Chapter 9 Petrogenesis of IBM Volcanic Ashes and Geochemical Evolution of the IBM Arc-Backarc Basin System

9.1 Introduction

Generally, the IBM volcanic ash layers consist of glass and mineral crystal shards, lithic fragments and different types of sediment particles. In most cases, glass shards are predominant. For the volcanic ash layers recovered from DSDP Leg 60 Sites 458 and 459B and ODP Leg 125 Sites 782A, 784A and 786A drilled in the Izu-Bonin-Mariana forearc, the major element and trace element characteristics analysed by PIXE of representative individual glass shards, the compositions of crystalline mineral shards, and the ICP-MS trace element and Sr-Nd isotopic ratio characteristics of representative bulk ashes (free of rock fragments and sediment particles) are discussed separately and compared to IBM volcanic rocks in Chapters 4, 5, 6, 7, and 8, and Appendices 2 and 3. In this Chapter, all element and isotope data are integrated to address a number of questions: 1) what, if any, are the significant differences between the IBM volcanic ashes and IBM volcanic rocks? 2) do the volcanic ashes represent island arc volcanic rocks? 3) where are the possible sources of DSDP Leg 60 and ODP Leg 125 volcanic ashes? 4) are there any sediments involved in the genesis of IBM volcanic rocks? 5) is there a common MORB-mantle source and/or OIB-mantle source for the IBM magmas? 6) are there any temporal and spatial geochemical changes in the IBM system and, if so, what is their cause? 7) what are the next steps in studies of volcanic ash in marine settings.

9.2 Possible provenance of DSDP Leg 60 and ODP Leg 125 ashes

9.2.1 Basaltic and boninitic glasses (ashes)?

Only 23 out of ~ 1750 analysed shards are basaltic from DSDP Leg 60 Sites 458 and 459B and ODP Leg 125 Sites 782A, 784A and 786A ash layers according to the IUGS classification of volcanic rocks (LeBas et al., 1986). Taking the MORB glass compositional range (47 to 54 wt %

SiO_2 and 12 to 4 wt % MgO, see Chapter 4 for references) as a comparator, there are ~ 120 added "basaltic" analyses (GL BII) available from the ash layers studied. Although the basaltic glasses from 184 representative DSDP Leg 60 Sites 458 and 459B and ODP Leg 125 Sites 782A, 784A, and 786A ash layers are less in number, their importance is clearly as true liquid compositions. Because the basaltic glass shards are relatively fine particles (generally < 0.040 mm in diameter), it is difficult to obtain good quality PIXE trace element data for these basaltic materials (see Appendix 2). Only one basaltic glass shard was analysed by PIXE-PMP and the result is similar to Izu-Bonin arc basalts (see Chapter 6). The major element compositions of these basaltic glasses (Gl BI 23 and Gl BII) are plotted in Figure 9-1 and listed in Table 9-1 for GL BI 23. The Gl BI and Gl BII glasses are distributed in the ash layers of all five Sites in the age range 0-31 Ma. They are all tholeiitic based on the AFM and Al_2O_3-*an* diagrams (Irvine and Baragar, 1971) and on the FeO*/MgO-SiO_2 diagram (Miyashiro, 1974) with a few exceptions (Figure 9-1). These basaltic glasses are overwhelmingly low- to medium-K with only one high-K composition on the basis of Gill's (1981) classification. The basaltic glasses range from 49 to 54 wt% SiO_2, 12 to 4 wt% MgO, 10 to 16 wt% Al_2O_3 with a few exceptions, and 0.1 to 2.3 wt% K_2O (Figure 9-1). The relationship between Al_2O_3/TiO_2 or CaO/TiO_2 and TiO_2 of these basaltic glasses is similar to that of MORB described by Sun et al. (1979). The simplest interpretation by analogy with MORB is that the range of IBM basaltic glasses between 0.7% and 1.5% TiO_2 were derived from about 25 to 15 % partial melting, respectively, of a MORB-type mantle source.

The major element data for 23 IBM basaltic glasses together with IBM modern subaerial basalts and MORB glasses are plotted in Figures 9-2A,B,C,D. Generally, the chemical compositions of IBM basaltic glasses straddle the spectrum of MORB and IBM arc basalts except for K_2O and FeO* contents, and FeO*/MgO ratios. The K_2O contents of IBM glasses span the same range as IBM arc basalts. However, the IBM glasses have higher FeO*, TiO2 abundances and FeO*/MgO ratios and lower Al_2O_3 than IBM basalts.

Are there any boninitic glasses in the ash layers during long-term eruptive activity of the IBM system? Of the extensive studies on volcanic ashes from the IBM system since the 1980's, only Warner et al. (1987) have reported a brief period of boninitic ash deposition at DSDP Leg 59 Site 450 in the Parece Vela basin at 15-14 Ma, presumably derived from the West Mariana Ridge.

We sampled 133 ash layers from DSDP Leg 60 Sites 458 and 459B in the Mariana forearc spanning the Mariana arc's explosive history from 35 Ma to present. In addition, the boninitic basement volcanic rocks under the lowest ash layer at Site 458 were sampled and analysed for their glass and mineral compositions, and Sr-Nd isotopic ratios of bulk boninitic volcanic rocks. All of these data, including 15 major element analyses of individual glass shards, 1 PIXE trace element analysis of an individual glass shard, 1 set of Sr-Nd isotopic ratios, and about 50 mineral analyses of the boninitic basement volcanic samples show that they are completely different from all of the ash layers studied as discussed in Chapters 4, 5, 6, 7, and 8. The representative major element data of true boninitic glasses from site 458 basement volcanic rocks and MgO-rich glasses from the ash layers studied are given in Table 9-2 and plotted in Figure 9-3 with the data set of the boninite suite of Site 458 basement and Warner et al. (1987). Clearly, all the glass shards from Mariana ash layers (including the glasses studied by Warner et al., 1987) are distinctive compared with the boninitic glasses from Site 458 basement in much higher TiO_2, FeO* and FeO*/MgO. The N-MORB element pattern of one boninitic glass from Site 458 basement volcanic rocks is similar to those of boninites from Bonin island (Figure 9-4) and is different from those of about 220 glass shards from Mariana ash layers (see Chapter 6).

According to the classification schemes suggested by Hickey and Reagan (1987) and Crawford et al. (1989), boninites should have: $SiO_2 > 55$ wt%, $TiO_2 < 0.4$ wt% and MgO 9-15 wt%; no plagioclase and co-existence of Mg-rich olivine and/or low-Ca pyroxene -- enstatite or clinoenstatite; low Ba and Zr, MREE-depleted REE patterns. There are no ash layers with these characteristics in the Izu-Bonin and Mariana region. Extensive studies of Middle Miocene volcanic ashes in the IBM system (Arculus and Bloomfield, 1992; Fujioka et al., 1992a,b; Lee and Stern, 1993; Arculus et al., 1995; this study) show that it is extremely unlikely for boninitic ashes (rocks) to have been erupted at the West Mariana Ridge during these times.

9.2.2 Similarity and difference between ashes and IBM volcanic rocks

Systematic comparative studies of IBM volcanic glasses (ashes) and IBM volcanic rocks from (Eocene) Oligocene through Miocene to present show that there are significant differences of major element composition between glasses and volcanic rocks while trace element and Sr-Nd

isotopic compositions are similar. As shown in Tables 4-1 and 4-2, the proportion of rock types from basalt through andesite to dacite and rhyolite between glasses and volcanic rocks varies greatly. For example, in the Mariana arc region, basaltic glasses are < 5-8% while basaltic rocks are > 30%. The abundance of felsic glasses varies from ~ 13% in the Quaternary-Pliocene through ~ 30-50% in the Miocene to ~ 30% in the Oligocene. Felsic rocks, on the other hand, constitute ~ 6-12% in Recent times to ~ 25% in the Eocene-Oligocene. Clearly, the tephra glasses are volumetrically dominated by intermediate and felsic compositions while the arc volcanic rocks are predominantly mafic.

Compared to modern Mariana arc basalts and basaltic andesites, the corresponding glasses have significantly higher TiO_2 (1.1-1.4 vs. 0.8-1.0 wt%) and FeO* (13.0-15.0 vs. 9.6-10.7 wt%) and lower Al_2O_3 (14.2-14.6 vs. 16.1-18.1 wt%). Although sometimes glasses have slightly higher SiO_2 and K_2O, lower MgO and CaO (Lee and Stern, 1993), they generally have similar ranges compared with arc volcanic rocks (subaerial and submarine) (see Tables 4-1 and 4-2). This difference in major element compositions between IBM arc volcanic rocks and glasses has been reported previously by Arculus and Bloomfield (1992), Lee and Stern (1993) and Straub (1993). Detailed studies of mineral crystal fragments from IBM volcanic ashes (see Chapter 5) may help to explain these systematic differences. The glasses represent the true liquid (melt) compositions of arc magmas and the plagioclase-pyroxene-olivine phyric nature of Mariana arc volcanic rocks results largely in the differences of Al_2O_3, CaO, and MgO contents observed between glasses and volcanic rocks (e.g., Lee and Stern, 1993). The higher FeO* and TiO_2 abundances typical of glasses relative to arc volcanic rocks (see Chapter 3) may be due to dilution of FeO* and TiO_2 through plagioclase accumulation.

Except for significantly higher FeO* and TiO_2, and lower Al_2O_3 contents of glasses relative to arc volcanic rocks, there are no other significant differences in chemical composition between the two sample populations. Other major element and trace element abundances determined by PIXE, such as Rb, Ba, Sr, Zr, and Y, are very similar. The magma series of glasses given by different methods such as AFM and Al_2O_3 - *an* diagrams (Irvine and Baragar, 1971) and FeO*/MgO-SiO_2 diagram (Miyashiro, 1974) are consistently tholeiitic in the whole IBM region (DSDP and ODP Sites in the IBM region). Incompatible elements such as Ba/Rb,

K/Rb, and K/Ba of individual glass shards and arc volcanic rocks are similarly fractionation-independent. The trace element abundances of homogeneous bulk ashes and their corresponding bulk glasses are very similar and vary within relatively narrow limits. The Sr-Nd isotopic ratios of bulk ashes and arc volcanic rocks are identical. All these similarities indicate that volcanic ashes truly represent contemporaneous arc magmas and can be used to track the magmatic evolution of these arc systems (e.g., Arculus et al., 1992, 1995; Lee and Stern, 1993).

