Major-element Petrochemistry of Some Extrusive Rocks from the Volcanically Active Mariana Islands

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U.S. - Japan Paleomagnetic Cooperation Project in Micronesia

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Abstract

Volcanic rocks from six of the currently or recently active volcanoes of the Mariana Island arc show little variation in major element abundances. SiO_2 content averages 51.5 wt. %. The flows are high in Al_2O_3 (mean 17.7 wt. %) and Fe oxides (mean 10.1 wt. % calculated as FeO only), and moderate in MgO content (mean 4.7 wt. %), Na_2O (mean 2.7 wt. %), and K_2O (mean 0.7 wt. %). Only the rocks from Farallon de Pajaros, the northernmost of the Mariana Islands, deviate slightly from the average of the analyses. Three analyses from this island are slightly higher in SiO_2 (about 54 wt. %) and Al_2O_3, and are lower in total Fe oxides and MgO. According to preferred classification, the lavas of the Mariana Islands can be termed mela-andesites, high-alumina basalts, or calc-alkaline (orogenic) basalts.

The K_2O values (mean 0.7 wt. %) obtained from lavas of the Mariana Islands are significantly higher than the K_2O values (about 0.33 wt. %) from volcanics

of the Izu chain to the north. Inasmuch as the substantial scatter in location of earthquake foci beneath both arcs prevents accurate delineation of the upper boundary of the Benioff zone, it presently cannot be determined whether this discrepancy in K_2O values reflects a difference in depth from the volcanic arc to the dipping seismic zone or relates to other phenomena.

The older volcanic islands within the Mariana-Bonin island chain apparently defined an island arc system during Eocene to Miocene time. This indicates that the present plane of convergence between the Pacific plate and the Philippine Sea plate has defined the convergence between these plates since Eocene time.

Acknowledgements

We are grateful to Dr. Corwin, U. S. Geological Survey, Washington, D. C., for his assistance and for sharing with us unpublished information on the geology of the Mariana Islands. We are indebted to the Japan-U. S. Scientific Cooperation Program for funds enabling travel to and from the Mariana Islands. This program was supported by National Science Foundation grant GF-441 and the Japan Society for Promotion of Science grant 4 R 008.

Introduction

The Mariana Islands form the southernmost segment (about 650 km long) of the Izu-Bonin-Volcano-Mariana archipelago, which extends from Guam northward to the main island of Japan, a distance of about 3000 km (Fig. 1). From south to north, the Mariana segment includes the following major islands: Guam, Rota, Tinian, Saipan, Anatahan, Sarigan, Guguan, Alamagan, Pagan, Agrihan, Asuncion, Maug, and Farallon de Pajaros (Fig. 2).

The southernmost four islands are largely composed of early to middle Tertiary volcanic, volcanoclastic, and coralline reef materials (TRACEY *et al.*, 1964; STARK, 1963; SCHMIDT, 1957). None of the four has been recently volcanically active. The remaining islands in the Mariana arc are the exposed portions of volcanic cones which are presently active or appear to have been recently active (KUNO, 1962). Eruptions within this century have been reported for Pagan (1924, 1966), Farallon de Pajaros (1936, 1969), Guguan (1901), and Agrihan (1917).

The Mariana Ridge, upon which the islands have been built, is actually composed of two arcuate subridges. The older islands project

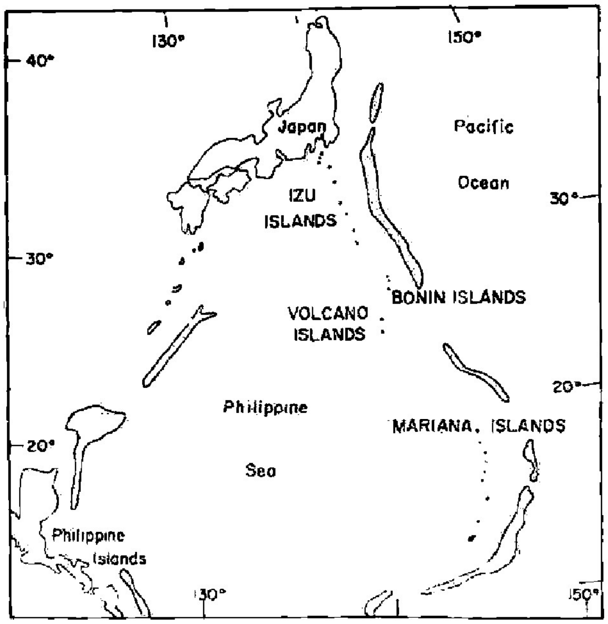

FIG. 1 - Generalized map of portion of the western Pacific Ocean. Position of trenches denoted by hachuring.

