Chapter 7 Trace Element Characteristics of Bulk Ashes and Bulk Glass Shards from DSDP Leg 60 and ODP Leg 125 Ash Layers

7.1 Introduction

Major and trace element analysis of individual glass shards shows that the majority of ash layers from DSDP Leg 60 Sites 458 and 459B and ODP Leg 125 Sites 782A, 784A and 786A are heterogeneous (Tables A 1-1 and A 1-2). Recent developments in the laser ablation microprobe-ICP-MS (LAM-ICP-MS) have shown that a comprehensive suite of trace element analytical data can be obtained (Westgate et al., 1995). The unavailability of such techniques during the present study required bulk trace element analytical work by ICP-MS on the relatively homogeneous ash layers. As demonstrated for volcaniclastic turbidites by Gill et al (1994), relatively homogeneous bulk ash samples (glass plus mineral shards) are good average samples of arc pyroclastic materials. High quality trace element (including all REE and HFS elements) data for volcanic ashes from island arcs are rare. Gill et al. (1994) reported ICP-MS data for 24 turbidites recovered by ODP Leg 126. Chen and Arculus (1994a) reported ICP-MS REE data only for the Izu-Bonin-Mariana volcanic ashes. In this Chapter a more comprehensive presentation of the trace element characteristics of bulk ash layers is made together with a systematic comparison of these data with published data for IBM volcanic rocks. Chondrite-normalised Ba-REE and N-MORB normalised multi-element patterns are combined to use for these comparative studies. Normalising values are from Sun and McDonough (1989) with the exception of Cr and Ni from Pearce (1983). The major element compositions of these 29 bulk ash samples are estimated by averaging all the individual glass shard data (see Tables A 3-15, A 3-16).

7.2 Trace Elements of bulk ashes from Leg 60 and Leg 125 ash layers

Seventeen representative ash layers from DSDP Leg 60 Sites 458 and 459B (among them, 4 heterogeneous layers) and 12 ash layers from ODP Leg 125 Sites 782A, 784A and 786A (among them, 1 heterogeneous layer) were chosen for ICP-MS trace element analysis. Furthermore, 6 bulk samples of pure glass shards were handpicked from their bulk ash layers for comparison. The six glass samples are from: the Izu-Bonin glasses (from Sites 782A, 784A and 786A) and Mariana glasses (from Sites 458 and 459B). All these 29 bulk ash samples and 6 bulk glass samples were handpicked and examined under binocular and optical microscopes to obtain samples free of rock fragments and sediments.

The ICP-MS data for these samples are given in Tables A 3-15 and A 3-16 of Appendix 3 and shown in Figures 7-1 and 7-2. The Mariana ashes are characterised by relatively flat, unfractionated REE patterns, generally within 10 to 30 times chondritic, regardless of age and composition. However, four samples (three heterogeneous and one homogeneous dacitic ash) have LREE-enriched patterns (La_N = 30 to 70 times chondritic). In addition, these four samples have higher LILE abundances such as K, Rb, Ba and Sr. Corresponding to the REE patterns, the N-MORB normalised multi-element patterns show "positive spikes" at Cs, K, Ba, and Pb, characteristic of island arc magmas. The abundances of LILE such as Cs, Rb, Ba, Th, U, K, La, Ce, Pb and Sr of LREE-enriched samples are significantly higher than those with unfractionated (relative to chondrites) REE, while the HFS element abundances are close to average N-MORB for mafic andesitic ashes. All these samples are relatively depleted in Cr and Ni.

The REE abundance pattern for the Izu-Bonin ashes are different from those of the Mariana ashes. Mostly, they are characterised by LREE-depleted patterns within 5 to 10 times La_N with HREE ~ 10 to 30 times chondritic, as is the case with the Mariana ashes during the period 0-17 Ma. The N-MORB normalised multi-element patterns are similar to those of the Mariana ashes but with overall lower LILE abundances (Figure 7-2).

7.3 Trace elements of bulk handpicked glasses from Legs 60 and 125 ash layers

The major and trace element data of the six handpicked bulk glass samples and their respective bulk ash layer hosts are listed in Table A 3-14 of Appendix 3 and shown in Figure 7-3. It is clear that the chondrite-normalised Ba-REE and N-MORB normalised multi-element patterns of bulk glass and their corresponding bulk ash samples are very similar. Obvious conclusions are that the ash layers are dominated by glasses, and that analysis of bulk samples (mineral fragments together with glass) is a close approximation to the original liquid compositions.

