BULLETIN OF THE EARTHQUAKE
RESEARCH INSTITUTE
UNIVERSITY OF TOKYO
Vol. 66 (1991) pp. 151-177

Report on DELP 1988 Cruises in the Okinawa Trough
Part 6: Petrology of Volcanic Rocks

Masanori ISHIKAWA[1], Hiroaki SATO[2],
Masahide FURUKAWA[3], Masaki KIMURA[4], Yuzo KATO[4],
Ryosuke TSUGARU[4] and Kiyoshi SHIMAMURA[5]

[1] Department of Marine Mineral Resources, Tokai University
[2] Fac. Integ. Arts and Sci., Hiroshima University
[3] Department of Earth Science, Kobe University
[4] Department of Marine Sciences, University of the Ryukyus
[5] School of Agriculture, Kyushu Tokai University

(Received May 15, 1990)

Abstract

During the DELP-88 Cruise, a large amount of volcanic rocks was collected from five dredge sites in the Southern Okinawa Trough and the Middle Okinawa Trough. Samples from the central graben structure (DR3, DR8) show the chemical compositions of calc-alkaline rock or tholeiitic rock of Island Arc type, as reported previously. The results are concordant with geophysical data suggesting that oceanic crust is absent in this area.

Volcanic rocks of DR5B are low-alkali tholeiitic rocks of Island Arc type and they are marked off from the volcanic rocks of the Middle and Southern Okinawa Trough by the oxide-SiO_2 variation diagram. The volcanic rocks of DR5B may represent the southwestern extention of Quaternary-volcanic front of the Ryukyu Arc.

The K-Ar ages of samples from the Iheya Deep in the Middle Okinawa Trough indicate that these rocks are mostly younger than 1Ma (DR7; 0.112 ± 0.019Ma and DR8; 0.496 ± 0.380Ma). Since the K-Ar ages of dredged samples from the Yaeyama Graben in the Southern Okinawa Trough are also younger than 1Ma, the formation of the Iheya Deep and the Yaeyama Graben took place concurrently. The K-Ar age of basalt from DR5B which is located near the supposed Quaternary-volcanic front, is also 0.505 ± 0.453Ma.

The temperatures of crystallization of phenocrysts of samples from DELP-88 were found to be 1100°C for basalt (DR5B-H), 783 to 800°C for dacite (DR7-H), and 900 to 950°C for andesite (DR8-H) under 1 atmospheric pressure. These volcanic rocks in the Okinawa Trough region were crystallized under redox conditions near fayalite-magnetite-quartz assemblage.

1. Introduction

The Okinawa Trough is a big graben behind the Ryukyu Arc. The width of the trough is 100–150 km and the length is about 1200 km along the Ryukyu Arc. The water depth in the Middle and Southern Okinawa Trough is between 1000–2000 m and the Northern Okinawa Trough shows a shallower water depth of 500–1000 m. Several central grabens are formed within the big graben, which shows the echelon arrangment along the axis of the Okinawa Trough (UYEDA *et al.*, 1985; KIMURA *et al.*, 1986). It is known that the volcanic rocks from a minor ridge (Iheya Central Minor Ridge) in one of the central grabens are calc-alkaline rocks and high-alumina basalt (UYEDA *et al.*, 1985; KIMURA *et al.*, 1986).

During the DELP-88 KAIKO Cruise of R/V Daigo-Kaiko-Maru, a large amount of volcanic rocks was sampled from the Yaeyama Central Knoll in the Southern Okinawa Trough, and northern wall of the Iheya Deep and northern wall of the Izena Depression in the Middle Okinawa Trough. Dredge locations are shown in Fig. 1. The characteristics of major chemical compositions and phase chemistry of these rocks are presented in this paper.

2. Dredged samples

Volcanic and sedimentary rocks were dredged from eight stations; five stations in the Southern Okinawa Trough (DR2, DR3, DR4, DR5A and DR5B) and three stations in the Middle Okinawa Trough (DR7, DR8 and DR10), during the DELP-88 KAIKO Cruise (Fig. 1 and Table 1). The dredger was chain bag type of Ocean Research Institute, University of Tokyo.

Basaltic scoria and fresh basalt lava blocks were obtained at the Yaeyama Central Knoll (DR3) and the Irabu Knoll located in eastern part of the Yaeyama Graben (DR5B), respectively. Dacite lava and woody pumice blocks were sampled from northeastern wall (DR7) of the Iheya Deep that is located in the eastern edge of the Iheya Minor Ridge. Andesite lava and woody pumice blocks were sampled from northwestern wall (DR8) of the Iheya Deep. Acidic tuff, tuff breccia blocks, and fine grained pieces of aphyric andesite which constitute tuff breccia were collected from the Izena Depression (DR10). Dredged samples are shown in Plate 1.

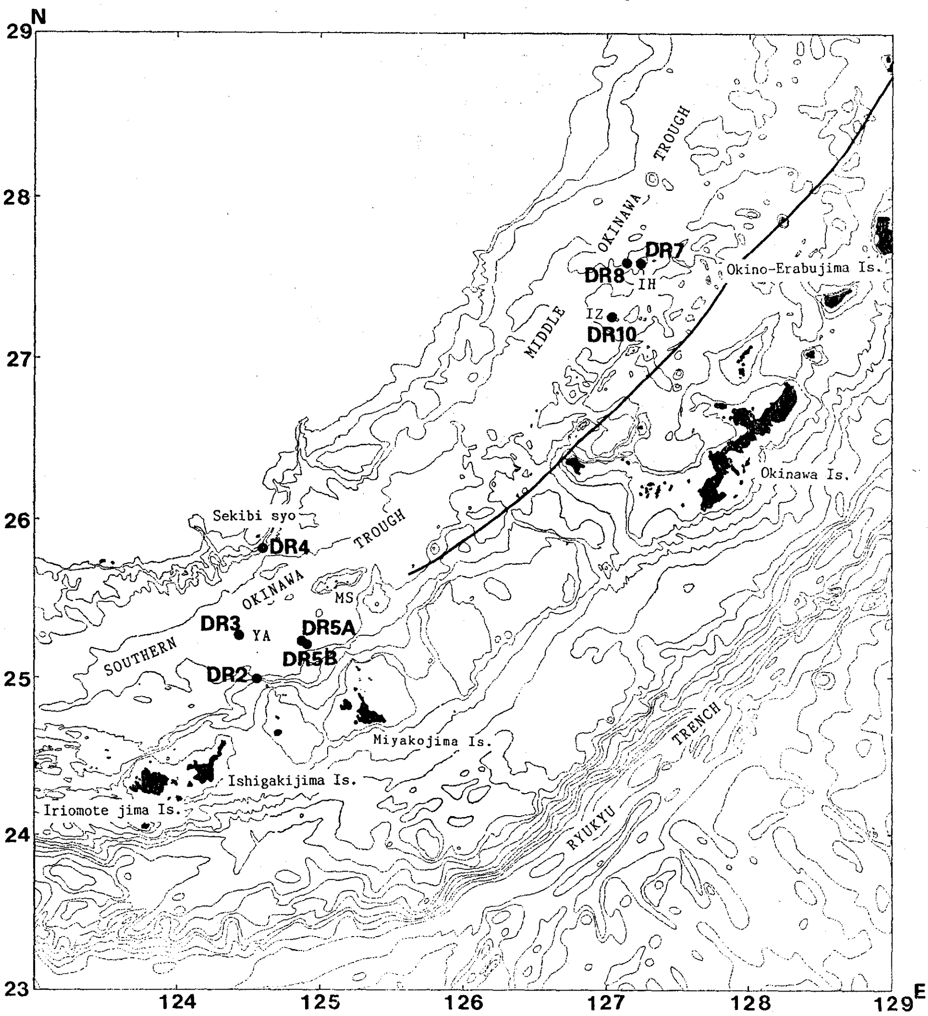


Fig. 1. Location map of the dredge hauls during the DELP-88 KAIKO Cruise in the Okinawa Trough. The bathymetric contours are 200 m and at 500 m intervals. Solid line shows Quaternary-volcanic front (KATO *et al.*, 1982 and UEDA, 1986).

YA: Yaeyama Graben, MS: Miyako Seamount, IZ: Izena Depression, IH: Iheya Deep

3. Petrography of volcanic rocks

(1) DR3-1T ⟨Basaltic scoria⟩

The scoria is vesicular and fresh on the whole, and is aphyric with dendritic plagioclase and clinopyroxene, acicular iron oxides and brown glass in the groundmass.