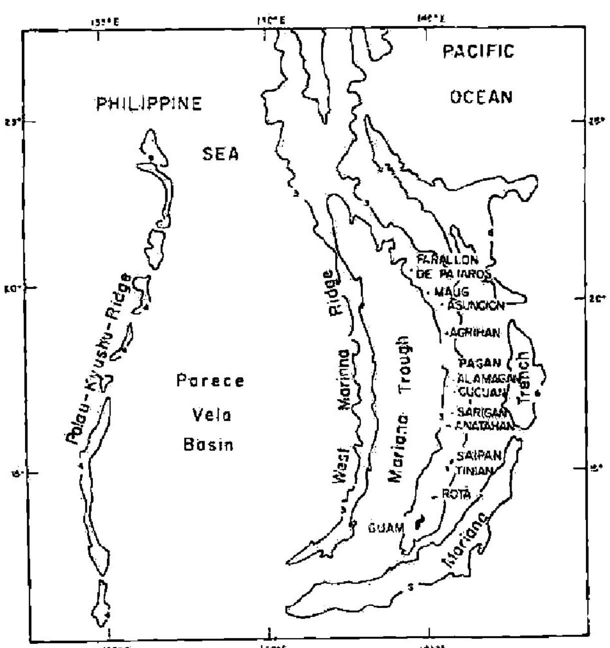

FIG. 2 - Location map for Mariana Islands and environs. Numbers give depth contours, in thousands of meters.

above the easternmost subridge in the southern portion of the Mariana arc, whereas the volcanically active islands are built on the western

TABLE 1 - Chemical Analyses

	Anatahan		*Sarigan*	*Alamagan*	*Pagan*					
									1925 Flow	
SiO_2	52.3	52.6	51.5	53.1	51.5	47.6	50.0	51.8	50.1	50.3
Al_2O_3	18.4	17.4	15.7	16.3	15.9	18.9	18.1	17.2	18.1	17.9
Fe_2O_3	7.6	4.5	4.3	4.5	6.1	6.2	4.3	3.8	5.0	4.7
FeO	3.1	5.8	5.4	4.7	6.5	4.9	5.8	6.3	5.7	6.6
MgO	4.3	4.3	6.1	6.0	5.1	5.9	5.0	4.7	4.8	4.8
CaO	8.9	9.1	10.6	10.2	9.2	11.8	10.5	10.5	10.8	10.6
Na_2O	3.2	2.8	2.4	2.6	3.0	2.8	2.7	2.7	2.7	2.7
K_2O	0.55	0.48	0.59	0.88	0.78	0.66	0.66	0.64	0.72	0.70
H_2O^+	—	—	—	0.43	—	—	—	—	—	—
H_2O^-	—	—	—	0.07	—	—	—	—	—	—
TiO	0.88	0.78	0.78	0.80	0.96	0.88	0.75	1.5	0.98	1.0
P_2O_5	0.09	0.07	0.05	0.25	0.092	0.069	0.069	0.046	0.069	0.012
MnO	0.05	0.03	0.04	0.19	0.034	0.044	0.039	0.039	0.026	0.026
CO	0.2	0.1	0.1	—	0.1	0.1	0.3	0.1	0.1	0.1
F	0.4	—	—	—	0.04	0.04	0.03	0.04	0.05	0.04
Cl	0.08	0.03	0.04	—	0.02	0.01	0.01	0.04	0.01	0.01
H_2O_{tot}	0.2	0.2	1.0	—	0.2	0.2	0.2	0.2	0.2	0.2
Sample	1	2	3	4	5	6	7	8	9	10

Norms

	1	2	3	4	5	6	7	8	9	10
Quartz	9.06	8.82	6.24	6.78	5.54	—	3.35	6.00	3.51	3.17
Orthocl.	3.25	2.84	3.49	5.00	4.61	3.90	3.90	3.78	4.25	4.14
Albite	26.47	23.43	20.01	21.48	25.25	23.62	22.76	22.51	22.78	22.77
Anorth.	34.53	33.63	30.48	30.58	27.68	37.08	35.36	33.10	35.17	34.69
Diopside										
Wollast.	3.13	4.49	8.97	8.35	7.00	8.40	5.92	7.44	7.10	7.07
Enst.	2.71	2.76	6.15	6.00	4.58	6.43	3.75	4.62	4.71	4.29
Ferrosil.	—	1.47	2.11	1.58	1.94	1.10	1.79	2.38	1.88	2.38
Hypersth.										
Enst.	8.00	7.95	9.04	9.00	8.12	3.98	8.70	7.08	7.25	11.91
Ferrosil.	—	4.24	3.09	2.38	3.44	0.68	4.14	3.65	2.90	7.66
Olivine										
Forst.	—	—	—	—	—	3.00	—	—	—	—
Fayal.	—	—	—	—	—	0.56	—	—	—	—
Magnet.	7.61	6.53	6.24	6.50	8.85	8.99	6.24	5.51	7.25	6.82
Hemat.	2.35	—	—	—	—	—	—	—	—	—
Imen.	1.67	1.48	1.42	1.52	1.82	1.67	1.42	2.85	1.86	1.90
Apat.	0.22	0.16	0.11	Tr	0.22	0.16	0.16	0.11	0.16	0.03

