GEOCHEMICAL STUDY OF VOLCANIC PRODUCTS, IN PARTICULAR TO PUMICE FLOW, OF THE KRAKATAU GROUP, INDONESIA

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GEOCHEMICAL STUDY OF VOLCANIC PRODUCTS, IN PARTICULAR TO PUMICE FLOW, OF THE KRAKATAU GROUP, INDONESIA

By

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Abstract

In referring to the genetical consideration for the mechanism of formation of the 1883 Krakatau pumice flow, the geochemical relation between the pumice flow and lithic fragments of granitic rock found from the pumice flow was discussed. Following to the discovery of foreign lithic fragments of granitic rock found from the pumice flow in 1981, more several lithic fragments of granitic rock and other different kinds of fragments, i.e., metabasic igneous rock, tuff, and glassy andesite, presumably, of cogenetic material, were newly found from the pumice flow in 1982. From several evidences, it should be considered that the lithic fragments of granitic rock came from the underlying complex at depths, where the fragments were captured as foreign materials by magma. The pumice flow significantly differs in both mineral and chemical compositions against all kinds of volcanic rocks and ejecta of the Krakatau Group, called for the whole islands of Anak Krakatau, Small Rakata, Rakata and Sertung. Thus, it may possibly be considered that sialic crustal materials, such as granitic rocks and sediments those which occur in Sumatra, plunged into depths along the peculiar tectonic structure locating at the Sunda Strait waters between Sumatra and Java, and were partially melted and mixed with or assimilated by the ascending basaltic magma, and, as a result, dacitic magma distinctly dominant in silica, alkalies and volatile components as compared to any other volcanic rock and ejecta of the Krakatau Group, was produced, and the 1883 Krakatau eruption characterized by the pumice flow of dacitic composition took place.

Besides, the distributions in question for 1972-1973 and 1975 lava flows were renewed, and those for 1963 and 1979 lava flows were corrected in part in this paper. Stratigraphic successions, in particular to the relation between the pumice flow, a product of the 1883 eruption, and the pre-1883 volcanic products at Small Rakata, Rakata and Sertung were established. Volcanic rocks and ejecta of the Krakatau Group were also geochemically and petrographically reviewed.

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Introduction

Following to 1981, field work was done at the Krakatau Group, called for the whole islands of Anak Krakatau, Small Rakata, Rakata and Sertung, Indonesia in 1982. Courses where geological survey was taken and localities where samples were collected are shown in Figs. 1 and 2. Laboratory works on mineral and chemical compositions of lava flows, ejecta and pumice flow have been carried out. Major attention will be given in this paper to geochemical nature of volcanic products, in particular to pumice flow, a volcanic product of the 1883 Krakatau eruption; and to genetical consideration of the pumice flow in relation to lithic fragments of granitic rock found from the pumice flow.

Geology

1. Anak Krakatau

Anak Krakatau Volcano Island, for which simply Anak Krakatau will be used here, is a double cone consisting of an outer cone, which may possibly be a pyroclastic cone (ŌBA and others, 1982) (Fig. 7, A), and an inner cone characterized by the frequent summit eruption of volcanic ejecta with gases at the present time.

Since the field work in 1981, some questions, in particular to the distributions of lava flows of 1972-1973, 1975 and of unknown-age at Anak Krakatau have been remained. The distributions of lava flows in question were dissolved on the field work in 1982. Geologic

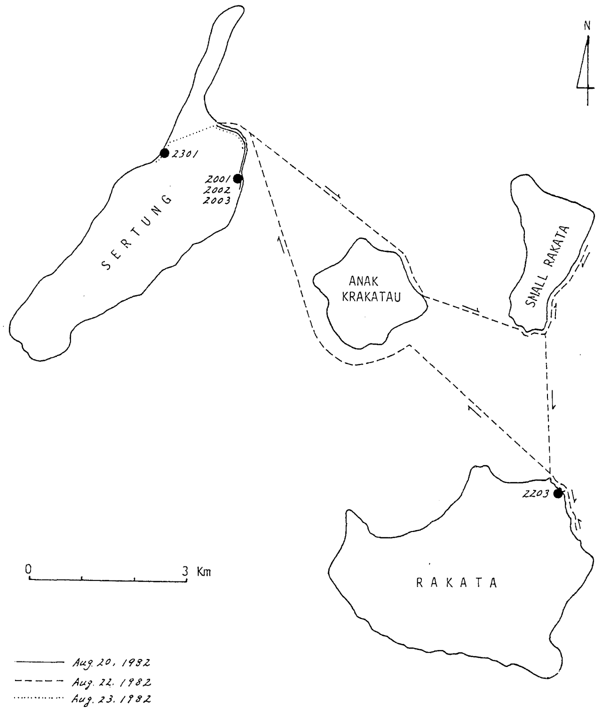

Fig. 1. Courses where geologic observation was done and localities where samples were collected at Small Rakata, Rakata and Sertung of the Krapatau Group, Indonesia. Attached numbers show sample no.

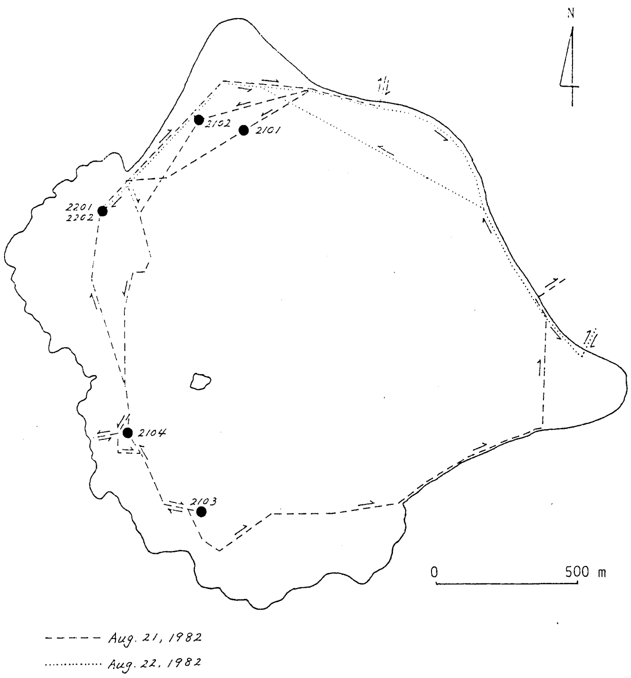

Fig. 2. Surveyed courses at Anak Krakatau, Indonesia. Solid circles and attached numbers represent localities where samples were collected.