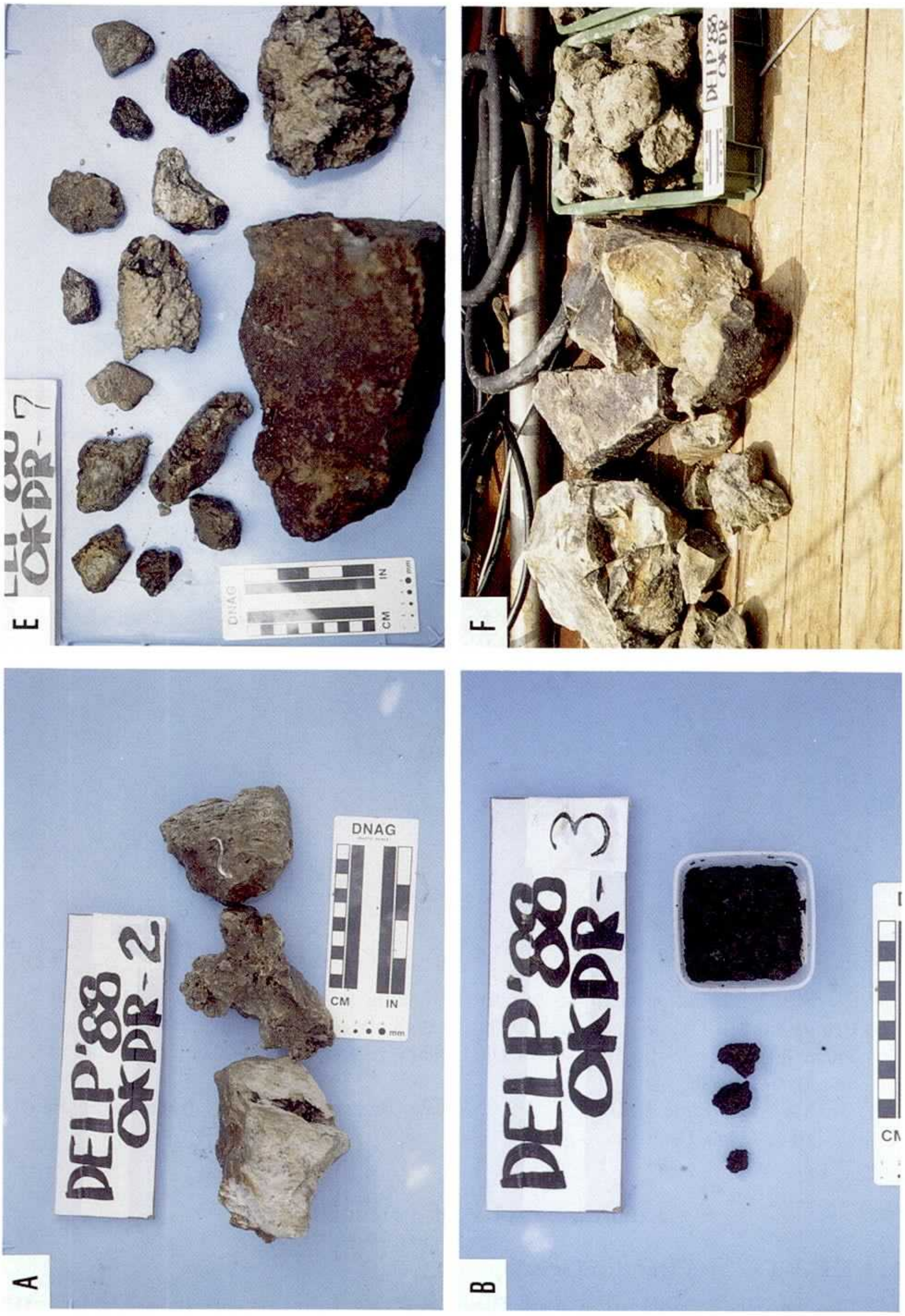
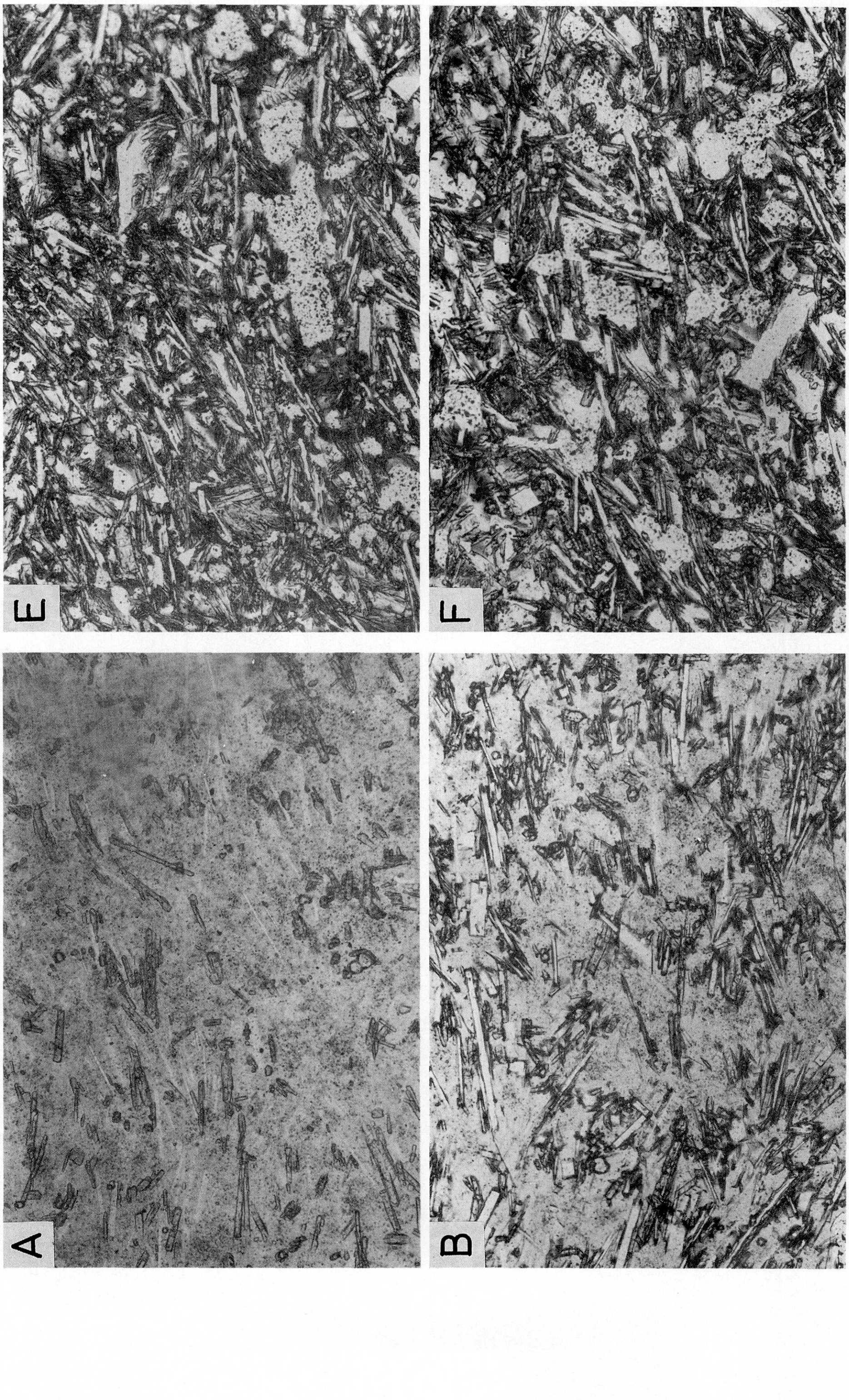

E
F
A
B
DELP'88 OKDR-2
DELP'88 OKDR-3
DNAG
CM
IN

Plate 1. Photographs of dredged rock samples. (A: pumice blocks of DR2, B: scoria samples of DR3, C: sandstone blocks of DR4, D: basalt lava blocks of DR5B, E: andesite blocks of DR7, F: andesite blocks of DR8, G and H: acidic tuff and tuff breccia blocks of of DR10).


E
F
A
B

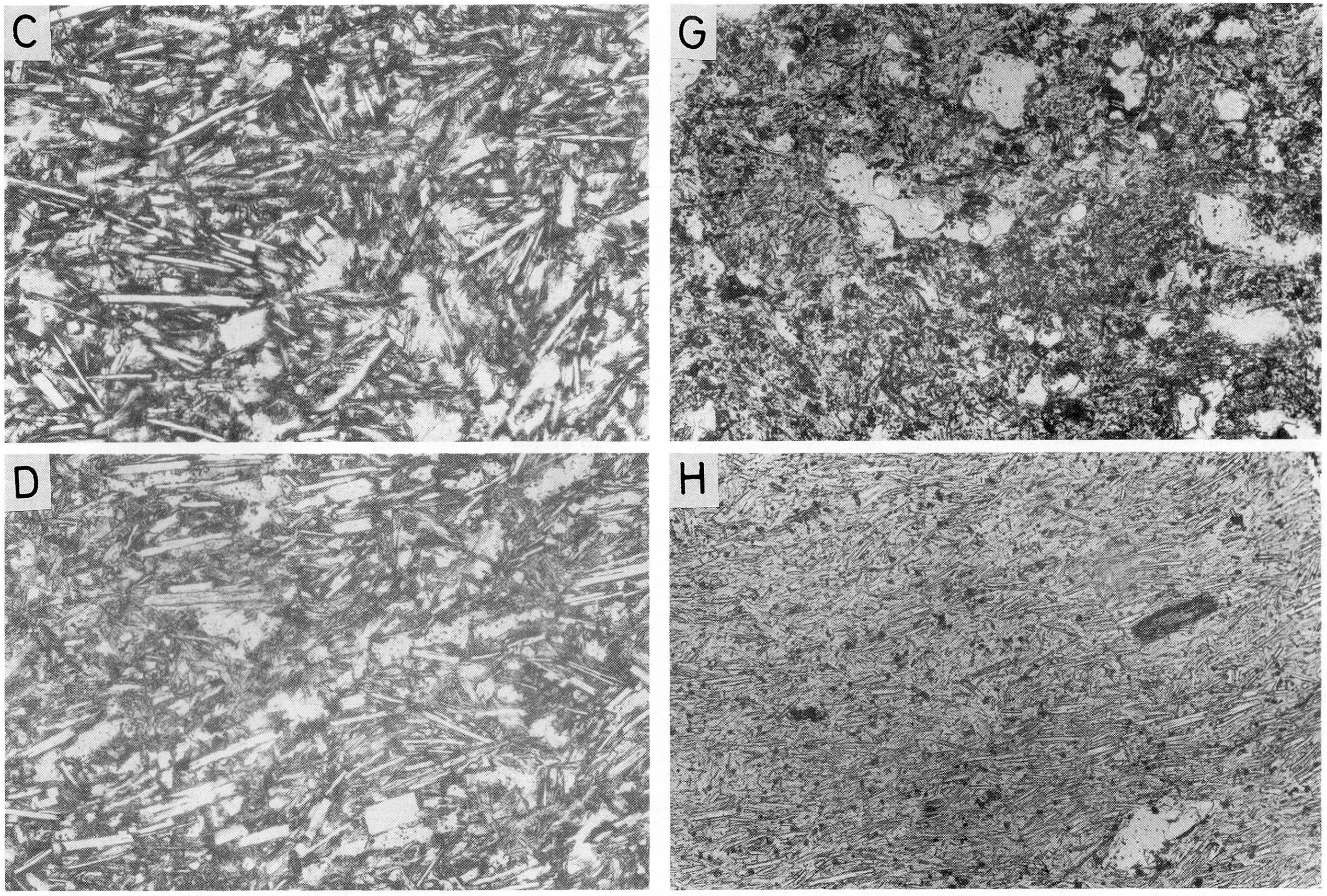


Plate 2. Photomicrographs of thin sections of DELP-88 samples. Photographs A-F represent DR5B-H samples. A. 1 mm, B. 6 mm, C. 8.5 mm, D. 12 mm, E. 16.5 mm, F. 30 mm, from the surface of the pillow lava. Note the variations of crystallinity and crystal habits and the increase of vesicles from the rim to the interior of the pillow. Photo G shows the DR7-H sample. The glass is charged with thin needles of crystals. Vesicles often contain euhedral cristobalite. Photo H displays the groundmass texture of DR8-H. Thin laths of plagioclase show flow structure. Dark microphenocryst is hornblende. Scale bar represents 100 microns.

