Bull Volcanol (1989) 51:210-224

Bulletin of
Volcanology

Physical volcanology of the submarine Mariana and Volcano Arcs

Sherman H Bloomer[1], Robert J Stern[2], and N Christian Smoot[3]

[1] Department of Geology, Duke University, Box 6729, College Station, Durham, NC 27708, USA
[2] Center for Lithospheric Studies, University of Texas at Dallas, Richardson, TX 75083-0688, USA
[3] Ocean Surveys Division, U.S. Naval Oceanographic Office, Bay St. Louis, MS 39522, USA

Abstract. Narrow-beam maps, selected dredge samplings, and surveys of the Mariana and Volcano Arcs identify 42 submarine volcanos. Observed activity and sample characteristics indicate 22 of these to be active or dormant. Edifices in the Volcano Arc are larger than most of the Mariana Arc edifices, more irregularly shaped with numerous subsidiary cones, and regularly spaced at 50–70 km. Volcanos in the Mariana Arc tend to be simple cones. Sets of individual cones and volcanic ridges are elongate parallel to the trend of the arc or at 110° counterclockwise from that trend, suggesting a strong fault control on the distribution of arc magmas. Volcanos in the Mariana Arc are generally developed west of the frontal arc ridge, on rifted frontal arc crust or new back-arc basin crust. Volcanos in the central Mariana Arc are usually subaerial, large (>500 km^3), and spaced about 50–70 km apart. Those in the northern and southern Marianas are largely submarine, closer together, and generally less than 500 km^3 in volume. There is a shoaling of the arc basement around Iwo Jima, accompanied by the appearance of incompatible-element enriched lavas with alkalic affinities. The larger volcanic edifices must reflect either a higher magma supply rate or a greater age for the larger volcanos. If the magma supply (estimated at 10–20 km^3/km of arc per million years at 18° N) has been relatively constant along the Mariana Arc, we can infer a possible evolutionary sequence for arc volcanos from small, irregularly spaced edifices to large (over 1000 km^3) edifices spaced at 50–70 km. The volcano distribution and basal depths are consistent with the hypothesis of back-arc propagation into the Volcano Arc.

Introduction

Submarine volcanic activity is an important constructional process in intraoceanic volcanic arcs. Submarine edifices necessarily precede the development of larger, subaerial edifices, and must be the first manifestation of arc activity when an arc is reestablished after back-arc spreading. Parts of some supra-subduction zone ophiolites may have formed as submarine, nascent island arcs (Pearce et al. 1984; Rautenschlein et al. 1985). Despite the importance of submarine volcanic activity in arc construction, and its possible representation in the geologic record, we know very little about the physical and chemical characteristics of such volcanism.

The Mariana Arc is one of the best examples of an intraoceanic island arc, and there have been numerous studies of its subaerial volcanos (Meijer 1976; Stein 1979; Dixon and Batiza 1979; Meijer and Reagan 1981; Meijer 1982; Stern and Ito 1983; Hole et al. 1984; Woodhead and Fraser 1985). The submarine portion of the arc has been described in detail only at its southern end (Corwin and Tracey 1965; Dixon and Stern 1983; Stern and Bibee 1984; Stern et al. 1988a) and in the vicinity of Fukujin at 22° N (Garcia et al. 1979; Wood et al. 1981; Jackson and Fryer 1986), despite the fact that between 20°30′N and 24° N the entire arc is submarine.

We present here a description of the submarine portions of the Mariana and Volcano Arcs. This discussion is based on US Navy SASS maps of the arc from 14° to 27° N, and dredge sampling and surveys of portions of the arc. We discuss the distribution of active, dormant and extinct edifices, the location of frontal arc basement ridges, and the petrographic characteristics of the volcanic rocks recovered from the arc.

Offprint requests to: S. H. Bloomer

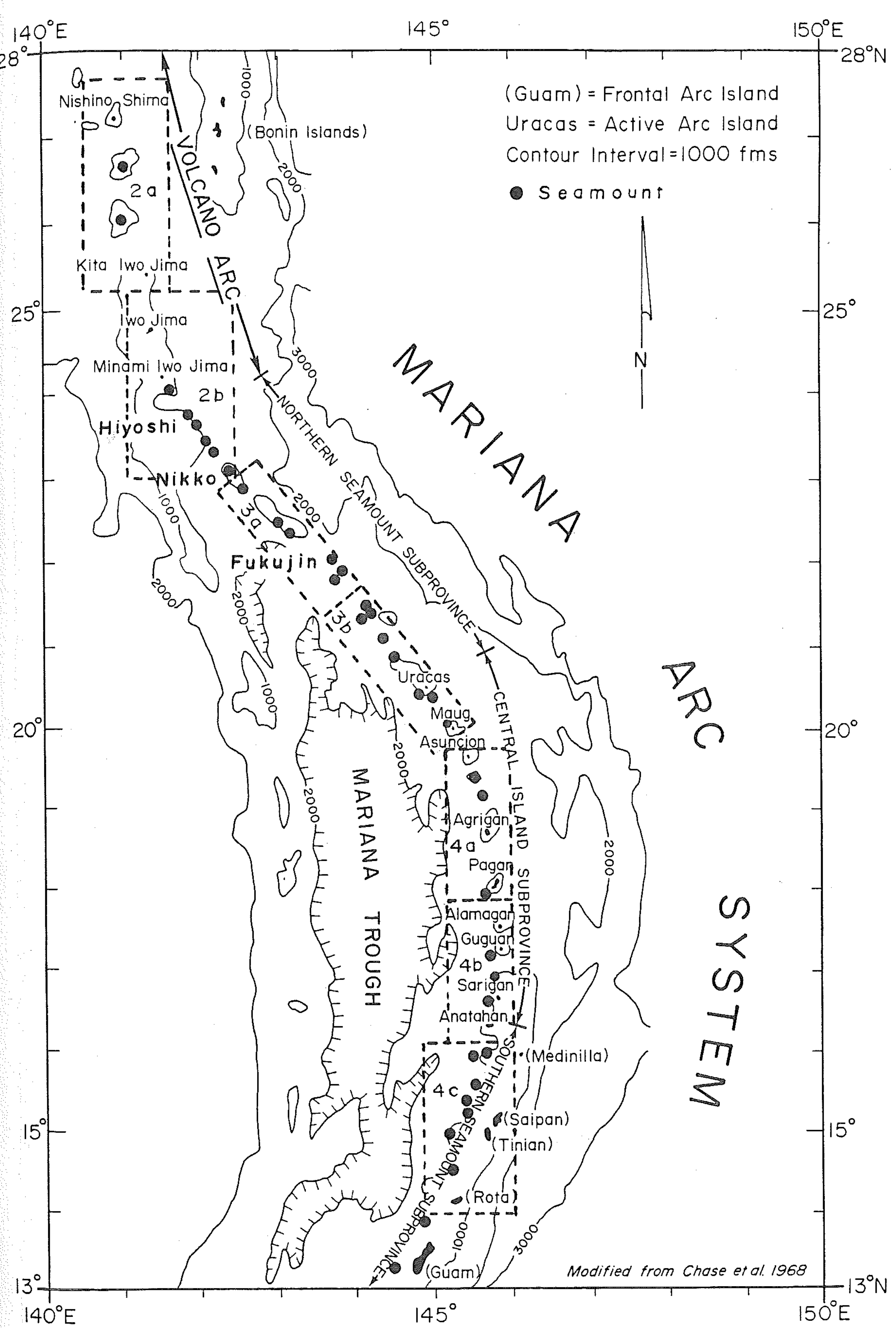

Fig. 1. Bathymetric map of the Mariana and Volcano Arcs, with morphologic provinces identified. *Large dots* indicate the principal submarine volcanos. *Outlined boxes* correspond to the areas in Figs. 2–4. The Iwo Jima platform within the Volcano Arc extends from Minami Iwo Jima to Kita Iwo Jima

Background

The present Mariana active arc is that part of the arc defined by the locus of active and dormant edifices and extends from 14° N to 24° N, where it merges with the Volcano Arc (Fig. 1). It has developed after the rifting of a Miocene and older arc and the development of a back-arc basin (Karig 1971). Spreading in this basin, the Mariana Trough, began about 5 Ma at 18° N (Hussong and Uyeda 1981) and the arc is inferred to be no older, though in places it may be considerably younger. The western half of the older rifted arc, the West Mariana Ridge, is a remnant arc that borders the west side of the Mariana Trough. The eastern half of the older arc makes up the frontal arc and is present to the east of the active arc (Fig. 1). The back-arc basin closes to the north. The Volcano Arc is built on crust that has not been rifted since the cessation of spreading in the Shikoku Basin 17 My ago (de Vries-Klein and Kobayashi 1980), though there is evidence of nascent back-arc depressions north of Nishinoshima (Yuasa 1985; Honza and Tamaki 1985).