9.2.3 Possible sources of DSDP Leg 60 and ODP Leg 125 ashes

Generally, it is very difficult to identify precisely the sources of deep-sea volcanic ashes. Geochemical methods are not definite because a number of intraoceanic island arcs share common geochemical characteristics (e.g., Gill, 1981; Arculus, 1994). Therefore, geochemical similarity between volcanic ashes and arc volcanic rocks is only one of the necessary conditions. Tectonic and geological features of the region studied are also important factors in tracking the possible sources of deep-sea ashes. The physical properties of volcanic ash layers and ash particles also provide useful information. In the case of Izu-Bonin-Mariana arc-trench system, the possible sources of the volcanic ashes recovered from DSDP Leg 60 Sites 458 and 459B and ODP Leg 125 Sites 782A, 784A, and 786A drilled in the IBM forearc are relatively constrained due to the detailed age studies, the unique geological and tectonic environment and the extensive comparative studies of volcanic ashes and volcanic rocks. The Oligocene Leg 60 ashes are probably the products of arc volcanism of the Palau-Kyushu Ridge; the Miocene Leg 60 ashes were probably derived from the West Mariana Ridge; and the Quaternary-Pliocene Leg 60 ashes are the products of subaerial volcanism of the active Mariana arc. The Quaternary-Pliocene Leg 125 ashes are the products of subaerial volcanism of the northern part of the Izu-Bonin arc while the Miocene Leg 125 ashes may be derived from the northern part of the Izu-Bonin arc. Early Miocene and Oligocene Leg 125 ashes are lacking. It is difficult to infer the possible source of the Eocene Leg 125 ashes because of the limited number of available analyses. In addition, there is no record of shoshonitic or boninitic ashes in the whole IBM region. High-K volcanic ashes are present but are minor in occurrence (< 2%). They are all tholeiitic series from basaltic andesite through andesite to dacite and rhyolite and they occurred predominantly in the Late Miocene (11.2-5.3 Ma). It is likely

that these high-K ashes were derived from southern part of Izu-Bonin arc at the junction between the Izu-Bonin and Mariana systems.

9.3 Petrogenesis of the IBM volcanic ashes

It is clear that magmas produced in island arcs differ consistently in their chemistry from magmas in most other tectonic environments such as modern ocean ridges and ocean islands, and the association of island arc volcanism with subduction in both space and time has been well established (e.g., Gill, 1981). At present, there is wide agreement that subduction influences the compositions of island arc magmas, though there is less agreement on the nature of this influence (e.g., Arculus, 1994; Pearce and Peate, 1995). The petrological, trace element, and isotopic evidence of island arc volcanic rocks clearly shows that the subducting altered oceanic crust and sediments are involved in the arc magmas (e.g., Gill, 1981; Arculus and Powell, 1986; Tera et al., 1986; White, 1989; Woodhead, 1989; Chen and Arculus, 1994b; Stolper and Newman, 1994; Pearce and Peate, 1995). If OIB type mantle or OIB 'plums' in a MORB-type 'pudding' mantle (Stern, 1981; Morris and Hart, 1983; Stern et al., 1993) is the magma source of IBM island arc volcanic rocks, it is hard to account for the high concentrations of H_2O and other volatiles (Garcia et al., 1979; Stolper and Newman, 1994), steep slopes of $^{207}Pb/^{204}Pb$ vs. $^{206}Pb/^{204}Pb$ (Woodhead and Fraser, 1985; Woodhead et al., 1987), high Cs/Rb ratios (Perfit et al., 1980; Perfit and Kay, 1986), enrichment in the most fluid-mobile element B (Ryan and Langmuir, 1993; Ishikawa and Nakamura, 1994) and high Ba/Rb (Chen and Arculus, 1994b and Chapter 8).

OIB suites geochemically diverse, as evident in their major and trace element, and isotopic compositions (e.g., Zindler and Hart, 1986; Weaver, 1991). The incompatible trace element and isotopic ratios of OIB reflect considerable heterogeneity in the mantle source regions. Three end-member compositions (termed EM I, EM II and HIMU) are generally invoked to explain the isotopic heterogeneity of OIB (Hart, 1988). However, relatively few OIB have end-member (or close to end-member) isotopic compositions, and the majority are mixtures between these end-members and depleted upper mantle sources of N-MORB (Hart, 1988). The EM I and HIMU components may be metasomatic in origin and stored at the core/mantle boundary layer while for a

sediment-based EM II, short-term storage in a mesosphere boundary layer as advocated by Allegre and Turcotte (1985) may be a possibility (Hart, 1988).

Indeed, a number of geochemical parameters such as Sr-Nd-Hf isotopic ratios, average K content, K/Rb, K/Ba and K/Sr for IBM volcanic rocks show an overlap with OIB compositions (e.g., Stern, 1981; Morris and Hart, 1983; White and Patchett, 1984), indicating that there are some close relationships among N-MORB, OIB and IAB (island arc basalts). On the basis of similarities between IAB and OIB, Morris and Hart (1983) proposed a "plum-pudding" model in which the upper mantle, including the mantle wedge beneath island arcs, consists of "plums" of OIB source embedded in a MORB-source "pudding". IAB originate by preferential melting of the "plums". More recently, on the basis of detailed examination of combined trace element and isotopic constraints for the three OIB end-members, sediments and N-MORB, Weaver (1991) suggested a relative simple model for the origin of OIB end-members. The dominant component in all OIB is ancient recycled basaltic oceanic crust (MORB) which has been processed through a subduction zone, and which carries the trace element and isotopic signature of a dehydration residue (enrichment in HFSE relative to LILE and LREE, low Rb/Sr, but high U/Pb and Th/Pb ratios leading to the development of radiogenic Pb isotope compositions). HIMU, EM I, and EM II are all derived from the ancient recycled MORB: - HIMU with little contamination from other components; EM I with a dominant pelagic sediment component (higher Ba/La, Ba/Th and lower U/Pb ratios); EM II with predominant terrigenous sediment components (higher U/Pb, Rb/Sr, and lacking relative Ba enrichment).

However, MORB are volumetrically the most important igneous rock types sampled at the Earth's surface and are distributed over the entire ~ 44,000 km length of the ridge system. The mantle is probably chemically heterogeneous on small (10 m) and very large (> 1000 km) scales, but the MORB source reservoir, situated in the upper mantle, is relatively homogeneous, containing only small-scale heterogeneities (e.g., Zindler and Hart, 1986; LeRoex, 1987; Hart, 1988; Saunders et al., 1988). On the grounds of prevalence, it is more reasonable to assume an N-MORB type mantle source as the mantle wedge beneath the IBM arc-backarc system. The extensive studies of trace elements and isotopic characteristics of the IBM arc-basin volcanic rocks and ashes (see Chapter 2, 3 and this study) favour this model, namely a N-MORB-source mantle

wedge modified by incompatible element-rich fluids derived from the subducted altered oceanic crust with sediment inputs as the source of IBM magmas.

9.4 Geochemical evolution of the IBM arc-backarc basin system

Understanding the geochemical evolution of arc systems has been a specific goal of geochemists and petrologists interested in the processes of supra subduction zone (SSZ) magmatism. These systems have been regarded as the locus of initial growth of the continents (Taylor, 1967), so that identification of long-term changes within a specific arc has been viewed as crucial for understanding the process of formation and modification of the continental crust. Following the documentation of spatial variety of characteristics within island arcs (Kuno, 1959; Sugimura, 1960), geochemical evolution has been claimed for example, from early low-alkali through intermediate- to highly-alkaline compositions with "maturing" of the arc in the sense of changes in crustal character from intraoceanic to continental (Baker, 1968; Gill, 1970). Within any individual arc however, onland exposures are typically incomplete or poor rendering decipherment of the temporal record an awkward task, and restricting our view to a narrow period of development. Experience has shown that lengthy records of arc activity as volcanic ash layers can be obtained by drilling of deposits in the marine realm, optimally sited to avoid disturbance, reworking, and with reasonable penetration thickness (e.g., Arculus and Bloomfield, 1992; Arculus et al., 1995). The volcanic ash samples studied in this thesis from ODP Leg 125 and DSDP Leg 60 Sites drilled in the IBM forearc, which span the IBM arcs' explosive history from ~ 42 Ma to present, provide an excellent opportunity to evaluate the geochemical evolution of the IBM arc system.

9.4.1 Spatial and temporal geochemical changes

Recognising the difficulty inherent in all of the ash studies of detecting the exact location of eruptive sources, there are clearly evidence of spatial and temporal geochemical changes for the Izu-Bonin-Mariana arcs. Element and isotope studies of IBM ashes show persistent differences that existed in the modern (Middle Miocene to present) Mariana arc and contemporaneous Izu-Bonin arc (Arculus et al., 1992; Chen and Arculus, 1993a, 1994a; this study). The modern Izu-

Bonin ashes are dominated by low-K tholeiitic series which have lower K_2O and LIL element abundances, higher CaO contents, LREE-depleted REE patterns, higher ε_{Nd} values and slightly lower $^{87}Sr/^{86}Sr$ ratios, while the contemporaneous Mariana ashes are dominated by medium-K tholeiitic series which show higher K_2O and LIL element abundances, lower CaO contents, LREE-flat to slightly enriched REE pattern, lower ε_{Nd} and slightly higher $^{87}Sr/^{86}Sr$ ratios. These differences do not result from the degree of partial melting of mantle source. They may be either due to the mantle heterogeneity where the upper mantle wedge sources tapped by arc magmatism are more fertile in the modern Mariana arc relative to the Izu-Bonin arc (Arculus et al., 1992; Gill et al., 1994; Arculus et al., 1995) and/or due to the processes where by different types of sediment are involved in the respective arc magma sources.

With a more complete temporal ash record from the Mariana arc region, it is clear that the products of the Middle Miocene to currently active arc are predominantly medium-K tholeiitic while those of Oligocene to Early Miocene arc are predominantly low-K tholeiitic. Trace element data show that higher abundances of LIL element such as Rb, Ba and Sr do occur at 8-11 Ma and ~ 2 Ma. LREE-enriched REE patterns corresponding to lower ε_{Nd} values are also found in the Middle Miocene to presently active arc. However, there is no temporal changes for $^{87}Sr/^{86}Sr$ ratios, which are in the narrow range from ~ 0.7034 to 0.7040. Similarly, for Middle Miocene to the presently active Izu-Bonin arc (except for the IwoJima region), there are no temporal geochemical changes and all are low-K tholeiitic series. Quite markedly alkaline lavas with LREE-enriched patterns, lower ε_{Nd} values but similar $^{87}Sr/^{86}Sr$ ratios are being erupted in the zone near the junction of the Izu-Bonin and Mariana arcs in the vicinity of IwoJima region. Obviously, the temporal geochemical changes are not caused by the upper mantle wedge but by the subducted slab. Different types of sediments and lack of altered oceanic crust involvement in arc magma sources may explain the temporal changes.