Table 1. Location of the dredgre hauls and principal rock types of DELP-88 dredged samples.

Dredge station	Data (1988)	Time (on & off)	Position		Depth (m)	Samples
			Latitude (N)	Longitude (E)		
D R2	July, 22	7:30 8:09	24°59.32′ 24°59.21′	124°33.83′ 124°33.78′	1,240 950	Three pieces of pumice blocks (Max. size: 12×9×8 cm). Large amount of soft sediment (Total weigt: 20 kg). (Southern wall of the Southern Okinawa Trough)
D R3	July, 21	17:52 18:51	25°16.84′ 25°15.31′*	124°25.75′ 124°22.22′	2,130 2,325	Less amount of scoria (Max. size: 1×1×1 cm, Total weight: 20 kg). (Yaeyama central Knoll)
D R4	July, 20	18:59 19:59	25°49. 4′ 25°50. 5′	124°37. 1′ 124°36. 9′	1,420 975	Several pieces of sandstone blocks (Max. size: 20×15×10 cm and abundant size: 15×10×7 cm). Total weight of rock samples: 30 kg. Yaeyama Group? Large amount of soft sediment. (Northern wall of the Southern Okinawa Trough)
D R5A	July, 23	7:19 7:57	25°14.28′ 25°14.28′	124°53.62′ 124°52.71′	2,210 2,215	Empty. (East Yaeyama central Knoll)
D R5B	July, 23	8:52 10:00	25°13.68′* 25°13.80′	124°54.67′ 124°53.18′	2,205 2,050	Fresh basalt (olivine basalt) lava blocks (Size of three blocks: 12×8×3 cm, five blocks: 11×5×3 cm, twenty blocks: 5×4×2 cm, Total weight: 10 kg). Platy lava with flow structure. (East Yaeyama central Knoll)
D R7	July, 26	11:30 12:36	27°35.63′ 27°36.93′	127°13.48′ 127°15.31′	1,760 1,530	Dacite lava blocks (Max. size: 24×17×11 cm). Woody pumice blocks (Max. size: 14×10×10 cm). Several pieses of host rocks forming the hydrthermal mound (four blocks with dark green and yellow hydrothermal deposition, Max. size: 10×9×5 cm), and three blocks with iron oxide (Max. size: 11×8×7 cm). Total weight of rock samples: 5 kg. (Northeastern wall of the Iheya Deep)
D R8	July, 26	9:13 10:02	27°35.50′ 27°36.14′	127°09.25′ 127°08.98′	1,630 1,400	Andesite lava blocks (Max. size: 40×35×22 cm). Weathered andesite blocks (Max. size: 20×15×10 cm). Woody pumice blocks (Max. size: 19×14×11 cm). Total weight of rock samples: 100 kg. (Northwestern wall of the Iheya Deep)
D R10	July, 25	13:42 15:28	27°15.77′ 27°16.17′	127°03.29′ 127°04.35′	1,660 1,490	Acidic tuff and tuff breccia blocks (Max. size: 35×25×20 cm) and tuffaceous sandstone blocks (Max. size: 30×19×17 cm), with thin ferro-manganese coating. One sulfide block with pyrite (Size: 12×9×4 cm). Small amount of soft sediment. Total weight of rock samples: 60 kg. (Northern wall of the Izena Depression)

*: NNSS

Table 2. Modal compositions of DELP-88 dredged samples, obtained by 2000 point countings.

sample No.	DR5B-H	DR7-H	DR8-H
vesicle	4.1	13.6	3.5
phenocryst			
plagioclase	11.9	4.4	3.7
olivine	1.6	—	—
augite	7.1	0.0	0.2
orthopyroxene	0.2	0.1	0.0
hornblende	—	0.0	—
titanomagnetite	—	0.1	0.2
ilmenite	—	0.0	0.0
groundmass	79.2	95.4	95.9

(2) **DR5B-H, DR5B-1T, DR5B-2T** **〈Olivine-two pyroxene basalt〉**

The rocks are fresh basalt lava blocks with chilled margin glass. The phenocrysts include augite, orthopyroxene, olivine and plagioclase. The groundmass is composed of augite, orthopyroxene, plagioclase, titanomagnetite and glass. The groundmass shows textural variation from the outer glassy texture to inner intersertal texture. The crystallinity of DR5B-H basalt increases from the surface inward within the marginal 30 mm of the pillow lava (Plate 2; A to F). The plate also shows the variation of crystal habit of clinopyroxene from dendritic in B, C and D to thin prismatic in F.

Olivine phenocryst is euhedral to subhedral, and is 0.3–1 mm in diameter. Thin reaction corona of pyroxenes is ubiquitously observed. Glass inclusion is also common in olivine phenocryst. Modal compositions of the basalt are shown with the other DELP-88 dredged samples in Table 2.

(3) **DR7-H** **〈Two pyroxene dacite〉**

The rock is an augite-orthopyroxene dacite with phenocrysts of augite, orthopyroxene, titanomagnetite, ilmenite, apatite and plagioclase. The groundmass is hyalopilitic with microlites of plagioclase, pyroxene, iron oxides and colorless glass (Plate 2-G). Vesicle (13.6 vol. %) is irregular in form, and is often filled with euhedral crystobalite.

(4) **DR8-H, DR8-1T, DR8-2T, DR8-3T** **〈Two pyroxene andesite〉**

The samples are augite-orthopyroxene andesite with phenocrysts of augite, orthopyoxene, plagioclase, titanomagnetite, ilmenite and microphenocrysts of hornblende and apatite. The groundmass consists of plagioclase lath, pyroxene, iron-titanium oxides, cristobalite and glass. They show pilotaxitic texture (Plate 2-H).

4. Petrochemistry

The bulk chemical compositions of the major elements of the DELP-

Table 3. Major chemical compositions of the volcanic rocks during the DELP-88 KAIKO Cruise.

	1	2	3	4	5	6
DR	3-1T	5B-1T	5B-2T	8-1T	8-2T	8-3T
SiO_2	49.71	52.13	51.56	58.34	56.62	56.59
TiO_2	1.03	0.65	0.68	1.32	1.35	1.40
Al_2O_3	15.71	16.47	17.45	15.26	15.74	15.34
FeO*	9.79	9.17	9.03	7.17	8.01	8.58
MnO	0.22	0.17	0.22	0.18	0.18	0.19
MgO	6.34	5.29	4.89	2.97	3.12	3.06
CaO	12.28	11.53	11.86	6.77	6.91	6.98
Na_2O	2.66	2.15	2.22	3.88	3.91	3.87
K_2O	0.47	0.29	0.28	1.04	0.98	1.05
Cr_2O_3	—	0.02	0.02	0.01	0.02	0.03
V_2O_3	0.02	0.04	0.02	0.08	0.08	0.10
NiO	0.06	0.05	0.03	0.04	0.02	—
P_2O_5	0.17	0.08	0.06	0.09	0.12	0.11
H_2O*	0.98	1.52	1.06	2.39	2.36	1.98
Total	99.44	99.56	99.38	99.54	99.43	99.28
Qz	0.0	6.6	5.4	13.1	10.4	10.2
Or	2.8	1.7	1.7	6.3	6.0	6.4
Ab	22.8	18.5	19.1	33.8	34.0	33.6
An	29.9	35.1	37.4	21.8	23.2	22.0
Ne	—	—	—	—	—	—
DiWo	12.8	9.5	9.2	5.1	4.7	5.4
DiEn	7.5	5.2	4.9	2.6	2.4	2.6
DiFs	4.7	3.9	3.9	2.3	2.2	2.7
HyEn	6.6	8.2	7.4	5.0	5.6	5.2
HyFs	4.2	6.1	5.9	4.3	5.3	5.4
OlFo	1.3	—	—	—	—	—
OlFa	0.9	—	—	—	—	—
Il	2.0	1.3	1.3	2.6	2.6	2.7
Mt	4.0	3.8	3.7	3.0	3.3	3.5
Ap	0.4	0.2	0.1	0.2	0.3	0.3
Total	99.9	100.1	100.0	100.1	100.0	100.0

88 volcanic rocks were obtained by EPMA. For EPMA analysis, JEOL LTD' EPMA type JXA-733 of the Ocean Research Institute, University of Tokyo, was used, and Fused Glass Method (glass specimen prepared by fusing pulverised rock sample on Ir foil) was applied. Beam diameter was 10 micron and beam current was kept at 12 nA. Correction method described by BENCE and ALBEE (1968) was applied.

The analytical results are presented in Table 3. Total Fe was converted to FeO. In norm calculation, Fe_2O_3/FeO ratio is assumed to be 0.37 (weight ratio) which is determind from the lowest Fe_2O_3/FeO ratio of the volcanic rocks, dredged from some knolls at the Myojin Basin and adjacent knolls of the basin (ISHIKAWA, unpublished data).