The Mariana Arc has been divided into three provinces (Fig. 1): the Northern Seamount Province (NSP), the Central Island Province (CIP), and the Southern Seamount Province (SSP) (Dixon and Stern 1983; Stern et al. 1988b). The subaerial volcanos in the CIP have erupted mostly tholeiitic and calc-alkaline basalts and basaltic andesites (Stern 1979; Meijer 1982; Meijer and Reagan 1981; Meijer and Reagan 1983). Andesitic and dacitic compositions in the subaerial parts of the arc result principally from low-pressure fractionation of basaltic magmas (Stern 1979; Meijer and Reagan 1981). A number of historic eruptions and frequent reports of discolored water indicate that submarine volcanos are active throughout the arc (e.g. Anon 1976; Ronck 1975). Submarine volcanos in the SSP have erupted basalt through dacite (Dixon and Stern 1983).

Hussong and Uyeda (1981) have suggested, based on bathymetric data and the truncation of magnetic anomalies by the active arc volcanos, that the active Mariana Arc is constructed on young, back-arc basin crust, just west of the frontal arc ridge. Associated with several of the young arc edifices are chains of smaller volcanos extending into the back-arc basin at a WSW trend (Hussong and Fryer 1983; Jackson and Fryer 1986). There are extensive volcanoclastic aprons associated with the arc, both between edifices and extending as aprons into the back-arc basin (Karig 1971; Hussong and Uyeda 1981).

Iwo Jima sits near the closure of the Mariana Trough at 24° N. It has erupted trachyandesitic lavas and pyroclastics with very high Ba, Sr and light-rare-earth element abundances (Tsuya 1936; Stern et al. 1984). Stern et al. (1984) have suggested that the back-arc basin originally opened near 18° N and has since propagated northwards into the Volcano Arc at a rate of about 10 cm/year, and that the alkalic volcanism at Iwo Jima represents the interaction of arc and back-arc sources. Such a model implies that the volcanos in the NSP should be younger, and presumably smaller, northwards towards Iwo Jima. An alternative explanation for the narrowing of the Mariana Trough is that the pole of rotation is located near Iwo Jima, and that the spreading rates are lower in the north end than the south. The alkalic volcanism at Iwo Jima might then be related to the collision of the Ogasawara Plateau with the Volcano Arc (Delong et al. 1975), whereupon the volcanos of the northern Mariana Arc should be of similar ages, and presumably of similar size, if magma production rates have been constant.

Methods

The bathymetric maps of the Mariana and Volcano Arcs presented in Figs. 2–4 are based on US Navy narrow-beam SASS bathymetric data. These charts were used to guide sampling and detailed surveys of the submarine portions of the arc during cruise TT-192 of the R/V Thomas Thompson in November 1985. Forty-two submarine volcanic edifices have been identified in the portion of the two arcs shown in Figs. 2–4, and 31 of these were sampled during the cruise. In addition, several dredges were taken on ridges suspected to be fragments of the older, frontal arc.

Rock distributions and petrographic summaries presented here (Figs. 2–4) are from shipboard classification of dredged materials and shore-based examination of representative thin sections of all volcanic rock types in each haul. Proportions of rock types shown in Figs. 2–4 are relative abundances and are intended to indicate only the principal constituents in the hauls. Absolute recovery ranged from 1 or 2 kg to over 1000 kg.

Volcanic edifices were classified when possible as active, dormant, or extinct. Active volcanos are those for which there are reports of observed or inferred eruptions (e.g. Anon 1976). In the case of subaerial eruptions, this documentation is

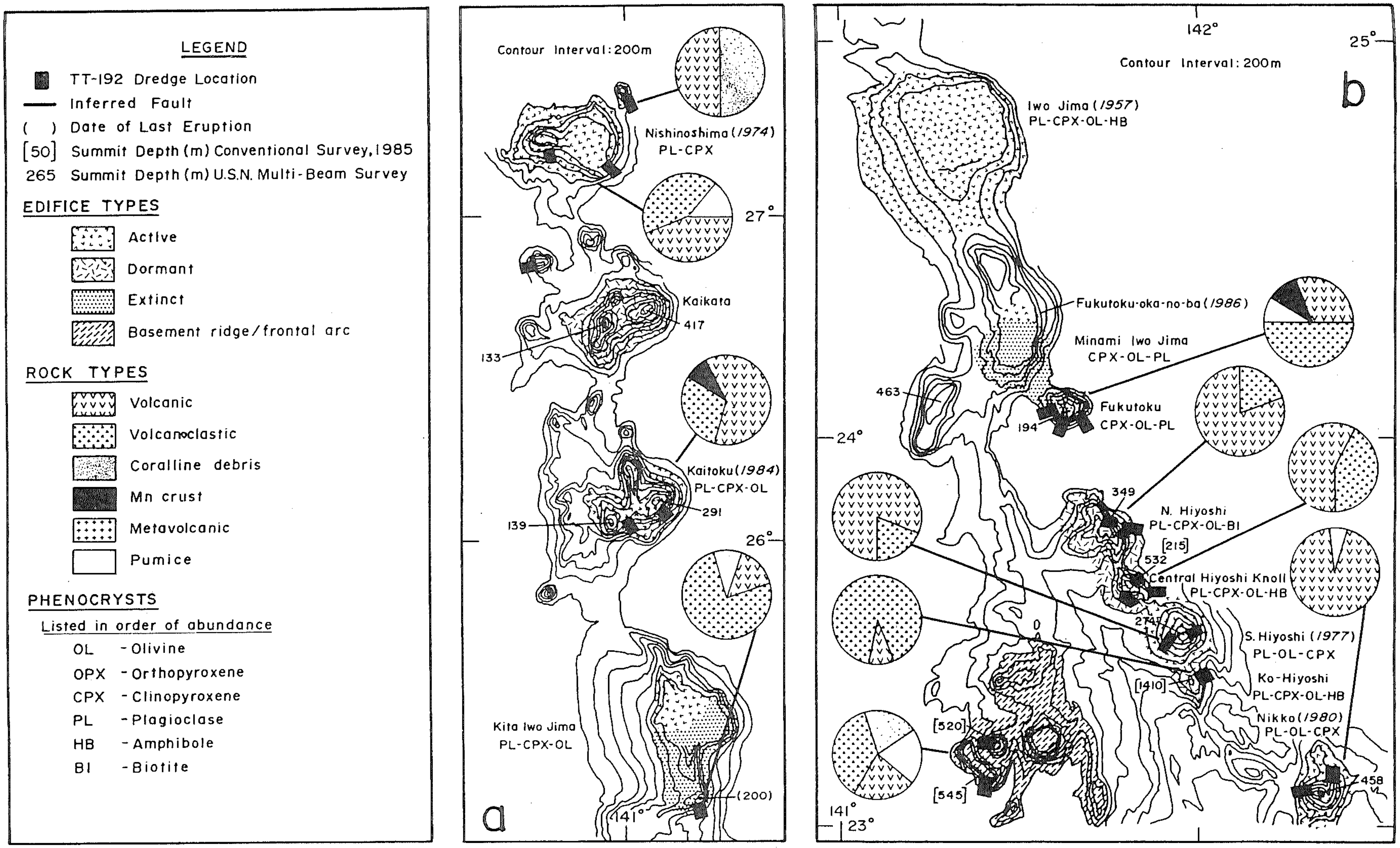

Fig. 2a, b. Interpretative geologic map of the Volcano Arc and northern Mariana Arc from 23 °N to 27 °N. Shown are edifice type, dredge locations *(solid bars)*, relative proportions of rock types in each haul, and phenocryst distribution in each edifice. Bathymetry is based on US Navy narrow-beam SASS data. Contour interval is 200 m. Summit elevations in *square brackets* are from wide-beam surveys in November 1985; those without brackets are from the SASS data. Dates in *italics* next to edifice names indicate the last reported activity at the edifice. Based on this work and data from Stern (1979), Dixon and Batiza (1979), Meijer and Reagan (1981), Stern et al. (1984), Dixon and Stern (1983), Stern and Bibee (1984), Garcia et al. (1979), Jackson and Fryer (1986), Johnson (1973), Ronck (1975), Kuno (1962), Yoshida et al. (1987), Yuasa and Tamaki (1982).

