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Regional variation of $^{87}Sr/^{86}Sr$ ratio in late Cenozoic volcanic rocks from southern Peru

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We determined the $^{87}Sr/^{86}Sr$ ratios of 53 late Cenozoic volcanic rocks collected in an area of 700km × 300km in southern Peru along the Central Andes volcanic arc. The measured $^{87}Sr/^{86}Sr$ ratios scatter largely, ranging from 0.7049 to 0.7082. The ratios roughly correlate with SiO_2 contents, suggesting that the source magma is contaminated by crustal materials during fractional crystallization process. The lowest value is obtained in a basaltic rock.

Regional variation in $^{87}Sr/^{86}Sr$ ratios is observed. In the along-arc direction from northwest to southeast, the ratios increase, reach the maximum value near Arequipa City and then decrease in accordance with the change of descending mode of the Nazca plate. The maximum $^{87}Sr/^{86}Sr$ ratio is observed in the region where the simple subduction of the Nazca plate is being distorted.

INTRODUCTION

The volcanic arc extends along the boundary between the Nazca and South America plates, parallel to the Peru-Chile Trench. This arc is usually divided into three parts, northern part (5°N-2°S), central part (14°S-28°S) and southern part (33°S-52°S). Volcanic rocks from each part are different in terms of petrography, major, minor and trace element chemistry and isotope composition (THORPE and FRANCIS, 1979). The central part, which is called the Central Andes arc in this paper, is characterized by its very thick crust of up to 70km (JAMES, 1971) and andesitic rocks are predominant in the area.

The Andean andesite has been considered to be the best example to elucidate the contribution of the crustal material to the arc magma genesis. Many geochemical investigations have been done concerning the genetic problems of the volcanic rocks in the Central Andes arc, and different conclusive models were reported. PICHLER and ZEIL (1972) claimed on the basis of major, trace element and $^{87}Sr/^{86}Sr$ characteristics that the andesitic magmas have originated through widespread partial fusion of the lower crust. THORPE *et al.* (1976) proposed on the basis of the rare-earth data a model of melting of the oceanic crust in the subduction zone. JAMES *et al.* (1976) suggested that volcanic rocks from southern Peru were the products of magmas derived from the thick lithosphere of the South America plate. A similar model was also suggested by HAWKESWORTH *et al.* (1979). Many other studies on Sr and other isotopes of the volcanic rocks from the Central Andes arc favored the assimilation model of continental crust material by the source magma (KLERKX *et al.*, 1977; DEPAOLO and WASSERBURG, 1977; FRANCIS *et al.*, 1977; BRIQUEU and LANCELOT, 1979; FRANCIS *et al.*, 1980; HARMON *et al.* 1981; DEPAOLO, 1981; and JAMES, 1982). For example, JAMES (1982) proposed a model on the basis of combined Sr, O, Pb and Nd isotope data that the andesite magma was subjected to crustal contamination during plagioclase fractional crystallization.

Recently, NOTSU (1983) and NOTSU *et al.* (1983) suggested that the spatial distributions of $^{87}Sr/^{86}Sr$ ratios in volcanic rocks in the Northeast Japan arc and the Izu-Ogasawara arc were indicative of the structure of the subduction. It is essential to make a $^{87}Sr/^{86}Sr$ ratio distribution map of the Central Andes arc for understanding the magma genesis of Andean andesites. However, as strontium isotope data of late Cenozoic volcanic rocks in southern Peru are only available in the limited regions (JAMES *et al.,* 1976; BRIQUEU and LANCELOT, 1979; and JAMES, 1982), it is difficult to draw the spatial distribution map of the ratios in the area as a whole.

In this work, we present the spatial distribution of $^{87}Sr/^{86}Sr$ ratios in late Cenozoic volcanic rocks in southern Peru, the northern part of the Central Andes arc. The results are discussed in relation to the magma genesis in the arc system with special interest in the relationship with subduction modes.

