Petrogenesis of Plutonic Rocks in the Ryukyu Arc, Japan

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Abstract

The Cretaceous to Neogene plutonic rocks are distributed over the eight islands of the Ryukyu Arc, namely Amami-O-shima, Kakeroma-jima, Uke-jima, Tokuno-shima, Okinoerabu-jima, Okinawa-jima, Tonaki-jima, and Ishigaki-jima. These plutonic rocks can be categorized based on their petrological characteristics and active periods into four groups: early Cretaceous (EC), late Cretaceous (LC), Poleogene (PG), and Neogene (NG). The initial Sr isotopic ratio of the PG and NG groups increased, whereas the initial Nd isotopic ratio decreased with increasing aluminum saturation index (ASI), thereby indicating the influence of the upper crustal material. The LC group also exhibits a high initial Sr isotopic ratio, a low initial Nd isotopic ratio, and high ASI, presuming that the source magma reacted with the upper portion of the crustal material. Such reactions with the upper crustal material were observed to have occurred three times between Cretaceous and Neogene, and these events may have been caused by changes in the tectonics of the Ryukyu Arc.

Introduction

The Ryukyu Arc is an arcuate archipelago extending from the Amami Islands to the Sakishima Islands and is a new island arc that was formed in the early Pliocene owing to the expansion of its back-arc basin, the Okinawa Trough (Miki et al., 1990). This arc comprises a wide distribution of plutonic rocks that were active between the Cretaceous and Miocene periods, which predate the expansion of the Okinawa Trough. The eight islands in the Arc of exposed plutonic bodies are Amami-O-shima, Kakeroma-jima, Uke-jima, Tokuno-shima, Okinoerabu-jima, Okinawa-jima, Tonaki-jima, and Ishigaki-jima from north to south (Fig. 1). Among these plutonic rocks, petrochemical studies have been conducted on the Amami plutonic rocks (distributed across Amami-O-shima, Kakeroma-jima, and Uke-jima), Tokuno-shima plutonic rocks, Nagahama Diorites (Okinawa-jima), Nishinomori Diorites (Tonaki-jima), and Omoto Pluton (Ishigaki-jima) (Kawano and Kato, 1989, 1990; Kawano, 1997; Kawano et al., 1997; Kawano, 2013). In addition, an overview of the plutonic rocks in Okinoerabu-jima has been reported by Kato et al. (1992) and Kawano (2007). The Sr isotopic composition of the aforementioned plutonic rocks has been reported by Kawano and Kagami (1993), Kawano et al. (1997), Kawano (2007), and Kawano (2013). However, a comprehensive study that takes into account the Nd isotopic composition has not, before now, had yet been conducted.

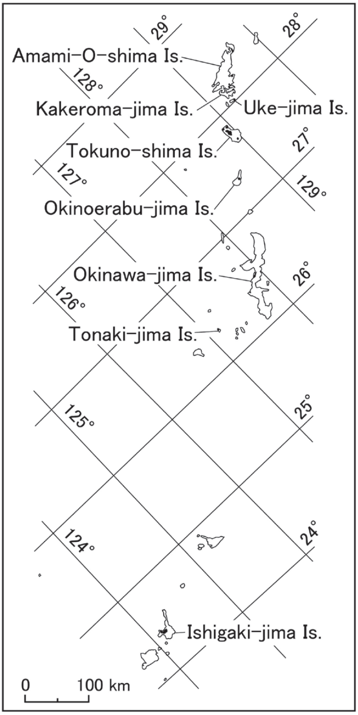


Fig.1 Location of the islands wherein the plutonic rocks are distributed within the Ryukyu Arc
Is stands for "island"

This study adds the newly obtained chemical and Nd isotopic compositions of the whole rock to previous geochemical studies on the plutonic rocks from the Ryukyu Arc and discusses the origin of these rocks.

1. Outline of the plutonic rocks

1.1 The Amami plutonic rocks

The pre-Tertiary system of the three islands, including the Amami Islands in northern Ryukyu, Amami-O-shima, Kakeroma-jima, and Uke-jima, comprises six plutons intruding from the northeast to the southwest in Kasari, Ichi, Kachiura, Koniya, Ankyaba, and Uke; these are collectively called the Amami plutonic rocks (Kawano et al., 1997). The Kasari body intrudes into the Naze Formation concordantly and partially discordantly from Akagina to Myojinzaki in Kasari-cho, Amami City, and it contains enclaves and xenoliths originating from the basement rocks. The Ichi body intrudes concordantly and partially discordantly into the Naze Formation, primarily in Ichi village in Sumiyo-cho, Amami City, and it contains a roof pendant. Similar to the Kasari body, the Ichi body contains xenoliths and enclaves. The Kachiura body intrudes into the Naze Formation with contact metamorphism in the eastern region of Kachiura village in Oshima-gun, and it is characterized by a significant proportion of enclaves. The Koniya body intrudes discordantly into the Odana Formation between Jizotoge and Koniya in Setouchi-cho and has miarolitic cavities. The remaining two rock bodies, the Ankyaba and the Uke, intrude discordantly into Naze Formation with a clear boundary near Ankyaba village in Kakeroma-jima, Setouchi-cho and the eastern edge of Uke-jima, respectively (Kawano et al., 1997).

The five rock bodies, namely, Kasari, Ichi, Kachiura, Koniya, and Ankyaba, are composed of granodiorite to adamellite, whereas the Uke body is composed of gabbro and adamellite. The Ichi body has a weak foliation structure, whereas the Kasari, Kachiura, and Koniya bodies exhibit graphic textures composed of quartz, and potassium feldspar, and have miarolitic cavities. The gabbro in the Uke body is intruded by adamellite (Kawano et al., 1997).

Shibata and Nozawa (1966) measured the K–Ar biotite ages for three rock bodies in the Amami plutonic rocks and reported the ages as 49 Ma for the Kasari body, 55 Ma for the Ichi body (in Shibata and Nozawa, 1966, reported as the Yanma body), and 54 and 56 Ma in the Koniya body. Further, Kawano et al. (1997) reported a K–Ar biotite age of 17.23 ± 0.22 Ma for the Kachiura body and a K–Ar amphibole age of 110.3 ± 1.2 Ma for the gabbro of Uke body. As stated above, the adamellite in the Uke body intrudes into gabbro, and the isochron age of two points between these rocks is 71.7 ± 9.7 Ma. Although further verification is clearly needed, for the purposes of this study, this value is used as the active age of the adamellite in the Uke body. Furthermore, isochron calculations between two points were attempted for other bodies that are yet to be aged; however, significant values could not be obtained.

1.2 The Tokuno-shima plutonic rocks

The Yonama, Kanemi, and Todoroki bodies with 15 small bodies of the Tokuno-shima plutonic rocks intruded into the Mesozoic in Tokuno-shima in Northern Ryukyu (Kawano and Kato, 1989). This study investigates the three rock bodies with large-scale surface exposure of Yonama, Kanemi, and Todoroki. The Yonama body extends from Yonama in Amagi-cho, Oshima-gun, across the Sakibarusaki Point to Tete; contact metamorphism is observed as it intrudes into the Yonama Formation. The Kanemi body extends from San, Amagi-cho to Kanemi and exhibits contact metamorphism with the Tete Formation, accompanied by sublithofacies that display fine grain in the southwest edge of the body. The Todoroki body has the largest exposed area of the Tokuno-shima plutonic rocks, extending wide from Matsubara, Amagi-cho, across Todoroki, Tokunoshima-cho, to Mikyo, Amagi-cho, and from Ketoku, Tokunoshima-cho, to Setaki, Amagi-cho; the body intrudes into the Tete and the Akirikamigawa formations resulting in contact metamorphism in both formations. Significant weathering is observed, and the body is characterized by a foliation structure composed of a sequence of biotite.

The rocks are composed primarily of granodiorite to adamellite. The Yonama and the Kanemi bodies contain biotite and amphibole as the main colored mineral; however, the Todoroki body lacks amphibole and only contains biotite. In addition, the colored-mineral content is high in the Todoroki body and low in the Yonama and Kanemi bodies.

Kawano and Ueda (1966) reported the K–Ar biotite age in the Todoroki body as 61 Ma, whereas Kawano and Kato (1989) dated the K–Ar biotite age in the Yonama body as 59.1 ± 3.0 Ma. Kawano and Kagami (1993) employed

Rb–Sr dating to obtain the whole-rock isochron age of 69.8 ± 8.0 Ma and 61.0 ± 6.7 Ma for the Yonama and Kanemi bodies, respectively, and the mineral (biotite) isochron age of 69.3 ± 2.6 Ma for the Todoroki body. This clearly dates the active period of magma for the Tokuno-shima plutonic rocks as far back as the end of the Cretaceous period.

1.3 The Okinoerabu body

In the middle Ryukyu region, the Koshiyama area at the center of Okinoerabu-jima contains a small body composed primarily of granodiorites that intrude into the Mesozoic Neori Formation in sills; the body is collectively called the Okinoerabu body (Kawano, 2007). The center of the body contains enclaves reaching a maximum length of 50 cm. Furthermore, although the relationships with this granodiorite are not clear, multiple porphyritic dykes have been observed (Nakagawa, 1967).

The rocks are coarse-to-medium-grained granodiorites that contain augite, biotite, and amphibole; however, weathering in the body is significant and only a portion of the body exhibits fresh outcrops.

This body was dated to 32.9 Ma radiometrically using the fission track zircon method (Daishi et al., 1986), and Kawano et al. (1999) determined a K–Ar biotite age of 17.2 Ma from fresh granodiorite, indicating the presence of multiple bodies in different active periods.