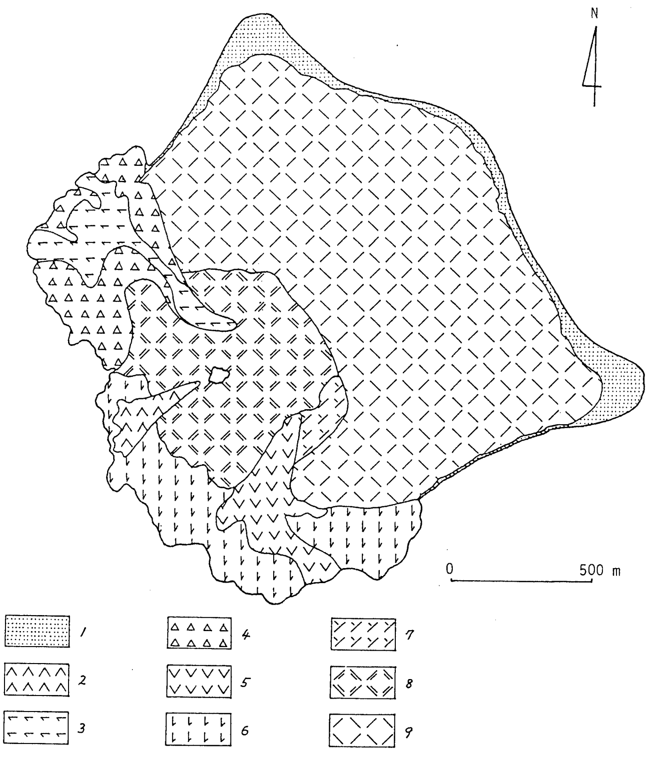

Fig. 3. Geologic map of Anak Krakatau, compiled from the published geologic maps and this work. Stratigraphic sequence: 1. alluvial deposits; 2. 1979 lava flow; 3. second stage lava flow of 1975; 4. first stage lava flow of 1975; 5. 1973 lava flow; 6. 1972 lava flow; 7. 1963 lava flow; 8. scoria and lithic block of the inner cone; 9. scoria and lithic block of the outer cone. See Fig. 9, A and B, Fig. 10, A.

map showing the distributions of lava flows could be established, and, accordingly, the former geologic map of Anak Krakatau (ŌBA and others, 1982) was renewed in this paper, as is shown in Fig. 3 : 1972-1973 lava flow in the former geologic map was divided into 1972 lava flow (see a in Fig. 7, A and B) and 1973 lava flow (see b in Fig. 7, A), and 1975 lava flow in the former geologic map was divided into two ; first stage- and second stage-lava flows (see b in Fig. 7, B, and a and b in Fig. 8, A). The distribution-area for 1963 lava flow and that for 1979 lava flow (see c in Fig. 7, B) on the former geologic map were corrected in part, as is shown in Fig. 3.

2. Small Rakata, Rakata and Sertung

Small Rakata

The schematic columnar section, which was taken at the exposure along the sea-coast of the southern extreme of Small Rakata, showing volcanostratigraphic seccession is

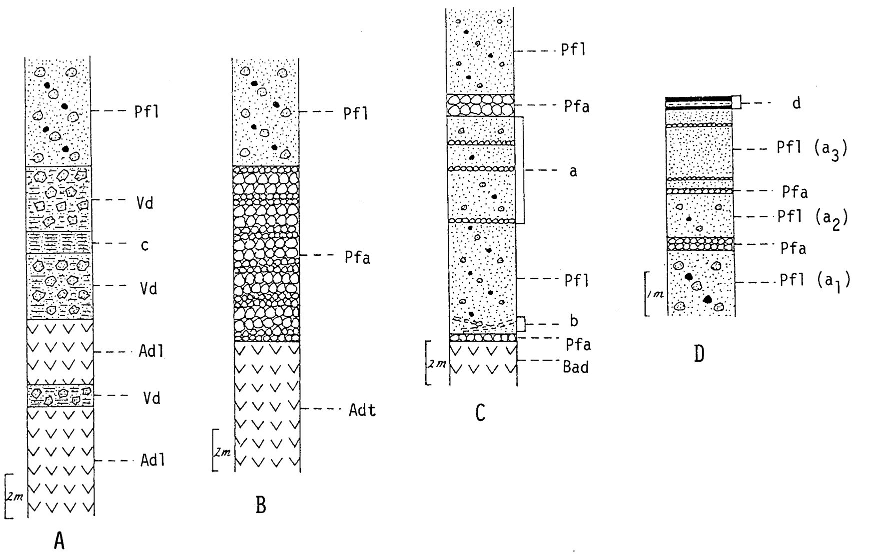

Fig. 4. Schematic columnar sections showing the stratigraphic relation between the 1883 Krakatau pumice flow and the pre-1883 volcanic products at Small Rakata, Rakata and Sertung, Krakatau Group, Indonesia.

A. Showing the relation between the 1883 pumice flow (top) and the pre-1883 volcanic products (middle and low) at the exposure of the southern extreme of Small Rakata. See Fig. 8, B and C.

B. Showing the relation between volcanic products of the 1883 Krakatau eruption, i.e., pumice fall (middle) and pumice flow (top), and lava flow of andesite (low), one of the basement complex of the pre-1883 volcanic products at the exposure on the northeastern sea-coast of Rakata. Sample no. 2203, andesite, was collected here. See Fig. 9, A, B and C.

C. Mode of occurrence of the pumice flow at the exposure on the eastern sea-coast of Sertung. Samples of no. 2001, 2002 and 2003 were collected here.

D. Mode of occurrence of the pumice flow at the exposure on the northwestern sea-coast of Sertung. See Fig. 8, D and E.

Abbreviations.-Pfl, pumice flow ; Pfa, pumice fall ; Adl, lava flow of andesite ; Adt, lava flow of augite-hypersthene andesite with cavities filled by tridymite ; Bad, lava flow of basaltic andesite ; Vd, volcanic debris. a. a_1, a_2, a_3 and b : pumice flows.-a, with air fall ; a_1. coarse-grained ; a_2. medium-grained ; a_3. fine-grained with air fall ; b. with pyroclastic surge. c. rock with pyroclastic surge ; d. soil.

shown in Fig. 4, A. The pumice flow, which will be used in this paper in place of pyroclastic flow as will be mentioned later (see "pumice flow" in Fig. 4, A), at upper most is one of the 1883 volcanic products, and others at lower half are volcanic products of the pre-1883 eruption (see Fig. 8, B and C).

Rakata

Volcanostratigraphic relation between the 1883 volcanic products and the pre-1883 volcanic rocks was examined at the exposure on the northeastern sea-coast of Rakata. It was recognized that pumice fall of 8 m in thickness, a volcanic product preceeding to the pumice flow erupted in 1883, occurs, and lava flow of augite-hypersthene andesite is overlaid by the pumice fall, as is shown in the schematic columnar section Fig. 4, B and Fig. 9, A, B and C.

Sertung

At the exposure on the eastern sea-coast of Sertung, as is shown in the schematic columnar section Fig. 4, C, showing the stratigraphic succession, the pumice flow is repeatedly accompanied with air fall, and pyroclastic surge can also be observed on its base. The pumice flow is interculated with a pumice fall of 1 m in thickness, so it looks to be composed of two flow units. However, there is scarecely time gap between the pumice flow and the pumice fall. Therefore, it can be considered, as a whole, to be one flow unit. Schematic columnar section for the pumice flow which occurs at the exposure on the northwestern sea-coast of Sertung is given in Fig.4, D (see Fig. 8, D and E). There were found many kinds of fragments, such as granitic rock, metabasic igneous rock, tuff and black-colored glassy andesite, from the pumice flow.