DELP-88-T volcanic samples are basalt to andesite which show SiO_2 contents of 49.7 to 58.4%. Volcanic rock samples (DR8-1T to DR8-3T) from the northern wall of the Iheya Deep located in the Middle Okinawa Trough show SiO_2 contents of 56.5 to 58.4%. Normative quartz is cal-

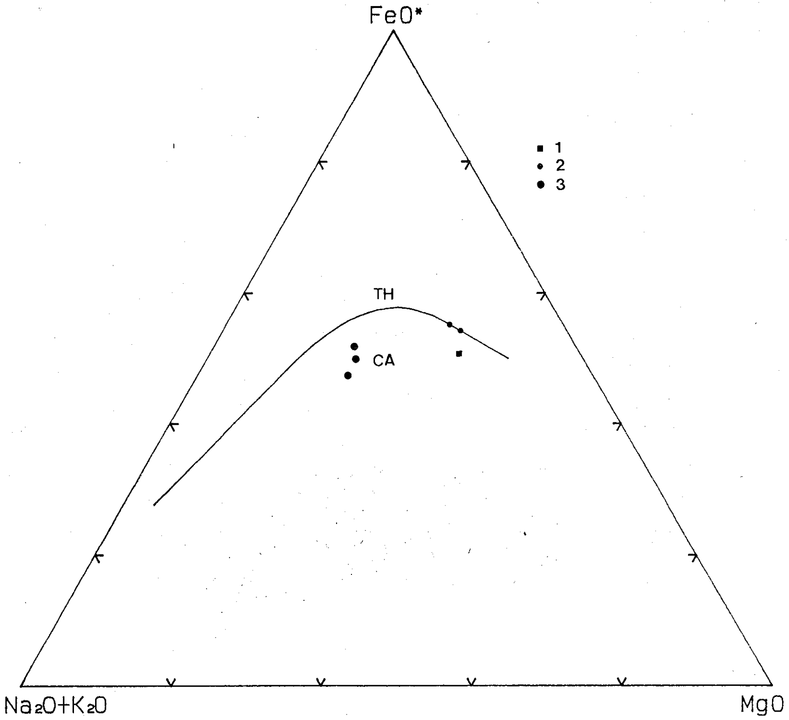


Fig. 2. AMF diagram of the volcanic rocks. Solid curve shows boundary of Pigeonitic (tholeiitic) and hypersthenic (calc-alkaline) rock series (KUNO, 1976). 1: DR3-1T (basaltic scoria), 2: DR5B-1T and DR5B-2T (olvine-two pyroxene basalt), 3: DR8-1T to 3T (two pyroxene andesite), TH: tholeiitic rock series, CA: calc-alkaline rock series

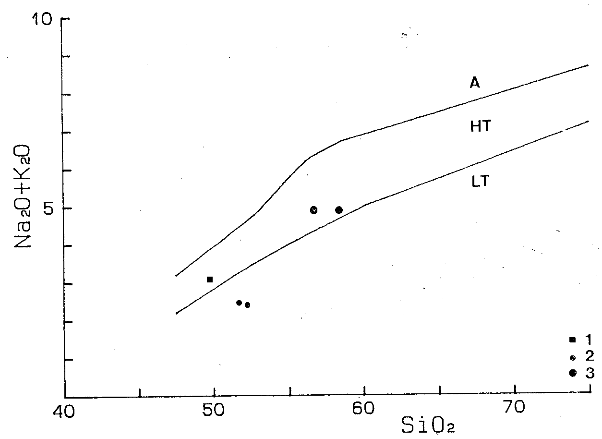


Fig. 3. $(Na_2O+K_2O)-SiO_2$ diagram of the volcanic rocks. Boundaries between the fields of three rock types (so-called low-alkali tholeiitic, high-alkali tholeiitic and alkaline rocks) are shown by curves (after KUNO, 1968a). Symbols are the same as those in Fig. 2.
LT: low-alkali tholeiitic rocks, HT: high-alkali tholeiitic rocks,
A: alkaline rocks

culated for both volcanic rocks of the Middle and Southern Okinawa Trough except for DR3-1T sample from the Yaeyama Central Knoll. The volcanic rocks taken from Middle Okinawa Trough contain 10.2 to 13.1% of normative quarts, and the volcanic rocks from the Southern Okinawa Trough 5.4% and 6.6%.

In AMF diagram by KUNO (1976), DR3-1T (basaltic scoria) and DR8-1T to DR8-3T (two pyroxene andesite) samples do not show FeO*-enrichment and fall in the calc-alkaline field (Fig. 2). DR5B-1T and DR5B-2T (olivine-two pyroxene basalt) samples are plotted around the boundary line between tholeiitic and calc-alkaline rocks in Fig. 2, and fall in the field of low-alkali tholeiitic rocks in the $(Na_2O+K_2O)-SiO_2$ diagram by KUNO (1968a) (Fig. 3). In the FeO/MgO-SiO_2 diagram (MIYASHIRO, 1974), the volcanic rocks are plotted near the boundary between calc-alkaline and tholeiitic series. In the oxide-SiO_2 variation diagram (Fig. 4), the values of Na_2O, K_2O and TiO_2 against SiO_2 content of DR5B-1T and DR5B-2T samples are higher than those of DR3-1T and DR3-1T and DR8-1T to DR8-3T samples which are characteristic of calc-alkaline rocks. In contrast, the value of CaO against SiO_2 of DR5B-1T and DR5B-2T samples show slightly high values when compared with those of DR3-1T and DR8-1T to DR8-3T samples. The oxide values of the samples from the central graben structure (DR3-1T and DR8-1T to DR8-3T) are plotted along the variation trend of the volcanic rocks in the Middle and Southern

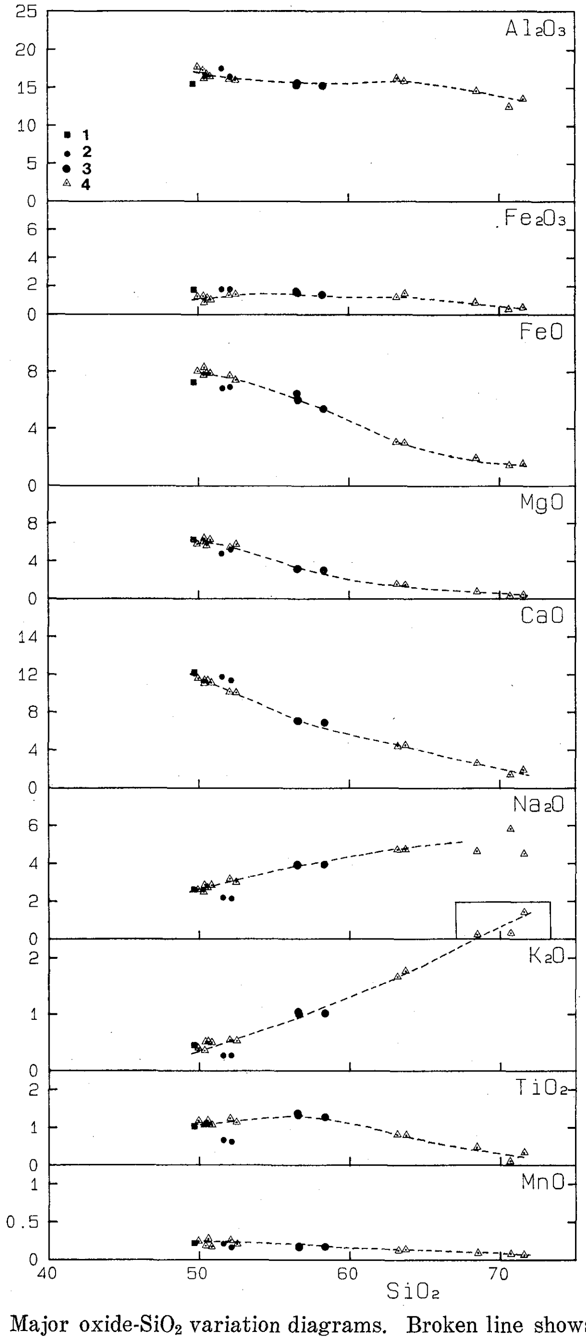


Fig. 4. Major oxide-SiO_2 variation diagrams. Broken line shows the variation trend of the volcanic rocks in the Middle and Southern Okinawa Trough. 1: DR3-1T (basaltic scoria), 2: DR5B-1T and DR5B-2T (olvine-two pyroxene basalt), 3: DR8-1T to 3T (two pyroxene andesite), 4: volcanic rocks from the Middle Okinawa Trough (KIMURA *et al.*, 1986).

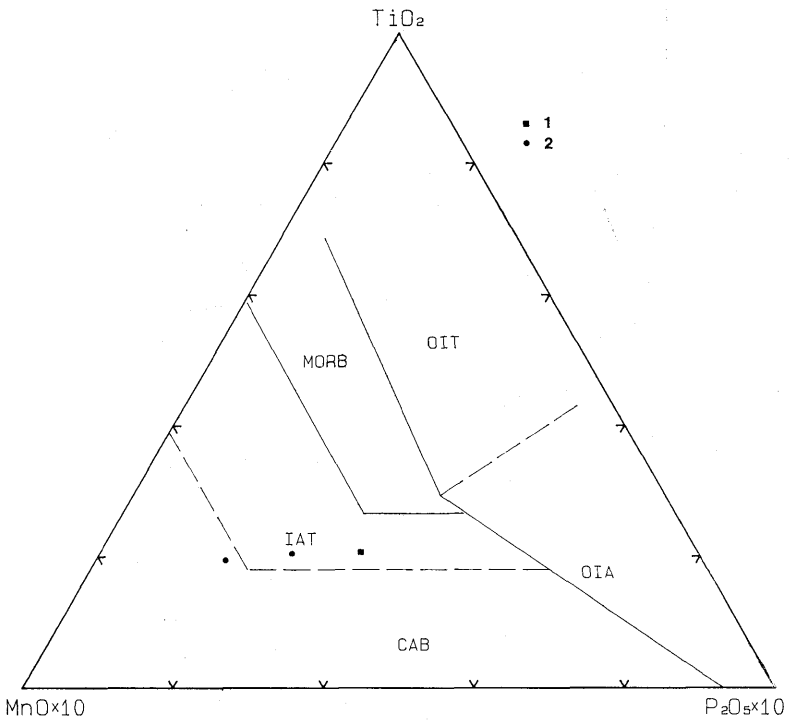


Fig. 5. $MnO \times 10$-$P_2O_5 \times 10$-TiO_2 discriminant diagram for basalts and basaltic andesites (45–54% SiO_2) of oceanic regions. Boundaries between five fields are after MULLEN (1982). Symbols are the same as those in Fig. 2.
CAB: calc-alkaline basalts, IAT: island arc tholeiites, MORB: mid-oceanic ridge and marginal basin basalts, OIT: oceanic island tholeiites, OIA: oceanic island alkaline basalts.

Okinawa Trough of which data is cited from KIMURA *et al.* (1986). In the $MnO \times 10-P_2O_5 \times 10-TiO_2$ diagram (Fig. 5) by MULLEN (1982), DELP-88-T volcanic rocks are plotted in the fields of IAT (Island arc tholeiites) and CAB (Calc-alkaline basalts). DR3-1T and DR8-1T to DR8-3T samples show the cemical composition of calc-alkaline rock or tholeiitic rock of Island Arc type, as reported previously (KIMURA *et al.*, 1986; UYEDA *et al.*, 1985). The result is concordant with the geophysical data suggesting that oceanic crust is absent in the central graben structure (NAGUMO *et al.*, 1986).