1.4 Nagahama Diorites

The lower reaches of the Nagahamagawa River in Yomitan village, Okinawa-jima, located in the middle Ryukyu region, have a distribution of dioritic hypabyssal-plutonic rocks known as the Nagahama Diorites (Kawano, 1997). The Nagahama Diorites intrude into the Nago Formation and are covered by the Quaternary Zakimi Conglomerate Formation and the Ryukyu Group. The body has little exposure along the Nagahamagawa river bed; however, weathering in this region is significant, and most rocks in the areas have been integrated. According to boring surveys conducted for a dam construction, the depth of the body increases as it extends northwestward.

The rocks are fine-to-medium-grained granodiorite to diorite and contain bronzite, hypersthene, and clinopyroxene as phenocrysts.

The Nagahama Diorites have been dated to 30.2 ± 4.7 Ma using the fission track zircon method (Daishi et al., 1986).

1.5 Nishinomori Diorites

Tonaki-jima, located approximately 50 km west of Okinawa-jima in the middle Ryukyu region, has plutonic bodies that intrude into the Paleozoic. Together with related igneous rocks, they are collectively called the Nishinomori Complex (Kato, 1985; Kawano, 2013). The Nishinomori Complex is mainly composed of dacitic tuff, porphyry, porphyrite, and diorite distributed in the northern area of the island and the aplitic porphyry located in the southwestern area of the island. Igneous activity is divided into three periods, namely, those corresponding to dacitic tuff, porphyry to diorite, and aplite (Kato, 1985). The dacitic tuff that was active in the first period has metamorphosed to quartz feldspathic hornfels that exhibit heterogeneity and weak layered structures; it is exposed on the northeastern coast across approximately 560 m. With regard to the second period porphyry to diorite activity, porphyry is distributed in the northern area of the island, where it intrudes as sheets or dykes; diorite caused contact metamorphism on the Paleozoic limestone in the northern part of the island. In the contact area, skarns were formed via metasomatism. The aplitic dyke from the third period of activity intrudes into the tuffaceous hornfels of the first period (Kato, 1985; Kawano, 2013).

The fine-to-medium-grained diorites active in the second period are composed of orthopyroxene, clinopyroxene, amphibolite, and biotite; however, the colored-mineral content differs.

The Nishinomori Diorites have a K–Ar biotite age of 19 Ma (Kawano et al., 1999), which closely matches that dated by Ueda et al. (1999), with both dates indicating an age corresponding to the Miocene.

1.6 The Omoto Pluton

The Omotodake region in the northwestern area of Ishigaki-jima, located in the southern Ryukyu region, has an 8 × 8 km^2 distribution of plutonic rocks from the north to south and the east to west and is known as the Omoto Pluton (Kawano and Kato, 1990). The Omoto Pluton is categorized into six rock types according to their lithofacies and chemical characteristics: Ishigaki, Naguragawa, Chayama, Otake, Miyaragawa, and Omoto; of these, four rock types, Ishigaki, Naguragawa, Chayama, and Otake originate from the

Chayama body, and the other two, namely, Miyaragawa and Omoto originate from the Omoto body (Kawano and Kagami, 1993). The Ishigaki type and Naguragawa type are distributed southward from Omotodake and westward of Otake in small scales, and the Chayama type is centered around Chayama, located southward from Omotodake; it exists as an arc-like body spanning approximately 3 km from the northeast to the southwest. The Otake type is distributed in the western edge of the Omoto Pluton, spanning approximately 3 km toward north and south; it has undergone contact metamorphism with the Nosoko Formation. The Omoto type, which forms the main body of the Omoto Pluton, is characterized by the presence of miarolitic cavities, and its distribution tends to be concentrated in the northeastern area of the Omoto type distribution. The Miyaragawa type is in contact with the Omoto type and is distributed on its eastern edge, extending 200 m wide and 3 km long. The rock type intrudes into the Tomuru Formation and is giving contact metamorphism to the formation.

The Ishigaki and Naguragawa types are composed of medium-grain granodiorite, whereas the Chayama type is composed of medium-to-coarse-grain diorite, quartz diorite, and granodiorite. The Otake type is composed primarily of fine adamellite accompanied by granite. The Omoto type is composed of adamellite–potassium feldspar granite containing pink potassium feldspar accompanied by granophyre. The Miyaragawa type rock is composed of coarse quartzdiorite and diorite, and similar to the Omoto type, it is characterized by the presence of miarolitic cavities.

The radiometric age of the Omoto Pluton has been obtained as 21 Ma (Kawano and Ueda, 1966) and 28.7–29.9 Ma using the K–Ar biotite method and fission track zircon method (Daishi et al., 1986), respectively. Furthermore, Kawano and Kagami (1993) reported Rb–Sr whole-rock isochron ages of 39.3 ± 2.0 Ma in the Omoto body and 40.7 ± 14.5 Ma in the Chayama body. Kawano and Ueda (1966) suggested the possibility of rejuvenation due to an alteration in the K–Ar age; therefore, it is interpreted that the magma activity period is in the late Eocene and an intrusion and cooling period is in the Oligocene (Kawano and Kagami, 1993).

2. Active period of the plutonic rocks

Fig.2 shows the active ages of the plutons in the Ryukyu Arc, categorized by

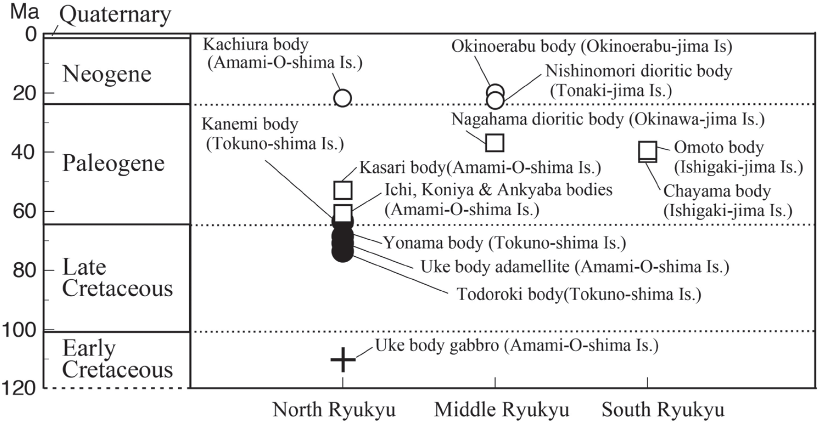


Fig.2 Plutonic rock bodies according to the active period
Age data were obtained from Shibata and Nozawa (1966), Kawano and Ueda (1966), Daishi et al. (1986), Kawano and Kato (1989), Kawano and Kagami (1993), Kawano et al. (1997), and Kawano et al. (1999).
Is stands for "island"

distribution. The ages mentioned in this paper include K–Ar biotite ages, K–Ar amphibole ages, Rb–Sr whole-rock isochronages, Rb–Sr mineral (biotite) isochron ages, and FT zircon ages. However, the closure temperatures and the interpretation of the ages differ. For example, the age derived by the Rb–Sr whole-rock isochron method is considered to indicate the active period of magma; however, the K–Ar biotite age, Rb–Sr mineral (biotite) isochron age, and FT zircon age are considered to indicate the period when the body cooled to approximately 250–300 °C (Harrison et al., 1985; Nishimura and Mogi,1986). In general, the Rb–Sr whole-rock isochron age and K–Ar biotite age are recognized to differ by approximately 4 m.y. (Kagami et al., 1988). In addition, the K–Ar biotite age of late Cretaceous granitic bodies in southwestern Japan is considered to be 4–9 m.y. younger than the Rb–Sr whole-rock isochron age (Shibata and Ishihara, 1979). Therefore, the K–Ar biotite age, Rb–Sr mineral (biotite) isochron age, and FT zircon age considered in this study have added 5 m.y. in active ages. Therefore, the ages for the bodies are indicated in the Fig as follows: the Kasari body, 54 Ma; the Ichi body, 60 Ma; the Kachiura body, 22 Ma; the Koniya body, 60 Ma; the Todoroki body, 74 Ma; the Okinoerabu body, 22 Ma; the Nagahama Diorites, 35 Ma; and the Nishinomori Diorites, 24 Ma. Ages of the Koniya body of the Amami plutonic rocks are calculated on the basis of the average value because multiple K–Ar biotite ages have been reported. In addition, in the case of the Okinoerabu body, the K–Ar biotite age and FT zircon age show a large difference; therefore, the K–Ar biotite age derived from the sample used in this study was utilized as the standard. In the case of the Nishinomori Diorites, the values obtained from the samples used in this study have also been utilized. Note that the closure temperature for the K–Ar amphibole age is relatively high; hence, the age of Uke body gabbro (110 Ma) was treated as the magma activity period. Furthermore, the Ankyaba body in the Amami plutonic rocks is the only body whose age has not been reported; its age was estimated to be 60 Ma based on the K–Ar biotite age (average of 55 Ma) for the Koniya body, which has petrological characteristics similar to that of the Ankyaba body and is also the nearest body.