1. Flow in cove at NW side of Anatahan.
2. Flow in cove at NW side of Anatahan; separated from Flow 1 by erosion surface.
3. Flow in cove at N end of Sarigan; exposed at beach.
4. Flow, 1500 feet SW of village, south Alamagan; equivalent to no. 7, table 6, p. 157, SCHMIDT (1957).
5. Flow at Bandeera Peninsula, Pagan.
6. Flow near base of caldera rim, Pagan.
7. Flow inside caldera NW of Mt. Pagan, Pagan.
8. Flow near beach about 500 m N of Bandeera Peninsula, Pagan.
9. Flow in crater wall SW side of Mt. Pagan, Pagan.
10. 1925 flow, Mt. Pagan, Pagan.
11. 1925 flow, Mt. Pagan, Pagan; TANAKADATE (1940), p. 220; equivalent to no. 2, table 6, p. 157, SCHMIDT (1957).
12. 1925 flow. Mt. Pagan, Pagan; TANAKADATE (1940), p. 220; equivalent to no. 6, table 6, p. 157, SCHMIDT (1957).

					Agrihan	*Farallon de Pajaros*			*Mean*	*Std Dev*
50.3	51.5	49.9	50.9	51.0	50.5	52.8	53.9	57.0	51.5	± 1.9
18.1	17.7	18.9	15.5	17.0	16.9	21.4	19.6	17.5	17.7	± 1.36
4.5	2.6	3.3	4.3	3.4	2.7	2.1	2.7	4.6	4.27	
6.7	8.2	6.7	8.2	8.3	8.6	6.2	6.7	4.4	6.25	
4.8	4.6	4.7	5.6	4.7	5.4	2.4	2.4	3.2	4.7	
10.8	11.8	11.8	10.6	10.0	10.8	10.5	9.8	8.5	10.3	
2.5	2.4	2.4	2.6	2.9	2.7	2.8	2.7	3.0	2.7	± 0.2
0.70	0.63	0.61	0.71	0.78	0.76	0.62	0.67	1.15	0.7	± 0.14
0.23	0.32	0.10	0.24	0.30	0.13	0.10	0.15	—		
0.13	0.07	0.06	0.02	0.06	0.05	0.06	0.10	—		
1.06	—	0.80	0.95	0.97	1.04	0.86	—	—	0.94	
0.16	0.12	0.23	0.24	0.24	0.18	0.15	0.12	0.19		
0.21	0.20	0.19	0.21	0.21	0.22	0.14	0.17	—		
—	—	—	—	—	—	—	—	—		
—	—	—	—	—	—	—	—	—		
—	—	—	—	—	—	—	—	—		
—	—	—	—	—	—	—	—	0.21		
11	12	13	14	15	16	17	18	19		

(weight %)

3.60	2.94	1.68	2.34	1.74	0.18	6.30	8.64	12.78
3.89	3.34	3.34	3.89	4.45	4.45	3.34	3.89	6.67
20.96	20.44	20.44	22.53	24.63	22.53	23.58	22.53	25.15
36.14	35.86	38.92	28.08	31.14	31.97	44.20	39.58	30.86
7.31	7.77	8.24	10.32	7.66	8.93	3.36	3.83	4.76
4.40	3.50	4.50	5.70	3.90	4.60	1.40	1.50	2.90
2.51	4.22	3.43	4.22	3.56	4.09	1.98	2.38	1.58
7.6	7.80	7.30	8.20	7.90	8.80	4.60	4.60	5.20
4.62	9.11	5.02	6.07	7.26	8.05	6.20	7.79	2.77
—	—	—	—	—	—	—	—	—
—	—	—	—	—	—	—	—	—
4.48	3.71	4.64	6.26	4.87	3.94	2.08	3.94	6.73
—	—	—	—	—	—	—	—	—
2.13	—	1.52	1.82	1.82	1.98	1.67	—	—
Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr

13. Flow 650 N of Bandeera Peninsula, Pagan; equivalent to no. 1, table 6, p. 157, SCHMIDT (1957).
14. Flow in caldera wall, 800 m E of Bandeera Peninsula, Pagan; equivalent to no. 4, table 6, p. 157. SCHMIDT (1957).
15. Flow at base of caldera wall, 2000 m SE of Bandeera Peninsula, Pagan; equivalent to no. 5, table 6, p. 157, SCHMIDT (1957).
16. Flow at promintory of landing beach, S. Agrihan; equivalent to no. 3, table 6, p. 157, SCHMIDT (1957).
17. Flow at S coast of Farallon de Pajaros; equivalent to no. 8, table 6, p. 157, SCHMIDT (1957); original reference, TANAKADATE (1940), p. 220.
18. Flow at foot of volcanic cone, SE Farallon de Parajos; equivalent to no. 9, table 6, p. 157, SCHMIDT (1957); original reference, TANAKADATE (1940), p. 220.
19. Flow, Farallon de Parajos; equivalent to no. 10, tabel 6, p. 157, SCHMIDT (1957); original reference, KAISER (1903), p. 117.

subridge in the middle and northern part of the arc system. East of the Mariana Ridge is a deep subparallel arcuate trench; west of it, in progressive order are the Mariana Trough, West Mariana Ridge, Parece Vela Basin, Palau-Kyushu Ridge, and Philippine Sea Basin (Fig. 2). The seismicity associated with the arc-trench system has been described by KATSUMATA and SYKES (1969). The possible modes of formation of the complex arc system have been given by TRACEY *et al.*, 1964; KARIG, 1971 *a*; UYEDA and BEN-AVRAHAM, 1972; BRACEY and OGDEN, 1972; and LARSON *et al.*, 1974.