Petrography

Eleven samples, in which six from Anak Krakatau, one from Rakata and four from

Table 1. Rock types and localities of samples collected from the Krakatau Group, Indonesia

SAMPLE NO.	LOCALITIES	ROCK TYPES	NOTES
2001	Sertung	Basaltic andesite	Lava of unknown age
2002	Sertung	Pumice	From pumice fall of 1883 eruption
2003	Sertung	Pumice flow	Product of 1883 eruption
2101	Anak Krakatau	Basaltic andesite	Bomb
2102	Anak Krakatau	Basaltic andesite	Bread-crust bomb
2103	Anak Krakatau	Basaltic andesite	1972 lava
2104	Anak Krakatau	Basaltic andesite	1979 lava
2201	Anak Krakatau	Basaltic andesite	Second stage lava of 1975
2202	Anak Krakatau	Pumice	Accompanied by bomb
2203	Rakata	Augite-hypersthene andesite with cavities filled by tridymite	Lava of unknown age
2301	Sertung	Granitic rocks, metabasic igneous rock and others	Lithic fragments found from 1883 pumice flow

Total 11 samples.

Table 2. Renewed name of lava flows of Anak Krakatau, listed in Table 1 of the former paper*

SAMPLE NO.	LOCALITIES	ROCK TYPES	RENEWED NAME OF LAVA FLOWS
504	Anak Krakatau	Olivine-bearing hypersthene-augite andesite	1973 lava
506	Anak Krakatau	Olivine-bearing hypersthene-augite andesite	1973 lava
507	Anak Krakatau	Olivine-bearing hypersthene-augite andesite	1973 lava
605	Anak Krakatau	Olivine-hypersthene-augite andesite	First stage lava of 1975
606-A	Anak Krakatau	Basaltic andesite	1972 lava
606-B	Anak Krakatau	Basaltic andesite	1972 lava

* Ōba and others (1982).

Sertung, of lava flows, pumice flow and lithic fragments were collected at the Krakatau Group for geochemical and petrographical investigations. Sample no., localities and rock types of collected samples are listed in Table 1.

As a result of the correction in the distributions for 1972-1973, 1975 and 1979 lava flows on the former geologic map of Anak Krakatau, name of lava flows of sample nos. 504, 506, 507, 605, 606-A and 606-B in Table 1 of the former paper (ŌBA and others, 1982) were renewed, as is shown in Table 2. Thin sections were made of twelve samples of pumice flow and lithic fragments for microscopic examination.

1. Anak Krakatau

Volcanic rocks which make a major portion of lava flows at the inner cone are basaltic andesite, represented by olivine-hypersthene-augite andesite and olivine-bearing hypersthene-augite andesite in rock type. Phenocrystic minerals are plagioclase, augite, hypersthene, olivine and titanomagnetite. The groundmass, which is characterized by the hyalopilitic texture, is assembled by plagioclase microlite, augite, hypersthene, titanomagnetite and a large amount of brown-colored volcanic glass. Major mineral constituents of volcanic ash erupted out from the inner cone in 1981 are essentially the same as those of volcanic rocks.

2. Small Rakata, Rakata and Sertung

(1) Small Rakata

The basement of Small Rakata is composed mainly of agglutinate lava flow, lithologically, of olivine-bearing hypersthene-augite andesite which has the pilotaxitic texture in the groundmass with an amygdaloidal pattern.

Xenoliths, contained in rock of the agglutinate lava flow, show the intergranular texture consisting of phenocrystic minerals and interstitial augite micrograins which fill lath-shaped plagioclase microlites. They are quite the same as augite andesite which occurs as lava flow at Rakata in both phenocrystic minerals and the groundmass texture.

This fact suggests that the xenoliths were captured from the underbeneath, where augite andesite may have been one of the constituents of the "Krakatau Volcano" before the 1883 eruption or the ancient "Krakatau Volcano".

(2) Rakata

The basement complex of Rakata is composed mainly of augite andesite, augite-hypersthene andesite and olivine basalt. Augite andesite, characterized by phenocrystic plagioclase and augite and the groundmass of the intergranular texture, occurs as lava flow and is intruded by many small dikes of olivine basalt whose groundmass has the intersertal texture. Augite-hypersthene andesite occurs as lava flow and is accompanied by many cavities fllled with an aggregate of tridymite crystal.

(3) Sertung

The basement of Sertung is composed of olivine-hypersthene-augite andesite which occurs as lava flow and has the hyalopilitic texture in the groundmass. The following facts are recognized in the andesite: most phenocrystic plagioclases are saussuritized in their cores; some phenocrystic olivines are serpentinized in part; and some phenocrystic pyroxenes are chloritized.

3. Pumice flow of the 1883 Krakatau eruption

Pumice flow, characterized by abundant pumice and dacitic composition in both chemical and mineral compositions in many cases, is used in a narrow sense against pyroclastic flow which is used in a broad sense for volcanic product which was formed from the so-called "nuée ardente"; i.e., "glowing avalanche", "glowing cloud", "hot cloud" ("awan panas" in Indonesia) and so on. In this sense, pumice flow is appropriate to call for

Table 3. Modal compositions (vol. %) of the 1883 Krakatau pumice flow and the Ata and Aira "Shirasu" pumice flows

No.		1	2	3
Analyzed samples		1883 Krakatau pumice flow	Ata "Shirasu" pumice flow	Aira "Shirasu" pumice flow
Analysts		T. Ishii	T. Ishii	K. Inoue & K. Yokoyama
Grain size (mesh)		60-115	60-115	
Felsic minerals	Volcanic glass	92.2	87.1	86.5
	Plagioclase	5.7	9.5	7.7
	Quartz	n.p.	n.p.	1.8
Mafic minerals	Orthopyroxene	0.6	1.4	1.1
	Clinopyroxene	0.4	0.9	0.2
	Hornblende	n.p.	0.1	0.1
	Opaque mineral*	1.1	0.9	2.6
	Others	p.	0.1	0.1

1.Collected at Sertung, Krakatau, Indonesia, sample no. 811, new analysis; 2. collected at Ōnejime, Kagoshima, Japan, sample no. 66122505, new analysis; 3. arithmetic mean of 3 modal analyses, data from Ōba and othes (1980); p, present; n. p., not present. *Magnetite and other iron oxide.

one of the volcanic products of the 1883 Krakatau eruption to be discriminated from pyroclastic flow, for example, lithificated rock which was formed from "glowing avalanche" or "nuée ardente" from Galunggung Volcano in referring to the suggested genetical classification for volcanic fragmental rocks proposed by Department of Geology, Gadjan Mada University, Indonesia (WIDIASMORO and others, 1977).