As clearly shown in Fig.2, the only body showing in the early Crefaceous (EC) is the gabbro in the Uke body within the Amami plutonic rocks, and the bodies active in the late Cretaceous are the adamellite in the Uke body within the Amami plutonic rocks and the Yonama and Todoroki bodies within the Tokuno-shima plutonic rocks. By the Paleogene, the bodies that became active include the Kasari, Koniya, Ichi, and Ankyaba bodies of the Amami plutonic rocks; the Kanemi body of the Tokuno-shima plutonic rocks; the Nagahama Diorites of Okinawa-jima; and the Omoto and Chayama bodies of Ishigaki-jima. Later, in the Neogene, the following bodies were identified to be active: the Kachiura body in the Amami plutonic rocks, the Okinoerabu body and the Nishinomori Diorites of Tonaki-jima, respectively.

As one observes the spatial changes in the periods of activity, one can find only the northern Ryukyu region displays evidence of activity in the early to late Cretaceous; in the Paleogene, evidence of activity is observed in the northern, middle, and southern Ryukyu regions. In addition, the middle and northern Ryukyu experienced activity in the Neogene. As the plutonic rocks that were active in the same period are distributed in different regions, the plutonic rocks in the Ryukyu Arc are categorized as EC, late Cretaceous (LC), Paleogene (PG), and Neogene (NG) in this study. However, these categories were not strictly based on active ages and the petrological characteristics were also considered. In other words, the Kanemi body in the Tokuno-shima plutonic rocks is 61 Ma, corresponding to the Paleogene. However, their petrological characteristics are quite similar to those of the Yonama body (Kawano and Kato, 1989); therefore, in this study, the Kanemi body is included in the LC group. The EC group comprises the Uke body gabbro; the LC group comprises the Uke body adamellite and the Yonama, Kanemi, and Todoroki bodies; the PG group includes the Kasari, Ichi, Koniya, Ankyaba, and Nagahama Diorites and the Omoto and Chayama bodies; and the NG group comprises the Kachiura and Okinoerabu bodies and the Nishinomori Diorites.

3. Whole-rock chemical composition

To understand the chemical characteristics of plutonic rocks, X-ray fluorescence spectrometers installed at the Faculty of Geo-environmental Science in Rissho University, at the Faculty of Science in Niigata University and at the Analytical Research Center in Saga University were used to analyze the major and trace element compositions. The analysis methods were based on those of Nakagawa and Komatsu (1983), Tamura et al. (1989), Kawano et al. (1992), Kakubuchi et al (1999), and Kawano (2010). The measurement results, excluding the analysis values reported by Kawano and Kato (1989; 1990), Kawano (1997) and Kawano et al. (1997), are listed in Table 1. The behavior of the major and trace element compositions of plutonic rocks, excluding the Okinoerabu body, have been reported by Kawano and Kato (1989; 1990), Kawano (1997), Kawano et al. (1997), and Kawano (2013). Therefore, in this paper, only the characteristic chemical properties are discussed to avoid repetition of discussion.

Fig.3 shows the SiO_2 content histogram for plutonic rocks categorized by the epoch. The number of samples analyzed differs between bodies; however, this is related to exposure scales, i.e., the number of analytical samples is greater for more exposed bodies, whereas the number of samples tends to be less for less exposed bodies. Therefore, it is possible to roughly determine the body composition based on the active period shown in Fig.3, which illustrates that the Uke body gabbro in the Amami plutonic rocks, which belongs to the EC group, has an SiO_2 content of 46–62 wt%; since the scale of exposure is small, the frequency of occurrence is also small. The Uke body adamellite in the Amami plutonic rocks and the Yonama, Kanemi, and Todoroki bodies, all of which belong to the LC group, exhibit SiO_2 contents of 54–78 wt%; compared with the EC group, the composition range in this group is wider. In addition, the peak frequency occurrence was observed at a

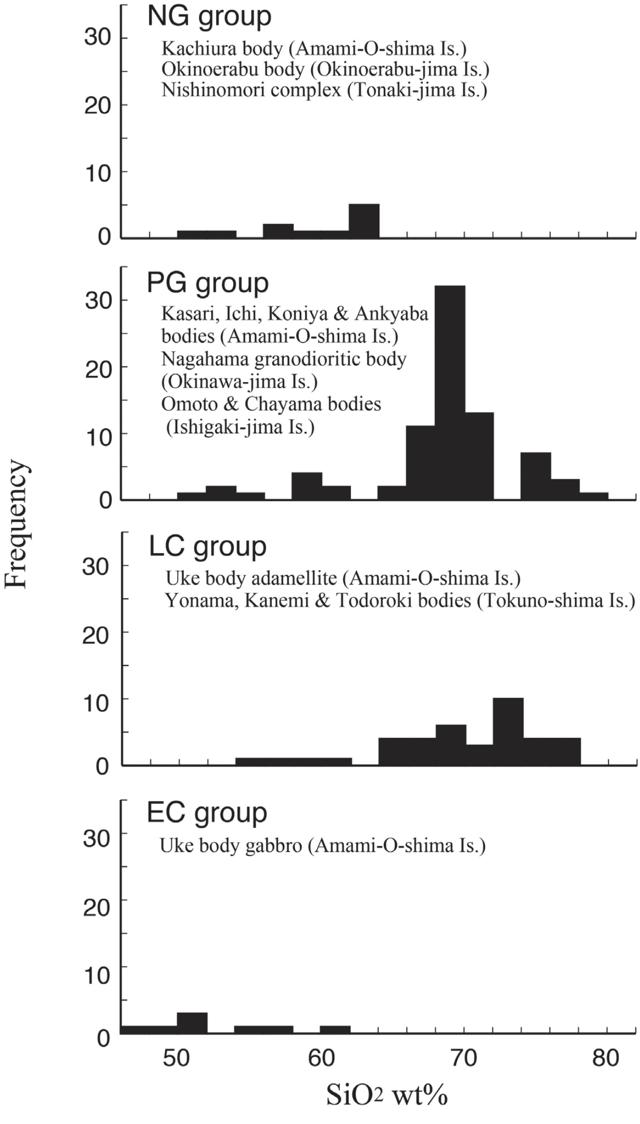


Fig.3 Histogram of the SiO_2 volumes in each group
Geochemical data of the plutonic rock were analyzed in this study and also obtained from Kawano and Kato (1989; 1990), Kawano (1997), and Kawano et al. (1997).
Is stands for "Island"

Table 1 Whole-rock chemical composition of plutonic rocks, plutonic xenoliths,

	Tokuno-shima Is.				Okinoerabu-jima Is.		Tonaki-jima Is.	
	Yonama	Kanemi	Kanemi	Todoroki	Okinoerabu body		Nishinomori dioritic body	
Name	32308	71701	71705	1118	62102	62103	61701	61703
SiO_2 (wt%)	77.74	55.74	57.67	64.33	61.09	63.73	56.80	58.59
TiO_2	0.21	1.71	1.87	0.92	1.05	0.72	0.92	0.82
Al_2O_3	12.85	14.80	14.95	15.95	16.77	17.14	17.66	17.58
Fe_2O_3	1.81*	13.19*	9.96*	5.97*	2.35	1.19	0.71	1.01
FeO	nd	nd	nd	nd	3.98	3.62	6.68	5.41
MnO	0.06	0.16	0.14	0.16	0.11	0.10	0.13	0.10
MgO	0.27	2.08	2.26	2.33	2.94	2.00	4.16	3.39
CaO	1.05	6.73	5.68	2.35	4.10	4.45	7.66	6.76
Na_2O	4.34	3.82	4.39	2.64	3.89	3.99	3.58	3.46
K_2O	2.75	1.17	1.60	3.31	2.68	2.41	1.74	1.73
P_2O_5	0.04	0.48	0.25	0.13	0.19	0.20	0.15	0.16
H_2O+	0.44	0.23	1.13	2.88**	0.63	0.60	0.17	0.43
H_2O-	0.02	0.04	0.08	nd	0.22	0.09	0.15	0.06
Total	101.54	100.15	99.98	100.97	100.00	100.24	100.51	99.50
Ba (ppm)	328	206	239	nd	453	444	264	325
Cr	10	21	74	55	59	11	23	60
Cu	0	13	8	28	3	6	3	11
Nb	9.5	17.0	11.4	13.2	12.6	9.2	6.0	5.6
Ni	tr	2	8	27	31	6	16	8
Rb	111	48	62	148	121	102	53	63
Sr	45	186	168	176	369	402	282	317
Y	78	97	69	26	14	15	32	31
Zn	43	121	110	97	88	79	78	58
Zr	159	245	197	204	177	203	123	176
ASI	1.069	0.748	0.775	1.308	1.001	0.993	0.814	0.885

Is., island; F., Formation; *, Total Fe as Fe_2O_3; **, loss on ignition; ASI, aluminum saturation and pelitic rocks

			Xenoliths in Aguni volcanic rocks			Pelitic rocks			
61704	61708	61709	Amphi bolite	Tonalite	Gabbro	Tete F.	Tonaki F.	Nago F.	Tomuru F.
50.50	53.92	57.75	43.15	63.05	54.89	63.43	66.35	65.86	75.09
1.17	1.02	0.82	3.20	0.60	0.88	0.75	0.74	0.71	0.24
18.59	18.52	18.11	11.33	17.62	21.37	17.54	17.70	16.72	13.89
1.15	2.77	1.27	16.35*	4.51*	6.54*	6.84*	5.40*	6.81*	1.46*
8.61	5.93	5.81	nd	nd	nd	nd	nd	nd	nd
0.17	0.15	0.12	0.25	0.10	0.11	0.11	0.09	0.32	0.07
6.91	4.64	3.38	13.10	2.20	2.39	2.51	2.23	2.21	0.87
10.26	8.11	7.16	9.40	5.30	9.15	2.29	1.09	1.16	0.13
2.38	3.10	3.20	2.32	4.40	3.87	3.73	2.60	1.84	5.90
0.66	1.22	1.89	0.18	1.53	0.65	2.61	3.69	3.62	1.85
0.08	0.14	0.17	0.03	0.18	0.23	0.17	0.14	0.09	0.04
0.41	1.00	0.55**	nd	nd	nd	nd	nd	nd	nd
0.12	0.13	nd	nd	nd	nd	nd	nd	nd	nd
101.01	100.65	100.23	99.31	99.49	100.08	99.98	100.03	99.34	99.54
69	209	278	nd	nd	nd	nd	694	nd	nd
43	19	41	713	16	9	66	10	61	5
2	3	2	8	5	4	19	20	49	3
5.4	5.6	4.9	8.6	2.3	4.4	11.3	16.3	13.1	10.0
9	5	7	540	9	3	19	23	36	4
25	40	83	3	31	161	139	144	130	54
374	294	232	306	951	449	367	154	51	30
18	24	41	30	6	22	24	38	22	22
87	96	70	113	69	50	114	100	105	25
45	61	173	152	93	63	165	214	145	159
0.798	0.875	0.891	0.537	0.951	0.901	1.336	1.617	1.847	1.163

index; nd, not determined.