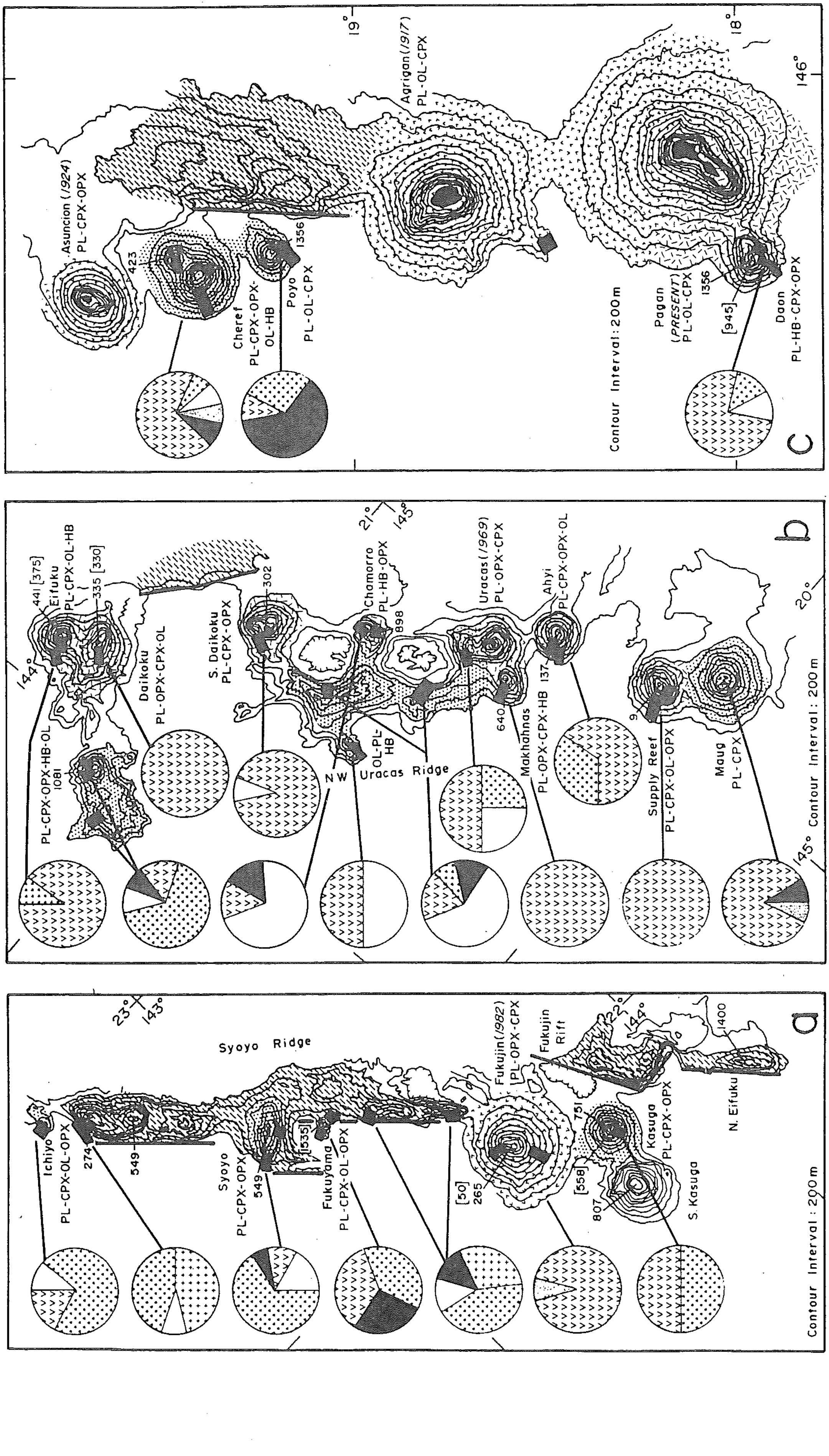

Fig. 3a–c. Interpretive geologic map of the Mariana Arc from 18° to 23°. Explanation as in Fig. 2

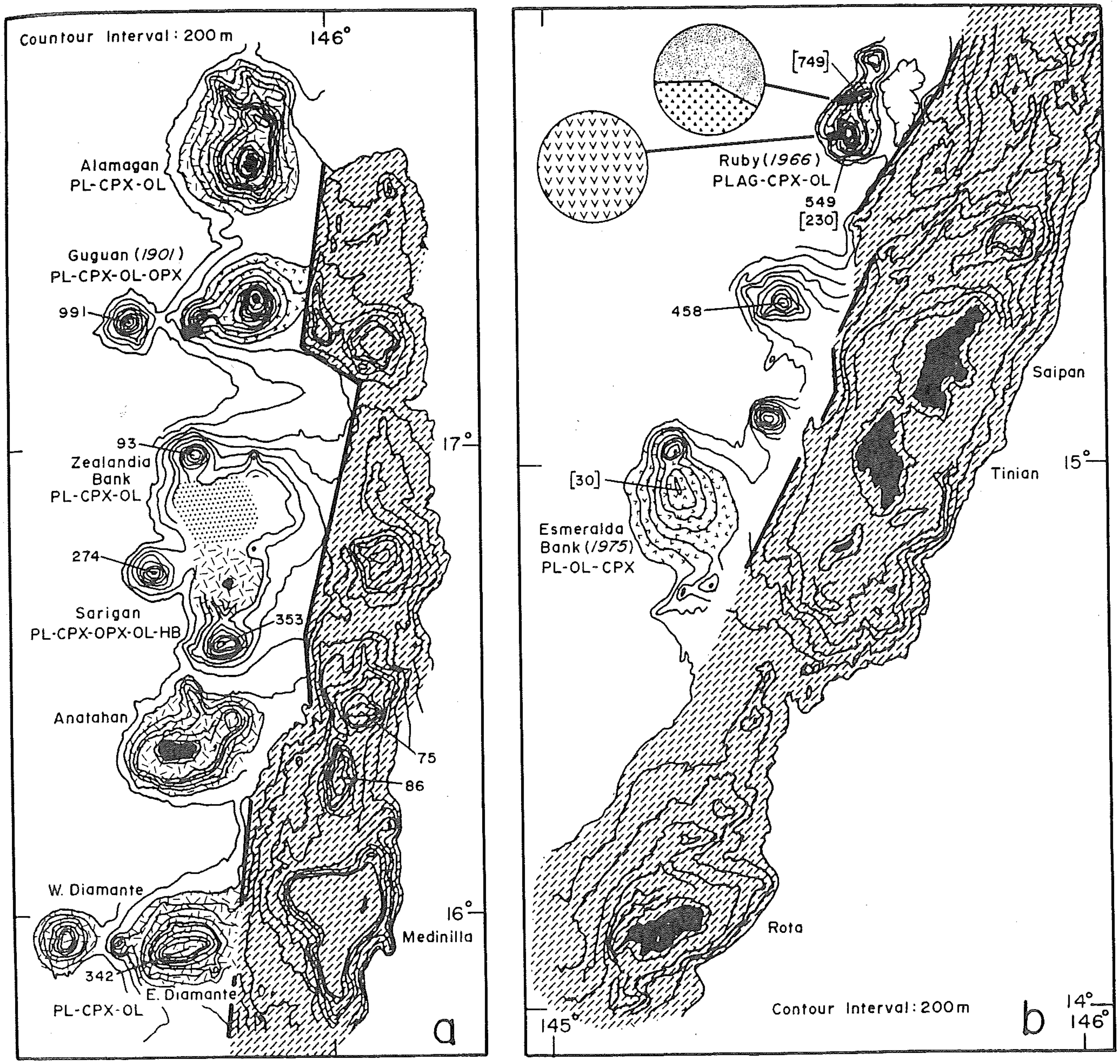

Fig. 4a, b. Interpretative geolocic map of the Mariana Arc from 14° to 18°. Explanation as in Fig. 2

straightforward. In the case of submarine eruptions, documentation is more difficult and ranges from observations of discolored water (Ronck 1975) to location of low-frequency submarine acoustic emissions (Johnson 1973). Dormant subaerial edifices have no known historic eruptions, but have some expression of potential activity such as hot springs. Dormant submarine edifices have distinct conical shapes and yielded very fresh lavas, with little or no Mn-oxide straining. Subaerial edifices which showed no sign of any activity, or submarine edifices which had roughly conical shapes and heavily altered or thickly Mn-encrusted samples, were classified as extinct. Basement ridges, interpreted as portions of the frontal arc, were identified by the recovery of greenschist metavolcanics or by distinctly elongate morphologies with steep west-facing scarps. The classification of ridges and edifices was based on this work and all available published information on the seamounts and islands of both arcs (see Fig. 2).