9.4.2 Any variation of crustal thicknesses in IBM arcs?

Correlations of geochemical parameters of MORB with physical factors such as ridge crest depths and inferred percentages of melting in the mantle have proved to be successful on a global scale (Klein and Langmuir, 1987) even if problematic in detail. In a survey of the geochemistry of

the world's arc systems, Plank and Langmuir (1988) discovered a remarkable degree of overlap between MORB and arc basalts, and suggested degrees of melting are controlled at least in part by arc crustal (or lithospheric) thicknesses. Given that island arcs are believed to be the locus of continental crustal growth, we might anticipate some indication of crustal thickening as a function of arc longevity (e.g., decreasing wt% CaO and increasing wt% Na_2O at specific wt% MgO). Concentrating on the Izu-Bonin-Mariana arc system, a large amounts of data including individual Mariana active island such as Agrigan, Asuncion, Gugan, Pagan and Sarigan, Izu-Bonin island such as Torishima, and different time intervals (from Oligocene to present) of IBM glasses have been tested using the method of Plank and Langmuir (1988). Unfortunately, the calculated crustal thicknesses of IBM arc system vary greatly from < 10 km to 40 km (see Chapter 4) while the measured thicknesses of the Izu-Bonin arc are ~ 20 km (Shinohara et al., 1992; Takahashi et al., 1993). Therefore, it is difficult to evaluate the true crustal thickness of island arcs using any geochemical method including that of Plank and Langmuir (1988).

9.5 Concluding remarks and future studies of volcanic ashes

9.5.1 Concluding remarks

In this thesis, I have attempted to make a systematic geochemical study on a major representative set of volcanic ash samples recovered from DSDP Leg 60 Sites 458 and 459B and ODP Leg 125 Sites 782A, 784A and 786A drilled in the IBM forearc. A series of analytical techniques have been used to disclose as much information as practicable about major and/or trace element abundances and/or Sr-Nd isotopic ratios on individual glass shards, individual mineral crystal fragments, pure bulk glass separates, pure bulk homogeneous and heterogeneous ashes, and sediment-containing bulk ashes. The results are significant and summarised as follows:

1. The collected 133 ash samples from DSDP Leg 60 Sites 458 and 459B span the Mariana arc's explosive history from about 0.25 Ma to 35 Ma. The glass shards are typically highly vesicular, with elongate, flattened bubbles, varying from 0.01 mm to 0.50 mm. They range compositionally from basalt through basaltic andesite and andesite to dacite and rhyolite. Based on 1200 analyses, the basaltic glasses are volumetrically < 5-8% while dacitic and rhyolitic glasses are

~ 15-50%. All these glasses are subalkaline, predominantly tholeiitic low-K to high-K series. The dominant crystalline phases are plagioclase, clinopyroxene, orthopyroxene and titanomagnetite with less olivine and ilmenite, and only a few grains of garnet, amphibole, K-feldspar, titanite and apatite. The assumed equilibrium temperatures from pyroxene and Fe-Ti oxide thermometry are predominantly in the 750-1200° C range at fO_2's = ~ FMQ + 2.5 $\log_{10}$units. These glasses were probably derived from fractional crystallisation differentiation at low pressures in crustal-level magma chambers.

2. Detailed examination of Leg 60 glasses shows that there are two subgroups: A. glasses which are predominantly low-K tholeiitic series aged 35-18 Ma; and B. glasses which are predominantly medium-K tholeiitic series aged 17-0 Ma. The 115 representative PIXE trace element analyses of individual glass shards supports this division into two subgroups. L60A andesitic glasses have lower LIL element abundances such as Rb (< 18 ppm), Ba (20-250 ppm), Sr (100-250 ppm) and slightly lower HFS element abundances such as Zr (30-90 ppm) and Y (15-35 ppm). L60B andesitic glasses have higher LIL element abundances such as Rb (10-45 ppm), Ba (250-800 ppm), Sr (250-600 ppm) and slightly higher HFS element abundances such as Zr (40-110 ppm) and Y (20-40 ppm). A complete set of trace element data including REE and HFSE of L60 bulk ashes supports the division into A and B subgroups. Ashes having higher LILE and LREE abundances are LREE-enriched at 30 to 70 times La_N occurring at ~ 2 Ma and 8-11 Ma, and are also characterised by relatively low ε_{Nd} values (+5.6±0.3). All other Leg 60 ashes ranging from 35 Ma to present have very similar flat REE patterns within 10 to 30 times chondritic abundances and with uniform ε_{Nd} values (+7.7±0.8). All the Leg 60 ashes studied are characterised by a uniform $^{87}Sr/^{86}Sr$ ratios from 0.7035 to 0.7040, regardless of rock type, time interval, and from homogeneous or heterogeneous ash layers.

3. The 51 selected ash samples from ODP Leg 125 Sites 782A, 784A and 786A only span the Izu-Bonin arc's explosive history from about 0.25 Ma to 17 Ma, and a single layer from about 42 Ma. The Leg 125 glasses range compositionally from basalt through basaltic andesite and andesite to dacite and rhyolite. The basaltic glasses are volumetrically < 3-5% while dacitic and rhyolitic glasses are ~ 15-40%. The dominant crystalline phases are plagioclase, clinopyroxene, orthopyroxene and titanomagnetite with less ilmenite. The assumed equilibrium temperatures from

pyroxene and Fe-Ti oxide thermometry concentrated in the 900-1150° C range at fO_2's = ~ FMQ + 2.5 $\log_{10}$units. Relative to L60A ashes, L125 ashes have LREE-depleted to flat (within 5 to 30 times La_N abundance) patterns, high ε_{Nd} values (+8.8±0.8), and low $^{87}Sr/^{86}Sr$ ratios from 0.7034 to 0.7038.

4. A comparison of IBM glasses (ashes) with IBM arc-backarc basin volcanic rocks indicates that ashes are the products of subaerial volcanism of this system and represent the true liquid (melt) compositions of the IBM arc magmas. The bulk ashes represent average mixtures of arc volcanic rocks when heterogeneous glasses are predominant. If the bulk ashes contain significant amounts of sediments, their Sr and Nd isotopic ratios are significantly changed. On the basis of tectonic constraints, the Oligocene Leg 60 ashes were the products of arc volcanism of the Palau-Kyushu Ridge; the Miocene Leg 60 ashes were derived from the West Mariana Ridge; the Quaternary-Pliocene Leg 60 ashes are the products of subaerial volcanism of the active Mariana arc; the Quaternary-Pliocene-Miocene Leg 125 ashes are most probably the products of subaerial volcanism of the northern part of the Izu-Bonin arc. Early Miocene and Oligocene Leg 125 ashes are lacking. It is difficult to infer the possible source of the Eocene Leg 125 ashes because of the limited number of analyses available. High-K volcanic ashes from ODP and DSDP Sites are volumetrically < ~ 2%, occurred predominantly in the Late Miocene (11.2-5.3 Ma), and may have been derived from the southern part of the Izu-Bonin arc at the junction between the Izu-Bonin and Mariana systems.

5. The highly incompatible element ratio Ba/Rb of MORB and OIB are constant at 11±3, and therefore mantle melting- independent. The average Ba/Rb of individual glass shards from Leg 60 and Leg 125 ash layers are constant at 20±4, independent of fractionation. The fact that the mobility of Ba is less than that of Rb (Tatsumi et al., 1986) in fluids transported subduction zone requires that sediments with Ba/Rb >> mantle value (11±3) must be involved in the genesis of arc magmas. On the basis of collected data for Pacific oceanic sediments, altered oceanic crust and arc volcanic rocks, a bulk subducted altered oceanic crust with sediments (BSAOCSS) is calculated and about 10-30% BSAOCSS is inferred to be involved in the IBM arc magmas. Considering the mobility of the elements Pb, Sr and Nd in the siliceous fluid or melt derived from BSAOCSS (Tatsumi et al, 1986; Randle and Odling, 1992), only a few percent sediment can be incorporated

in IBM arc magma sources, similar to the level proposed by Woodhead (1989) and Pearce and Peate (1995).

6. On the basis of geochemical similarities of arc volcanic rocks (including ashes) of large IBM arc-backarc basin region, covering a strike length of ~ 2400 km and a width of ~ 2000 km, including uniform $^{87}Sr/^{86}Sr$ ratios from 0.7032 to 0.7040, flat HREE at 10 to 30 times chondritic abundance patterns, and consistent geochemical relationships among IBM arc and backarc volcanic rocks and N-MORB, there is possibly a common N-MORB-type mantle source beneath the Philippine Sea Plate. This common source shows no systematic temporal and spatial geochemical changes during the development of the Philippine Sea Plate.

9.5.2 Future studies of volcanic ashes

Based on the results from the present geochemical studies of volcanic ashes, we recognise that there are some difficulties inherent in the overall approach and review possible future research directions.

1. Volcanic ash sampling Because of technical drilling problems with recovery of coarse clastic sequences and the possibility of incomplete records through erosion and non-deposition, DSDP and ODP have historically failed to recover a complete set of volcanic ash layers in most cases. However, this is not a major problem in general because we can usually collect sufficient ash samples between different Sites in the same Leg or region. Major problems are the paucity of basaltic ashes and temporal hiatuses. Why for example, are there extensive records of arc volcanism from the Eocene-Oligocene (45-30 Ma) (Leg 125 shipboard scientific party, 1989) but no volcanic ashes during this period? For the geochemical study of island arc magmatism, it is useful to have basaltic ashes (if possible, primary basaltic ashes); and for understanding the geochemical evolution of an arc system through the explosive record, it is extremely important to have a complete set of ashes spanning the arc's history from the beginning to present.