SAMPLES

Volcanic rock samples analyzed in this work were collected during the Japan-Peru joint-expedition entitled "Geochemical investigation of central Andes volcanic zone", sponsored by the Ministry of Education, Science and Culture of Japan. A total of 53 specimens of rock samples were selected with regard to the spatial distribution of their localities. They are all late Cenozoic volcanic rocks, including 40 andesites, 3 basalts, 2 dacites, 2 rhyolites, 5 shoshonites and one basanite. Figure 1 shows the sites of samples. Detailed sample localities and descriptions are reported by ARAMAKI *et al.* (1984). In Fig. 1, eight lines (A-H) are drawn perpendicular to the axis of the Peru-Chile Trench. The schematic underground structures of cross-

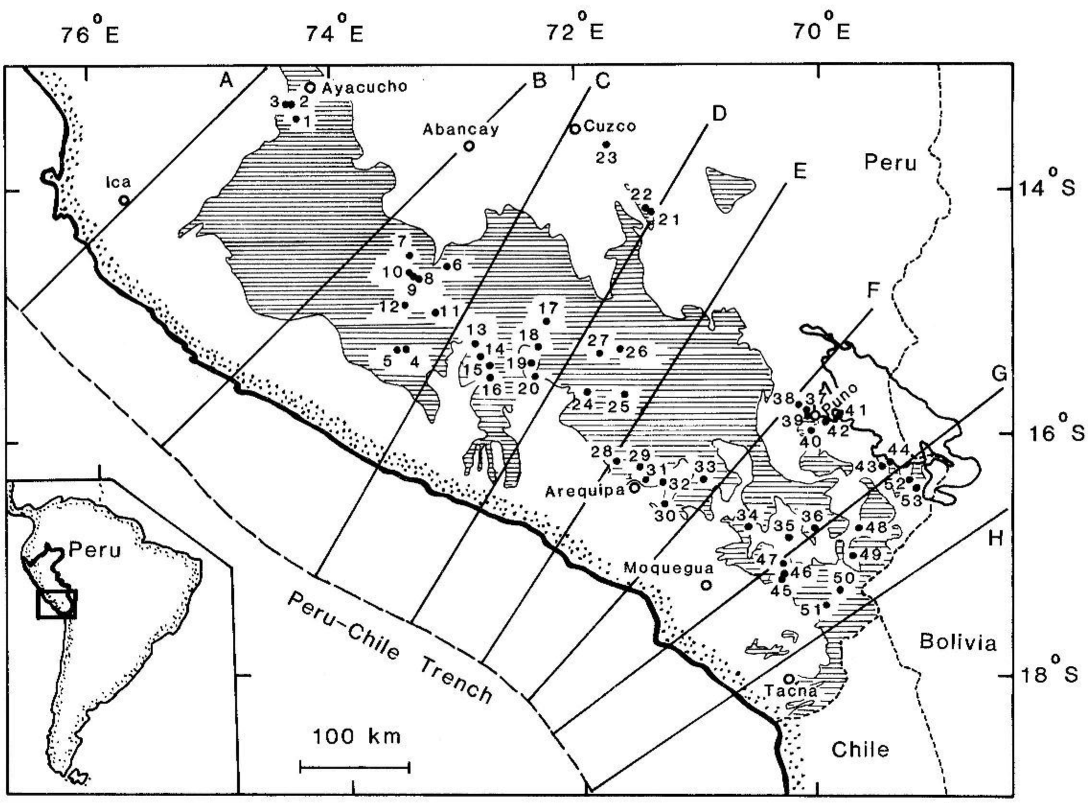

Fig. 1. Sample localities.
Numbers correspond to those in Table 1. Lines C-F denote the cross sections of Fig. 2. Hatched area denotes Cenozoic volcanic series (BELLIDO, 1979).

Table 1.