Volcanic rocks from DR5B are low-alkali tholeiitic rocks of Island Arc type. In the oxide-SiO_2 variation diagram (Fig. 4), the plots for these rocks are off the variation trend of volcanic rocks in the Middle and Southern Okinawa Trough. The volcanic rocks of DR5B appear to represent volcanic eruption on island arc setting, rather than a back-arc

Table 4. Phase chemistry of DR5B-H sample. Only representative analyses are listed.

	chilled margin glass				glass inclusion in ol-4			glass inclusion in plag-2		glass inclusion in px-1-1		
spot No.	232	233	234	236	257	258	259	265		270	271	
SiO_2	55.31	55.35	55.80	55.93	54.24	54.05	54.24	59.17		59.69	56.59	
TiO_2	0.92	0.86	1.11	1.15	0.83	0.86	0.89	0.70		0.70	0.81	
Al_2O_3	16.31	16.88	13.57	13.43	14.34	14.27	14.35	14.33		19.46	17.58	
FeO	10.85	9.57	11.77	11.68	12.55	12.52	12.58	9.53		2.82	8.80	
MnO	0.15	0.17	0.22	0.18	0.20	0.12	0.24	0.14		0.11	0.15	
MgO	3.31	3.06	3.67	3.72	4.26	4.26	4.43	3.75		0.84	2.36	
CaO	9.30	9.71	8.42	8.86	7.61	7.52	7.85	6.31		7.07	6.32	
Na_2O	1.83	2.10	1.42	1.03	0.96	1.00	0.89	0.77		0.72	0.62	
K_2O	0.45	0.39	0.50	0.45	0.37	0.38	0.33	0.44		0.33	0.25	
total	98.43	98.09	96.48	96.43	95.36	95.04	95.80	95.14		90.74	93.48	

	olivine-11		olivine-4				cp/ol-4		ol-2	ol/op-5	ol-3	ol/px-3
spot No.	core 249	rim 250	rim 251	c-50 252	c-100 253	c-400 256	core 260	core 261	rim 275	core 281	rim 282	core 274
SiO_2	37.88	37.68	37.61	37.00	37.03	37.03	51.90	37.24	37.83	38.65	38.33	38.08
TiO_2	0.00	0.01	0.00	0.00	0.03	0.00	0.31	0.02	0.03	0.02	0.00	0.00
Al_2O_3	0.03	0.02	0.03	0.02	0.01	0.02	2.16	0.02	0.02	0.03	0.03	0.03
FeO	23.66	23.98	25.65	28.10	27.95	27.47	9.25	26.38	23.76	20.43	21.71	22.88
MnO	0.38	0.34	0.41	0.42	0.38	0.45	0.24	0.38	0.32	0.27	0.32	0.37
MgO	37.25	37.02	35.04	34.10	33.84	33.82	15.59	35.04	36.95	40.28	38.99	37.75
CaO	0.22	0.23	0.22	0.20	0.18	0.17	20.47	0.25	0.19	0.23	0.20	0.21
Na_2O	0.03	0.01	0.03	0.00	0.01	0.01	0.13	0.01	0.03	0.01	0.02	0.03
Cr_2O_3	0.02	0.00	0.00	0.00	0.02	0.00	0.03	0.00	0.00	0.01	0.02	0.00
NiO	0.05	0.00	0.04	0.02	0.00	0.04	0.00	0.05	0.00	0.05	0.04	0.04
total	99.52	99.29	99.03	99.86	99.45	99.01	100.08	99.39	99.13	99.98	99.66	99.39

spot No.	pyroxene-06				pyroxene-11				pyroxene-12		pyroxene-06	
	240/241 240	241/240 241	242/243 242	243/242 243	245	246	247	248	267	269	272	273/274 273
SiO_2	53.53	52.43	53.13	52.31	53.29	52.01	51.41	52.41	53.28	53.31	53.27	51.51
TiO_2	0.15	0.21	0.20	0.23	0.21	0.20	0.35	0.27	0.13	0.12	0.15	0.25
Al_2O_3	1.26	3.00	1.58	2.72	1.51	3.39	3.11	1.89	1.69	2.07	1.16	3.94
FeO	16.23	5.90	17.53	6.17	16.87	5.12	7.67	10.34	4.13	3.38	16.81	5.10
MnO	0.31	0.16	0.45	0.16	0.39	0.11	0.22	0.29	0.09	0.08	0.37	0.15
MgO	25.15	17.19	24.58	17.51	24.63	16.32	15.40	17.50	17.79	17.47	25.06	16.68
CaO	1.89	20.96	1.89	20.59	2.07	22.71	21.35	16.63	22.63	23.47	1.88	21.88
Na_2O	0.03	0.12	0.02	0.10	0.02	0.10	0.13	0.10	0.09	0.09	0.03	0.12
K_2O	0.00	0.01	0.00	0.01	0.00	0.02	0.00	0.01	0.01	0.01	0.01	0.00
Cr_2O_3	0.02	0.05	0.00	0.04	0.03	0.52	0.16	0.05	0.32	0.21	0.00	0.48
NiO	0.04	0.00	0.04	0.02	0.00	0.02	0.00	0.00	0.05	0.00	0.08	0.00
total	98.61	100.03	99.42	99.86	99.02	100.52	99.80	99.49	100.21	100.21	99.27	100.11

spot No.	plagioclase-13		plagioclase-02			plagioclase-12			plag-05	plagioclase-03	
	rim 276	core 283	rim 262	c-50 263	core 264	rim 277	core 278	core 279	rim 280	rim 284	core 285
SiO_2	48.58	47.84	50.60	46.18	47.51	45.71	44.21	50.85	46.84	46.12	46.16
TiO_2	0.00	0.02	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00
Al_2O_3	31.63	32.08	30.10	33.24	32.25	33.55	34.77	30.27	33.13	33.26	33.39
FeO	0.69	0.68	0.79	0.60	0.66	0.59	0.45	0.75	0.69	0.58	0.63
MnO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0 00	0.00	0.00
MgO	0.18	0.16	0.25	0.12	0.12	0.11	0.07	0.22	0.13	0.10	0.10
CaO	16.58	17.18	15.04	17.68	17.17	18.57	19.74	15.01	17.80	18.44	18.19
Na_2O	2.32	2.05	2.62	1.26	1.87	1.12	0.54	3.15	1.67	1.42	1.45
K_2O	0.03	0.04	0.04	0.02	0.03	0.02	0.02	0.04	0.01	0.03	0.03
total	99.99	100.05	99.44	99.10	99.61	99.69	99.80	100.29	100.27	99.95	99.95

Table 5. phase chemistry of DR7-H sample.

spot No.	pyroxene-02		px-12	pyroxene-11		pyroxene-13		pyroxene-14	
	rim 350	core 351	rim 354	rim 358	core 359	rim 368	core 369	371	372
SiO_2	50.40	49.79	48.77	49.04	49.05	49.52	50.07	50.67	50.65
TiO_2	0.18	0.17	0.16	0.17	0.16	0.12	0.12	0.19	0.20
Al_2O_3	0.56	0.67	0.30	0.29	0.28	0.23	0.29	0.32	0.55
FeO	20.87	22.45	37.23	37.71	38.03	36.85	35.90	21.30	20.11
MnO	1.16	1.17	1.83	1.89	2.10	1.95	1.73	1.14	1.13
MgO	7.63	7.93	9.22	8.79	8.55	9.66	10.87	7.21	8.02
CaO	18.79	16.75	1.57	1.57	1.47	1.55	1.54	18.97	19.22
Na_2O	0.32	0.23	0.02	0.04	0.02	0.03	0.04	0.25	0.25
K_2O	0.01	0.00	0.02	0.01	0.01	0.03	0.02	0.02	0.01
total	99.92	99.16	99.11	99.51	99.67	99.94	100.07	100.07	100.14

	ilm-01	ilmenite-03		magnetite-01			glass inclusion		
	370	rim 352	core 353	365	367		/pl-2 362	/pl-1 365	
SiO_2	0.14	0.09	0.05	0.18	0.15		78.68	79.87	
TiO_2	49.68	49.32	49.98	18.41	18.37		0.16	0.18	
Al_2O_3	0.07	0.06	0.07	1.17	1.23		11.14	10.17	
FeO	46.63	46.21	46.85	74.49	74.97		1.99	2.01	
MnO	1.62	1.67	1.33	0.86	0.83		0.06	0.02	
MgO	0.49	0.54	0.65	0.40	0.40		0.13	0.10	
CaO	0.06	0.04	0.07	0.01	0.01		0.72	0.66	
Na_2O	0.02	0.02	0.03	0.04	0.05		0.97	1.09	
K_2O							2.72	3.40	
Cr_2O_3	0.00	0.00	0.00	0.08	0.07				
V_2O_3	0.64	0.00	0.00	0.07	0.18				
total	99.35	97.95	99.03	95.71	96.26		96.57	97.50	

	pl-08	pl-17	plagioclase-03		plagioclase-02		pl-01	plagioclase-16	
	core 349	core 355	core 356	core 357	rim 360	core 361	core 364	rim 373	core 374
SiO_2	62.71	63.22	64.50	64.78	63.62	61.92	63.21	63.32	64.56
TiO_2	0.02	0.00	0.00	0.02	0.01	0.02	0.00	0.00	0.00
Al_2O_3	24.31	24.67	23.80	23.53	23.77	24.40	23.83	23.98	23.43
FeO	0.20	0.16	0.16	0.14	0.12	0.18	0.15	0.16	0.16
MnO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MgO	0.03	0.02	0.03	0.02	0.02	0.02	0.03	0.02	0.02
CaO	6.07	5.94	5.17	5.00	5.19	6.46	5.74	5.56	4.99
Na_2O	8.20	7.95	8.30	7.89	8.04	7.73	8.16	8.16	8.19
K_2O	0.28	0.28	0.32	0.32	0.29	0.28	0.30	0.29	0.31
total	101.82	102.24	102.28	101.70	101.06	101.01	101.42	101.59	101.66

