Spatiotemporal Distributions of Chemical and Isotopic Compositions for Tertiary Volcanic Rocks of Central Japan

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ABSTRACT

To clarify spatiotemporal distributions of Tertiary volcanic rocks of central Japan, K-Ar ages, geochemical data (major and trace element compositions, Sr and Nd isotopic ratios) of selected volcanic rocks both in the eastern and western sides of the Itoigawa-Shizuoka Tectonic Line in central Japan were analyzed.

146 rock samples from the Sado Island and Mt. Yahiko in Niigata Prefecture, Shimonita Town in Gunma Prefecture, Maruko Town in Nagano Prefecture, Hida area in Gifu Prefecture, Asahi Town and Riga Village and Kamiichi Town in Toyama Prefecture, Noto Peninsula and Kanazawa City in Ishikawa Prefecture, Echizen Coastal area in Ishikawa and Fukui Prefecture, and Shidara area in Aich Prefecture, were analyzed for $^{87}Sr/^{86}Sr$ ratios. $^{87}Sr/^{86}Sr$ ratios of these Tertiary volcanic rocks from central Japan, are widely variable. And from the point of view of existence of low $^{87}Sr/^{86}Sr$ ratio ($\sim$0.704), which represents depleted, Tertiary volcanic rocks from central Japan divide into two groups. In the Sado Island, Shimonita Town and around Mt. Yahiko, $^{87}Sr/^{86}Sr$ ratios ranges both high (>0.705) and low (<0.704). In contrast, the ratios of those from Toyama, Gifu (north part) and Ishikawa Prefectures range only high. Heterogeneity of original materials depending on time and space made distributions of $^{87}Sr/^{86}Sr$ ratios widely variable. Before ca. 15Ma, in both eastern and western

sides of the Itoigawa-Shizuoka Tectonic Line, the original materials of the volcanic rocks were undepleted rather enriched one (>0.705) in the back-arc side of central Japan. After that, only in the eastern side of the Itoigawa-Shizuoka Tectonic Line, the original materials changed to be depleted one (<0.704). The timing of this temporal changing synchronized with the opening of the Japan Sea. Thus it is sure that changing of magma source to depleted one was caused by the same mechanism of the opening of the Japan Sea.

In the Japan arc, $^{87}Sr/^{86}Sr$ ratios are low only in the Yamato Basin, back-arc side of northeast Japan, and in the eastern part of central Japan (Fossa Magna area), but those in the other areas are high after ca. 15 Ma to present. Such a drastic spatio and temporal change can be explained by a new, depleted magma source, a mantle plume, emplacing the Japan Sea and the Fossa Magna area during or the opening of the Japan Sea just at 15 Ma. So it is possible to explain the mechanism of magma generation since ca. 15 Ma, as permanent small-scale layered plumes up welling.

CONTENTS

ABSTRACT i
CONTENTS iii
LIST OF TABLES vi
LIST OF FIGURES vii

Chapter 1 INTRODUCTION 1

Chapter 2 GEOLOGICAL SETTINGS AND SAMPLES 3

Chapter 3 ANALYTICAL PROCEDURES 12
3.1 K-Ar Age Determination 12
3.2 X-Ray Fluorescence Analysis 12
3.3 Sr Isotope Analysis 13
(1) Rock Samples 13
(2) Olivine Phenocryst of Picrite 14
3.4 Nd Isotope Analysis 14

Chapter 4 RESULTS 16
4.1 K-Ar Ages 16
(1) Sado Island 16
(2) Shimonita Town 17
(3) Maruko Town 17

(4) Asahi Town 17

(5) Hida area 18

(6) Riga Village 18

(7) Kamiichi Town 19

(8) Noto Peninsula 19

4.2 Major and Trace Element Compositions 19

(1) SiO_2 vs. (Na_2O + K_2O) 31

(2) SiO_2 vs. FeO/(FeO + MgO) 31

(3) Discriminating between tectonic environments 34

4.3 Sr Isotope Data 34

(1) Sado Island 36

(2) Mt. Yahiko 37

(3) Shimonita Town 37

(4) Maruko Town 37

(5) Asahi Town 38

(6) Hida area 38

(7) Riga Village 38

(8) Kamiichi Town 39

(9) Noto Peninsula 39

(10) Kanazawa City 39

(11) Echizen coast 40

(12) Shidara area 40

4.4 Nd Isotope Data 45

(1) Sado Island 46

(2) Asahi Town 47

(3) Hida area 47

(4) Riga Village 47

(5) Kamiichi Town 47

(6) Noto Peninsula 48

(7) Kanazawa City 48

(8) Echizen coast 48

4.5 ε^{0}_{CHUR}(Nd) and ε^{0}_{UR}(Sr) Isotope Correlation Diagram 48

Chapter 5 DISCUSSION 62

5.1 Distributions of Isotopic Ratios 62

(1) 87Sr/86Sr ratios 62

(2) ε Nd values 62

5.2 Temporal Changing of Isotopic Ratios 63

5.3 Main Factors for Enrichment of Volcanic Rocks 66

(1) Crustal contaminations 66

(2) Sea water effect 77

(3) Heterogeneity of original magma 78

5.4 Relations Between Temporal Changing of Volcanic Rocks and Opening of the Japan Sea 79

5.5 Mechanism of Magma Origin

(1) Spatiotemporal distributions of Isotope Data in Japan 79

(2) Mechanism of Generation of Magma 81

Chapter 6 CONCLUSION 86

ACKNOWLEDGMENTS 88

REFERENCES 90

LIST OF TABLES

Table 1. List of rock samples, localities, occurrences, stratigraphies and rock types.
Table 2. Results of K-Ar dating of the volcanic rocks.
Table 3. Results of major element contents.
Table 4. Results of trace element contents.
Table 5. Results of Sr and Nd isotopic ratios and Sr and Rb contents.

LIST OF FIGURES

Fig. 1. Distribution of Tertiary volcanic rocks of central Japan (hatched area) and sampling localities of this study.

Fig. 2. SiO_2 vs. (Na_2O + K_2O) plots, volcanic rocks from the Sado Island, Shimonita Town, Noto Peninsula and Shidara area.

Fig. 3. SiO_2 vs. FeO/(FeO + MgO) plots of non-alkaline rocks from the Sado Island, Shimonita Town and Noto Peninsula.

Fig. 4. FeO-MgO-Al_2O_3 discrimination diagram for basalt and basaltic andesite defined by Pearce (1977).

Fig. 5-1. Histograms of distributions of $^{87}Sr/^{86}Sr$ ratios of Tertiary volcanic rocks from the Sado Island, Mt. Yahiko, and Maruko Town.

Fig. 5-2. Histograms of distributions of $^{87}Sr/^{86}Sr$ ratios of Tertiary volcanic rocks from Shimonita Town and Shidara area.

Fig. 5-3. Histograms of distributions of $^{87}Sr/^{86}Sr$ ratios of Tertiary volcanic rocks from Asahi Town, Hida area, Riga Village, Kamiichi Town, Noto Peninsula, Kanazawa City and Echizen coast.

Fig. 6. Histograms of distributions of εNd values of Tertiary volcanic rocks from the Sado Island, Asahi Town, Hida area, Riga Village, Kamiichi Town, Noto Peninsula, Kanazawa City, Echizen coast.

Fig. 7. ε Nd vs. ε Sr isotope correlation diagram showing the relative position of depleted and enriched mantle source.

Fig. 8. ε Nd vs. ε Sr isotope correlation diagram of Tertiary to Quaternary volcanic rocks from Japan and Mariana, arranged by Kaneoka (1990).

Fig. 9. ε Nd vs. ε Sr isotope correlation diagram of volcanic rock from central Japan (the Sado Island, Asahi Town, Hida area, Riga Village, Kamiichi Town, Noto Peninsula, Kanazawa City and Echizen coast) analyzed in this study.

Fig. 10. $^{87}Sr/^{86}Sr$ ratios vs. age for volcanic rocks (with SiO_2 contents lower than 60 wt%) from the back-arc side of the NE Japan arc (Ohki *et al.*, 1994).

Fig. 11. ε Nd values vs. age for volcanic rocks (with SiO_2 contents lower than 60 wt%) from the back-arc side of the NE Japan arc (Ohki *et al.*, 1994).

Fig. 12. $^{87}Sr/^{86}Sr$ ratios vs. ages of Tertiary volcanic rocks from the Sado Island.

Fig. 13. $^{87}Sr/^{86}Sr$ ratios vs. ages of Tertiary volcanic rocks from Mt. Yahiko Island.

Fig. 14. $^{87}Sr/^{86}Sr$ ratios vs. ages of Tertiary volcanic rocks from Shimonita Town and Maruko Town .

Fig. 15. $^{87}Sr/^{86}Sr$ ratios vs. ages of Tertiary volcanic rocks from Noto Peninsula.

Fig. 16. $^{87}Sr/^{86}Sr$ ratios vs. ages of Tertiary volcanic rocks from Asahi

Town, Kamiichi Town, Riga Village, Hida areas and Kanazawa City.

Fig. 17. $^{87}Sr/^{86}Sr$ ratios vs. ages of Tertiary volcanic rocks from Echizen coast.

Fig. 18. ε Nd values vs. ages of Tertiary volcanic rocks from the Sado Island.

Fig. 19. ε Nd values vs. ages of Tertiary volcanic rocks from Noto Peninsula.

Fig. 20. ε Nd values vs. ages of Tertiary volcanic rocks from Asahi Town, Kamiichi Town, Riga Village, Hida areas and Kanazawa City.

Fig. 21. ε Nd values vs. ages of Tertiary volcanic rocks from Echizen coast.

Fig. 22. $^{87}Sr/^{86}Sr$ ratios vs. ages of Tertiary basalt and basaltic andesite (<56 SiO_2wt%) from central Japan.

Fig. 23. Distributions of $^{87}Sr/^{86}Sr$ ratios of Tertiary (>15Ma) volcanic rocks of Japan and the Japan Sea.

Fig. 23. Distributions of $^{87}Sr/^{86}Sr$ ratios of Tertiary (<15Ma) volcanic rocks of Japan and the Japan Sea.

Fig. 24. Distributions of $^{87}Sr/^{86}Sr$ ratios of Quaternary volcanic rocks of Japan.

Chapter 1

INTRODUCTION

Tertiary volcanic rocks are widely distributed in central Japan. The opening of the Japan Sea, considered taking place in Miocene, is one of the most important phenomena in the history of the Japan arc. Otofuji *et al.* (1985) proposed that it took place between 21 − 11 Ma and reached its climax at around 15 Ma on the basis of paleomagnetic data of volcanic rocks. On the other hand, Tada and Tamaki (1992) proposed it started before 28 Ma in the eastern margin of the Japan Sea, and they thought that it propagated westward at about 18 Ma on the basis of the Japan Sea Legs of the Ocean Drilling Program.

To clarify the petrogenesis of Tertiary volcanic rocks is one of the most profitable ways for making clear about formative process of the Japan arc during this period. Sr and Nd isotopic ratios ($^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ respectively) and major and trace elements analyses are the chief methods for studying of the petrogenesis. Sr and Nd isotopic ratios are considered to hold the original information for volcanic rocks, especially for basaltic rocks.

Ujike and Tsuchiya (1993), Shuto *et al.* (1993), Tatsumi *et al.* (1988, 1990), Nohda and Wasserburg (1981, 1986), Kurasawa and Konda (1986) measured Sr isotopic ratios of Tertiary volcanic rocks in northeastern Japan, and reported that the ratios were changed from high to low value at 15 or 16 Ma, and interpreted to be related to the opening of the Japan Sea.

Though in southwest Japan the change of ratios in time and space were known (Fujimaki *et al.*, 1991; Kagami and Genbudo Research Group, 1990; Morris and Kagami, 1989; Ishizaka and Carlson, 1983), such change at 15 or 16 Ma was not reported. As a whole in the Japan arc, the interpretations for the reasons of the Sr isotopic ratios of volcanic rocks might be different in each area. Therefore, the Sr isotope data of the volcanic rocks in central Japan are requested to give an explanation.

In this study (after careful researches and analyses), I present K-Ar data, geochemical data (major and trace element compositions, Sr and Nd isotopic ratios) of the Tertiary volcanic rocks in central Japan. I selected the study area as follows; the Sado Island and Mt. Yahiko in Niigata Prefecture, Shimonita Town in Gunma Prefecture, Maruko Town in Nagano Prefecture, Hida area in Gifu Prefecture, Asahi Town and Riga Village and Kamiichi Town in Toyama Prefecture, Noto Peninsula and Kanazawa City in Ishikawa Prefecture, Echizen Coastal area in Ishikawa and Fukui Prefectures, Shidara area in Aich Prefecture. This study aims (1) to clarify the distribution of isotopic ratios whole in Japan in Tertiary, (2) to clarify space and time variations of isotopic ratios, (3) to compare to the distributions of isotopic ratios of Quaternary volcanic rocks, (4) to give explanations to (1)-(3). With these data, petrogenesis of these rocks and the relation between the opening of the Japan Sea and volcanism are discussed.

Chapter 2

GEOLOGICAL SETTINGS AND SAMPLES

In central Japan, Tertiary volcanic rocks are widely distributed (Fig. 1). But these rocks are as so called "green tuff", most of them were altered. Therefore, for both K-Ar dating and geochemical analyses, careful researches to collect fresh rock samples were taken. And the samples must have variety of their age, because time variation was the one of the main subjects of this study. Under such requirements, I selected the study area as follows (Fig. 1); the Sado Island and Mt. Yahiko in Niigata Prefecture, Shimonita Town in Gunma Prefecture, Maruko Town in Nagano Prefecture, Hida area in Gifu Prefecture, Asahi Town and Riga Village and Kamiichi Town in Toyama Prefecture, Noto Peninsula and Kanazawa City in Ishikawa Prefecture, Echizen Coastal area in Ishikawa and Fukui Prefecture, and Shidara area in Aich Prefecture. Most of these samples were the products of volcanic activities from the Oligocene to the Pliocene in central Japan. List of rock samples analyzed in this study, their localities, stratigraphies, occurrences and rock types were listed in Table 1.

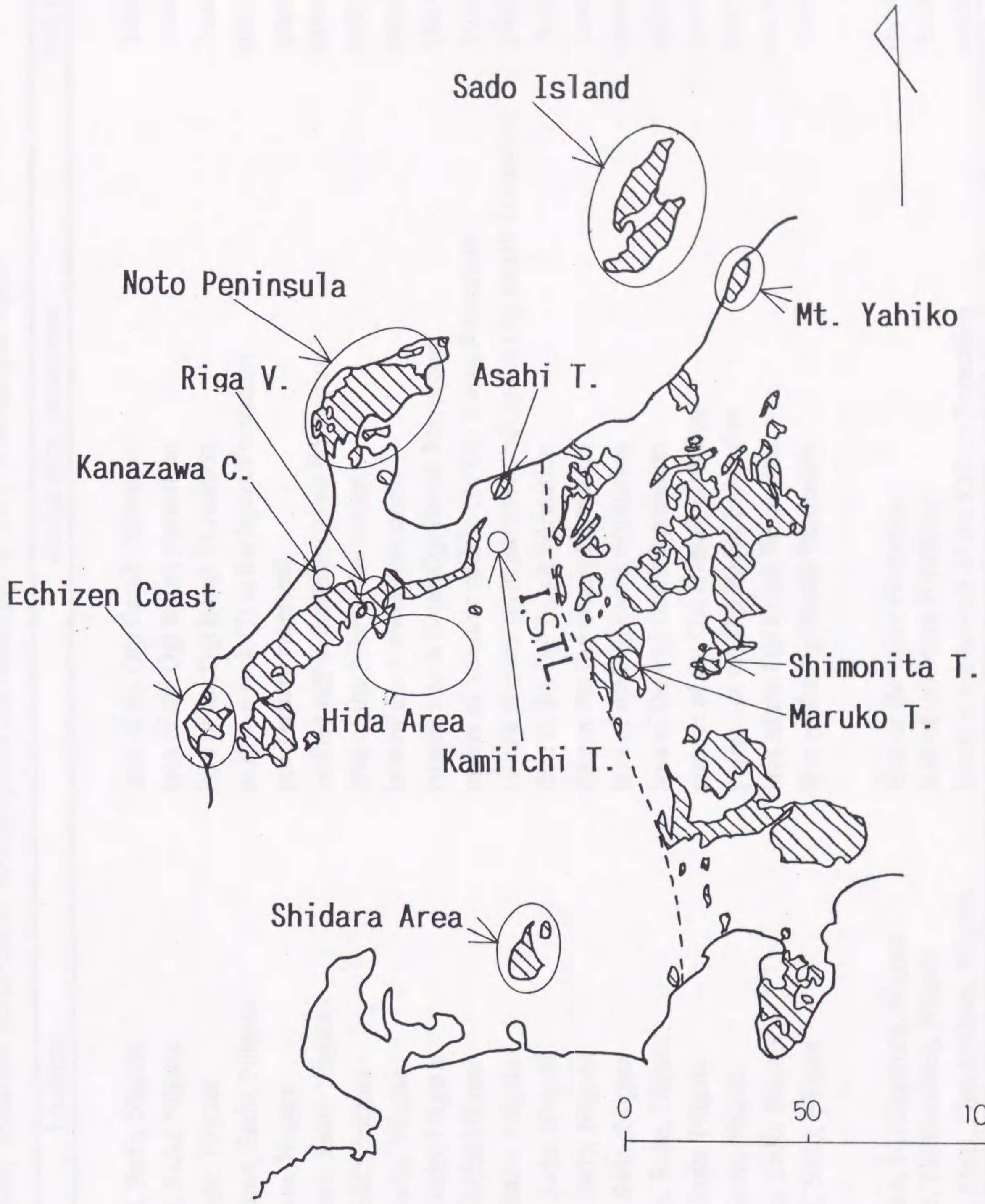

Fig. 1 Distribution of Tertiary volcanic rocks of central Japan (hatched area) and sampling localities of this study shown by circle (I. S. T. L.: Itoigawa-Shizuoka Tectonic Line).

Table 1. List of rock samples, localities, occurrences, stratigraphies and rock types of rocks from central Japan

Sample No.	Location	stratigraphy, occurrence	rock type
Sado			
1 87040501	Shiroyama, Ogi, Sado, Niigata	lava of the Ogi Basalt Formation	basalt
2 87040503	Konagashi, Ogi, Sado, Niigata	lava of the Ogi Basalt Formation	basalt
3 87040504	Shiraki, Ogi, Sado, Niigata	lava of the Ogi Basalt Formation	basalt
4 87040505	Nojimabana, Hamo, Sado, Niigata	intrusive rock (?) in the Sanze Formation	andesite
5 87040601	Kitaujima, Ryotsu, Niigata	pre Tertiary basement	granite
6 87082101	Kitaebisu, Aikawa, Sado, Niigata	welded tuff in the Msaragawa Formattion	andesite
7 87082103	Heji, Aikawa, Sado, Niigata	lava of the Aikawa Formation	andesite
8 87082106	Heji, Aikawa, Sado, Niigata	lava of the Aikawa Formation	andesite
9 87082202	Mikoiwa, Ogi, Sado, Niigata	intrusive rock in the Ogi Basalt Formation	picrite
10 87082202-M	Mikoiwa, Ogi, Sado, Niigata	matrix of intrusive rock in the Ogi Basalt Formation	picrite
11 87082202-O	Mikoiwa, Ogi, Sado, Niigata	olivine phenocryst in intrusive rock in the Ogi Basalt Formation	picrite
12 87082203	Sawasaki, Ogi, Sado, Niigata	dike in the Ogi Basalt Formation	basalt
13 87082204	Sawasaki, Ogi, Sado, Niigata	dike in the Ogi Basalt Formation	basalt
14 87082205	Oginoura, Ogi, Sado, Niigata	lava of the Ogi Basalt Formation	andesite
15 87082206	Nansenkyo, Ogi, Sado, Niigata	lava of the Ogi Basalt Formation	andesite
16 87082207	Mikoiwa, Ogi, Sado, Niigata	pumice of the Ogi Basalt Formation	rhyolite
17 87082208	Mitsuya, Ogi, Sado, Niigata	pumice of the Ogi Basalt Formation	rhyolite
18 87082209	Nagatesaki, Ogi, Sado, Niigata	lava of the Ogi Basalt Formation	andesite
19 87082210	Shukunegi, Ogi, Sado, Niigata	lava of the Ogi Basalt Formation	dacite
Yahiko			
20 88090602	Takaya, Iwamuro, Nishikanbara, Niigata	lava of the Maze Formation	rhyolite
21 88090604	Maze, Iwamuro, Nishikanbara, Niigata	lava of the Maze Formation	basalt
22 88090607	Echigonanaura, Maki, Nishikanbara, Niigata	block in tuff breccia of the Kakuta Formation	andesite

1/7 *(continued)*

Table 1. List of rock samples, localities, occurrences, stratigraphies and rock types of rocks from central Japan (continued)

Sample No.	Location	stratigraphy, occurrence	rock type
23 88090608	Echigonanaura, Maki, Nishikanbara, Niigata	lava of the Kakuta Formation	andesite
24 88090613	Kakutahama, Maki, Nishikanbara, Niigata	lava of the Kakuta Formation	andesite
25 88090618	Ishisetoge, Iwamuro, Nishikanbara, Niigata	lava of the Kannonji Formation	basalt
26 88090619	Yahikosancho, Iwamuro, Nishikanbara, Niigata	sill in the Teradomari Formation	dolerite
27 88090621	Amogoiyama, Teradomari, Mishima, Niigata	lava of the Teradomari Formation	basalt
Shimonita			
28 88060301	Kamisokose, Nanboku, Kanra, Gunma	sill in the Motojuku Formation	andesite
29 88060302	Kamisokose, Nanboku, Kanra, Gunma	lava of the Motojuku Formation	andesite
30 88060303	Dojo, Nanboku, Kanra, Gunma	lava of the Motojuku Formation	rhyolite
31 88060305	Nakakosaka, Shimonita, Kanra, Gunma	lava of the Motojuku Formation	andesite
32 88060306	Nakakosaka, Shimonita, Kanra, Gunma	dike in the Motojuku Formation	andesite
33 88060307	Nakakosaka, Shimonita, Kanra, Gunma	dike in the Motojuku Formation	andesite
34 88060308	Aizawa, Shimonita, Kanra, Gunma	lava of the Motojuku Formation	dacite
35 88060309	Aizawa, Shimonita, Kanra, Gunma	lava of the Motojuku Formation	dacite
36 88060310	Ichinokaya, Shimonita, Kanra, Gunma	lava of the Motojuku Formation	basalt
37 88060401	Ichinokaya, Shimonita, Kanra, Gunma	lava of the Motojuku Formation	andesite
38 88060402	Uchiyamabokujo, Shimonita, Kanra, Gunma	lava of the Mizuochikannon Lava	basalt
39 88060403	Monomiyama, Shimonita, Kanra, Gunma	lava of the Mizuochikannon Lava	andesite
40 88060404	Uchiyamabokujo, Shimonita, Kanra, Gunma	lava of the Mizuochikannon Lava	basalt
41 88060405	Uchiyamatoge, Saku, Nagano	lava of the Mizuochikannon Lava	andesite
42 88060406	Arafunesan, Usuda, Minamisaku, Nagano	lava of the Motojuku Formation	dacite
43 88060407	Arafunesan, Nanboku, Kanra, Gunma	lava of the Motojuku Formation	andesite
44 88060408	Arafunesan, Shimonita, Kanra, Gunma	lava of the Motojuku Formation	andesite

2/7 (continued)

Table 1. List of rock samples, localities, occurrences, stratigraphies and rock types of rocks from central Japan (continued)

Sample No.	Location	stratigraphy, occurrence	rock type
Maruko			
45 88020402	Kokuzo, Maruko, Chiisagata, Nagano	dike in the Kokuzo Formation	andesite
46 88020403	Kokuzo, Maruko, Chiisagata, Nagano	lava of the Kokuzo Formation	basalt
47 88020404	Reisenji, Maruko, Chiisagata, Nagano	dike in the Kokuzo Formation	andesite
48 88020405	Kakeyu, Maruko, Chiisagata, Nagano	dike in the Kokuzo Formation	andesite
49 88020407	Numasawa, Maruko, Chiisagata, Nagano	lava of the Fujisan Formation	andesite
Asahi			
50 87051802	Saizen, Asahi, Shinkawa, Toyama	lava of the Ganzo Formation	andesite
Hida			
51 87051906	Nakayama, Kamioka, Yoshiki, Gifu	dike in the Tetori Formation	andesite
52 87051908	Wariishi, Kamioka, Yoshiki, Gifu	dike in the Hida gneiss	andesite
53 87051909	Shikama, Kamioka, Yoshiki, Gifu	dike in the Hida gneiss	andesite
54 87052001	Shimoho, Nyukawa, Ono, Gifu	dike in the Arakigawa Formation	andesite
55 87052002	Shimoho, Nyukawa, Ono, Gifu	dike in the Arakigawa Formation	andesite
56 87052005	Tsubakihara, Shirakawa, Ono, Gifu	dike in the Shirakawa granite	andesite
57 87052006	Tsubakihara, Shirakawa, Ono, Gifu	dike in the Shirakawa granite	basalt
Riga			
58 87052011	Omaki, Riga, Higashitonami, Toyama	dike in the Funatsu granite	andesite
59 87052013	Kitahara, Riga, Higashitonami, Toyama	lava of the Iwaine Formation	andesite
Kamiichi			
60 87052416	Babajimaso, Kamiichi, Nakashinkawa, Toyama	dike in the Hida gneiss	andesite
Noto			
61 87040201	Ushinoshita, Togi, Hakui, Ishikawa	lava of the Anamizu Formation	andesite

3/7 (continued)

Table 1. List of rock samples, localities, occurrences, stratigraphies and rock types of rocks from central Japan (continued)