No.*	Sample No.	Rock type	SiO_2** (%)	Rb (ppm)	Sr (ppm)	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	Age*** (Ma)
A-B region								
1	A100	Andesite	65.54	99	685	0.421	0.70552	
2	A113	Andesite	52.54	38	504	0.219	0.70549	
3	A166	Rhyolite		134	613	0.636	0.70654	2.45 ± 0.06
B-C region								
4	PA02	Andesite	61.40	81	663	0.356	0.70590	1.62 ± 0.03
5	PA05	Andesite	60.57	71	658	0.314	0.70584	
6	PPD10	Andesite	56.27	80	702	0.332	0.70538	
7	PPD30	Basalt	51.95	25	891	0.082	0.70490	
8	PPD47	Basalt		44	814	0.157	0.70548	
9	PPD48	Rhyolite	74.10	175	133	3.830	0.70600	
10	PPD56	Basalt		32	1,336	0.070	0.70524	
11	PPD101	Andesite	55.10	84	2,525	0.097	0.70608	
12	PPD108	Andesite	60.20	83	703	0.344	0.70552	
C-D region								
13	CS05	Andesite	56.05	32	1,018	0.092	0.70609	1.19 ± 0.03
14	CS07-03	Andesite		95	790	0.350	0.70623	
15	CS09	Andesite	57.02	33	1,113	0.086	0.70607	1.02 ± 0.04
16	CS12-03	Andesite	63.50	108	773	0.407	0.70643	(0)****
17	OP03-01	Andesite		42	1,162	0.105	0.70598	
18	OP07	Andesite		171	285	1.747	0.70673	
19	OP10-02	Andesite	63.66	100	949	0.307	0.70618	
20	OP14-02	Andesite	56.93	33	919	0.105	0.70627	0.50 ± 0.07
21	CZ02-01	Shoshonite	56.71	162	1,226	0.385	0.70707	< 0.027
22	CZ03	Shoshonite	60.97	210	923	0.662	0.70765	
23	CZ04	Andesite	63.82	131	984	0.388	0.70670	< 0.7
D-E region								
24	CV01	Andesite	64.58	123	668	0.536	0.70687	
25	CV07-02	Andesite	58.37	55	1,276	0.125	0.70602	0.23 ± 0.05
26	CM01	Andesite	56.78	40	1,048	0.111	0.70706	3.77 ± 0.14
27	CM05-01	Andesite	55.21	36	1,083	0.097	0.70716	0.06 ± 0.23
E-F region								
28	AR07-02	Andesite	54.30	32	991	0.094	0.70677	0.28 ± 0.10
29	AR09	Andesite	63.12	80	691	0.337	0.70816	
30	AR12	Andesite	68.59	131	469	0.813	0.70768	
31	AR18	Andesite		47	784	0.175	0.70767	
32	CH02	Andesite	61.69	51	738	0.201	0.70763	6.71 ± 0.57
33	CH07	Andesite	60.62	77	765	0.293	0.70704	
F-G region								
34	OM03	Dacite	65.72	97	718	0.393	0.70690	
35	OM10	Andesite	62.06	107	498	0.625	0.70677	6.43 ± 0.20
36	OM16	Andesite	60.77	134	554	0.704	0.70596	
37	PU01	Shoshonite	59.67	90	1,129	0.232	0.70701	5.97 ± 0.20
38	PU03	Shoshonite	55.20	69	1,329	0.151	0.70649	5.05 ± 0.17
39	PU05	Shoshonite	55.44	73	1,017	0.209	0.70679	5.91 ± 0.16
40	PU07	Andesite	63.04	106	476	0.648	0.70727	
41	AC01	Basanite	49.99	60	1,501	0.116	0.70728	
42	AC04	Andesite	61.17	97	1,066	0.265	0.70699	
43	JL02	Andesite	61.24	131	895	0.426	0.70702	6.56 ± 0.64
44	JL03	Andesite	59.14	111	1,060	0.305	0.70651	
G-H region								
45	TA07	Andesite	59.76	69	688	0.292	0.70656	
46	TA10	Andesite	60.91	149	640	0.678	0.70658	6.23 ± 0.10
47	TA12	Andesite	63.00	97	613	0.461	0.70656	

(To be cont'd)

No.*	Sample No.	Rock type	SiO_2** (%)	Rb (ppm)	Sr (ppm)	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	Age*** (Ma)
48	MC03	Andesite	62.03	172	572	0.875	0.70640	3.20 ± 0.11
49	MC06	Dacite	67.96	206	346	1.733	0.70611	5.59 ± 0.11
50	MC11	Andesite	57.56	71	713	0.290	0.70643	
51	MC14	Andesite	58.77	84	633	0.386	0.70581	
52	JL10	Andesite	63.79	101	929	0.316	0.70708	
53	JL11	Andesite	55.15	71	1,630	0.127	0.70634	7.02 ± 0.09

* *These numbers correspond to those in Fig. 1.*
** *ARAMAKI et al. (1984).*
*** *KANEOKA and GUEVARA (1984).*
**** *Based on the field observation.*

sections along C, D, E and F lines are shown in Fig. 2. The mantle-crust boundary is drawn by referring to the contour map of the Moho discontinuity by JAMES (1971), and the upper boundary of the descending Nazca plate by HASEGAWA and SACKS (1984). It is obvious that the subducting feature of the Nazca plate changes in the along-arc direction, from northwest to southeast.

