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Forty million years of magmatic evolution in the Mariana arc: The tephra glass record

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Abstract. Tephra glasses retrieved from 10 Deep Sea Drilling Project (DSDP) cores around the Mariana arc system make up a remarkable record of explosive volcanism in the Marianas over the past 40 m.y. Major element compositions for approximately 1800 tephra glasses, from basalt through rhyolite, are reported and used to examine the nature and history of this activity. Three maxima of volcanic explosivity, presumably related to especially vigorous volcanism in the Mariana arc, are identified, with the biggest maximum at around 18-11 Ma and two other maxima at 35-24 and 6-0 Ma; the two younger maxima are contemporaneous with peaks in explosive volcanism observed for other western Pacific arcs. Explosive arc volcanism has been predominantly tholeiitic since shortly after arc inception; no boninitic glasses were found. The tephra glasses belong to the low- to medium-K suite, except during an enigmatic phase of medium- to high-K explosive volcanism during the late Miocene (11-7 Ma). Even though Mariana tephra glasses are largely similar in composition to Mariana arc lavas, the tephra show a much larger compositional range than that found for subaerial Mariana arc lavas, which totally lack dacitic to rhyolitic volcanic products. The tephra glasses define a bimodal population in terms of silica content, with a pronounced minimum, or "Daly gap," around 65-66% SiO_2. Mariana tephra glasses are fractionated, with the least evolved glass being Fe-rich and having a magnesium number (Mg #) ($100Mg/Mg+Fe^{2+}$) of 55. Basaltic tephra glasses contain ≤16% Al_2O_3 (average 14.3% Al_2O_3) and are not high-alumina basalts; this contrasts with the observation that modern Mariana arc lavas contain 15-21% (average 17.4%) Al_2O_3. The high-alumina basalt lavas of the Mariana arc probably reflect plagioclase accumulation and not liquid compositions. All tephra glasses plot near low-pressure cotectics and reaction curves on the subprojection olivine-clinopyroxene-quartz; mafic and felsic samples define distinct trends. The mafic trend reflects fractional crystallization of mantle-derived basaltic magma, whereas the felsic trend may be due either to anatexis of Mariana arc crust or to fractionation of mafic melts. The tephra glass data reinforce the model that the magmatic evolution of the Mariana arc has been dominated by low-pressure fractionation, perhaps accompanied by anatexis. Episodic changes in melting regime to generate Miocene potassic tephra may be related to changing mantle sources and processes related to episodes of back arc basin spreading. These episodic changes are superimposed on a long-term increase in potassium that reflects progressive metasomatism of the mantle source. Long-term increases in K_2O contents for Mariana arc magmas inferred from the tephra glass record are 0.004 wt % m.y.$^{-1}$ (mafic), 0.011 wt % m.y.$^{-1}$ (intermediate), and 0.023 wt % m.y.$^{-1}$ (felsic).

Introduction

A better understanding of how arc magmas change through time is required to constrain models for the thermal and chemical evolution of convergent margins. For example, if subarc asthenospheric recharge rates are slow compared to the rate of depletion due to melting, there should be a progressive depletion in the composition of arc magmas with time. Correspondingly, if progressive cooling affects the thermal structure of the mantle wedge, this might be manifested in the depth and degree of melting, again recorded in the composition of arc magmas. Because arc magmas reflect mixtures of mantle, crust, and slab-derived components which are melted in response to a complex and poorly constrained thermal structure, it will not be easy to unravel the causes of progressive magmatic changes. Nevertheless, the changes in magma chemistry observed over the life of an arc provide powerful but largely unexploited constraints for models of convergent margin processes.

The question of how arc magmas change through time has been an important scientific question for over 20 years. Impelled by the models proposed by Jakes and coworkers in a series of papers [*Jakes and White*, 1969, 1972; *Jakes and Gill*, 1970], the arc petrologic community has made efforts to

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evaluate the hypothesis that arc magmas become increasingly enriched over the life of the arc. These efforts have traditionally concentrated on samples of lava obtained by outcrop or drill sampling [e.g., *Gill*, 1987]. This approach rarely provides adequate samples because most of the magmatic record is buried beneath younger lavas or it is removed by erosion. An alternate approach is to isolate distal tephra contained in pelagic sediments and to study these with microanalytical techniques. These samples come from Deep Sea Drilling Project (DSDP) and Ocean Drilling Program (ODP) cores. There are disadvantages of this approach; these include difficulties in identifying the volcanic source, postdepositional alteration, and incomplete records resulting from erosion and nondeposition [*Arculus et al.*, 1995]. In addition, distal tephra deposited in pelagic sequences result from explosive, subaerial eruptions, and the more explosive the eruption, the more likely that it will produce abundant tephra far from the volcano. Sampling distal tephra thus discriminates against the more common and milder proximal basaltic eruptions and mostly misses the record of submarine arc volcanism.

In spite of these shortcomings, studying the tephra record has several advantages. Biostratigraphic assignments are readily made for the layers that contain the tephra, providing an unparalleled opportunity to reconstruct millions of years of evolution of arc volcanism. Because tephra glasses are reliable melt proxies, studying their compositions overcomes a vexing problem with arc lavas: To what extent are these overwhelmingly porphyritic lavas accumulates as opposed to liquid compositions? Tephra at any horizon were likely derived from several volcanoes, and this opens the way for integrating the composition of an entire arc system over time. Furthermore, many scientists have noted the importance of intraoceanic arcs (arcs built on oceanic crust) to an understanding of a wide range of geologic problems, from the origin of ophiolites to the mechanisms of continental growth, but these arcs are largely submerged. Obtaining a reliable record of their magmatic evolution from surface outcrops is thus much more difficult than for arcs built on continental crust. The tephra glass record, although biased, is thus invaluable for reconstructing how an intraoceanic arc like the Marianas changes over time. Recent studies of the chemical composition of submarine tephra layers (mostly tephra glasses) have demonstrated their value in examining arc volcanism over extended periods [*Scheidegger et al.*, 1978; *Ninkovich*, 1979; *Cadet and Fujioka*, 1980; *Packham and Williams*, 1981; *Pouclet et al.*, 1985; *Fujioka*, 1985; *Furuta et al.*, 1986; *Warner et al.*, 1987; *Pouclet et al.*, 1991; *Arculus and Bloomfield*, 1992; *Cambray et al.*, 1993; *Arculus et al.*, 1995]. These studies agree that stratigraphic sampling of tephra provides a representative record of violent, subaerial eruptions through time, a record that offers significant advantages over traditional approaches to arc magmatic evolution.

The focus of this contribution is to use the tephra glass record to infer the magmatic evolution of the Mariana arc system over the past 40 m.y. The data provide new perspectives on the history of Mariana arc volcanism and on the composition of modern Mariana arc lavas. We use these data to answer the question of whether or not the magmatic evolution of this arc system was accompanied by systematic changes in composition.

Geologic Setting and Source of the Tephra Glass

The Mariana arc system lies along the western Pacific rim (Figure 1). It marks not only a zone of convergence between oceanic lithosphere plates but also extension to generate back arc basins such as the Parece Vela basin and the Mariana trough. It is built on oceanic crust and is isolated from continental landmasses. The approximately 2500 km long Izu-Bonin-Mariana (IBM) arc system formed around 45 Ma [*Meijer et al.*, 1983], when a subduction zone nucleated along a former transform fault [*Uyeda and Ben-Avraham*, 1972]. The first episode of back arc basin rifting began about 32 Ma when the arc was split into the remnant Palau-Kyushu ridge and active West Mariana ridge [*Mrozowski and Hayes*, 1979]. Subsequent seafloor spreading in the Parece Vela and Shikoku basins continued until about 15 Ma. A second episode of rifting to form the Mariana trough began around 7 Ma [*Fryer and Hussong*, 1981], separating the remnant West Mariana ridge and the Mariana arc. The Mariana trough has been spreading at a half rate of ~ 2 cm/yr. since about 3.5 Ma [*Yamazaki et al.*, 1993].

Ten DSDP sites were examined for this study (Figure 1): 447A and 290 in the West Philippine basin, 448 in the western sedimentary apron of Palau-Kyushu ridge, 449 in western part of the Parece Vela basin, 53 and 54 in eastern part of the Parece Vela basin, 451 and 453 in the Mariana trough, and 458 and 459 in the Mariana forearc. Several workers have previously carried out similar studies around the IBM arc system: DSDP Sites 453 and 454 in the western side of Mariana trough [*Packham and Williams*, 1981], DSDP Site 450 in the Parece Vela basin [*Warner et al.*, 1987], ODP Sites 782, 784, and 786 in the Bonin forearc [*Arculus and Bloomfield*, 1992]. *Arculus et al.* [1995] combined studies of ashes and turbidites retrieved from ODP and DSDP drilling in the western Pacific to outline a model of geochemical evolution of arc systems in the region.

We assert that tephra fallout recovered from the 10 DSDP sites studied here provides representative samples of explosive volcanism occurring in the Mariana arc system and adjacent portion of the Izu-Bonin arc system during the past 40 m.y. This is based on likely wind and ocean current patterns and the relationship between tephra size and the distances that different sizes of tephra can be transported in the air. The Marianas have been located in a near-equatorial position since their formation [*Larson et al.*, 1975], so wind patterns throughout the Cenozoic should have been similar to those of today. The low-altitude atmospheric layer over the Marianas lies in the zone of northeast trade winds during winter and intertropical convergence zone during summer [*Gross*, 1993]. Thus the surface winds blow from northeast to southwest, as indicated by the heavy arrow in Figure 1. Correspondingly, oceanic surface currents around the Marianas are dominated by the westward flowing North Equatorial Current. However, the likely dispersal pattern is complicated by the antitrades (westerlies) at altitudes between 5-8 km and the tropopause, with easterlies again above the tropopause at about 18-20 km. This is the case for the Lesser Antilles arc [*Newell et al.*, 1972; *Sigurdsson et al.*, 1980], which lies along nearly the same latitude as the Mariana arc. This argument is evidenced by the May 15, 1981, eruption of Mount Pagan in the Mariana islands, which produced a strong Plinian column at least 13.5 km high and dispersed ash south-