Sample No.	Location	stratigraphy, occurrence	rock type
62 87040202	Kurosaki, Togi, Hakui, Ishikawa	intrusive rock of the Kurosaki volcanic rock	andesite
63 87040301	Shirahage, Monzen, Fugeshi, Ishikawa	pre Tertiary basement	granite
64 87040302	Kuwatsukayama, Monzen, Fugeshi, Ishikawa	block in volcanic breccia of the Anamizu Formation	andesite
65 87040303	Beshodake, Anamizu, Fugeshi, Ishikawa	block in volcanic breccia of the Anamizu Formation	andesite
66 87040304	Beshodake, Anamizu, Fugeshi, Ishikawa	block in volcanic breccia of the Anamizu Formation	andesite
67 87040305	Honki, Noto, Fugeshi, Ishikawa	lava of the Anamizu Formation	andesite
68 87040306	Kamiwazumi, Yanagida, Fugeshi, Ishikawa	lava of the Yanagida Formation	dacite
69 87040307	Yotsuya, Yanagida, Fugeshi, Ishikawa	lava of the Yanagida Formation	andesite
70 87040308	Kandadani, Ishiyasumiba, Wajima, Ishikawa	lava of the Anamizu Formation	andesite
71 87040309	Sosogi, Machinomachisosogi, Wajima, Ishikawa	lava of the Iwakurayama rhyolite	rhyolite
72 88090301	Kandadani, Ishiyasumiba, Wajima, Ishikawa	lava of the Anamizu Formation	andesite
73 88090402	Toriyao, Hodatsu, Suzu, Ishikawa	lava of the Yanagida Formation	rhyolite
Kanazawa			
74 86010101	Mizubuchi, Kanazawa, Ishikawa	dike in the Nanamagari Fromation	basalt
Echizen			
75 90081401	Konan, Kaga, Ishikawa	lava of the Konan Formation	rhyolite
76 90081402	Hamachi, Mikuni, Sakai, Fukui	dike in the Yonegawaki	andesite
77 90081403	Oshima, Mikuni, Sakai, Fukui	lava of the Yonegawaki Formation	dacite
78 90081502	Mera, Fukui, Fukui	lava of the Takasuyama andesite	dacite
79 90081602	Ichinose, Fukui, Fukui	dike in the Ichinose Formation	dacite
80 90081604	Tobu, Fukui, Fukui	lava of the Kunimi Formation	andesite
81 90081606	Oya, Fukui, Fukui	lava of the Kunimi Formation	andesite
82 90081607	Umeura, Echizen, Nibu, Fukui	intrusive rock in the Itou Formation	andesite
83 90081608	Nunogataki, Echizen, Nibu, Fukui	welded tuff of the Itou Formation	dacite

4/7 *(continued)*

Table 1. List of rock samples, localities, occurrences, stratigraphies and rock types of rocks from central Japan (continued)

Sample No.	Location	stratigraphy, occurrence	rock type
84 90081609	Irio, Oda, Nibu, Fukui	lava of the Itou Formation	andesite
85 90081610	Kunimi, Fukui, Fukui	lava of the Kunimi andesite	andesite
86 86090101	Kaji, Mikuni, Sakai, Fukui	lava of the Matsushima volcanic rock	andesite
87 86090104	Tojinbo, Mikuni, Sakai, Fukui	intrusive rock (the Tojinbo volcanic rock)	andesite
88 86090105	Jingaoka, Mikuni, Sakai, Fukui	intrusive rock (the Jingaoka volcanic rock)	andesite
Shidara			
89 89012101	Toyoka, Horai, Minamishitara, Aichi	dike of the Shitara igneous complex	andesite
90 89012103	Kawai, Horai, Minamishitara, Aichi	lava of the Shitara igneous complex	rhyolite
91 89012104	Ure, Horai, Minamishitara, Aichi	lava of the Shitara igneous complex	rhyolite
92 89012105	Horaiko, Horai, Minamishitara, Aichi	lava of the Shitara igneous complex	rhyolite
93 89012201	Ebi, Horai, Minamishitara, Aichi	lava of the Shitara igneous complex	rhyolite
94 89012202	Ebi, Horai, Minamishitara, Aichi	lava of the Shitara igneous complex	rhyolite
95 89012204	Ebi, Horai, Minamishitara, Aichi	lava of the Shitara igneous complex	dacite
96 89012205	Oro, Toei, Kitashitara, Aichi	lava of the Shitara igneous complex	rhyolite
97 90032710	Sainoko, Tugu, Kitashitara, Aichi	sheet of the Otoge ring complex	andesite
98 90032711	Sainoko, Tugu, Kitashitara, Aichi	pre Tertiary basement (the Ryoke metamorphic rock)	gneiss
99 90032712	Sainoko, Tugu, Kitashitara, Aichi	sheet of the Otoge ring complex	andesite
100 90032713	Sainoko, Tugu, Kitashitara, Aichi	sheet of the Otoge ring complex	dacite
101 90032801	Urugitoge, Urugi, Shimoina, Nagano	lava of the Otoge ring complex	dacite
102 90032803	Orimototoge, Tugu, Kitashitara, Aichi	sheet of the Otoge ring complex	andesite
103 90032809	Orimototoge, Tugu, Kitashitara, Aichi	sheet of the Otoge ring complex	andesite
104 90032810	Furumachitakayama, Tugu, Kitashitara, Aichi	lava of the Tsugu volcanic rock	andesite
105 90032811	Oidaira, Toyone, Kitashitara, Aichi	sheet of the Otoge ring complex	andesite
106 90032812	Kawai, Toei, Kitashitara, Aichi	sheet of the Otoge ring complex	dacite

5/7 *(continued)*

Table 1. List of rock samples, localities, occurrences, stratigraphies and rock types of rocks from central Japan (continued)

Sample No.	Location	stratigraphy, occurrence	rock type
107 90032813	Tsuzumiishi-Tunnel, Shitara, Kitashitara, Aichi	lava of the Shitara igneous complex	dacite
108 90032814	Tsuzumiishi-Tunnel, Shitara, Kitashitara, Aichi	lava of the Shitara igneous complex	dacite
109 90071801	Kawai, Toei, Kitashitara, Aichi	sheet of the Otoge ring complex	basalt
110 90082702	Kawai, Toei, Kitashitara, Aichi	sheet of the Otoge ring complex	andesite
111 90082809	Kawai, Toei, Kitashitara, Aichi	sheet of the Otoge ring complex	dacite
112 90083007	Kawai, Toei, Kitashitara, Aichi	sheet of the Otoge ring complex	basalt
113 90083008	Kawai, Toei, Kitashitara, Aichi	sheet of the Otoge ring complex	andesite
114 90083009	Kawai, Toei, Kitashitara, Aichi	sheet of the Otoge ring complex	dacite
115 90100101	Kawai, Toei, Kitashitara, Aichi	sheet of the Otoge ring complex	andesite
116 90100102	Kawai, Toei, Kitashitara, Aichi	sheet of the Otoge ring complex	dacite
117 90100103	Kawai, Toei, Kitashitara, Aichi	sheet of the Otoge ring complex	rhyolite
118 90100104	Kawai, Toei, Kitashitara, Aichi	sheet of the Otoge ring complex	basalt
119 90100106	Kawai, Toei, Kitashitara, Aichi	sheet of the Otoge ring complex	dacite
120 90100201	Kawai, Toei, Kitashitara, Aichi	sheet of the Otoge ring complex	andesite
121 90100608	Kawai, Toei, Kitashitara, Aichi	sheet of the Otoge ring complex	dacite
122 90100702-2	Sainoko, Tugu, Kitashitara, Aichi	sheet of the Otoge ring complex	andesite
123 90100702-3	Sainoko, Tugu, Kitashitara, Aichi	sheet of the Otoge ring complex	andesite
124 90100703	Sainoko, Tugu, Kitashitara, Aichi	sheet of the Otoge ring complex	rhyolite
125 90100707	Okuwa, Tugu, Kitashitara, Aichi	sheet of the Otoge ring complex	basalt
126 90101108	Kawai, Toei, Kitashitara, Aichi	sheet of the Otoge ring complex	andesite
127 90101109	Kawai, Toei, Kitashitara, Aichi	sheet of the Otoge ring complex	andesite
128 90101205-2	Kawai, Toei, Kitashitara, Aichi	sheet of the Otoge ring complex	andesite
129 90101205-3	Kawai, Toei, Kitashitara, Aichi	sheet of the Otoge ring complex	andesite
130 90101206	Kawai, Toei, Kitashitara, Aichi	sheet of the Otoge ring complex	andesite

6/7 (continued)

Table 1. List of rock samples, localities, occurrences, stratigraphies and rock types of rocks from central Japan (continued)

Sample No.		Location	stratigraphy, occurrence	rock type
131	92010901-1	Osawa, Toyone, Kitashitara, Aichi	pre Tertiary basement (the Ryoke metamorphic rock)	gneiss
132	92010901-2	Osawa, Toyone, Kitashitara, Aichi	pre Tertiary basement (the Ryoke metamorphic rock)	gneiss
133	92011113	Osawa, Toyone, Kitashitara, Aichi	pre Tertiary basement (the Ryoke metamorphic rock)	gneiss
134	92011209	Osawa, Toyone, Kitashitara, Aichi	intrusive rock of the Otoge ring complex	andesite
135	92011212	Osawa, Toyone, Kitashitara, Aichi	dike of the Otoge ring complex	andesite
136	92011303-1	Kuroze, Horai, Minamishitara, Aichi	sheet of the Shitara igneous complex	dacite
137	92011303-2	Kuroze, Horai, Minamishitara, Aichi	sheet of the Shitara igneous complex	andesite
138	92011303-4	Kuroze, Horai, Minamishitara, Aichi	sheet of the Shitara igneous complex	andesite
139	92011305	Kuroze, Horai, Minamishitara, Aichi	sheet of the Shitara igneous complex	andesite
140	92011306-1	Kuroze, Horai, Minamishitara, Aichi	pre Tertiary basement (the Ryoke metamorphic rock)	gneiss
141	92011306-2	Kuroze, Horai, Minamishitara, Aichi	pre Tertiary basement (the Ryoke metamorphic rock)	gneiss
142	92011307	Ikenotairabokujo, Onose, Inabu, Kitashitara, Aichi	lava of the Tsugu volcanic rock	basalt
143	92011308	Ikenotairabokujo, Onose, Inabu, Kitashitara, Aichi	lava of the Tsugu volcanic rock	basalt
144	92011309	Ikenotairabokujo, Onose, Inabu, Kitashitara, Aichi	lava of the Tsugu volcanic rock	basalt
145	92011310	Munebatabokujo, Neba, Shimoina, Nagano	lava of the Tsugu volcanic rock	basalt
146	92011311	Munebatabokujo, Neba, Shimoina, Nagano	lava of the Tsugu volcanic rock	basalt

Chapter 3

ANALYTICAL PROCEDURES

3.1 K-Ar Age Determination

Rock samples (500g each) were crushed and sieved. The 30 to 60 mesh-size fractions were washed using distilled water to exclude powder residue from the fractions and then dried in an oven (80℃). Phenocrysts were separated by an isodynamic separator. Fractions removed phenocrysts were used for ^{40}Ar analysis, and furthermore, fractions were ground in an agate mill to fine powder for potassium analysis.

^{40}Ar was analyzed by isotope dilution method with ^{38}Ar as a tracer, using the mass spectrometer of Okayama University of Science (Nagao and Itaya, 1988; Itaya *et al*, 1991). Each fraction was degassed at 200℃ for more than 12 hours, Ar was extracted at 1500℃ and purified with Ti-Zr getter. Error was given as 1 σ . K-Ar age was calculated using the physical constants, $^{40}K\lambda_{\beta} = 4.962 \times 10^{-10}/y$, $^{40}K\lambda_{e} = 0.581 \times 10^{-10}/y$, $^{40}K/K = 0.0001167$ atm (Steiger and Jäger, 1977).

Potassium analysis was determined by flame photometry (Nagao *et al.*, 1984; Doi and Itaya, 1992). Although analysis was in error by 1－3%, ages calculated with 5% error as potassium analysis.

3.2 X-Ray Fluorescence Analysis

Samples were ground in a tungsten carbide mill to fine powder. For major element analysis, 0.4g of powdered sample was mixed with 4.0g of anhydrous lithium tetraborate ($Li_2B_4O_7$). The mixture was fused in a Pt-Au crucible and processed to a glass bead. For trace elements, 4.0g of powdered sample sustained by granular boron was pressed to a pellet with a hydraulic press.

Chemical compositions were determined with a Phillips PW-1404 X-ray fluorescence spectrometer (XRF) with scandium-molybdenum target tube installed at the Institute of Geoscience, the University of Tsukuba. Thirteen G.S.J. (Geological Survey of Japan) standard samples (JB-1, JB-1A, JB-2, JB-3, JA-1, JA-2, JA-3, JR-1, JR-2, JG-1, JG-1A, JG-2, JG-3) were used for the processing of the regression lines of major elements and trace elements.

3.3 Sr Isotope Analysis

(1) Rock Samples

Samples were ground in a tungsten carbide mill to fine powder. Approximately 100mg of powdered samples were dissolved in $HClO_4$ and HF. Sr was purified by a cation exchange chromatography, using the similar method of Arakawa (1985).

The extracted Sr samples were loaded on tantalum filaments as phosphates using 10% H_3PO_4 and the measurements were performed on double filament assemblies (tantalum in evaporation side and rhenium in ionization side)(partially performed on single filament assemblies). Isotopic ratios were measured with Finnigan Mat Instruments MAT-262Q nine-collector thermal ionization mass spectrometer in the static mode, installed at the Institute of Geoscience, the University of Tsukuba. The data were accumulated in the static mode with pre-measurement gain calibration of each Faraday collector. Mass fractionation was normalized to the $^{87}Sr/^{86}Sr$ ratio of 0.1194. Each sample was measured by 100 scans (10 scans in each of 10 blocks). The NBS987 $SrCO_3$ standard during this study gave an average $^{87}Sr/^{86}Sr$ value of 0.710237 ± 10 (2σ m).

(2) Olivine Phenocryst of Picrite

Picrite samples were crushed and sieved. The 30 to 60 mesh size fractions were washed using distilled water to exclude powder residue from the fractions and then dried in an oven (80℃). Olivine phenocrysts were separated with an isodynamic separator. Fractions containing other materials were removed by hand picking under a stereomicroscope. Almost pure olivine fractions were ground in an agate mill to fine powder and used for measurement of $^{87}Sr/^{86}Sr$ ratio by the same method as mentioned above.

3.4 Nd Isotope Analysis

About 100mg of fine-ground (in a tungsten carbide mill) samples was dissolved in HF, HNO_3 and $HClO_4$. Nd was purified in two stages, using similar method of Na *et al.*(1992). The first step of purification was to concentrate of rare earth elements (REE) from other elements by cation exchange chromatography (modified from Crock *et al.*, 1984). And then, Nd was isolated from other REE elements by High-performance liquid chromatography (HPLC).

The extracted Nd samples were loaded on rhenium filaments as nitrates using HNO_3 and the measurements were performed on a double filament assemblies (Nd for both evaporation side and ionization side). Nd isotopic ratios were measured with the same equipment as Sr isotope analysis (Finnigan Mat Instruments MAT-262Q nine-collector thermal ionization mass spectrometer in the static mode, installed at the Institute of Geoscience, the University of Tsukuba). The data were accumulated in the static mode with pre-measurement gain calibration of each Faraday collector. The measured $^{143}Nd/^{144}Nd$ ratios were normalized to the $^{146}Nd/^{144}Nd$ ratio of 0.7219. Each sample was measured by 100 scans (10 scans in each of 10 blocks). The J.M. standard during this study gave an average $^{143}Nd/^{144}Nd$ value of 0.511300 ± 5 (2σ m).

Chapter 4

RESULTS

4.1 K-Ar Ages

Analytical results and errors of K-Ar dating are shown in Table 2. Results of the analyses of samples from the Sado Island, Hida area, Asahi Town , Riga Village and Kamiichi Town were already reported and discussed in Shinmura *et al.* (1994, 1995) respectively, therefore obtained data of these are briefly described here.

(1) Sado Island

Obtained ages are 22.82±0.57 Ma for the welded tuff of the Masaragawa Formation, 17.81±0.47−21.33±0.58 Ma for the dacite lavas of the Aikawa Formation, 14.5±1.4 Ma for the glassy andesite of the Sanze Formation, 10.70±0.43−14.0±1.5 Ma for the basalts of the Ogi Basalt Formation (from the lowest to the uppermost) and 15.5±2.2 Ma for the picrite intrusive rock in the Ogi Basalt Formation. The obtained ages of the Masaragawa Formation and Aikawa Formation are concordant with the stratigraphy and ages (K-Ar and fission track methods) (Shimazu *et al.*, 1977a, 1977b). The volcanic activity of the Ogi Basalt Formation ranges about 11−13 Ma (Shinmura *et al.*, 1995). Thus, our results show that the Ogi Basalt Formation distributed in the Ogi Peninsula was the final volcanic activity in the Sado Island.

(2) Shimonita Town

Only one sample 88060306, the andesite dike in the Motojuku Formation was dated. We have had no information about age determination from this area, and the newly obtained age was 4.2 ± 2.0 Ma, the Pliocene. The Motojuku Formation mainly consists of the late Miocene to the Pliocene volcanic rocks (Motojuku Volcanic Rocks Research Subgroup, 1970; Motojuku Collaborative Research Group, 1970; Kaneoka *et al.* 1979). The dated dike is inferred to be the final or following volcanic activities of this formation.

(3) Maruko Town

Four volcanic rocks were dated from this area. The andesite dike in the Kokuzo Formation and the basaltic lava of the Kokuzo Formation. We have had no information about age determination from this area. The newly obtained ages range 11.60－16.32 Ma, middle Miocene. These are concordant with the stratigraphy of this formation (Sugiyama *et al.*, 1973).

(4) Asahi Town

One sample 87051802, the andesite lava of the Ganzo Andesite was dated. We have had no information about age determination from this, and the newly obtained age was 2.2±0.7 Ma, the Pliocene . It is younger than ever expected, for the Ganzo Andesite was correlated with the Iwaine Formation (the early Miocene series) from their facies (Ito, 1985). This correlation needs to be reconsider, because this sample was not altered very much and there was no substantial problem in its analysis.

(5) Hida area

The obtained ages of seven andesite and basaltic dikes from this area are classified into three groups; ca. 100 Ma (one sample), 53−61 Ma (five samples) and ca. 16 Ma (one sample). The one dike yielding ca. 16 Ma are in close relation to the Miocene volcanic activities which produced the volcanic rocks of Iwaine Formation in the northern margin of the Hida region. Other dikes of ca. 100 Ma and 53−61Ma are distinctly older than those estimated by Nozawa et al. (1975, 1981).

(6) Riga Village

The andesite dike in the Funatsu granite (87052011) and the andesite lava of the Iwaine Formation (87052013) were dated, and obtained ages were 16.82±0.43 and 17.3±1.0 Ma respectively, early to middle Miocene. The former can be correlate with the Iwaine Formation from their ages and distributions, and the latter is concordant with the stratigraphy of Iwaine Formation.

(7) Kamiichi Town

The andesite dike in Hida gneiss was dated and the obtained age was 15.68 ± 0.83 Ma, early to middle Miocene. This dike inferred to be in close relation to the Miocene volcanic activities which produced the volcanic rocks of Iwaine Formation from their ages and distributions.

(8) Noto Peninsula

Some of Tertiary volcanic rocks have been already dated (Shibata *et al*, 1981) in Noto Peninsula. But in Noto Peninsula, the Oligocene to the Pliocene volcanic rocks are widely distributed, and to date more is significance for getting informations about time changing of their compositions. The lava of the Anamizu Formation (88090301) and the lava of the Yanagida Formation (88090402) were 28.38 ± 0.93 Ma and 17.50 ± 0.61 Ma, the Oligocene and Miocene respectively. These are concordant with the stratigraphies and reported ages (Kaseno, 1977 and Shibata *et al*, 1981, respectively).

4.2 Major and Trace Element Compositions

Concentrations of major and trace element analyzed using XRF were listed in Table 3 and Table 4.

Table 2. Results of K-Ar dating of the volcanic rocks from central Japan.

Sample No.	Age (Ma)	Potassium (wt.%)	Rad. ^{40}Ar (10^{-8}ccSTP/g)	Non Rad. Ar (%)
Sado				
1 87040501	12.3 ± 2.4	0.94	44	13.6
		0.94	46	15.3
2 87040503	11.70 ± 0.50	1.287 ± 0.026	58.6 ± 2.2	66.7
3 87040504	11.12 ± 0.98	0.252 ± 0.013	10.90 ± 0.79	81.0
4 87040505	14.5 ± 1.4	1.290 ± 0.026	73.1 ± 6.9	84.5
5 87082101	22.82 ± 0.57	1.866 ± 0.037	166.3 ± 2.5	30.9
6 87082103	17.81 ± 0.47	2.559 ± 0.051	177.7 ± 3.1	38.2
7 87082106	21.33 ± 0.58	1.489 ± 0.030	124.0 ± 2.3	41.7
8 87082202	15.5 ± 2.2	0.637 ± 0.019	38.4 ± 5.4	89.4
9 87082203	14.0 ± 1.5	0.404 ± 0.020	22.0 ± 2.0	84.5
10 87082204	10.70 ± 0.43	0.891 ± 0.027	37.1 ± 1.0	56.8
Shimonita				
11 88060306	4.2 ± 2.0	0.59	10	8.4
		0.58	9.0	6.0
Maruko				
12 88020402	16.32 ± 0.85	0.539 ± 0.016	34.3 ± 1.5	69.8
13 88020403	15.0 ± 1.2	0.323 ± 0.016	18.9 ± 1.1	77.8
14 88020404	11.60 ± 0.26	3.142 ± 0.063	141.9 ± 1.6	10.6
15 88020405	13.38 ± 0.31	2.218 ± 0.044	115.6 ± 1.4	20.8
Asahi				
16 87051802	2.2 ± 0.7	1.80	15	9.1
		1.79	16	9.0
Hida				
17 87051906	60.3 ± 1.3	1.711 ± 0.034	406.8 ± 4.4	8.0
18 87051908	58.7 ± 1.3	2.390 ± 0.048	553.6 ± 6.3	14.6
19 87051909	99.6 ± 3.1	0.749 () 0.022	297.6 ± 3.2	10.1
20 87052001	59.3 ± 1.3	1.958 ± 0.039	457.8 ± 4.9	8.6
21 87052002	60.9 ± 1.4	1.862 ± 0.037	447.8 ± 4.9	11.9
22 87052005	53.1 ± 1.2	2.075 ± 0.042	433.6 ± 5.1	14.1
23 87052006	16.31 ± 0.44	1.682 ± 0.034	106.9 ± 2.0	41.5
Riga				
24 87052011	16.82 ± 0.43	2.435 ± 0.049	159.7 ± 2.6	36.1
25 87052013	17.3 ± 1.0	0.83	58	42.4
		0.83	54	36.0

1/2 (continued)

Table 2. Results of K-Ar dating of the volcanic rocks from central Japan. (continued)

Sample No.	Age (Ma)	Potassium (wt.%)	Rad. ^{40}Ar (10^{-8}ccSTP/g)	Non Rad. Ar (%)
Kamiichi				
26 87052416	15.68 ± 0.83	0.331 ± 0.017	20.22 ± 0.35	38.1
Noto				
27 88090301	28.38 ± 0.93	0.830 ± 0.025	92.1 ± 1.2	23.6
28 88090402	17.50 ± 0.61	2.230 ± 0.045	152.2 ± 4.4	58.5

2/2

Table 3. Results of major element contents of Tertiary volcanic rocks from central Japan (units:%)

	Sample No.	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	total
	Sado											
1	87040501	52.07	0.90	15.85	7.33	0.12	7.51	10.30	2.26	1.12	0.22	97.69
2	87040503	53.13	1.07	16.21	7.13	0.11	6.27	9.16	2.47	1.54	0.28	97.37
3	87040504	49.40	1.07	15.41	7.22	0.13	10.00	10.66	1.90	0.36	0.21	96.36
4	87040505	59.24	1.04	16.57	6.62	0.13	2.41	6.23	3.77	1.53	0.20	97.73
5	87040601											
6	87082101	60.92	0.94	16.23	6.06	0.09	2.21	5.53	2.80	1.98	0.20	96.94
7	87082103	60.07	0.77	16.38	6.07	0.11	3.09	4.15	3.66	3.09	0.22	97.60
8	87082106	57.28	0.86	15.97	5.57	0.10	3.61	4.84	4.80	1.74	0.20	94.96
9	87082202	44.39	0.55	10.76	9.16	0.15	23.26	6.44	0.86	0.37	0.11	96.05
10	87082202-M	49.28	0.96	15.05	8.43	0.14	13.73	9.75	1.68	0.78	0.21	100.00
11	87082202-O											
12	87082203	49.50	0.63	16.11	7.03	0.11	8.84	14.04	1.47	0.49	0.13	98.36
13	87082204	50.14	0.89	16.22	7.85	0.10	7.74	11.81	1.94	1.23	0.26	98.17
14	87082205	57.50	0.84	15.67	6.52	0.13	5.45	9.10	2.78	1.83	0.22	100.04
15	87082206	57.30	0.89	15.70	6.73	0.13	5.31	9.21	2.72	1.71	0.31	100.01
16	87082207	74.49	0.31	13.32	2.04	0.05	0.53	1.20	3.60	4.44	0.03	100.00
17	87082208	70.54	0.43	13.52	2.88	0.06	2.84	1.32	5.16	3.21	0.05	100.00
18	87082209	57.40	0.89	15.70	6.72	0.12	5.62	9.14	2.76	1.42	0.26	100.03
19	87082210	65.84	0.65	14.79	4.51	0.09	2.62	4.59	3.36	3.42	0.14	100.00
	Yahiko											
20	88090602	80.21	0.11	11.13	0.58	0.01	0.04	0.80	3.70	3.50	0.03	100.10
21	88090604											
22	88090607											
23	88090608											

1/7 (continued)

Table 3. Results of major element contents of Tertiary volcanic rocks from central Japan (units:%) (continued)