Pumice flow which was erupted out in 1883 occurs at Small Rakata, Rakata and Sertung, those which are isolated one another and roughly correspond to the wall of the

Table 4. Chemical analyses (wt. %) of the 1883 Krakatau pumice flow and the Ata and Aira "Shirasu" pumice flows

No.		1	2	3
Analysts		M. Yamamoto	N. Ōba & H. Ebihara	N. Ōba & H. Ebihara
SiO_2		65.22	65.37	70.91
TiO_2		0.71	0.64	0.24
Al_2O_3		14.18	15.44	14.05
Fe_2O_3		1.39	3.77	0.83
FeO		2.16	1.65	0.97
MnO		0.13	0.10	0.09
MgO		1.10	0.93	0.54
CaO		2.54	3.51	2.20
Na_2O		4.91	3.34	3.31
K_2O		2.15	1.69	2.56
H_2O-		4.76	3.06	3.14
H_2O+		0.58	0.50	0.55
P_2O_5		0.15	0.15	0.07
Total		99.98	100.15	99.46
Q		21.19	30.99	36.14
Or		12.71	9.99	15.13
Ab		41.55	28.26	28.01
An		10.30	16.43	10.46
Di	Wo	0.55	-	-
	En	0.31	-	-
	Fs	0.22	-	-
Hy	En	2.43	-	1.35
	Fs	1.67	-	1.20
Mt		2.02	3.79	1.20
Il		1.35	1.22	0.46
Ap		0.35	0.35	0.16
C		-	2.09	2.17
Hm		-	1.16	-
En		-	2.32	-

1. 1883 Krakatau pumice flow, Sertung, Krakatau, Indonesia, sample no. 811; 2. arithmetic mean of 2 analyses of Ata "Shirasu" pumice flow, Kagoshima, Japan; 3. arithmetic mean of 13 analyses of Aira "Shirasu" pumice flow, Kagoshima, Japan. References: 1, from ŌBA and others (1982); 2, from ŌBA and others (1967a); 3, from ŌBA and others (1980). Normative minerals were calculated by J. NAKAMURA.

Table 5. Modal analyses (vol. %) of lithic fragments of granitic rock aound from the 1883 Krakatau pumice flow

Sample no.	811-1*	2301-a**
Quartz	11.5	16.6
Plagioclase	54.0	47.2
Potash feldspar	24.9	29.4
Biotite	6.4	0.8
Hornblende	-	3.5
Opaque mineral	3.1***	2.4
Others	-	0.1

Analyst : S. KIYOSAKI. *from ŌBA and others (1982). **New analysis in this paper. *** Opaque mineral and others. Samples were collected at Sertung, Krakatau, Indonesia.

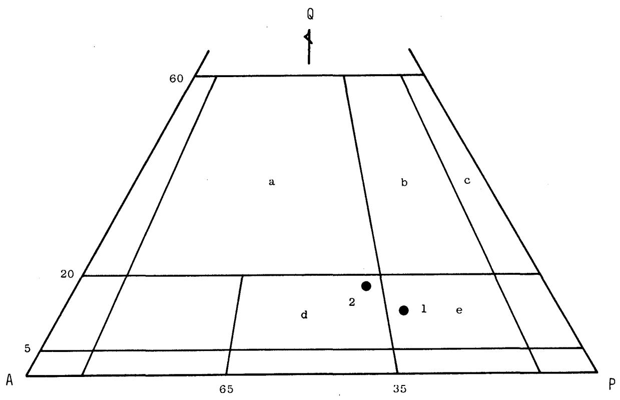

Fig. 5. Plots of lithic fragments of granitic rock found from the 1883 Krakatau pumice flow on the modal Q(quartz)-A(alkali feldspar)-P(plagioclase) diagram. 1 and 2 : analyzed lithic fragments of granitic rock, sample no. 811-1 and 2301-a, found from pumice flow at Sertung, Krakatau Group, Indonesia. a, granite ; b, granodiorite ; c, tonalite ; d, quartz monzonite ; e, quartz monzodiorite.

Krakatau caldera, for which there is a discussion on whether it is an explosion caldera or a depression caldera. Pumice fall preceeding to the successive eruption of the pumice flow overlays the basement complex composed mainly of volcanic rocks of these islands.

The pumice flow is composed of plagioclase, hypersthene, augite, a large amount of volcanic glass with microlite, a small amount of ore minerals and an accompanying apatite. Modal analysis of the pumice flow, sample no. 811, from Sertung is given in Table 3. For comparison, modal compositions of Ata and Aira "Shirasu" pumice flows which came from Ata and Aira calderas (ŌBA and others, 1967a, b), having been believed to have had the so-called "Krakatau-type" eruption, Kagoshima, South Kyushu, Japan, are also tabulated in the same table. Pumices of 2-3 cm in diameter are contained as the essential material in the pumice flow. The matrix of the pumice flow is, in mineral composition, essentially the same as pumice itself contained in it.

4. Lithic fragments found from the 1883 Krakatau pumice flow

Three different kinds of foreign lithic fragments, i.e., granitic rock, metabasic igneous rock and tuff, and another kind of lithic fragment of black-colored glassy andesite, presumably, of cogenetic rock, were found from the pumice flow.

(1) Lithic fragments of granitic rock

In 1981, a lithic fragment of granitic rock of 5 cm in diameter was found from the pumice flow which occurs on the southeastern sea-coast of Sertung. Later, another one small fragment of the same rock was found from the collected same sample at laboratory room. From such a fact, it was suggested that this kind of lithic fragment may be much more contained in the pumice flow (ŌBA and others, 1982 ; ŌBA and others, in contribution). In 1982, several lithic fragments of granitic rock, one of which reaches about 30 cm in maximum size, were found together with other different kinds of lithic fragments from the pumice flow which occurs on the northwestern sea-coast of Sertung (see Fig. 4, D, and Fig. 8, D and E).

The lithic fragments of granitic rock are composed of quartz, plagioclase, potash feldspar, biotite alone or both of biotite and hornblende, and opaque mineral. Modal analyses of the rocks are given in Table 5. According to the classification and nomenclature of plutonic rocks by the IUGS Subcommission on the Systematics of Igneous Rocks (1973), as seen from Fig. 5, the rocks range in modal composition from quartz monzonite to quartz monzodiorite. The rock is characterized by the presence of well-developed myrmekites which are common in granodiorite in its texture.

(2) Lithic fragment of metabasic igneous rock

Only one lithic fragment of metabasic igneous rock of about 10 cm in diameter was newly found together with other different kinds of fragments from the pumice flow which occurs on the northwestern sea-coast of Sertung. None of metamorphic rock occurs throughout over the Krakatau Group, and lithic fragment of metamorphic rock has never been reported from the Krakatau Group. Therefore, it should be considered that the lithic fragment of metabasic igneous rock came from the underlying complex at depths, where it was captured as a foreign material by magma.

(3) Fragments of tuff

Several numbers of fragments of tuff in various sizes were collected together with other different kinds of lithic fragments at the exposure of the pumice flow on the northwestern sea-coast of Sertung. These are grey-colored tuff, with or without stratification, and, rarely, with a fused thin skin, for which much interest is concerned.

(4) Lithic fragments of glassy andesite

Many lithic fragments in various sizes of black-colored glassy andesite are contained in the pumice flow at Sertung. Some of them are extremely vitreous, and, sometimes, very much porous. Thus, some of them look obsidian or obsidian-like andesite, and, sometimes, they are gradationally changed into pumice. Such a fact appears to suggest that this kind of lithic fragment may not be foreign material, but cogenetic material which was derived from the same source magma of the pumice flow. Besides, lithic fragments of altered andesite were also observed at the exposure of the pumice flow at Small Rakata.

Mineralogy

Alunite crystals occur as masses of platy ones on the surface of the slope of the inner cone at Anak Krakatau. They occur at places where volcanic materials were subjected to solfataric alteration. As the results obtained from X-ray diffraction, differential thermal analysis, scanning electron microscopy and infrared absorption spectra, some of them could be identified to natroalunite, which is very close to the sodium end member of alunite-natroalunite series (TOMITA and others, 1982). Besides, gypsum crystals occur as a needle-shaped crystal on the thermally altered andesite at Anak Krakatau.