The petrochemistry of the early to middle Tertiary volcanic rocks of Guam and Saipan have been discussed by STARK (1963) and SCHMIDT (1957), respectively. Schmidt also included a summary of the petrochemical data available from the recently active islands of the Mariana arc. He presented four analyses from Pagan, three from Farallon de Pajaros, and one each from Agrihan and Alamagan. Strontium ratios have been determined by HEDGE (1966) for some of these same rocks. In addition, we have obtained chemical analyses from nine lava samples collected from the recently active islands of Anatahan, Sarigan, and Pagan. With the addition of these data, there is at least one analysis from six of the recently or currently active volcanoes of the Mariana Islands. It is now possible to formulate some general conclusions concerning the petrochemical nature of this segment of the Izu-Bonin-Volcano-Mariana island system and to compare its characteristics with those of the young volcanoes in the Volcano and Izu islands and with the older inactive segments in the Mariana and Bonin islands. Inasmuch as the Mariana arc is intraoceanic in nature, it is especially important to study the character of its eruptive rocks.

Chemical Analyses

Chemical analyses from the recently active volcanoes of the Mariana Islands are given in Table 1. Six of the new analyses have been obtained from flows on Pagan Island (see Fig. 3). All six samples came from the northern part of the island: two from the wall of the old caldera rim, two from the younger flows associated with presently active Mount Pagan, and two from flows of intermediate age within the caldera. There is no way of knowing the time span repres ented by these six flows. All are normally magnetized and therefore appear to be younger than 0.7 m.y. Attempts to date the older flows by whole-rock K-Ar methods proved futile. Of the five chemical analyses reported by SCHMIDT (1957, p. 157) for Pagan, two are from the 1925 flow (see Table 1; original data from TANAKADATE, 1940). One of our analyses is also from the 1925 flow. It is impossible to tell from SCHMIDT's (1957) descriptions whether we have duplicated any other

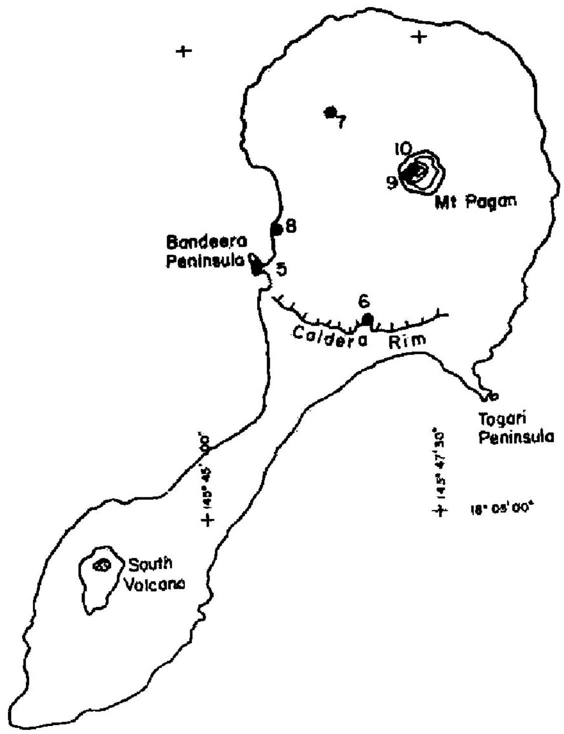

FIG. 3 - Outline map of Pagan Island, showing sample locations. Numbering is consistent with sample numbers given in Table 1.

analyses of Pagan flows. Because of the thinness and discontinuous nature of the flows, we feel that the chances of duplication are minimal.

The two samples from Anatahan came from two flows (separated by an unconformity) exposed near the beach directly south of the abandoned village at the northwest point of the island. According to CORWIN (written communication. 1971) both flows are part of the pre-caldera set of flows. The one sample from Sarigan was obtained from a flow exposed in a cove on the west margin of the island; it is one of the pre-caldera flows on that island (CORWIN, written communication, 1971).

The most striking characteristic observable from the chemical analyses in Table 1 is their similarity. This holds true whether one is comparing analyses from one island such as Pagan or from all six of the islands. Mean values of the major oxides and standard deviations (Table 1, columns 20 and 21 respectively), demonstrate the similarity in composition of all 19 flows. All major oxides (SiO_2, Al_2O_3, total iron oxides, MgO, CaO, Na_2O, K_2O, and TiO_2) show restricted variation about their mean values, and all rocks except those from Farallon de Pajaros can be classified as basalts or basaltic andesites.