Table 6. phase chemistry of DR8-H sample.

	gm-1	gm-2	gm-3	glass incl. in pl-12		glass incl. in pl-01		glass incl. in pl-02	
spot No.	298	331	332	303	304	329	330	343	344
SiO_2	77.79	77.22	77.56	76.14	78.83	75.85	75.21	76.68	76.23
TiO_2	0.38	0.21	0.20	0.41	0.44	0.18	0.17	0.26	0.35
Al_2O_3	11.19	11.34	10.37	12.41	11.68	11.42	11.23	11.52	10.74
FeO	1.41	1.33	1.13	3.31	2.06	2.50	2.62	4.32	4.48
MnO	0.05	0.00	0.01	0.06	0.04	0.11	0.07	0.07	0.15
MgO	0.10	0.05	0.07	0.17	0.09	0.33	0.29	0.40	0.49
CaO	0.53	0.70	0.42	1.05	0.51	0.60	0.59	0.34	0.76
Na_2O	0.47	1.62	0.78	1.16	0.92	0.69	0.64	0.60	0.36
K_2O	1.93	1.38	1.68	2.15	1.73	1.14	1.43	2.31	1.12
total	93.85	93.85	92.22	96.96	96.30	92.82	92.25	96.50	94.68

	pyroxene-11			pyroxene-12		px-13	pyroxene-14			
spot No.	rim 295	core 296	core 297	core 316	core 317	core 318	core 333	core 334	core 335	rim 337
SiO_2	52.15	52.29	50.35	51.23	51.50	51.63	51.25	51.72	51.23	49.98
TiO_2	0.33	0.40	1.02	0.46	0.51	0.31	0.25	0.20	0.23	0.24
Al_2O_3	1.00	1.30	2.72	1.47	1.77	0.74	0.82	1.15	0.72	0.73
FeO	21.84	20.16	10.28	14.72	12.31	24.49	13.54	22.12	13.17	31.06
MnO	0.81	0.68	0.35	0.78	0.49	1.04	0.45	0.72	0.54	0.87
MgO	21.14	22.45	13.48	12.57	12.75	19.47	11.89	20.86	11.92	14.42
CaO	1.51	1.70	21.01	18.20	20.52	1.63	20.08	1.30	19.91	1.46
Na_2O	0.03	0.03	0.33	0.22	0.26	0.03	0.23	0.04	0.25	0.03
K_2O	0.02	0.00	0.00	0.01	0.02	0.02	0.01	0.00	0.02	0.01
Cr_2O_3	0.02	0.00	0.00	0.02	0.00	0.02	0.10	0.03	0.03	0.00
total	98.83	99.01	99.54	99.68	101.13	99.37	99.62	98.14	98.02	98.80

	ilmenite-11			ilmenite-03		magnetite-04		magnetite-01		
spot No.	rim 292	core 293	core 294	rim 305	core 306	core 339	rim 340	rim 345	core 346	core 347
SiO_2	0.15	0.06	0.06	0.22	0.04	0.25	0.32	0.28	0.14	0.18
TiO_2	48.29	49.55	48.40	50.10	49.88	18.35	18.04	17.51	18.56	18.90
Al_2O_3	0.18	0.25	0.24	0.11	0.11	1.70	1.55	1.63	1.67	1.64
FeO	45.77	45.98	45.65	46.90	46.52	73.82	72.34	74.36	74.42	73.32
MnO	0.75	0.75	0.69	1.03	0.95	0.69	0.73	0.84	0.77	0.69
MgO	2.39	2.53	2.75	1.25	1.39	0.86	0.87	0.72	0.84	0.82
CaO	0.03	0.01	0.01	0.03	0.08	0.00	0.06	0.01	0.00	0.02
Cr_2O_3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
V_2O_3	0.00	0.20	0.49	0.63	1.00	0.65	0.84	1.01	1.12	1.33
total	97.56	99.33	98.29	100.27	99.97	96.32	94.75	96.36	97.52	96.90

	plagioclase-11		plagioclase-12		pl-13	plagioclase-14		plagioclase-01		pl-02
spot No.	rim 286	core 288	rim 299	core 300	core 310	core 314	core 319	rim 320	core 328	core 342
SiO_2	55.76	53.99	57.83	59.40	54.32	60.52	53.88	61.28	61.92	58.83
TiO_2	0.04	0.04	0.01	0.00	0.03	0.01	0.04	0.00	0.00	0.01
Al_2O_3	27.67	28.89	26.63	25.89	28.74	25.55	28.68	25.06	23.77	25.99
FeO	0.37	0.31	0.23	0.21	0.32	0.18	0.58	0.17	0.13	0.18
MnO	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00
MgO	0.07	0.07	0.04	0.04	0.07	0.03	0.08	0.04	0.02	0.04
CaO	10.82	12.34	9.57	8.36	12.21	7.61	12.27	7.10	5.72	8.73
Na_2O	5.66	4.83	6.34	6.81	4.98	6.47	4.84	7.46	7.73	6.97
K_2O	0.13	0.09	0.14	0.16	0.07	0.21	0.04	0.19	0.22	0.17
total	100.52	100.56	100.79	100.87	100.74	100.58	100.42	101.30	99.51	100.92

Table 7. Temperature and oxygen fugacity for phenocryst and microphenocryst crystallization of DELP-88 samples.

Sample No.	DR5B-H	DR7-H	DR8-H
T°C (1)	1100	800	950
T°C (2)		782	880
Δlog fO_2 (FMQ) (2)		− 0.7	− 0.1
Δlog fO_2 (FMQ) (3)	−1.4		

(1) pyroxene thermometry after the method of Lindsley (1983).
(2) Iron-titanium oxides thermometry and oxygen barometry after the method of Anderson and Lindsley (1988).
(3) Redox estimation by Mg-Fe partitioning between magma and plagioclase (Sato 1989).

rift system. In fact, the location of DR5B can be regarded as southwestern continuation of Quaternary-volcanic front of the Ryukyu Arc (Kato *et al.*, 1982; Ueda, 1986).

5. Phase chemistry

Chemical compositions of glass and phenocrysts of DELP-88 samples are obtained using JEOL JXA-733 of the Ocean Research Institute, University of Tokyo, and tabulated in Table 4 to 6, and shown in Fig. 6 through 9.

Fig. 6 shows the composition of olivine and pyroxene phenocrysts in basalt (DR5B-H), dacite (DR7-H) and andesite (DR8-H). Olivine phenocrysts in the basalt show both nomal and reverse zonings, and their Mg/(Mg+Fe) ratios range from 0.68 to 0.79. Mg/(Mg+Fe) ratio

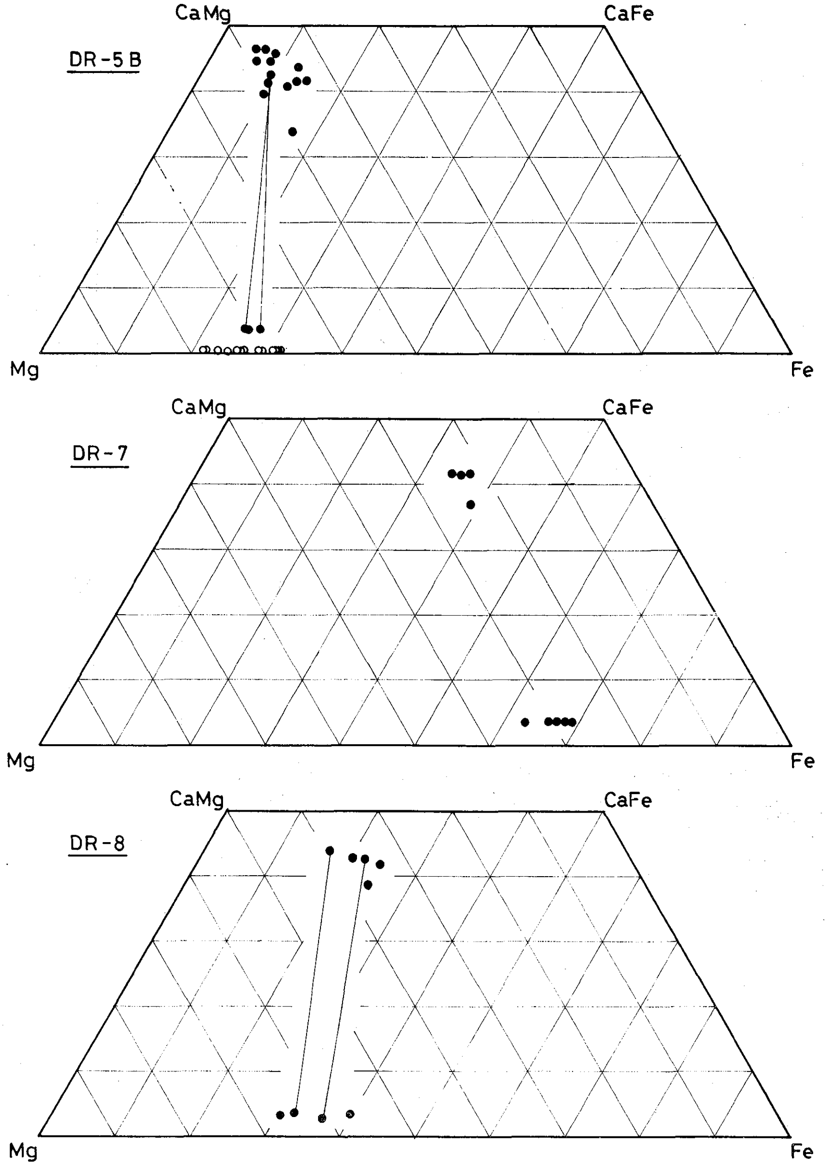


Fig. 6. Pyroxene quadrilateral of DELP-88 samples. Analyses of contiguous crystals are shown by tie-lines. Olivine composition is also shown in the base of DR5B quadrilateral.

of orthopyroxene phenocrysts are 0.70–0.74 in the basalt, 0.58–0.68 in the andesite and 0.28–0.36 in the dacite. As a whole, it apparently shows iron enrichment trend common to tholeiitic rock series (KUNO, 1968b). This is in harmony with the reduced nature of the magma as

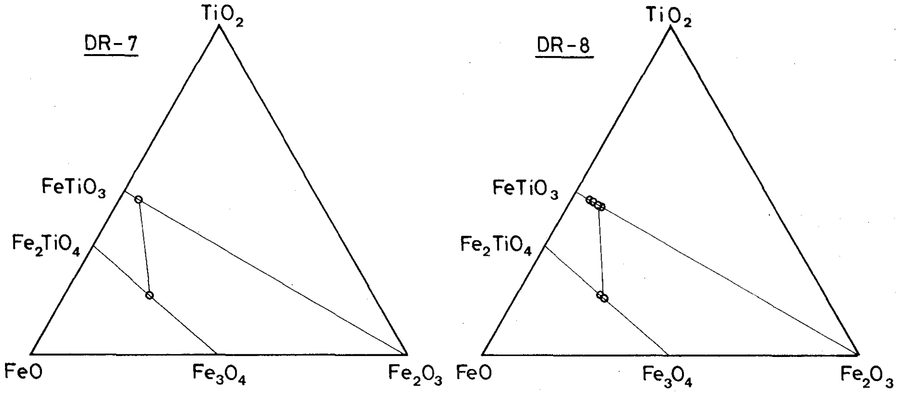


Fig. 7. Compositions of iron-titanium oxides in DR7 and DR8 samples.