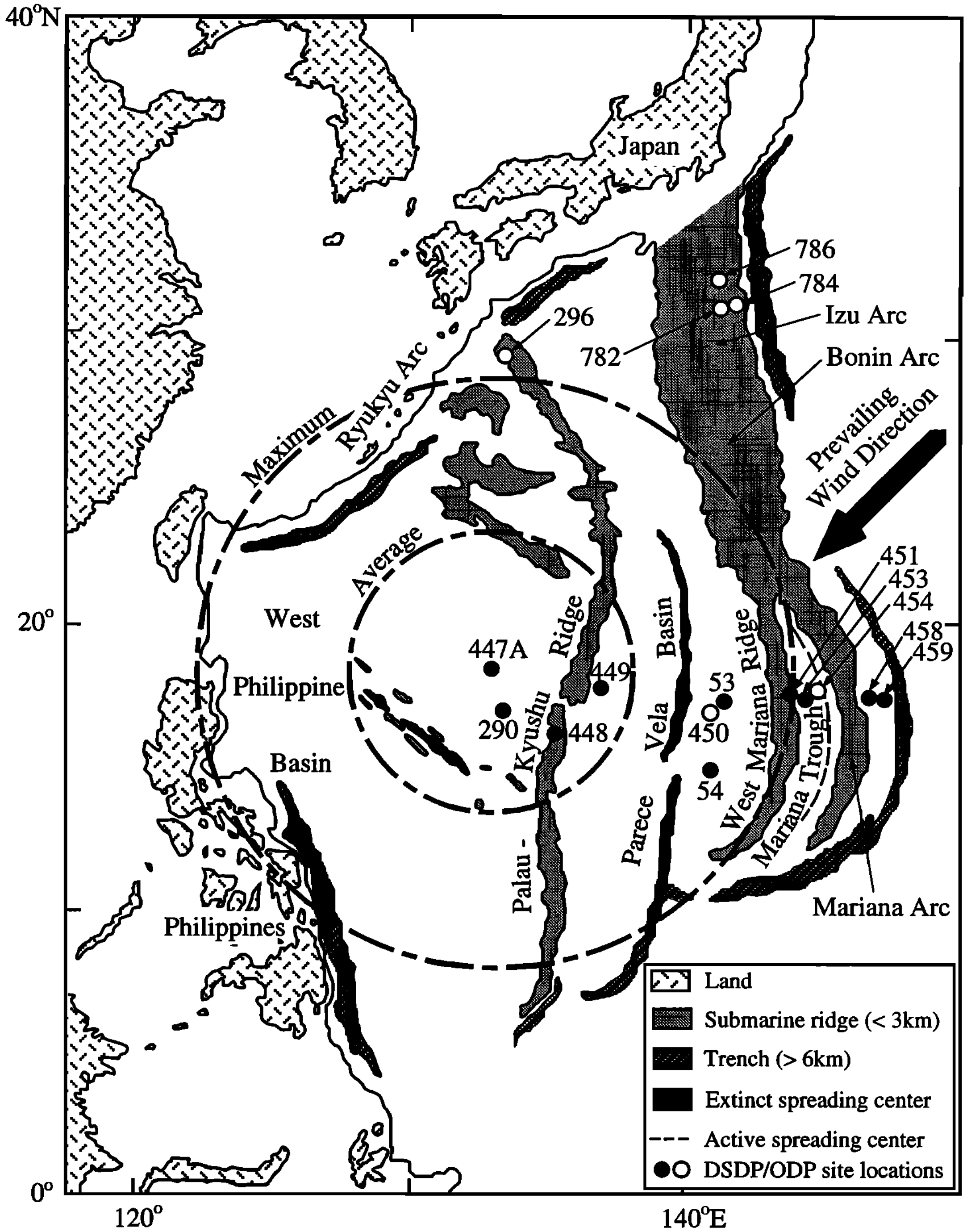

Figure 1. Sketch map showing tectonic features of the Izu-Bonin-Mariana arc system and the Philippine basin. Ten solid circles represent DSDP sites sampled for this study; open circles are other DSDP and ODP sites discussed in text. The heavy arrow indicates the prevailing wind direction around the Marianas. Two large, dashed circles show a maximum and an average dispersal radii for ashfall tephra >16 μm in size [*Fisher*, 1964].

southeast almost 1000 km, although the prevailing low-altitude southeasterly winds are responsible for thick ash and scoria deposits in the northwest part of the island [*Banks et al.*, 1984].

The general relationship between particle size of tephra, distance traveled, wind velocity, and explosivity indicates that the Mariana and southern Bonin arc are the source of the tephra sampled in the 10 DSDP sites. We used the conclusions of *Fisher* [1964] to estimate a maximum and an average dispersal range. Considering the minimum size of tephra analyzed in our study (16 μm), we estimate a maximum and an average dispersal radius of 1300 km and 600 km; this constrains possible ash sources to subaerial volcanoes in the southern IBM arc. These distances are plotted as two circles, arbitrarily centered on DSDP Site 447A in Figure 1. More realistically, tephra isopachs should approximate ellipsoids or fans from the erupting volcano because of the influence of winds and currents. The overlap of larger circles centered on all 10 DSDP sites would encompass predominantly the Mariana arc system and part of the Izu-Bonin arc to the north. Some of the westernmost sites have radii of dispersal that encompass part of the Philippine and the Ryukyu arcs. Tephra fallout in southeast Asia is primarily to the west of the source [*Kennett*, 1981], and Philippine tephra are transported dominantly to the west (e.g., the 1991 Pinatubo eruption); these arcs are not expected to contribute significantly to the sampled sites. The Caroline Islands lie within the maximum radii of dispersal of some eastern sites, but volcaniclastic glass of Caroline Islands (ODP Site 802) is of a distinctly different composition than any of the tephra that we have analyzed (i.e., >3% TiO_2 (J. Lee and R. J. Stern, unpublished data, 1993)). Combining this information, we conclude that the source for the tephra glasses is the Mariana arc system and the southern part of the Bonin arc.

Sampling and Analytical Techniques

We worked on 143 tephra glass-bearing core sections from 10 DSDP sites. Tephra examined in this study occurs in one of three ways: (1) as dispersed within predominantly clay-rich, pelagic sediments; (2) as part of vitric-rich, silty or sandy beds; or (3) as part of coarser volcaniclastic beds. The first two occurrences constitute ≥95% of all core sections examined. Minerals in ash layers commonly preserve reticulate glass coatings, suggesting that the ash layers were not turbidites but were derived as airborne fallout from subaerial eruptions [*Carey and Sigurdsson*, 1978]. Occurrence of the tephra with nannofossils allows an accurate biostratigraphic and thus absolute age assignment for each core section using the nannofossil zonation schemes of *Martini* [1980] and *Ellis* [1981]. Ages range from about 40 Ma to 0.3 Ma (Figure 2). Most individual sites provide limited tephra records. As an example, cores collected from DSDP Sites 458 and 459 have hiatuses at 32-30 Ma and 6-3 Ma [*Hussong and Uyeda*, 1981], even though these cores provide the most complete record of volcanogenic sedimentation among all Leg 59 and 60 sites. Our sampling of the 10 DSDP sites, however, is sufficiently comprehensive and complementary as to allow us to track explosive volcanism in the Mariana arc system from just after its formation at 45 Ma, beginning at about 40 Ma (Figure 2). There are fewer glass-bearing tephra samples from late Eocene and earliest Oligocene horizons than from younger ones. This may be partly due to diagenesis, which reduces the amount of glass in progressively older sediments [*Hein and Scholl*, 1978; *Hein et al.*, 1978; *Desprairies*, 1981].

Each core was sampled from a ≤2-cm interval to yield one "section population" of glass. Typically, 1 to 2 cm^3 of material was placed in a beaker with water, stirred manually, and agitated in an ultrasonic bath to remove adhering clay, with the cloudy liquid poured off continuously. This treatment was repeated until the supernatant water was clear. Slight grinding and repeated treatment after drying were occasionally necessary, particularly for very fine ash contained in muds. Moderately indurated samples (marly nannofossil chalk, mudstone, and tuff) were pulverized in a hand mortar. The residue after this treatment consists of minerals, lithic fragments, glass, and fossil fragments, all of which are larger than 10 μm. Glass was picked from this residue under the polarizing microscope using the isotropic property of glass. During picking, care was taken to obtain fresh, large, and thick glass free of alteration signs such as strain birefringence (in hydrated felsic glass), orange color (in palagonitized mafic glass), and fine fractures or cracked surfaces. Analyzed glass shards range in size from 16 to 150 μm. More than one glass color was observed in >92% of the 143 section populations. In such cases, the section population was divided into dark brown (mafic), light brown (intermediate), and colorless (felsic) subgroups. If glass was abundant, the maximum number of grains picked was limited to about 10 for analysis from each color subgroup. In many cases, fewer than 10 grains from each color group could be found. Because we are especially interested in primitive melt compositions, we took extra care to isolate dark brown mafic glass shards, which were commonly smaller than other tephra from other color groups. Another part of this selection effort was to sample color groups proportionately from each section population for microprobe analysis. Glass grains were mounted on a brass disc with a low-temperature epoxy resin and cured for several days at room temperature. The discs then were polished from 600 grit sandpaper through 9 μm alumina-impregnated mylar and 3 μm, 1 μm, and down to 0.1 μm diamond-impregnated mylars. The polished samples were coated with approximately 0.2 μm carbon.

Major element analyses were carried out using the fully automated, five-spectrometer JEOL JXA-8600 electron microprobe at the University of Texas at Dallas. Particular care was taken to ensure that only glass was analyzed. Analysis of microphenocryst or microlite-bearing glass can give erroneous results, especially for Al and Ca (plagioclase microlites), Fe (oxide microlites), and Mg (by olivine and/or pyroxene microlites); for example, the composition of boninite may be obtained if an olivine microphenocryst occupies part of the analyzed spot. We avoided selecting dubious fragments and further checked by examining the electron backscattered images before each analysis. Analysis was performed using a stationary beam, because this provides results that are similar to those obtained by moving the sample or rastering the beam [*Jezek and Noble*, 1978], whereas moving/rastering techniques are not suitable for small glass shards. In order to minimize Na loss due to vaporization of glass, various combinations of beam currents and beam spot sizes were tested. A low beam current and large beam diameter gave the best results. We used an accelerating voltage of 15 kV, a beam current of 5 nA, and a beam diameter of 15 μm. Sodium was analyzed first and counted for 10 s, and this technique eliminated the problem of Na_2O loss (see below). At the same time, Si was measured for 40 s and P counted for 10 s, then counts were collected for Mg (40 s), Al (60 s), and finally Ti, K, Mn, Ca, and Fe (30 s each). The accumulated counts were processed on-line using a Tracor Northern computer, and the raw data were reduced by the methods of *Bence and Albee* [1968] and *Albee and Ray* [1970]. Natural rhyolitic (RLS-132) and basaltic glass standards (USNM 113498/1 and USNM 111240/52) as well as a fayalite standard (USNM 85276) were used for calibration. Replicate analyses of RLS-132 during each analytical session reproduced the composition of the standard within analytical uncertainty. Analytical totals for the tephra glasses range from 89.2% to 99.7%, and all analyses are recalculated to 100 wt % volatile-free. For magnesium number (Mg #) ($100Mg/Mg+Fe^{2+}$)