2. Validity of comparison of volcanic glasses and volcanic rocks All ash researchers (e.g., Jones, 1973; Scheidegger, 1973; Arculus and Bloomfield, 1992; Natland, 1993; Calanchi et

al., 1994; Clift and Dixon, 1994) use methods derived from volcanic rock studies including type nomenclature (basalt to rhyolite), magma series from tholeiitic, calc-alkaline to alkaline, shosholitic and boninitic series, applied to volcanic glasses from ash layers in order to compare with the corresponding volcanic rocks and to discuss the petrogenesis of volcanic ashes. This study has clearly shown that volcanic glasses have significantly higher FeO* and TiO_2 and lower Al_2O_3 abundances than IBM volcanic rocks. Even compared to MORB, the TiO_2 contents of IBM basaltic and basaltic andesite glasses are in the same range, but the FeO* contents are higher and Al_2O_3 abundances are lower. This study has also shown the overwhelmingly tholeiitic character of the glassy ashes using different classifications such as the AFM and Al_2O_3-*an* diagrams (Irvine and Baragar, 1971) and FeO*/MgO-SiO_2 diagram (Miyashiro, 1974). The K_2O contents however, are variable from low- through medium- to high-K series (Gill, 1981). The LREE-enriched REE patterns and higher LIL element abundances of volcanic rocks and ashes clearly indicate sediment contributions to the magma sources (lower ε_{Nd} values and higher or slightly higher $^{87}Sr/^{86}Sr$ ratios depending on different types of sediment) (e.g., Vroon, 1992; this study). Therefore, K- series of glasses (combined with the REE patterns of bulk ashes) may be an indicator of sediment involvement with/without altered oceanic crust contribution to arc magma sources but may not be evidence of classification of magma series such as tholeiitic or calc-alkaline (cf. Jakes and Gill, 1970). It may also not be reasonable to equate medium-K series as calc-alkaline (cf. Peccerillo and Taylor, 1976; Wilson, 1989). In addition, higher Al_2O_3 and higher Sr contents of volcanic rocks may be derived from plagioclase accumulation (e.g., Perfit et al., 1980; this study) and may also not be evidence of calc-alkaline character (e.g., Jake and White, 1972). For convenience of comparison, the total alkali-silica (TAS) diagram recommended by the IUGS Subcommission on the Systematics of Igneous Rocks (LeBas et al., 1986) should be used in ash (glass) studies for rock types and rock series such as subalkaline and alkaline series, and the divisions of Kuno (1965) and Peccerillo and Taylor (1976) should be abandoned.

3. Heterogeneous ashes Heterogeneous volcanic ashes have been recognised for a long time (e.g., Jezek, 1976; Arculus and Bloomfield, 1992). Most recently, Arculus et al. (1992) and Chen and Arculus (1993a, 1994b) studied individual glass shards from the heterogeneous and homogeneous ash layers by PIXE-PMP. This study has recovered more detailed information. For the majority of DSDP Leg 60 and ODP Leg 125 ash layers, the chemical compositions of

individual glass shards in the same layer may have a considerable range from basaltic to dacite or from andesite to rhyolite. Their LIL trace element contents such as Rb, Ba and Sr, also vary considerably but HFS element contents such as Ti, Zr and Y are in the similar range for andesitic glasses. LILE enrichment of arc volcanic glasses (ashes) and rocks relative to MORB is clear and caused by sediment contribution to arc magma sources (e.g., Arculus, 1994; Pearce and Peate, 1995; this study). However, the ongoing HFSE depletions or anomalies in arc volcanic rocks is uncertain and controversial. Some favour generation in the mantle wedge, either because of pre-existing HFSE depletion in the mantle (Salters and Shimizu, 1988), or because of processes related to melt production and transport (e.g., Green, 1981; Foley and Wheller, 1990; Kelemen et al., 1990a,b, 1993; McKenzie and O'Nions, 1991). Others favour generation by solid-fluid interactions in the subducting lithosphere or in the immediately overlying mantle dragged down by subduction (e.g., Saunders et al., 1980; Arculus and Powell, 1986; McCulloch and Gamble, 1991). Considering that there are no HFSE depletions or anomalies in MORB and OIB, it may be more reasonable to suggest that HFSE anomaly relative to LILE and LREE in arc volcanic rocks is largely caused by the higher abundances of LILE and LREE derived from subducted sediments and/or altered oceanic crust, and relatively slightly larger partial melting of N-MORB mantle source in IAB relative to MORB. Plank et al. (1994) redetermined Nb and Ta by ICP-MS on a suite of recent basalts and andesites from the Mariana arc and found that all Marianas lavas show Nb anomalies relative to La and proposed that the Nb anomaly is due primarily to LREE enrichment in the inferred source and not Nb depletion. Similarly, Pearce and Peate (1995) showed that the HFSE abundances in arc volcanic rocks are generally in the MORB array. In most arc magmas (usually < 6 wt% MgO), fractionation is probably a major control on the extent of Ti and Zr anomalies (Thirlwall et al., 1994). However, there are lack of accurate HFSE data of arc basalts to make further comparison. For basaltic glasses (ashes), there are no HFSE especially Nb and Ta data because of the problems of ash sampling, the occurrence of heterogeneous ashes and existing analytical techniques. The trace elements including REE and HFSE analyses of individual glass shards by laser ablation ICP-MS (LA ICP-MS) may disclose much more information than by PIXE-PMP. The larger glass shards, for example, 0.08 x 0.05 x 0.05 mm^3, free of inclusions should be prepared for LA ICP-MS. It may be difficult to obtain such kinds of basaltic glass shards. For fine homogeneous glasses or heterogeneous glasses, the ICP-MS method can be used to analyse a complete set of trace elements from small amounts of bulk glass separates (10-50 mg)

handpicked by colour and shape (Chen and Arculus, 1994, unpub. data). If possible, Pb isotopic ratios should be obtained from the homogeneous and heterogeneous volcanic ashes to test whether there are any sediment signatures.

4. Limit of discussion of petrogenesis of ashes Generally, deep-sea volcanic ashes are airfall deposits of eruptive products from one or more arc system at specific explosive time intervals. It is difficult to detect the exact location of eruptive sources and detailed along- and across- arc geochemical variations. On the basis of tectonic and time constraints and geochemical similarities between volcanic glasses (ashes) and temporally equivalent volcanic rocks, we have discussed the possible origin of DSDP Leg 60 and ODP Leg 125 volcanic glasses (ashes) and the geochemical evolution of the IBM arc system. But there are some significant differences between volcanic ashes and arc volcanic rocks such as distribution of the rock types. The lack of Early Miocene volcanic rocks in the Mariana arc compared with the abundance of ash samples derived from the West Mariana Ridge is notable. There is also a lack of Middle to Late Miocene volcanic rocks in the Izu-Bonin arc while there are a number of volcanic ashes from this time period. Further drilling on the West Mariana Ridge or the IwoJima region at the junction between the Izu-Bonin and Mariana arc systems is required to test the validity of the conclusions drawn from volcanic ash studies.

5. Relationship among deep-sea ashes, arc volcanism and tectonic events? Since the early 1970's, scientists have been interested in understanding the relations between explosive volcanism and ash layers interbedded with marine sediments (e.g., Kennett and Watkins, 1970; Kennett and Thunell, 1975; Cambray and Cadet, 1994). It is widely accepted that volcanic ashes are possibly the direct record of significant volcanic events (Kennett, 1981; Cambray and Cadet, 1994; Arculus et al., 1995). On the basis of the volcanic activity of the IBM arc-backarc system documented in DSDP Legs 6, 31, 58, 59, 60 and ODP Legs 125 and 126 (see Chapter 2 for references), many workers have proposed different evolutionary models of this system (see Taylor, 1992). After Karig (1971a,b) initially demonstrated that the Philippine Sea had formed by backarc spreading, an intense debate arose about the temporal relationship between arc volcanism and backarc spreading. Karig, Ingle, et al. (1975) concluded from the results of Leg 31 that backarc spreading occurred during maxima in arc volcanism, and Karig (1983) restated and defended this position. In contrast,

Rodolfo (1980), Scott and Kroenke (1980), Scott et al. (1980), Crawford et al. (1981), and Sharaskin et al. (1981) interpreted the successions drilled during Leg 59 as evidence that backarc opening behind the Mariana arc occurred during periods of relative quiescence in arc volcanism. Discussing the results of Leg 60, Hussong and Uyeda (1981) suggested that backarc opening had no temporal relationship with arc volcanism. Summarising all the information about the Philippine Sea Plate, Taylor (1992) suggested that many, but not all, arc segments go through a cycle of (1) frequent volcanism before and during rifting; (2) reduced and/or less disseminated volcanism during latest rifting and early backarc spreading as new frontal arc volcanoes are being constructed and growing to sea level; and (3) increasingly vigorous volcanism during middle and late stage backarc spreading until the next rift cycle begins. Even within periods of intense volcanism, 100-km-long arc segments may be quiescent for periods of up to 0.4 Ma. Detailed examination of ash layers from the DSDP Sites drilled in the Mariana region indicates that the first arc volcanism continued from Late Eocene to the end of the Oligocene (~ 25.7 Ma). The location of Leg 60 Site 458 and 459B was the forearc of the Palau-Kyushu Ridge (PKR), recovering volcanic ashes from ~ 35 Ma to 25.7 Ma. Clearly, when the Parece Vela basin was spreading from ~ 30 Ma to ~ 17 Ma, the PKR arc experienced decreasing subaerial explosive volcanism. On the other hand, the West Mariana Ridge was erupting extensively from the Early Miocene to the end of the Middle Miocene (~ 23 Ma to 17 Ma). Sites 449 and 450 in the Parece Vela basin have no pre-23 Ma ash records while Sites 458 and 459B have ash records from 23 Ma to 5.8 Ma, indicating that the location of Leg 60 Site 458 and 459B was also the forearc of the WMR arc from Early Miocene to end of the Late Miocene. Interestingly, Sites 453, 454, 455 and 456 and the active Mariana arc all lack pre-5.3 Ma ash records, indicating that the WMR had already subsided below sea level prior to 5.3 Ma ago. After a lull in arc volcanism, the Mariana Trough began spreading and the Mariana active arc was forming at almost the same time. Sites 458 and 459B have ash records of Pliocene to Quaternary, being located in the forearc of the currently active Mariana arc. Obviously, the observation of ash records as simply described above generally agrees with the suggestion of Taylor (1992), but there is a difference in that the Mariana Trough apparently began spreading after a lull in the West Mariana Ridge arc volcanism.