Volcano volumes (Table 1) were calculated by stepwise measurements of areas enclosed by 200-

Table 1. Latitudes and volumes for the principal islands and seamounts in the Mariana and Volcano Arcs

	Volcano	Latitude	Activity	Volume (km³)
	Esmeralda	15°00′	Active	312
S	unnamed	15°05′		45
	unnamed	15°18′		150
S	Ruby	15°37′	Active	135
	N. Ruby	15°46′	Extinct	25
P	W. Diamante	15°57′	Dormant	114
	E. Diamante	15°55′	Dormant	412
	Anatahan*	16°20′	Dormant	543
	West Sarigan	16°43′		95
	South Sarigan	16°34′		98
C	Sarigan*	16°42′	Dormant	187
	Zealandia Bank	16°55′	Extinct	420
	W. Guguan	17°15′		97
	Guguan*	17°18′	Active	338
	Alamagan*	17°36′	Dormant	750
I	Daon	17°58′	Dormant	150
	Pagan*	18°07′	Active	2160
	Agrigan*	18°45′	Active	1640
	Poyo	19°15′	Extinct	106
P	Cheref	19°25′	Extinct	320
	Ascuncion*	19°42′	Active	500
	Maug*	20°02′	Extinct	342
	Supply Reef	20°08′	Dormant	160
	Ahyi	20°25′	Dormant	103
	Makhahnas	20°28′	Dormant	57
	Uracas*	20°32′	Active	215
	Chammoro	20°45′	Dormant	51
	South Daikoku	21°03′	Dormant	111
	Daikoku	21°20′	Dormant	171
N	Eifuku	21°25′	Dormant	96
	S. Kasuga	21°35′		233
	Kasuga	21°45′	Extinct	132
S	Fukujin	21°55′	Active	587
	Fukuyama	22°23′	Dormant	10
	Shyoyo	22°30′	Extinct	155
P	Ichiyo	23°00′	Extinct	15
	Nikko	23°05′	Active	120
	Ko-Hiyoshi	23°11′	Dormant	
	South Hiyoshi	23°15′	Active	109
	Central Hiyoshi	23°18′	Dormant	67
	North Hiyoshi	23°22′	Dormant	220
	Fukutoku	23°33′	Extinct	88
	Minami Iwo Jima	24°12′	Extinct	282
	Fukutoku-oka-no-ba	24°18′	Active	
V	Iwo Jima	24°45′	Active	558
	Sin Kita Io Jima	25°06′	Extinct	
A	Kita Iwo Jima	25°30′	Active	1576
	Kaitoku	26°05′	Active	1177
	Kaikata	26°40′	Dormant	670
	Nishino shima	27°37′	Active	534

An *asterisk* by the volcano name indicates an island. Criteria for active, dormant and extinct are discussed in the text. Volumes for volcanos less than 100 km³ were calculated using the last closed contour calculation; larger edifices or composite edifices were calculated using the last contour enclosing two-thirds or more of the volcano, as explained in the text

m contours from the summit to the last closed contour or the last contour which enclosed more than two-thirds of the feature. Areas were measured with a LICOR LI3000 portable area meter. Volumes were calculated as the sum of 200-m-thick slabs for each measured area. To this was added the volume of a cone with a basal area defined by the shallowest contour and a height equal to the edifice height above that contour. These calculations yield a volume slightly less than the actual edifice volume, but are low by only a few percent, reproducible within 5%–10%, and consistent from edifice to edifice. These values underestimate the volcanic material produced at each magmatic center, as they do not include the plutonic or buried portions of the edifice. The volume of deeper magmatic material is likely to be roughly proportional to the volume of the volcanic edifice calculated here. The volumes of an individual edifice are also underestimated where individual edifices have merged to form volcanic complexes or ridges (as in the Hiyoshi Seamounts, Fig. 2) or where the volcanos are built on a broad volcanic ridge (as in Nishinoshima and Kaitoku, Fig. 2).

The basal depths of the arc edifices were estimated from a profile constructed from the SASS maps along the main axis of the active arc (Fig. 5). The deepest points between clearly identifiable volcanos (as opposed to multicentered complexes) were connected and assumed to represent the depth of the arc basement. Volcano spacings were calculated as distance from peak to peak.

Results

Descriptive volcanology

There are 13 islands in the active Mariana and Volcano Arcs, 11 of which are classified as active or dormant (Kuno 1962). Of the 42 distinct submarine edifices identifiable on the SASS charts (Figs. 2–4), 22 are active or dormant. There is no information available on eight of these edifices. There are two additional seamounts to the south of Fig. 4b, both of which may be dormant (Corwin and Tracey 1965; Dixon and Stern 1983). In addition, nine small, subsidiary seamounts are associated with volcanos in the Volcano Arc (Fig. 2a). Two of them are extinct and there is no information on the other seven.

The islands in the Marianas typically evolve by the initial eruption of numerous small lava flows, followed by thicker, more siliceous flows

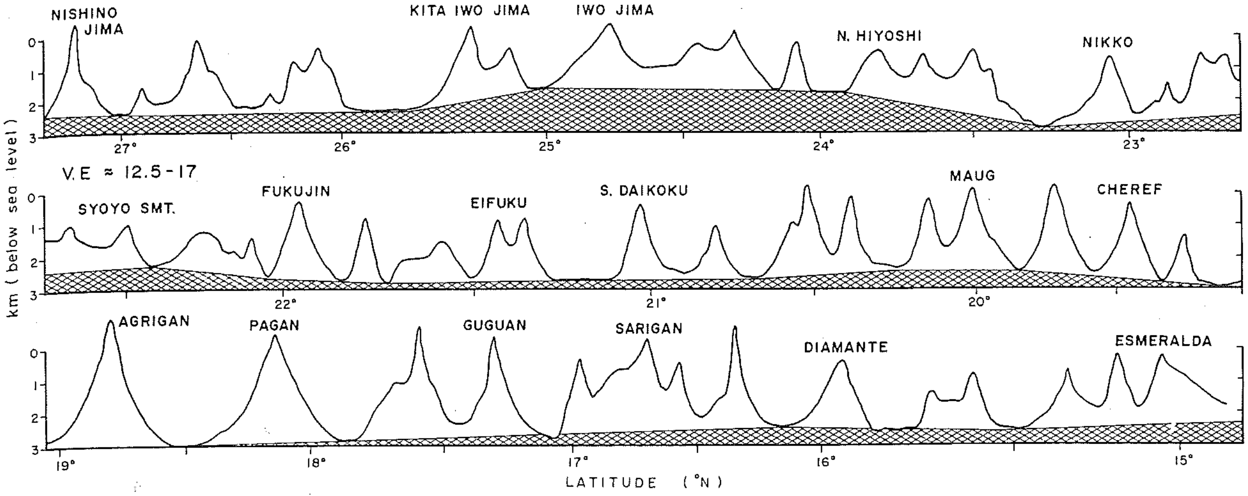

Fig. 5. Cross-section of the axis of the Mariana–Volcano arc. The top of the shaded region is interpreted to be the base of the arc edifices

with a greater proportion of pyroclastic material, and culminating in collapse to form large craters or calderas (Meijer 1982). A new basalt cone may be constructed in this collapse feature, as on Pagan, Guguan and Uracas (Kuno 1962; Meijer 1982), or there may be post-collapse domes and flows from the crater rim as on Sarigan (Meijer 1982) or as evidenced by a dacitic dome in the Maug caldera (Hochstaedter et al. 1986). Subsidiary or parasitic cones are rare on the islands in the Marianas, with the exception of Pagan (Meijer 1982).

The seamounts in the Mariana Arc are generally simple cones (Figs. 3 and 4). Only Esmeralda and east Diamante (Fig. 4b; Dixon and Stern 1983; Stern and Bibee 1984) have had summit craters identified. On both, the craters are about 200 m deep and have been identified by wide-beam profiles during slow traverses of the seamounts. The SASS maps do not show craters on either edifice; several of the other seamounts may have small summit craters which are not apparent in the SASS data. It is, however, unlikely that any have large craters or calderas. Five of the seamounts are binary cones — Esmeralda and Ruby (Fig. 4b), Cheref (Fig. 3c), the Eifuku-Daikoku complex and the Uracas-North Uracas complex (Fig. 3b).

An unusual feature of the Mariana Arc is the arrangement of several of the seamounts in chains extending into the back-arc basin at a high angle to the trend of the main arc (Hussong and Fryer 1983; Jackson and Freyer 1986). Six such cross-chains can be clearly identified from the SASS charts presented here: at Kasuga (Fig. 3a), west of Daikoku and Uracas (Fig. 3b), southwest of Pagan (Fig. 3c), west of Guguan, and at the Diamante Seamounts (Fig. 4a). There may also be cross-chain structures west of Sarigan or Zealandia Bank (Fig. 4) and southwest of South Daikoku Seamount (Fig. 3b). Several volcanic centers have merged to form elongate ridges or complexes near Sarigan (Fig. 4a), Uracas (Fig. 3b), Minami Iwo Jima and Iwo Jima (Fig. 2b), and Central Hiyoshi Knoll (Fig. 2b). Only in the last are all the edifices considered to be still active or dormant; in the other three complexes some of the centers appear to be extinct.