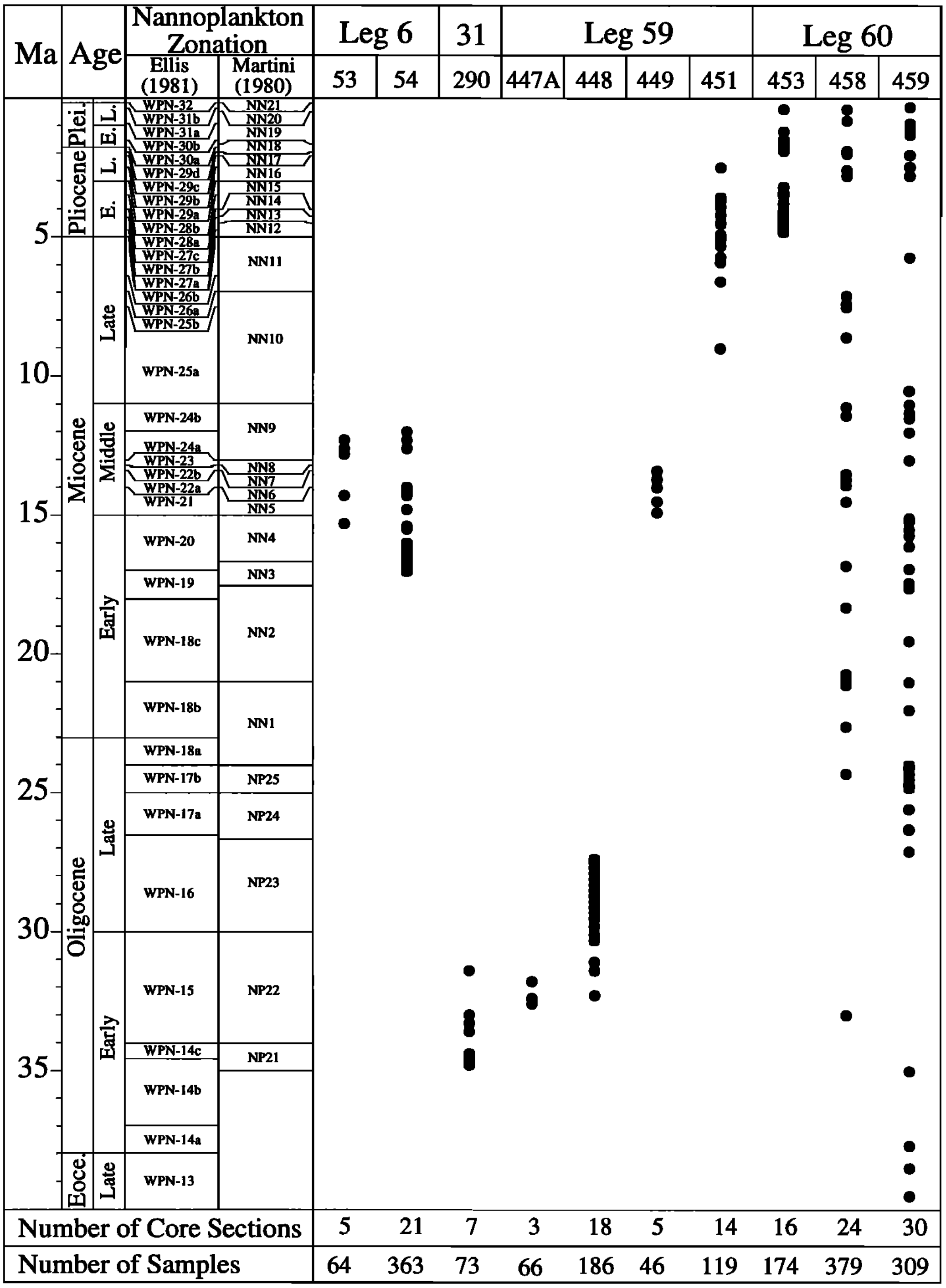

Figure 2. Stratigraphic occurrence of 143 tephra glass-bearing core sections. The age of the tephra was inferred from nannofossil zonation schemes by *Martini* [1980] and *Ellis* [1981].

calculation, we assume $Fe^{2+}/(Fe^{2+}+Fe^{3+}) = 0.9$. A total of 1812 analyses are reported in this study. (The complete data set (raw and normalized to 100 wt %) is available from the first author upon request, either as paper copy or as computer disc.)

Some scientists have noted the loss of Na during microprobe analysis of hydrous glass. *Nielsen and Sigurdsson* [1981] showed a 50% decrease of Na counts within the first 10 s of analysis using a focused beam and high beam current (20 nA). They estimated the initial sodium concentration from the decay rate of sodium counts. We examined the Na loss problem by determining Na_2O variations during the first 10 s of analysis of andesitic and rhyolitic glasses using two conditions: (1) 5 nA beam current and 15 μm spot size (used in this study) and (2) 12 nA beam current and 5 μm spot size (used by *Rutherford et al.* [1985]). No Na_2O was lost within analytical errors from the andesitic glass using either condition. For the rhyolitic glass, however, the 5 nA /15 μm condition yielded no Na_2O loss, whereas the 12 nA/5 μm condition showed loss of about 12% Na_2O after 2 s and about 30% loss after 10 s. We suspect that the greater vulnerability of the felsic glass to Na loss is related to its more hydrated condition.

Glass Alteration

A critical assumption in this study is that tephra glasses preserve magmatic compositions through time. Because glass is vulnerable to alteration, this assumption may not be valid. Older glasses, regardless of their composition, are typically hydrated [*Scheidegger et al.*, 1978; this study]. It is therefore critical that we evaluate the extent to which alteration has affected the composition of the DSDP tephra glasses.

Most alteration of glass is accompanied by readily recognizable physical changes, such as palagonitization and/or devitrification. We have scrupulously avoided samples showing visible signs of alteration, but the question of cryptic alteration remains. Many scientists have noted that felsic tephra glasses yield lower microprobe totals compared to mafic and intermediate tephra glasses and infer that the deficit is due to water in the glass [*Packham and Williams*, 1981; *Warner et al.*, 1987; *Pouclet et al.*, 1991]. *Warner et al.* [1987] showed that inferred H_2O contents equivalent to departures from 100% oxide sums are confirmed by loss-on-ignition method on basaltic andesites (average 2.5%) and rhyodacite (average 9.5%). Our results show this as well, with felsic glasses generally showing the lowest totals, followed by intermediate glasses, whereas totals for mafic glasses are generally closest to 100% (Table 1a). Fresh obsidians from pyroclastic layers at Mono Craters, California, yield initial water contents that range from 2.7% to 0.4-0.5%, reflecting varying degassing processes from closed system to open system [*Newman et al.*, 1988]. On this basis, <3% of the water in the tephra studied here may be magmatic, so the greatest proportion of water is due to postdepositional hydration. If water gain due to hydration is the only alteration effect to be considered, then recalculation to 100% volatile-free is appropriate. This procedure is supported by our observation that different rhyolitic glass fragments obtained from a single ash layer have very similar chemical compositions after normalization to 100%, although analyses of different grains provide different microprobe totals (Table 1b). We conclude that normalizing data to 100% on a volatile-free basis is warranted and necessary.

Recognizing that the tephra glasses are hydrated leads to the possibility that other elements were exchanged with seawater. The freshness or possible alteration of individual glass shards can be tested by comparing major element contents obtained by electron microprobe spot analysis and by wet chemical analysis of bulk glass samples [*Scheidegger et al.*, 1978]. Scheidegger et al. analyzed rhyolitic glass shards from Pleistocene and Pliocene ash layers from DSDP Site 192 by these two methods and found that the bulk glass samples gained 0.1-0.2% K_2O, MgO, and CaO, and lost a corresponding amount of SiO_2, with almost no change in Na_2O. They concluded that the glasses have undergone only subtle, surficial ion exchange along with hydration. Cryptic alteration can lead to potassium enrichment of submarine glass surfaces during the early stages of alteration to palagonite [*Staudigel and Hart*, 1983]. However, microprobe spot analysis examines the inner portions of glass shards, which are less vulnerable to seawater alteration than shard margins. Furthermore, Na is most likely to be gained from seawater, but this element is not enriched in the felsic, most hydrated samples (see Figure 3). We conclude that except for the addition of water and possible minor changes in alkalies, alkaline earth, and/or silica contents, cryptic alteration has not significantly affected the original composition of the glass shards that we have analyzed.

Results

We observe two distinct chemical groups of glasses. These show significant differences in FeO* and Al_2O_3 (Figure 3). Group I constitutes the predominant part (98.7%, N= 1779) of all analyses and exhibits a coherent chemical trend (Figure 4). Group I has a compositional range that is much more siliceous than that recorded for Mariana arc lavas, although basalt-to-andesite glasses have compositions that are grossly similar to those of Mariana arc lavas. We infer that Group I records Mariana arc volcanism. Group II, a minor (1.3%, N=33) component, exclusively occurs in sedimentary sections from back arc basin sites (Sites 453, 451, and 447A) as admixtures with predominant Group I. Group II has FeO*, TiO_2, Al_2O_3, K_2O, and MgO contents similar to those of Mariana trough basalt glasses (Figure 3). Group II basalts also have higher CaO/Al_2O_3 at a given FeO* content than do Group I tephra glass and Mariana arc lavas but are very similar to Mariana trough basalts. We infer that Group II tephra were locally derived from back arc basin volcanoes, probably as hyaloclastites. For the purpose of examining the evolution of Mariana arc magmas, we exclude Group II from further discussion and focus on Group I.

Unlike the limited basalt-to-andesite range and the unimodal distribution of SiO_2 content of Mariana arc lavas,

Table 1a. Major Element Compositions of Representative Tephra Glasses From a Single Core Section (53-1-1)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
SiO_2	52.99	53.95	54.11	54.21	54.32	55.89	56.18	59.97	62.30	66.20	67.74	67.94	68.04	68.40	69.21	69.52	70.89	73.09
TiO_2	1.22	1.05	1.44	1.17	1.11	1.01	1.11	0.86	0.85	0.64	0.62	0.58	0.61	0.66	0.42	0.43	0.37	0.31
Al_2O_3	14.63	14.60	14.63	14.81	15.31	14.62	15.11	14.58	13.66	13.45	13.44	13.33	13.16	12.44	12.62	12.58	11.66	11.62
FeO*	12.23	11.47	11.46	11.50	10.67	10.86	10.67	8.11	7.90	3.05	2.99	3.14	2.97	3.57	1.93	1.94	1.76	1.57
MgO	4.19	4.47	3.95	4.11	3.81	3.28	3.29	2.46	1.63	0.70	0.73	0.70	0.64	0.66	0.40	0.42	0.32	0.25
CaO	8.70	8.79	8.33	8.77	8.50	7.67	7.69	6.11	5.06	2.49	2.57	2.53	2.32	2.53	1.65	1.66	1.56	1.44
Na_2O	2.88	3.06	3.09	2.83	3.01	2.99	2.98	3.65	3.75	3.59	3.60	3.93	3.61	4.00	3.21	3.28	2.75	3.27
K_2O	0.71	0.74	0.80	0.74	0.73	0.98	0.86	1.02	1.29	2.72	2.46	2.55	2.57	1.44	2.93	2.83	2.56	3.05
MnO	0.24	0.25	0.26	0.21	0.21	0.20	0.27	0.19	0.18	0.13	0.12	0.15	0.13	0.17	0.06	0.10	0.03	0.05
P_2O_5	0.18	0.18	0.10	0.20	0.19	0.25	0.25	0.25	0.34	0.12	0.18	0.14	0.02	0.12	0.06	0.05	0.04	0.02
Total	97.97	98.56	98.17	98.55	97.86	97.75	98.41	97.20	96.96	93.09	94.45	94.99	94.07	93.99	92.49	92.81	91.94	94.67