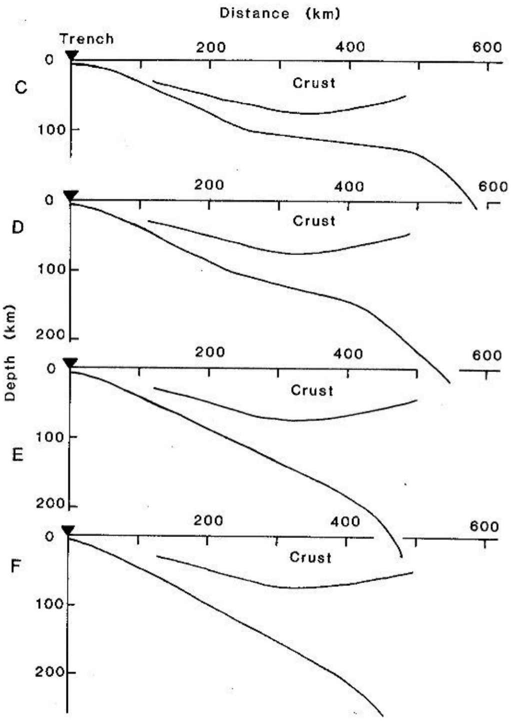

Fig. 2. Cross sections showing the mantle-crust boundary and the upper boundary of the descending Nazca plate.
Locations of C-F lines are shown in Fig. 1. Descending mode of the Nazca plate changes from the normal subduction (F), via the transitional one (D,E) and to the abnormal one (C).
(Data sources: JAMES, 1971; HASEGAWA and SACKS, 1984)

EXPERIMENTAL AND RESULTS

Experimental procedures for determination of strontium isotope compositions and concentrations of Sr and Rb were reported by NOTSU (1983). The strontium isotope compositions were determined on a VG-Micromass MM-30 double collector type mass spectrometer. The $^{87}Sr/^{86}Sr$ ratios of NBS 987 standard sample were 0.71028-0.71033 throughout this work. Concentrations of Rb and Sr were measured by X-ray fluolescence spectrometry.

Results are shown in Table 1. The uncertainty associated with $^{87}Sr/^{86}Sr$ ratio analyses is estimated to be less than 0.00005 from the replicated analyses of the standard sample. Uncertainties in Rb and Sr concentrations are less than ±5%. In Table 1, SiO_2 contents by ARAMAKI *et al.* (1984) and K-Ar ages by KANEOKA and GUEVARA (1984) are also listed.

The $^{87}Sr/^{86}Sr$ ratios in Table 1 are the observed values and no age correction is made for them, because the effect of the age correction on $^{87}Sr/^{86}Sr$ ratios is negligible for most samples. For example, the differences between measured and corrected ratios are less than 0.00004 for 19 samples out of 22 whose absolute ages are available, and less than 0.00002 for 17 out of 22 samples. Even for the sample with the maximum age correction (No. 49 - MC06), the difference is 0.00014.

DISCUSSIONS

General characteristics of the $^{87}Sr/^{86}Sr$ ratios in the Central Andes arc Our results show that the $^{87}Sr/^{86}Sr$ ratios in late Cenozoic volcanic rocks from southern Peru scatter in the range between 0.7049 and 0.7082. Published $^{87}Sr/^{86}Sr$ ratios of volcanic rocks in the Central Andes arc also scatter very largely. They are 0.7054-0.7080 for Arequipa and Barroso volcanics in southern Peru (JAMES *et al.*, 1976), 0.7055-0.7081 for the same two volcanics (BRIQUEU and LANCELOT, 1979), 0.7056-0.7116 for the Cerro Galan area in northwestern Argentina (FRANCIS *et al.*, 1980), 0.7057-0.7072 for San Pedro and San Pablo volcano complex in northern Chile (FRANCIS *et al.*, 1977), 0.7065-0.7080 for Cenozoic extrusives from northern Chile and northwestern Argentina (MCNUTT *et al.*, 1975), 0.7051-0.7133 for volcanic rocks in northern Chile, northwestern Argentina and southwestern Bolivia (KLERKX *et al.*, 1977) and 0.7053-0.7150 in the same three regions (DERUELLE *et al.*, 1983). In addition to these data, exceptionally low ratios were reported for 3 rock samples. Those are a low-Si latite (0.7042) and a low-Si andesite (0.7042) in central Peru, the northernmost region of the Central Andes arc (NOBLE *et al.*, 1975), and an alkali basalt (0.7041) in Bolivia (THORPE and FRANCIS, 1979). The $^{87}Sr/^{86}Sr$ ratios for rocks in southern Peru obtained in this work overlap the normal range of the ratios (above 0.7051) for those of the Central Andes arc, except for one sample (No. 7 - PPD30) with the ratio of 0.70490.

