geol.*, **65**, 230–245.

KAWANO, Y. and UEDA, Y. (1966): K–Ar dating on the igneous rocks in Japan(V) — Granitic rocks in southwestern Japan — (in Japanese with English abstract). *Ibid.*, **56**, 191–211.

KOBAYASHI, K. and ISEZAKI, N. (1976): Magnetic anomalies in the Sea of Japan and the Shikoku basin: Possible tectonic implications, in *The Geophysics of the Pacific Ocean Basin and its Margin, AGU Geophys. Monogr.*, **16**, 235–251.

MASUDA RESEARCH GROUP (1982): Paleogene Masuda cauldrons (in Japanese with English abstract). *Jour. Geol. Soc. Japan.*, **88**, 321–335.

MATSUDA, T. and ODA, M. (1982): Geology of the late Cretaceous to Paleogene igneous rocks in the Kawamoto area, Shimane Prefecture (in Japanese with English abstract). *Jour. Geol. Soc. Japan,* **88**. 31–42.

———, IIZUMI, S. and IMAOKA, T. (1981): The Takahata granite in the cental part of Shimane Prefecture, Southwest Japan (in Japanese). *Program 1979 Joint Meeting of Miner. Soc. Japan, Soc. Mining Geol. Japan, and Japan. Assoc. Min. Pet. Econ. Geol.*, Okayama, p. 150.

MINISTRY OF INTERNATIONAL TRADE AND INDUSTRY (1970): *Report of regional geological survey* (*Masuda region*) (in Japanese).

MIYASHIRO, A. (1964): Oxidation and reduction in the Earth's crust with special reference to the role of graphite. *Geochim. Cosmochim. Acta,* **28**, 717–729.

MOONEY, H. M. and BLEIFUSS, R. (1953): Magnetic susceptibility measurement in Minesota, Part II: analysis of field results. *Geophysics,* **18**, 383–393.

MURAKAMI, N. (1960): Cretaceous and Tertiary igneous activity in western Chugoku (in Japanese with English abstract). *Sci. Rept. Yamaguchi Univ.*, **11**, 21–126.

——— (1973): A consideration on the mechanism of formation of the Paleogene Tamagawa cauldron, Southwest Japan (in Japanese with English abstract). *Mem. Geol. Soc. Japan,* No. 9, 93–105.

——— (1974): Some problems concerning late Mesozoic to early Tertiary igneous activity on the inner side of Southwest Japan. *Pacific Geol.*, **8**, 139–151.

——— (1977): Compositional variation of some constituent minerals of the late Mesozoic to early Tertiary granitic rocks of Southwest Japan. *Geol. Soc. Malaysia, Bull.*, **9**, 75–85.

——— and HASE, A. (1967): Stratigraphy and correlation of the late Mesozoic volcanic formations in the Inner zone of Southwest Japan (in Japanese). *Monogr. No.* 13, *Assoc. Geol. Collaboration,* 1–24.

——— and MATSUSATO, H. (1970): Intrusive volcanic breccia in the Late Mesozoic Zenjoji-yama formation in western Chugoku and their possible relevance to the formation of cauldron structure. *Jour. Japan. Assoc. Min. Pet. Econ. Geol.*, **64**, 73–94.

——— and IMAOKA, T. (1980): Chemistry of late Mesozoic to Paleogene volcanic rocks in the Inner side of Southwest Japan with special reference to West Chugoku (in Japanese with English abstract). *Jour. Japan. Assoc. Min. Pet. Econ. Geol. Spec. Issue,* No. 2, 263–278.

———, IMAOKA, T. and IZUTSU, K. (1982): Geology and structure of Paleogene Haza cauldron, Shimane Prefecture, Southwest Japan (in Japanese with English abstract). *Jour. Geol. Soc. Japan,* **88**, 311–319.

MURAUCHI, S. (1966): Explosion seismology, in *Second Progress Report on the Upper Mantle Project of Japan* (1965-1966), 1–13. Natl. Comm. for UMP, Sci. Council of Japan.

——— (1971): The renewal of island arc and the tectonics of marginal seas, in *Island Arc and Marginal Sea,* edited by S. ASANO and G. B. UDINTSEV, 39–56, Tokai Univ. Press, Tokyo.

NAKADA, S. and SENO, M. (1980): Oxygen fugacity in ilmenite-series magma estimated from compositions of ilmenites in acid volcanic rocks (in Japanese). *Bull. Volcano. Soc. Japan,* **25**, 292.

NAKAMURA, E. (1979): On structure of volcanic depression, Paleogene Tertiary, Asahi-cho area, Shimane Prefecture, in the inner side of Southwest Japan (in Japanese). *Abstr. Issue,* 86th *Ann. Meet. Geol. Soc. Japan,* 275.

NAKAMURA, K., JACOB, K. and DAVIES, J. N. (1977): Volcanoes as possible indicators of tectonic stress orientation — Aleutians and Alaska. *Pageoph,* **115**, 87–112.

——— and UYEDA, S. (1980): Stress gradient in arc–back arc regions and plate subduction. *Jour. Geophys. Res.*, **85**, 6419–6428.

NUREKI, T. (1957): Genesis of some basic inclusions and granitic "pseudo-xenoliths" found in the Okami plutonic complex, Shimane Prefecture (in Japanese with English abstract). *Jour. Geol. Soc. Japan,* **63**, 35–47.

OTSUKI, K. and EHIRO, M. (1978): Major strike-slip faults and their bearing on spreading in the Japan Sea. *Jour. Phys. Earth,* **26**, Suppl., S537–S555.