Table 1b. Comparison of Compositions of Tephra Glasses From Several Ash Layers Before and After Normalization to 100 wt %

	Core Section													
	54-3-1			290-6-2			458-4-2(b)			459-6-4(a)				
	1	2	3	1	2	3	1	2	3	1	2	3	4	5
	Before normalization													
SiO_2	66.84	67.43	68.91	71.50	72.38	73.52	67.86	68.39	69.48	66.94	67.55	68.11	68.87	69.69
TiO_2	0.46	0.47	0.47	0.13	0.10	0.11	0.37	0.43	0.47	0.27	0.39	0.40	0.34	0.31
Al_2O_3	12.81	12.57	12.40	11.69	11.54	11.56	12.56	12.59	12.83	13.92	14.04	14.46	14.12	14.57
FeO*	3.36	3.35	3.25	1.22	0.90	1.24	4.05	4.32	3.88	2.46	2.42	2.65	2.77	2.56
MgO	0.61	0.64	0.53	0.24	0.11	0.13	0.51	0.64	0.61	0.62	0.55	0.59	0.58	0.54
CaO	2.70	2.81	2.62	1.31	0.91	1.03	2.58	2.86	2.80	2.52	2.36	2.50	2.45	2.35
Na_2O	3.72	3.97	4.40	2.61	2.87	2.92	4.01	3.87	4.27	3.70	3.60	3.91	4.22	4.04
K_2O	1.57	1.50	1.61	4.14	4.25	3.96	1.34	1.36	1.29	2.38	2.32	2.51	2.42	2.55
MnO	0.17	0.24	0.16	n.d.	n.d.	0.10	0.07	0.12	0.12	0.08	0.11	0.20	0.15	0.13
P_2O_5	0.12	0.08	0.06	n.d.	0.02	n.d.	0.12	0.12	0.22	0.06	0.06	n.d.	n.d.	0.08
Total	92.36	93.06	94.41	92.84	93.08	94.57	93.47	94.70	95.97	92.95	93.40	95.33	95.92	96.82
	After normalization													
SiO_2	72.37	72.46	72.99	77.01	77.76	77.74	72.60	72.22	72.40	72.02	72.32	71.45	71.80	71.98
TiO_2	0.50	0.51	0.50	0.14	0.11	0.12	0.40	0.45	0.49	0.29	0.42	0.42	0.35	0.32
Al_2O_3	13.87	13.51	13.13	12.59	12.40	12.22	13.44	13.29	13.37	14.98	15.03	15.17	14.72	15.05
FeO*	3.64	3.60	3.44	1.31	0.97	1.31	4.33	4.56	4.04	2.65	2.59	2.78	2.89	2.64
MgO	0.66	0.69	0.56	0.26	0.12	0.14	0.55	0.68	0.64	0.67	0.59	0.62	0.60	0.56
CaO	2.92	3.02	2.78	1.41	0.98	1.09	2.76	3.02	2.92	2.71	2.53	2.62	2.55	2.43
Na_2O	4.03	4.27	4.66	2.81	3.08	3.09	4.29	4.09	4.45	3.98	3.85	4.10	4.40	4.17
K_2O	1.70	1.61	1.71	4.46	4.57	4.19	1.43	1.44	1.34	2.56	2.48	2.63	2.52	2.63
MnO	0.18	0.26	0.17	n.d.	n.d.	0.11	0.07	0.13	0.13	0.09	0.12	0.21	0.16	0.13
P_2O_5	0.13	0.09	0.06	n.d.	0.02	n.d.	0.13	0.13	0.23	0.06	0.06	n.d.	n.d.	0.08
Total	100	100	100	100	100	100	100	100	100	100	100	100	100	100

Here, n.d. is not detected.

tephra glass compositions range from basalt to rhyolite and are characterized by two peaks, with modes about 54-61% and 68-79% SiO_2 and a broad minimum between 62% and 68% (centered on 65-66%) SiO_2 (Figure 5). All basaltic glasses are fractionated. The most primitive tephra glass that we have analyzed has a Mg # of 55 and about 7% MgO. Fe/Mg ratios for most tephra glasses are high and covary with SiO_2, indicating a tholeiitic trend. Approximately 92% of all section populations show compositional heterogeneity (we define a section population to be heterogeneous if it has >3% range in SiO_2), and these belong to type II in the nomenclature of *Huang* [1980]. The occurrence of "heteromagmatic" ash layers is fairly common [e.g., *Carey and Sigurdsson*, 1978; *Scheidegger et al.*, 1978; *Huang*, 1980; *Pouclet et al.*, 1985; *Arculus and Bloomfield*, 1992]. Thus one should be cautious when trying to infer the composition of an eruption from bulk analyses of ash layers.

Diagrams of major elements versus SiO_2 (Harker variation diagrams) for Group I are shown in Figure 4. These data represent innumerable liquid lines of descent of Mariana arc magmas. Considering the variability in compositions of arc lavas in general [*Perfit et al.*, 1980], the Mariana tephra glasses show remarkably coherent compositional trends for major elements except Na_2O, K_2O, and P_2O_5. TiO_2 (2.16-0.03%), FeO* (17-0.8%), CaO (12.5-0.2%), and MgO (7.3-0.02%) decrease in slightly curvilinear fashion with increasing SiO_2. FeO* contents of mafic tephra glasses are notably high compared to those of Mariana arc lavas (see also Figure 3). Al_2O_3 (16.5-11.2%) increases until about 60% SiO_2 and decreases afterward. Na_2O (5.7-1.6%) contents show a wide range. However, the basaltic and andesitic glasses have Na_2O contents comparable to the Mariana arc lavas (see Figure 3), suggesting that gain by alteration or loss during microprobe analysis is negligible. K_2O (5.6-0.1%) shows a considerable data fan. Considering that K_2O is an incompatible element, such large variations should indicate various melt compositions that have recorded differences in magma sources or extent of melting and degree of crystal fractionation. The K_2O versus SiO_2 trends for individual volcanoes can be readily attributed to crystal fractionation [*Kuno*, 1968; *Cawthorn*, 1977]. However, offsets between the trends generated by different volcanoes may be explained by differences in the degree of partial melting from a relatively homogeneous source [*Meijer and Reagan*, 1983]. P_2O_5 (< 0.85%) behaves like Al_2O_3, with maximum abundances reached about 60% SiO_2.

Discussion

The magmatic record preserved in the Mariana tephra glasses offers several valuable perspectives on how Mariana arc magmas have changed over time, and these are often constraints that could not have been obtained by surface sampling or drilling. In the following discussion, we first outline an apparent episodicity in explosive volcanism. We then present and interpret similarities and differences in compositional trends for tephra glasses and Mariana arc lavas, including the significance of abundant felsic tephra, a

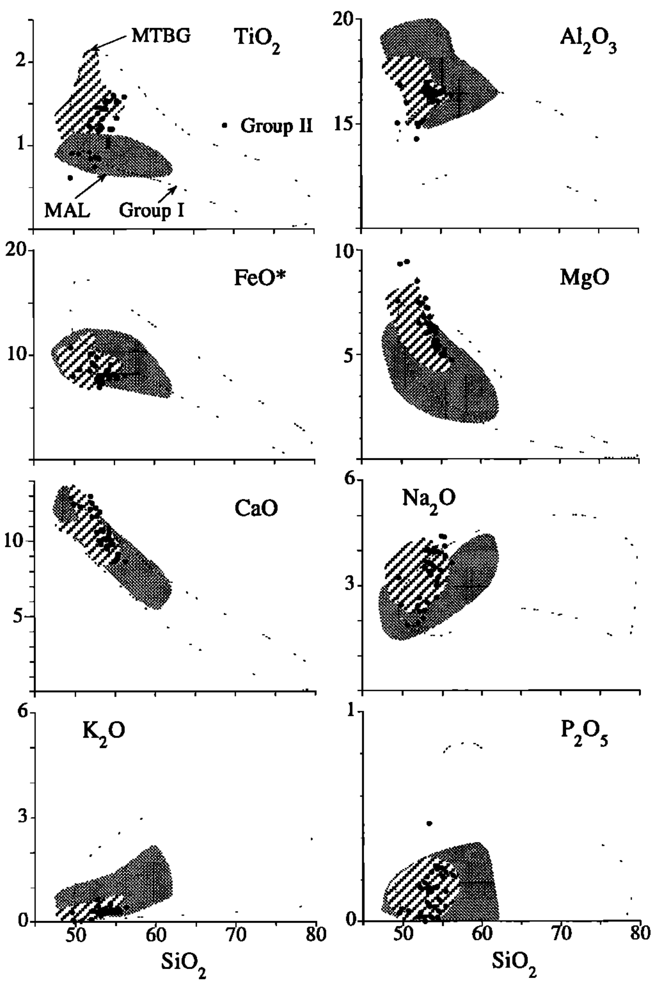

Figure 3. Harker diagram for Group I and II Mariana tephra glasses, compared to modern subaerial Mariana arc lavas (MAL) and Mariana trough basalt glasses (MTBG). Group I glasses have similar chemical compositions to MAL, and Group II glasses, to MTBG. A total of 91 major element analyses for MAL were compiled from *Larson et al.* [1974], *Dixon and Batiza* [1979], *Meijer and Reagan* [1981], *Banks et al.* [1984], *Stern* [1979], and *Hole et al.* [1984]. A total of 91 major element analyses were used for MTBG (R. F. Gribble, unpublished data, 1995).

volcanic rock type not reported from the subaerial Mariana arc. Finally, we discuss the implications of the tephra glass data for models of long-term arc magmatic evolution.

For the purposes of this discussion, we divide the tectonic evolution of the Mariana arc system into four episodes (Figure 6): (1) ~48-30 Ma (subduction initiation to beginning of spreading in the Parece Vela basin); (2) 30-15 Ma (spreading in the Parece Vela basin); (3) 15-7 Ma (end of spreading in the Parece Vela basin to beginning of rifting in the Mariana trough); and (4) 7-0 Ma (beginning of rifting in the Mariana trough to present). Episodes 1 and 3 are times when the arc was not paired with an actively spreading back arc basin, whereas episodes 2 and 4 are intervals of active back arc spreading. With the exception of the fact that our data cover only the last 10 m.y. (40-30 Ma) of the first tectonic episode, the tephra glass record allows us to examine how magma compositions changed over the history of the arc and in association with these tectonic changes.