Whether some level of global synchroneity of explosive volcanism exist and whether such pulses could be climatically significant (e.g., Kennett and Thunell, 1975; Ninkovich and Donn,

1976; Kennett et al., 1977; Cambray and Cadet, 1994) have been controversial issues. Kennett and Thunell (1975) first systematically discussed the possible global synchroneity of explosive volcanism by analysing the worldwide distribution of volcanic ashes from 320 DSDP deep-sea sections. They suggested that there has been a much higher rate of explosive volcanism from island arc and hot spot volcanoes during the last 2 Ma and perhaps another pulse in the Middle Miocene. After detailed studies of Cenozoic volcanic ashes in the circum-Pacific region, Kennett et al. (1977) found that two important pulses of Neogene volcanism (the Cascadian and Columbian episodes) occurred during the Quaternary (~ 2 Ma) and within the Middle Miocene (16-14 Ma), with two less important episodes in the latest Miocene to Early Pliocene (6-3 Ma, Fijian episode) and Late Miocene (11-8 Ma, Andean episode). They suggested that synchronous episodic volcanism is related to changes in rates of sea-floor spreading and subduction and volcanism records fundamental tectonic changes throughout the entire Pacific region. Recently, Cambray et al. (1993) and Cambray and Cadet (1994) examined quantitatively the volcanic ash records from DSDP and ODP Sites along the Pacific rim and verified that there are two major pulses of arc volcanism occurring at Middle Miocene times (18-13 Ma) and Pliocene-Quaternary times (5-0 Ma). They argue that these pulses are relate to the tectonic (stress) regime of the arc lithosphere rather than to subduction rate. These episodes of arc volcanism activity coincide with major tectonic events documented on circum-Pacific subduction zones. As a consequence, a global control of plate kinematics could influence both volcanic and tectonic evolution of Pacific convergent margins (Cambray and Cadet, 1994). In this study, it is shown that there are abundant Early Miocene ash records in Sites 458 and 459B. There is also sufficient evidence to support major Eocene-Oligocene (45-30) volcanic activity in the IBM region (Leg 125 shipboard scientific party, 1989; Stern and Bloomer, 1992; Taylor, 1992). Nevertheless, it may be more apparent than true that for exposing major arc volcanism episodicity, more information relating land to marine volcanism is required.

Table 9-1 Major element compositions and CIPW values of individual basaltic glass shards from Leg125 and Leg 60 ash layers

Hole-Layer-Core-Section,Interval,Depth	Age (Ma)	No.A0	SiO_2	TiO_2	Al_2O_3	FeO*	MnO	MgO	CaO	K_2O	Na_2O	AN*	q	or	ab	an	di	hy	ol	mt	il
459B-1-1-2,117-118,2.67	0.25	8707c	51.76	0.71	15.30	11.87	0.13	5.41	11.01	0.88	2.93	51.2		5.2	24.7	25.9	23.7	13.5	1.8	3.8	1.4
458-2-1-3,98-99,3.98	0.35	5955c	49.49	1.97	11.21	18.55	0.18	6.31	9.75	0.87	1.67	59.3	2.6	5.1	14.1	20.4	23.2	24.9		6.0	3.7
459B-2-1-4,122-123,5.72	0.40	8748c	51.99	1.23	15.97	12.48	0.23	4.33	9.50	0.94	3.34	47.7	0.2	5.6	28.2	25.7	17.8	16.3		4.0	2.3
458-7-2-4,28-29,14.28	1.15	6179c	51.84	1.24	14.11	13.82	0.18	4.77	10.71	0.80	2.53	53.7	2.8	4.7	21.3	24.7	23.6	16.0		4.4	2.4
458-10-2-4,118-119,15.18	1.35	6264c	52.00	1.18	14.72	13.31	0.28	4.96	9.85	0.62	3.09	48.4	1.3	3.7	26.1	24.4	20.3	17.8		4.3	2.2
458-10-2-4,118-119,15.18	1.35	6265c	51.05	0.91	13.99	13.31	0.18	5.68	11.97	0.50	2.42	55.8	0.9	3.0	20.4	25.8	27.7	16.2		4.3	1.7
458-13-3-2,121-122,21.71	2.20	6337c	51.89	0.94	13.63	13.92		5.59	11.35	0.41	2.27	57.4	3.6	2.4	19.1	25.7	25.3	17.5		4.5	1.8
786A-2-5X-1,74-76,38.9	5.60	5079c	51.85	0.94	12.96	13.72	0.16	7.31	10.69	0.16	2.20	57.4	3.2	1.0	18.5	25.0	23.0	23.1		4.4	1.8
784A-5-16R-4,103-105,141.5	6.10	4937c	51.89	1.12	11.34	13.54	0.14	8.73	11.72	0.19	1.33	68.4	5.4	1.1	11.3	24.3	27.5	23.9		4.4	2.1
784A-8-18R-2,32-35,157.1	6.80	4992c	51.82	1.36	14.15	14.88	0.23	4.85	10.88	0.38	1.46	71.4	8.4	2.3	12.4	30.8	19.2	19.6		4.8	2.6
784A-8-18R-2,32-35,157.1	6.80	4994c	51.84	1.51	13.49	14.98	0.14	5.08	10.68	0.45	1.84	63.7	6.8	2.7	15.5	27.1	21.4	18.8		4.8	2.9
784A-8-18R-2,32-35,157.1	6.80	5001c	51.46	1.45	14.17	14.66	0.17	5.19	10.48	0.44	1.97	63.2	5.6	2.6	16.6	28.5	19.5	19.8		4.7	2.8
784A-8-18R-2,32-35,157.1	6.80	5002c	51.96	1.26	14.24	14.40		5.36	10.65	0.39	1.73	67.3	7.1	2.3	14.6	29.9	19.0	20.2		4.6	2.4
784A-8-18R-2,32-35,157.1	6.80	5006c	50.70	1.24	14.63	14.17	0.14	5.89	11.27	0.34	1.61	69.9	4.8	2.0	13.6	31.6	20.1	21.0		4.6	2.4
784A-9-18R-2,102-104,157.8	6.80	5030c	50.51	0.41	17.06	10.70		6.55	12.92	0.11	1.73	72.4	2.1	0.7	14.6	38.4	21.0	19.0		3.4	0.8
782A-13-29X-6,39-41,277.1	12.40	5485c	51.80	1.04	16.94	11.40		4.70	11.64	0.48	2.01	67.9	5.2	2.8	16.9	35.7	18.2	15.5		3.7	2.0
786A-8-7X-5,64-66,63.7	12.50	5201c	51.85	1.10	13.68	16.43		5.32	9.21	0.38	2.03	61.2	6.1	2.3	17.1	27.0	15.5	24.6		5.3	2.1
782A-21-33X-5,86-90,310.4	14.30	5889c	51.74	0.92	15.97	13.45		4.78	10.66	0.39	2.08	65.3	5.3	2.3	17.5	33.0	16.5	19.3		4.3	1.8
782A-21-33X-5,86-90,310.4	14.30	5890r	51.62	1.10	15.71	13.45	0.23	4.89	10.49	0.40	2.10	64.5	5.1	2.4	17.7	32.2	16.5	19.8		4.3	2.1
458-45-13-1,6-7,114.06	16.90	8203c	49.87	1.22	11.68	13.58	0.23	8.88	12.44	0.37	1.74	61.0		2.2	14.6	22.9	31.6	20.9	1.0	4.4	2.3
459B-15-24-2,49-50,218.49	17.00	9074c	51.84	0.48	15.65	11.36		6.14	12.30	0.34	1.89	67.4	3.7	2.0	16.0	33.1	22.9	17.7		3.7	0.9
459B-24-29-1,26-27,264.26	19.00	9271c	49.21	1.25	11.11	16.00	0.23	9.08	11.69	0.16	1.28	68.9	1.2	1.0	10.8	24.0	27.8	27.6		5.1	2.4
459B-28-30-3,141-142,277.91	19.60	9361c	51.86	1.19	11.70	14.32	0.21	8.24	10.06	0.51	1.92	57.4	3.3	3.0	16.2	21.7	23.0	25.8		4.6	2.3

All analyses recalculated to 100 per cent and free of H_2O and volatiles (from LeBas et al., 1986).
Total Fe reported as FeO*, AN meanes normative plagioclase composition (AN = an/(an+ab+5/3 ne) x 100) from Irvine and Baragar, 1971.

Table 9-2 The representative major element composition of boninite and boninite-like (?) glass shards from Leg125 and Leg 60