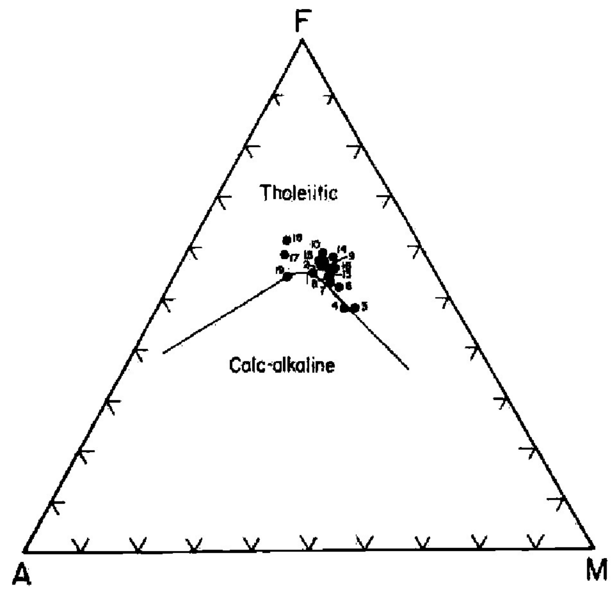

FIG. 4 - Ternary plot of: A ($K_2O + Na_2O$) vs - F (FeO +0.899 Fe_2O_3) vs - M (MgO) for all samples from the active Mariana Islands (see Table 1). Division between calc-alkaline and tholeiitic fields taken from IRVINE and BARAGAR, 1971. Note tight grouping of most flows, and slightly more differentiated nature of the three flows from Farallon de Parajos (Nos. 17, 18, 19).

The flows are high in Al_2O_3 (mean 17.7 wt. %), moderately high in CaO (mean 10.3 wt. %) and iron oxides (mean 10.1 wt. % calculated as FeO only), and moderate in amounts of MgO (mean 4.7 wt. %), Na_2O (mean 2.7 wt. %), and K_2O (mean 0.7 wt. %).

The flows that deviate most from the average are the three andesites from Farallon de Pajaros (Table 1; columns 17, 18, 19). These three appear slightly higher in SiO_2 and Al_2O_3, and lower in total iron oxides and MgO. Farallon de Pajaros is the farthest north of the active Mariana Islands and is about 150 km north of Agrihan, the next island to the south for which an analysis is available (Table 1; column 16). Samples 1 through 16, which are from five islands located within a distance of 175 km along the Mariana arc, are extremely similar in their petrochemistry. The possibility that there is a progressive variation in petrochemistry northward from Agrihan to Farallon de Pajaros cannot be investigated inasmuch as analyses are unavailable from Asuncion and Maug.

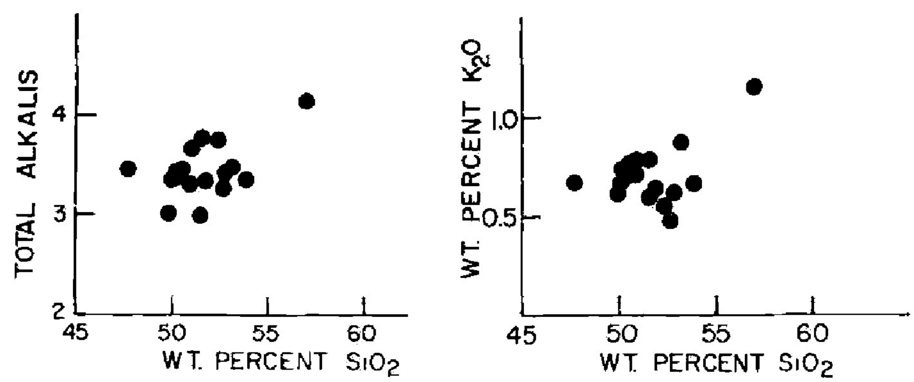

FIG. 5 - (Left). Plot of total alkalis ($K_2O + Na_2O$) vs - SiO_2 for the active Mariana Islands. Note general lack of large-scale variation in both SiO and total-alkali content.
(Right). Plot of K_2O vs - SiO_2 for samples from the active Mariana Islands. The average K_2O content is about 0.7 wt. %, which is about twice that of rocks with similar silica content from the Izu arc (see Fig. 8).

The similarity in composition of lavas from Anatahan, Sarigan, Alamagan, Pagan, and Agrihan and the discordant character of the Farallon de Pajaros flows can be seen in a plot of alkalis (A)-total iron, as FeO, (F)-MgO (M) as shown in Fig. 4.

It is to be noted that although the total percentage of iron oxides is quite similar from flow to flow (Table 1), the amounts of FeO and Fe_2O_3 are highly variable. The FeO-Fe_2O_3 ratio apparently is dependent on the extent of post-eruption oxidation (deuteric or hydrothermal). Unfortunately, calculation of C.I.P.W. norms is greatly affected by the FeO-Fe_2O_3 ratio; therefore, the norms (Table 1) cannot be used in any detailed way for comparison between flows. A general character is evident, however, in that hypersthene appears in the norm for all 19 analyses and quartz in 18 of the analyses. Only sample 6, from Pagan, lacks quartz. Essentially all flows appear slightly oversaturated in silica and could be termed tholeiites according to the criteria of YODER and TILLEY (1962).