Pulses of Explosive Mariana Arc Volcanism

Several workers have proposed ways to estimate the scale of explosive eruptions [e.g., *Gorshkov*, 1960; *Walker*, 1980; *Newhall and Self*, 1982], but these require a knowledge of the physical parameters of the eruption such as volume of ejecta and column height. Unfortunately, we are unable to constrain these factors to infer the paleoexplosivity of the Mariana arc. However, tephra glass (plus associated alteration products) is the most abundant component in many submarine ash layers encountered in DSDP Legs 58-60 [*Nagel et al.*, 1981]. In the region sampled during Leg 60, periods of vigorous explosive volcanism were responsible for deposits rich in tephra glass and igneous minerals, with relatively quite periods being dominated by clays and zeolites [*Latouche et al.*, 1981]. We developed the explosivity index (E.I.) to represent the level of explosive volcanism over a 1-m.y. time interval. After tephra were separated, a class from 1 to 5 was assigned, depending upon the abundance of glass in each core sample: 1 = <10% glass, 2 = 10-20% glass, 3 = 20-30% glass, 4 = 30-40% glass, and 5 = >40% glass. We then counted the total number of glass-bearing core sections for each 1-m.y. interval and multiplied this by the class number to obtain the E.I. The E.I. is plotted against age as a stack histogram (Figure 7). Three maxima are identified, with the most important at around 18-11 Ma and two other moderate maxima around 35-24 and 6-0 Ma.

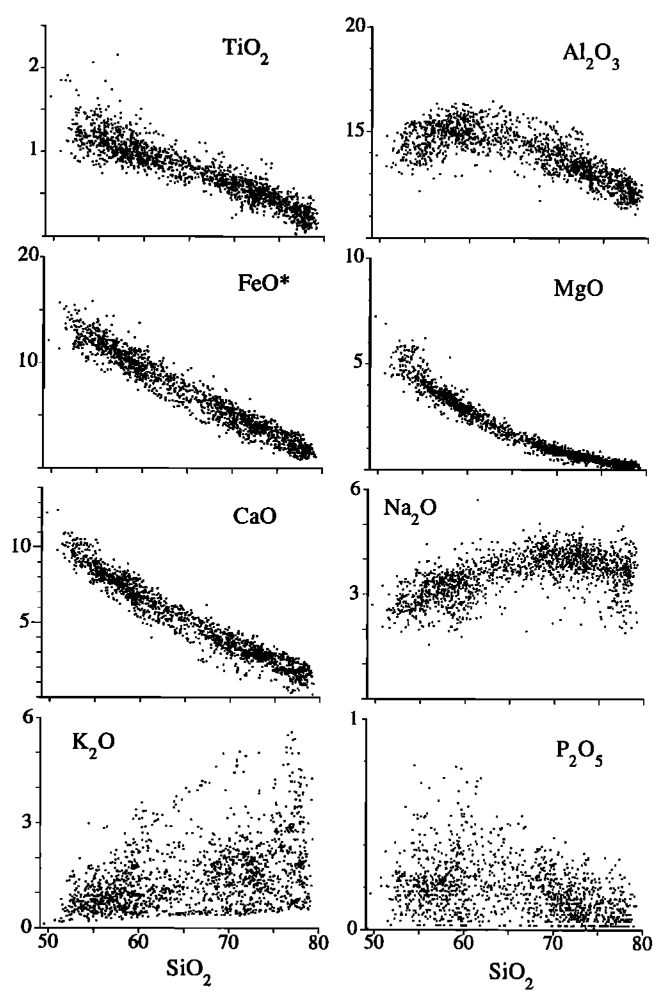

Figure 4. Harker diagrams for the Mariana tephra glasses (Group I only).

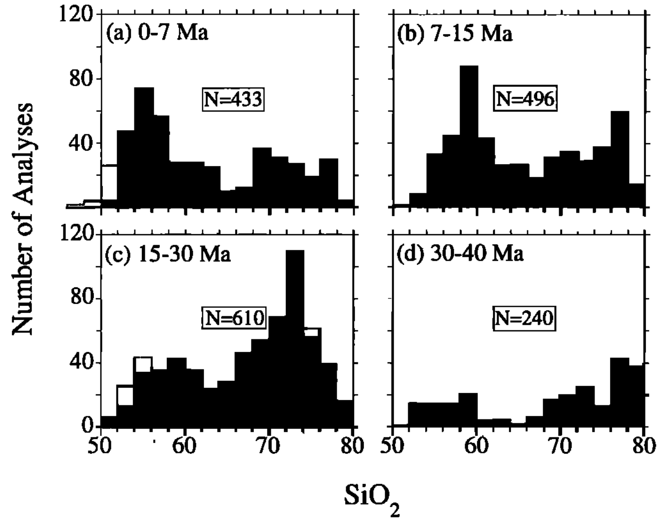

Figure 5. Frequency distribution of SiO_2 for four stages: (a) 0-7 Ma; (b) 7-15 Ma; (c) 15-30 Ma; and (d) 30-40 Ma. Numbers in boxes are total numbers of samples analyzed. Also shown are MAL data as dotted line in Figure 5a and tephra glass data (14-25 Ma) from *Warner et al.* [1987] as a dotted line in Figure 5c. Note that MAL is unimodal and of limited compositional range in silica, but the tephra glasses do show bimodal silica distribution with abundant dacite-rhyolite occurrences.

Similar studies by *Kennett et al.* [1977], *Cambray et al.* [1993], and *Cambray and Cadet* [1994] also documented two important pulses of Neogene volcanism in other circum-Pacific arcs, which are consistent with the second and third maxima of volcanic explosivity reported here. The first maximum is more poorly defined and its significance is more contentious. *Arculus et al.* [1995] summarized arguments for a major eruptive episode between 23 and 30 Ma, largely based on ash layers from DSDP site 296 in the northern Palu-Kyushu ridge (Figure 1), but also noted that the record from the Izu-Bonin forearc indicates a period of arc quiescence during the same period. The maxima identified above must be related to vigorous episodes of arc volcanism in the Marianas. Waning volcanism, as evidenced by lower levels of volcanic activity during 24-18 and 11-6 Ma, does not correlate with back arc spreading of the Parece Vela basin and the Mariana trough. For example, the second maximum occurred during the transition between the time of back arc spreading in the Parece Vela basin and the time after this spreading ceased, whereas the third maximum occurred while spreading continued in the Mariana trough. Models calling for arc volcanism to wane as back arc basin spreading waxes [e.g., *Crawford et al.*, 1981] are refuted [*Karig*, 1983]. Volcanic activity has been fairly continuous, even though intensities have varied through time, and where volcanic minima appear, these are not directly related to times of back arc spreading.

The question remains why the intensity of explosive arc volcanism should show such large variations that are not related to the tectonic episodes. One possibility is that the rate of plate convergence has changed, but we know of no evidence for significant fluctuations in convergence rates between the Marianas and the Pacific plate [e.g., *Jurdy*, 1979]. Furthermore, what is the relationship between the biggest maximum of explosive volcanism and the fact that tephras generated at this time belong to a medium- and high-K suite? If other variables are held constant, increased K could be interpreted as reflecting lower degrees of melting, but this is difficult to reconcile with the observation that the most potassic tephra were erupted during a portion of the second explosivity maximum, the most important pulse of explosive Mariana arc volcanism. Another possibility is that a synchronous fluctuation in tephra abundance may not be a source function but rather a climate-related variation [*Sigurdsson*, 1990]. This argument is supported by a good correlation between high eolian transport (vigorous atmospheric circulation), positive $\delta^{18}O$ of benthonic foraminifera (indicating cooling) and increased ash transport. Thus variations in the strength of atmospheric circulation could change tephra transport at these times, implying that the volcanic ash frequency may be not a reliable indicator of variation in volcanic production rate with time. On the other hand, *Cambray et al.* [1993] concluded, after analyzing five controlling factors (including nature of eruption, wind influence, and diagenesis) on ash distribution on the opposite

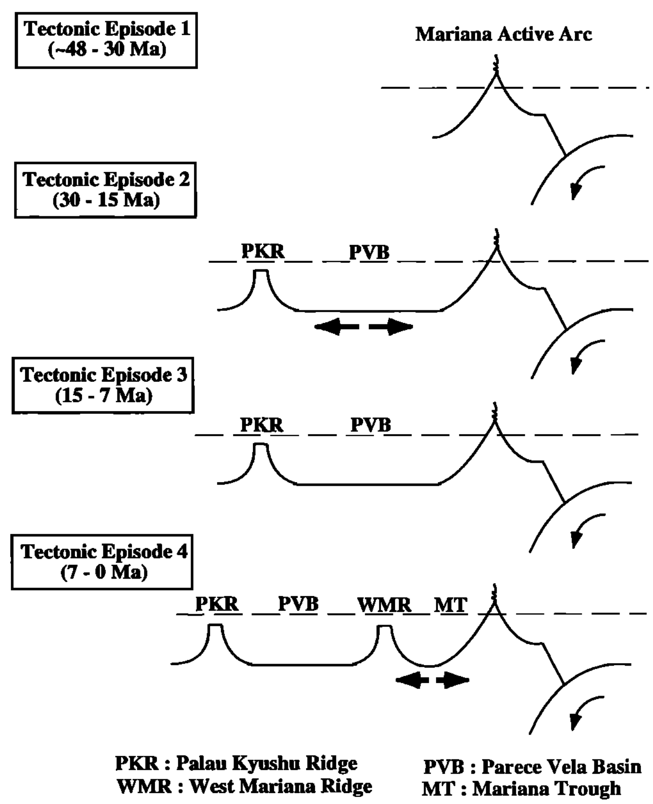

Figure 6. Diagrams showing four tectonic episodes occurred in the Mariana arc system since its formation about 45 Ma. Heavy arrows indicate periods of back arc basin spreading. Tectonic episodes 2 and 4 are characterized by back arc basin formation of the Parece Vela basin and the Mariana trough. The boundaries between tectonic episodes 1 and 2 (30 Ma) and 2 and 3 (15 Ma) are based upon the interpretation of magnetic anomaly pattern for the Parece Vela basin [*Mrozowski and Hayes*, 1979] and the boundary between tectonic episodes 3 and 4 (7 Ma), the extrapolated magnetic age for the oldest sediments at site 453 in the Mariana trough [*Bleil*, 1981]. Magnetic anomalies 10 (30 Ma) to 5D (17 Ma) exist in the Parece Vela basin and the youngest anomaly is not identified [*Mrozowski and Hayes*, 1979]. For this reason the younger limit of tectonic episode 2 is set at 15 Ma. The basement age at site 453 was inferred to be about 6.5 Ma [*Bleil*, 1981].