Type	Sites	Core	Interval (cm)	Depth (mbsf)	Age (Ma)	No.A0	SiO_2	TiO_2	Al_2O_3	FeO*	MnO	MgO	CaO	K_2O	Na_2O	Mg#	Na_2O+K_2O	CaO/Al_2O_3
BON	458 Base	27	24-25	247.24	33.40	8659c	57.81	0.10	13.35	8.39		8.28	9.63	0.53	1.91	63.8	2.44	0.72
BON	458 Base	27	24-25	247.24	33.40	8662c	57.91	0.10	13.49	8.59		7.56	9.77	0.56	2.02	61.1	2.58	0.72
BON	458 Base	27	24-25	247.24	33.40	8665c	58.49	0.10	12.83	8.49		8.52	9.46	0.56	1.56	64.1	2.12	0.74
BON	458 Base	27	24-25	247.24	33.40	8666c	58.52	0.10	13.53	8.22		7.95	9.37	0.48	1.83	63.3	2.31	0.69
BON	458 Base	27	24-25	247.24	33.40	8663c	58.59	0.10	13.08	8.47		8.27	9.40	0.55	1.54	63.5	2.09	0.72
BON	458 Base	27	24-25	247.24	33.40	8673c	58.68	0.10	13.30	8.11		8.08	9.25	0.57	1.92	64.0	2.49	0.70
BON	458 Base	27	24-25	247.24	33.40	8670c	58.73	0.10	13.87	8.09		6.91	9.80	0.55	1.96	60.4	2.51	0.71
BON	458 Base	27	24-25	247.24	33.40	8671c	58.84	0.10	13.36	8.04		8.01	9.27	0.58	1.80	64.0	2.38	0.69
BON	458 Base	27	24-25	247.24	33.40	8674c	59.23	0.10	11.76	8.13		10.31	8.55	0.57	1.36	69.3	1.93	0.73
BON	458 Base	27	24-25	247.24	33.40	8675c	59.84	0.10	13.37	7.68		7.36	9.44	0.64	1.57	63.1	2.21	0.71
B II	458	19	75-76	171.75	22.40	8568C	53.18	0.47	16.27	8.74		7.90	12.49	0.07	0.87	61.7	0.94	0.77
B II	458	11	4--5	98.31	14.10	8155c	52.16	0.96	10.64	13.34	0.13	8.24	12.95	0.68	0.91	52.4	1.59	1.22
B II	458	25	80-81	230.3	30.90	8640c	52.58	1.13	7.86	19.21	0.25	8.74	9.32	0.28	0.64	44.8	0.92	1.19
B II	458	1	139-140	8.89	0.45	6053c	52.57	1.04	7.80	16.85	0.35	8.87	10.35	0.63	1.54	48.4	2.17	1.33
B II	458	11	4--5	98.31	14.10	8148c	52.28	0.52	13.07	11.64		9.75	10.98	0.13	1.63	59.9	1.76	0.84
B II	458	19	75-76	171.75	22.40	8559C	52.74	0.37	10.82	9.69		13.20	12.42	0.05	0.75	70.8	0.80	1.15
B II	459B	11	60-61	95.1	9.30	8920c	53.74	0.78	11.88	11.71	0.20	9.18	10.31	0.89	1.31	58.3	2.20	0.87
B II	459B	11	63-64	93.63	9.30	8894c	52.19	0.62	13.25	11.50		9.51	10.91	0.49	1.52	59.6	2.01	0.82
B II	784A	20R	67-69	178.4	7.50	5044c	53.13	0.89	12.18	12.85	0.18	8.25	10.41	0.25	1.86	53.4	2.11	0.85
B II	786A	7X	127-129	59.9	11.50	5167c	52.26	0.82	12.16	14.63	0.26	8.88	9.69	0.24	1.06	52.0	1.30	0.80
B II	786A	7X	127-129	59.9	11.50	5166c	52.88	0.66	9.74	13.84	0.17	9.47	11.70	0.27	1.27	55.0	1.54	1.20
BA	458	4	75-76	30.75	2.80	6429c	55.19	0.55	8.05	18.40	0.35	9.59	5.76	0.42	1.69	48.2	2.11	0.72
BA	458	19	75-76	171.75	22.40	8570C	54.74	0.50	16.58	8.94		6.75	10.66	0.17	1.66	57.4	1.83	0.64
BA	459B	1	67-68	6.67	0.46	C 8766	54.12	0.51	13.96	12.74	0.21	6.56	8.59	0.25	3.07	47.9	3.32	0.62
BA	459B	6	51-52	50.51	1.70	C 8846	56.86	0.47	9.40	10.10		7.52	10.92	2.22	2.50	57.0	4.72	1.16
BA	459B	29	90-91	266.4	19.20	9290c	54.65	0.71	12.11	13.46	0.21	8.73	7.31	0.40	2.41	53.6	2.81	0.60
BA	782A	2H	84-87	18.2	1.20	5294c	54.23	0.48	13.93	10.81		7.93	10.34	0.32	1.96	56.7	2.28	0.74
BA	782A	19X	12--14	179	5.75	5731c	54.31	0.86	10.61	14.92		9.02	9.05	0.35	0.87	51.9	1.22	0.85
BA	782A	33X	27-30	312.8	14.50	5904c	56.29	0.68	10.27	14.07		8.60	8.10	0.38	1.60	52.1	1.98	0.79
A	782A	26X	141-144	241.7	8.10	5465r	57.23	1.01	8.48	15.49	0.31	8.99	6.51	0.26	1.73	50.8	1.99	0.77
A	459B	15	59-60	131.59	10.00	8975c	57.36	0.87	9.46	15.08	0.28	8.64	5.13	1.20	1.99	50.5	3.19	0.54

* Total Fe reported as FeO*, Mg#*=Mg/(Mg+Fe), where Fe is calcauated as total Fe (2+)

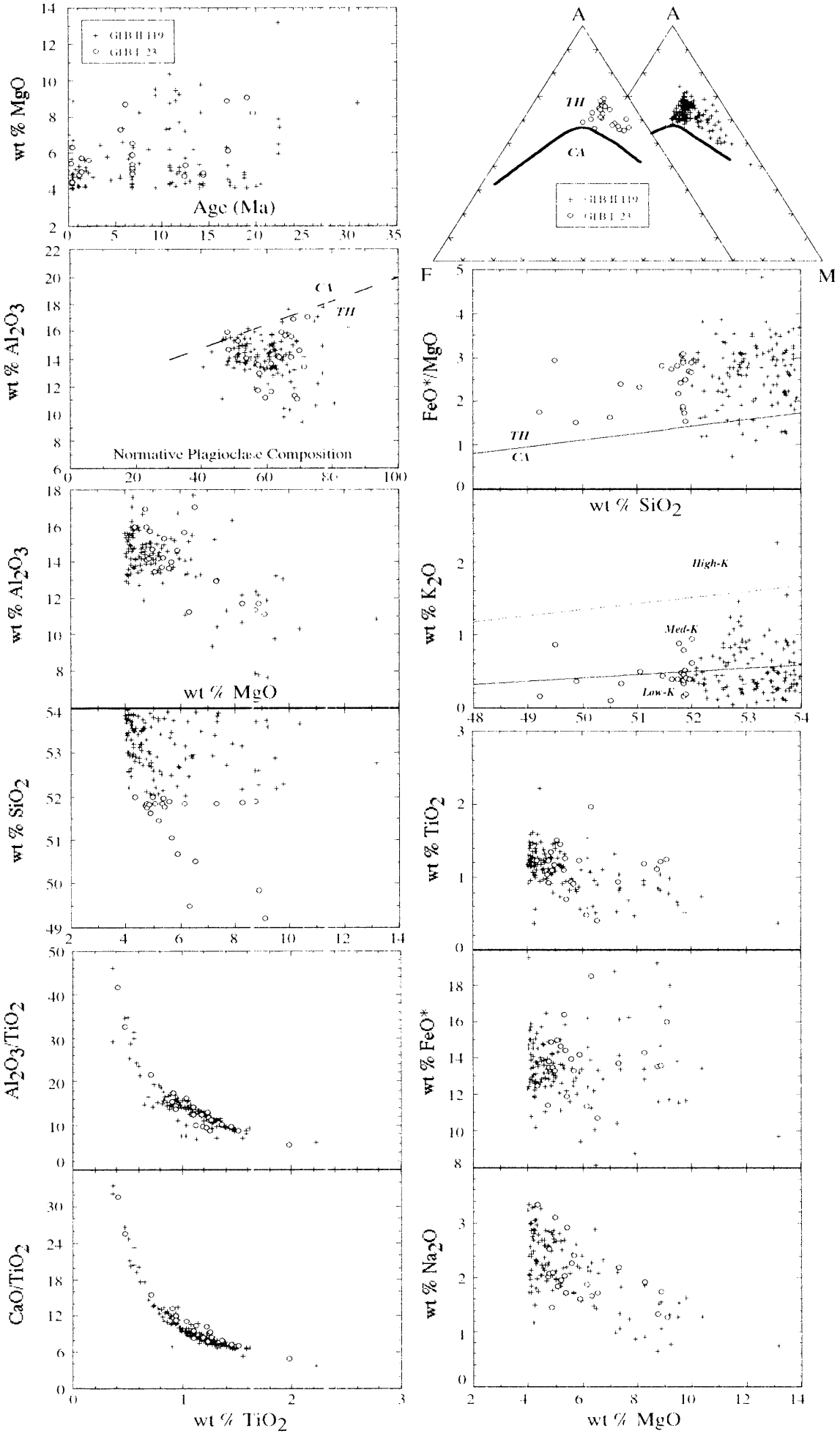

Figure 9-1 Comparison of compositions of basaltic glass shards from DSDP Leg 60 and ODP Leg 125 ash layers. See text for discussion and classifications.