Plots of total alkalis (K_2O + Na_2O) vs. SiO_2 (Fig. 5, left), lie in the subalkaline field (IRVINE and BARAGAR, 1971). Plots of Al_2O_3 vs. normative-plagioclase composition can further be used to classify this subalkaline group into either a calc-alkaline or tholeiitic association (Fig. 6). The analyses lie close to the dividing line between these two fields (IRVINE and BARAGAR, 1971) but plot more abundantly in the calc-alkaline field. However, the analyses fall almost entirely within the tholeiitic region when plotted on an A-F-M ternary diagram (Fig. 4).

RITTMANN (1970) has suggested that an effective separation between orogenic (calc-alkaline) and non-orogenic basaltic rocks can

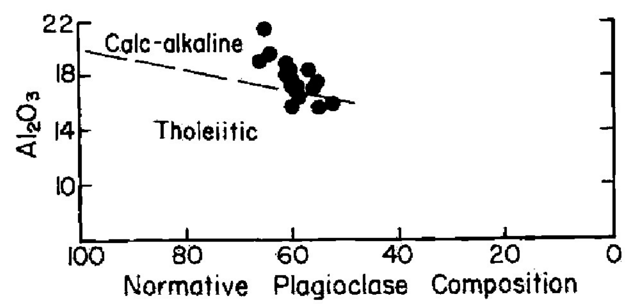

FIG. 6 - Plot of Al_2O_3 content (wt. %) vs · normative plagioclase composition for samples from active Mariana Islands. Division between calc-alkaline and tholeiitic fields taken from IRVINE and BARAGAR, 1971. Most flows plot in calc-alkaline field but lie close to the line. Normative plagioclase is just about at subdivision between labradorite and andesine. Note that most samples have Al_2O_3 contents equal to, or greater than 16 wt. %.

be made by comparison of weight percentages of several oxides. He defines: $\sigma = (Na_2O + K_2O)^2/(SiO_2 - 43)$ and $\tau = (Al_2O_3 - Na_2O)/TiO_2$ and plots $\log_{10}\sigma$ vs. $\log_{10}\tau$. A plot of this type for the rocks of the Mariana Islands with Rittmann's classification is given in Fig. 7. All of the Mariana lavas group closely in the calc-alkaline (orogenic) field. Rittmann contends that basaltic rocks of the orogenic suite should be designated as « mela-andesites » to stress their similarity to orogenic calc-alkaline andesites and to avoid confusion of these rocks with non-orogenic tholeiites.

JAKES and GILL (1970) have similarly noted that orogenic tholeiitic basalts are petrochemically unique and have suggested that they be termed « island-arc tholeiites ». They contend, however, that island-arc tholeiitic lavas are not typically calc-alkaline in nature but differ in subtle but discernible ways. Unfortunately, much of their reasoning, which is based on variations in amounts of minor elements in the rocks, cannot be applied to the Marianas lavas because of a lack of minor-element data for these rocks.

In summary, the Mariana volcanoes show little petrochemical variation within and between islands. The rocks mostly include high-

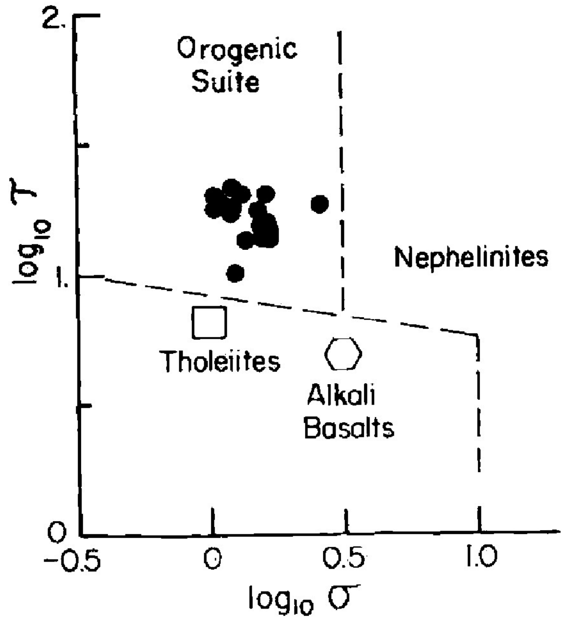

FIG. 7 - Plot of $\log_{10} \sigma$ vs - $\log_{10} \tau$ for samples from active Mariana Islands. Usage and subdivisions are taken from RITTMANN, 1970 [$\sigma \equiv (Na_2O + K_2O)^2/(SiO_2 - 43)$; $\tau \equiv (Al_2O_3 - Na_2O)/TiO_2$]. Note that all samples tightly cluster and all fall within the field characteristic of orogenic belts.

alumina, subalkali, slightly over-saturated basaltic and andesitic lavas which, according to preference, could be termed mela-andesites, high-alumina basalts, or calc-alkaline (orogenic) basalts.