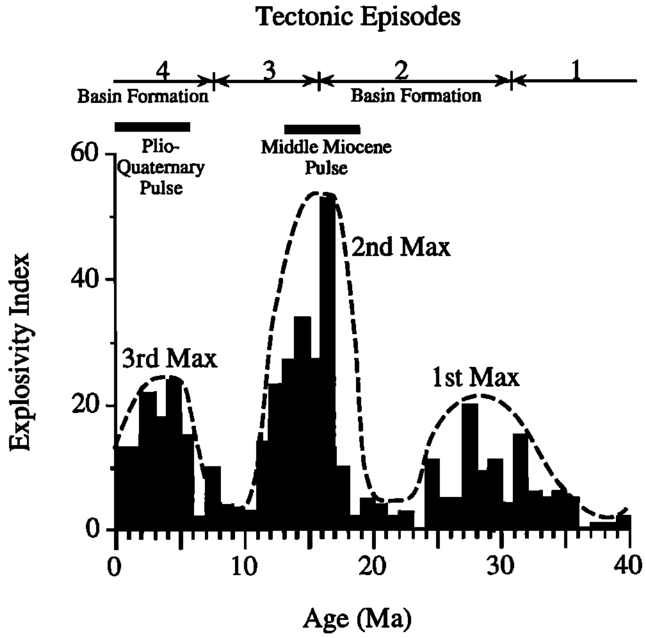

Figure 7. Explosivity index versus age. Explosive arc volcanisms have been nearly continuous, with three volcanic maxima at 35-24, 18-11, and 6-0 Ma. Also shown as thick solid lines are the two major pulses of arc volcanism recorded in the circum-Pacific [*Cambray et al.*, 1993; *Cambray and Cadet*, 1994].

side of the Pacific Ocean, that two important pulses of arc volcanisms occurred during middle Miocene times (18-13 Ma) and Pliocene-Quaternary times (5-0 Ma; see Figure 7) and that sampling of submarine ash layers provides a reliable indicator for episodes of arc volcanism. These pulses are likely linked with a global control of plate kinematics in which the reorganization of lithospheric plates rather than subduction rate is related to synchronous volcano-tectonic activity around the circum-Pacific [*Cambray and Cadet*, 1994].

Comparison of Tephra Glass and Modern Mariana Arc Lava Compositions

If we are to infer magmatic evolution of the Mariana arc from the tephra glass record, we must understand the biases in this record. As previously discussed, the nature of explosive volcanism and the effect that this has on tephra distribution mean that the tephra glass record will be biased towards felsic and more fractionated mafic samples. Tephra glasses differ further from arc lavas because the former are liquid compositions, whereas the latter are generally not. Tephra thus offer a way to use phase equilibrium constraints for understanding arc magmatic evolution. A key for using tephra glass data to infer arc magmatic evolution is thus understanding how and why the lava and the tephra records differ.

We start by comparing young (5-0.3 Ma) tephra with recently erupted lavas in the subaerial, active volcanic arc. To minimize the effects of crystal fractionation, we compared the major element compositions (extrapolated by least squares fit at 6 wt % MgO) of three Mariana volcanoes, Maug, Pagan, and Sarigan [*Plank and Langmuir*, 1988], with the similarly normalized compositions for young tephra glasses (Table 2). Lava and tephra compositions are similar for silica, calcium,

Table 2. Average Major Element Abundance at 6 wt % MgO of Tephra Glasses (5-0.3 Ma) and Mariana Volcanoes (Maug, Pagan, and Sarigan)

	5-0.3 Ma Tephra Glasses	Mariana Volcanoes
$Si_{6.0}$	52.10	51.40
$Ti_{6.0}$	1.10	0.83
$Al_{6.0}$	14.00	16.40
$Fe_{6.0}$	12.00	10.60
$Ca_{6.0}$	10.50	10.90
$Na_{6.0}$	2.40	2.40
$K_{6.0}$	0.70	0.63

sodium, and potassium but are distinct for aluminum, titanium, and iron. The difference is especially striking for aluminum: basaltic tephra glasses (<53% SiO_2) contain <16% Al_2O_3 (mean = 14.3% Al_2O_3) and are not high-Al basalts. The tephra data show almost no overlap with Mariana arc lavas, which contain 15-21%, with a mean of 17.4% Al_2O_3 (also see Figure 3). All basaltic tephra glasses plot in the tholeiitic field, whereas most Mariana arc lavas plot in the high-alumina or calc-alkaline basalt field (Figure 8). This observation suggests that the majority of high-alumina basalts of the Mariana arc are enriched in Al_2O_3 by plagioclase phenocryst accumulation [*Crawford et al.*, 1987; *Woodhead*, 1988; *Jackson*, 1993]. The major element content at 6% MgO for the young tephra glass yields an anhydrous density of 0.00268 kg/cm^3 (at 1250°C [*Bottinga and Weill*, 1970]); this varies inversely with water content (see Figure 6 of *Woodhead* [1988]). Plagioclase densities covary with Ca content, but at similar temperatures, An_{80} has a density of 0.00267 kg/cm^3 [*Bottinga and Weill*, 1970]. Thus it is uncertain whether plagioclase floats in melts corresponding to the mafic tephra

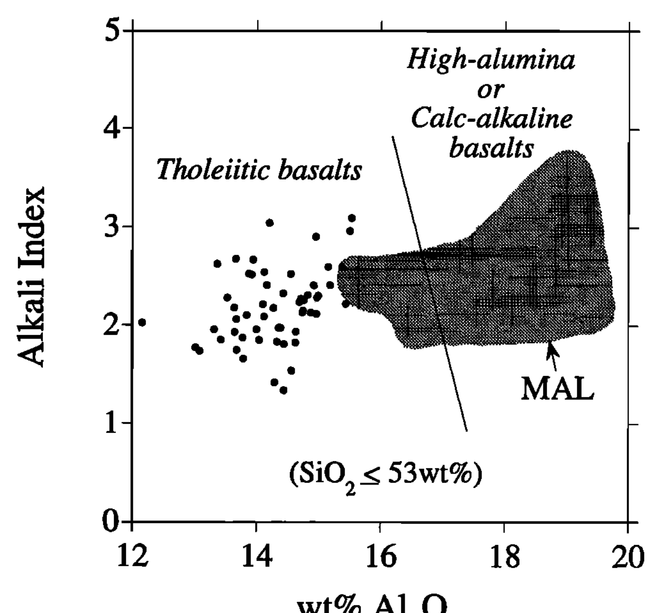

Figure 8. Plot of alkali index versus weight percent Al_2O_3 for basaltic tephra glasses (dots) and Mariana arc lavas (MAL). Alkali index $(=(Na_2O+K_2O)/\{(SiO_2-43)*0.17\})$ and the boundary between tholeiitic and high-alumina or calc-alkaline basalts are from *Middlemost* [1975].

glasses, but even if plagioclase does not float, even weak convection will concentrate it in the upper part of the magma chamber relative to olivine, pyroxene, and magnetite. We agree with *Woodhead* [1988] that the plagioclase-porphyritic nature of Mariana arc lavas reflects eruption from a magma chamber where plagioclase has been kept in suspension, and we believe that this effect is responsible for the striking differences in Fe, Ti, and Al concentrations between Mariana arc lavas and mafic tephra glasses.

Elemental ratios can yield further insights into the differences between the young tephra glasses and Mariana arc lavas. If it is correct that the most important differences between basaltic to andesitic Mariana arc lavas and recent tephra glasses are due to plagioclase accumulation in the former, then the glasses must have higher CaO/Al_2O_3 and K_2O/Na_2O and lower CaO/MgO than lavas of similar silica content. The prediction is validated. CaO/Al_2O_3 for the tephra glasses decreases with fractionation (from a mean of 0.7 for basaltic tephra), whereas Mariana arc basalts have a mean CaO/Al_2O_3 of 0.63. The smallest differences for K_2O/Na_2O will seen when comparing basaltic tephra and lava (which contain Na-poor plagioclase) and the greatest difference observed for felsic tephra and lava, which contain Na-rich plagioclase. This effect is seen in comparisons between basaltic tephra and lavas (K_2O/Na_2O = 0.27 versus 0.26) and between andesitic tephra and lavas (0.34 versus 0.27). As expected, CaO/MgO is higher in basaltic lavas (2.14) than in basaltic tephra (1.91), with the difference being reduced for andesitic samples (2.29 versus 2.19).

The tephra glasses are enriched in titanium and iron relative to Mariana arc lavas (Table 2), further indicating that the most primitive tephra-producing magma was fractionated. Both Fe and Ti decrease in abundance over the range of silica in the tephra, supporting models calling for magnetite fractionation to be important in the magmatic evolution of Mariana arc magmas [*Stern*, 1979; *Woodhead*, 1988]. The Fe-rich nature of Mariana arc basalts has previously only been identified for Esmeralda Bank lavas (FeO* = 10.3-13.9%), which are among the most aphyric lavas erupted in the Mariana arc [*Stern and Bibee*, 1984]. Esmeralda Bank samples were suspected of being anomalous, but the mean tephra data and the trends shown in Figure 3 strongly suggest that the predominant Mariana arc basaltic magma is Fe- and Ti-rich. *Meijer* [1982] commented on the different Fe-enrichment trends of Mariana arc lavas, and an alternative explanation is that high-Fe basalts (and their differentiates) are systematically more explosive, and therefore preferentially preserved as distal tephra, than low-Fe basalts.

Significance of Silica Bimodality

During each of the four tectonic episodes, tephra glasses define a bimodal population in terms of silica contents (Figure 5). This result is not unique to our study; tephra glasses retrieved from DSDP Site 450 in the Parece Vela basin [*Warner et al.*, 1987] and ODP Leg 125 in the Bonin forearc [*Arculus and Bloomfield*, 1992] show similar bimodal distributions of silica contents. This result is puzzling, because similar bimodality has not been reported for subaerial Mariana arc lavas, which contain <62% SiO_2 (Figure 3, stippled field). Felsic volcanic products are common in some submarine edifices, such as the Kasuga cross chain (up to 66% SiO_2 [*Stern et al.*, 1993]), but are not reported from Mariana subaerial arc volcanoes. Part of reason for this may be a sampling bias on land in favor of hard lava and away from poorly consolidated tuffs; for example, *Stern* [1978] mapped a sequence of "Mantling Tuffs" on Agrigan, which he related to caldera collapse. These tuffs were up to 100 m thick but no chemical data have ever been reported. A resurgent dacite (68% SiO_2) dome was dredged in Maug caldera (A. Hochstaedter, personal communication, 1994), but tuffs visible on the slopes of the old volcano have not been analyzed. We conclude that felsic tephra is present in the Mariana arc subaerial volcanoes but is probably only produced during relatively rare (every 10,000-100,000 years?) climatic eruptions.

Felsic eruptions will be overrepresented in the tephra record relative to their total erupted volume, but the observed silica bimodality is unlikely to be an artifact of sampling or preservation. Both of these effects will tend to increase the apparent abundance of felsic tephra compared to true magmatic volumes produced or even erupted, but neither are likely to cause a bimodal silica population to appear where it did not exist. This is because the increase in explosivity is known to vary with silica content, and there is no evidence that intermediate glasses are more unstable than mafic glasses, so that just as more dacitic tephra are deposited and preserved relative to andesitic tephra, so should more andesitic tephra be relative to basaltic tephra. These effects should bias the tephra record towards more felsic material but cannot account for the observed minima in intermediate compositions. Granting this, the key question is what is the origin of the heretofore largely unappreciated siliceous Mariana arc component?