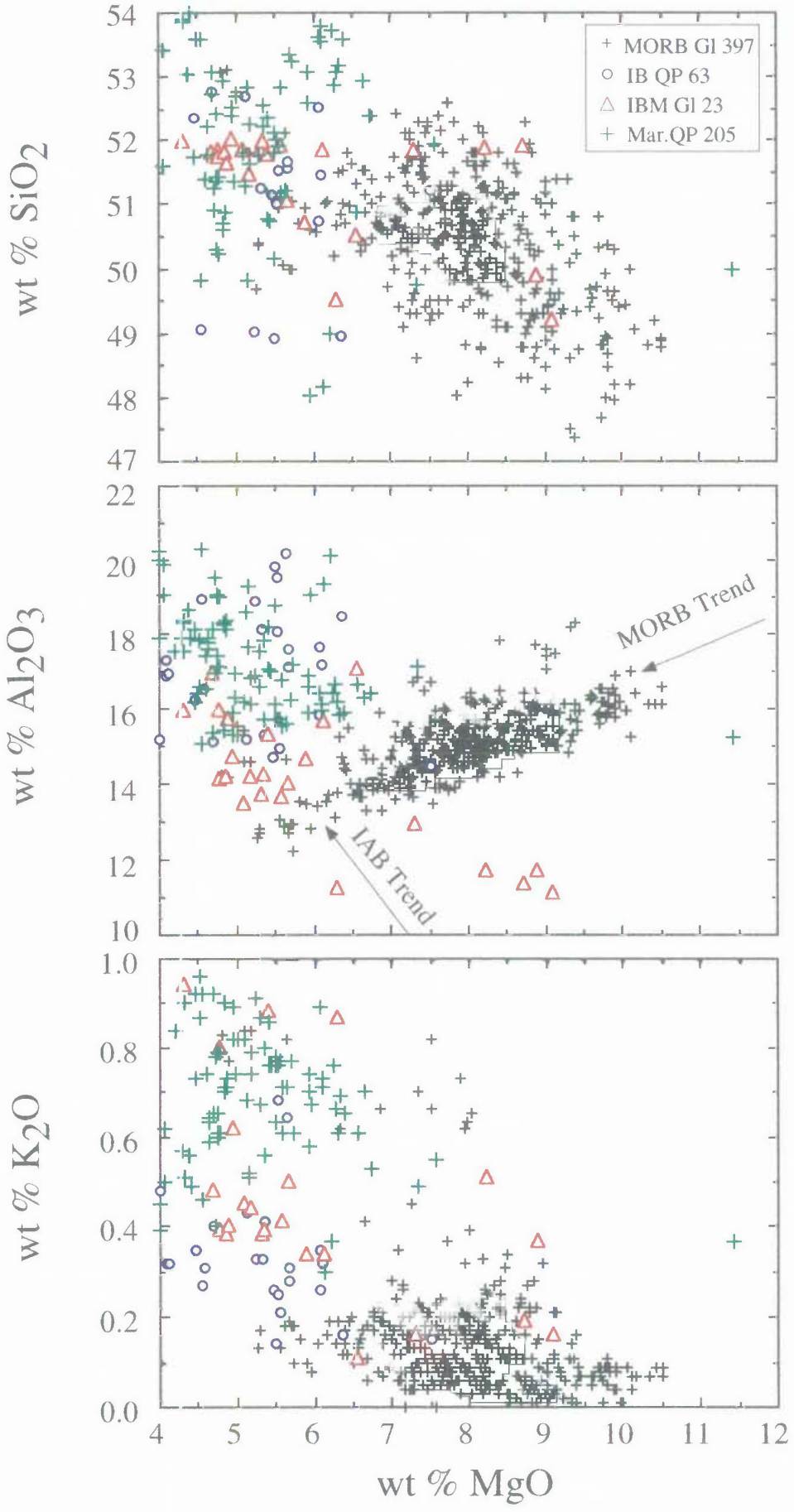

Figure 9-2A Comparison of compositions of individual basaltic glass shards (IBM Gl 23) from DSDP Leg 60 and ODP Leg 125 ash layers with Izu-Bonin modern arc volcanic rocks (IB QP 63), Mariana modern volcanic rocks (Mar.QP 205) and MORB glasses (MORB Gl 397). See text for data sources and discussion.

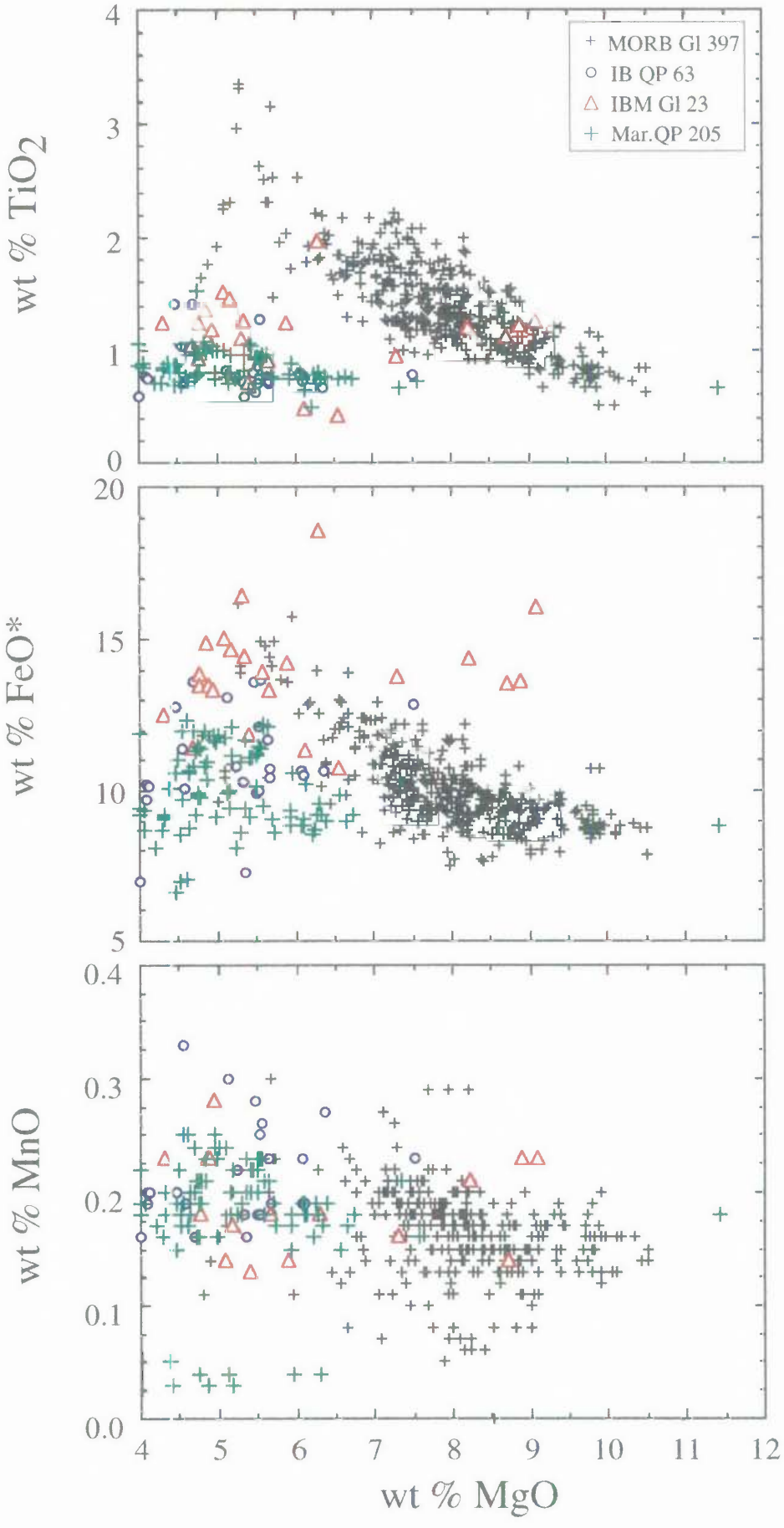

Figure 9-2B Comparison of compositions of individual basaltic glass shards (IBM Gl 23) from DSDP Leg 60 and ODP Leg 125 ash layers with Izu-Bonin modern arc volcanic rocks (IB QP 63), Mariana modern volcanic rocks (Mar.QP 205) and MORB glasses (MORB Gl 397). See text for data sources and discussion.

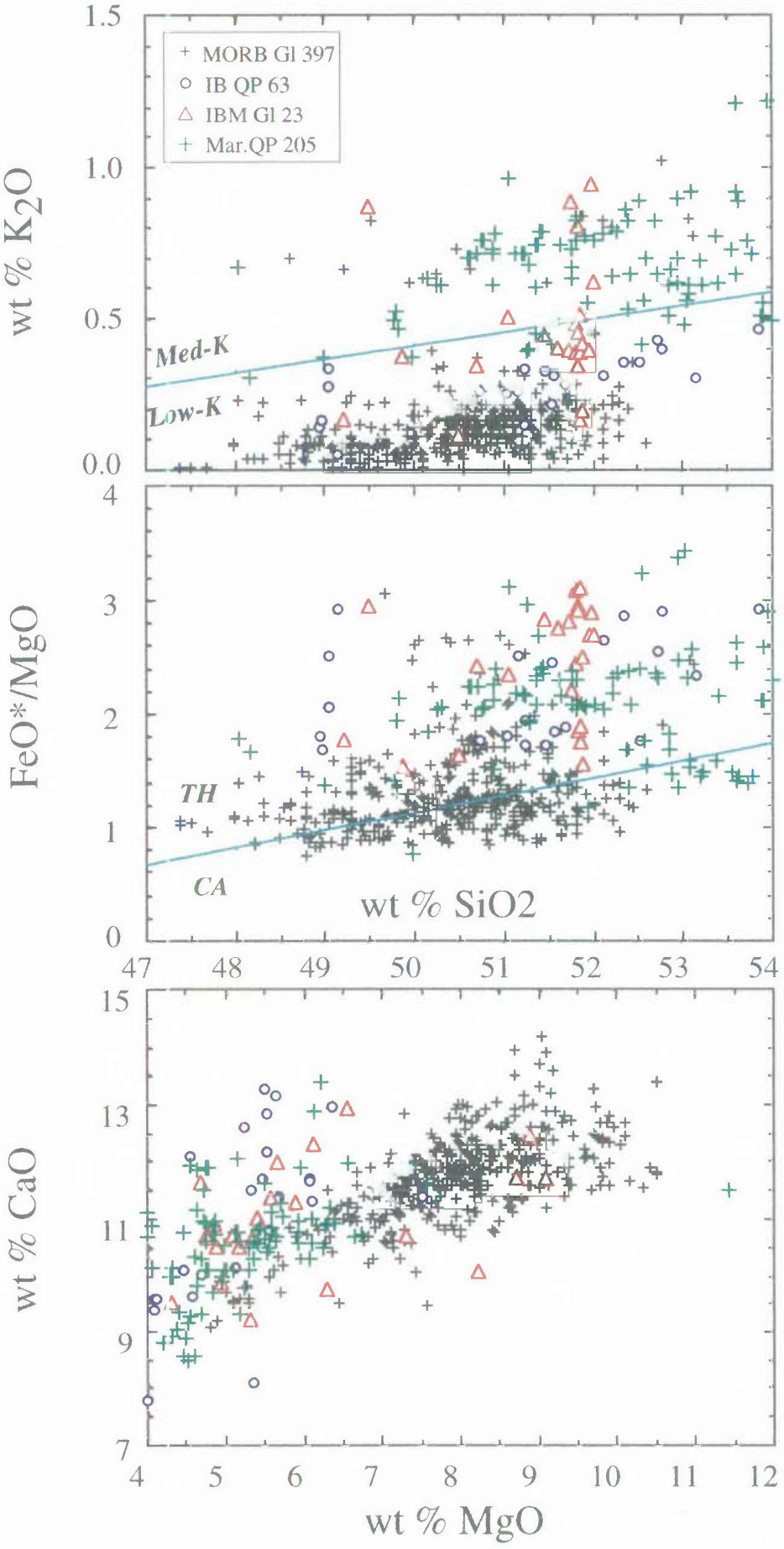

Figure 9-2C Comparison of compositions of individual basaltic glass shards (IBM Gl 23) from DSDP Leg 60 and ODP Leg 125 ash layers with Izu-Bonin modern arc volcanic rocks (IB QP 63), Mariana modern volcanic rocks (Mar.QP 205) and MORB glasses (MORB Gl 397). See text for data sources and discussion.