Compared with the $^{87}Sr/^{86}Sr$ ratios in volcanic rocks from other arcs in the world, those from the Central Andes arc are remarkably high and scatter largely. These characteristics have been explained in terms of the contamination by thick continental crust materials with higher $^{87}Sr/^{86}Sr$ ratios, as already mentioned.

It is suggestive that the lowest $^{87}Sr/^{86}Sr$ ratio of this work is obtained from one specimen of basaltic rock, which occurs rarely in the Central Andes arc. If the crustal contamination occurs together with fractional crystallization process, the $^{87}Sr/^{86}Sr$ ratios will change as the process proceeds. Figure 3 shows the relation between $^{87}Sr/^{86}Sr$ ratios and SiO_2 contents of volcanic rocks for each region. In the B-C region, where basaltic rock extrudes, the $^{87}Sr/^{86}Sr$ ratios seem to increase with increasing SiO_2 contents. Similar obscure trends are observed in the C-D, E-F, F-G and G-H regions lacking basaltic rocks. In the case of the C-D and F-G regions, basanite and shoshonite are excluded to obtain the trends, because these rocks are considered to be generated as a result of different fractionation process from basalt, andesite and dacite. Even

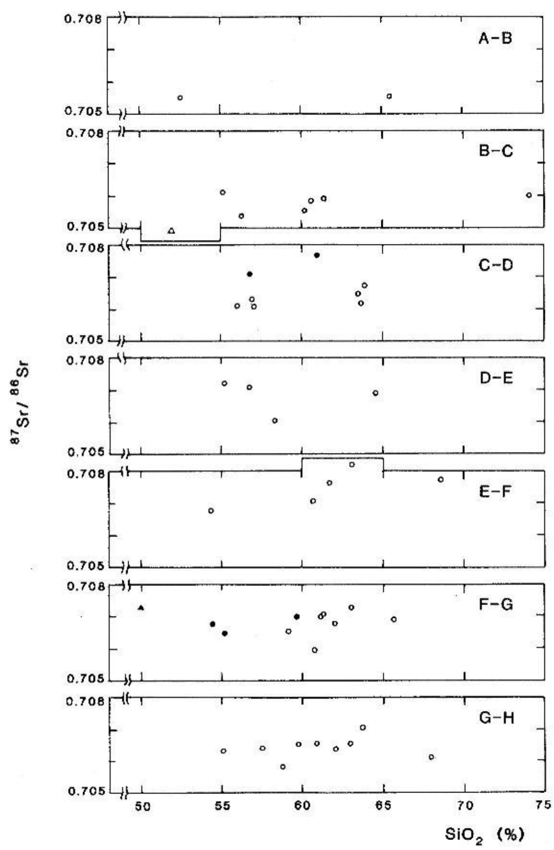

Fig. 3. Variation in $^{87}Sr/^{86}Sr$ versus SiO_2 in each region.

△ Basalt ○ Andesite, dacite and rhyolite

▲ Basanite ● Shoshonite

(Data source of SiO_2 contents: ARAMAKI et al., 1984)

in the same region, individual rock samples are considered to be the products extruded from different magma chambers, because most of them were collected from different lava flows of different volcanoes. They are not products of progressive fractional crystallization of a single source magma and hence they do not make a smooth trend on this diagram. Such rough correlations observed in several regions may be interpreted that the source magmas in the same region have similar $^{87}Sr/^{86}Sr$ ratios and that they are contaminated to varying extent by the crustal materials with high $^{87}Sr/^{86}Sr$ ratios. It is also suggested that the $^{87}Sr/^{86}Sr$ ratios of source magmas are regionally different. The lowest $^{87}Sr/^{86}Sr$ ratio (0.7049) in a basaltic rock in the B-C region is higher than the exceptionally low ratios (0.7041-0.7042) reported for samples in the Central Andes arc (NOBLE *et al.*, 1975; THORPE and FRANCIS, 1979). This may be due to the heterogeneity in the $^{87}Sr/^{86}Sr$ ratio of the source material beneath the Central Andes arc.