Unlike Mariana arc lavas, the tephra glasses are liquid compositions and can be directly compared with experimentally determined phase equilibria. We plot the data on the olivine-clinopyroxene-quartz subprojection from plagioclase (Figure 9a), which can be used to infer the anhydrous, 1-bar crystallization paths of plagioclase-saturated liquids [*Grove et al.*, 1982; *Grove and Baker*, 1984; *Grove*, 1993]. The key points to note: (1) All tephra glasses plot near low-pressure cotectics. Mariana arc lavas also plot broadly near the same cotectics but are somewhat displaced towards olivine due to their higher Al_2O_3 contents [*Sisson and Grove*, 1993]. (2) Tephra from all four tectonic episodes show a break in their compositional trends, and these breaks correspond to the minima in the silica frequency diagrams (65-66 wt % SiO_2). Two different fractionation trends become apparent when the mafic (<66 wt % SiO_2) and felsic (≥66 wt % SiO_2) mode groups are separately plotted on the same projection (Figure 9b). The discontinuities in the liquid paths occur where the data move from along the olivine-augite-plagioclase cotectic, olivine-pigeonite-plagioclase, or orthopyroxene-pigeonite-plagioclase reaction curve to the augite-pigeonite-plagioclase cotectic. The trend of mafic glasses can be explained by low-pressure crystal-liquid fractionation, a result previously established for subaerial Mariana arc lavas on the basis of experimental results [*Baker*, 1987] and geochemical modeling [*Stern*, 1979; *Woodhead*, 1988]. The change in magmatic evolutionary trajectory occurring at the silica gap indicates that the relationship between mafic and felsic tephra is not necessarily one of simple fractionation.

Two different processes have been invoked to explain similar bimodal igneous associations: (1) crystal fractionation, due either to rapid changes in liquid compositions during a small temperature drop [e.g., *Wyllie*,

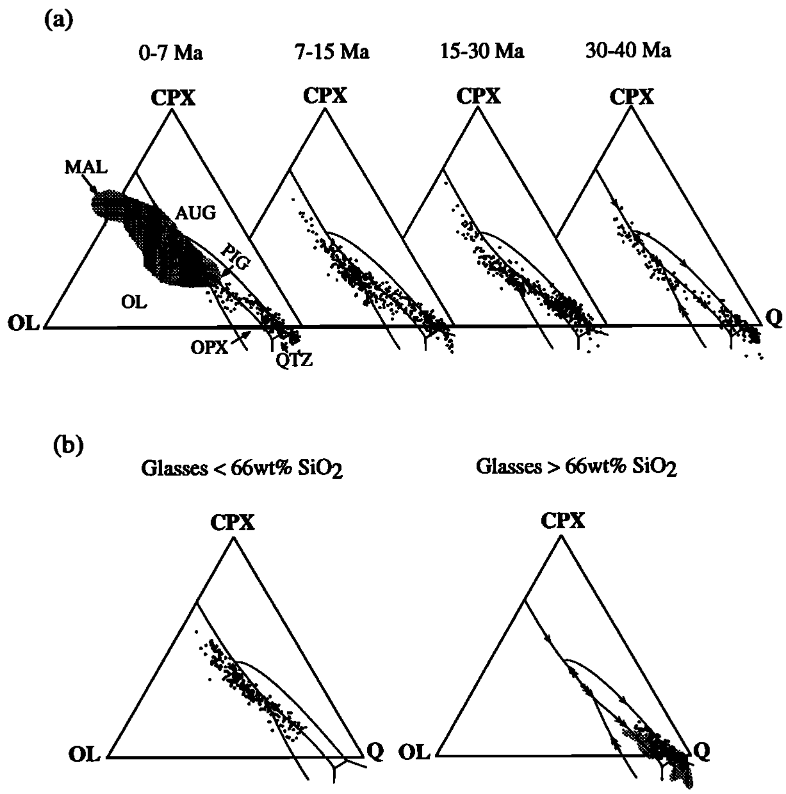

Figure 9. (a) Subprojection olivine-clinopyroxene-quartz from plagioclase [*Grove and Baker*, 1984; *Grove*, 1993]. Lines are 1-atmosphere cotectics (single arrow) and reaction curves (double arrows) and small open circle (rightmost subprojection) represents a thermal divide [*Grove and Baker*, 1984]. All four stage tephra glasses plot near the low-pressure cotectics. There are discontinuities in compositional trends, where central minimum points (65-66 wt % SiO_2) in the silica frequency diagram are located. The MAL field is shown as the shaded area. (b) Separate subprojection olivine-clinopyroxene-quartz for mafic (<66 wt % SiO_2) and felsic (≥66 wt % SiO_2) mode glasses from tectonic episode 4. Data on partial melts [*Beard and Lofgren*, 1991] are shown by the shaded area. See the text for discussion.

1963; *Grove and Donelly-Nolan*, 1986; *Bacon and Druitt*, 1988; *Sigurdsson et al.*, 1990], or through buoyancy-driven crystal-liquid segregation due to low crystal settling/retention rates and eventual cessation of convection at the early stages of magmatic conduit development [*Brophy*, 1991]; and (2) crustal anatexis to produce silicic magmas [e.g., *Bailey*, 1974; *Sigurdsson*, 1977; *Myers and Marsh*, 1981]. In a recent review of the two hypotheses and variants, *Beard* [1995] concludes that either process may operate and that it is often difficult to demonstrate which was responsible.

We propose two simple models of fractionation and anatexis for the origin of the felsic mode recorded in Mariana tephra glasses. In the case of crystal fractionation, basaltic magma fractionates extensively under low-pressure conditions. With low rates of magmatic recharge, this results in a basalt-andesite-dacite-rhyolite series. In the case of anatexis, the mafic mode also reflects low-pressure fractionation. However, the felsic mode manifests combined crystal fractionation and anatexis of the arc crust as a result of heating by the magma chamber or due to basaltic magma underplating.

Beard and Lofgren [1989, 1991] reported that dehydration melting of metamorphosed arc crust (greenstones and amphibolites) can generate low-K and low-alumina felsic magmas, which may be responsible for common occurrence of tonalite, trondhjemite, and dacite in many arcs. To examine this possibility, we use partial melt data derived from the dehydration melting experiment on five basaltic and andesitic greenstones and amphibolites collected from the Smartville complex of northern California [*Beard and Lofgren*, 1991] and plot on the same projection (Figure 9b). The compositional range of the partial melts overlaps with most of the range defined by the felsic mode group. This suggests that partial melting of the Mariana arc crust may account for the origin of a part of felsic mode group, especially of low-K and low-alumina tephra glasses, and that the bimodality of Mariana glass tephra indicates that mafic melt fractionation and crustal anatexis are both important processes.

We are presently unable to unequivocally choose between the anatexis and fractionation model for the origin of the felsic tephra glasses, and we think this is an important target for future research. However, two considerations lead us to favor fractionation. First, Eocene felsic lavas on Saipan have been modeled as fractionates of a boninite parent [*Meijer*, 1983]. Second, in the next section we document systematic variations in K as a function of age. These variations are observed for felsic as well as mafic lithologies. A fractionation model better explains the simultaneous enrichment of K in mafic and felsic compositions than does a model of anatexis. Specifically, fractionation of high-K basaltic magma must fractionate to high-K felsic magma, whereas crustal anatexis is less likely to produce such coupled compositional variations in the heat source (basalt) and the crustal melt (rhyodacite).

Temporal Changes in the Composition of Mariana Arc Magmas

Systematic changes in the composition of arc magmas through time may be related to either changes in tectonic regime, such as the presence or absence of active back arc basin spreading, or progressive changes in source composition, reflecting progressive enrichment or depletion of the mantle source, composition of subducted material, or processes of melt generation. The former possibility is the thrust of models whereby arc magmas change with tectonic environment [e.g., *Crawford et al.*, 1981; *Stern et al.*, 1988], whereas the latter is articulated by arc evolutionary models, whereby arc magmas become progressively enriched as the arc ages [*Jakes and White*, 1969, 1972; *Jakes and Gill*, 1970; *Hawkins et al.*, 1984]. Determining whether or not there is a signal, and if so, what this is caused by, may seem to be an insurmountable challenge [e.g., *Arculus and Johnson*, 1978]. Our philosophy is to decide whether or not systematic compositional changes can be identified over the 40 m.y. of Mariana arc evolution. Because compositional changes are observed, we address the question of whether these reflect tectonic changes or are better ascribed to changes in source compositions or processes. Grouping the data into the four tectonic episodes outlined at the beginning of the discussion reveals few striking changes. Glasses from all four episodes are predominantly tholeiitic as shown on AFM (A, Na_2O+K_2O; F, FeO*; M, MgO) plots (Figure 10). A minor proportion of calc-alkaline glasses occur in all four stages. This mirrors the composition of Mariana arc lavas, which are generally tholeiitic except Sarigan, which is calc-alkaline [*Meijer and Reagan*, 1981].

We have not found tephra glasses of boninitic composition from any core samples. Boninites in the Mariana arc were generated only in the earliest stages of subduction [e.g., *Bloomer and Hawkins*, 1987] and preserved and exposed as a late Eocene-early Oligocene forearc basement as a result of tectonic erosion [*Bloomer*, 1987]. *Meijer* [1980] reported late Eocene to Oligocene boninite series lavas in sections below Core 28 at Mariana forearc site 458. We have tephra glass records down to Core 26 of Site 458, which is younger than the boninite basement. *Arculus and Bloomfield* [1992] also reported an absence of any boninitic component from the ashes recovered during ODP Leg 125 from the Bonin forearc (Sites 782, 784, and 786). In contrast, *Warner et al.* [1987] suggested that based on tephra glasses from DSDP Site 450, boninitic lavas are typical of the latest stages of arc activity just before rifting to form a back arc basin begins (see also work by *Crawford et al.* [1981]). *Warner et al.* [1987] obtained the evidence for boninitic volcanism from microprobe analyses of glasses separated from 15-14 Ma volcanic ash layers of Site 450 (Figure 1). Our data do not confirm their suggestion of a mid-Miocene pulse of boninitic volcanism and instead indicate a lack of explosive subaerial boninite volcanism in the Mariana arc since 40 Ma.