Comparison with the Volcano-Izu Islands

Active volcanism is present north of the Mariana Islands, throughout the length of the Volcano and Izu Island chains (Fig. 1). The Volcano Islands, the next group of active volcanic centers north of the Marianas, consist of three cones, the largest being the island of Iwo-Jima. In a fashion similar to that of the Mariana Islands, this part of the island-ridge system is composed of two subridges about 100 km apart. The active vents of the Volcano Islands project above the western subridge, and the Bonin Islands, composed of early to middle Tertiary volcanic, volcaniclastic, and coralline reefal rocks, rise above the eastern subridge.

The northernmost island of the Volcano group, Kita-Iwo-Jima, is composed of tholeiitic basalt (KUNO, 1962) which is lithologically similar to flows of the Izu Islands farther north. Iwo-Jima and Sin-Iwo-Jima lack basaltic rocks and are composed largely of alkali-enriched

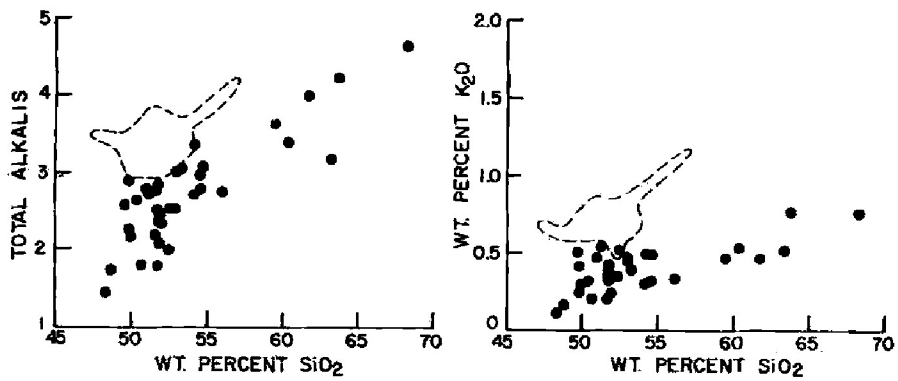

FIG. 8 - (Left). Plot of total alkali content ($K_2O + Na_2O$) vs - SiO_2 for samples from the Izu Islands. Dashed area represents plot of all samples from the active Mariana Islands and is given for comparison. Note the complete lack of overlap between rocks from the two arc segments.
(Right). Plot of K_2O vs - SiO_2 for samples from the Izu Islands. The plot-field for samples from the active Mariana Islands (see Fig. 5, on the right) is outlined by dashes for comparison. Note almost total lack of overlap between rocks from the Mariana and Izu arcs.

trachyandesite and appear to be the product of late-stage differentiation from a basaltic magma (MAC DONALD, 1948).

In contrast, the Izu Islands, which extend over a distance of about 500 km, consist primarily of basalt, basaltic andesite, and andesite (KUNO, 1962). Differentiation seems to have been minimal: some dacite is found at Myozin Reef at Bayonnaise Rocks (in the middle part of the island chain), and rhyolite is predominant on the islands of Niishima and Kozushima near the north end of the chain.

The Izu Island mafic extrusions appear to be more variable from island to island than are those of the Mariana Islands. However, on any one island, the rocks are quite uniform. Lavas from Oshima, Miyakeshima, and Aogashima are characterized by moderate alumina contents; and those from Oshima are also high in iron-oxide content. The extrusives of Hachyjoshima, Bayonnaise Rocks and Torishima contain rather high amounts of alumina and are quite similar in composition to those of the Mariana Islands.

The alkali content is extremely uniform in all of the Volcano Izu basaltic-andesitic lavas: Na_2O averages about 2.2 wt. % and K_2O

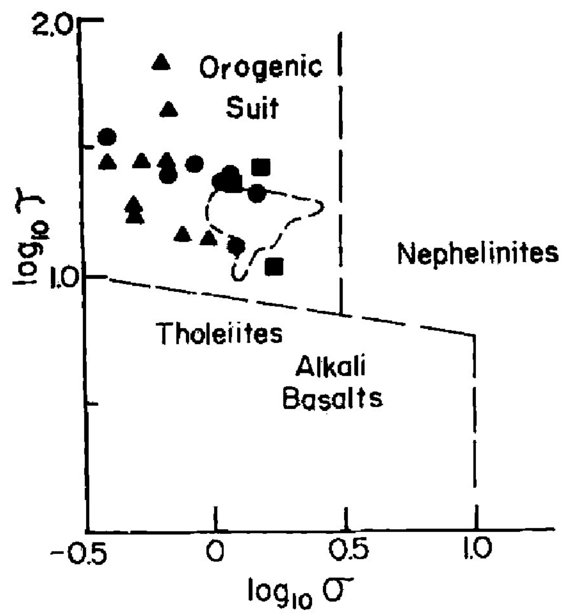

FIG. 9 - Plot of $\log_{10}\sigma$ vs $\cdot$ $\log_{10}\tau$ from the Izu Islands and older islands in the Mariana arc and in the Bonin arc. Definitions of τ and σ given in Fig. 7; squares denote samples from Saipan; circles denote samples from Guam, and triangles denote samples from Izu Islands. Area outlined by dashes includes all samples from active Mariana Islands.