In order to make clear the cause of the large spread in the $^{87}Sr/^{86}Sr$ ratios in volcanic rocks from southern Peru, we must also take into account whether the ratios change with age or not. MCNUTT *et al.* (1975) showed that the initial $^{87}Sr/^{86}Sr$ ratios in the central Andes between 26°S and 29°S increased from 0.7022 to 0.7077 in the period from Mid Cretaceous to Quaternary. Out of all samples in this work, K-Ar ages have been determined on 21 samples (KANEOKA and GUEVARA, 1984). One sample (No. 16 - CS12-03) is identified as a historical lava flow on the basis of the field observation. A diagram between the $^{87}Sr/^{86}Sr$ ratio and K-Ar age is shown in Fig. 4, indicating that the ratios have not changed systematically during the last 8Ma, remaining with a large scattering range of the ratios.

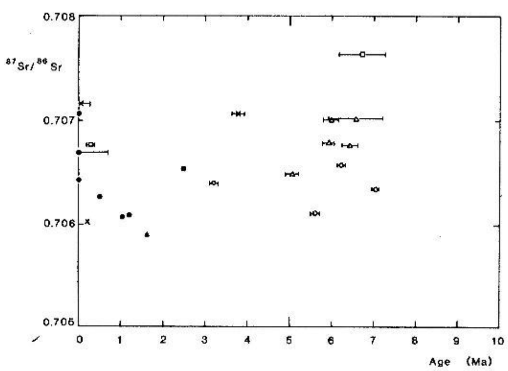

Fig. 4. Variation in $^{87}Sr/^{86}Sr$ versus age.
■ A-B ▲ B-C ● C-D x D-E □ E-F △ F-G ○ G-H region
(Data source of K-Ar ages: KANEOKA and GUEVARA, 1984)

Crustal assimilation in southern Peru In order to estimate the nature of the crustal contamination, $^{87}Sr/^{86}Sr$ ratios are plotted against the crustal thickness for all regions in Fig. 5. The crustal thickness of each sample site was taken from the contour map of the Moho discontinuity by JAMES (1971). No correlation between the $^{87}Sr/^{86}Sr$ ratios and the crustal thickness is observed for all regions. The ratios differ by more than 0.001 in sites with nearly the same crustal thickness. This means that the magnitude of the enhancement in the $^{87}Sr/^{86}Sr$ ratios during the crustal contamination process is not dependent on the crustal thickness, but on other factors such as local variation of the ratios of the crustal materials, the duration of assimilation, physical condition of magma chamber, etc.

Across-arc variation in $^{87}Sr/^{86}Sr$ ratios DUPUY and LEFÈVRE (1974) pointed out that shoshonitic rocks occur in areas far distant from the trench and that the chemical zoning is observed in the across-arc direction. In order to examine the across-arc variation in $^{87}Sr/^{86}Sr$ ratio, the ratios are plotted against the distances from the Peru-Chile Trench in each region (Fig. 6). In the A-B, D-E and E-F regions, rock samples are available only for so limited range of distance from the trench that it is difficult to check the across-arc variation. In the C-D, F-G and G-H regions, the ratios seem to increase with the increasing distance from the trench, though the data are scattered too largely to claim a definite conclusion. On the contrary, the ratios seem to decrease in the B-C region. These findings suggest that the $^{87}Sr/^{86}Sr$ ratio does not change systematically in the across-arc direction of the Central Andes arc.

Along-arc variation in $^{87}Sr/^{86}Sr$ ratios Regional variation in $^{87}Sr/^{86}Sr$ ratio is obvious in the histograms shown in Fig. 7. In the along-arc direction, the ratios increase from the A-B region, reach the maximum values in the E-F region and then decrease to the G-H region. Regional variation in the $^{87}Sr/^{86}Sr$ ratios in southern Peru was previously pointed out by JAMES *et al.* (1976), who showed that the ratios of Arequipa volcanics which are located in the E-F region in Fig. 1 were higher than those of Barroso volcanics mainly in the G-H region. Our data expand the results by JAMES *et al.* (1976) to broader areas, indicating the systematic variation in $^{87}Sr/^{86}Sr$ ratios in volcanic rocks from southern Peru in the along-arc direction.