	Sample No.	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	total
24	88090613	57.59	1.03	16.59	7.81	0.13	2.88	7.15	3.11	1.75	0.36	98.39
25	88090618	49.91	1.07	16.48	9.17	0.15	7.83	8.40	2.18	0.93	0.18	96.29
26	88090619	53.31	1.20	15.78	9.76	0.20	9.99	2.55	2.63	3.55	0.18	99.13
27	88090621	46.98	1.76	14.52	10.65	0.15	8.94	7.43	2.37	0.28	0.21	93.29
	Arafune											
28	88060301	59.48	0.93	17.04	7.41	0.15	2.56	7.46	3.41	1.37	0.19	100.00
29	88060302	56.38	1.18	16.19	10.12	0.19	3.12	8.70	3.12	0.86	0.16	100.00
30	88060303	70.65	0.85	14.24	3.77	0.12	0.50	3.68	4.03	1.91	0.24	100.00
31	88060305	57.12	0.85	17.73	7.69	0.14	3.60	7.72	2.56	1.41	0.14	98.96
32	88060306	53.18	0.87	17.11	8.48	0.15	3.69	8.78	2.92	0.71	0.12	96.01
33	88060307	57.05	0.87	15.92	7.80	0.15	3.64	7.36	2.61	1.41	0.14	96.96
34	88060308	62.64	0.91	14.54	5.88	0.15	1.77	5.08	3.69	1.19	0.19	96.03
35	88060309	67.25	0.93	16.71	5.44	0.13	1.39	2.27	2.46	1.94	0.20	98.71
36	88060310	51.79	1.09	19.06	10.21	0.22	5.04	9.63	2.33	0.46	0.09	99.90
37	88060401	57.14	1.04	15.51	9.16	0.24	3.81	7.08	3.27	0.13	0.17	97.55
38	88060402	49.19	1.04	18.64	9.93	0.15	3.58	12.07	2.17	0.52	0.11	97.39
39	88060403	54.46	1.19	18.30	7.90	0.13	2.37	9.20	2.41	0.86	0.21	97.02
40	88060404	52.06	0.96	18.26	8.52	0.14	3.35	10.44	2.51	0.70	0.14	97.08
41	88060405	57.86	0.64	16.62	7.01	0.14	3.29	7.47	2.83	0.67	0.11	96.63
42	88060406	67.85	1.05	14.67	3.44	0.04	0.28	3.50	4.01	2.42	0.31	97.56
43	88060407	56.68	1.21	15.51	9.23	0.17	2.52	7.57	2.94	1.10	0.18	97.12
44	88060408	56.96	1.23	15.30	8.82	0.17	2.50	7.42	2.86	1.21	0.19	96.64
	Maruko											
45	88020402											
46	88020403											

2/7 (continued)

Table 3. *Results of major element contents of Tertiary volcanic rocks from central Japan (units:%) (continued)*

	Sample No.	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	total
47	88020404											
48	88020405											
49	88020407											
	Asahi											
50	87051802	55.69	0.91	18.14	6.75	0.12	3.60	8.58	2.75	2.07	0.20	98.80
	Hida											
51	87051906											
52	87051908											
53	87051909											
54	87052001											
55	87052002											
56	87052005											
57	87052006	51.76	1.11	17.70	9.07	0.16	3.68	6.61	3.46	2.63	0.23	96.39
	Riga											
58	87052011	59.21	1.37	14.78	7.36	0.12	2.37	4.29	3.11	3.05	0.32	95.98
59	87052013	54.37	1.12	16.45	7.08	0.14	4.76	8.95	2.53	1.01	0.30	96.69
	Kamiichi											
60	87052416	53.19	1.39	17.49	8.95	0.14	4.51	9.12	3.06	0.69	0.21	98.74
	Noto											
61	87040201	61.33	0.91	17.20	5.03	0.06	1.90	6.27	4.13	1.68	0.22	98.74
62	87040202	58.85	0.83	19.14	4.82	0.11	1.58	6.72	3.97	2.58	0.35	98.96
63	87040301											
64	87040302	59.81	0.76	17.90	5.20	0.08	2.87	6.29	3.53	1.52	0.18	98.13
65	87040303	58.37	0.92	17.45	6.64	0.15	3.52	7.21	3.64	1.32	0.17	99.39
66	87040304	60.87	1.19	15.73	6.36	0.18	1.96	5.05	3.78	2.24	0.41	97.76

3/7 (continued)

Table 3. Results of major element contents of Tertiary volcanic rocks from central Japan (units:%) (continued)

	Sample No.	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	total
67	87040305	59.63	0.83	17.25	5.39	0.12	2.89	5.58	4.01	1.98	0.22	97.88
68	87040306	62.38	0.67	16.94	5.18	0.08	2.03	5.27	4.08	1.91	0.17	98.70
69	87040307	58.44	1.06	16.80	6.30	0.11	4.73	6.18	3.77	1.61	0.21	99.21
70	87040308	61.17	0.77	15.92	5.11	0.08	4.84	6.15	4.03	1.00	0.16	99.23
71	87040309	78.41	0.10	11.33	0.50	0.01	0.06	0.24	1.96	6.40	0.02	99.03
72	88090301	60.45	0.74	15.43	5.06	0.09	4.64	6.23	3.84	0.97	0.17	97.62
73	88090402	72.06	0.52	14.18	2.37	0.03	0.14	2.21	5.35	2.42	0.13	99.41
	Kanazawa											
74	86010101	49.40	0.89	17.03	8.77	0.14	6.32	11.75	2.04	0.15	0.11	96.59
	Echizen											
75	90081401											
76	90081402											
77	90081403	72.27	0.38	14.08	2.44	0.04	0.23	1.61	3.96	3.41	0.06	98.46
78	90081502											
79	90081602	70.37	0.38	14.25	3.45	0.33	0.70	1.69	3.25	2.80	0.09	97.32
80	90081604											
81	90081606											
82	90081607											
83	90081608											
84	90081609											
85	90081610											
86	86090101	54.95	1.09	18.21	7.54	0.13	3.65	9.10	3.15	1.12	0.31	99.24
87	86090104	63.60	0.98	16.32	5.28	0.10	1.58	4.38	4.08	1.92	0.32	98.56
88	86090105	62.16	1.01	16.65	5.44	0.11	2.06	6.05	3.95	1.65	0.29	99.36

4/7 (continued)

Table 3. Results of major element contents of Tertiary volcanic rocks from central Japan (units:%) (continued)

	Sample No.	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	total
	Shidara											
89	89012101											
90	89012103	76.03	0.08	13.99	0.59	0.01	0.05	0.05	3.23	4.35	0.02	98.40
91	89012104	74.53	0.09	13.94	1.27	0.04	0.13	0.87	2.99	4.10	0.02	97.96
92	89012105	74.70	0.10	13.64	1.30	0.03	0.11	0.42	2.96	5.07	0.02	98.35
93	89012201	72.94	0.03	12.83	1.23	0.05	0.02	1.04	1.16	7.00	0.06	96.36
94	89012202	73.36	0.08	12.50	1.27	0.03	0.06	0.71	3.31	4.52	0.02	95.85
95	89012204	68.84	0.56	12.64	4.38	0.08	1.17	2.68	1.82	2.57	0.13	94.87
96	89012205	79.76	0.04	11.87	0.58	0.01	0.11	0.08	2.23	2.59	0.02	97.29
97	90032710	53.82	1.80	14.80	8.17	0.15	3.22	5.38	4.17	1.03	0.33	92.86
98	90032711	88.30	0.24	4.29	1.79	0.07	0.60	0.30	0.50	0.59	0.03	96.69
99	90032712	58.59	1.48	15.43	7.53	0.13	2.55	5.46	4.42	1.95	0.24	97.79
100	90032713	65.17	0.50	14.74	4.07	0.09	0.88	2.44	4.40	3.40	0.09	95.77
101	90032801	62.87	0.97	15.85	5.33	0.08	2.49	4.57	3.95	2.16	0.20	98.45
102	90032803	53.84	1.24	18.33	7.01	0.12	2.44	7.14	3.28	1.34	0.24	94.99
103	90032809	53.33	1.84	17.45	9.63	0.17	4.55	7.61	3.97	0.89	0.31	99.75
104	90032810	53.57	1.67	17.06	8.30	0.15	4.11	7.36	3.89	1.10	0.24	97.46
105	90032811	55.45	1.81	14.88	9.38	0.17	2.59	5.04	4.10	2.14	0.68	96.24
106	90032812	65.09	0.54	14.74	4.35	0.14	0.62	2.13	4.10	3.19	0.13	95.01
107	90032813	68.28	0.56	14.68	3.55	0.07	0.77	3.10	3.84	2.89	0.12	97.86
108	90032814	66.07	0.62	15.06	4.00	0.06	1.85	3.35	3.60	2.58	0.14	97.33
109	90071801	47.94	2.83	15.37	11.39	0.15	4.16	7.55	3.08	0.47	0.80	93.74
110	90082702	52.66	1.15	14.85	8.79	0.19	1.40	4.35	4.15	2.95	0.42	90.90
111	90082809	64.22	0.77	14.99	6.51	0.14	1.13	1.31	5.80	2.95	0.22	98.03
112	90083007	47.85	2.60	15.56	11.67	0.18	3.53	6.98	3.03	1.57	0.42	93.38

5/7 (continued)

Table 3. Results of major element contents of Tertiary volcanic rocks from central Japan (units:%) *(continued)*

	Sample No.	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	total
113	90083008	61.48	1.16	13.34	5.99	0.14	1.28	3.78	4.83	0.47	0.43	92.88
114	90083009	68.56	0.36	13.92	4.71	0.17	0.32	0.27	4.52	2.65	0.05	95.52
115	90100101	54.61	1.84	15.32	9.48	0.19	3.60	6.57	4.28	1.58	0.40	97.87
116	90100102	67.33	0.34	13.91	3.83	0.11	0.29	1.10	5.22	3.85	0.04	96.02
117	90100103	73.72	0.48	13.26	5.28	0.14	0.51	1.81	0.47	0.20	0.11	95.98
118	90100104	47.89	2.33	18.79	10.05	0.15	1.67	8.61	4.03	1.36	0.52	95.41
119	90100106	66.24	0.58	15.47	4.82	0.11	0.50	2.26	5.90	3.13	0.12	99.10
120	90100201	54.18	2.05	15.78	10.39	0.15	3.86	6.91	4.08	1.42	0.45	99.27
121	90100608	68.18	0.41	14.23	4.37	0.13	0.36	1.21	5.61	2.18	0.08	96.73
122	90100702-2	57.09	1.39	15.86	9.23	0.20	2.78	2.71	3.70	2.29	0.58	95.83
123	90100702-3	55.92	1.54	15.59	9.30	0.23	2.42	4.08	4.89	2.14	0.67	96.78
124	90100703	71.77	0.37	15.83	1.95	0.00	0.11	1.09	4.84	3.66	0.07	99.68
125	90100707											
126	90101108											
127	90101109											
128	90101205-2											
129	90101205-3											
130	90101206											
131	92010901-1											
132	92010901-2											
133	92011113											
134	92011209											
135	92011212											
136	92011303-1	62.15	1.22	15.64	7.13	0.11	2.05	3.62	4.91	3.08	0.42	100.33
137	92011303-2	60.46	1.31	15.42	7.75	0.13	2.05	4.93	4.29	2.22	0.47	99.04

6/7 (continued)

Table 3. Results of major element contents of Tertiary volcanic rocks from central Japan (units:%) (continued)

	Sample No.	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	total
138	92011303-4											
139	92011305	60.93	1.30	15.54	7.80	0.13	2.22	5.09	4.34	2.18	0.46	100.00
140	92011306-1	57.58	0.91	21.14	7.34	0.22	2.62	2.08	3.26	4.69	0.16	100.00
141	92011306-2	75.34	0.43	12.23	3.98	0.12	1.50	1.65	2.51	2.12	0.13	100.00
142	92011307	51.90	1.56	17.55	8.74	0.16	5.06	8.72	3.75	0.79	0.27	98.49
143	92011308	51.90	1.52	17.56	8.83	0.15	4.93	8.75	3.78	0.76	0.26	98.44
144	92011309	52.00	1.47	17.24	8.33	0.19	3.50	7.72	3.87	1.01	0.27	95.59
145	92011310	51.10	1.30	17.30	8.11	0.15	6.83	9.73	3.21	0.77	0.21	98.71
146	92011311	50.60	1.23	17.24	8.29	0.14	7.03	9.65	3.09	0.63	0.20	98.10

Table 4. *Results of trace element contents of Tertiary volcanic rocks from central Japan (units:ppm)*

	Sample No.	Ba	Y	Zr	V	Cr	Ni	Cu	Zn	Ga	Nb	La	Ce	Sc	Th
	Sado														
1	87040501	156.7	21.8	84.7	229.2	459.8	152.1	52.2	65.7	19.1	8.9	9.7	11.8	35.7	0.0
2	87082101	459.4	23.2	185.4	128.3	108.8	30.2	12.0	65.0	19.6	10.0	31.8	55.4	36.1	6.0
3	87082103														
4	87082106	533.9	24.1	176.8	131.0	178.9	42.3	17.5	74.2	20.1	9.5	17.5	53.4	34.6	6.1
5	87082202	50.8	13.1	40.1	139.9	1571.8	786.0	38.8	64.2	19.9	3.6	9.9	7.4	33.6	0.6
6	87082203	40.8	15.9	37.7	226.3	310.8	113.9	96.8	53.0	19.1	3.9	5.0	16.0	30.7	1.1
7	87082206	223.4	28.0	150.2	220.7										
8	87082208	435.6	38.8	262.1	43.9										
9	87082210	367.0	30.8	192.4	105.4										
	Hida														
10	87052006	527.1	22.8	128.0	242.3	64.3	16.6	21.6	83.1	19.2	6.0	12.1	23.6	34.4	1.2
	Noto														
11	88090301	185.7	18.5	164.1	111.1	189.8	117.1	48.7	52.3	19.5	5.0	10.0	18.9	38.6	1.5
12	88090402	544.9	45.4	331.7	15.6	141.4	35.2	4.3	94.2	20.6	10.1	21.9	55.2	35.1	7.8
	Echizen														
13	90081403	707.4	20.0	243.8	19.5	117.3	24.0	3.7	40.3	0.0	10.7	9.8	11.2	8.4	8.7
14	90081602	724.8	47.8	175.4	9.9	92.1	24.2	2.8	171.9	0.0	8.8	1.3	9.7	8.7	8.2
	Shidara														
15	89012103	606.2	36.7	112.0	0.0	102.3	26.8	1.4	14.8	20.1	7.9	44.0	60.6	34.6	14.4
16	89012104	693.1	37.9	114.9	4.0	71.3	22.6	2.0	25.2	20.7	8.1	27.5	60.6	35.3	20.1
17	89012105	574.9	35.7	111.9	0.1	38.2	10.9	9.6	38.7		9.1	14.4	41.7		14.7
18	89012201	609.0	32.7	65.9	5.7	271.8	74.7	3.0	52.4	20.9	9.0	11.5	36.8	35.5	6.5
19	89012202	615.9	39.6	102.7	0.0	233.9	67.5	4.0	33.2	20.5	9.0	36.7	64.1	36.9	13.8

1/2 (continued)

Table 4. Results of trace element contents of Tertiary volcanic rocks from central Japan (units:ppm) (continued)

	Sample No.	Ba	Y	Zr	V	Cr	Ni	Cu	Zn	Ga	Nb	La	Ce	Sc	Th
20	89012204	435.6	27.2	186.7	64.4	96.7	32.5	15.7	61.4		8.5	25.3	46.9		9.9
21	89012205	629.2	24.2	72.2	6.2	70.0	21.4	0.6	14.8		7.4	13.9	35.3		7.3
22	90032710	171.4	29.0	185.7	228.8	65.6	16.7	16.8	80.8	17.0	10.7	15.1	34.5	22.3	2.3
23	90032711	129.8	9.3	49.7	26.3	155.9	52.8	3.1	38.7	17.1	7.8	11.4	21.5	5.1	2.0
24	90032712	270.5	37.7	292.2	173.2	71.0	20.4	16.8	83.1	18.1	15.3	26.5	54.6	29.0	4.4
25	90032713	437.4	34.9	386.8	35.8	86.2	25.2	14.9	63.9	19.2	20.0	40.0	62.9	25.4	7.0
26	90032801	407.5	34.9	211.8	104.5	99.6	30.3	13.8	67.2		8.6	25.5	47.2		7.4
27	90032803	213.0	26.4	165.7	177.8	165.3	45.3	32.7	70.6		8.4	20.6	33.6		3.9
28	90032809	148.8	33.4	195.9	222.1	226.1	54.1	22.2	82.7		9.0	19.3	37.1		0.8
29	90032810	195.1	31.9	168.3	212.3	168.4	42.2	19.0	82.5		8.5	9.6	33.9		4.2
30	90032811	284.0	41.8	292.7	138.0	35.2	10.4	12.6	93.4		16.2	25.1	51.0		4.1
31	90032812	424.1	47.2	451.1	9.8	24.1	9.2	2.8	85.5		22.3	33.3	68.4		6.7
32	90032813	548.6	28.1	188.7	53.7	118.6	29.0	10.7	46.0		8.9	26.9	46.6		9.9
33	90032814	488.2	27.9	199.6	65.5	137.9	28.8	13.9	59.5	0.0	9.1	5.3	15.7	16.3	9.0
34	90071801	164.1	40.4	194.3	305.0	34.7	14.4	27.9	108.6	0.0	13.5	1.4	8.2	29.4	3.0
35	90082702	361.6	44.7	339.5	35.9	22.7	9.7	11.4	108.1	0.0	21.5	1.3	22.1	11.7	3.7
36	90082809	421.8	45.5	394.5	18.3	93.2	32.2	36.1	66.1	0.0	23.2	1.9	11.9	6.8	5.1
37	90083007	221.7	29.8	179.7	335.7	44.1	14.5	19.9	88.1	0.0	13.2	4.9	20.3	24.2	1.2
38	90083008	136.4	41.8	295.6	122.4	64.6	20.0	1.8	83.0	0.0	14.3	17.4	19.0	13.2	5.8
39	90083009	487.4	53.4	486.5	3.4	53.5	18.6	8.8	122.7	0.0	29.2	12.6	28.5	5.2	5.4
40	92011307	142.7	28.3	172.8	231.2	24.4	3.9	23.2	75.2	21.8	7.5			25.1	1.4
41	92011308	134.4	28.5	171.2	224.1	22.3	5.1	25.0	73.8	20.5	7.0			28.4	2.9
42	92011309	221.4	31.3	181.0	200.3	15.5	6.0	25.5	82.0	22.2	8.7			20.7	3.2
43	92011310	121.9	25.1	136.5	221.2	137.4	56.4	38.7	63.2	17.3	6.0			26.6	3.2
44	92011311	110.6	24.5	129.1	216.6	134.1	56.9	36.3	64.5	18.6	5.2			26.3	1.2

2/2

(1) SiO_2 vs. (Na_2O + K_2O)

Fig. 2, SiO_2 vs. (Na_2O + K_2O) plots show, volcanic rocks from Shidara area distribute in both alkaline and non-alkaline area, around the boundary of these areas. Volcanic rocks from Shimonita Town, the Sado Island and Noto Peninsula are distributed in non-alkaline area. Volcanic rocks from the Sado Island and Noto Peninsula are distributed nearer alkaline area than rocks from Shimonita Town. The ratios of alkaline elements vs. SiO_2 increase from the trench side towards back arc side, and these trends are regardless of their ages and, as a whole, same as the Quaternary volcanic rocks of northeastern Japan arc.

(2) SiO_2 vs. FeO/(FeO + MgO)

Fig. 3 is SiO_2 vs. FeO/(FeO + MgO) plots of non-alkaline rocks from Shimonita Town, the Sado Island and Noto Peninsula. All the volcanic rocks from both the Sado Island and Noto Peninsula are distributed in calc alkaline area. On the other hand, all the volcanic rocks from Shimonita Town are distributed in tholeiite area.

Volcanic rocks nearer trench side are distributed in tholeiite area, and volcanic rocks nearer back arc side are distributed in calc alkaline area. These trends are also regardless of their ages and, as a whole, same as the Quaternary volcanic rocks of northeastern Japan arc.

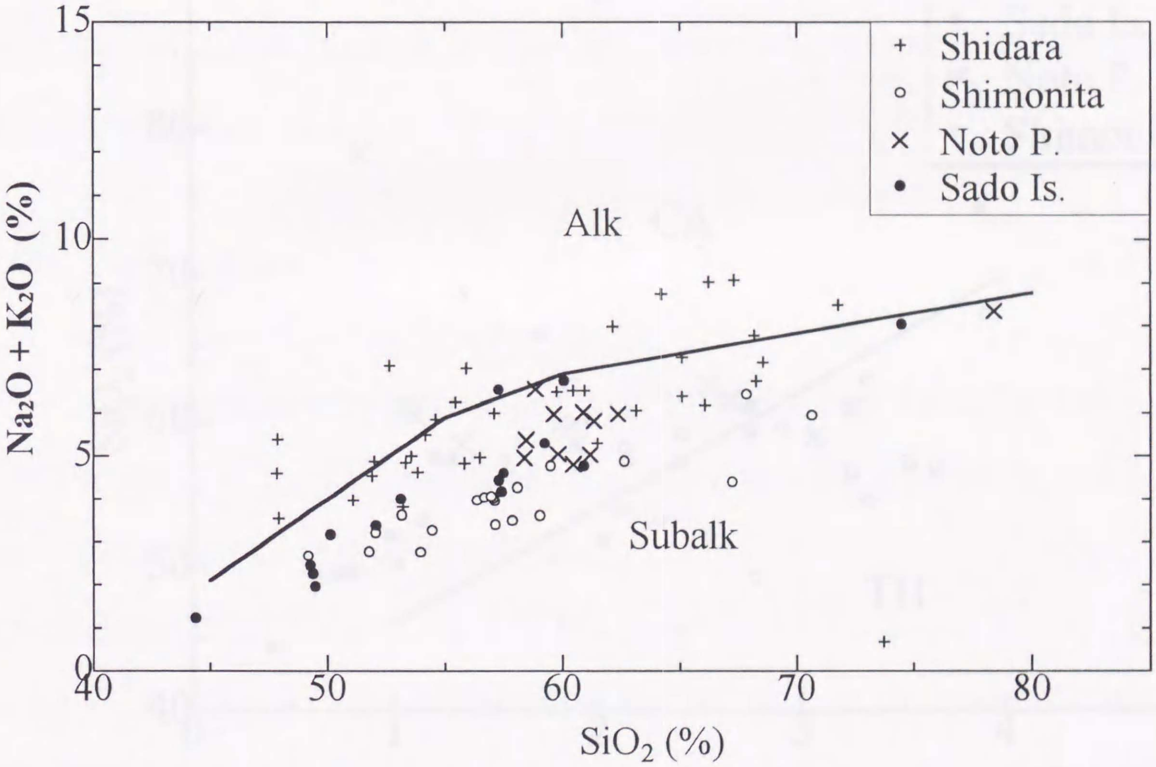

Fig. 2. SiO_2 vs. (Na_2O + K_2O) plots of volcanic rocks from the Sado Island, Noto Peninsula, Shimonita Town and Shidara area. Alkalic/Subalkalic boundary from Miyashiro (1978).

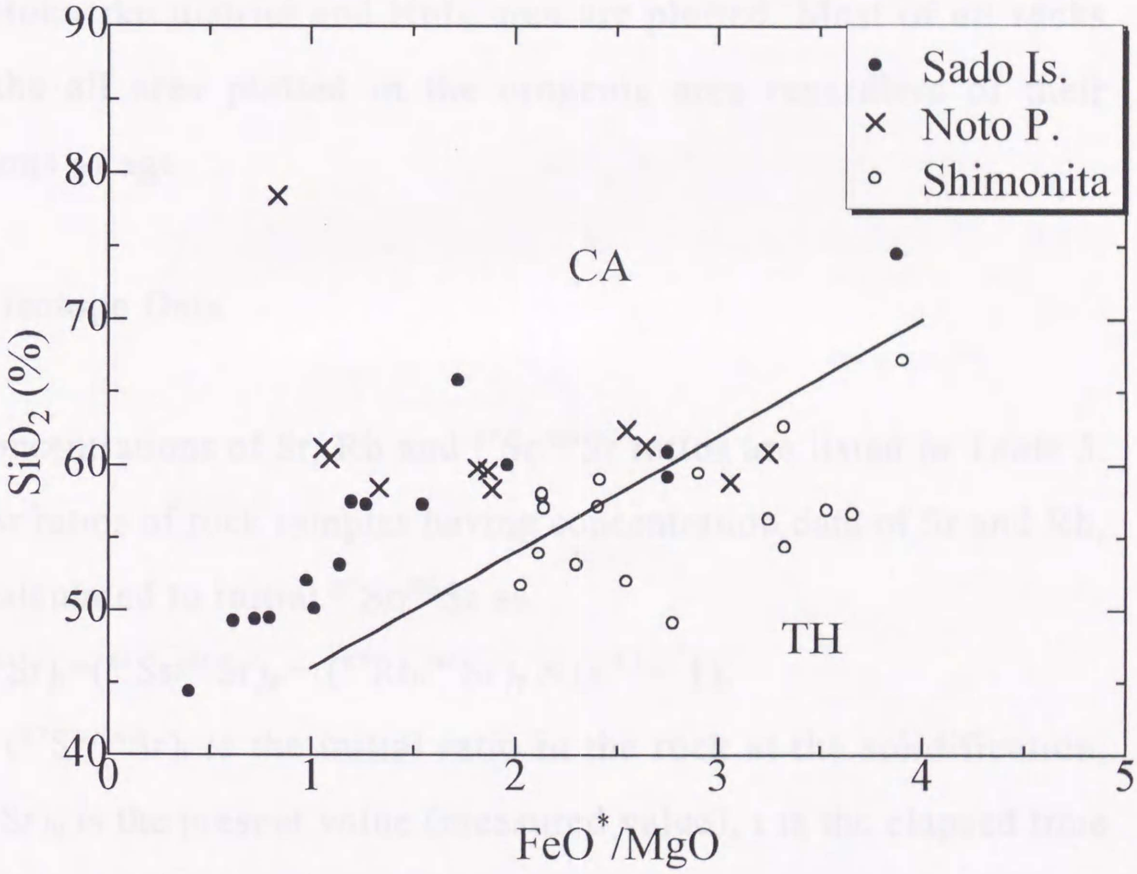

Fig. 3. SiO_2 vs. FeO^*/MgO plots of non-alkaline rocks from the Sado Island, Shimonita Town and Noto Peninsula. Tholeiitic/calc-alkalic boundary from Miyashiro (1974).

(3) Discriminating between tectonic environments

Fig. 4 shows a FeO-MgO-Al_2O_3 discrimination diagram for basaltic andesite and basalt defined by Pearce (1977). In this figure, data from basaltic andesite and basalt ($<$ 56 SiO_2 wt.%) from the Sado Island, Echizen coastal area, Shidara area, Shimonita Town, and other rocks from Hokuriku district and Hida area are plotted. Most of all rocks from the all area plotted in the orogenic area regardless of their variations of age.

4.3 Sr Isotope Data

Concentrations of Sr, Rb and $^{87}Sr/^{86}Sr$ ratios are listed in Table 5. $^{87}Sr/^{86}Sr$ ratios of rock samples having concentration data of Sr and Rb, were calculated to initial $^{87}Sr/^{86}Sr$ as:

$$(^{87}Sr/^{86}Sr)_i=(^{87}Sr/^{86}Sr)_p-(^{87}Rb/^{86}Sr)_p \times (e^{\lambda t}-1)$$

where $(^{87}Sr/^{86}Sr)_i$ is the initial ratio in the rock at the solidification, $(^{87}Sr/^{86}Sr)_p$ is the present value (measured value), t is the elapsed time and $^{87}Rb_{\lambda} = 1.42 \times 10^{-11}$/y (Steiger and Jäger, 1977). Data without absolute ages were calculated with expected ages, and they are reliable enough because the samples are younger than 30 Ma. In following of this paper, $^{87}Sr/^{86}Sr$ initial ratios will be used as $^{87}Sr/^{86}Sr$ ratio.