about 0.33 wt. %. It is the latter aspect which differentiates most strongly between lavas of the Mariana Islands and those of the Volcano-Izu Islands. As shown in Table 1, the content (in weight per cent) of K_2O in an average Mariana tholeiite is about 0.7, or about twice that of the average Izu tholeiite. In Figs. 8 (right) and 5 (right) are plotted the values of K_2O vs. silica content for all analyses from the Volcano-Izu lavas (KUNO, 1962), and from the Mariana lavas, respectively. The area covered by the 19 analyses of Mariana lavas is shown in Fig. 8 (right) for comparison. Total alkalis (K_2O + Na_2O) vs. SiO_2 for the Volcano-Izu lavas are also compared with those values of volcanics from the Mariana arc (Fig. 8, on the left). There is virtually no overlap in the plots from the rocks of the two island groups.

Relation of K_2O Content and Depth to the Benioff Zone

The increase in alkalis in basaltic rocks across the Japanese arc, observed by KUNO (1959), has been related to increasing depth to the dipping Benioff seismic zone (KUNO, 1959; SUGIMURA, 1960; and KATSUI, 1961). Subsequently, a general correlation of increasing K_2O-SiO_2 ratio with increasing depth to the seismic zone was given by DICKINSON and HATHERTON (1967) and HATHERTON and DICKINSON (1969). It might be expected then, that the observed difference in K_2O values between the Mariana and Izu arcs is directly related to differences in depth to the Benioff zone beneath the two arcs. Yet, from the data given by KATSUMATA and SYKES (1969), the depth to the top of the 50 km thick seismic zone is about the same ($\sim$ 110 km) in both arcs. However, there is evidence that the seismic events may be sufficiently mislocated that measurements of this type are presently meaningless.

ENGDAHL (1973) has demonstrated that because of the differences in acoustic properties between the downgoing slab and adjacent asthenosphere, epicentral positions calculated by usual techniques can be considerably mislocated. It is necessary to model the acoustic properties of the particular arc system before accurate determinations of the epicentral and hypocentral positions can be made. When this is done (see ENGDAHL, 1973), measurement from the volcanic arc to the seismic zone can be made with an accuracy of less than 10 km. When such a relocation of seismic events has been done for the Izu-Volcano-Mariana arc, only then will it be possible to evaluate whether the difference in K_2O content is dependent on depth to the seismic zone or on some other factor.

Comparison with Older Non-active Islands of the Mariana and Bonin Islands

Volcanic rocks of Eocene to Miocene age from Guam and Saipan have close affinities with the calc-alkaline suite. Rock types on Guam range from basalt to andesite and those on Saipan from andesite to dacite. The variation in the rock types of these two islands, therefore, is more reminiscent of that in the Izu chain than of that in the younger rocks of the Mariana Islands.

The Bonin Islands, that lie east and north of the Volcano Islands, are analogous in tectonic position and rock type to the older segment of the Mariana Islands. They consist of Eocene andesitic lavas overlain by Miocene and younger coralline reefal material (YOSHIWARA, 1902; TSUNYA, 1937, as given in SCHMIDT, 1957). The volcanics are chemically similar to some of the andesites of Saipan.

Plots of $\log_{10}\sigma$ vs. $\log_{10}\tau$ (RITTMAN, 1970), for the basalts and andesites from Guam and Saipan fall into the orogenic basalt and andesite suite, in the same general region as do the other lavas from the Mariana arc (Fig. 9). It is interesting that the Guam analyses scatter widely across the field whereas those from the six Mariana volcanoes are relatively closely grouped. In addition to the possibility of actual chemical variations, some of the scatter could be caused by the high degree of subaerial weathering of the rocks on Guam and Saipan. Some dispersion also might be due to the fact that the lavas on Guam have been beneath sea level during part of their history and could have reacted to some extent with the sea water.

Nonetheless, there seems little doubt, based on the lava types and other geologic information presented by SCHMIDT (1957), TRACEY *et al.* (1964), and CLOUD et al. (1957), that the volcanic rocks comprising Guam and Saipan were part of a volcanically active island arc from Eocene to Miocene time. Apparently this Eocene to Miocene age volcanic arc extended northward to include the Bonin Islands.

According to KARIG (1971 *a, b*) and UYEDA and BEN-AVRAHAM (1972), the development of the present form of the Mariana arc system and the marginal basins and ridges to the west is the result of extensional processes operating behind the frontal arc for the past 40 to 50 m.y. This extension has caused the Mariana arc-trench system to migrate eastward during at least part of this time interval; however, some extension may have been accommodated by subduction into the trenches bordering the western edge of the Philippine Sea plate (KARIG, 1971 *b;* WU, 1971). Nonetheless, it is important to note that the present volcanically active island-arc system is essentially coincident with the ancient volcanic arc. Apparently, the present plane of convergence between the Philippine Sea plate and the Pacific plate has defined the convergence between these plates for about 40 to 50 m.y.

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