JAMES (1982) calculated the $^{87}Sr/^{86}Sr$ ratios in the uncontaminated source magma of Arequipa and Barroso volcanic series, to be 0.7062-0.7067 and 0.7050-0.7052, respectively. The ranges of these values depend on the mixing models adopted for calculation. Our data may

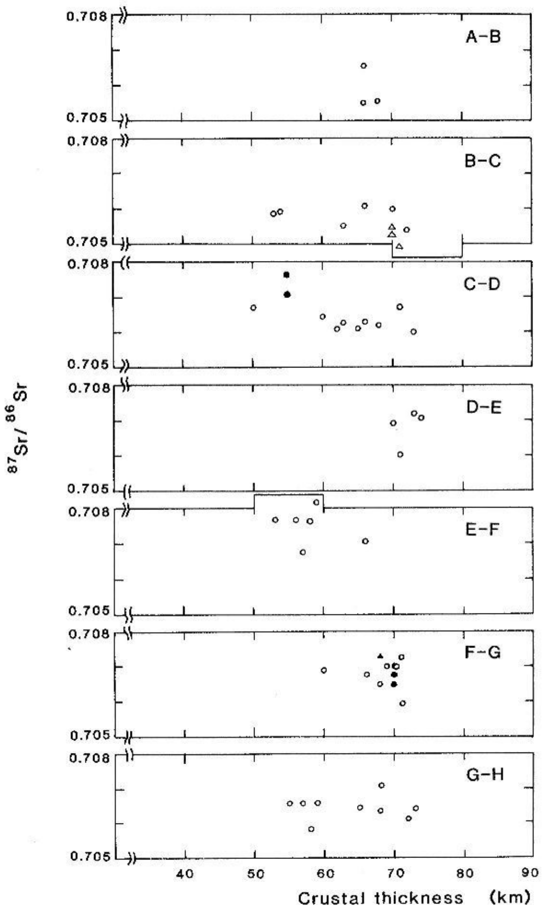

Fig. 5. Variation in $^{87}Sr/^{86}Sr$ versus crustal thickness.
△ *Basalt* ○ *Andesite, dacite and rhyolite*
▲ *Basanite* ● *Shoshonite*
(Data source of crustal thickness: JAMES, 1971)

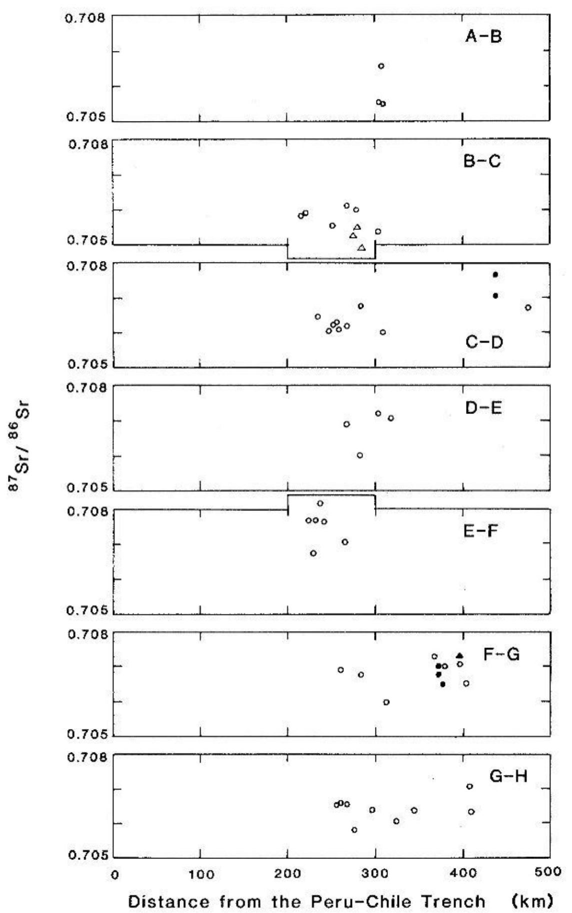

Fig. 6. Variation in $^{87}Sr/^{86}Sr$ versus distance from the Peru-Chile Trench.
△ *Basalt* ○ *Andesite, dacite and rhyolite*
▲ *Basanite* ● *Shoshonite*