Geochemistry

Basaltic andesite of the 1979 lava flow (sample no. 2104) and pumice of unknown age (sample no. 2102-B) from Anak Krakatau, olivine-bearing hypersthene-augite andesite of agglutinate lava flow (sample no. 805) from Small Rakata, augite-hypersthene andesite with cavities filled by tridymite and augite andesite of lava flows (sample no. 806 and 809) and olivine basalt of dike (sample no. 810-B and 810-C) from Rakata, and basaltic andesite of lava flow (sample no. 2001) and lithic fragment of granitic rock (sample no. 2301-a) found from the pumice flow from Sertung, were chemically analyzed by a combination of the gravimetric method for SiO_2 and $H_2O\pm$, the colorimetric method for TiO_2 and P_2O_5, the atomic absorption method for Al_2O_3, total Fe, MnO, MgO, CaO, Na_2O and K_2O, and the volumetric method for FeO. Chemical analyses are given in Tables 6 and 7 together with their CIPW normative compositions.

Table 6. Chemical analysis (wt. %) and CIPW norms of lithic fragment of granitic rock found from the 1883 Krakatau pumice flow

Sample no.	2301-a			
SiO_2	69.18	Q		20.77
TiO_2	0.62	Or		16.25
Al_2O_3	14.01	Ab		46.12
Fe_2O_3	1.25	Di	Wo	2.96
FeO	2.38		En	1.29
MnO	0.05		Fs	1.67
MgO	0.75	Hy	En	0.57
CaO	2.70		Fs	0.74
Na_2O	5.45	Mt		1.81
K_2O	2.75	Il		1.18
H_2O+	0.48	Ap		0.23
H_2O-	0.22			
P_2O_5	0.10			
Total	99.94			

Analyst: M. Yamamoto. New analysis.

Table 7. Chemical analyses and CIPW norms of volcanic products from the Krapatau Group

No.	1	2	3	4	5	6	7	8
Sample no.	2104	2102-B	805	806	809	810-C	810-B	2001
SiO_2	53.64	60.22	64.28	69.28	49.00	48.00	48.54	62.40
TiO_2	1.04	0.97	0.85	0.52	0.96	0.95	0.96	0.96
Al_2O_3	18.15	16.97	15.44	14.89	20.16	18.89	18.83	15.79
Fe_2O_3	3.16	2.20	1.64	2.26	3.14	3.92	3.56	2.03
FeO	6.02	4.33	4.06	1.59	6.40	6.81	6.67	4.01
MnO	0.19	0.17	0.16	0.11	0.18	0.20	0.19	0.14
MgO	4.30	2.27	1.83	0.61	4.35	5.30	5.42	1.73
CaO	8.30	5.65	3.85	2.19	10.81	10.01	10.23	4.61
Na_2O	3.53	4.55	4.57	5.36	2.54	2.56	2.52	4.46
K_2O	0.85	1.43	2.10	2.56	0.35	0.36	0.30	1.91
H_2O+	0.27	0.54	0.77	0.44	0.83	1.70	1.62	0.83
H_2O-	0.08	0.02	0.16	0.26	0.92	0.66	0.64	0.82
P_2O_5	0.28	0.27	0.14	0.09	0.11	0.14	0.11	0.23
Total	99.81	99.59	99.85	100.16	99.75	99.50	99.59	99.92
Q	4.99	12.34	17.40	23.05	2.18	1.21	1.71	16.20
Or	5.02	8.45	12.41	15.13	2.07	2.13	1.77	11.29
Ab	29.87	38.50	38.67	45.36	21.49	21.66	21.32	37.74
An	31.17	21.66	15.41	9.01	42.58	38.99	39.18	17.42
Di Wo	3.41	1.92	1.16	0.53	4.32	4.07	4.53	1.65
Di En	1.96	1.01	0.55	0.38	2.40	2.40	2.69	0.80
Di Fs	1.30	0.86	0.60	0.10	1.75	1.47	1.61	0.81
Hy En	8.75	4.65	4.01	1.14	8.44	10.80	10.81	3.51
Hy Fs	5.78	3.99	4.40	0.30	6.16	6.60	6.47	3.55
Mt	4.58	3.19	2.38	3.28	4.55	5.68	5.16	2.94
Il	1.98	1.84	1.61	0.99	1.82	1.80	1.82	1.82
Ap	0.65	0.63	0.32	0.21	0.25	0.32	0.25	0.53

Analyst: M. YAMAMOTO. 1. 1979 lava flow of basaltic andesite, Anak Krakatau; 2. pumice of unknown age, Anak Krakatau; 3. agglutinate lava flow of olivine-bearing hypersthene-augite andesite, Small Rakata; 4. lava flow of augite-hypersthene andesite with cavities filled by tridymite, Rakata; 5. lava flow of augite andesite, Rakata; 6. olivine basalt, margin of dike which cuts augite andesite lava flow (sample no. 809); 7. olivine basalt, core of dike (sample no. 810-C); 8. lava flow of basaltic andesite, Sertung.

1. Lava flows and ejecta of the Krakatau Group

Lava flows and ejecta of Anak Krakatau represent geochemically almost the same characteristic feature, common to basaltic andesites of typical volcanoes of island arcs of western and northern Pacific and Caribbean regions (ŌBA and others, 1982). Plotting of new analytical data of volcanic rocks and ejecta from the Krakatau Group in addition to the former analytical data on the MIYASHIRO's (1974) SiO_2-total FeO/MgO diagram (Fig. 6), the plots representing volcanic rocks and ejecta of Anak Krakatau fall within a field of the tholeiitic series and are clustered nearby the plot representing an average composition of basaltic andesites of Pacific and Caribbean island arcs. Meanwhile, the plots of rocks of basic type and those of rocks of acidic type from the basement complex of the Krakatau Group are scattered in a wide range, though all of them fall within the field of the tholeiitic

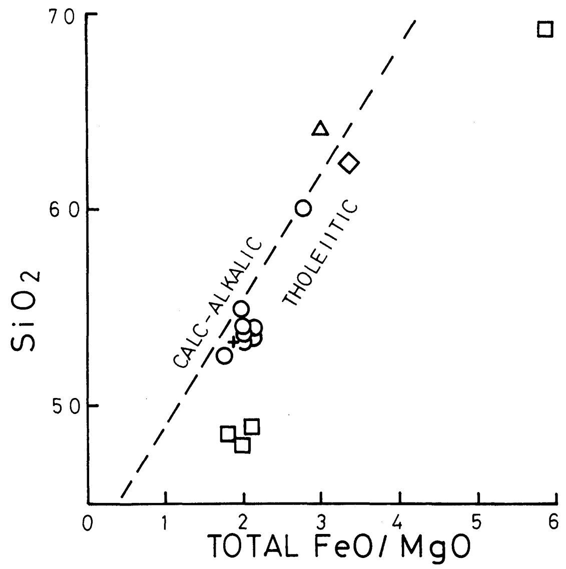

Fig. 6. Plots of analyzed volcanic rocks and ejecta from the Krakatau Group on MIYASHIRO's (1974) SiO_2-total FeO/MgO diagram. The dashed line represents the general boundary between the calc-alkalic rock series and the tholeiitic series for non-alkalic volcanic rocks of western Pacific island arcs. Symbols.-circles, volcanic rocks and ejecta from Anak Krakatau ; triangle, volcanic rock (lava) from Small Rakata ; squares, volcanic rocks (lavas and dike) of basic and acidic rock types from Rakata ; rhombus, volcanic rock (lava) from Sertung ; plus, an average composition of basaltic andesites of typical volcanoes of island arcs of western and northern Pacific and Carribean regions (EWART, 1976).

series, except one from Small Rakata. It seems that scattering in the plots on the diagram suggests each different stages in the processes during magmatic differentiation at each activities of the "Krakatau Volcano".