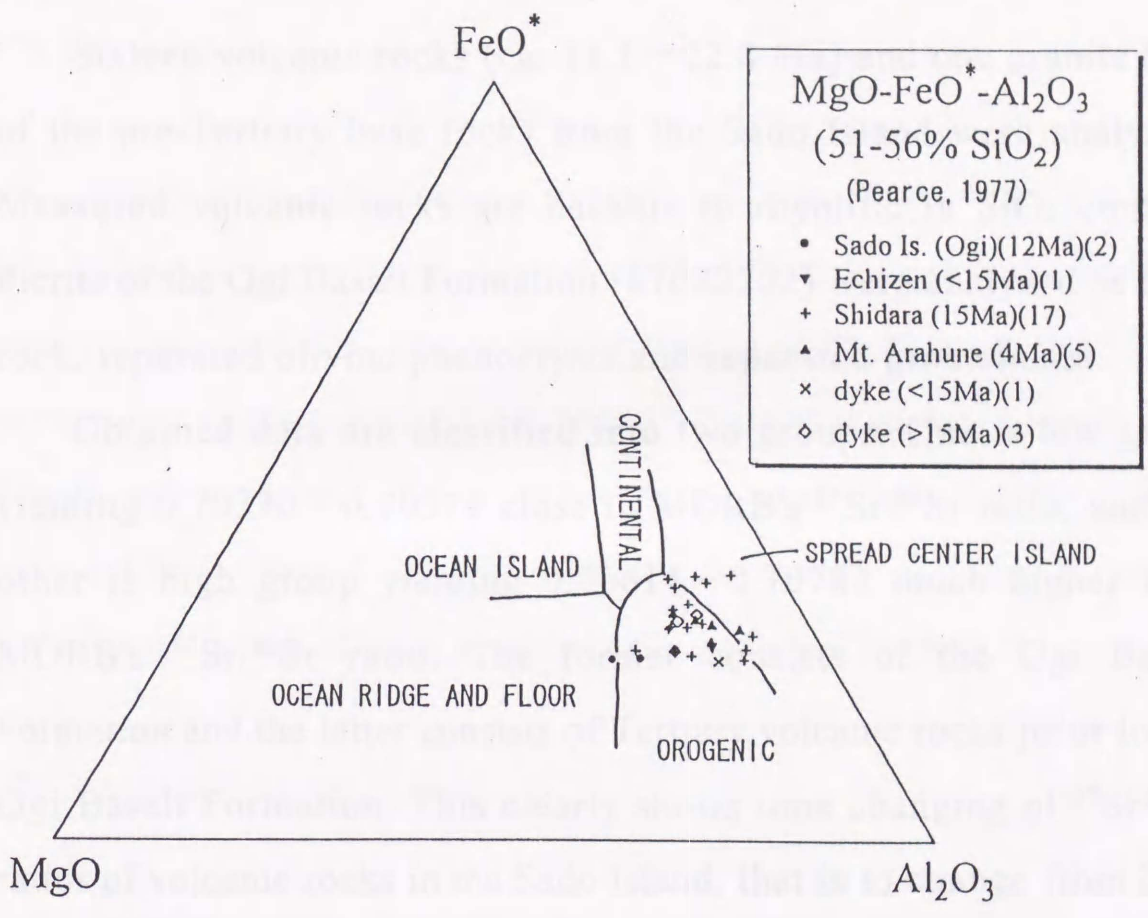

Fig. 4. FeO-MgO-Al_2O_3 discrimination diagram (defined by Pearce et al., 1977) for basalt and basaltic andesite (< 56 SiO_2 wt.%) from the Sado Island, Echizen coastal area, Shidara area, Shimonita Town, and othere rocks from Hokuriku district and Hida area.

Fig. 5-1, 2, 3 shows histogram of distributions of $^{87}Sr/^{86}Sr$ ratios in each area. $^{87}Sr/^{86}Sr$ ratios of each area are as follows.

(1) Sado Island

Sixteen volcanic rocks (ca. 11.1－22.8 Ma) and one granite (one of the pre-Tertiary base rock) from the Sado Island were analyzed. Measured volcanic rocks are basaltic to rhyolitic in SiO_2 content. Picrite of the Ogi Basalt Formation (87082202) were analyzed as bulk rock, separated olivine phenocrysts and separated groundmass.

Obtained data are classified into two groups. One is low group yielding 0.70330－0.70374 close to MORB's $^{87}Sr/^{86}Sr$ ratio, and the other is high group yielding 0.70614－0.70783 much higher than MORB's $^{87}Sr/^{86}Sr$ ratio. The former consists of the Ogi Basalt Formation and the latter consists of Tertiary volcanic rocks prior to the Ogi Basalt Formation. This clearly shows time changing of $^{87}Sr/^{86}Sr$ ratios of volcanic rocks in the Sado Island, that is to change from high value to low and limited value close to MORB's value.

Granite (87040601), one of the pre Tertiary basement, yielded 0.705657, intermediate value. Olivine phenocrysts in picrite (87082202) of the Ogi Basalt Formation yield 0.705924 that is close to the high group, therefore these olivine phenocrysts are residue of Tertiary volcanic rocks prior to the Ogi Basalt Formation and caught in a part of magma of the Ogi Basalt Formation which formed groundmass of this picrite.

When $^{87}Sr/^{86}Sr$ ratio of groundmass counts as $^{87}Sr/^{86}Sr$ ratio of this picrite, $^{87}Sr/^{86}Sr$ ratios of the Ogi Basalt Formation range 0.70330－0.70349, very limited range, whereas it varies in SiO_2 content.

(2) Mt. Yahiko

The Miocene eight basaltic to rhyolitic rocks from the area around Mt. Yahiko, were analyzed. Obtained $^{87}Sr/^{86}Sr$ ratios are classified into two groups, low and high groups, same as those in the Sado Island. Low group yields 0.703420－0.704158 (volcanic rocks of the Kakuta Formation and the Maze formation) and high group yields 0.704713－0.705904 (the Teradomari formation and the Kannonji formation), and that high group clearly prior to low group.

(3) Shimonita Town

Seventeen volcanic rocks (the Miocene to the Pliocene, basaltic to rhyolitic rocks) in this area were analyzed and obtained $^{87}Sr/^{86}Sr$ ratios ranges 0.70388－0.704763, and the ratios of most of samples yield 0.70388-0.70424, very limited range. Most of this range overlaps low group of the Sado Island.

(4) Maruko Town

Five Miocene (ca. 11.6－16.3 Ma) basalt and andesite were analyzed, and obtained $^{87}Sr/^{86}Sr$ ratios range 0.704450−0.706110, higher than that of MORB's, close to that of Quaternary volcanic rocks from northeast Japan (Notsu, 1983). This range overlaps high group of the Sado Island and Mt. Yahiko.

(5) Asahi Town

One sample of andesite lava (87051802) from this area was analyzed, and $^{87}Sr/^{86}Sr$ ratio is 0.705566, in the range of high group of the Sado Island.

(6) Hida area

Basalt dike aged ca. 16 Ma (87052006) yields 0.708511 which is higher than the range of high group of the Sado Island. Five Paleocene andesite dikes (87051906, 87051908, 87052001, 87052002, 87052005) aged ca. 53.1−60.9 Ma yield 0.70640−0.710327 (calculated to initial ratios using each obtained age), very high values. One Cretaceous andesite dike (87051909) aged ca. 99.6 Ma yields 0.71060, also very high value.

Therefore $^{87}Sr/^{86}Sr$ initial ratios of Cretaceous to Paleocene volcanic rocks in Hida area are very high compared to the ratios ever reported.

(7) Riga Village

Andesite dike aged ca. 16.8 Ma (87052011) and andesite lava aged ca. 17.3 Ma (87052013) yield 0.707482 and 0.707015 respectively. Both of them are within the range of high group of the Sado Island.

(8) Kamiichi Town

Andesite dike aged ca. 15.7 Ma (87052416) yields 0.70538, which is within the range of high group. All the $^{87}Sr/^{86}Sr$ of measured Tertiary volcanic rocks in Toyama and Gifu Prefecture ranges 0.70538－0.70851, and no ratio is lower than 0.705, in contrast some $^{87}Sr/^{86}Sr$ ratios of the rocks from Sado Island, Mt. Yahiko and Shimonita Town are lower than 0.705.

(9) Noto Peninsula

Twelve volcanic rocks (andesite, dacite and rhyolite) aged ca. 8.6－28.4 Ma and one granite which is one of the pre Tertiary basement (87040301) , were analyzed. Volcanic rocks yield 0.703799－0.706747. All, but 87040308 and 88090301, $^{87}Sr/^{86}Sr$ ratios of volcanic rocks range 0.705183－0.706747, same range as high group of the Sado Island.

$^{87}Sr/^{86}Sr$ ratios of granite was 0.708013 (not initial ratio but measured ratio), higher than those of volcanic rocks.

(10) Kanazawa City

Miocene Basalt dike in Kanazawa City (86010101) yields 0.707015, which is higher than those of volcanic rocks in Noto Peninsula.

(11) Echizen coast

Fourteen volcanic rocks (andesite, dacite and rhyolite) from Echizen coastal area aged ca. 7.9−17.1 Ma, yields 0.706131−0.712104. These obtained ratios are almost higher than ever reported as to volcanic rocks in Japan. No obtained ratio is lower than 0.704.

In the Japan Sea side area of central Japan, in the Sado Island, Shimonita Town and around Mt. Yahiko, $^{87}Sr/^{86}Sr$ ratios of Tertiary volcanic rocks ranges both high (>0.704) and low (<0.704). In contrast the ratios of Toyama, Gifu (north part) and Ishikawa Prefecture range only high. Therefore, difference of the distributions of $^{87}Sr/^{86}Sr$ ratios of Tertiary volcanic rocks is clearly found in the Japan Sea side area of central Japan.

(12) Shidara area

Shidara area is the only area where Tertiary volcanic rocks were widely erupted in situ in the Pacific side area of the central Japan. Because the Izu Peninsula where Tertiary volcanic rocks are widely distributed, was attached in Quaternary.

Fifty-two volcanic rocks and six gneiss of Ryoke metamorphic rock, pre Tertiary basement from Shidara area were analyzed. Acid eruptive rocks are widely distributed, but intermediate to basic volcanic rocks are limitedly distributed only as intrusive rocks in this area.

$^{87}Sr/^{86}Sr$ ratios of volcanic rocks range 0.703153－0.708587, widely vary. The more basic rocks yield the lower. Initial ratios (initialized as aged 15 Ma for comparing volcanic rocks) of gneiss ranges 0.704329-0.719157, much widely vary. The original rocks of gneiss vary, and it caused the dispersion of the ratios.

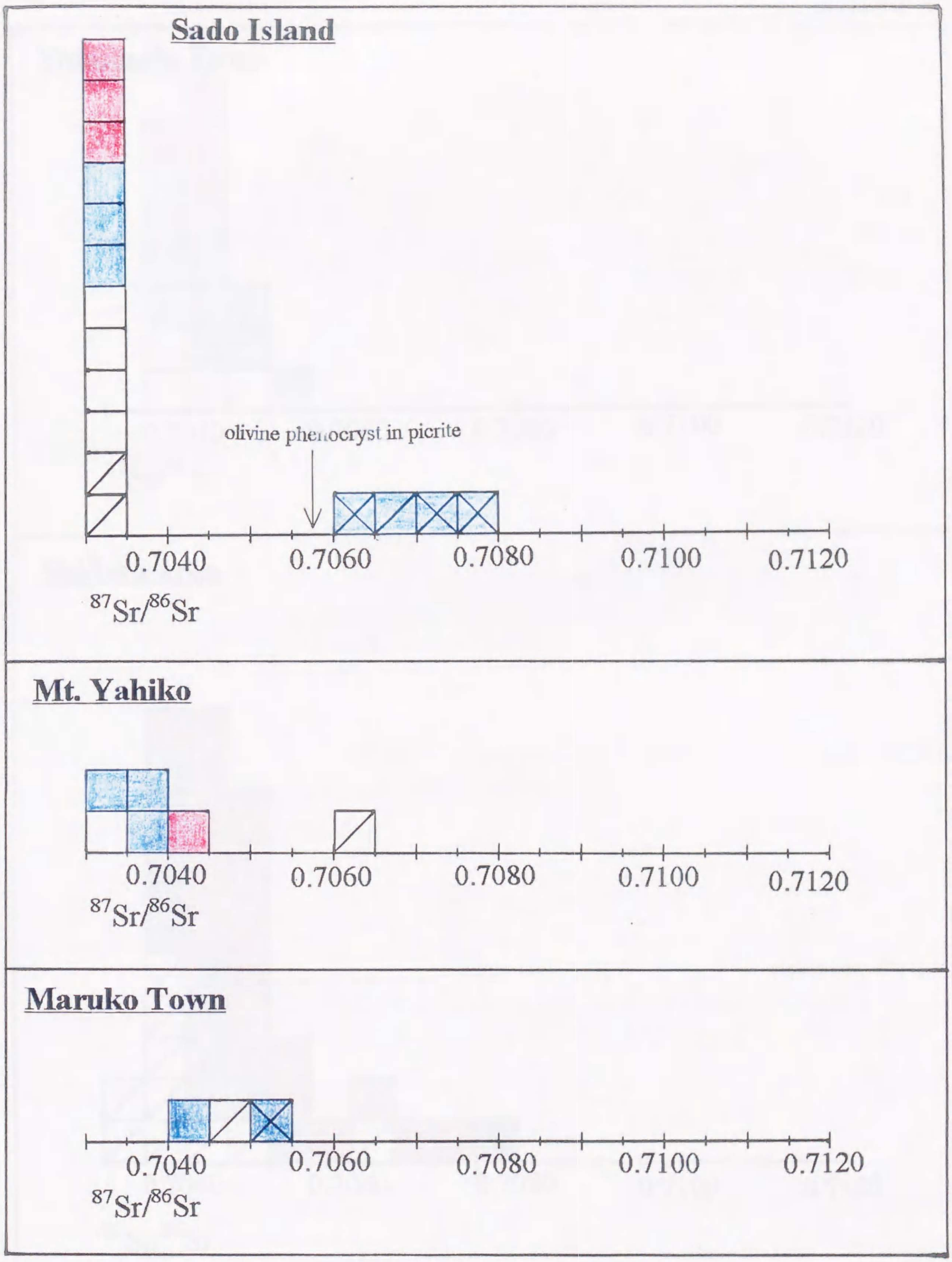

Fig. 5-1. Histograms of distributions of $^{87}Sr/^{86}Sr$ ratios of Tertiary volcanic rocks from the Sado Island, Mt. Yahiko and Maruko Town. Lines in squares show ages, cross: >16 Ma, slash: 14 – 16 Ma, non: <14 Ma. Colors show SiO_2 contents, red: >62.0 %, blue: 53.5 – 62.0 %, non: <53.5 %.

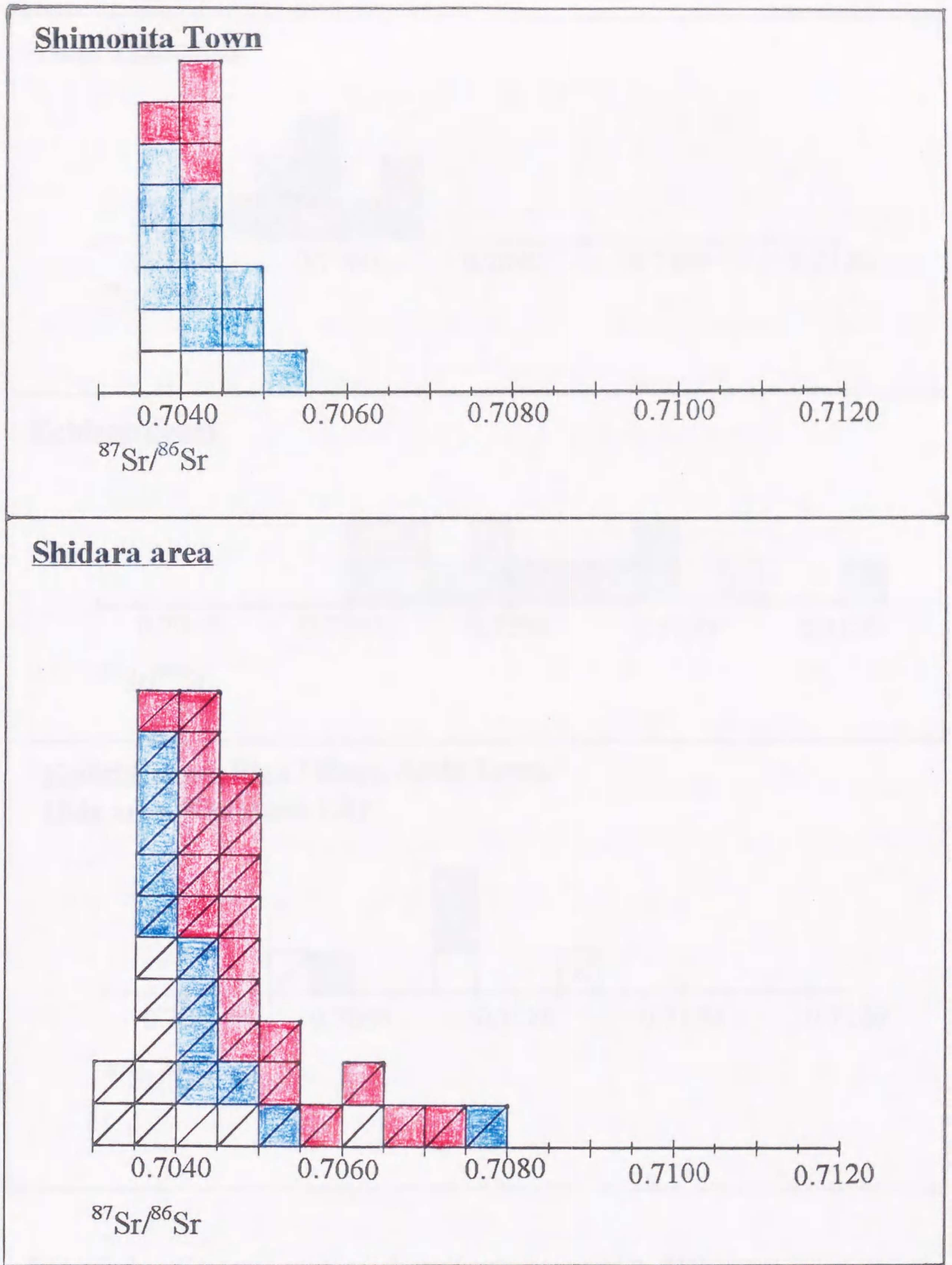

Fig. 5-2. Histograms of distributions of $^{87}Sr/^{86}Sr$ ratios of Tertiary volcanic rocks from Shimonita Town and Shidara area.

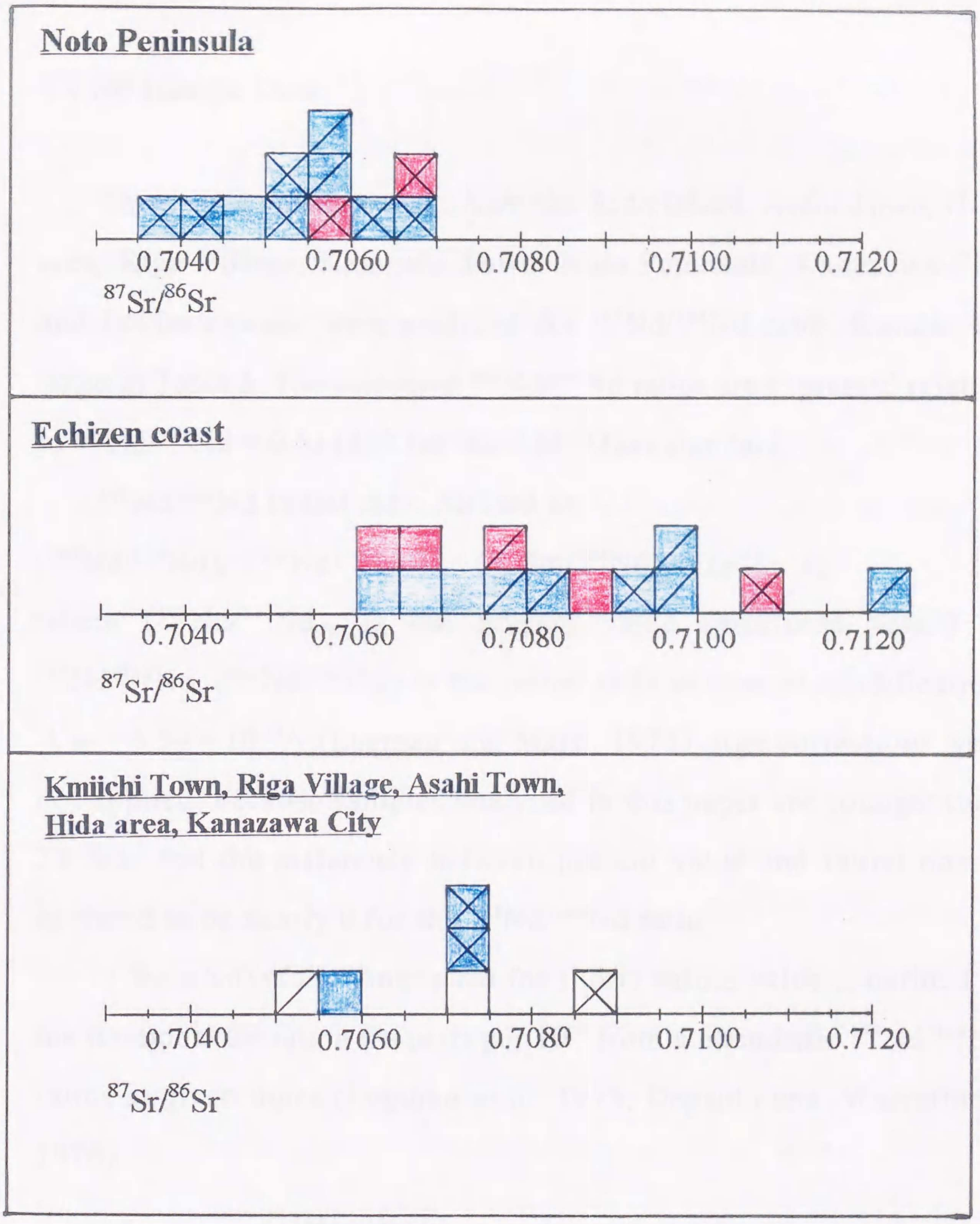

Fig. 5-3. Histograms of distributions of $^{87}Sr/^{86}Sr$ ratios of Tertiary volcanic rocks from Asahi Town, Hida area, Riga Village, Kamiichi Town, Noto Peninsula, Kanazawa City and Echizen coast.

4.4 Nd Isotope Data

Thirty-nine volcanic rocks from the Sado Island, Asahi Town, Hida area, Riga Village, Kamiichi Town, Noto Peninsula, Kanazawa City and Echizen coast, were analyzed for $^{143}Nd/^{144}Nd$ ratio. Results are listed in Table 5. The measured $^{143}Nd/^{144}Nd$ ratios are expressed relative to $^{143}Nd/^{144}Nd = 0.511300$ for the J.M. Mass standard.

$^{143}Nd/^{144}Nd$ initial ratio defined as

$(^{143}Nd/^{144}Nd)_i = (^{143}Nd/^{144}Nd)_p - (^{147}Sm/^{144}Nd)_p \times (e^{\lambda t} - 1)$

where $(^{143}Nd/^{144}Nd)_p$ is the present value (measured value) of $^{143}Nd/^{144}Nd$, $(^{143}Nd/^{144}Nd)_i$ is the initial ratio at time of solidification, $\lambda_{Sm} = 6.54 \times 10^{-12}/y$ (Lugmair and Marti, 1978). Age corrections were not applied, because samples analyzed in this paper are younger than 30 Ma, and the difference between present value and initial one is assumed to be nearly 0 for the $^{143}Nd/^{144}Nd$ ratio.

$\varepsilon^0_{CHUR}(Nd)$ (following εNd for short) values value is defined as the fractional deviation (in parts per 10^{-4} from a chondritic $^{143}Nd/^{144}Nd$ ratios at given times (Lugmair et al. 1975; Depaolo and Wasserburg 1976):

$$\varepsilon^0_{CHUR}(Nd) = \left\{ \frac{(^{143}Nd/^{144}Nd)^t_{sample}}{(^{143}Nd/^{144}Nd)^t_{chondritic}} - 1 \right\} \times 10^4$$

$$(^{143}Nd/^{144}Nd)^t_{condritic} = (^{143}Nd/^{144}Nd)^0_{condritic} - (^{147}Sm/^{144}Nd)^0_{condritic} (e^{\lambda_{Sm} t} - 1)$$

where parent-day reference values used are $(^{143}Nd/^{144}Nd)^0_{chondritic} =$

0.512638 and $(^{147}Sm/^{144}Nd)^0_{chondritic}$=0.1967 (Jacobsen and Wasserburg, 1980); and $\lambda_{Sm}=6.54\times10^{-12}yr^{-1}$. $(^{143}Nd/^{144}Nd)^t_{sample}$ is the initial ratio in the rock at the time of solidification t.

$^{143}Nd/^{144}Nd$ ratio inversely correlates $^{87}Sr/^{86}Sr$ ratio. Because incompatibility of Rb is higher than that of Sr, and that of Sm is higher than that of Nd.

Fig. 6 shows histogram of distributions of $\varepsilon^0_{CHUR}(Nd)$ (following ε Nd for short) values in each area. ε Nd values of each area are as follows.

(1) Sado Island

Nine volcanic rocks from the Sado Island were analyzed. ε Nd values range -3.76－+8.55, widely vary. These values are classified into two groups. One is high group yielding +6.28－+8.55 close to MORB's ε Nd value, and the other is low group yielding -3.76－-1.11 much lower than MORB's ε Nd value. There is a wide gap between these two groups as in the case of $^{87}Sr/^{86}Sr$ ratios. The former consists of the Ogi Basalt Formation and the latter consists of Tertiary volcanic rocks prior to the Ogi Basalt Formation. High group of ε Nd value matches low group of $^{87}Sr/^{86}Sr$ ratio and vice versa. This clearly shows time changing of ε Nd values of volcanic rocks in the Sado Island, that is to change from low value to high value close to MORB's value.