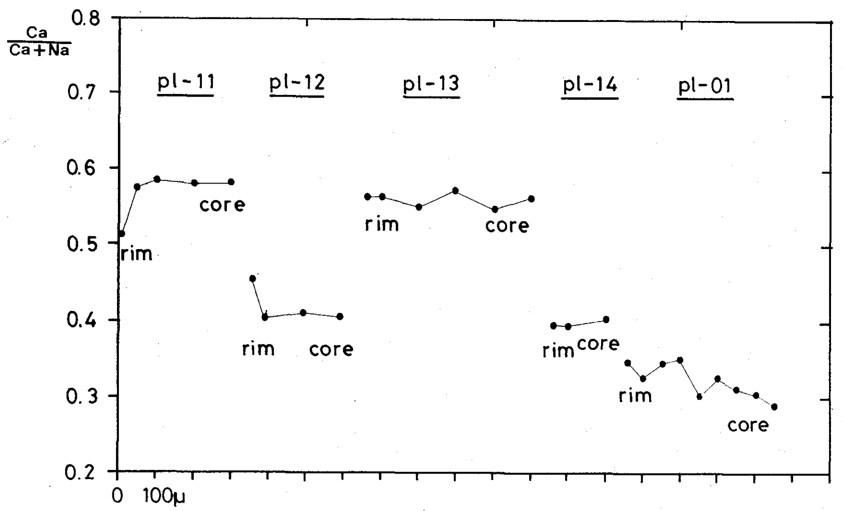


Fig. 8. Compositional profiles of plagioclase phenocrysts in DR8 andesite. Note that Ca/(Ca+Na) ratio of the core of each phenocryst is rather constant, but differs from one another.

will be discussed later. The lack of marked iron enrichment in the bulk rock composition of the suite may be caused partly by internal magma mixing as suggested by the presence of wide compositional range of phenocryst plagioclase in the andesite (Fig. 8). Fig. 7 shows the composition of microphenocryst magnetite and ilmenite in the andesite and dacite. Magnetites are rich in ulvospinel component, whereas ilmenites contain little hematite components in these volcanic rocks.

Zoning profiles of plagioclase phenocrysts in the andesite (DR8-H)

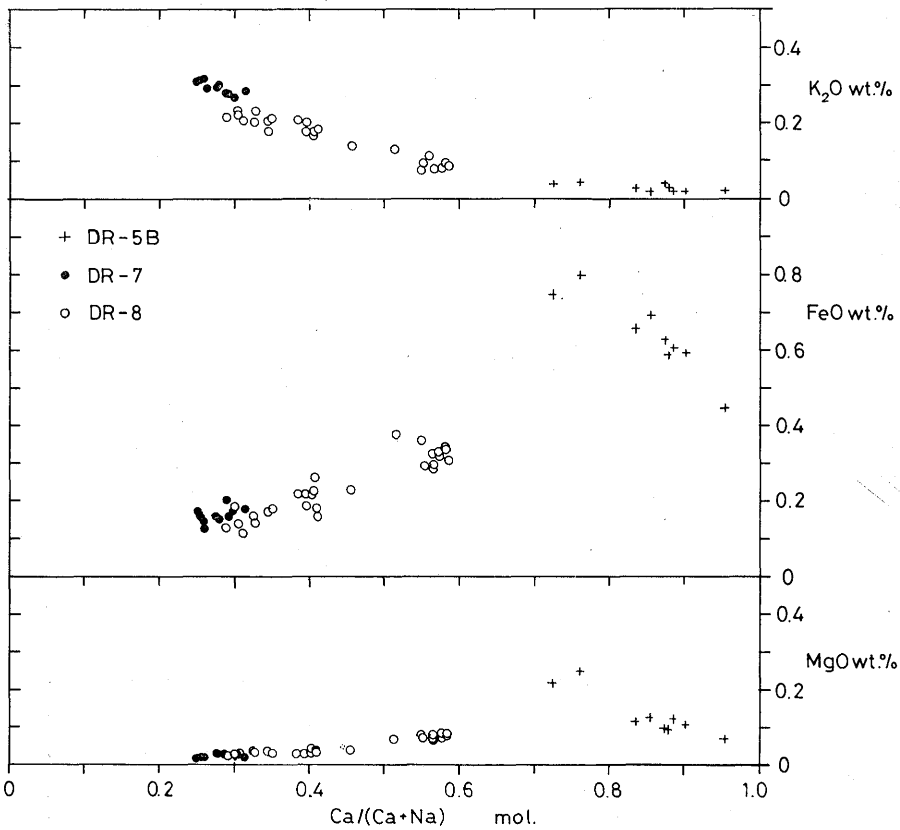


Fig. 9. Composition of plagioclase phenocrysts in DELP-88 samples.

are shown in Fig. 8, and compositional relations between K_2O, MgO, and FeO contents and Ca/(Ca+Na) ratio of plagioclase are shown in Fig. 9. Fig. 8 illustrates variable core compositions of plagioclase phenocrysts in the andesite. Ca/(Ca+Na) ratio of the core ranges from 0.29 to 0.59. The K_2O content of plagioclase increases and the MgO and FeO contents decreases as Ca/(Ca+Na) ratio decreases in the andesite and dacite, while both MgO and FeO contents of plagioclases as Ca/(Ca+Na) ratio decrease.

Temperature and oxygen fugacity of crystallization of magmas were obtained from the average compositions of phenocrysts and microphenocrysts in DELP-88 samples, and the result is shown n Table 7. Temperature of crystallization is estimated by the pyroxene thermometry of LINDSLEY (1983) for all the three samples, and also by iron-titanium oxide thermo-barometry after the method of ANDERSON and LINDSLEY (1988). The crystallization temperature of the DR5B-H basalt is ca.

1100°C at 1 atmosphere by pyroxene thermometry. The crystallization temperature of DR7-H dacite is ca. 800°C by pyroxene thermometry and 783°C by iron-titanium oxide thermometry. For DR8-H andesite, the two method show some discrepancy; i.e. 950°C by pyroxene thermometry and 880°C by iron-titanium oxide thermometry. The discrepancy may be caused partly by the wide compositional range of pyroxenes and iron oxides of the andesite (Fig. 6 and 7). DR8-H andesite contains microphenocryst of hornblende, and the experimentally determined maximum

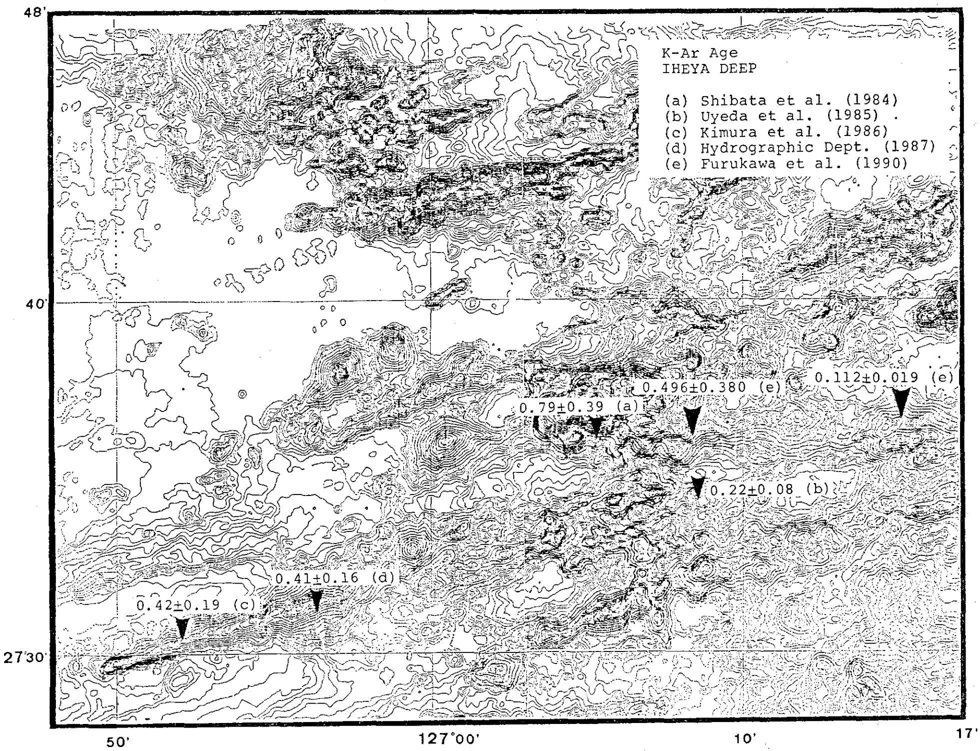


Fig. 10. Submarine topographic map and K-Ar ages of the Iheya Deep. Black arrows show the distribution of rocks dated by K-Ar method.

Table 8. K-Ar age of volcanic rocks determined by FURUKAWA (unpublished data). Location of samples are represented in Table 1.

Sample No.	K (wt%)	Radiometric $^{40}Ar \times 10^{-8}$ S.T.P. (cm^3/g)	Air contamination	K-Ar Age (Ma)
DR5B-K basalt	0.300	0.5884	98.3%	0.505±0.453
DR7-K dacite	1.954	0.8482	91.2%	0.112±0.019
DR8-K andesite	2.011	3.8711	98.0%	0.496±0.380

stability of hornblende in such magmas are 900–950°C (EGGLER and BURNHAM, 1973), and are in accord with the estimated temperature of the DR8-H magma by the present methods.