The Mariana Arc is distinctly arcuate, while the Volcano Arc is straight. These differences may have to do with the shape of the downgoing slab (Meijer 1982), the subduction of large volcanic ridges (McCabe 1984), or the effects of back-arc rift propagation (Stern et al. 1984). The trend of the main active arc changes from 24° in the south to 350° in the central section, to 315° in the northern seamount province and back to 355° in the Volcano Arc. Volcanic cones and ridges are paired or elongate either within 9° (±5°) of the trend of the main arc or at 110° (±15°) counterclockwise from the main arc. The latter is the trend of the cross-chain seamounts.

An irregularly developed frontal arc ridge is present from 14° to 23° N (Figs. 3 and 4). It is often bounded on the west by steep slopes, which may be the trace of the bounding faults developed during rifting to form the Mariana Trough. In most places, the active arc has been constructed just to the west of these steep scarps. Occasionally, an active arc edifice has been constructed on that frontal arc ridge (Syoyo Seamount, Fig. 3a) or has partially overlapped frontal arc fragments (Agrigan, Fig. 3c).

The volcanos in the Volcano Arc north of Iwo Jima (Fig. 2a), both submarine and subaerial, are larger, more irregular in shape, and have a greater number of subsidiary cones than their counterparts in the Marianas (Fig. 2a). The subsidiary cones show no consistent orientation relative to the main edifices, but are distributed in a roughly radial pattern around them.

A profile along the main axis of the Mariana and Volcano Arcs is shown in Fig. 5. The places where centers have merged to form volcanic complexes (23°30′N and 16°45′N) are clearly shown. There is a shoaling of the basal platform on which the arc is constructed between 23° N and 25° N, to depths of 1400 m near Iwo Jima. This base deepens rapidly northwards to 2400 m at 26°. Basal depths are consistently about 2400 m in the northern Volcano Arc and vary from 3000 to 2400 m in the Mariana Arc, averaging about 2600–2700 m.

Rock type and petrography

The rocks recovered from the seamounts can be classified as lavas, volcanoclastic sediments, coralline debris, pumice (at least some of which appear to be from outcrop), metavolcanics, and Mn crusts. The relative proportions of these rock types are shown in the pie charts in Figs. 2–4. The volcanoclastic material was very common in these hauls. Sands, silts, breccias, and hyaloclastite breccias were all recovered. Rare dioritic and pyroxenitic fragments were found in a few hauls.

Basalts and basaltic andesites account for over 60% of the recovered lavas. Andesites comprise about 30% of the volcanic rocks and dacitic and rhyolitic material is uncommon, comprising less than 10% of the lavas. There is not strong correlation of rock type (by SiO_2) with latitude, though the northern NSP and southern Volcano Arc include lower SiO_2 lavas than are typical of most of the arc (Fig. 6). This region corresponds to a zone of alkalic volcanics with high Na_2O+K_2O and K_2O/Na_2O (Stern et al. 1988b; Bloomer et al. 1988). At all latitudes, both large and small edifices show a wide range of silica values (Fig. 6).

Coralline debris was recovered from Fukujin, Maug, and Cheref. Hydrothermal Mn staining was common on nearly all samples from both active and dormant edifices. Many samples, from what were inferred to be dormant edifices, had thin Mn-oxide rims or crusts which appeared hydrothermal in origin, while samples from the extinct edifices and frontal arc ridges had thick crusts which included both hydrothermal and hydrogenous Mn oxides (Hein et al. 1987).

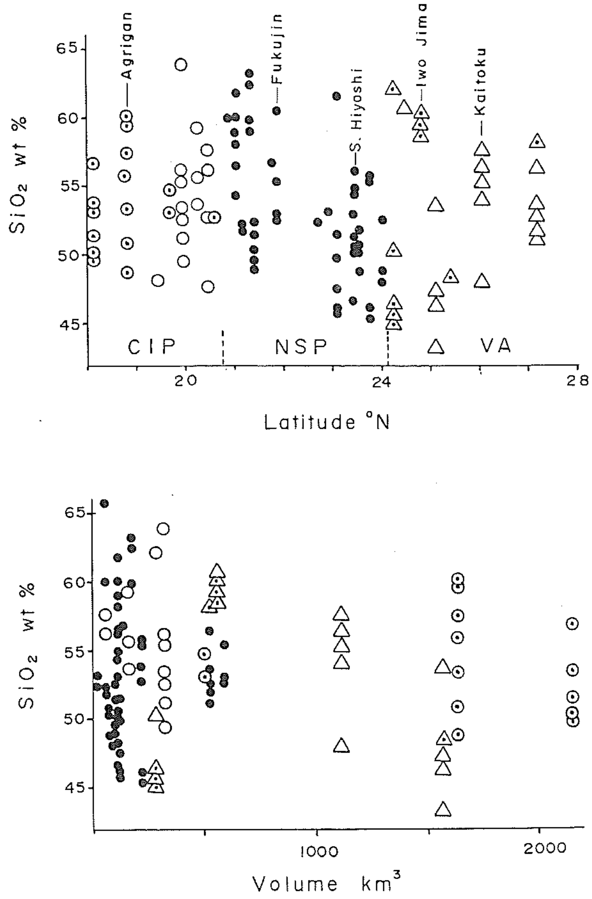

Fig. 6. SiO_2 vs latitude and vs volume for Mariana Volcano Arc samples. Data from this work and Stern (1979), Dixon and Batiza (1979), Dixon and Stern (1983), Stern and Bibee (1984), Wood et al. (1981), Meijer (1982), Meijer and Reagan (1981), Stern et al. (1984), Yuasa and Tamaki (1982). *Circles* indicate samples in the Central Island Province, *filled circles* the Northern Seamount Province, and *triangles* the Volcano Arc. Islands within the CIP and Volcano Arc are indicated by the *dotted symbols*

Greenschist facies metavolcanic samples were recovered in two dredges from the Syoyo Ridge (Fig. 3a). These comprise relict calcic plagioclase and clinopyroxene, as well as chlorite, sodic plagioclase, quartz, calcite, and epidote. Several of these samples have a well-developed penetrative fabric. Samples, from what are interpreted to be extinct edifices, are often altered — plagioclase is slightly sericitized, clinopyroxene may be partially uralitized, and there is some groundmass devitrification and zeolite fillings in fractures and veins. None of these samples, however, show evidence of greenschist facies metamorphism like that of the frontal arc samples.

Phenocrysts in the volcanic rocks include olivine (OL), plagioclase (PLAG), clinopyroxene (CPX), orthopyroxene (OPX), and amphibole (HB). Biotite occurs in the alkalic lavas on North Hiyoshi Seamount. The SSP, and southern CIP (to 19° N), are characterized principally by PLAG-CPX-OL assemblages, though there is minor HB and OPX in some samples, and trace BI in some Sarigan samples (Meijer and Reagan 1981). Between 19° N and 23° N orthopyroxene is an important phenocryst, and olivine is much less common. Amphibole occurs in several edifices in this zone. Between Nikko and Iwo Jima the principal assemblage is again PLAG-CPX-OL; OPX reappears in lavas from the northern Volcano Arc. Detailed petrographic data on these rocks is included in Bloomer et al. (1988).

Edifice volume and spacing

Edifice volumes vary from less than 100 km^3 to over 2000 km^3 (Table 1; Fig. 7). Volume maxima occur at 18° N near Agrigan and Pagan, and at Kita Iwo Jima and Iwo Jima in the Volcano Arc (Fig. 7). Most of the other edifices in the northern Volcano Arc have volumes of 500–1500 km^3. Most Mariana Arc volcanos have volumes less than 750 km^3 and over 70% are under 500 km^3. There is a relatively smooth decrease in volume away from each of the volume maxima (Fig. 7).

The peak-to-peak spacing of the volcanic edifices, particularly those less than 200 km^3 in volume, varies from 15 to 70 km. The larger volcanos show a clear increase in spacing with increasing volume (Fig. 7).

Discussion

The only prominent chemical or petrographic segmentation in the Mariana and Volcano Arcs is a province of LIL-enriched alkalic volcanism in the northern NSP and southern Volcano Arc (South Hiyoshi Seamount through Iwo Jima) (Stern et al. 1988b). This corresponds to an OPX-absent petrographic province and a region characterized by small, closely spaced volcanic edifices (Fig. 2). The petrographic and chemical characteristics of both the alkalic and subalkalic arc volcanics in the CIP, NSP and Volcano Arc are detailed elsewhere (Bloomer et al. 1988; Lin et al. 1988).