2. 1883 Krakatau pumice flow

The 1883 Krakatau pumice flow is significantly different in chemical composition against any other volcanic rock of the Krakatau Group ; characteristically the pumice flow is rich in SiO_2 and alkalies, but, in contrast, poor in MgO, FeO and CaO. Naturally, a large amount of normative quartz and orthoclase are calculated (Table 4). Thus, it can be said that in chemical composition the pumice flow is dacitic.

For comparison, chemical analysis of the Krakatau pumice flow and arithmetic means of chemical analyses of Ata "Shirasu" pumice flow and Aira "Shirasu" pumice flow are tabulated in the same Table 4. As seen from this, the 1883 Krakatau pumice flow is, in chemical composition, similar to Ata "Shirasu" pumice flow rather than Aira "Shirasu" pumice flow.

Geochemical consideration for the mechanism of formation of the 1883 Krakatau pumice flow

1. Petrogenic significance of lithic fragments of granitic rock found from the 1883 Krakatau pumice flow

None of granitic rock occurs throughout over the whole islands of the Krakatau Group, and lithic fragment of granitic rock has never been reported from the 1883 Krakatau pumice flow which occurs in Small Rakata, Rakata and Sertung, except only one quartz diorite inclusion which was found at Pandjang (Small Rakata) according to DE NÉVE (1981a, b).

Lithic fragments of quartz monzonite and quartz monzodiorite in modal composition found from the pumice flow at Sertung, therefore, should be considered that they came from the underlying complex at depths, where they were captured as foreign materials by magma. Meanwhile, the pumice flow significantly differs in both mineral and chemical compositions against all volcanic rocks of the Krakatau Group. The pumice flow is characterized, in mineral composition, by abundant volcanic glass in a vesiculating state that vesicles or bubbles contained in the volcanic glasses are expanding and escaping gases, and, in chemical composition, by the high-contents of silica and alkalies and the low-contents of magnesia, ferrous iron oxide and lime; it is dacitic.

Thus, it may possibly be considered that the pumice flow would have genetically been related with the underlying granitic complex in regard to the generation of its source magma. The lithic fragments of granitic rock found from the pumice flow will be important to discuss the mechanism of the 1883 Krakatau eruption.

2. Genetical consideration of the 1883 Krakatau pumice flow

Some of calderas of Japan, such as Ata and Aira, is believed to have had such a great eruption as called "Krakatau-type". Therefore, geochemical comparisons between the pumice flow from Krakatau caldera and pumice flows from Ata and Aira calderas and between volcanic rocks of the Krakatau Group and those of volcanoes related to the Ata and Aira calderas will be worthful to obtain the informations concerning the mechanisms of their eruption and magma genesis.

With respect to the genesis of the so-called Ata and Aira "Shirasu" pumice flows in a narrow sense and pyroclastic flows in a broad sense, prevailing over South Kyushu, Japan, ŌBA and others (1976b) concluded that genetically the "Shirasu" pumice flows are, in general, closely related with granitic materials in a broad sense, such as granitic rocks and sediments, e.g., pelitic and psammitic rocks, and suggested that the "Shirasu" pumice flows came from one source magma, which was produced through assimilation of granitic materials in a broad sense by the essential magma in the processes of differentiation.

The composition of any melt would depend on that of the source rock, phase chemistry and the degree of melting (CARMICHAEL and others, 1974). It was noted by ŌBA and others (1967b) that individual "Shirasu" pumice flow is correlative in chemical character with individual adjacent granitic rock which occurs as batholith or rock body. Ignimbrites and tuffs at Lake Toba, Sumatra, Indonesia, appears to be related to the peculiar tectonic setting of Sumatra, and plate movement appears to be taken up in part at least (WHITFORD, 1975), along the transcurrent Semangko Fault which extends along the length of Sumatra and possibly into West Java (FITCH, 1972). WHITFORD (1975) showed that rhyolitic ignimbrite and tuff from Lake Toba have an $^{87}Sr/^{86}Sr$ ratio, 0.7139, very much higher than that for any other analyzed lava from the Sunda arc, and such a ratio argues for crustal derivation rather than a mantle origin for these rocks. Such a consideration will be useful to account the mechanism of formation of the 1883 Krakatau pumice flow.

On the basis of the experimental framework for the complex synthetic system gabbro-tonalite-granite-H_2O, WYLLIE and others (1976) suggested that the batholiths may be generated in different ways from different sources, and argued that batholiths composed of granite are readily generated in the continental crust. The experimental work by WYLLIE and TUTTLE (1961a) showed that shales begin to liquefy at temperatures ranging from 700° to 800℃, under water activities produced by about 2 kb H_2O pressure ; liquids of granodioritic composition are produced. If alkalies and volatile components such as HF and NaF are present in addition to water, shales begin to melt at lower temperatures (KOSTER VAN CROOS and WYLLIE, 1968 ; WYLLIE and TUTTLE, 1961b). WINKLER and v. PLATEN (1961a, b) established that granitic, granodioritic and tonalitic melts can be formed by the partial melting of sediments such as shale and greywacke as a result of their experimental studies.

Thus, an suggestion to account for the genesis of the 1883 Krakatau pumice flow is that sialic crustal materials, such as granitic rock and sediments those which occur in Sumatra, those which plunged into the depths along the peculiar tectonic structure locating at the Sunda Strait waters between Sumatra and Java, were partially melted, and mixed with or assimilated by the ascending basaltic magma, and dacitic magma distinctly dominant in silica, alkalies and volatile components was produced, and, as a result, the 1883 Krakatau eruption characterized by the pumice flow of dacitic composition took place.

Meanwhile, the fragments of tuff found from the pumice flow may have been derived from the overlying sediments on the plunged sialic crustal materials, because very thick abyssal clastic sediments are subducted in the Sumatra trench (HAMILTON, 1973) and the thick sediments pile was pushed up into an actual island chain (KATILI, 1975). The fragment of metabasic igneous rock found from the pumice flow should be considered that it came from basic or ultrabasic rocks at depths when the dacitic magma travelled upward.

Before and after the 1883 Krakatau eruption, tholeiitic magma would have been generated by partial melting of rocks of basic and ultrabasic composition at depths, where seismic activity and the occurrence of volcanism in island arcs are good correlative. NICHOLLS and RINGWOOD (1973) and NICHOLLS (1974) suggested that parental magmas are olivine- to quartz-normative tholeiites produced by partial melting of hydrous peridotite at relatively shallow depths (<70 km). The tholeiitic magma in which differentiation was advancing would have been contaminated with the plunged sialic crustal materials, such as granitic rock and sediments those which occur in Sumatra, in the processes of its upward transfer. Thus, volcanic activities characterized by basaltic andesite in composition took place before and after the 1883 Krakatau eruption.