SiO_2 content of 72–74 wt%, indicating that the nature of the active magma changed to acidic. Four bodies of the Kasari, Ichi, Koniya, and Ankyaba of the Amami plutonic rocks, belonging to the PG group; the Nagahama Diorites of Okinawa-jima; and both the Omoto and Chayama bodies of Ishigaki-jima exhibit SiO_2 contents of 50–80 wt%, with a clear peak of frequency occurrence observed at a content of 68–70 wt%; this also indicates the high activity of acidic magma. In contrast, the SiO_2 content for the NG group plutonic rocks has a smaller composition range, between 50 and 64 wt%, with a tendency of lower occurrence frequencies. In this way, the plutonic rocks of the Ryukyu Arc are characterized by great activity of acidic magma from the late Cretaceous to the Paleogene.

Fig.4 shows the relationship between (Na_2O + K_2O) and the aluminum saturation index (ASI) with respect to SiO_2. The Fig showing (SiO_2–Na_2O + K_2O) indicates that although the EC group is limited to areas poor in SiO_2 content, it tends to be the richest in (Na_2O + K_2O). The LC and PG groups occupy very similar areas, and no clear differences can be seen between them. The NG group shows levels of concentration similar to those of the LC or PC groups, which show the same SiO_2 composition range. Meanwhile, the SiO_2–ASI Fig shows that the rocks of the EC group exhibit metaluminous properties. The rocks of the LC group exhibit metaluminous properties when SiO_2 is 65 wt% or lower and exhibit peraluminous properties when SiO_2 is higher than the aforementioned value. In the PG group, the ASI is the highest in the SiO_2 range of 65–72 wt%, with the value reaching 1.4. For the NG group, only one sample was peraluminous and the rest exhibited metaluminous properties.

Pearce et al. (1984) categorized granites in different tectonic setting into four groups, namely, volcanic arc granites (VAG), collision granites (syn-COLG), within plate granites (WPG), and ocean ridge granites (ORG). To estimate how these tectonic setting changed in each era, the plutonic rocks in the Ryukyu Arc were plotted in a Y–Nb Fig and an Rb–(Y + Nb) Fig (Fig.5). From the Y–Nb Fig, in the EC and LC groups, some samples are plotted partially in the VAG and syn-COLG areas; however, most samples reside in the WPG area. The PG and NG groups are plotted in the VAG and syn-COLG areas, with the exception of two samples plotted in the WPG area. In addition, the Rb–(Y + Nb) Fig shows that the EC group is plotted both in the VAG and WPG areas and that the majority of the LC group resides in the WPG area. In the PG and NG groups, there are many samples plotted in the VAG area and

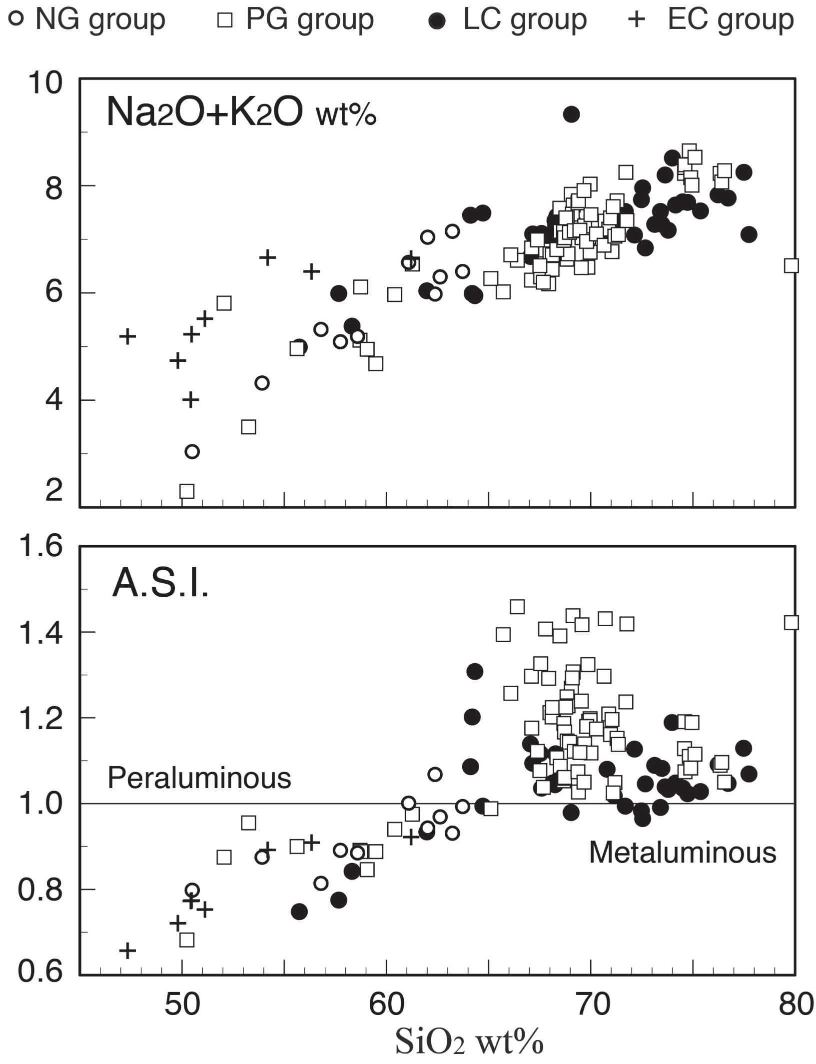


Fig.4 SiO_2–Na_2O + K_2 O and SiO_2–ASI for plutonic rocks in the Ryukyu Arc
Geochemical data of the plutonic rock were analyzed in this study and also obtained from Kawano and Kato (1989; 1990), Kawano (1997), and Kawano et al. (1997)

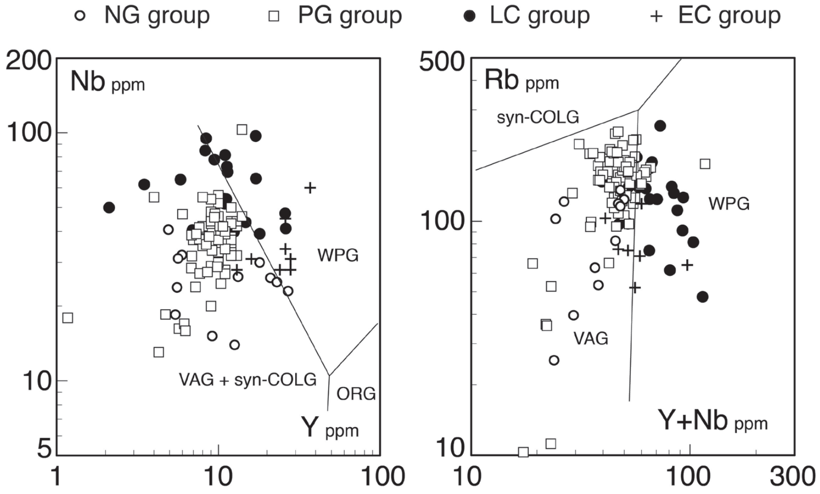


Fig.5 Nb–Y and Rb–Y + Nb for plutonic rocks in the Ryukyu Arc (Pearce et al., 1984)
Geochemical data of the plutonic rock were analyzed in this study and also obtained from Kawano and Kato (1989; 1990), Kawano (1997), and Kawano et al. (1997).
WPG, within plate granite; ORG, oceanic ridge granite; VAG, volcanic arc granite; syn-COLG, syn-tectonic collision granite.

only a few are plotted in the WPG area. Furthermore, in the EC and LC groups, Rb increases as the amount of Y + Nb decreases, whereas in the PG and NG groups, Rb decreases as the amount of Y + Nb decreases.