(2) Asahi Town

Andesite lava from this area (87051802) yields -0.06, close to low group of the Sado Island. $^{87}Sr/^{86}Sr$ ratios of this sample was in the range of high group.

(3) Hida area

Miocene basalt dike was analyzed from this area (87052006). Obtained ε Nd value was -7.79 and lower than the range of low group. $^{87}Sr/^{86}Sr$ ratios of this sample was higher than the range of high group.

(4) Riga Village

ε Nd values of andesite dike (87052011) and andesite lava (87052013) from this area were -0.90 and -3.43 respectively. The former is close to low group and the latter is within the range of low group. $^{87}Sr/^{86}Sr$ ratios of both of these two samples were within the range of high group.

(5) Kamiichi Town

Andesite dike (87052416) yields +4.37 and this value is close to high group. But $^{87}Sr/^{86}Sr$ ratio of this sample was close to high group.

(6) Noto Peninsula

Ten Tertiary volcanic rocks from Noto Peninsula were analyzed. Obtained values range -4.10－+6.07, widely vary. These values cover both low group and high group of the Sado Island. The lower ε Nd values are the higher $^{87}Sr/^{86}Sr$ ratios.

(7) Kanazawa City

Basalt dike from this area (86010101) yields -2.26, and this value is within low group of the Sado Island. $^{87}Sr/^{86}Sr$ ratio of this sample was within high group.

(8) Echizen coast

Fourteen Tertiary volcanic rocks (andesite, dacite and rhyolite) from this area were analyzed, and obtained ε values range -11.47－+0.88. Some of these values are within low group and some are lower than low group. $^{87}Sr/^{86}Sr$ ratios of this area were very high, and $^{87}Sr/^{86}Sr$ ratios and ε Nd values of this area show clear inverse correlation.

4.5 $\varepsilon^{0}_{CHUR}(Nd)$ and $\varepsilon^{0}_{UR}(Sr)$ Isotope Correlation Diagram

$\varepsilon^{0}_{UR}(Sr)$ (following ε Sr for short) values is defined as the fractional deviation (in parts per 10^{-4} from a UR (=uniform reservoir)

$^{87}Sr/^{86}Sr$ ratios at given times :

$$\varepsilon^{0}_{UR}(Sr) = \left\{ \frac{(^{87}Sr/^{86}Sr)^{t}_{sample}}{(^{87}Sr/^{86}Sr)^{t}_{UR}} - 1 \right\} \times 10^{4}$$

where $(^{87}Sr/^{86}Sr)^{0}_{UR}=0.7045$ (DePaolo and Wasserburg, 1976).

Fig. 7 is εNd vs. εSr isotope correlation diagram which shows the relative position of depleted and enriched mantle source. Most non-enriched mantle reservoirs are plotted in the upper left 'depleted' quadrant whereas most crustal rocks are plotted in the lower right 'enriched' quadrant. Upper and lower crust tend to be plotted in different positions in the crustal quadrant (from DePaolo and Wasserburg, 1979).

Fig. 8 shows εNd vs. εSr isotope correlation diagram of Tertiary to Quaternary volcanic rocks from Japan and Mariana, ever reported, arranged by Kaneoka (1990) and Kaneoka *et al.* (1990). Most of volcanic rocks fall close to the mantle array, in the upper right and upper left quadrant. But rocks from Mariana are elongate horizontally, which represents effects of sea water on the magma.

εNd vs. εSr isotope correlation diagram of volcanic rock from central Japan (the Sado Island, Asahi Town, Hida area, Riga Village, Kamiichi Town, Noto Peninsula, Kanazawa City and Echizen coast) analyzed in this study, is shown in Fig. 9. All the volcanic rocks of low group (as to $^{87}Sr/^{86}Sr$) of the Sado Island fall close to the MORB's area. Most of other volcanic rocks, except for one of from Noto Peninsula, fall far from MORB's area, the long and narrow band prolonged from upper bulk area to lower right parallel to mantle array. All the volcanic rocks of the Sado Island, Asahi Town, Hida area, Riga Village, Kanazawa City and Echizen coast, and some of Noto Peninsula fall in the lower right 'enriched' quadrant, where upper crust falls.

Table 5. Results of Sr and Nd isotopic ratios and Sr and Rb contents of Tertiary volcanic rocks from central Japan

Sample No.	Rb (ppm)	Sr (ppm)	Rb/Sr	$^{87}Sr/^{86}Sr$	2 σ (m)	$^{87}Sr/^{86}Sr$ I	$\varepsilon^{0}_{UR}(Sr)$	$\varepsilon^{0}_{UR}(SrI)$	$^{143}Nd/^{144}Nd$	2 σ (m)	$\varepsilon^{0}_{CHUR}(Nd)$
Sado											
1 87040501	12.8	309.7	0.0413	0.703452	0.000009	0.70343	-18.417	-18.714	0.5129731	0.0000053	6.536
2 87040503	20.5	330.0	0.0621	0.703375	0.000010	0.70335	-19.506	-19.930	0.5129600	0.0000057	6.281
3 87040504	5.1	252.0	0.0202	0.703394	0.000018	0.70339	-19.235	-19.366	0.5130764	0.0000051	8.551
4 87040505	79.7	440.0	0.1811	0.706801	0.000010	0.70669	29.103	27.571	0.5125812	0.0000050	-1.107
5 87040601				0.705657	0.000014		12.869				
6 87082101	53.0	372.3	0.1424	0.707966	0.000010	0.70783	45.636	43.742	0.5124452	0.0000053	-3.760
7 87082103	70.8	430.0	0.1647	0.706256	0.000013	0.70614	21.372	19.662			
8 87082106	40.7	404.7	0.1006	0.707273	0.000013	0.70719	35.805	34.555	0.5125440	0.0000052	-1.833
9 87082202	3.6	134.1	0.0268	0.703761	0.000015	0.70374	-14.027	-14.270			
10 87082202-M	13.6	193.9	0.0705	0.703403	0.000010	0.70336	-19.115	-19.753	0.5129796	0.0000066	6.663
11 87082202-O				0.705924	0.000018		16.661				
12 87082203	4.8	339.5	0.0141	0.703377	0.000015	0.70337	-19.484	-19.600	0.5130334	0.0000115	7.713
13 87082204	21.1	317.0	0.0666	0.703416	0.000011	0.70339	-18.934	-19.349	0.5130397	0.0000052	7.835
14 87082205	35.0	274.7	0.1275	0.703393	0.000009	0.70333	-19.255	-20.146			
15 87082206	33.4	283.7	0.1178	0.703448	0.000007	0.70339	-18.474	-19.298			
16 87082207	105.5	95.0	1.1113	0.703848	0.000019	0.70330	-12.798	-20.574			
17 87082208	84.7	113.7	0.7455	0.703755	0.000014	0.70339	-14.125	-19.342			
18 87082209	23.0	292.4	0.0788	0.703528	0.000009	0.70349	-17.339	-17.890			
19 87082210	73.3	241.6	0.3034	0.703626	0.000009	0.70348	-15.954	-18.077			
Yahiko											
20 88090602	66.1	83.1	0.7955	0.704420	0.000039	0.70416	-4.682	-8.393			
21 88090604	14.2	344.9	0.0412	0.703434	0.000025	0.70342	-18.673	-18.865			
22 88090607	16.5	390.3	0.0424	0.703570	0.000011	0.70355	-16.743	-17.065			

1/7 (continued)

Table 5. Results of Sr and Nd isotopic ratios and Sr and Rb contents of Tertiary volcanic rocks from central Japan (continued)

	Sample No.	Rb (ppm)	Sr (ppm)	Rb/Sr	$^{87}Sr/^{86}Sr$	2 σ (m)	$^{87}Sr/^{86}Sr$ I	ε $^{0}_{UR}$(Sr)	ε $^{0}_{UR}$(SrI)	$^{143}Nd/^{144}Nd$	2 σ (m)	ε $^{0}_{CHUR}$(Nd)
23	88090608	43.4	477.7	0.0910	0.703700	0.000010	0.70365	-14.898	-15.589			
24	88090613	33.8	466.0	0.0727	0.703460	0.000011	0.70342	-18.304	-18.855			
25	88090618	14.1	225.4	0.0627	0.704755	0.000012	0.70471	0.073	-0.511			
26	88090619	42.3	87.0	0.4867	0.706060	0.000010	0.70574	18.588	14.046			
27	88090621	10.4	270.8	0.0385	0.705930	0.000009	0.70590	16.743	16.384			
	Shimonita											
28	88060301	34.3	345.1	0.0994	0.704012	0.000016	0.70401	-10.471	-10.471			
29	88060302	27.3	340.5	0.0802	0.703956	0.000010	0.70396	-11.209	-11.209			
30	88060303	63.8	286.5	0.2227	0.704083	0.000014	0.70408	-9.506	-9.506			
31	88060305	41.0	299.3	0.1372	0.704702	0.000014	0.70470	-0.709	-0.709			
32	88060306	19.6	320.7	0.0614	0.704744	0.000005	0.70474	-0.141	-0.141			
33	88060307	43.2	291.4	0.1486	0.704763	0.000014	0.70476	0.141	0.141			
34	88060308	43.9	367.3	0.1196	0.704231	0.000011	0.70423	-7.378	-7.378			
35	88060309	59.0	300.3	0.1967	0.704116	0.000008	0.70412	-8.939	-8.939			
36	88060310	12.8	329.7	0.0389	0.704236	0.000027	0.70424	-7.236	-7.236			
37	88060401	7.5	307.6	0.0245	0.704069	0.000014	0.70407	-9.648	-9.648			
38	88060402	13.7	316.2	0.0436	0.703969	0.000008	0.70397	-11.067	-11.067			
39	88060403	32.3	383.8	0.0844	0.704000	0.000014	0.70400	-10.642	-10.642			
40	88060404	18.2	344.8	0.0529	0.703941	0.000011	0.70394	-11.476	-11.476			
41	88060405	17.1	300.6	0.0571	0.703882	0.000014	0.70388	-12.322	-12.322			
42	88060406	70.3	332.7	0.2114	0.703877	0.000013	0.70388	-12.381	-12.381			
43	88060407	45.4	328.6	0.1383	0.703908	0.000011	0.70391	-11.943	-11.943			
44	88060408	40.2	332.6	0.1211	0.703884	0.000015	0.70388	-12.289	-12.289			

2/7 (continued)

Table 5. Results of Sr and Nd isotopic ratios and Sr and Rb contents of Tertiary volcanic rocks from central Japan (continued)

	Sample No.	Rb (ppm)	Sr (ppm)	Rb/Sr	$^{87}Sr/^{86}Sr$	2 σ (m)	$^{87}Sr/^{86}Sr$ I	$\varepsilon^{0}_{UR}(Sr)$	$\varepsilon^{0}_{UR}(SrI)$	$^{143}Nd/^{144}Nd$	2 σ (m)	$\varepsilon^{0}_{CHUR}(Nd)$
	Maruko											
45	88020402				0.705242	0.000016		6.952				
46	88020403				0.704680	0.000020		-0.993				
47	88020404				0.706113	0.000019		19.297				
48	88020405				0.705981	0.000012		17.452				
49	88020407				0.704454	0.000022		-4.256				
	Asahi											
50	87051802	72.4	412.0	0.1757	0.705567	0.000011	0.70557	11.589	11.589	0.5126347	0.0000064	-0.064
	Hida											
51	87051906				0.709222	0.000017		63.426				
52	87051908	77.6	1048.0	0.0740	0.707634	0.000018	0.70745	40.865	38.329			
53	87051909	30.4	836.0	0.0364	0.710752	0.000021	0.71060	85.136	83.021			
54	87052001	48.2	521.0	0.0925	0.706633	0.000011	0.70640	26.676	23.475			
55	87052002				0.706554	0.000020		25.540				
56	87052005	75.6	342.0	0.2211	0.710810	0.000013	0.71033	85.987	79.136			
57	87052006	83.4	473.1	0.1763	0.708630	0.000010	0.70851	55.054	53.378	0.5122385	0.0000056	-7.793
	Riga											
58	87052011	98.3	443.0	0.2219	0.707635	0.000010	0.70748	40.940	38.766	0.5125918	0.0000053	-0.901
59	87052013	18.4	540.0	0.0341	0.707039	0.000010	0.70702	32.483	32.139	0.5124623	0.0000067	-3.427
	Kamiichi											
60	87052416	17.9	333.0	0.0538	0.705415	0.000009	0.70538	9.435	8.943	0.5128622	0.0000040	4.373
	Noto											
61	87040201	39.4	553.0	0.0712	0.705225	0.000009	0.70517	6.737	6.026	0.5127583	0.0000051	2.346

3/7 (continued)

Table 5. Results of Sr and Nd isotopic ratios and Sr and Rb contents of Tertiary volcanic rocks from central Japan (continued)

Sample No.	Rb (ppm)	Sr (ppm)	Rb/Sr	$^{87}Sr/^{86}Sr$	2 σ (m)	$^{87}Sr/^{86}Sr$ I	$\varepsilon^0_{UR}(Sr)$	$\varepsilon^0_{UR}(SrI)$	$^{143}Nd/^{144}Nd$	2 σ (m)	$\varepsilon^0_{CHUR}(Nd)$
62 87040202	76.7	492.0	0.1559	0.704839	0.000010	0.70478	1.268	0.486	0.5127231	0.0000055	1.660
63 87040301				0.708013	0.000008		46.300				
64 87040302	35.2	448.0	0.0786	0.705766	0.000009	0.70571	14.417	13.689	0.5128597	0.0000050	4.324
65 87040303	31.2	525.0	0.0594	0.706117	0.000010	0.70608	19.394	18.811	0.5126057	0.0000058	-0.630
66 87040304	41.1	338.0	0.1216	0.706061	0.000009	0.70598	18.602	17.474	0.5126814	0.0000063	0.846
67 87040305	71.1	417.0	0.1705	0.706943	0.000013	0.70675	31.120	28.345	0.5124278	0.0000056	-4.100
68 87040306	63.5	273.0	0.2326	0.705445	0.000012	0.70518	9.861	6.157	0.5127232	0.0000061	1.661
69 87040307	44.1	397.0	0.1111	0.705578	0.000010	0.70549	11.748	10.472	0.5126571	0.0000057	0.372
70 87040308	10.5	578.0	0.0182	0.703820	0.000010	0.70380	-13.197	-13.493	0.5129492	0.0000059	6.070
71 87040309	123.9	60.0	2.0650	0.708090	0.000011	0.70672	47.395	27.999	0.5126103	0.0000084	-0.540
72 88090301	6.9	551.1	0.0125	0.704040	0.000010	0.70403	-10.074	-10.281			
73 88090402	61.7	146.7	0.4206	0.705900	0.000011	0.70560	16.317	12.024			
Kanazawa											
74 86010101	1.2	419.0	0.0029	0.707017	0.000009	0.70702	32.168	32.147	0.5125015	0.0000055	-2.662
Echizen											
75 90081401				0.708517	0.000010		53.454		0.5123768	0.0000059	-5.095
76 90081402				0.707013	0.000010		32.107		0.5125758	0.0000053	-1.213
77 90081403	111.2	184.4	0.6030	0.706639	0.000011	0.70632	26.809	22.236	0.5126829	0.0000075	0.875
78 90081502				0.708299	0.000008		50.351		0.5122892	0.0000042	-6.804
79 90081602	69.3	227.1	0.3052	0.708012	0.000009	0.70782	46.285	43.562	0.5123224	0.0000055	-6.156
80 90081604				0.709961	0.000009		73.945		0.5122214	0.0000072	-8.126
81 90081606				0.709994	0.000008		74.409		0.5122081	0.0000053	-8.386
82 90081607				0.709106	0.000011		61.806		0.5122175	0.0000056	-8.202
83 90081608				0.710778	0.000012		85.538		0.5120499	0.0000052	-11.472

4/7 (continued)

Table 5. Results of Sr and Nd isotopic ratios and Sr and Rb contents of Tertiary volcanic rocks from central Japan *(continued)*

Sample No.	Rb (ppm)	Sr (ppm)	Rb/Sr	$^{87}Sr/^{86}Sr$	2σ (m)	$^{87}Sr/^{86}Sr$ I	$\varepsilon^{0}_{UR}(Sr)$	$\varepsilon^{0}_{UR}(SrI)$	$^{143}Nd/^{144}Nd$	2σ (m)	$\varepsilon^{0}_{CHUR}(Nd)$
84 90081609				0.712104	0.000010		104.344		0.5119664	0.0000047	-13.100
85 90081610				0.707842	0.000009		43.866		0.5123833	0.0000051	-4.968
86 86090101	27.9	544.0	0.0513	0.706652	0.000010	0.70663	26.991	26.620	0.5125691	0.0000057	-1.344
87 86090104	49.0	391.0	0.1253	0.706837	0.000011	0.70677	29.617	28.689	0.5125691	0.0000053	-1.344
88 86090105	47.9	434.0	0.1104	0.706131	0.000010	0.70607	19.591	18.741	0.5126364	0.0000054	-0.031
Shidara											
89 89012101	73.0	312.1	0.2340	0.707051	0.000041	0.70691	32.649	30.602			
90 89012103	172.7	30.3	5.6997	0.707781	0.000010	0.70427	43.002	-6.872			
91 89012104	184.2	44.8	4.1116	0.707382	0.000017	0.70485	37.346	1.369			
92 89012105	181.5	41.7	4.3525	0.707387	0.000029	0.70470	37.417	-0.667			
93 89012201	97.2	46.6	2.0858	0.706653	0.000031	0.70537	27.008	8.758			
94 89012202	184.6	46.1	4.0043	0.707254	0.000013	0.70478	35.533	0.495			
95 89012204	89.8	136.4	0.6584	0.705284	0.000017	0.70488	7.575	1.816			
96 89012205	86.5	22.7	3.8106	0.707429	0.000013	0.70508	38.012	4.668			
97 90032710	22.8	320.5	0.0711	0.705455	0.000012	0.70541	10.003	9.381			
98 90032711	18.4	26.0	0.7077	0.712908	0.000010	0.71247	115.757	109.561			
99 90032712	45.2	351.3	0.1287	0.703880	0.000012	0.70380	-12.344	-13.47			
100 90032713	86.6	162.6	0.5326	0.704829	0.000015	0.70450	1.126	-3.532			
101 90032801	78.1	263.8	0.2961	0.704449	0.000017	0.70427	-4.271	-6.860			
102 90032803	38.5	435.2	0.0885	0.703885	0.000015	0.70383	-12.273	-13.047			
103 90032809	17.1	409.2	0.0418	0.703873	0.000008	0.70385	-12.444	-12.809			
104 90032810	29.1	372.1	0.0782	0.704012	0.000010	0.70396	-10.471	-11.155			
105 90032811	58.6	337.4	0.1737	0.705019	0.000011	0.70491	3.809	2.290			
106 90032812	87.0	164.3	0.5295	0.705177	0.000007	0.70485	6.064	1.432			

5/7 (continued)

Table 5. Results of Sr and Nd isotopic ratios and Sr and Rb contents of Tertiary volcanic rocks from central Japan (continued)

Sample No.	Rb (ppm)	Sr (ppm)	Rb/Sr	$^{87}Sr/^{86}Sr$	2 σ (m)	$^{87}Sr/^{86}Sr$ I	$\varepsilon^{0}_{UR}(Sr)$	$\varepsilon^{0}_{UR}(SrI)$	$^{143}Nd/^{144}Nd$	2 σ (m)	$\varepsilon^{0}_{CHUR}(Nd)$
107 90032813	107.3	210.1	0.5107	0.704714	0.000013	0.70440	-0.515	-4.982			
108 90032814	96.2	206.6	0.4656	0.704722	0.000012	0.70444	-0.393	-4.466			
109 90071801	3.5	496.8	0.0070	0.703651	0.000015	0.70365	-15.598	-15.66			
110 90082702	46.2	346.4	0.1334	0.704005	0.000013	0.70392	-10.566	-11.733			
111 90082809	57.4	284.4	0.2018	0.706708	0.000000	0.70658	27.777	26.011			
112 90083007	33.4	427.6	0.0783	0.706397	0.000008	0.70635	23.369	22.685			
113 90083008	10.3	260.6	0.0395	0.708607	0.000026	0.70858	54.728	54.382			
114 90083009	48.5	175.1	0.2770	0.707609	0.000012	0.70744	40.567	38.143			
115 90100101	30.5	348.8	0.0876	0.703826	0.000012	0.70377	-13.111	-13.877			
116 90100102	100.5	105.0	0.9568	0.705110	0.000021	0.70452	5.108	-3.262			
117 90100103	10.3	312.5	0.0331	0.706148	0.000011	0.70613	19.832	19.542			
118 90100104	22.6	602.6	0.0376	0.704660	0.000022	0.70464	-1.277	-1.605			
119 90100106	71.6	202.6	0.3532	0.704297	0.000023	0.70408	-6.424	-9.514			
120 90100201	26.6	362.9	0.0734	0.703683	0.000017	0.70364	-15.14	-15.781			
121 90100608	47.5	355.3	0.1337	0.704034	0.000012	0.70395	-10.158	-11.327			
122 90100702-2	45.7	201.4	0.2273	0.704240	0.000023	0.70410	-7.236	-9.224			
123 90100702-3	37.8	363.3	0.1042	0.704162	0.000022	0.70410	-8.343	-9.255			
124 90100703	111.5	172.0	0.6483	0.704434	0.000017	0.70403	-4.483	-10.155			
125 90100707	34.3	558.1	0.0615	0.706716	0.000014	0.70668	27.899	27.361			
126 90101108	54.2	274.3	0.1977	0.708468	0.000013	0.70835	52.754	51.024			
127 90101109	52.2	330.3	0.1581	0.705585	0.000019	0.70549	11.849	10.466			
128 90101205-2	69.5	198.1	0.3508	0.704209	0.000014	0.70399	-7.676	-10.745			
129 90101205-3	69.2	226.6	0.3058	0.704363	0.000009	0.70417	-5.498	-8.173			
130 90101206	75.2	268.9	0.2798	0.704609	0.000011	0.70444	-2.003	-4.450			

6/7 (continued)

Table 5. Results of Sr and Nd isotopic ratios and Sr and Rb contents of Tertiary volcanic rocks from central Japan (continued)

Sample No.	Rb (ppm)	Sr (ppm)	Rb/Sr	$^{87}Sr/^{86}Sr$	2 σ (m)	$^{87}Sr/^{86}Sr$ I	$\varepsilon^{0}_{UR}(Sr)$	$\varepsilon^{0}_{UR}(SrI)$	$^{143}Nd/^{144}Nd$	2 σ (m)	$\varepsilon^{0}_{CHUR}(Nd)$
131 92010901-1	39.6	357.1	0.1109	0.704398	0.000014	0.70433	-4.997	-5.967			
132 92010901-2	37.7	78.2	0.4821	0.711006	0.000017	0.71071	88.770	84.55			
133 92011113				0.708428	0.000014		52.183				
134 92011209	91.1	339.3	0.2687	0.704899	0.000011	0.70473	2.109	-0.240			
135 92011212	89.3	240.4	0.3718	0.708817	0.000013	0.70859	57.705	54.452			
136 92011303-1	99.4	288.6	0.3444	0.706038	0.000018	0.70583	18.275	15.262			
137 92011303-2	51.2	329.2	0.1555	0.704413	0.000010	0.70432	-4.778	-6.139			
138 92011303-4				0.704527	0.000010		-3.164				
139 92011305	51.8	322.4	0.1608	0.704416	0.000011	0.70432	-4.743	-6.150			
140 92011306-1	141.8	236.2	0.6003	0.719528	0.000014	0.71916	209.694	204.434			
141 92011306-2	85.0	146.0	0.5824	0.719372	0.000012	0.71901	207.473	202.371			
142 92011307	15.1	444.9	0.0339	0.703848	0.000014	0.70383	-12.796	-13.092			
143 92011308	15.5	447.1	0.0347	0.703810	0.000010	0.70379	-13.336	-13.639			
144 92011309	23.3	379.1	0.0615	0.704421	0.000009	0.70438	-4.666	-5.204			
145 92011310	16.9	428.8	0.0394	0.703189	0.000016	0.70316	-22.146	-22.491			
146 92011311	16.1	428.1	0.0376	0.703177	0.000011	0.70315	-22.321	-22.65			

7/7

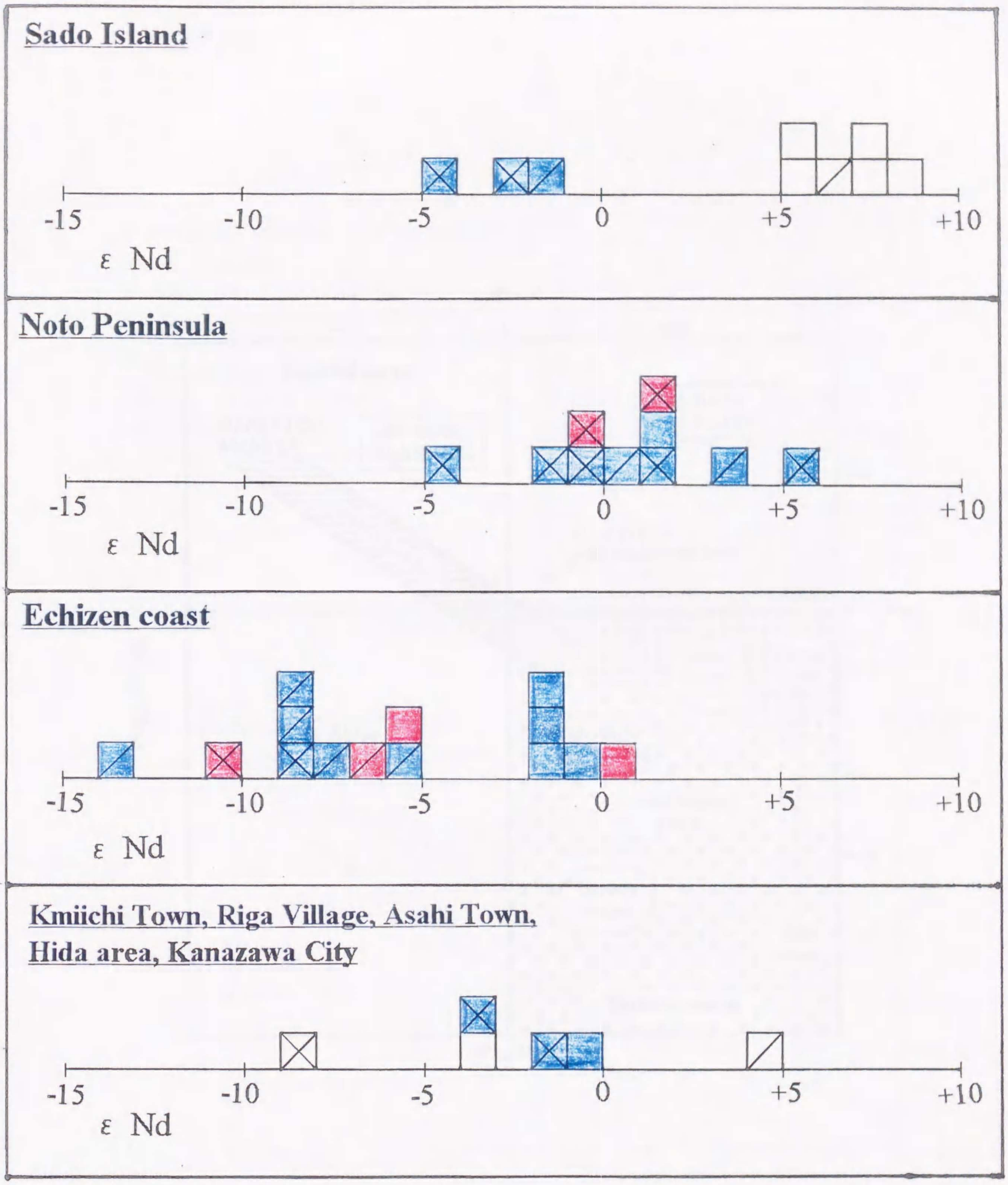

Fig. 6. Histograms of distributions of ε Nd values of Tertiary volcanic rocks from the Sado Island, Asahi Town, Hida area, Riga Village, Kamiichi Town, Noto Peninsula, Kanazawa City, Echizen coast. Lines in squares show ages, cross: >16 Ma, slash: 14 – 16 Ma, non: <14 Ma. Colors show SiO_2 contents, red: >62.0 %, blue: 53.5 – 62.0 %, non: <53.5 %.