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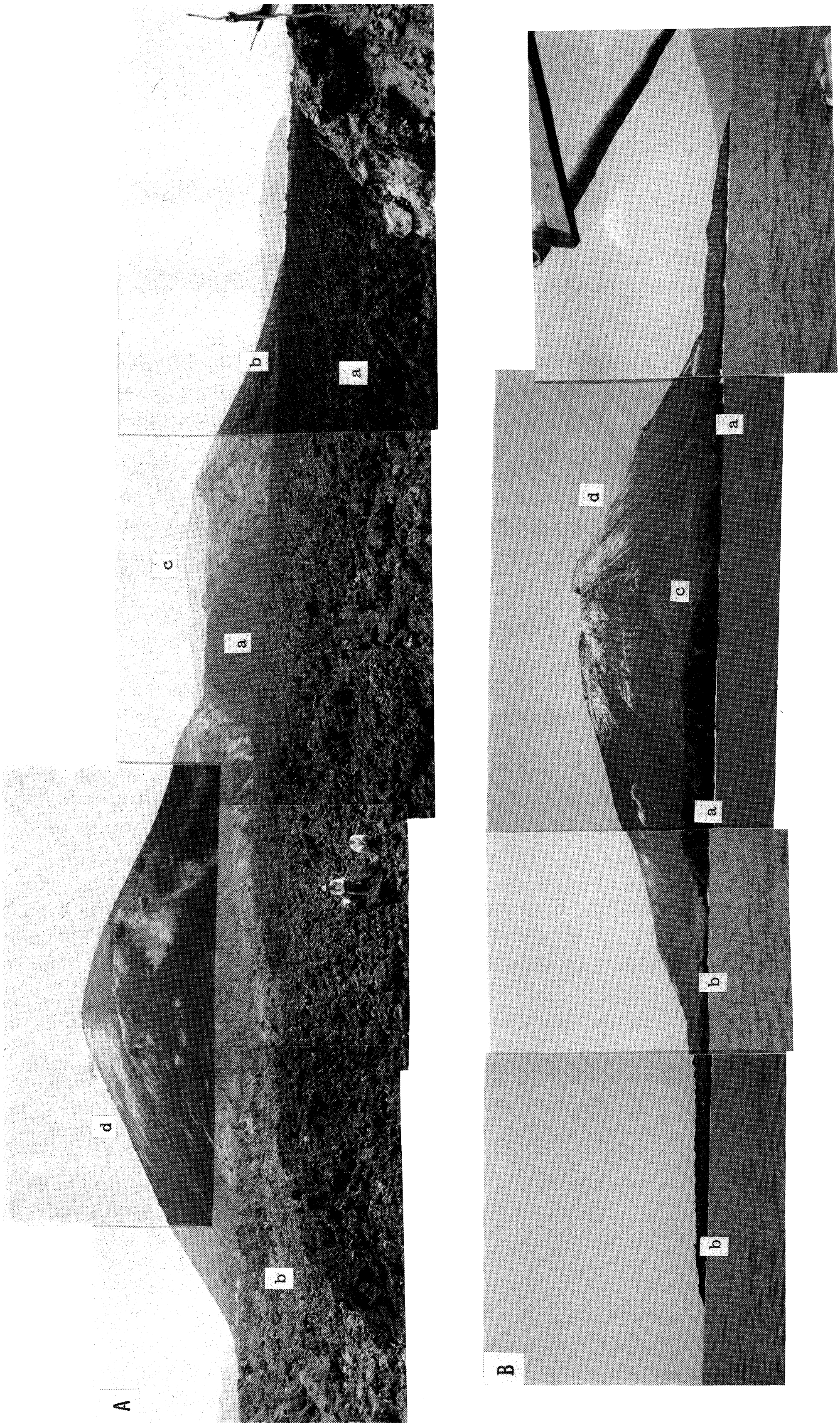

Fig. 7. Distribution of lava flows at Anak Krakatau.
A. Distributions of 1973 lava flow (a) and 1972 lava flow (b) at Anak Krakatau, a double cone, composing of an outer cone (c) and an inner cone (d). Photo taken from south towards north at the southern foot. See Fig. 3. Small Rakata, background at right.
B. Distibutions of 1972 lava flow (a), the first stage lava flow of 1975 (b) and 1979 lava flow (c) at the southwestern foot of the inner cone (d) of Anak Krakatau. Photo taken from southwest towards northeast on the fishing boat. See Fig. 3. Rakata, background at right.