In spite of the long-lived tholeiitic nature of the arc, some systematic changes in potassium contents are observed. Grouped according to tectonic episode (TE), the four groups belong to (1) a predominantly low-K suite (TE1); (2) a low- to medium-K suite (TE2); (3) a medium- to high-K suite (TE3); and (4) a low- to medium-K suite (TE4) (Figure 11). The low-K suite has always occurred but is least important during TE3. Samples from all four tectonic episodes contain some high-K samples, but those from TE3 contain especially abundant high-K glass. Three core sections (8.6-7.4 Ma) at Site 458 contain shoshonitic glass shards, with K_2O contents that range from 3% (at 54% SiO_2) to 4.9% (at 72% SiO_2). Several other ash layers at Site 458, all of which belong to TE3, contain high-K tephra glass. *Arculus et al.* [1995] noted, on the basis of analyses of tephra glasses from Sites 458 and 459, that a high-K pulse appeared at ~8-11 Ma. Shoshonitic glasses (≥1.0 K_2O/Na_2O, based on the criteria of *Jakes and White* [1969]) are especially abundant during TE1 and TE3. *Stern et al.* [1988] suggested that shoshonitic lavas in the northern Mariana and southern Volcano arcs track the northward propagation of rifting of the arc to form the Mariana trough. The more common occurrence of high-K tephra glass during two periods of pre-back arc spreading (TE1 and TE3) as well as sporadic but continual existence of high-K tephra glass is consistent with their model. *Bloomer et al.* [1989] argued that the prerift tholeiitic or calc-alkalic

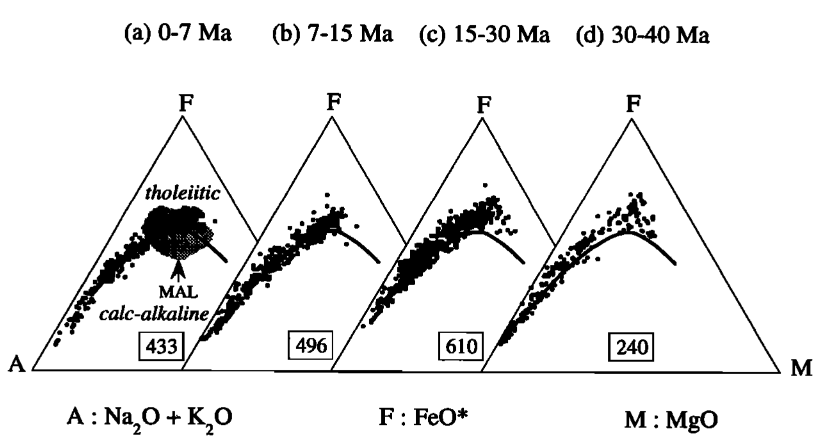

Figure 10. AFM diagrams for four tectonic stages. The boundary between tholeiitic and calc-alkaline fields is from *Irvine and Baragar* [1971]. Stippled area represents compositions of MAL. Numbers in boxes are numbers of samples analyzed for each stage. Note that the tholeiitic nature of the arc has persisted throughout the history of the arc.

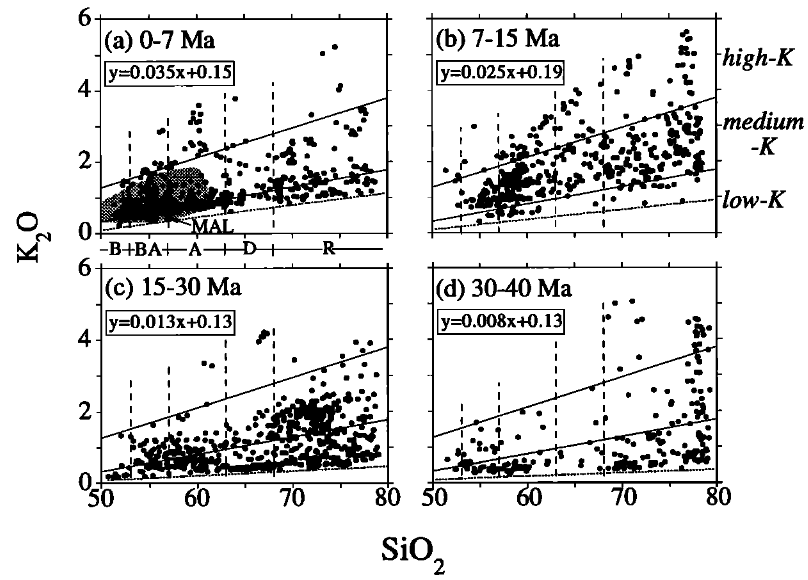

Figure 11. Plot of weight percent K_2O versus SiO_2 for tephra glasses from four tectonic episodes: (a) 0-7 Ma; (b) 7-15 Ma; (c) 15-30 Ma; and (d) 30-40 Ma. MAL is shown by the stippled field. Solid lines separate the fields for low-K, medium-K, and high-K series. Dashed lines separate the fields of basalt (B), basaltic andesite (BA), andesite (A), dacite (D), and rhyolite (R). These fields are from *Basaltic Volcanism Study Project* [1981, Figure 1.2.7.1), extended for basaltic and rhyolitic glass compositions. Dotted line approximates minimum K contents for each time interval. Equation in each box describes the dotted line. Note that the slope for this line increases with time, which is consistent with a long-term increase in potassium, as discussed in the text.

volcanism, interrupted by an alkalic phase during the onset of back arc spreading, quickly returns to tholeiitic compositions following reestablishment of the arc. The subsequent decrease in K_2O contents from TE3 to TE4 is also generally consistent with the above model.

Although there may be a tectonic signal in magmatic compositions, we infer that the short-wavelength tectonic signal is superimposed on a longer-term increase in potassium contents over the life of the arc (Figure 12). One of the difficulties in interpreting these data is how to evaluate variations in composition, which may reflect fractionation or anatexis and not indicate source evolution. To reduce variations due to fractionation, we have divided the data into mafic, intermediate, and felsic populations. Within these groups, variations in the minimum K_2O contents most reliably indicate source evolution. This is because maximum K_2O contents may be defined by a few atypical magmatic events, such as unusually low degrees of partial melting, that are not representative of source evolution. On the other hand, the minimum K_2O content found at any time interval likely reflects the highest degree of melting of the predominant source. Changes in the minimum K_2O content with time are similar for mafic, intermediate, and felsic and are consistent with the volcanic sequences exposed on Mariana frontal arc islands of Guam and Saipan and from drilling on the West Mariana ridge (Figure 12). The most spectacular increase in minimum K_2O content occurs about 11 to 7 Ma, and this may herald rifting to form the Mariana trough, as suggested above. There is also the suggestion that minimum K_2O increases over the life of the arc. This conclusion is not compelled by the mafic data but becomes more apparent in the intermediate and felsic samples. This relationship can also be seen in Figure 11, where the dotted line bounds the least potassic samples from each tectonic episode. The progressive increase in slope with age indicates that the most depleted magmas have become more potassic with time. Considered together, these data support models whereby arcs evolve with time from less to more enriched in large-ion lithophile and other incompatible elements [*Jakes and White*, 1972].

Conclusions

Major element data for Mariana tephra glasses provide new insights for understanding the magmatic evolution of Mariana arc explosive volcanism over the past 40 m.y. Volcanism has been continuous, but marked increases are observed for the time periods 6 Ma to present and 18 to 11 Ma. These correspond to peaks in volcanism inferred for other regions of the circum-Pacific. We tentatively identify a third volcanic peak of Oligocene age, but further studies are need to confirm this. Mariana arc explosive volcanism has been predominantly tholeiitic for the past 40 m.y. The tephra glasses largely belong to the low- to medium-K suite, except during the mid- to late Miocene (15-7 Ma), when medium- and high-K explosive volcanism predominated. There are striking differences between the composition of recent mafic tephra and lava. The tephra glasses approximate magma compositions more faithfully than do Mariana arc lavas because the latter contain abundant accumulative phenocrysts, especially plagioclase, and indicate that mafic Mariana arc magmas are normal tholeiites and not high-Al basalts. Abundant felsic tephra also reveal that felsic volcanism has characterized the Mariana arc, a feature that studies of modern subaerial Mariana volcanoes have missed. Tephra glasses reflect magmas that have undergone extensive fractionation at shallow depths. This process has long been known for the modern arc but also seems to be characteristic of the arc system for the past 40 m.y. The tephra record reveals that the

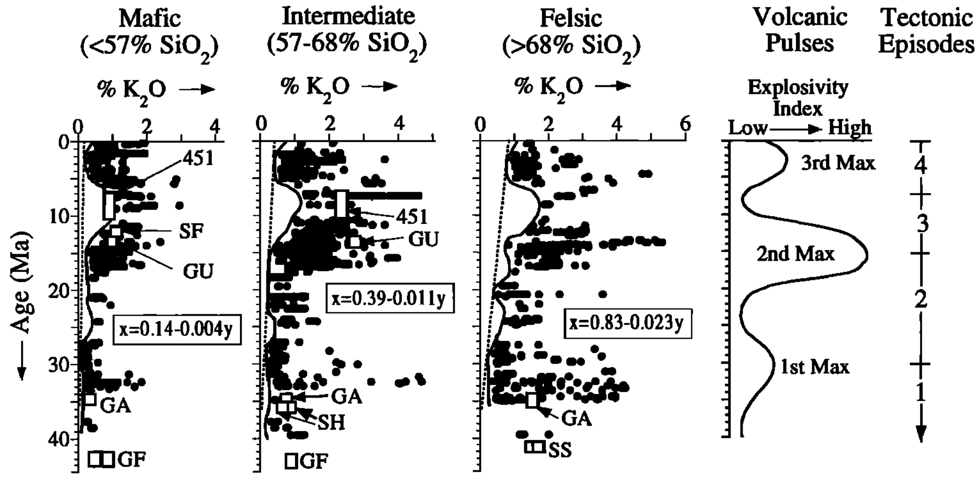

Figure 12. Potassium contents in Mariana tephra glasses as a function of age. Data are plotted for three lithologies: mafic (<57% SiO_2), intermediate (57-68% SiO_2), and felsic (>68% SiO_2). For each lithology, two lines are drawn. The solid line defines how the minimum potassium content has varied with time, whereas the dashed line approximates the long-term variation in minimum potassium contents over the history of the arc. The equation for each lithology describes the dotted line, where x is weight percent K_2O and y is age in Ma. The difference between the dashed line and the solid line approximates the short-term signal. The short-term signal is equated with tectonic and other episodic changes, whereas the long-term signal reflects the evolution of the mantle source. Small open boxes show the ranges for volcanic rocks exposed on Mariana frontal arc islands of Guam and Saipan and from DSDP Site 451 on the West Mariana ridge. (GF = Guam, Facpi formation; GA = Guam, Alutom formation; GU = Guam, Umatac formation; SS = Saipan, Sankakuyama formation; SH = Saipan, Hagman formation; SF = Saipan, Fina Sisu formation; 451 = DSDP Site 451 clasts). Data sources are *Schmidt* [1957]; *Mattey et al.* [1981]; *Meijer* [1983]; *Meijer et al.* [1983]; *Reagan and Meijer* [1984]; and *Hickey-Vargas and Reagan* [1987]. To the right are shown the variations in volcanic pulses and tectonic episodes discussed in the text.

Mariana arc is characterized by a bimodal silica distribution, another aspect that was missed from studies of recent volcanoes. The origin of the bimodal silica distribution awaits resolution; competing models of crystal fractionation and anatexis remain viable for generating the felsic magmas. The tephra glass record reveals an important episode of potassic volcanism during the late Miocene. This provides support for models whereby magmatic precursors to back arc rifting are strongly enriched in potassium. This tectonic signal is superimposed on a longer-term and more gradual increase in potassium contents. We subscribe to the idea that arcs evolve with time towards more potassic compositions, but this progression is slow and easily masked by compositional changes due to tectonic or other causes. The record that we have examined is 40 m.y. long, and the Mariana arc is still predominantly tholeiitic!

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