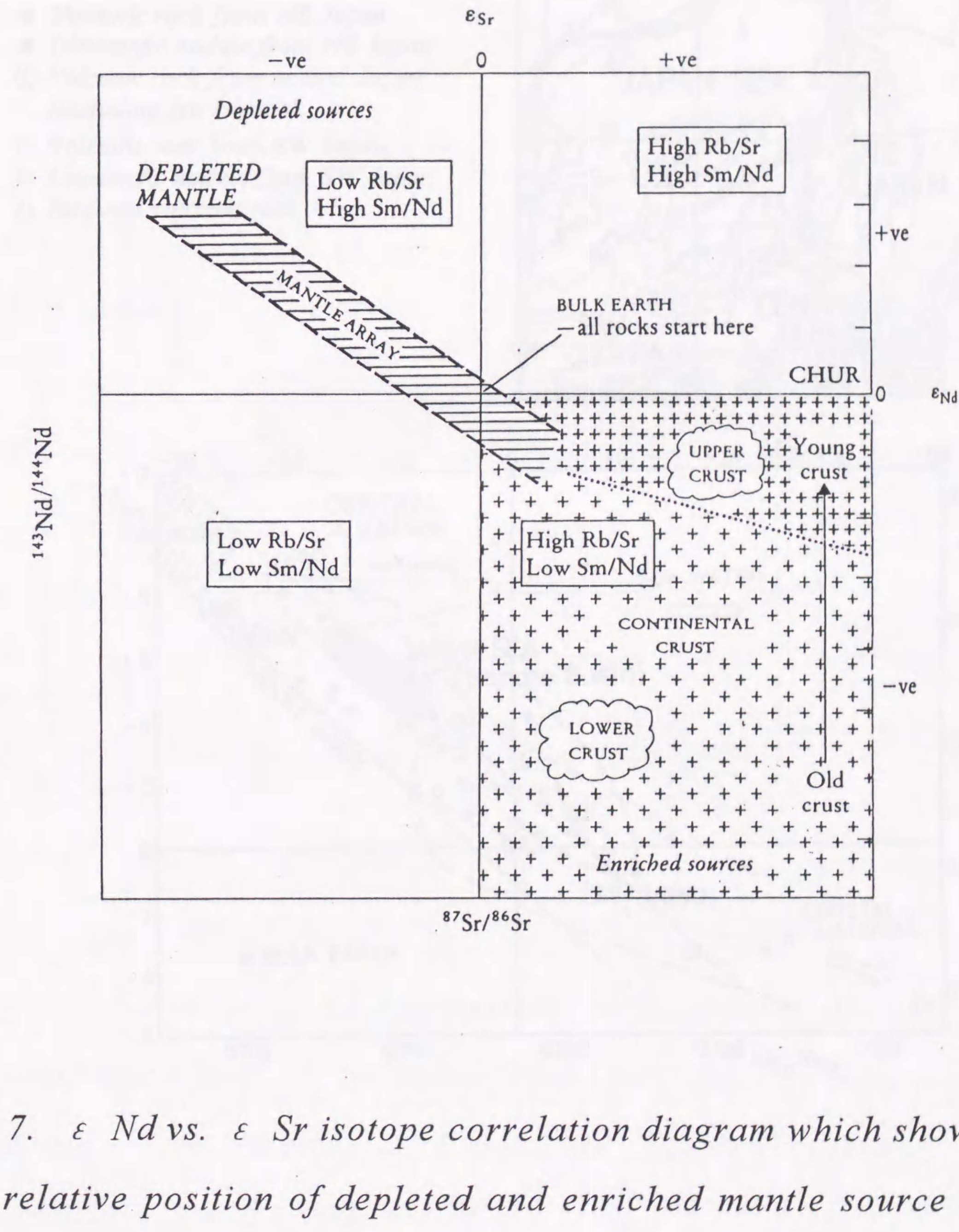

Fig. 7. ε Nd vs. ε Sr isotope correlation diagram which shows the relative position of depleted and enriched mantle source (from DePaolo and Wasserburg, 1979).

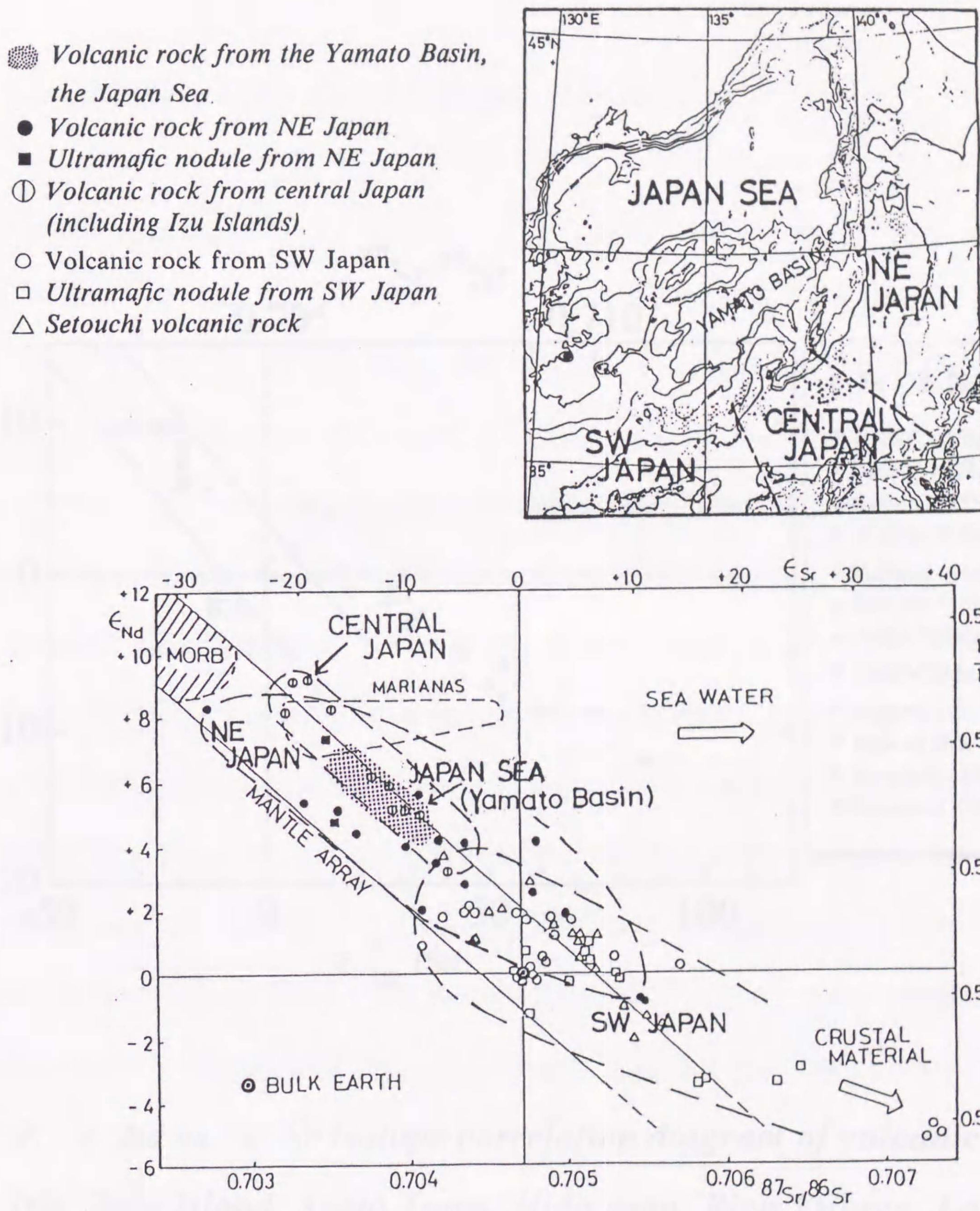

Fig. 8. ε Nd vs. ε Sr isotope correlation diagram of Tertiary to Quaternary volcanic rocks from Japan and Mariana, arranged by Kaneoka (1990).

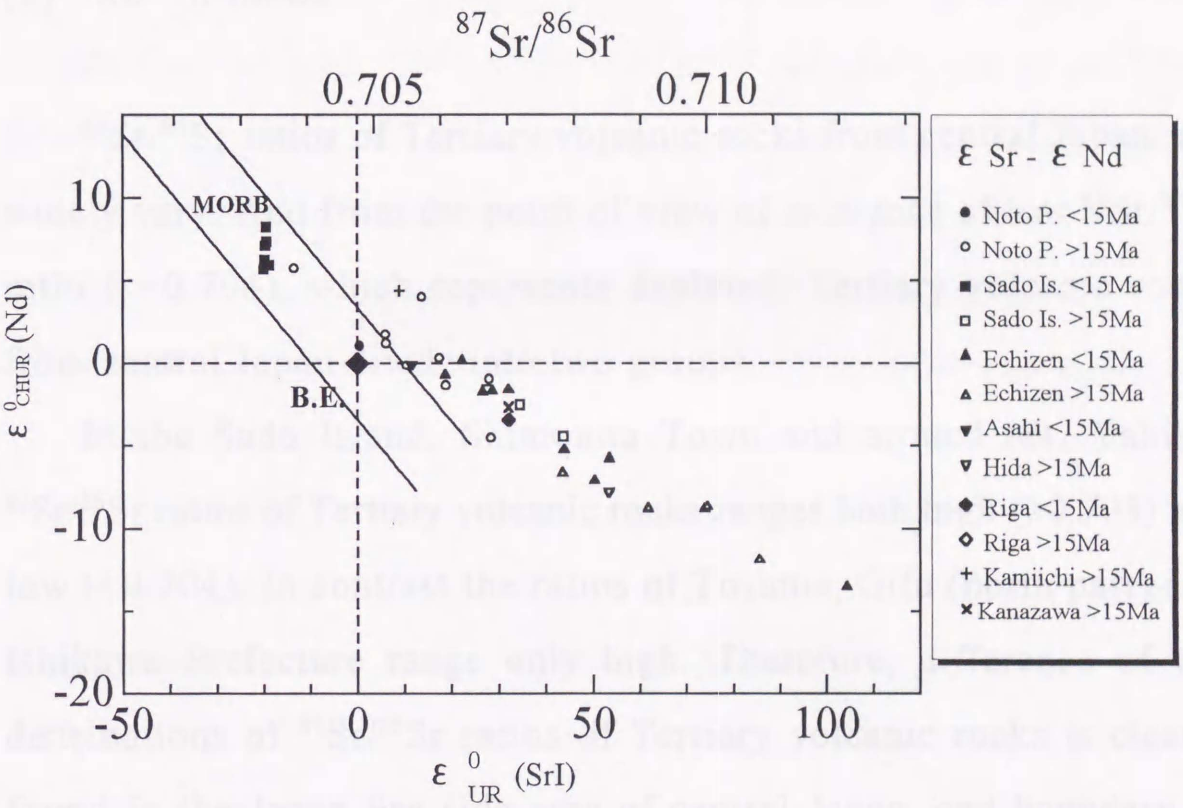

Fig. 9. ε Nd vs. ε Sr isotope correlation diagram of volcanic rocks (the Sado Island, Asahi Town, Hida area, Riga Village, Kamiichi Town, Noto Peninsula, Kanazawa City and Echizen coast) analyzed in this study.

Chapter 5

DISCUSSION

5.1 Spacial Distributions of Isotopic Ratios

(1) $^{87}Sr/^{86}Sr$ ratios

$^{87}Sr/^{86}Sr$ ratios of Tertiary volcanic rocks from central Japan, are widely vary. And from the point of view of existence of low $^{87}Sr/^{86}Sr$ ratio (~0.704), which represents depleted, Tertiary volcanic rocks from central Japan divide into two groups.

In the Sado Island, Shimonita Town and around Mt. Yahiko, $^{87}Sr/^{86}Sr$ ratios of Tertiary volcanic rocks ranges both high (>0.705) and low (<0.704). In contrast the ratios of Toyama, Gifu (north part) and Ishikawa Prefecture range only high. Therefore, difference of the distributions of $^{87}Sr/^{86}Sr$ ratios of Tertiary volcanic rocks is clearly found in the Japan Sea side area of central Japan, and boundary of these seems to lay around the Itoigawa-Shizuoka tectonic line (Fig. 1).

(2) ε Nd values

ε Nd value and $^{87}Sr/^{86}Sr$ ratio correlate inversely in general, and as seemed in ε Nd- ε Sr diagram, Tertiary volcanic rocks from central Japan clearly showed such relation. So reflecting the distribution of $^{87}Sr/^{86}Sr$, almost high ε Nd value (higher than +5.0) can be seen only in the Sado Island, east of the Itoigawa-Shizuoka tectonic line.

5.2 Temporal Changing of Isotopic Ratios

Temporal variations of $^{87}Sr/^{86}Sr$ ratio of Tertiary volcanic rocks from northeast Japan were reported (Kurasawa and Konda, 1986; Nohda and Tatsumi, 1986; Nohda *et al.*, 1988; Shimazu *et al.*, 1993; Shuto *et al.*, 1992; Ujike and Tsuchiya, 1993; Ohki *et al.*, 1994). Basaltic rock (including basalts, dolerites, basaltic andesites and andesite with SiO_2 contents lower than 60 wt%) from the back-arc side of northeast Japan are plotted in terms of $^{87}Sr/^{86}Sr$ ratios and ages (Fig. 10, Ohki *et al.*, 1994). Most of basaltic rocks with ages between 15 and 35 Ma show $^{87}Sr/^{86}Sr$ ratio in a range of 0.704－0.706. However, the Oligocene (about 34－35 Ma) basalts from Okushiri Island have slightly higher than those of N-type MORB (Shuto *et al.*, 1992). Although $^{87}Sr/^{86}Sr$ ratios of basaltic rocks younger than 15 Ma are generally lower than 0.704, basaltic rocks from some locations such as Tobishima Island and Tappi area in the back-arc side (with ages around 10 Ma) have $^{87}Sr/^{86}Sr$ ratios significantly higher than 0.704 (0.70524－0.70534) (Tobishima Island) and 0.70479 (Tappi)). Similar features are also observed for basaltic rocks from the trench-side and the transitional zone in northeast Japan arc (Fig. 11, Ohki *et al.*, 1994).

Temporal variations of ε Nd value are also observed as shown in Fig. 12 (Ohki *et al.*, 1994). This variations also show temporal

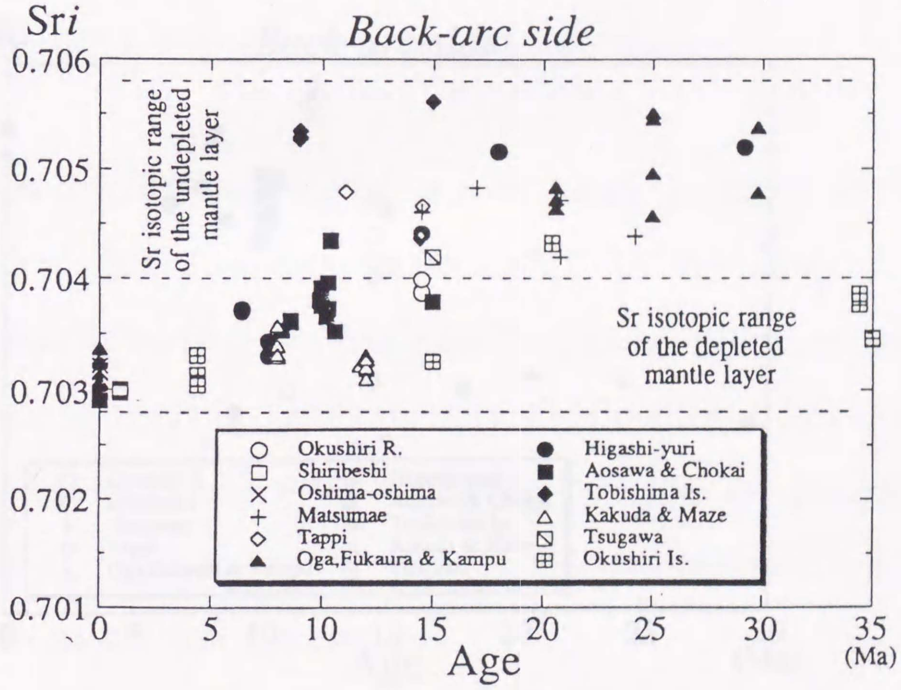

Fig. 10. $^{87}Sr/^{86}Sr$ ratios vs. age for volcanic rocks (with SiO_2 contents lower than 60 wt%) from the back-arc side of the NE Japan arc (Ohki et al., 1994).

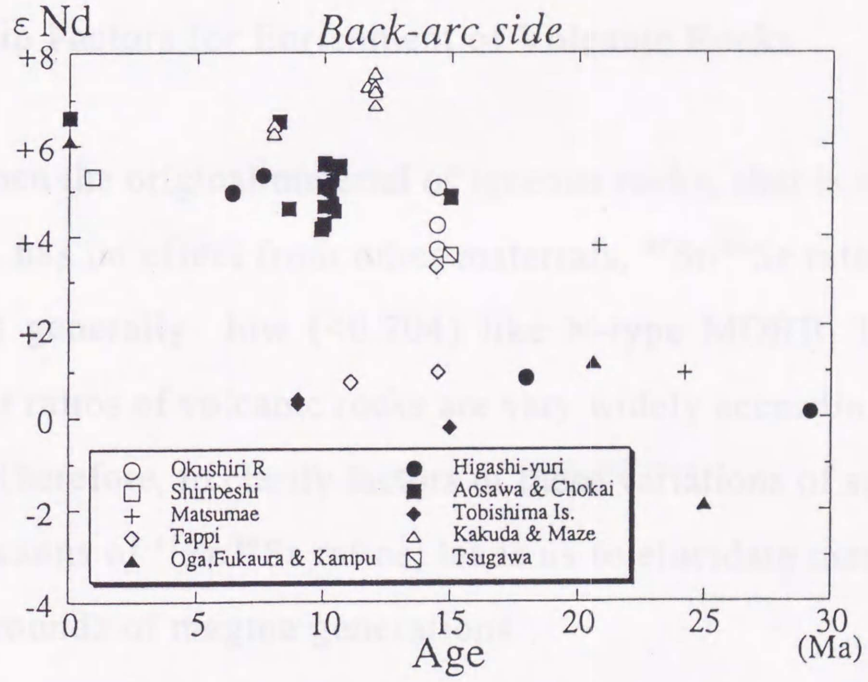

Fig. 11. Nd values vs. age for volcanic rocks (with SiO_2 contents lower than 60 wt%) from the back-arc side of the NE Japan arc (Ohki et al., 1994).

changing from undepleted area to depleted area of magma sources at around 15 Ma.

As seen in northeast Japan arc, it is important to notice this temporal changing of isotope data at around 15 Ma in central Japan. $^{87}Sr/^{86}Sr$ ratios vs. ages of volcanic rocks in studied area, central Japan are shown in Fig. 12 to 17. And temporal changing of ε Nd values in central Japan are shown in Fig. 18 to 21.

5.3 Main Factors for Enrichment of Volcanic Rocks

When the original material of igneous rocks, that is to say magma source, has no effect from other materials, $^{87}Sr/^{86}Sr$ ratios of igneous rock is generally low (<0.704) like N-type MORB. In Japan arc, $^{87}Sr/^{86}Sr$ ratios of volcanic rocks are vary widely according to time and space. Therefore, to clarify factors of these variations of spatiotemporal distributions of $^{87}Sr/^{86}Sr$ ratios, leads us to elucidate mechanisms and back grounds of magma generations.

Considerable main factors that vary $^{87}Sr/^{86}Sr$ ratios, except for alteration and weathering on or near the surface, are:

① crustal contamination

② sea water effect

③ heterogeneity of original magmas.

(1) Crustal contaminations

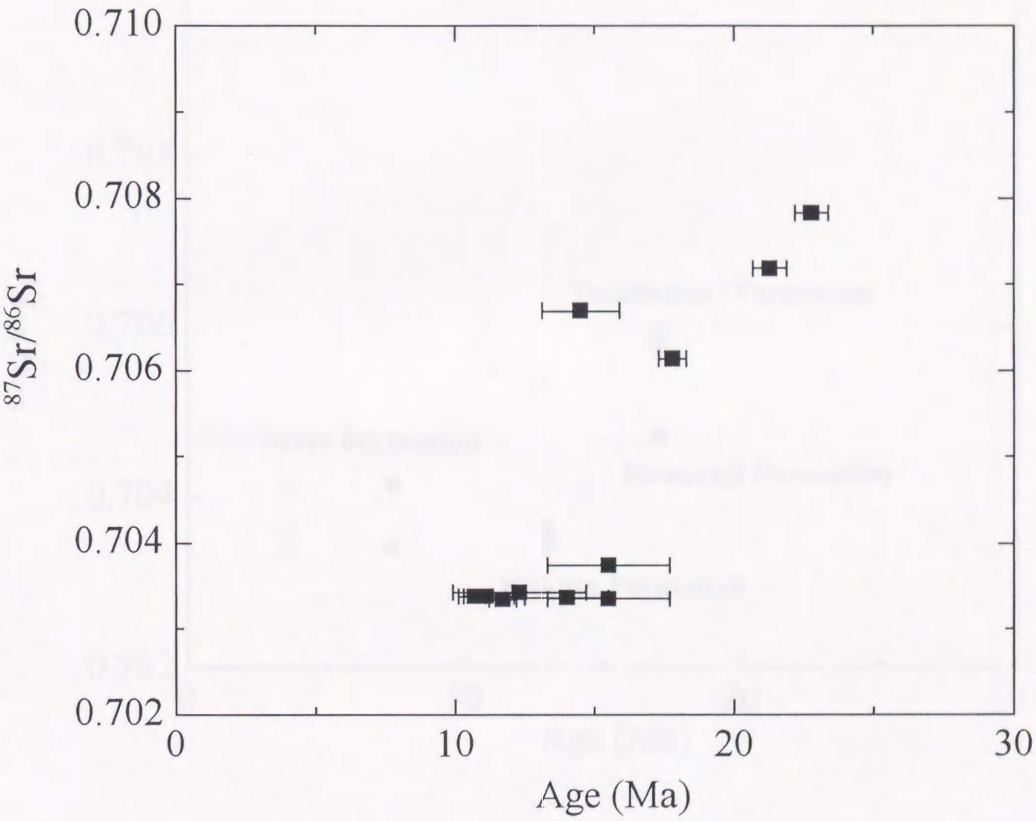

Fig. 12. $^{87}Sr/^{86}Sr$ ratios vs. ages of Tertiary volcanic rocks from the Sado Island.

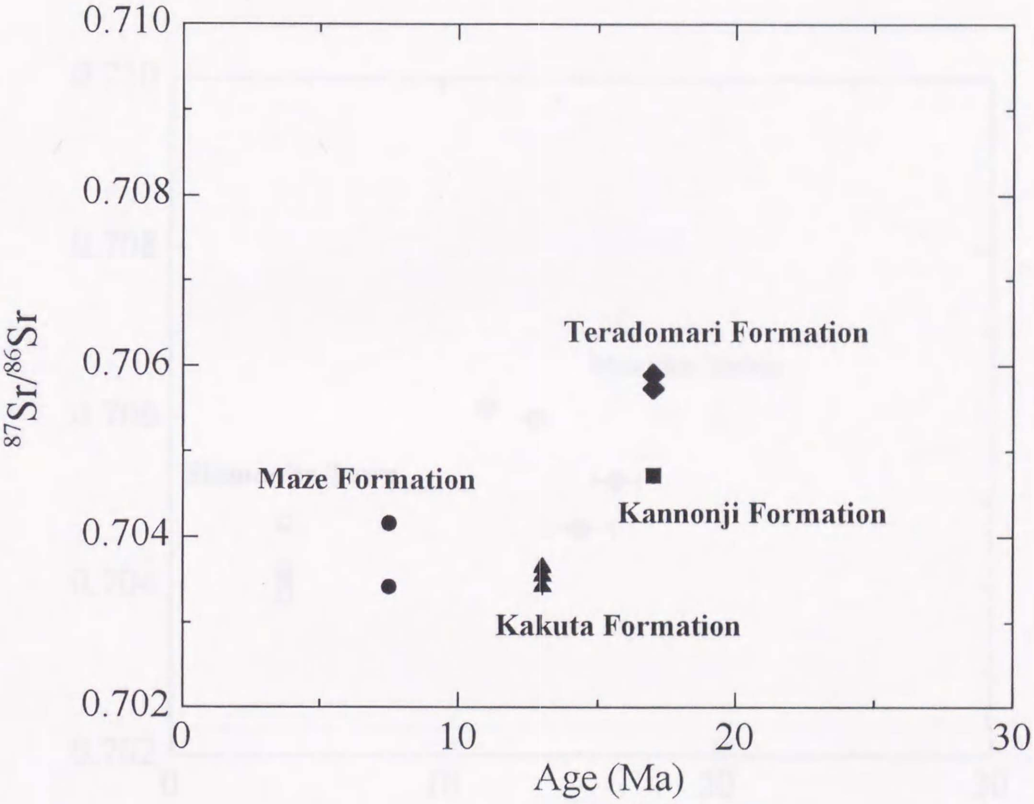

Fig. 13. $^{87}Sr/^{86}Sr$ ratios vs. ages of Tertiary volcanic rocks from Mt. Yahiko.