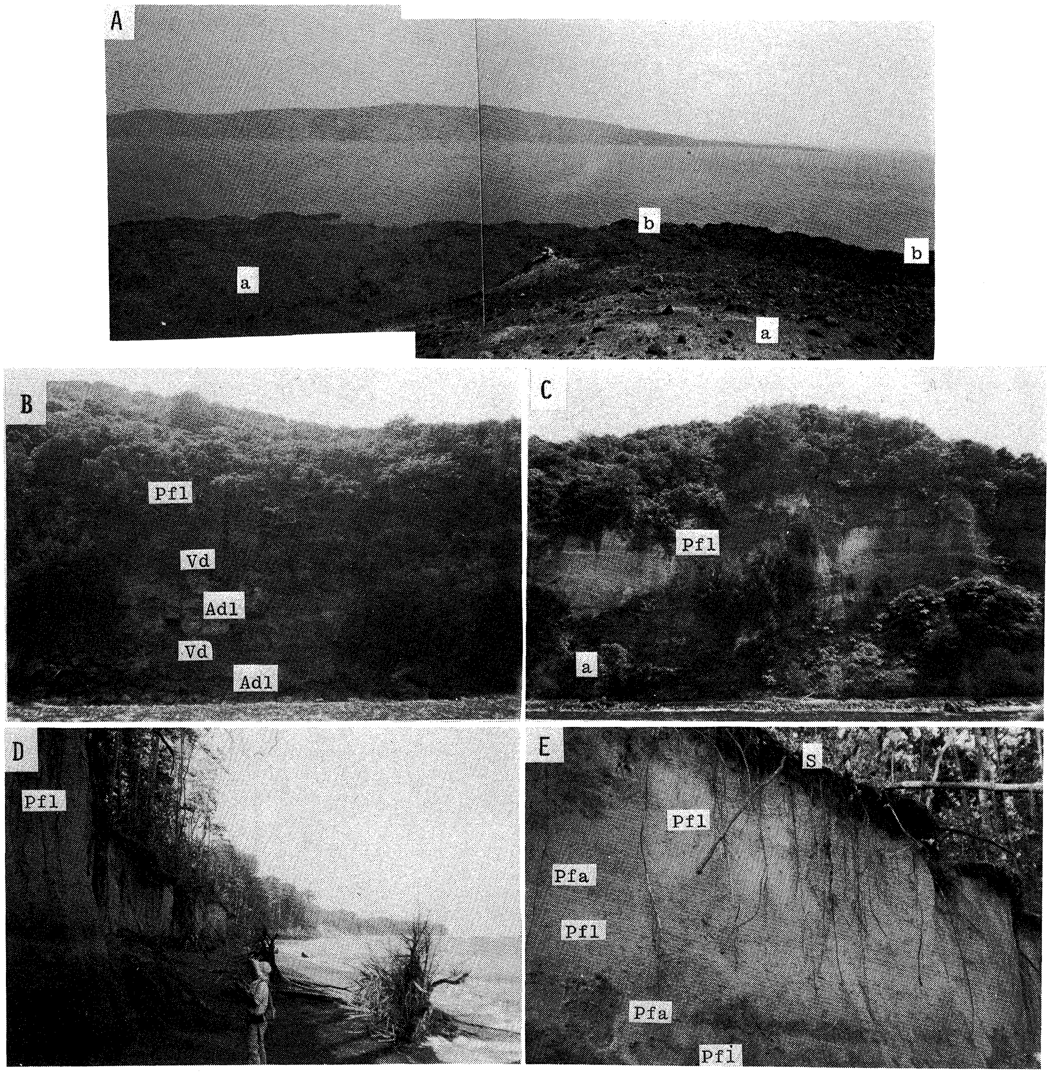

Fig. 8. Distribution of lava flows at Anak Krakatau, exposures of the 1883 Krakatau pumice flow and the pre-1883 volcanic products at Small Rakata, and mode of occurrence of the 1883 pumice flow at Sertung.

A. Distributions of the first stage lava flow of 1975 (a) and the second stage lava flow of 1975 (b) at Anak Krakatau. Photo taken from east towards west at the western slope of the inner cone of Anak Krakatau. See Fig. 3. Sertung, upper.

B. Exposure showing volcanostratigraphic succession of the 1883 pumice flow and the pre-1883 volcanic products at Small Rakata. See Fig. 4, A. Photo taken for the southern extreme of Small Rakata on the fishing boat.

C. Exposure of pumice flow, volcanic product of the 1883 Krakatau eruption, at Small Rakata. a. pre-1883 volcanic products. Photo taken for the southern most of Small Rakata. See Fig. 4, A.

D. Mode of occurrence of the 1883 Krakatau pumice flow at the exposure along the north-western sea-coast of Sertung.

E. Same. See Fig. 4, D.

Abbreviations.-Pfl, pumice flow ; Pfa, pumice fall ; Adl, lava flow of andesite ; Vd, volcanic debris ; S, soil.

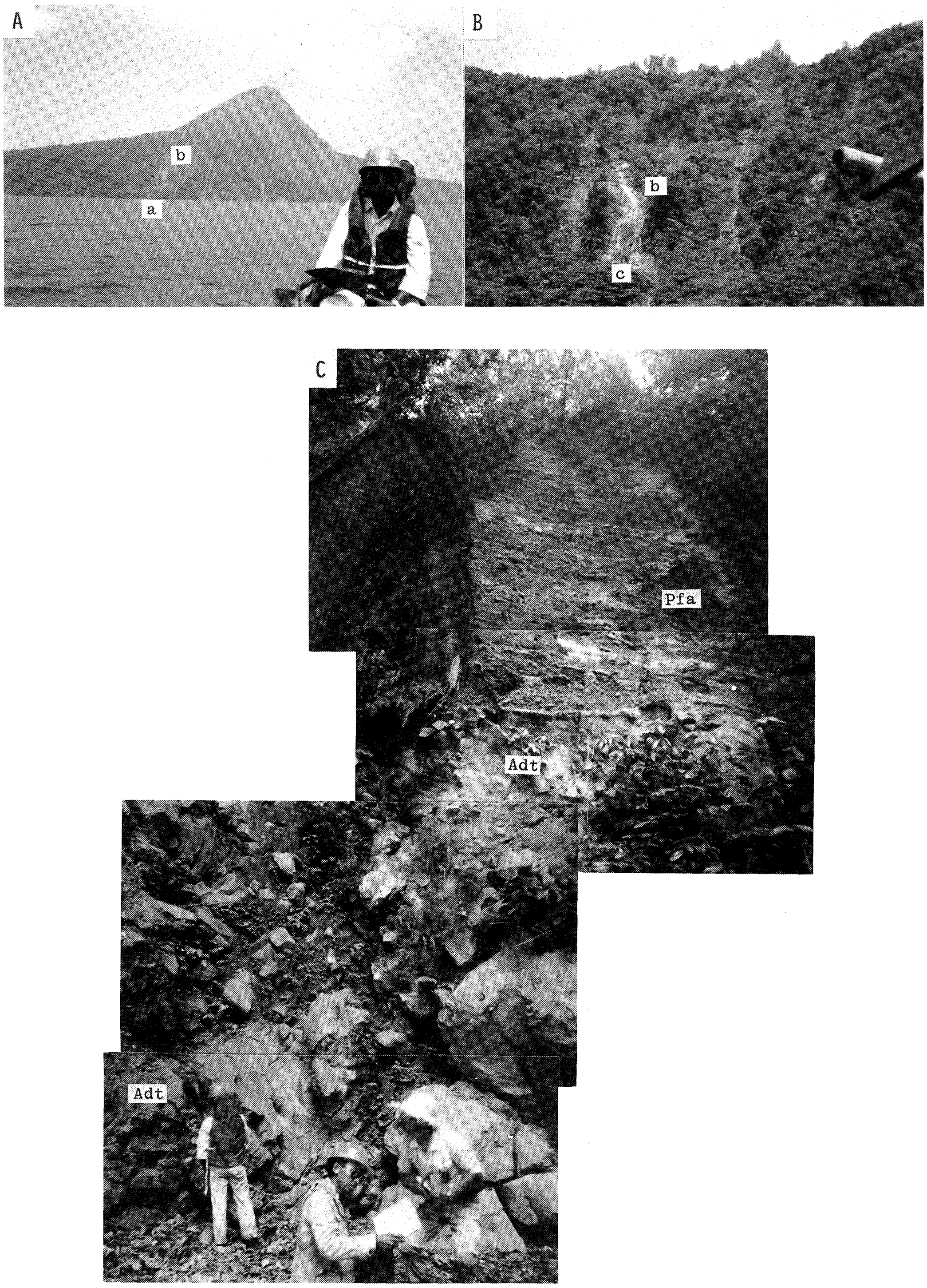
A
b
a
B
b
c
C
Pfa
Adt
Adt

Fig. 9. Mode of occurrence of the 1883 pumice flow and the volcanostratigraphic relation between the 1883 pumice flow and the pre-1883 volcanic products at Rakata.

A. Distance view of the northwestern sea-coast of Rakata, landed point (a) and the exposure of the 1883 pumice flow (b) where the stratigraphic relation between the pumice flow and the pre-1883 volcanic products was observed.

B. Close up of the exposure of the 1883 pumice flow (b) and the pre-1883 volcanic products (c) at the same landed point as a in the former A.

C. Showing the stratigraphic relation between the 1883 pumice flow and the pre-1883 volcanic products, one of the basement complex of Rakata, at the same exposure as in the former B. See Fig. 4, B. The pumice fall is overlaid by the pumice flow just over the top of the exposure.

Abbrevations.-Pfa, pumice fall ; a preceeding product of the successive pumice flow in the 1883 Krakatau eruption ; Adt, lava flow of augite-hypersthene andesite with cavities filled by tridymite.