There seems to be little correlation between volcano size and volcano composition. The smaller edifices do not seem to have a lower proportion of siliceous eruptives than their larger, subaerial counterparts (Fig. 6), as was suggested by Dixon and Batiza (1979). There is a slight tendency for the smaller centers to erupt more magnesian and Cr-rich melts more often than the larger edifices (Bloomer et al. 1988). There is, in

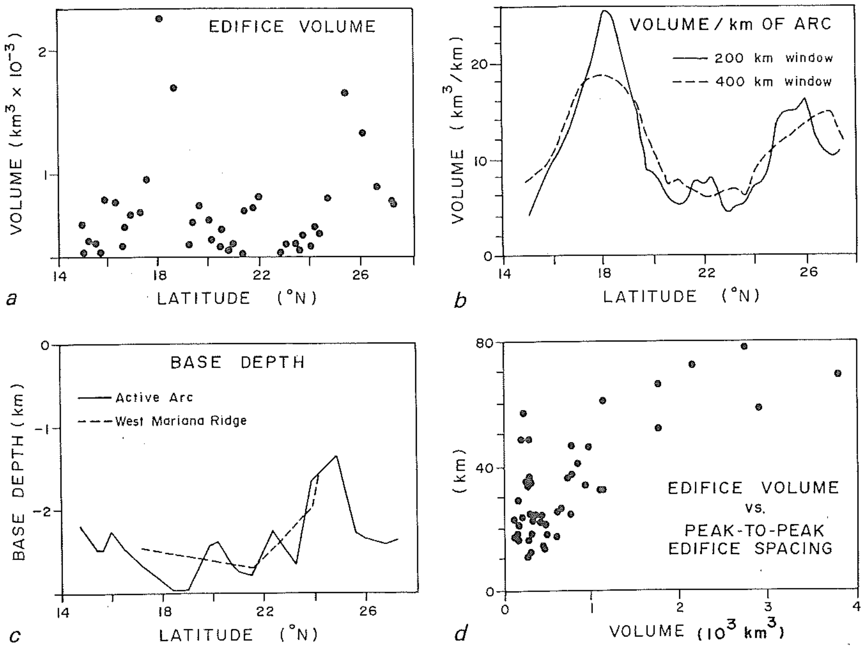

Fig. 7a–d. Volume, spacing and basal depth relationships of volcanos in the Volcano and Mariana Arcs. Methods of calculation are described in text. Basal depths are from Fig. 5. **a** Volume versus latitude for individual edifices in Mariana–Volcano Arcs. **b** Volume per km of arc, using both a 200- and 400-km window and interval spacing of 50 km. Based on volumes and spacings calculated as in text. **c** Base depth of Mariana and Volcano active arc volcanos in *solid line,* from Fig. 5. *Dotted line* is similar calculation for the Palau Kyushu Ridge, from 19° N to Minami Iwo Jima. **d** Volume versus spacing for Mariana and Volcano Arc edifices. The distance between a pair of volcanos is plotted with the sum of the volumes of the pair

general, no difference in chemical or petrographic characteristics in samples from large and small edifices at a given latitude (Bloomer et al. 1988). The composition of volcanos in the arc is principally related to position along the arc, not to size.

It should be noted that despite the depths to the summits of some of these edifices (to 1000 m), many of them are producing significant amounts of fragmental material. Nearly one-quarter of the recovered samples were volcanoclastic. The actual abundance of volcanoclastic material in the volcanos is probably higher, as these samples are often poorly consolidated and friable and would be more likely to wash out of a dredge bag than would volcanic rock samples. Similar volcanoclastic materials from intraplate seamounts have been attributed to a variety of processes, including lava fountaining, turbiditic transport, and redeposition by erosion and mass-wasting (Smith and Batiza 1986).

The most interesting aspect of the data presented here concerns the differences in volcano morphologies, sizes, and orientation along the arc. We will focus on these problems in the rest of this discussion.

Structural controls on arc volcanism

The volcanos of the active arc, as suggested by Hussong and Uyeda (1981), are clearly built to the west of the frontal arc scarp. This deeper basement, on which the arc volcanos and their volcanoclastic aprons have been constructed, must either be new back-arc crust (Hussong and Uyeda 1981) or frontal arc crust which has been faulted and downdropped as the arc was rifted apart (Fig. 8). The cross-chain seamounts in the Marianas may have developed along fractures which can be traced into supposed fracture zones in the Mariana Trough (Fryer 1985; Jackson and Fryer 1986). A similar distribution of cross-chains from the West-Mariana Ridge into the Parce-Vela Basin indicates that these fractures may be relatively long-lived features (Hussong and Fryer 1983; Fryer 1985).

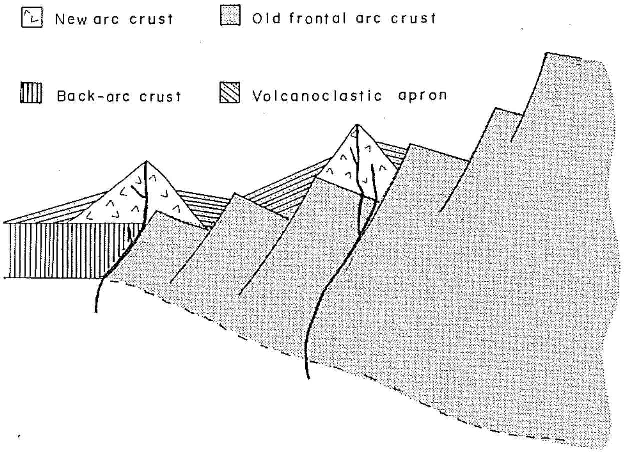

Fig. 8. Schematic diagram of the initiation of a new arc volcano on rifted frontal arc crust. The basal depth of the new arc volcano will depend on which fault block the volcano is developed on (note the difference in basal depths of the two volcanos shown). The boundary faults of the rifted margin may serve as conduits for melts form the sub-arc mantle

The alignment of sets of cones and the elongation of individual edifices and ridges in the Marianas are parallel either to the frontal arc scarp or to the trend of the cross-chain volcanos (about 110° counterclockwise from the main trend of the arc). This alignment suggests that the access of magmas to the surface is controlled by border faults along the western edge of the frontal arc and the long-lived cross-arc fractures.

Much of the variation in basal platform depth in the Mariana Arc may be due to construction of the arc on such rifted frontal arc blocks (Fig. 8). Both the area around Syoyo Seamount and the southern arc (15°-17° N) have large fore-arc ridges immediately under or near the active arc edifices, and the basal depth of the arc is unusually shallow there.

The Iwo Jima Platform

The arc basement shows a marked shoaling between 23° and 25° N to the 1400-m-deep platform on which Minami Iwo Jima and Iwo Jima are built. The basal depth then increases rapidly from Iwo Jima to just north of Kita Iwo Jima (Fig. 5), reaching a depth of 2400 m which is maintained throughout most of the Volcano Arc. This is significantly deeper than the 2600–2700 m average basal depth of the Mariana Arc edifices. The Volcano Arc has not been rifted since spreading in the Shikoku Basin started about 22 Ma ago (de Vries-Klein and Kobayashi 1980) and should have a thicker crustal section that the active Mariana Arc. This would result in a more constant and somewhat shoaler average basal depth than the Marianas, as is observed (Fig. 5).

The shoaling of the basement from Nikko to Iwo Jima may be due in part to the transition from stretched and rifted crust to thick, unrifted arc crust. In part though, it must also be a thermal effect, as suggested by Stern et al. (1984). The Iwo

Jima platform is significantly shoaler than the Volcano Arc basement to the north, despite the fact that both are unrifted arc crust of similar age and thickness. This shoaling at Iwo Jima suggests that the crust has been recently heated and thermally uplifted, relative to the Volcano Arc to the north. Recent uplift rates of 50 cm/year have been reported for Iwo Jima (Morimoto et al. 1968), probably in response to magma injection beneath the edifice. These unusually shallow depths at Iwo Jima are consistent with the hypothesis that Iwo Jima is the manifestation of a thermal and magmatic anomaly in the arc related to propagation of the Mariana Trough northwards into the Volcano Arc (Stern et al. 1984).

The northern end of the West Mariana Ridge also shows a very rapid shoaling towards Iwo Jima, which could be a result of localized heating of the arc crust there (Fig. 7). However, the case for the West Mariana Ridge is complicated because it has both been cooling as arc volcanism waned and been heated and uplifted during the initial opening of the back-arc basin. It is therefore difficult to predict what the basal depth of the ridge should be in the absence of any local heating.

Age relations and volcano morphology

There are some clear differences between volcanos in the Volcano and Mariana Arcs. The edifices of the northern Volcano Arc are generally larger (at least 500 km^3), more irregularly shaped, more likely to have subsidiary cones than those in the Marianas, and are built on a broad volcanic ridge. They are spaced about 50–70 km apart. The Mariana Arc, in contrast, is built on back-arc crust or thinned frontal arc crust, and is characterized by simple conical volcanos with a range of sizes and spacings.

The differences between the two provinces might be considered a reflection of the relative maturity of the volcanic province. The Mariana Arc is reestablishing itself after a recent episode of back-arc rifting, while the Volcano Arc has been continuously active since the Shikoku Basin opened 22 Ma ago (deVries-Klein and Kobayashi 1980). This is not to say that the individual volcanic centers on the Volcano Ridge have been active since the Miocene. The arc is atop a large volcanic ridge with a complex history; the presently active centers may have only existed for a few million years. Their irregular shapes may have more to do with complex stress distributions in the thick, underlying arc crust than with the age of an individual active volcano.