also imply the $^{87}Sr/^{86}Sr$ ratios in the source magmas in each region. On the assumption that the enhancement in the $^{87}Sr/^{86}Sr$ ratios from the values of the source magma is dependent on the degree of fractional crystallization during the combined processes of fractional crystallization and crustal contamination, the ratios in less fractionated rocks such as basalt may approximate those in the source magma. This means the ratios of the source magma in the B-C region may be near or a little less than 0.7049. In other regions lacking basaltic rocks, it seems difficult to estimate the $^{87}Sr/^{86}Sr$ ratios in the source magma from our data. We can only guess that the ratios in the source magmas are at least less than the minimum values in each region. The minimum $^{87}Sr/^{86}Sr$ ratios in the E-F and G-H regions, which include Arequipa and Barroso volcanics, are obtained to be 0.7068 and 0.7058, respectively, in this work. These values are slightly higher than those in source magmas calculated by JAMES (1982). Therefore, the $^{87}Sr/^{86}Sr$ ratios in the source magma in the regions lacking basaltic rocks are expected to be slightly less than the lowest values analyzed in this work.

The $^{87}Sr/^{86}Sr$ ratio of the source magma is considered to change parallel to the trend of the variation of the $^{87}Sr/^{86}Sr$ ratios in the volcanic rocks, in the along-arc direction. From northwest to southeast, the ratios in the source magma increase from a little less than 0.7049 in the B-C region, reach the maximum value of about 0.7065 in the E-F region and then decrease.

Why the $^{87}Sr/^{86}Sr$ ratios in the source magma change in the along-arc direction with the maximum value in the E-F region? According to HASEGAWA and SACKS (1981), the subducting structure of the Nazca plate is different under southern Peru and under central Peru, as shown in Fig. 2. In the former area (F-H region), the Nazca plate subducts simply to the depth of 600km with a dip angle slightly increasing with depth (normal subduction), while in the latter (A-C region), it subducts with 30° dip angle to the depth of 100km, bends to a nearly horizontal angle, extending about 300km and then goes down with a steeper angle (abnormal subduction). In the transition zone (C-F region) between the normal and abnormal subduction areas, the descending Nazca plate is distorted. The maximum $^{87}Sr/^{86}Sr$ ratios are observed on the southeastern side of the transition zone. Therefore, components with high $^{87}Sr/^{86}Sr$ ratios might be supplied from the Nazca plate to the mantle wedge beneath the E-F region more effectively.

CONCLUSIONS

The $^{87}Sr/^{86}Sr$ ratios in late Cenozoic volcanic rocks from southern Peru in the Central Andes arc range from 0.7049 to 0.7082, which are significantly higher than those from other subduction areas in the world.

The lowest $^{87}Sr/^{86}Sr$ ratio is obtained in a basaltic rock. The large variations in the ratios may be due to the different degree of the crustal contamination.

Regional variation in $^{87}Sr/^{86}Sr$ ratios is observed. In the along-arc direction, from northwest to southeast, the ratios increase, reach the maximum value in the E-F region and then decrease in accordance with the changes of descending mode of the Nazca plate. It is suggested that the ratios in the source magma also change in a similar fashion. The maximum $^{87}Sr/^{86}Sr$ ratios are obtained in the region where the simple subduction of the Nazca plate is distorted.

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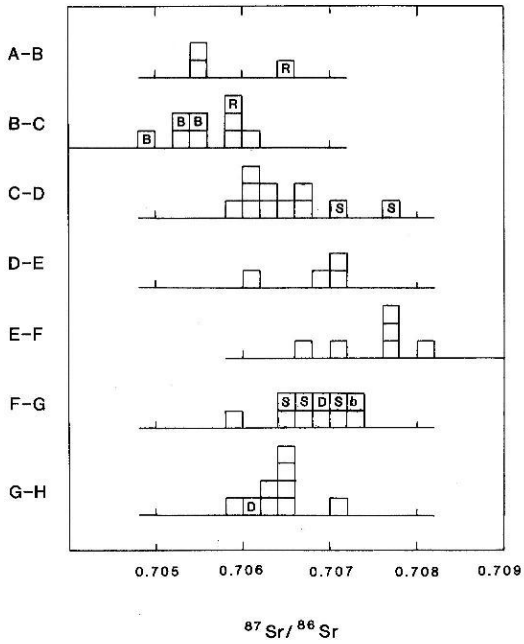

Fig. 7. Along-arc variation in $^{87}Sr/^{86}Sr$.
[B] *Basalt* [ ] *Andesite* [D] *Dacite*
[R] *Rhyolite* [b] *Basanite* [S] *Shoshonite*

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