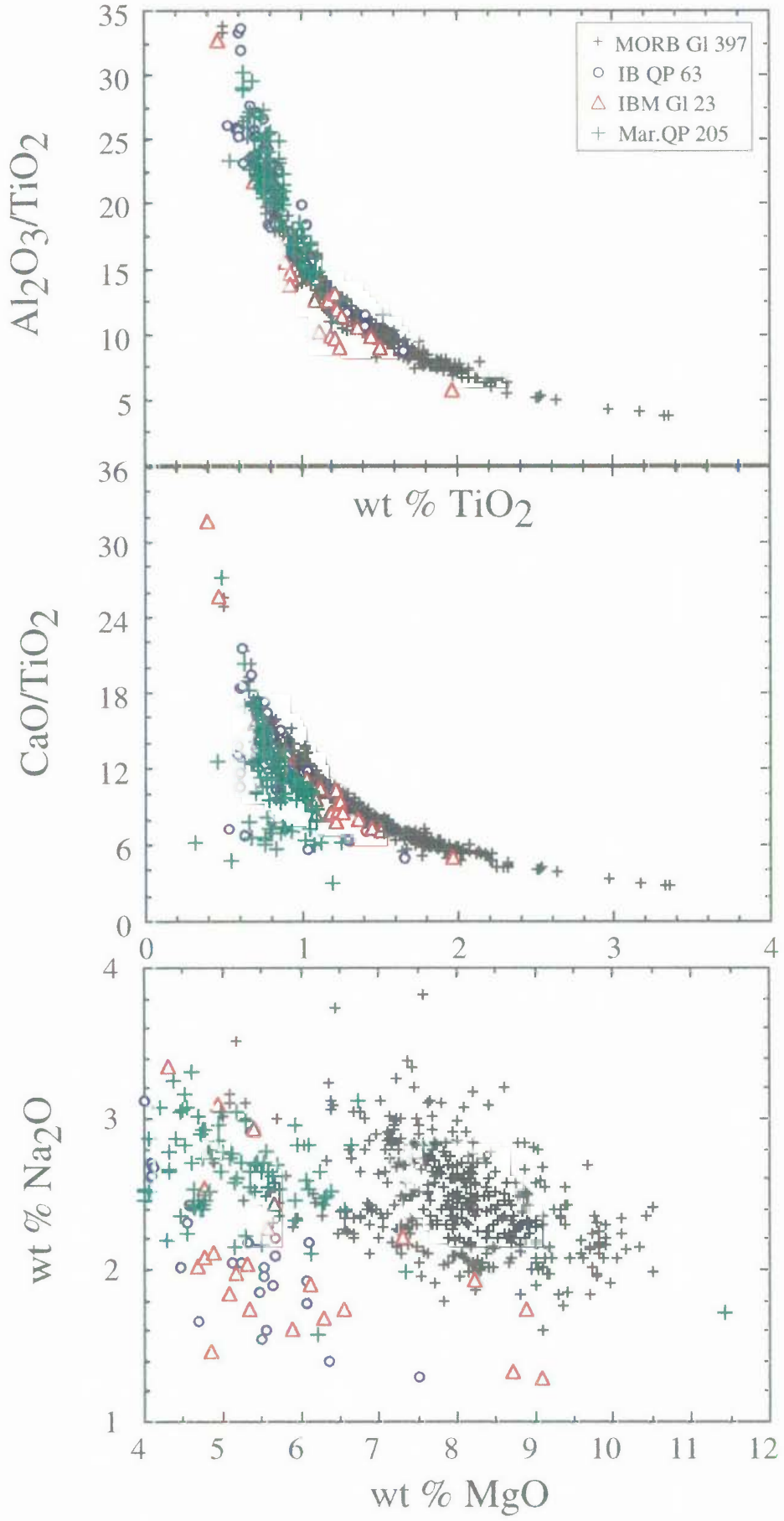

Figure 9-2D Comparison of compositions of individual basaltic glass shards (IBM Gl 23) from DSDP Leg 60 and ODP Leg 125 ash layers with Izu-Bonin modern arc volcanic rocks (IB QP 63), Mariana modern volcanic rocks (Mar.QP 205) and MORB glasses (MORB Gl 397). See text for data sources and discussion.

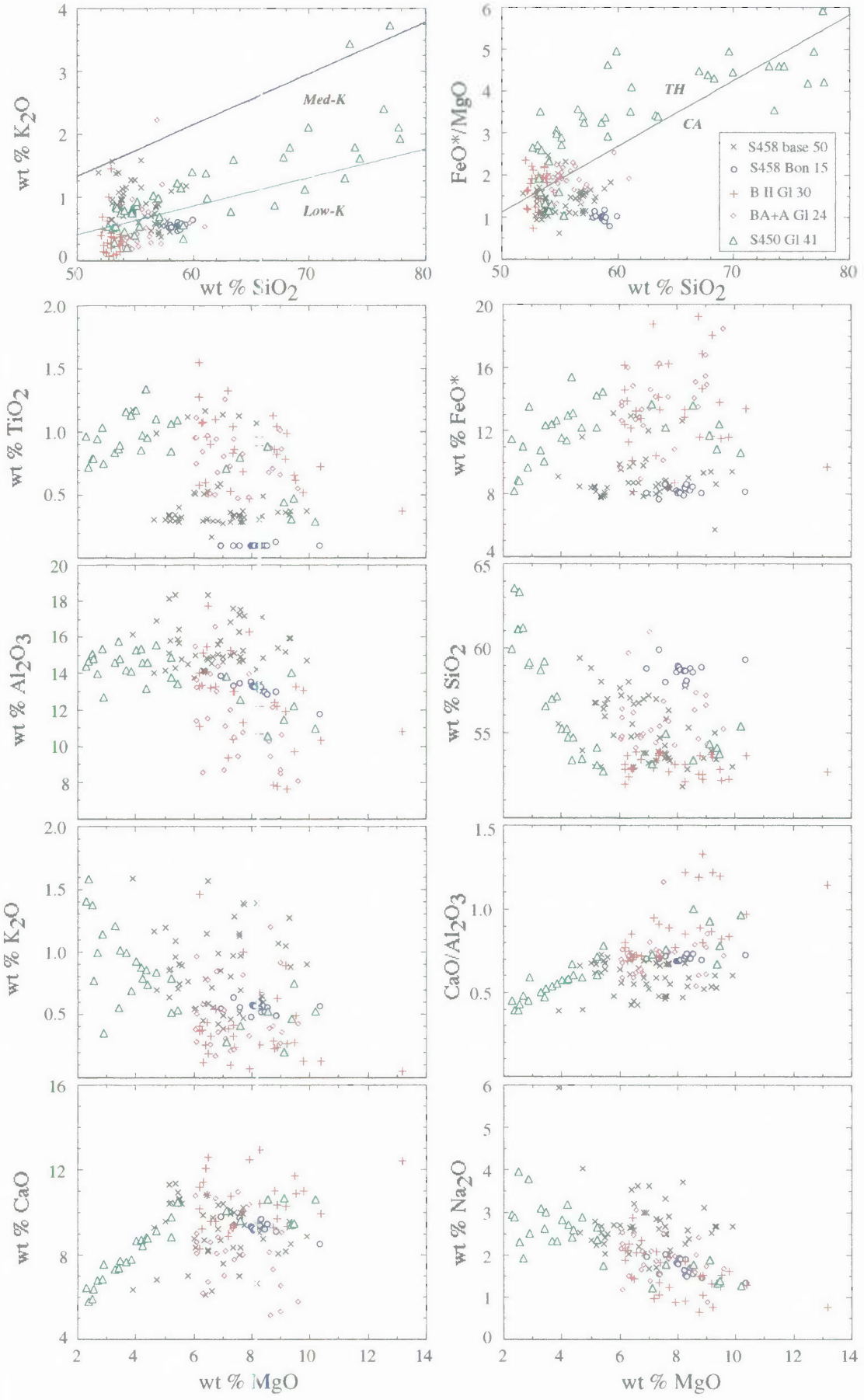

Figure 9-3 Comparison of compositions of individual basaltic and andesitic glass shards (B II Gl 30 and BA+A Gl 24)) from DSDP Leg 60 and ODP Leg 125 ash layers with drilled basement volcanic rocks in the Mariana forearc (S458 base 50 and S458 Bon 15) and representative glass shards from DSDP Leg 58 Site 450 (S450 Gl 41). See text for data sources and discussion.

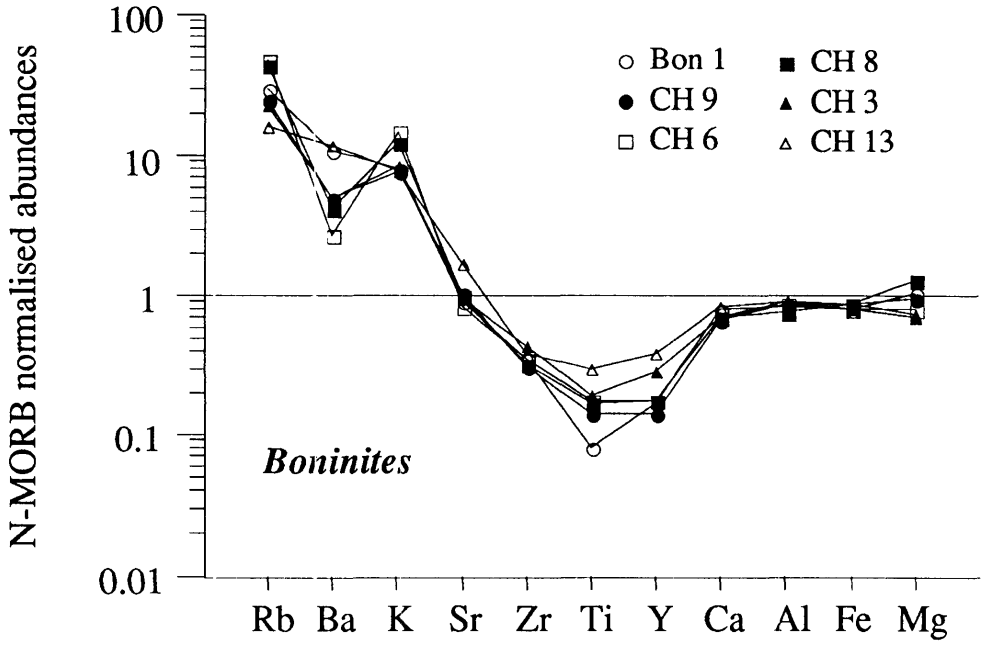

Figure 9-4 N-MORB normalised abundances of a representative boninite derived from DSDP Leg 60 Site 458 basement (Bon 1) compared with the Chichijima boninites (CH 3 to CH 13, from Arculus et al. 1992). See Figure 6-7 for the normalising values. See text for data sources and discussion.

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