4. Sr and Nd isotopic compositions

Sr isotopic ratios were measured for 56 samples of plutonic rocks in the Ryukyu Arc. Furthermore, the Sm and Nd contents and the Nd isotopic compositions of 24 samples from this group and three samples of plutonic xenoliths from the Aguni volcanic rocks (Shinjo et al., 1990) were measured. In addition, the Sr isotopic ratios of four samples of pelitic rocks from Tokuno-shima, Tonaki-jima, Okinawa-jima, and Ishigaki-jima were measured. The Sm and Nd contents and the Nd isotopic ratio were measured for three of these samples, namely, those from Tokuno-shima, Okinawa-jima, and Ishigaki-jima. Isotopic ratio measurement and quantitative analysis were conducted using MAT261 and MAT262 mass spectrometers at the Graduate

School of Science and Technology in Niigata University. The measurement method was in accordance with that reported by Miyazaki and Shuto (1998). The $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ values of the samples were standardized as $^{86}Sr/^{88}Sr = 0.1194$ and $^{146}Nd/^{144}Nd = 0.7219$, respectively. To calculate the current values of bulk earth used for calculating ε, the following ratios were adopted: $^{87}Sr/^{86}Sr = 07045$, $^{87}Rb/^{86}Sr = 0.0827$ (Depaolo, 1988), $^{143}Nd/^{144}Nd = 0.512638$, and $^{147}Sm/^{144}Nd = 0.1966$ (Goldstein et al., 1984). The previously mentioned corrected value was used as the active period for each body. Table 2 lists the isotopic compositions with the newly measured data in addition to the previously published Sr isotopic compositions.

Fig.6 shows a ε*SrI*–ε*NdI* diagram. The Fig shows the regions of volcanic rocks from the Tokara islands, the Ryukyu Arc, and the Okinawa Trough (Notsu et al., 1990; Honma et al., 1991; Shinjo et al., 1999; Shinjo et al., 2000; Shinjo and Kato, 2000) in addition to providing the values for the xenoliths from the Aguni volcanic rocks and the pelitic rocks from the Ryukyu

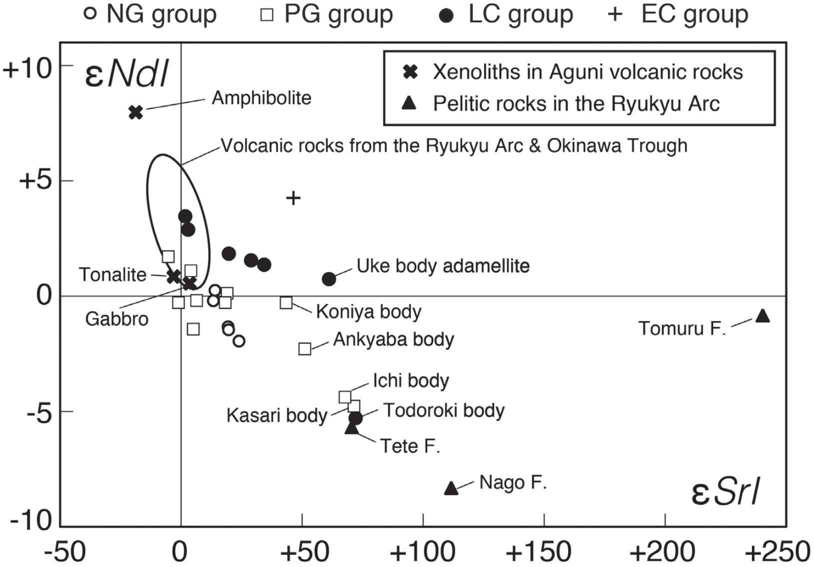


Fig.6 ε*SrI*–ε*NdI* for plutonic rocks in the Ryukyu Arc
The isotopic composition of volcanic rocks in the Tokara islands, the Ryukyu Arc, and the Okinawa Trough were obtained from Notsu et al. (1990), Shinjo et al. (1990), Honma et al. (1991), Shinjo et al. (1999), Shinjo et al. (2000), and Shinjo and Kato (2000). "F." stands for Formation.

Table 2 Sr and Nd isotopic compositions of plutonic rocks, plutonic xenoliths, and pelitic rocks in the Ryukyu Arc

Island	Body	Sample Name	Rb (ppm)	Sr (ppm)	^{87}Sr/^{86}Sr	^{87}Rb/^{86}Sr	SrI	Sm (ppm)	Nd (ppm)	^{143}Nd/^{144}Nd	^{147}Sm/^{144}Nd	NdI
Amami-O-shima	Kasari	71501	119	200	0.710788	1.72	0.70947	7.66	35.61	0.512370	0.130	0.512324
		62602	173	167	0.711773	3.00	0.70947					
		62603	158	146	0.712066	3.13	0.70966					
	Ichi	62301	126	180	0.710925	2.03	0.70920	4.76	22.81	0.512386	0.126	0.512336
		62302	161	140	0.711570	3.33	0.70873					
		62304	155	159	0.711232	2.82	0.70883					
		62303	166	155	0.710976	3.10	0.70833					
		62305	162	133	0.711630	3.53	0.70863					
	Kachiura	42604	124	374	0.706138	0.96	0.70584	6.61	35.28	0.512558	0.113	0.512542
		62308	116	330	0.706671	1.02	0.70635					
	Koniya	AC-3	157	103	0.711250	4.41	0.70749	7.22	31.79	0.512600	0.137	0.512546
		62310	145	114	0.709992	3.68	0.70685					
		81205	180	152	0.710912	3.43	0.70799					
		AC-2	114	149	0.709344	2.21	0.70746					
	Ankyaba	80402	171	126	0.712477	3.93	0.70913					
		80502	171	90	0.712718	5.50	0.70803	4.55	21.38	0.512494	0.129	0.512443
	Uke (gabbro)	1405a	71	392	0.707755	0.52	0.70693					
		1703a	65	310	0.708592	0.61	0.70764	9.64	40.98	0.512817	0.142	0.512714
	Uke (adamellite)	1302b	179	73	0.715907	7.10	0.70867					
		1305b	256	59	0.721480	12.57	0.70867	5.73	29.94	0.512647	0.116	0.512593
Tokuno-shima	Yonama	85032203	124	65	0.710014	5.52	0.70454	7.10	27.80	0.512796	0.154	0.512725
		85071502	127	68	0.709982	5.40	0.70462	7.60	31.20	0.512763	0.147	0.512696
		85032309	98	40	0.711696	7.09	0.70466					
		32308	111	45	0.711659	7.14	0.70458					
	Kanemi	71701	48	186	0.706463	0.75	0.70582	9.23	30.10	0.512728	0.185	0.512654
		71705	62	168	0.707768	1.07	0.70684	5.52	21.64	0.512691	0.154	0.512629
		85071706	75	221	0.708453	0.98	0.70760					
		85032508	97	116	0.708558	2.42	0.70646	8.20	36.70	0.512693	0.135	0.512639
		85032503	124	73	0.710785	4.92	0.70652					
		85032606	91	62	0.709750	4.25	0.70607					
		85032603	81	82	0.708886	2.86	0.70641					
		85072006	168	32	0.719710	15.21	0.70653					
	Todoroki	85040204	132	202	0.711499	1.89	0.70949	3.63	18.75	0.512328	0.117	0.512271
		1118	149	178	0.712206	2.42	0.70963					
		85032702	140	159	0.710668	2.55	0.70796					

Island	Body	Sample Name	Rb (ppm)	Sr (ppm)	^{87}Sr/^{86}Sr	^{87}Rb/^{86}Sr	SrI	Sm (ppm)	Nd (ppm)	^{143}Nd/^{144}Nd	^{147}Sm/^{144}Nd	NdI
Okinoerabu-jima		62102	121	369	0.706151	0.95	0.70585	4.81	27.81	0.512550	0.105	0.512535
		62103	102	402	0.706385	0.73	0.70616	4.63	27.81	0.512524	0.101	0.512510
Tonaki-jima	Nishinomori dioritic	61701	53	282	0.705594	0.54	0.70541	4.66	19.15	0.512620	0.147	0.512597
		61708	40	294	0.705592	0.39	0.70546	3.47	14.79	0.512642	0.142	0.512620
		61710	83	213	0.705975	1.13	0.70559					
		61712	125	302	0.705653	1.20	0.70524					
		61713	62	269	0.706224	0.67	0.70600					
Okinawa-jima	Nagahama dioritic	BH64	11	428	0.704780	0.07	0.70474	2.73	11.61	0.512682	0.142	0.512649
		61605	36	330	0.704243	0.32	0.70409	2.80	11.91	0.512713	0.142	0.512680
		BH45	36	314	0.704546	0.33	0.70438	2.52	11.07	0.512610	0.138	0.512579
Ishigaki-jima	Omoto	51602	10	243	0.704733	0.12	0.70467					
		80701	66	197	0.705449	0.97	0.70491	5.82	25.66	0.512613	0.137	0.512578
		81601	195	49	0.711237	11.52	0.70481	5.69	26.02	0.512548	0.132	0.512514
		81111	195	53	0.710661	10.65	0.70472					
		51511	237	26	0.719270	26.40	0.70453					
		82004	211	33	0.715724	18.51	0.70539					
		51405	214	25	0.717950	24.79	0.70411					
	Chayama	82202	53	294	0.706091	0.52	0.70579	2.50	11.72	0.512626	0.129	0.512592
		81209	97	208	0.706861	1.35	0.70608					
		82102	95	186	0.706585	1.48	0.70573	4.95	23.48	0.512605	0.127	0.512571
		81309	140	118	0.707794	3.43	0.70581					
Aguni-jima	amphibolite (xenolith)		3	306	0.703170	0.03	0.70317	4.10	11.90	0.513047	0.208	0.513039
	tonalite (xenolith)		31	951	0.704280	0.09	0.70427	2.00	7.50	0.512680	0.161	0.512673
	gabbro (xenolith)		16	449	0.704750	0.10	0.70474	4.00	14.40	0.512665	0.168	0.512658
Tokuno-shima	Tete Formation		139	367	0.710450	1.10	0.70938	5.80	27.00	0.512317	0.130	0.512259
Tonaki-jima	Tonaki Formation		144	154	0.714051	2.71	0.71313					
Okinawa-jima	Nago Formation		130	51	0.715990	7.38	0.71232	4.60	20.40	0.512198	0.136	0.512167
Ishigaki-jima	Tumuru Formation		54	30	0.724270	5.22	0.72138	3.90	19.50	0.512576	0.121	0.512545

SrI, initial Sr isotopic ratio; NdI, initial Nd isotopic ratio.