RESEARCH GROUP FOR THE BATHOLITH IN THE SAN-IN ZONE (1982): The Neu granitic pluton—Petrographical study on the batholith in the San-in zone, Southwest Japan— (in Japanese with English abstract). *Jour. Geol. Soc. Japan,* **88**, 299–310.

RESEARCH GROUP FOR THE SAN-IN LATE MESOZOIC IGNEOUS ACTIVITY (1979): Late Cretaceous to Paleogene igneous rocks in the Ouchi district, central Shimane Prefecture, western Honshu (in Japanese with English abstract). *Mem. Geol. Soc. Japan,* No. 17, 249–258.

SASAKI, A. and ISHIHARA, S. (1979): Sulfur isotope composition of the magnetite-series and ilmenite-series granitoids in Japan. *Contrib. Mineral. Petrol.*, **68**, 105–117.

SAUCK, W. A. (1972): Magnetic susceptibility and magnetite content. *Econ. Geol.*, **67**, 383.

SAWADA, Y. (1978a): Geology of the area south of Izumo City, Shimane Prefecture, Southwest Japan (in Japanese with English abstract). *Jour. Geol. Soc. Japan,* **84**, 111–130.

——— (1978b): Intrusive complexes associated with the Neogene Kakeya cauldron, Shimane Prefecture, Southwest Japan — Several problems concerning the magma types and rock series of non-alkaline rocks — (in Japanese with English abstract). *Ibid.,* **84**, 177–200.

SCHOLZ, C., BARAZANGI, M. and SBAR, M. L. (1971): Late Cenozoic evolution of the Great Basin, western United States, as an ensialic interarc basin. *Geol. Soc. Am. Bull.,* **82**, 2979–2990.

SEKI, T. (1978): Rb–Sr geochronology and petrogenesis of the late Mesozoic igneous rocks in the Inner Zone of the southwestern part of Japan. *Mem. Fac. Sci., Kyoto Univ., Geol. Mineral.,* **XLV**, 71–110.

SENO, M. (1981): Estimation of physicochemical conditions during the crystallization of garnet from the Setouchi acidic rocks (in Japanese). *MAGMA,* No. 61, 22–27.

SEO, T. (1976): On the plutonic rocks and the Sangun metamorphic rocks of the Kibe area, Asa-gun, Yamaguchi Prefecture. *The Professor George Kojima Memorial Volume,* 276–284.

SHIBATA, K. and ISHIHARA, S. (1974): K–Ar ages of biotites across the central part of the Hiroshima granite (in Japanese with English abstract). *Jour. Geol. Soc. Japan,* **80**, 431–433.

——— and KAMITANI, M. (1974): K–Ar ages of the Roseki deposits in the Abu district, Yamaguchi Prefecture — Study on the Roseki deposits in the Abu district. Part 2 — (in Japanese with English abstract). *Bull. Geol. Surv. Japan,* **25**, 323–330.

——— and ISHIHARA, S. (1979a): Rb–Sr whole-rock and K–Ar mineral ages of granitic rocks in Japan. *Geochem. Jour.,* **13**, 111–117.

——— and ——— (1979b): Initial $^{87}Sr/^{86}Sr$ ratios of plutonic rocks from Japan. *Contrib. Mineral. Petrol.,* **70**, 381–390.

SHIMAZAKI, H. (1976): Granitic magma and ore deposits (2), oxidation state of magmas and ore deposits (in Japanese with English abstract). *Mining Geol. Spec. Issue,* **7**, 25–36.

TAI, Y. (1973): On the "Shinji Folded Zone" (in Japanese with English abstract). *Mem. Geol. Soc. Japan,* No. 9, 137–146.

TAKAHASHI, M., ARAMAKI, S. and ISHIHARA, S. (1980): Magnetite-series/ilmenite-series vs. I-type/S-type granitoids. *Mining Geol. Spec. Issue,* No. 8, 13–28.

TSUSUE, A. and ISHIHARA, S. (1974): The iron-titanium oxides in the granitic rocks of Southwest Japan (in Japanese with English abstract). *Mining Geol.,* **24**, 13–30.

UEDA, K., and NISHIMURA, S. (1982): Stratigraphy and fission-track age of late Cretaceous volcanic rocks in the Agawa-Yumoto and Omishima areas, Yamaguchi Prefecture, Japan (in Japanese). *Abstr. Issue 89th Ann. Meet., Geol. Soc. Japan,* 382.

WAKIZAKA, Y. (1982): Rb–Sr whole-rock ages of Cretaceous granitoids around the Ogori district, Yamaguchi Prefecture (in Japanese). *Ibid.,* 408.

WONES, D. R. (1981): Mafic silicates as indicators of intensive variables in granitic magmas. *Mining Geol.,* **31**, 191–212.

YAMAGUCHI PREFECTURE (1969): Geological map of Yamaguchi Prefecture. 1: 50,000.

YASUI, M., HASHIMOTO, Y., and UYEDA, S. (1967): Geomagnetic studies of the Japan Sea — anomaly pattern in the Japan Sea. *Oceanogr. Mag.* **19**, 221–231.

YOKOYAMA, S., KOJIMA, G. and HARA, I. (1976): A preliminary report on dyke swarms in the Ryoke belt and its northern outside (in Japanese). *The Professor George Kojima Memorial Volume,* 266–273.

——— and HARA, I. (1981): Analysis of Late Mesozoic tectonic stress field of Southwest Japan based on preferred orientation of dyke swarms (in Japanese), in *Studies on Late Mesozoic Tectonism in Japan,* **3**, 149–163.

YOSHIDA, H. (1961): The Late Mesozoic igneous activity in the middle Chugoku province (in Japanese with English abstract). *Geol. Rept. Hiroshima Univ.,* **8**, 1–39.

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