The active Mariana Arc from North Hiyoshi Seamount southwards is younger and in a somewhat more clearly defined tectonic setting than the Volcano Arc. There is a clearly defined remnant and active arc from 14° to 24° and we can assume that the distribution and morphology of the edifices in the active are reflect the reestablishment of arc volcanism after back-arc rifting.

In the active Mariana Arc, volcano spacings and volumes vary considerably. Most of the edifices have volumes of less than 1000 km^3, have simple conical shapes with no subsidiary cones, and are from 10 to 70 km apart. Small volcanos occur in both the southern and northern Mariana arcs, and in places merge to form volcanic ridges. Large edifices only occur in the central Mariana Arc, at Pagan and Agrigan. These, like the Volcano Arc cones, are spaced about 50–70 km apart. Both Pagan and Agrigan are much larger than typical subaerial active volcanos (Gill 1981), suggesting that the active Quaternary centers are built on a Plio-Pleistocene base. In discussing the volcano volumes and spacings along the arc we are really discussing the net volcanic activity since the last cycle of back-arc spreading, rather than simply the Quaternary activity along the arc.

At the southern end of the Mariana Arc the magma supply rate must decrease to zero. The Benioff–Wadati Zone shoals markedly (Katsumata and Sykes 1969; Eguchi 1984) and the southern Mariana Trench is probably a trench–trench transform with a very small component of subduction (McCabe and Uyeda 1983). The small-volume seamounts at the most southern end of the Mariana Arc (Fig. 7) are due principally to a decreased magma budget there.

Between the southern seamount province and Iwo Jima it is more difficult to assess the relative ages and magma supplies along the arc. The correlation of volcano size and spacing (Fig. 7) might suggest a constant magma budget along the arc, with the available magma distributed either to several volcanos close together or to a few volcanos far apart. In this case the volume per unit length of arc would be constant, barring different ages for edifices. However, calculation of volume per unit length of arc, using a 50-km interval and both a 200- and 400-km running average window, shows that the large volume islands also correspond to large volumes per unit length of arc (Fig. 7). This indicates that either these edifices are older, or there are variable supplies of magma at different latitudes along the arc.

The NSP appears to be as active as, or more active than, the CIP judging from both the number of extinct edifices and the number and recentness of reports of activity. Nikko, Minami Hiyoshi, and Fukujin, as well as Esmeralda in the SSP, all have had eruptions in the last 10 years. This suggests that, at least at present, there is not an order of magnitude difference in the magma supply along the arc, as would be required if the size difference in edifices was due to production rate. We favor, at present, the interpretation that the magma supply rate has been essentially constant along the arc and that the CIP volcanos are the oldest in the active Mariana Arc. The CIP islands are largest near 18° N, where the maximum width for the Mariana Trough is found and where one might seek a reasonable maximum age for most of the active Mariana Arc (about 5 My, Hussong and Uyeda 1981). The back-arc must then have propagated northwards, and possibly southwards as well, as suggested by Stern et al. (1984), and the volcanos of the northern Marianas have been more recently established than those of the CIP. The anomalous basal depth and high uplift rates at Iwo Jima are consistent with this hypothesis.

We can make a minimum estimate for the magma production rate around Pagan and Agrigan regardless of the age–rate question, since we have a reasonable maximum age (5 million years) and volume estimates (24 km^3/km of arc, Fig. 7) for the 18° N region. The edifices alone do not represent the total volume of arc magmatic material. Stern (1979) estimated that the 16.6 km^3 of the subaerial cone on Agrigan had a corresponding 16.6 km^3 of plutonic material at depth. Kay and Kay (1985) concluded for the Aleutian arc that the ratio (by mass) of new upper crust (lava) to new lower crust (cumulate) ranged from 0.65 to 0.80. If we assume that there is 1–2 times as much magmatic material at each center as is seen in the edifices themselves, the production rate is 10–14 km^3/km of arc per million years. These are minimum estimates since we accept that we have underestimated the true volume of volcanic material and have taken a maximum age for the volcanos. If we assume Pagan (2200 km^3) to have been produced from a point source and make a similar calculation, the rate is $0.9\text{–}1.3 \times 10^{-3}$ km^3/volcano per year. Estimates for other arcs range from 2 to 66 km^3/km of arc per million years and $0.5\text{–}5.0 \times 10^{-3}$ km^3/volcano per year (Gill 1981). At these rates the volcanos in the NSP, where the average volume is 7 km^3/km (plus 1–2 times that mass of cumulate material) of arc, could be constructed in 1.0–2.1 million years.

We suggest that the volcanos of the NSP, and possibly those in the SSP, are younger than those in the CIP. If the larger, more widely spaced edifices characteristic of the Volcano Arc and CIP in the Mariana Arc are more mature intraoceanic volcanos, and the small, closely spaced active edifices of the NSP immature centers, we can speculate about the development of arc edifices after an episode of back-arc rifting. It appears from the distribution of edifices in the Marianas that the volcanos re-establish themselves as small centers spaced at irregular intervals. These will begin to grow together into ridges. After a certain period of time, the sub-arc conduit system will reorganize iself into a system of fewer, more evenly spaced conduits, leading to the more rapid growth of a few edifices. Indeed in the CIP, interpreted here to be the more mature volcanic province, it is the smaller edifices that can be clearly identified as extinct (NW Uracas Ridge, Fig. 3b; Poyo and Cheref, Fig. 3c). Only in the northernmost part of the Mariana Arc, interpreted to be the youngest province, are there closely spaced active edifices with no intervening extinct volcanos (Hiyoshi complex, Fig. 2), consistent with the interpretation of this section of the arc as the youngest, with the least integrated conduit system, and the one most recently reestablished after back-arc rifting.

One of the portions of the arc about which we still have no information is that between the volcanos. In the Cascades, eruptions of basalts to form low plateaus account for well over 80% of the activity in the arc (Hughes and Taylor 1986). If, as is likely, such activity is common in the Mariana or Volcano Arcs, we have no evidence for it. The close spacing of edifices in the Marianas and the abundance of volcanoclastic material may well obscure any evidence of inter-edifice activity that could be obtained by surface ship observations or sampling. Only drilling or detailed side-scan sonar surveys of the arc might find evidence of such activity.

Conclusions

1. The submarine volcanos of the Volcano Arc are larger, shallower, and more complex in form than those in the Mariana Arc. Small, closely spaced, active submarine edifices characterize the northern Mariana Arc. Large active edifices interspersed with smaller extinct volcanos are typcial of the Central Mariana Arc. The volcanos of the Mariana Arc are built to the west of the frontal arc, and the location of individual edifices and

groups of edifices is strongly controlled by regional fault patterns. Large edifices in both the Volcano and Mariana Arcs are spaced 50–70 km apart.

2. Basalts and basaltic andesites are the principal rock type along the arc. Pumices and volcanoclastics are common throughout both arcs; volcanoclastics compose about 25% of the recovered material and are an important component of submarine arc volcanism. There are no consistent differences between large and small edifices at a given latitude, though there is a latitudinal variation in chemical composition (Bloomer et al. 1988; Lin et al. 1988).

3. Both subaerial and submarine volcanic ridges and composite cones are oriented either parallel to the frontal arc's western escarpment or at 110° to that scarp. These prominent linear directions suggest that the access of magmas to the surface is controlled by the boundary fault system to the frontal arc and by long-standing cross-arc fractures.

4. The variations in size and distribution of volcanos are a result of a constant magma supply along the arc and a younger age for the volcanos of the NSP. The younger age is a consequence of northwards propagation of the back-arc basin into the Volcano Arc. After back-arc splitting, the arc evolved from small, closely spaced centers to a system of large volcanos regularly spaced at 50–70 km. Magma production rates, where best controlled, are estimated at 10–14 km^3/km of arc per million years.

Acknowledgements. We thank the officers and crew of the R/V Thomas Thompson for their skill and enthusiasm in the collection of the samples from cruise TT-192. This work has benefitted from discussions with J. Morris, E. Ito, and T. Vallier. The comments of two anonymous reviewers greatly improved the manuscript. This work was supported by NSF grants OCE-84-15699 to S. H. Bloomer and OCE-84-15739 to R. J. Stern.