Arc. For the EC group in the first quadrant, ε*SrI* was plotted near +45, whereas ε*NdI* was plotted near +4, indicating the differences in isotopic composition compared with other plutonic rocks. The plot of the Uke body adamellite belonging to the LC group is shown in the lower-right part in the first quadrant. The Ryukyu Arc plutonic rocks, excluding these two samples, are scattered over the region of volcanic rocks from the Ryukyu Arc and Okinawa Trough and the region of pelitic rocks of the Tete and Nago Formations. The samples plotted in proximity to the pelitic rocks are the Todoroki bodies from the Tokuno-shima plutonic rocks, belonging to the LC group. The samples stretching to the upper left are the Kasari, Ichi, Ankyaba, and Koniya bodies from the Amami plutonic rocks that belong to the PG group. Two samples from the Yonama body in Tokuno-shima of the LC group and two out of three samples from the Nagahama Diorites in Okinawa-jima of the PG group are plotted in the overlapping area of the volcanic rocks from the Ryukyu Arc and the Okinawa Trough. The NG group overlaps with the area of the PG group and stretches to the lower right of the area; moreover, they are mostly plotted in the fourth quadrant. Among the xenoliths in the Aguni volcanic rocks, the amphibolite shows the highest ε*NdI* and are plotted in the second quadrant, extending from the Ryukyu Arc and Okinawa Trough volcanic rocks. Tonalite and gabbro are in the volcanic rock region. Among the pelitic rocks, the Tomuru Formation shows an extremely high ε*SrI* and is plotted in a region distant from the plutonic rocks; the other two pelitic samples have low ε*NdI*.

5. Discussion

The petrological characteristics of the Ryukyu Arc plutonic rocks stated so far are listed group-wise in Table 3. Many bodies are composed of granodiorite and adamellite, and only the Nishinomori Diorites in Tonaki-jima are composed of diorite. The Uke body is composed of gabbro and adamellite but the activity period is assumed to differ; hence, it is listed separately in Table 3. The SiO_2 composition range for each rock body is narrow for the EC and NG groups; however, for the LC and PG groups, the composition ranges overlap with each other, showing no clear difference. Considering the minimum value of ASI for each body, the Kasari, Ichi, Koniya, and Ankyaba bodies in the PG group all exceed 1.0 and exhibit peraluminous properties. In contrast, the maximum value for ASI exceeded 1.20 for the entire PG group of rocks, except for Nagahama Diorite, which showed high aluminum content. In general, the pelitic rocks that form the upper crust are rich in aluminum, and magma that reacts to it tends to exhibit peraluminous properties. As shown in Table 2, the pelitic rocks sampled in this study have a high Sr isotopic composition (0.70938–0.72138) and low Nd isotopic composition (0.512167–0.512545). As the reaction with magma proceeds, it is considered that both the ASI and the initial Sr isotopic ratios of plutonic rocks rise, whereas the initial Nd isotopic ratios decreases. The relationships between ASI and the initial Sr and Nd isotopic compositions are shown in Fig.7.

First, consider the variation in the initial ratio of the Sr isotopic compositions. Since only few samples of the EC group are available, the tendency of variation cannot be investigated for this group. In the LC group, some samples have a high ASI value and a high initial Sr isotopic ratio but are scattered overall; thus, the trend of the variation is not clear. In the PG group, with the exception of one sample from the Omoto body, a clear trend of increases in the initial ratio of the Sr isotopic compositions with increases in the ASI is observed. The sample that is an exception is extremely rich in SiO_2 (80 wt%), and it is estimated that the alkali feldspar differentiation progressed significantly to the point of leading to high ASI values. In the NG group, a slight trend of the occurrence of a high initial ratio of the Sr isotopic composition is

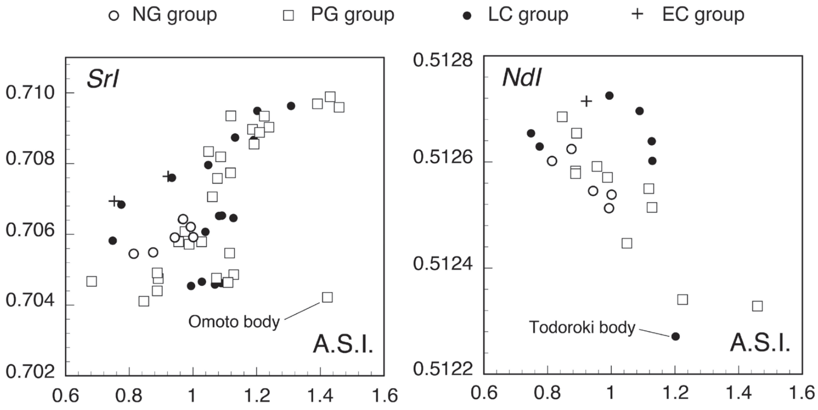


Fig.7 ASI–*SrI* and ASI–*NdI*
Geochemical data of the plutonic rock were analyzed in this study and also obtained from Kawano and Kato (1989; 1990), Kawano (1997), and Kawano et al. (1997).
SrI, initial Sr Isotopic composition; NdI, initial Nd isotopic composition.

Table 3 Petrological characteristics of the plutonic rocks in the Ryukyu Arc

Group Name	Island	Body/Group	Rock	Age (Ma)
NG	Tonaki-jima Is.	Nishinomori dioritic	Di	19
	Okinoerabu-jima Is.	Okinoerabu	GD	17.2
	Amami-O-shima Is.	Kachiura	GD, Ad	17.23
PG	Okinawa-jima Is.	Nagahama dioritic	Di, GD	30.2
	Ishigaki-jima Is.	Omoto	Di, GD, Ad, Gr	39.3
		Chyayama	Di, Ad, Gr	40.7
	Amami-O-shima Is.	Kasari	GD, Ad	49
		Ichi	GD, Ad	55
		Koniya	GD, Ad	54, 56
		Ankyaba	GD, Ad	(55)
LC	Tokuno-shima Is.	Kanemi	GD, Ad	61
		Yonama	GD, Ad	59, 69.8
		Todoroki	GD, Ad	61, 69.3
	Amami-O-shima Is.	Uke (adamellite)	Ad	(71.7)
EC	Amami-O-shima Is.	Uke (gabbro)	Gb	110.3

Age data were obtained from Shibata and Nozawa (1966), Kawano and Ueda (1966), Daishi et al. (1986), Kawano and Kato (1989), Kawano and Kagami (1993), Kawano et al. (1997), and Kawano et al. (1999). Of the age values, those in parentheses are the estimated values.
ASI, aluminum saturation index; WPG, within plate granite; VAG, volcanic arc granite; Di, diorite; Gb, gabbro; GD, granodiorite; Ad, adamellite; Gr, granite.

SiO_2(wt%)	ASI	Initial Sr isotopic ratio	Initial Nd isotopic ratio	Granitic type
50 - 58	0.79 - 0.89	0.70524 - 0.70600	0.512597 - 0.512620	VAG
61 - 64	0.99 - 1.00	0.70585 - 0.70616	0.512510 - 0.512535	VAG
62 - 63	0.93 - 1.07	0.70584 - 0.70635	0.512542	VAG
58 - 59	0.84 - 0.89	0.70409 - 0.70474	0.512579 - 0.512680	VAG
50 - 80	0.68 - 1.42	0.70411 - 0.70539	0.512514 - 0.512578	VAG
52 - 72	0.88 - 1.24	0.70573 - 0.70608	0.512571 - 0.512592	VAG
66 - 72	1.27 - 1.46	0.70947 - 0.70966	0.512324	VAG
66 - 71	1.15 - 1.39	0.70833 - 0.70923	0.512336	VAG
67 - 70	1.05 - 1.23	0.70635 - 0.70799	0.512546	VAG
69 - 71	1.05 - 1.30	0.70803 - 0.70913	0.512443	VAG
55 - 76	0.75 - 1.13	0.70582 - 0.70760	0.512629 - 0.512654	WPG
70 -78	0.99 - 1.09	0.70454 - 0.70466	0.512696 - 0.512725	WPG
64 - 68	0.99 - 1.31	0.70796 - 0.70963	0.512271	WPG
69 - 77	0.98 - 1.13	0.70867	0.512593	WPG
47 - 61	0.66 - 0.92	0.70478 - 0.70764	0.512714	WPG

observed with increases in the ASI.

Second, consider the variation in the initial ratio of the Nd isotopic composition. From the EC group, only one sample of plutonic rock was measured; hence, no trend can be investigated. In the LC group, even after excluding the Todoroki body, which has an extremely low initial ratio of the Nd isotopic composition, the values are scattered and show no clear trend. The PG and NG groups exhibit a decreasing trend of the initial ratio of the Nd isotopic composition as ASI increases, with the trend being more pronounced for the former group. According to the Fig, in the PG group, it is assumed that the involvement of the material of the upper crust is the most significant. In addition, the LC group shows characteristics of a high initial ratio of the Sr isotopic composition, low initial Nd isotopic composition, and high ASI, showing considerable reaction with the upper crustal material.