The oxygen fugacity of DELP-88 samples expressed by difference from those defined by fayalite-magnetite-quartz (FMQ) assemblage (Δlog fO_2) are shown in Table 7. Unequivocally, they indicate rather reducing conditions of crystallization of phenocrysts of basalt, andesite and dacite in the Okinawa Trough region. Most of mid-oceanic ridge basalt show Δlog fO_2 (FMQ) of 0 to -2 (CHRISTIE *et al.*, 1986; SATO, 1989), whereas the arc basalt shows slightly oxidized conditions of crystallization (CARMICHAEL, 1968). It is remarkable that basalt and andesite of DELP-88 taken from arc to back-arc environments have rather reducing conditions of phenocryst crystallization.

6. K-Ar age studies

K-Ar analyses were performed on three volcanic rocks dredged from the Irabu knoll (DR5B) and from northeastern and northwestern wall of the Iheya Deep (DR7 and DR8) (FURUKAWA, unpublished data).

Results of the K-Ar age studies are summarized in Table 8. In

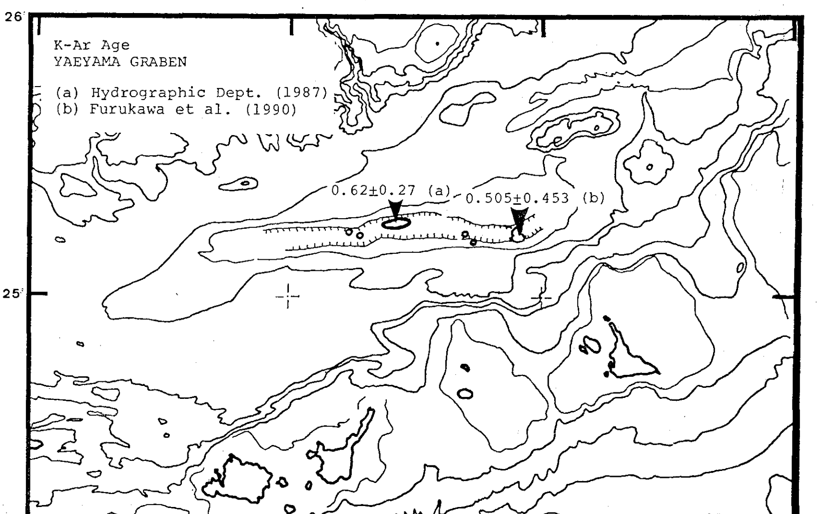


Fig. 11. Submarine topographic map of the southwestern part of the Okinawa Trough and its adjacent area. Black arrows show the distribution of rocks dated by K-Ar method.

Figs. 10 and 11, the present K-Ar age together with reported K-Ar age (HYDROGRAPHIC DEPARTMENT OF MARITIME SAFETY AGENCY JAPAN 1987; KIMURA *et al.*, 1986; SHIBATA *et al.*, 1985) are plotted on topographic maps.

The results, in addition to previous age studies, indicate that volcanic rocks erupted later than 1 Ma, and suggests that the volcanism occurred simultaneously in the Yaeyama Graben and in the Iheya Deep (FURUKAWA, unpublished data).

Acknowledgements

During the preparation of this paper, instructive advice and comments were given by Dr. H. AOKI of the Department of Marine Mineral Resources, Tokai University, and Dr. H. KINOSHITA of the Department of Earth Sciences, Chiba University, who was also the chief scientist of the DELP-88 Cruise. Dr. H. TOKUYAMA, Ocean Research Institute, University of Tokyo gave us instruction on EPMA analysis and great deal of advice. Comments by an anonymous reviewer of the Bulletin were helpful to improve the manuscript. This work was supported in part by funds from the Cooperative Program (No. 89117 and No. 89158) provided by Ocean Research Institute, University of Tokyo.

References

ANDERSON, D. J. and D. H. LINDSLEY, 1988. Internally consistent solution models for Fe-Mg-Mn-Ti oxides: Fe-Ti oxides, *Amer. Mineral.*, **73**, 714-726.

BENCE, A. E. and A. L. ALBEE, 1968. Empirical correction factors for the electron microanalysis of silicates and oxides, *Jour. Geol.*, **76**, 382-403.

CARMICHAEL, I.S.E., 1968. The iron-titanium oxides of salic volcanic rocks and their associated ferromagnesian silicates, *Contrib. Mineral. Petrol.*, **14**, 36-64.

CHRISTIE, D. M., I.S.E. CARMICHAEL and C. H. LANGMUIR, 1986. Oxidation states of mid-ocean ridge basalt glasses, *Earth Plan. Sci. Lett.*, **79**, 397-411.

EGGLER, D. H. and C. W. BURNHAM, 1973. Crystallization and fractionation trends in the system andesite-H_2O-CO_2-O_2 at presures to 10 kilobars, *Geol. Soc. Amer. Bull.*, **84**, 2517-2532.

HYDROGRAPHIC DEPARTMENT OF MARITIME SAFETY AGENCY JAPAN, 1987. Data report of hydrographic observation, *Series of continental shelf survey*, **3**, pp. 332.

KATO, S., T. KATSURA and K. HIRANO, 1982. Submarine geology off Okinawa Island, *Rep. Hydrogr. Res.*, (17), 31-70 (in Japanese with English abstract).

KIMURA, M., I. KANEOKA, Y. KATO, S. YAMAMOTO, I. KUSHIRO, H. TOKUYAMA, H. KINOSHITA, N. ISEZAKI, H. MASAKI, A. OSHIDA, S. UYEDA and T.W.C. HILDE, 1986. Report on DELP 1984 Cruises in the Middle Okinawa Trough, part 5: Topography and geology of the central grabens and their vicinity, *Bull. Earthq. Res. Inst., Univ. Tokyo*, **61**, 269-310.

KUNO, H., 1968a. Discussion of paper by H. AOKI and M. ITO, "Rocks in oceanic region —1. High-almina basalt—.", *Earth Sci.*, **22**, 195-197 (in Japanese with English abstract).

KUNO, H., 1968b. Differentiation of basalt magmas, in HESS, H. H. and A. POLDERVAAT ed., Basalts, Vol. 2. *New York Intersci. Pub.*, 623-688.

KUNO, H., 1976. Vocanos and volcanic rocks, p 283, Iwanami, Tokyo (in Japanese).

LINDSLEY, D. H., 1983. Pyroxene thermometry, *Amer. Mineral.*, **68**, 477-493.

MIYASHIRO, A., 1974. Volcanic rock series in island arcs and active continental margins, *Amer. J. Sci.*, **274**, 321-355.

MULLEN, E. D., 1982. $MnO/TiO_2/P_2O_5$: a minor element discriminant for basaltic rocks of oceanic environments and its implications for petrogenesis, *Earth Plan. Sci. Lett.*, **62**, 53-62.

NAGUMO, S., H. KINOSHITA, J. KASAHARA, T. OUCHI, H. TOKUYAWA and H. AKIYOSHI, 1986. Report on DELP 1984 Cruises in the Middle Okinawa Trough, part 2: Seismic structural studies, *Bull. Earthq. Res. Inst., Univ. Tokyo*, **61**, 167-202.

SATO, H., 1989. Mg-Fe partitioning between plagioclase and liquid in basalts of Hole 504B, ODP Leg 111, 1-atmosphere melting study, *Proceeding of Ocean Drilling Program, 111, Part B*, 17-26.

SHIBATA, K., S. UTSUMI, K. UTO, and T. NAKAGAWA, 1984. K-Ar age results 2: New data from the Geological Survey of Japan, *Bull. Geol. Surv. Japan*, **35**, 331-340 (in Japanese with English abstract).

UYEDA, S., M. KIMURA, T. TANAKA, I. KANEOKA, Y. KATO and I. KUSHIRO, 1985. Spreading center of the Okinawa Trough, *Technical Rep. JAMSTEC, Special Issue*, **16**, 123-142 (in Japanese with English abstract).

UEDA, Y., 1986. Geomagnetic anomalies around the Nansei Syoto (Ryukyu Islands) and their tectonic implications, *Bull. Volcanol. Soc. Japan, Ser.* 2, **31**, 134-135 (in Japanese with English abstract).

DELP 1988年度沖縄トラフ海域研究航海報告
6. 火山岩の岩石学

東海大学海洋学部 石川政憲
広島大学総合科学部 佐藤博明
神戸大学理学部 古川雅英
琉球大学理学部 木村政昭
加藤祐三
津輕良介
九州東海大学農学部 嶋村清

DELP-88 航海では，中部および南部沖縄トラフで8地点のドレッジがおこなわれ，その内の5地点 (DR3, DR5B, DR7, DR8, および DR10) で多くの火山岩類が採取された．これらのトラフ中に形成されているグラーベンの中軸部の岩石 (DR3, DR8) はカルクアルカリ岩または島弧ソレアイトの特徴を示し，これまで報告されている化学分析結果と調和的である．この結果は，この海域で海洋地殻が見出されていないという地球物理学のデータとも矛盾しない．

DR5B の火山岩は島弧型の特徴を有する低アルカリソレアイトであり，酸化物-SiO_2図で沖縄トラフ中軸部を構成する岩石とは区別される．DR5B の位置は，琉球弧の火山フロントの南西延長上にあることから，この火山岩の噴出は火山フロントに沿ったものである可能性もある．

Iheya Deep の火山岩の K-Ar 年代は 0.112±0.019 Ma (DR7) と 0.496±0.380 Ma (DR8) を示し，いずれも 1 Ma よりも新しい火山活動によるものである．さらに Yaeyama Graben の火山活動も 1 Ma より新しいことからほぼ同時期に活動したものである．火山フロントの延長上に位置する DR5B の K-Ar 年代は 0.505±0.453 Ma を示す．

DELP-88 火山岩の斑晶の晶出温度は，DR5B の玄武岩が 1100°C であり，DR7 のデイサイトが 783～800°C であり，DR8 の安山岩が 900～950°C である．これらの火山岩類の結晶作用は，還元的な環境でおこなわれた．