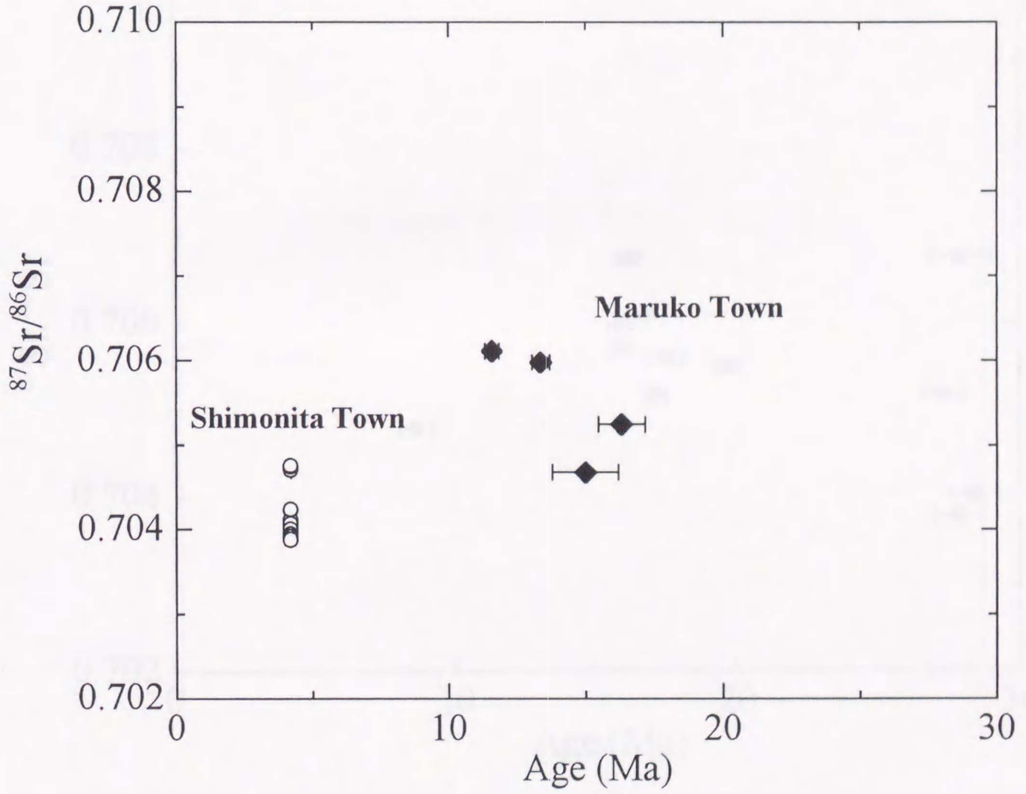

Fig. 14. $^{87}Sr/^{86}Sr$ ratios vs. ages of Tertiary volcanic rocks from Shimonita Town and Maruko Town .

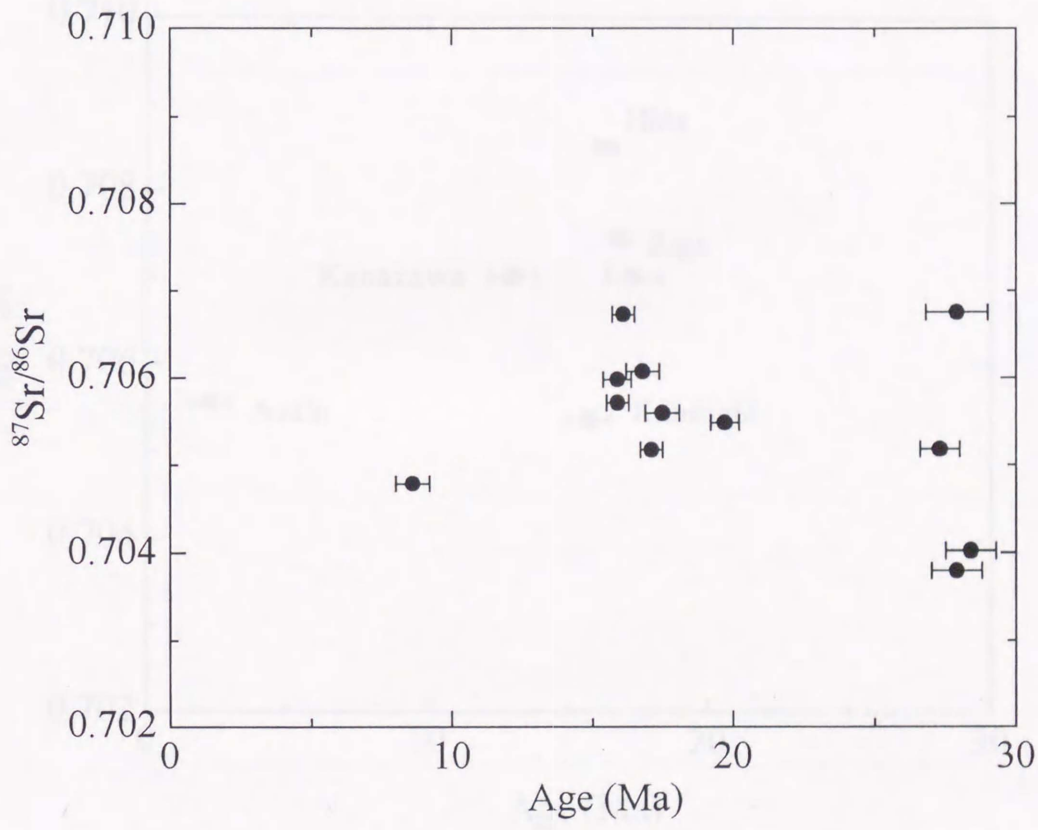

Fig. 15. $^{87}Sr/^{86}Sr$ *ratios vs. ages of Tertiary volcanic rocks from Noto Peninsula.*

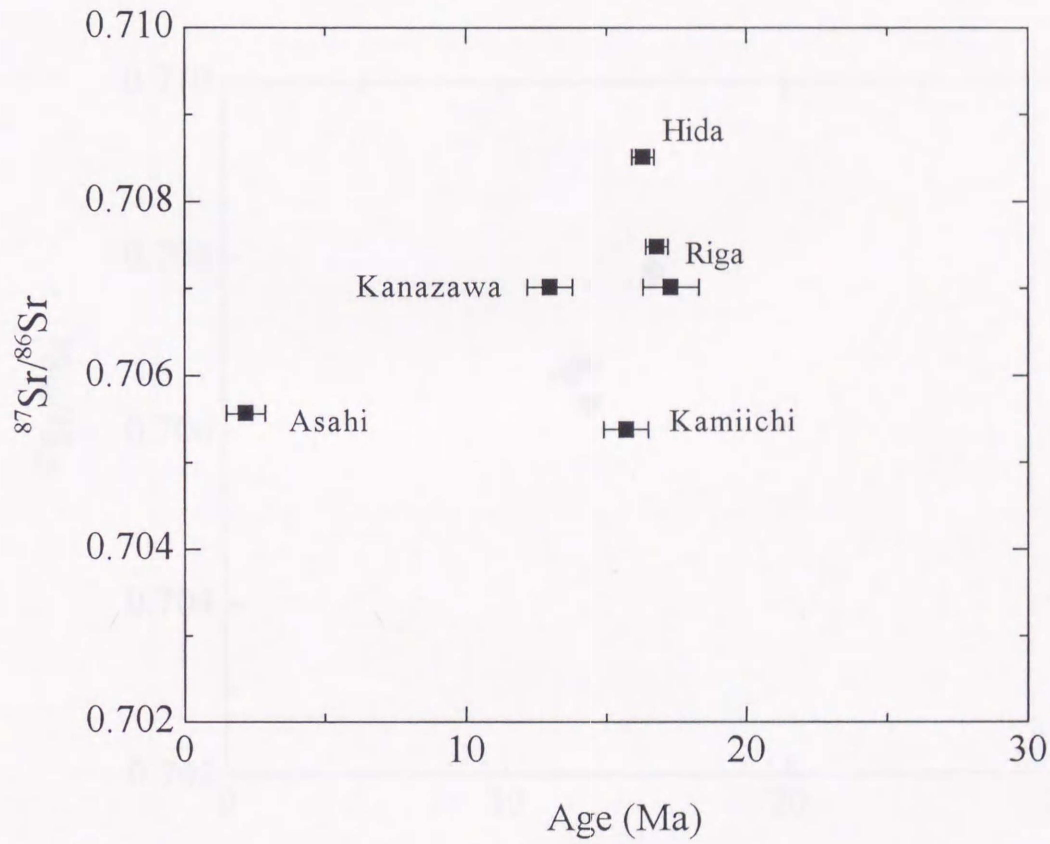

Fig. 16. $^{87}Sr/^{86}Sr$ *ratios vs. ages of Tertiary volcanic rocks from Asahi Town, Kamiichi Town, Riga Village, Hida areaea and Kanazawa City.*

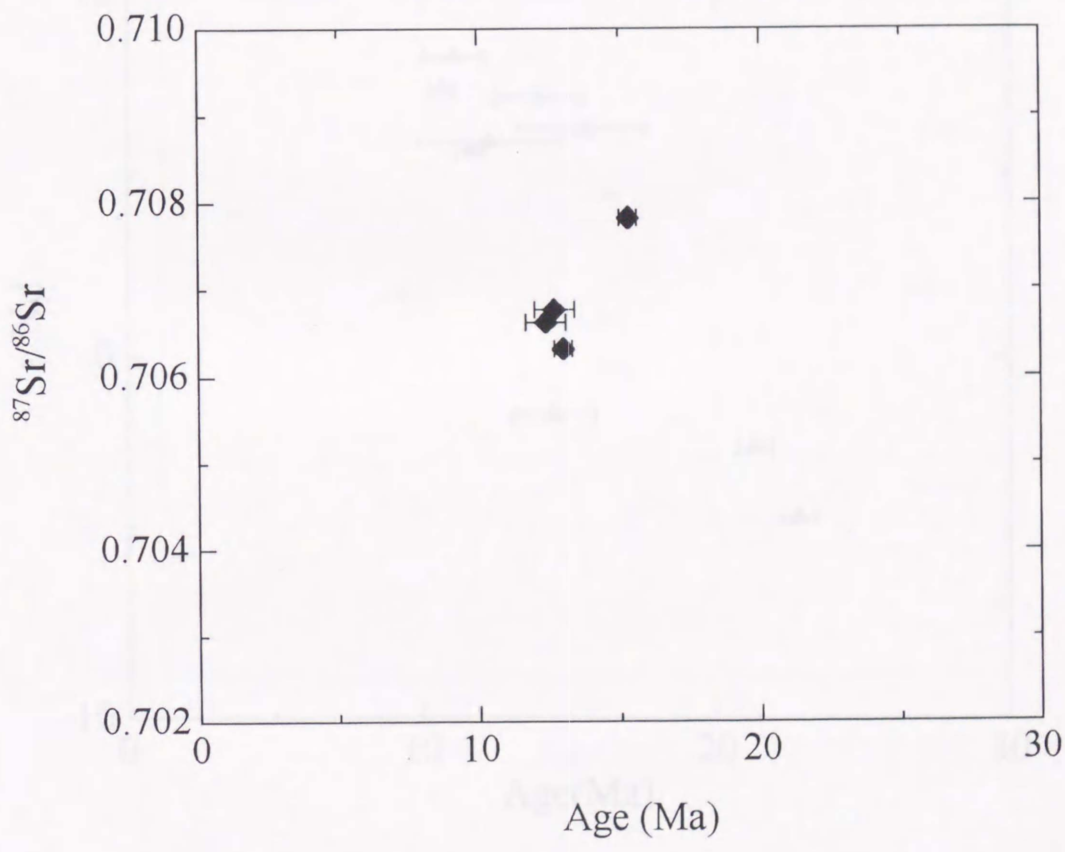

Fig. 17. $^{87}Sr/^{86}Sr$ ratios vs. ages of Tertiary volcanic rocks from Echizen coast.

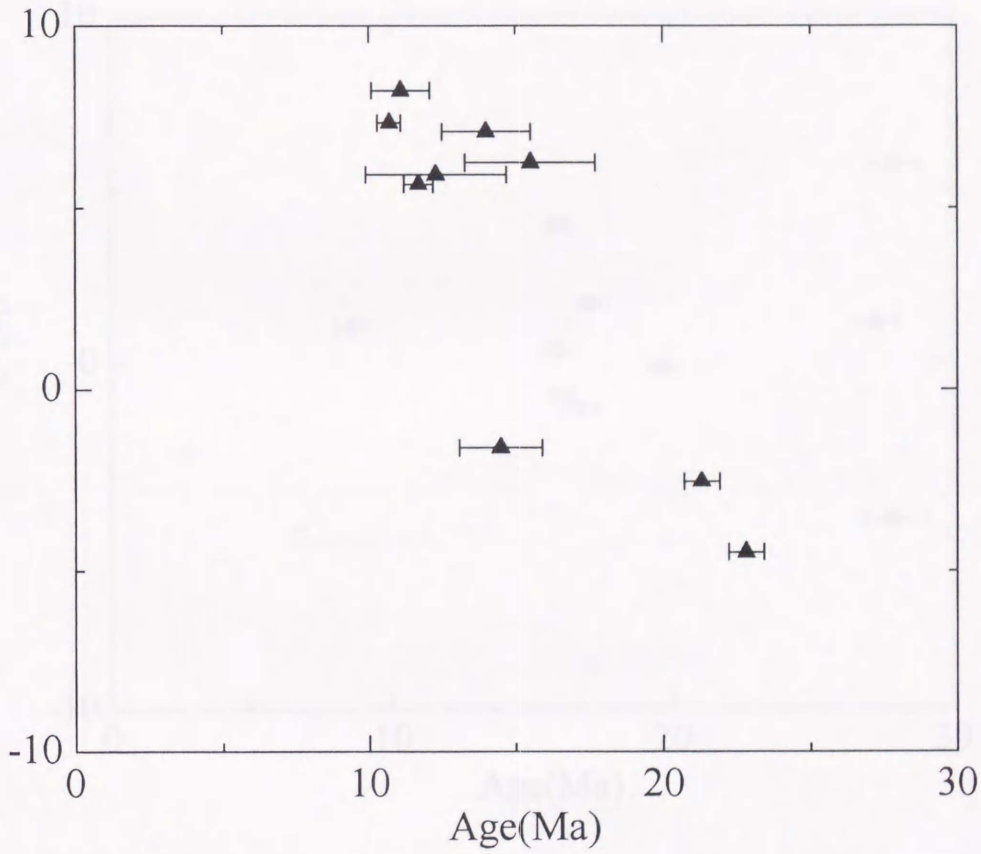

Fig. 18. ε Nd values vs. ages of Tertiary volcanic rocks from the Sado Island.

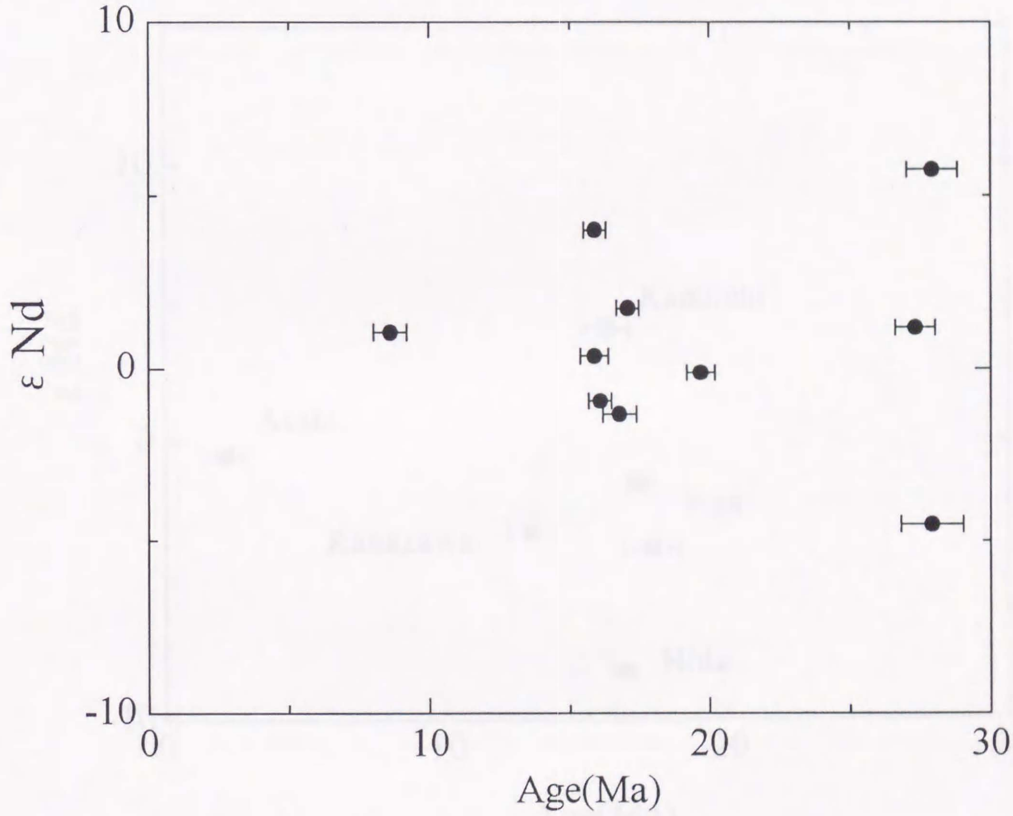

Fig. 19. ε Nd values vs. ages of Tertiary volcanic rocks from Noto Peninsula.

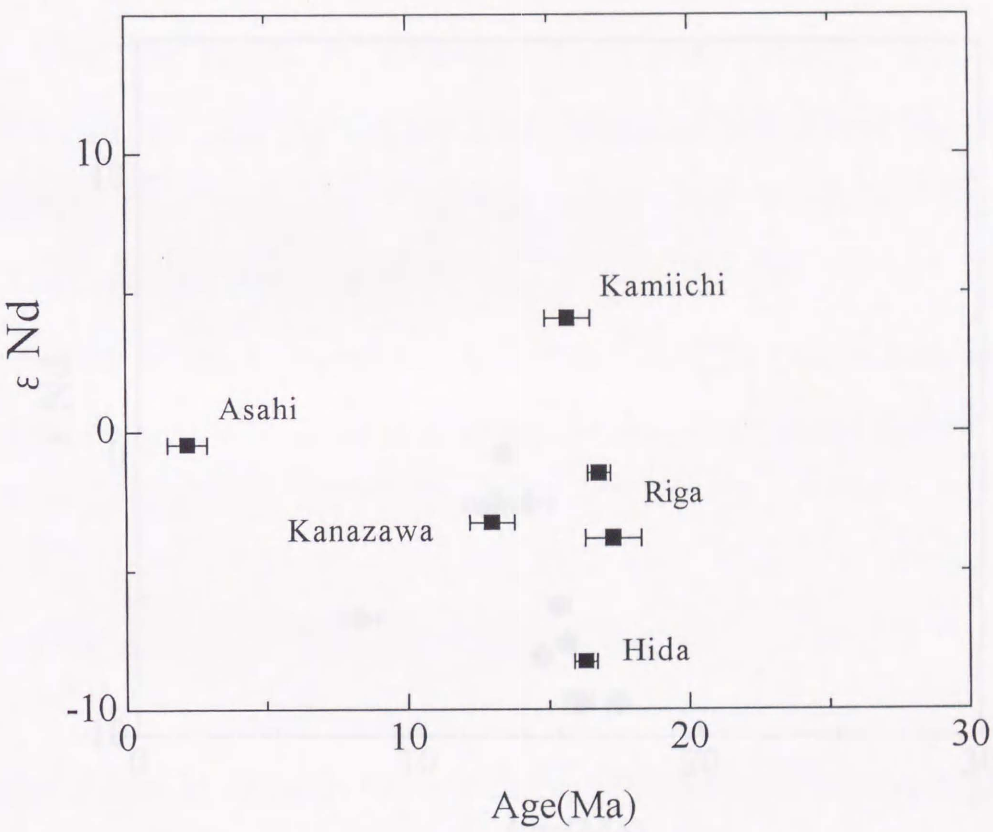

Fig. 20. ε Nd values vs. ages of Tertiary volcanic rocks from Asahi Town, Kamiichi Town, Riga Village, Hida area and Kanazawa City.

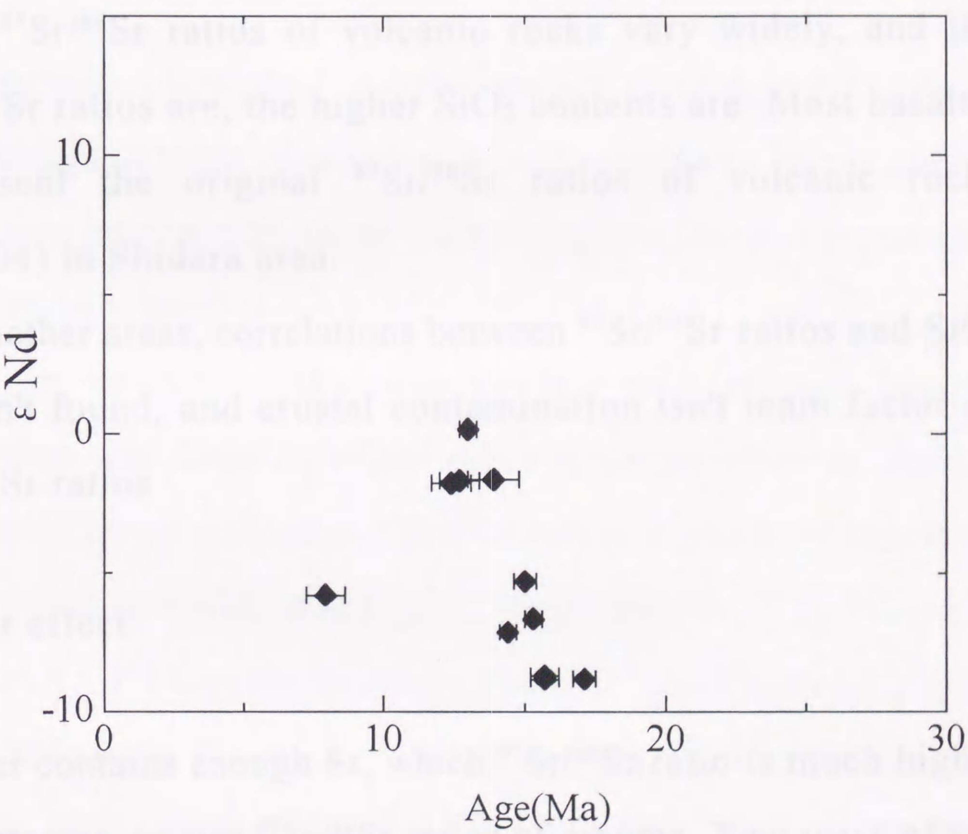

Fig. 21. ε Nd values vs. ages of Tertiary volcanic rocks from Echizen coast.

Crustal contamination is, that magma melts upper or lower crust having high $^{87}Sr/^{86}Sr$ ratios, and assimilate. This will be revealed, if compositions of crustal materials are well known.

Only in Shidara area, it is clear that crustal contamination rose $^{87}Sr/^{86}Sr$ ratios of volcanic rocks. Tertiary volcanic rocks are distributed within basement, Ryoke metamorphic rocks, which is widely distributed. $^{87}Sr/^{86}Sr$ ratios of volcanic rocks vary widely, and the higher $^{87}Sr/^{86}Sr$ ratios are, the higher SiO_2 contents are. Most basaltic rocks represent the original $^{87}Sr/^{86}Sr$ ratios of volcanic rocks (0.703 − 0.704) in Shidara area.

In the another areas, correlations between $^{87}Sr/^{86}Sr$ ratios and SiO_2 contents aren't found, and crustal contamination isn't main factor of rising $^{87}Sr/^{86}Sr$ ratios.

(2) Sea water effect

Sea water contains enough Sr, which $^{87}Sr/^{86}Sr$ ratio is much higher than that of magma, to rise $^{87}Sr/^{86}Sr$ ratios of magma. Two ways of sea water effects are possible. One is that magma or lava are effected by sea water directly on or near the surface. The other is that water originated sea water from subducted slab rises, and effect materials of magma in the wedge mantle. This process is easily found, for sea water contains little Nd, and ε Nd value is little effected by sea water. So in ε Sr- ε Nd diagram, when volcanic rocks are effected by sea water, they distribute horizontally from mantle array toward right like volcanic rocks from Mariana arc in Fig. 8.

As in Fig. 9, however, no series is horizontal, and sea water effect was not or little if it was.

(3) Heterogeneity of original magma

Heterogeneity of original magma are not so easy to be revealed, because original materials of magma are not possible to be got directly. However, their information is indirectly acquired from ultramafic or mafic xenolis or xenocryst.

Except for volcanic rocks from Shidara area, relation between $^{87}Sr/^{86}Sr$ ratios and SiO_2 contents are not found. But to evaluate heterogeneity of original magma, $^{87}Sr/^{86}Sr$ ratios vs. ages of basalt and basaltic andesite are replotted in Fig. 22. Open dots are $^{87}Sr/^{86}Sr$ ratios from eastern side of Itoigawa-Shizuoka Tectonic Line (Sado Island, Mt. Yahiko and Shimonita Town), and closed dots are $^{87}Sr/^{86}Sr$ ratios from western side of Itoigawa-Shizuoka Tectonic Line (Hida area, Riga Village, Kanazawa City, Kamiichi Town, Asahi Town and Echizen coast). $^{87}Sr/^{86}Sr$ ratios of the former group are almost low (0.703－0.704, depleted ratio) after ca. 15 Ma and almost high (>0.705, enriched ratio) before ca. 15 Ma. Hence, $^{87}Sr/^{86}Sr$ of the latter group are alwas high (>0.705, enriched ratio). This is the same tendancy as with acid to intermidiate rocks, and this leads that spatiotemporal tendancy of $^{87}Sr/^{86}Sr$ ratios almost shows that of their original materials. Before ca. 15Ma, it is clear that in both area eastern and western sides of Itoigawa-Shizuoka Tectonic Line, original materials of volcanic rocks were undepleted rather enriched one (>0.705) in the back-arc side of central Japan. And indeed, only in eastern side of Itoigawa-Shizuoka Tectonic Line, original materials changed to be depleted one (<0.704).