Now, let us practically consider which bodies were largely influenced by the upper crustal materials. For this purpose, the initial ratio of the Sr isotopic composition is used. The data in Table 3 indicate that the bodies that have a maximum initial ratio of the Sr isotopic composition of 0.705 or less are the Yonama body in the LC group and the Nagahama Diorites of the PG group. Those that do not attain a maximum of 0.707 are the Uke body gabbro in the EC group; the Omoto and Chayama bodies of the PG group; and the Kachiura body, Okinoerabu body, and Nishinomori Diorites of the NG group. Those with a maximum value exceeding 0.707 are the Uke body adamellite of the EC group; the Todoroki and Kanemi bodies of the LC group; and the Kasari, Ichi, Koniya, and Ankyaba bodies of the PG group. Therefore, bodies with their maxima exceeding 0.706 are deemed to be relatively highly influenced by upper crustal materials.

Next, let us consider how the influence of upper crustal materials has changed in different eras. To this end, the relationship between the active period and the initial ratio of the Sr and Nd isotopic compositions is shown in Fig.8. The Uke body gabbro from the EC group with the oldest activity has an initial ratio of the Sr isotopic composition of 0.7048–0.7076. The Todoroki body from the LC group has the second-oldest activity, with values of 0.7079–0.7096, showing a rise in the initial values with time. Thereafter, the initial values fall to 0.7045–0.7047 in the Uke body adamellite and the Yonama body but increase again for the Kanemi body and the Kasari, Ichi, Koniya, and Ankyaba bodies in the PG group. With time, the initial values slowly decline in the Chayama and Omoto bodies of Ishigaki-jima and the

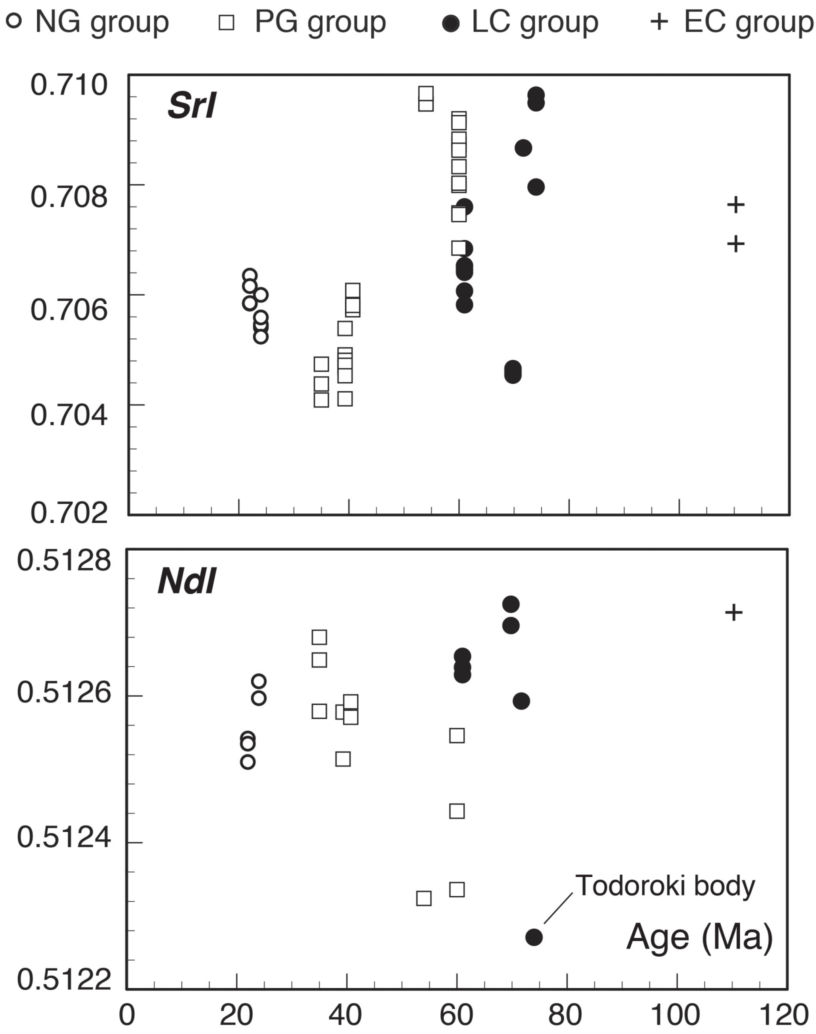


Fig.8 Relationship between the initial Sr isotopic ratio and the active period of plutonic rocks in the Ryukyu Arc

Age data were obtained from Shibata and Nozawa (1966), Kawano and Ueda (1966), Daishi et al. (1986), Kawano and Kato (1989), Kawano and Kagami (1993), Kawano et al. (1997), and Kawano et al. (1999).

Nagahama Diorites of Okinawa-jima and then increase by three times for the Kachiura and Okinoerabu bodies and the Nishinomori Diorites of the PG group.

In contrast, the variation in the initial ratio of the Nd isotopic composition over time shows a reverse trend compared to the trend of that of the Sr isotopic composition. The initial ratio of the Nd isotopic composition is 0.5127 for the Uke body gabbro of the EC group, which is the first activity; however, it decreases to 0.5123 for the Todoroki body in the LC group. Thereafter, the initial values increase to 0.5125–0.5127 in the Uke body adamellite and the Yonama body and then fall again for the Kanemi body and the Kasari, Ichi, Koniya, and Ankyaba bodies of the PG group. As the era gets younger, the initial ratio of the Nd isotopic composition continues to increase for the Chayama and Omoto bodies of Ishigaki-jima and the Nagahama Diorites in Okinawa-jima and then decreases by three times in the Kachiura and Okinoerabu bodies and the Nishinomori Diorites of the PG group. As discussed earlier, if we hypothesize that the Sr and Nd isotopic compositions of the source magma are constant, the change in the initial isotopic composition indicates three instances of reactions with the sedimentary rocks that form the upper crustal material in the late Cretaceous, the early Paleogene, and the early Neogene.

Next, we consider the variation in the initial ratio of the isotopic composition according to spatial location. Fig.9 shows a distribution diagram that combines the initial ratio of the Sr and Nd isotopic compositions of the plutonic rocks discussed so far with those of the volcanic rocks distributed in the Ryukyu Arc, the Okinawa Trough, and the Tokara islands (Notsu et al., 1990; Shinjo et al., 2000; Honma et al., 1991; Shinjo et al., 1999; Shinjo and Kato, 2000). With regard to the distribution of the initial ratio of the Sr isotopic composition, the Quaternary volcanic rocks in the middle to southern Okinawa Trough, which is located in the back-most part of the arc, have a low initial ratio of the initial Sr isotopic compositions of 0.7307–0.7049, whereas the Quaternary volcanic rocks in the Tokara islands in the front-arc and the Ryukyu Arc volcanic rocks have slightly higher initial values of 0.7043–0.7054. The plutonic rocks are distributed in the front-most part of the arc, with initial Sr isotopic ratios of 0.7041–0.7097, wherein bodies with initial values higher than those of the back-arc igneous rocks emerge.

The distribution of the initial ratio of the Nd isotopic composition shows that the Quaternary volcanic rocks of the middle to southern Okinawa Trough