References

Anonymous (1976) Bulletin of Volcanic Eruptions 14:39–40

Bloomer SH, Stern RJ, Fisk E, Geschwind C-H (1988) Shoshonitic volcanism in the northern Mariana Arc. 1. Petrographic and major and trace element characteristics. J Geophys Res (in press)

Chase TE, Menard HW, Mammerickx J (1968) Bathymetry of the northern Pacific (Chart#6). Inst Mar Resources Tech Rept TR-11

Corwin G, Tracey JI Jr (1965) Marine geologic investigations near the Palau Islands and Guam, Mariana Islands. International Indian Ocean Expedition, USC&GS Ship Pioneer 1:81–90

DeLong SE, Hodges FN, Arculus RJ (1975) Ultramafic and mafic inclusions, Kanaga Island, Alaska, and the occurrence of alkaline rocks in island arcs. J Geol 83:721–736

deVries-Klein G, Kobayashi K (1980) Geological summary of the north Philippine Sea, based on Deep Sea Drilling Project Leg 58 results. In: deVries Klein G, Kobayashi K et al. (eds) Init Rep Deep Sea Drilling Proj 58:951–970

Dixon TH, Batiza R (1979) Petrology and chemistry of recent lavas in the Northern Marianas: implications for the origin of island arc basalts. Contrib Mineral Petrol 70:167–181

Dixon TH, Stern RJ (1983) Petrology, chemistry and isotopic composition of submarine volcanoes in the southern Mariana arc. Geol Soc Am Bull 94:1159–1172

Eguchi T (1984) Seismotectonics around the Mariana Trough. Tectonophysics 102:33–52

Fryer P (1985) Morphology of seamounts in the Mariana island arc system. Eos 66:421

Garcia MO, Liu NWK, Muenow DW (1979) Volatiles in submarine volcanic rocks from the Mariana Island arc and trough. Geochim Cosmochim Acta 43:305–312

Gill JB (1981) Orogenic andesites and plate tectonics. Springer, Berlin Heidelberg New York

Hein JR, Fleishman CL, Morgenson LA, Bloomer SH, Stern RJ, Vallier TL (1987) Submarine ferromanganese deposits from the Mariana and Volcano volcanic arcs, West Pacific. USGS Open File Rep 87-281

Hochstaedter AG, Gill JB Meijer A (1986) Maug Volcano: tholeiitic volcanism in the Mariana Arc. Eos 67:1275

Hole MJ, Saunders AD, Marriner GF, Tarney J (1984) Subduction of pelagic sediments: implications for the origin of Ce-anomalous basalts from the Mariana islands. J Geol Soc London 141:453–472

Honza E, Tamaki K (1985) The Bonin Arc. In: Nairn A, Stehli F, Uyeda S (eds) The ocean basins and margins, vol 7A. Plenum Press, New York, pp 459–502

Hughes SS, Taylor EM (1986) Geochemistry, petrogenesis, and tectonic implications of central high Cascade mafic platform lavas. Geol Soc Am Bull 97:1024–1036

Hussong DM, Fryer P (1983) Back-arc seamounts and the SeaMARC II seafloor mapping system. Eos 64:627–632

Hussong DM, Uyeda S (1981) Tectonic processes and the history of the Mariana arc: a synthesis of the results of Deep Sea Drilling Project Leg 60. In: Hussong DM et al. (eds) Init Rep Deep Sea Drilling Proj 60:909–929

Jackson MC, Fryer P (1986) The Kasuga volcanic cross-chain: a calc-alkaline basalt-dacite suite in the northern Mariana island arc. Eos 67:1276

Johnson RH (1973) Acoustic observations of nonexplosive submarine volcanism. J Geophys Res 78:6093–6096

Karig DE (1971) Structural history of te Mariana island arc system. Geol Soc Am Bull 82:323–344

Katsumata M, Sykes LR (1969) Seismicity and tectonics of the western Pacific: Izu-Mariana-Caroline and Ryukyu-Taiwan regions. J Geophys Res 74:5923–

Kay SM, Kay RW (1985) Role of crystal cumulates and the oceanic crust in the formation of the lower crust of the Aleutian arc. Geology 13:461–464

Kuno H (1962) Catalogue of the Active Volcanos of the World Including Solfatara Fields. Part II. Japan, Taiwan, and Marianas. International Assoc Volcanology, Naples

Lin PN, Stern RJ, Bloomer SH (1988) Shoshonitic volcanism in the northern Mariana Arc. 2. Large-ion lithophile and rare earth element abundances-evidence for the source of incompatible element enrichments in intra-oceanic arcs. J Geophys Res (in press)

McCabe R (1984) Implications of paleomagnetic data on the collision related bending of island arcs. Tectonics 3:409–428

McCabe R, Uyeda S (1983) Hypothetical model for the bending of the Mariana Arc. In: Hayes DE (ed) The tectonic and geologic evolution of Southeast Asian seas and islands: Part 2. Geophys Monogr Am Geophys Union 23:281–293

Meijer A (1976) Pb and Sr isotopic data bearing on the origin of volcanic rocks from the Mariana island-arc system. Geol Soc Am Bull 87:1358–1369

Meijer A (1982) Mariana-Volcano Islands. In: Thorpe RS (ed) Andesites. Wiley, New York, pp 293–306

Meijer A, Reagan M (1981) Petrology and geochemistry of the island of Sarigan in the Mariana Arc: calc-alkaline volcanism in an oceanic setting. Contrib Mineral Petrol 77:337–354

Meijer A, Reagan M (1983) Origin of K_2O-SiO_2 trends in volcanoes of the Mariana arc. Geology 11:67–71

Morimoto R, Ossaka J, Hatori T, Izutsuya S, Uraabe K, Takahashi H, Okada Y, Hirabayashi J, Isa K, Isobe H (1968) The upheaval of an insular volcano Iwo-jima, Ogasawara Islands and its recent state of activity. J Geography Tokyo 77:255–283 (in Japanese)

Pearce JA, Lippard SJ, Roberts S (1984) Characteristics and tectionic significance of supra-subduction zone ophiolites. In: Kokekaar BP, Howells MF (eds) Marginal Basin Geology. Geol Soc London Spec Pub 16:77–94

Rautenschlein M, Jenner GA, Hertogen J, Hofmann AW, Kerrich R, Schminke H-U, White WM (1985) Isotopic and trace element compositions of volcanic glasses form the Akaki Canyon, Cyprus: implications for the origin of the Troodos ophiolite. Earth Planet Sci Lett 75:369–383

Ronck R (1975) Volcano erupting near Tinian. Pacific Daily News April 30, 1975:3

Smith TL, Batiza R (1986) Deep-sea hyaloclastites: new evidence for diversity of origin. Eos 67:1184

Stern RJ (1979) On the origin of andesite in the Northern Mariana island arc: implications from Agrigan. Contrib Mineral Petrol 68:207–219

Stern RJ, Bibee L (1984) Esmeralda Bank: geochemistry of an active submarine volcano in the Mariana Island arc. Contrib Mineral Petrol 86:159–169

Stern RJ, Ito E (1983) Trace-element and isotopic constraints on the source of magmas in the active Volcano and Mariana island arcs, western Pacific. J Volc Geotherm Res 18:461–482

Stern RJ, Smoot NC, Rubin M (1984) Unzipping of the volcano arc, Japan. Tectonophysics 102:153–174

Stern RJ, Bloomer SH, Lin PN, Smoot NC (1988a) Submarine arc volcanism in the southern Mariana Arc as an ophiolite analog. Tectonophysics (in press)

Stern RJ, Lin PN, Bloomer SH, Ito E, Morris J (1988b) LIL- and LREE-enriched magmatism in Mariana Arc Seamounts: effect of propagating back-arc extension. Geology (in press)

Tsuya H (1936) Geology and petrography of Io-Sima (Sulphur Island), Volcano Islands Group. Bull Earthquake Res Inst 14:453–480

Wood DA, Marsh NG, Tarney J, Joron JL, Fryer P, Treuil M (1981) Geochemistry of igneous rocks recovered from a transect across the Mariana Trough, Arc, Fore-arc, and Trench, sites 453 through 461, Deep Sea Drilling Project Leg 60, In: Hussong DM, Uyeda S (eds) Init Rep Deep Sea Drilling Proj 60:611–546

Woodhead JD, Fraser DG (1985) Pb, Sr, and Be isotopic studies of volcanic rocks from the northern Mariana islands: implications for magma genesis and crustal recycling in the western Pacific. Geochim Cosmochim Acta 49:1925–1930

Yoshida T, Fujiwara S, Ishii T, Aoki K (1987) Geochemistry of Fukutoku-oka-noba submarine volcano, Izu-Ogasawara arc. Res Rep Lab Nucl Sci Tohoku Univ 20:202–215

Yuasa M (1985) Sofugan Tectonic Line, a new tectonic boundary separating northern and southern parts of the Ogasawara (Bonin) Arc, NW Pacific. In: Nasu N, Kobayashi K, Uyeda S, Kushiro I, Kagami H (eds) Formation of active ocean margins. Terra Scientific Publishing, Toyko, pp 483–496

Yuasa M, Tamaki K (1982) Basalt from Minami-Iwo Jima Island, Volcano Islands. Bull Geol Surv Jpn 33:531–540

Received February 25, 1987/Accepted August 25, 1988