5.4 Relation Between Temporal Changing of Volcanic Rocks and Opening of the Japan Sea

(1) Spatiotemporal distributions of Isotope Data in Japan

Heterogeneity of oringinal materials depending on time and space made distributions of $^{87}Sr/^{86}Sr$ ratios widely vary. Original materials of volcanic rocks were undepleted rather enriched one (>0.705) in both area eastern and western sides of Itoigawa-Shizuoka Tectonic Line in central Japan before ca. 15Ma, and only in eastern side, original materials changed to be depleted one (<0.704). Temporal variations of $^{87}Sr/^{86}Sr$ ratio of Tertiary volcanic rocks from northeast Japan were reported (Kurasawa and Konda, 1986; Nohda *et al.*, 1988; Shimazu *et al.*, 1993; Shuto *et al.*, 1993; Ujike and Tsuchiya, 1993; Ohki *et al.*, 1994).

The areas of eastern side of Itoigawa-Shizuoka Tectonic Line is next to northeast Japan, and spatiotemporal distributions of $^{87}Sr/^{86}Sr$

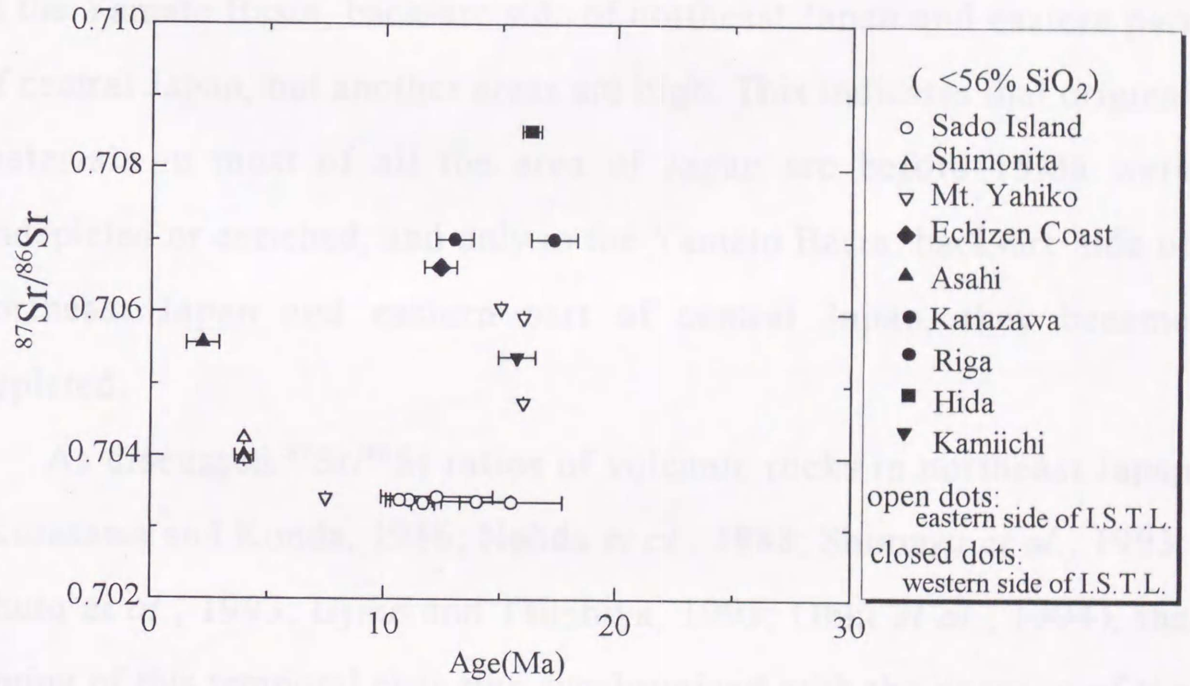

Fig. 22. $^{87}Sr/^{86}Sr$ ratios vs. ages of Tertiary basalt and basaltic andesite (<56 SiO_2wt%).

ratios are same. Almost all the data of $^{87}Sr/^{86}Sr$ ratios of Tertiary volcanic rocks of Japan and the Japan Sea, are plotted in Fig. 23 and 24. The former is $^{87}Sr/^{86}Sr$ ratios before 15 Ma and the latter is after 15 Ma of Tertiary volcanic rocks. They are divided into two groups; depleted group (<0.704) are red dots, clearly undepleted to enriched group (>0.705) are blue dots. Before 15 Ma (Fig. 23), all the volcanic rocks shows high ratios. And after 15Ma (Fig. 24), ratios are low only in the Yamato Basin, back-arc side of northeast Japan and eastern part of central Japan, but another areas are high. This indicates that original materials in most of all the area of Japan arc before 15Ma were undepleted or enriched, and only in the Yamato Basin, back-arc side of northeast Japan and eastern part of central Japan, they became depleted.

As discussed $^{87}Sr/^{86}Sr$ ratios of volcanic rocks in northeast Japan (Kurasawa and Konda, 1986; Nohda *et al.*, 1988; Shimazu *et al.*, 1993; Shuto *et al.*, 1993; Ujike and Tsuchiya, 1993; Ohki *et al.*, 1994), the timing of this temporal changing synchronized with the opening of the Japan Sea. Thus it is sure that changing of magma source to depleted one was caused by same mechanism of the opening of the Japan Sea.

(2) Mechanism of Generation of Magma

Fig. 25 shows distribution of $^{87}Sr/^{86}Sr$ ratios of Quaternary volcanic rocks as in the same way. Low areas are back-arc side of northeast

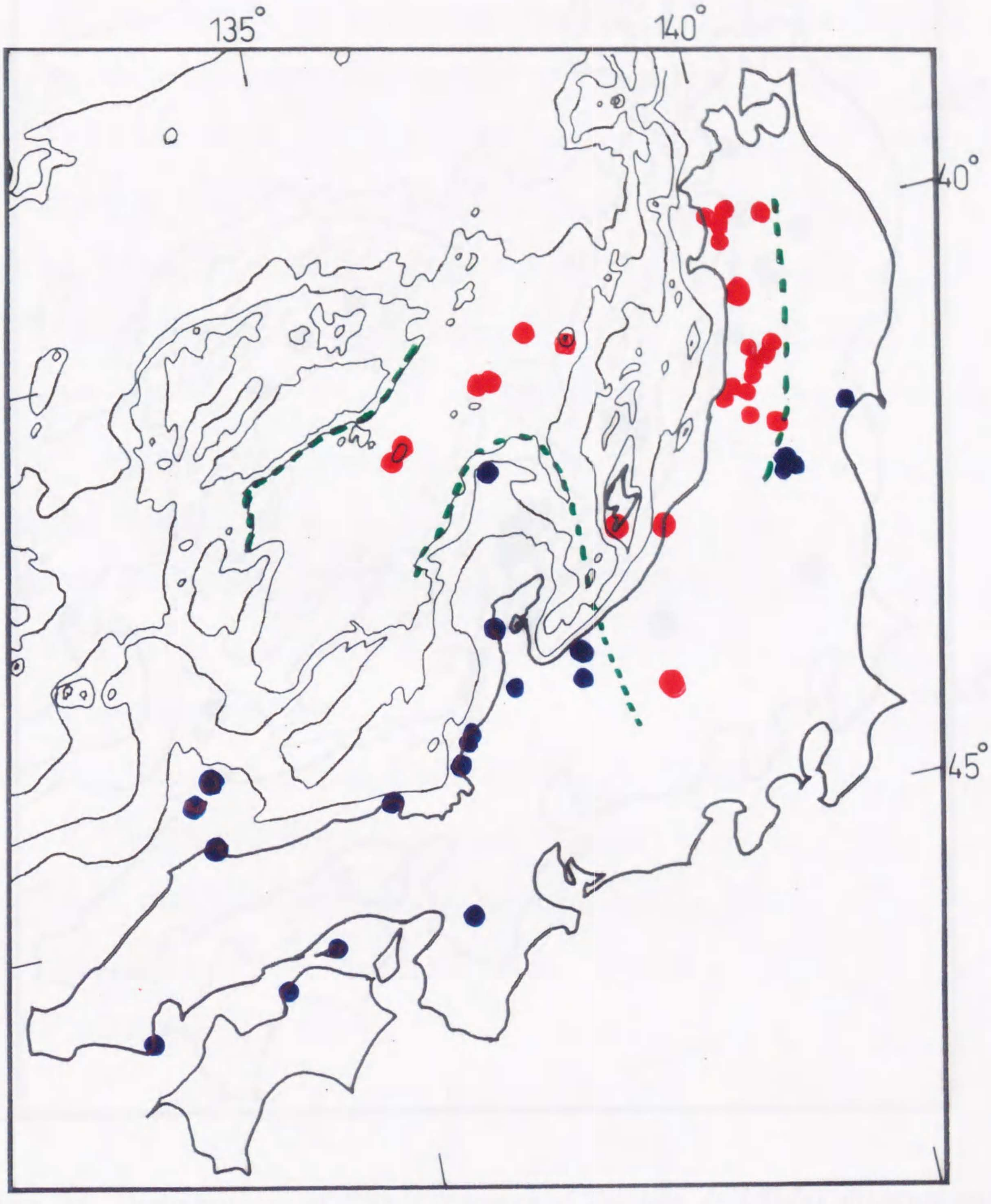

Fig. 22. Distributions of $^{87}Sr/^{86}Sr$ ratios of Tertiary (>15Ma) volcanic rocks of Japan and the Japan Sea. Blue dots represent high $^{87}Sr/^{86}Sr$ ratios, and red dots represent low $^{87}Sr/^{86}Sr$ ratios. ata for volcanic rocks of southwestern and northeastern Japan are taken from Fujimaki et al. (1991), Ujike and Tsuchiya (1993) and Tatsumi et al. (1988). Data of the Japan Sea are taken from Kaneoka (1990).

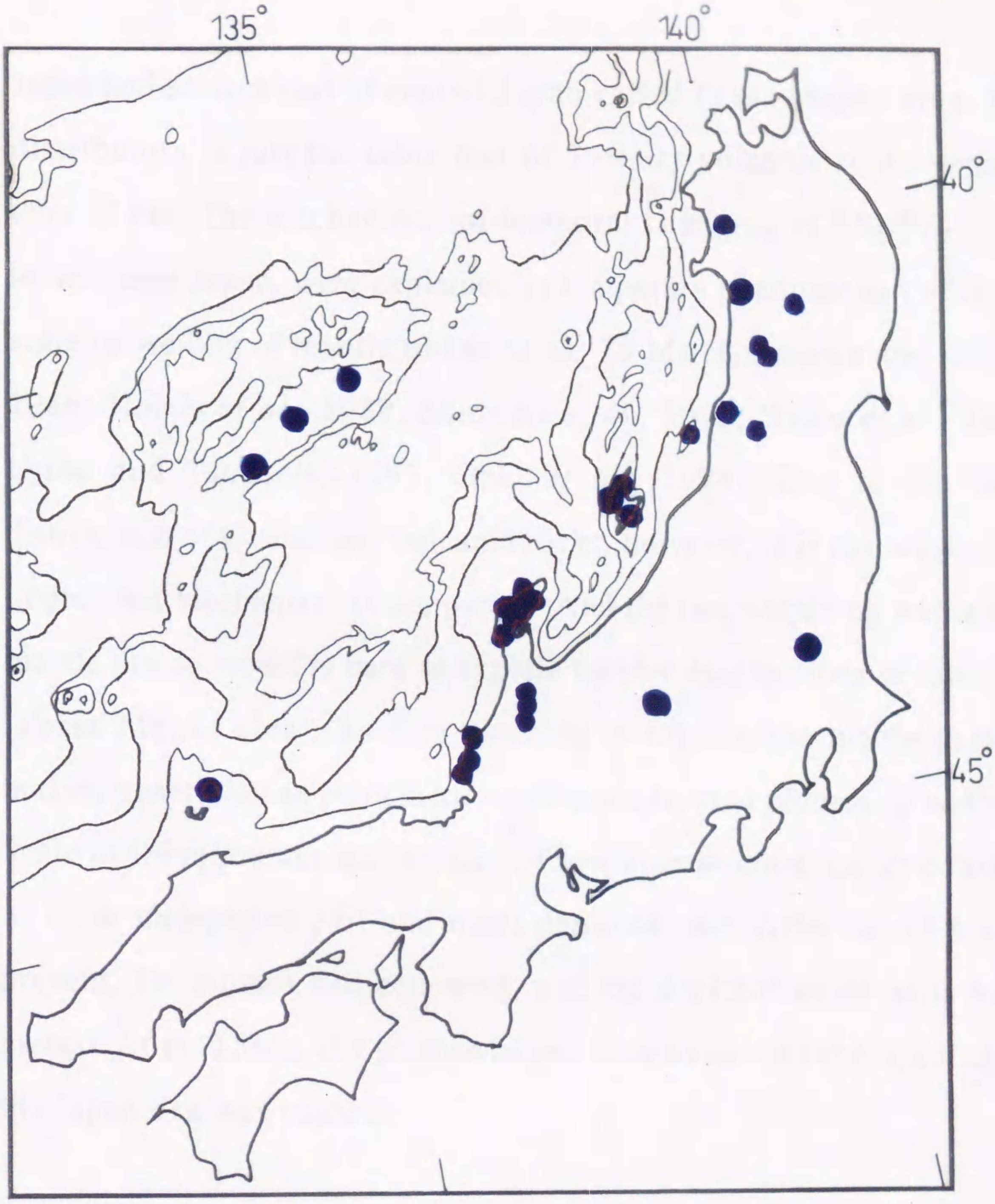

Fig. 23. Distributions of $^{87}Sr/^{86}Sr$ ratios of Tertiary (<15Ma) volcanic rocks of Japan and the Japan Sea. Blue dots represent high $^{87}Sr/^{86}Sr$ ratios, and red dots represent low $^{87}Sr/^{86}Sr$ ratios. Data for volcanic rocks of southwestern and northeastern Japan are taken from Morris and Kagami (1989), Kagami and Genbudo Research Group (1990), Ishizaka and Carlson (1983), Fujimaki et al. (1991), Ujike and Tsuchiya (1993) and Tatsumi et al. (1988). Data of the Japan Sea are taken from Kaneoka (1990).

Japan and eastern part of central Japan called Fossa Magna area. This distribution is just the same that of Tertiary volcanic rocks younger than 15 Ma. The mechanisms of temporal changing of $^{87}Sr/^{86}Sr$ ratios in northeast Japan, were explained as temporary phenomenon of large-scale up welling of mantle plume at ca. 15 Ma (Kurasawa and Konda, 1986; Nohda *et al.*, 1988; Shimazu *et al.*, 1993; Shuto *et al.*, 1993; Ujike and Tsuchiya, 1993; Ohki *et al.*, 1994). Due to the same distribution of Quaternary volcanic rocks, however, it is not reasonable to deal this mechanism as temporary. And the large-scale up welling of mantle plume model is hard to explain narrow distributions of low area (Fossa Magna area). So it is possible to explain the mechanism of magma generation as permanent small-scale layered plumes up welling. Scale of these plumes are the size of low area at most. Layer consists of outer undepleted part and inner depleted part. After ca. 15 Ma to present, the plumes had activated, and the depleted inner parts have melted. At ca. 15Ma, the plumes began to activate and the opening of the Japan Sea was caused.

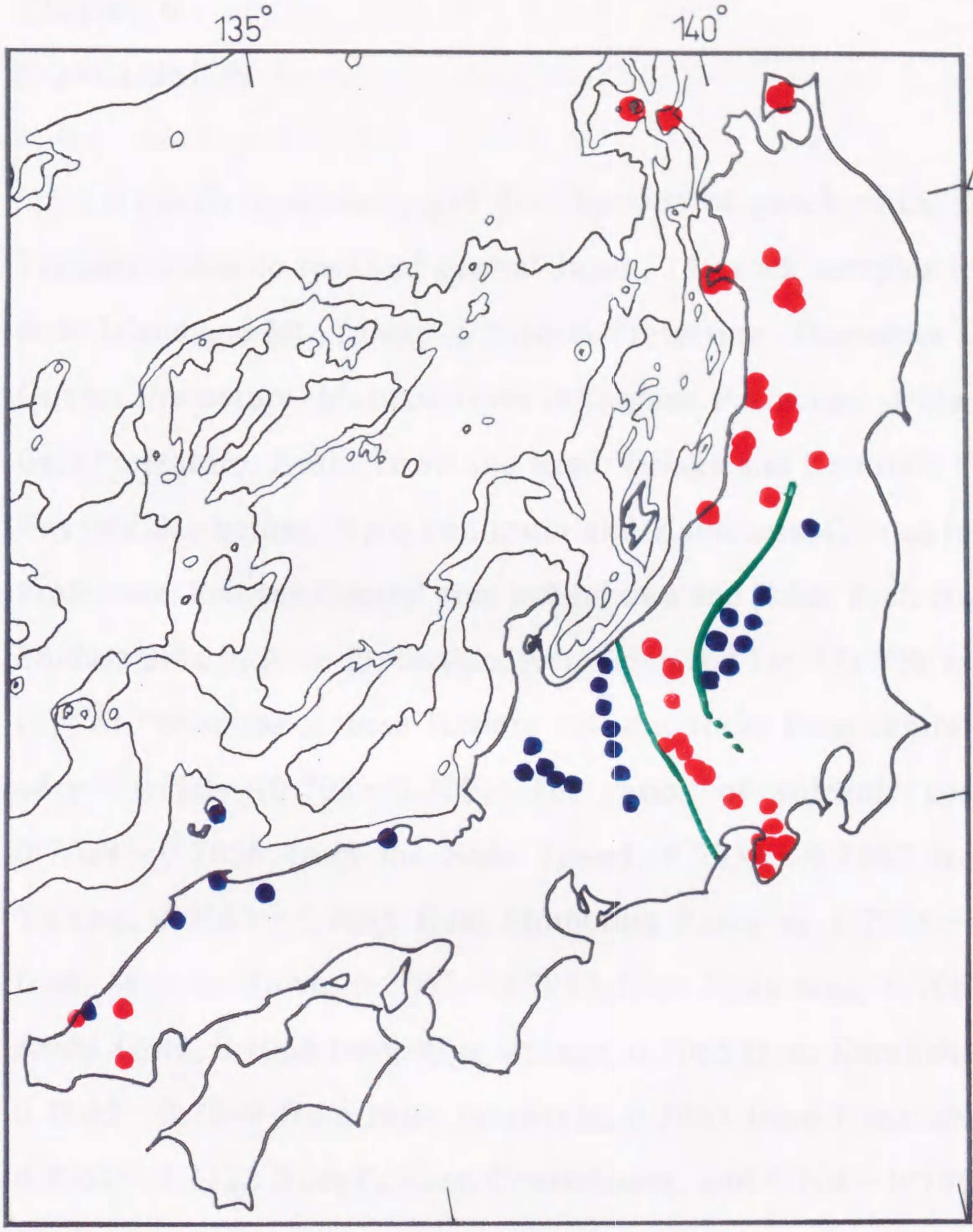

Fig. 24. Distributions of $^{87}Sr/^{86}Sr$ ratios of Quaternary volcanic rocks of Japan. Blue dots represent high $^{87}Sr/^{86}Sr$ ratios, and red dots represent low $^{87}Sr/^{86}Sr$ ratios. Data for Quaternary volcanic rocks are taken from Kurasawa (1978), Notsu (1983), Kaneko (1995).

Chapter 6

CONCLUSION

To clarify spatiotemporal distributions of geochemical data for Tertiary volcanic rocks of central Japan, 146 rock samples from the Sado Island and Mt. Yahiko in Niigata Prefecture, Shimonita Town in Gunma Prefecture, Maruko Town in Nagano Prefecture, Hida area in Gifu Prefecture, Asahi Town and Riga Village and Kamiichi Town in Toyama Prefecture, Noto Peninsula and Kanazawa City in Ishikawa Prefecture, Echizen Coastal area in Ishikawa and Fukui Prefecture, and Shidara area in Aich Prefecture, were analyzed for $^{87}Sr/^{86}Sr$ ratios.

(1) $^{87}Sr/^{86}Sr$ ratios of these Tertiary volcanic rocks from central Japan, vary widely (0.703－0.712). The ratios of volcanic rocks are 0.7034－0.7056 from the Sado Island, 0.7034－0.7067 from Mt. Yahiko, 0.7033－0.7045 from Shimonita Town in, 0.7056－0.7076 from Maruko Town, 0.7067－0.7087 from Hida area, 0.7067 from Asahi Town, 0.7056 from Riga Village, 0.7065 from Kamiichi Town, 0.7045－0.7089 from Noto Peninsula, 0.7067 from Kanazawa City, 0.7067－0.7122 from Echizen Coastal area, and 0.704－0.7053 from Shidara area.

(2) From the point of view of existence of low $^{87}Sr/^{86}Sr$ ratio (<0.704), which represents depleted, Tertiary volcanic rocks from central Japan divide into two groups. In the Sado Island, Shimonita Town and Mt. Yahiko, $^{87}Sr/^{86}Sr$ ratios of Tertiary volcanic rocks ranges both high

(>0.705) and low (<0.704).

(3) In contrast, the ratios of Toyama, Gifu (north part) and Ishikawa Prefecture range only high.

(4) Itoigawa-Shizuoka Tectonic Line (I. S. T. L.) seems to be a boundary for these two groups.

(5) In eastern side of I. S. T. L., $^{87}Sr/^{86}Sr$ ratios of Tertiary volcanic rocks were high (>0.705) before 15Ma, and changed to low ratios (<0.704) at 15 Ma.

(6) In western side of I. S. T. L., $^{87}Sr/^{86}Sr$ ratios were high (>0.705) before and remained high after 15 Ma.

(7) $^{144}Nd/^{143}Nd$ ratios shows inverse relation to $^{87}Sr/^{86}Sr$ ratios in each area.

(8) The timing of this temporal changing synchronized with the opening of the Japan Sea. Thus it is sure that changing of magma source to depleted one was caused by same mechanism of the opening of the Japan Sea.

(9) Low $^{87}Sr/^{86}Sr$ ratios (after 15 Ma) distributed only in the Yamato Basin, back-arc side of northeast Japan and eastern part of central Japan (Fossa Magna area).

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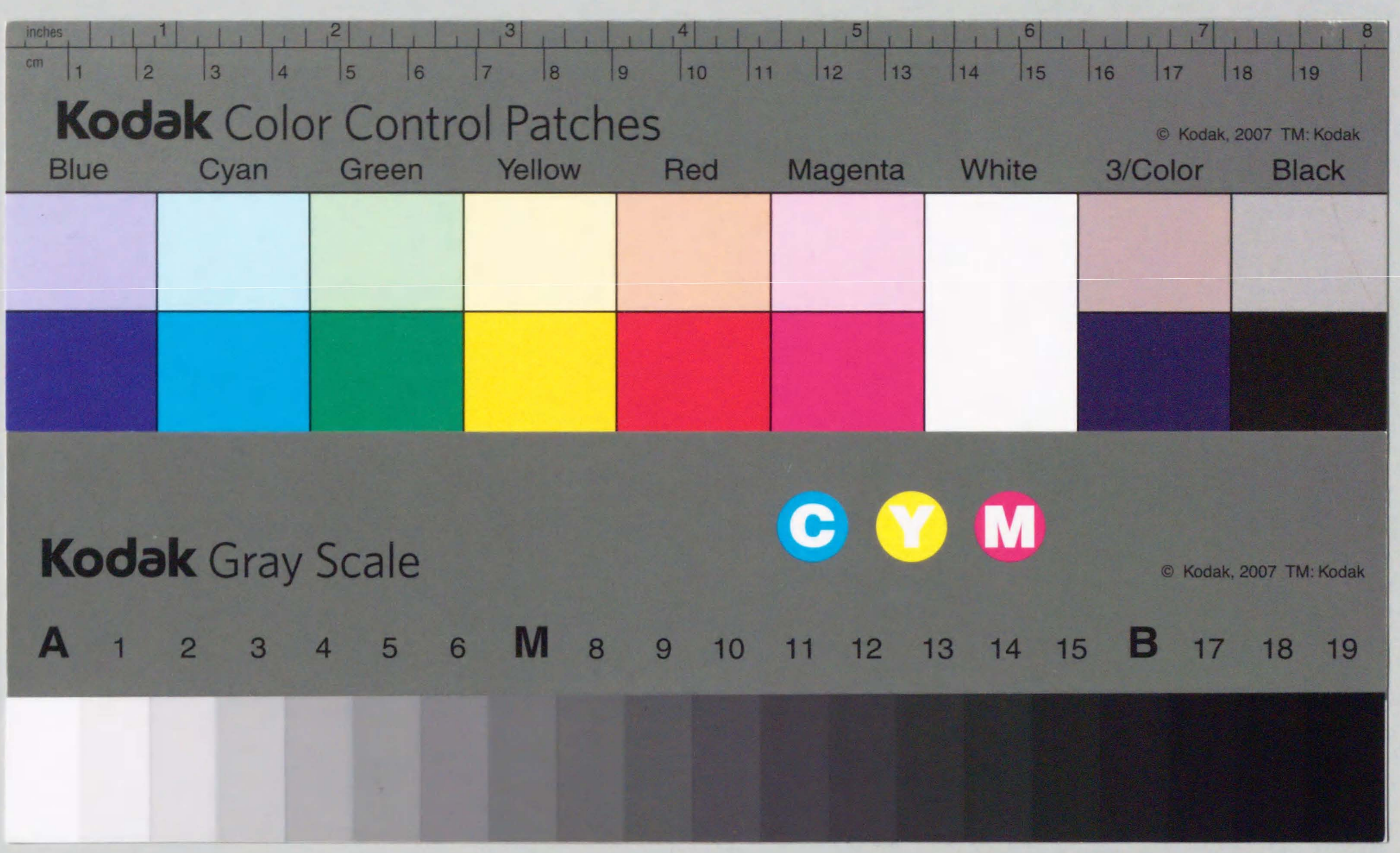
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