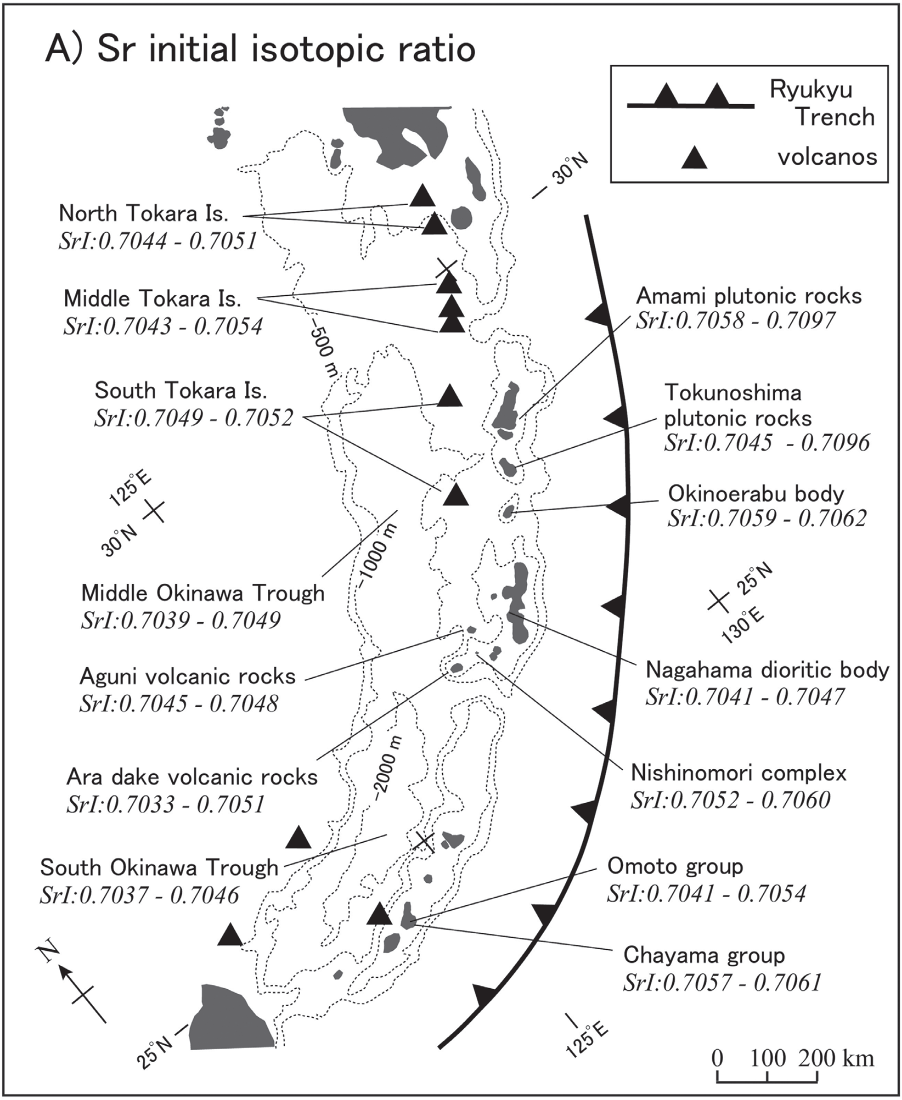
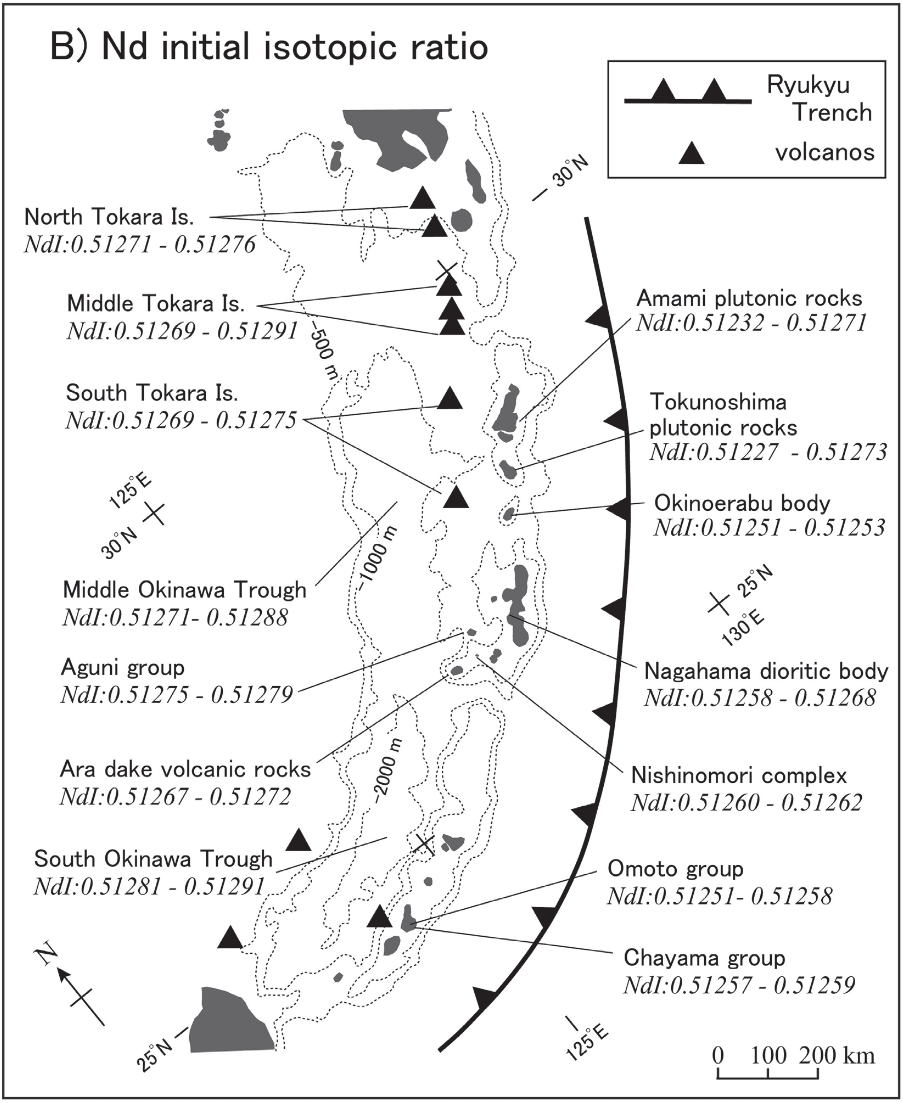


Fig.9 Distribution of volcanic rocks in the Ryukyu Arc and the initial Sr (A) and Nd isotopic ratios (B)
Volcanic rock isotopic ratios in the Tokara islands, the Ryukyu Arc, and the Okinawa Trough were obtained from Notsu et al. (1990), Shinjo et al. (1990), Honma et al. (1991), Shinjo et al. (1999), Shinjo et al. (2000), and Shinjo and Kato (2000).


B) Nd initial isotopic ratio
Ryukyu Trench
volcanos
North Tokara Is.
NdI:0.51271 - 0.51276
Middle Tokara Is.
NdI:0.51269 - 0.51291
South Tokara Is.
NdI:0.51269 - 0.51275
Middle Okinawa Trough
NdI:0.51271- 0.51288
Aguni group
NdI:0.51275 - 0.51279
Ara dake volcanic rocks
NdI:0.51267 - 0.51272
South Okinawa Trough
NdI:0.51281 - 0.51291
Amami plutonic rocks
NdI:0.51232 - 0.51271
Tokunoshima plutonic rocks
NdI:0.51227 - 0.51273
Okinoerabu body
NdI:0.51251 - 0.51253
Nagahama dioritic body
NdI:0.51258 - 0.51268
Nishinomori complex
NdI:0.51260 - 0.51262
Omoto group
NdI:0.51251- 0.51258
Chayama group
NdI:0.51257 - 0.51259
30°N
125°E
30°N
25°N
130°E
25°N
125°E
-500 m
-1000 m
-2000 m
N
0 100 200 km

have values of 0.51271–0.51291. Moreover, the compositions of the Quaternary volcanic rocks of the Tokara islands and the Ryukyu Arc volcanic rocks show initial ratios of 0.51269–0.51291, whereas the front-arc plutonic rocks have a low initial ratio of the Nd isotopic compositions of 0.51227–0.51273. The initial ratio of the Sr isotopic compositions of igneous rocks distributed in the Ryukyu Arc are low for the back-arc Quaternary volcanic rocks in the Tokara islands and the Okinawa Trough and high in the front-arc plutonic rocks from the Cretaceous and Neogene. The initial ratio of the Nd isotopic compositions is high in the front-arc plutonic rocks from the Cretaceous and Neogene, and they are characteristically low for the back-arc Quaternary volcanic rocks from the Tokara islands and the Okinawa Trough. If we hypothesize that the initial ratios of the Sr and Nd isotopic compositions in Quaternary volcanic rock indicate the composition of the mantle under the Ryukyu Arc and that the mantle composition did not change significantly between the Cretaceous and the Quaternary, we can estimate that magma with an initial ratio of the Sr isotopic composition of approximately 0.705 and an initial ratio of the Nd isotopic composition of 0.51291 reacted with the upper crustal material to form rocks with different isotopic compositions.

Finally, let us consider why more reactions of the Ryukyu Arc magma occurred with the upper crustal material from the Cretaceous to the Neogene. Fig.8 shows that the initial ratio of the Sr isotopic composition increases with time and that at three instances, the initial ratio of the Nd isotopic composition decreases. The first instance was from the Uke body gabbro in the EC group to the Todoroki body in the LC group, the second was from the Yonama body in the LC group to the Kasari body in the PG group, and the third was from the Nagahama Diorites in the PG group to the Nishinomori Diorites in the NG group. Of these, the greatest change occurred between the Yonama body and the Kasari body, wherein the initial ratio of the Sr isotopic composition changed from 0.70466 to 0.70966 and the initial ratio of the Nd isotopic composition changed from 0.512696 to 0.512324. This change can be regarded as a change from the LC group to the PG group. Fig.5 shows that the LC group lies in the WPG region and the PG group in the VAG region; thus, one can estimate that the former comprised plutonic rocks active in the plate on the edges of the continent and the latter were active in the volcanic arc on the plate boundary. This implies the possibility that the change in the tectonics of the Ryukyu Arc promoted more severe reactions between the source magma and upper crustal material. One can also assume that the changes from the Uke body gabbro of the EC group to the Todoroki body in the LC group and that from the Nagahama Diorites of the PG group to the Nishinomori Diorites of the NG group were due to some type of changes in the tectonics. For example, one could estimate that the position of the source magma moved from inside the plate to front-arc side, because there was a change in the direction of the movement of the descending plate or in the angle of descent.

Conclusion

The plutonic rocks produced in the Ryukyu Arc between the Cretaceous and Neogene were categorized by their whole-rock chemical compositions, Sr isotopic compositions, Nd isotopic compositions, and active periods, which were divided into four groups for conducting a petrological study: the EC, LC, PG, and NG groups. The results clarify that in three geological events that occurred between the Cretaceous and Neogene, the source magma reacted with the upper crustal material and that the phenomena that occurred from the late Cretaceous to the Paleogene were due to a change in the tectonics in the Ryukyu Arc. Although this study could not elucidate the other two phenomena, it pointed out the possibility of a change in the plate movement direction or the angle of descent. In the future, if the tectonics of the Ryukyu Arc is revealed through a variety of geological approaches, one may be able to conduct a more detailed study on the formation process of plutonic rocks in the region.

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