The chemical compositions of the six handpicked bulk glass shards range from basaltic andesite through andesite to dacitic-rhyolite. Generally, the LILE (including REE) abundances increase with increase of SiO_2. The three Izu-Bonin glass samples are LREE-depleted (4 to 7 times La_N) and have lower LILE abundances than the three Mariana bulk glasses, which are REE-flat to LREE-enriched (at 10 to 80 times La_N). All these bulk glass samples have a similar range of HREE abundances within 10 to 30 times chondrite and similar ranges of HFSE close to the average for N-MORB.

7.4 Trace element comparison of IBM bulk ashes and IBM volcanic rocks

There are extensive separate and combined studies of the Izu-Bonin and Mariana arc-backarc system as briefly discussed above. Data references for the IBM arc-backarc system are listed in Chapter 4. Relative to the major element data, there are fewer combined major and trace element data sets, especially including REE. In order to understand more clearly the systematics of these island arc-backarc magma types, chondrite-normalised Ba-REE pattern and N-MORB normalised multi-element patterns are combined to compare the IBM bulk ashes with the IBM arc-backarc volcanic rocks.

Available trace element data for the Eocene-Oligocene and Miocene Mariana volcanic rocks are shown in Figure 7-4A. Clearly, there are a lack of good quality data of LILE, REE and HFSE for the Site 448 igneous basement. In particular, there are few good quality combined major and trace element data for Mariana Miocene volcanic rocks. The Eocene-Oligocene Mariana volcanic rocks (e.g., Mattey et al., 1980; Scott, 1980; Meijer, 1983) have flat REE patterns at 10 to 30 times chondritic. Two Mariana Miocene volcanic rocks have LREE-enriched patterns at 70 to 200 times chondritic at La but HREE-flat patterns at 10 to 30 times chondritic at Yb (Hickey and Reagan, 1987). It is difficult to infer any systematics from the relatively poor N-MORB normalised multi-element patterns for these older Mariana volcanic rocks.

For modern Mariana subaerial and submarine volcanic rocks, there are substantial REE data but relatively few LILE (other than REE) and HFSE data. Representative data are plotted in Figures 7-4B,C and D. There are three types of REE patterns: type 1 is flat at 10 to 30 times chondritic and type 1a is LREE-enriched at 30 to 70 times chondritic but with flat HREE at 10 to 30 times chondritic patterns; type 2 also has flat LREE at 10 to 30 times chondritic but are HREE-slightly depleted (5 to 30 times chondritic at Yb) patterns and type 2a is slightly LREE-enriched at 30 to 80 times chondritic at La but depleted at 5 to 30 times chondritic at Yb patterns; type 3 is strongly enriched in the LREE (> 80 times chondritic but with flat HREE at 10 to 30 times chondritic. Typically, Eu and Ce anomalies are not developed. Generally, all of the SSP and CSP volcanic rocks, most of the southern NSP and about half of the subaerial Mariana arc (including Asuncion, Guguan, Pagan, Maug) volcanic rocks have type 1 and type 1a REE patterns. Most of the northern NSP volcanic rocks have type 3 REE patterns. About half of the Mariana arc (mainly Agrigan, Alamagan, Antaham, Sarigan and Uracas) volcanic rocks show type 2 and type 2a REE patterns. Types 2 and 3 have not been observed among the ash patterns.

Representative trace element data from the Izu-Bonin volcanic rocks and turbidites are shown in Figures 7-2, 7-5A and B. Excluding IwoJima, all the other samples have very similar patterns that are LREE-depleted to flat at 4 to 10 times chondritic, HREE-flat at 6 to 30 times chondritic, and with minor Ce and Eu anomalies. IwoJima volcanic rocks are quite different and exhibit strong LREE enrichment with more than 200 times chondritic at La but generally flat HREE at 20 to 40 times chondritic at Yb patterns. The ODP Leg 125 ashes have very similar REE patterns to the Izu-Bonin volcanic rocks, especially those from Torishima (see Figure 2-3). Interestingly, about half of the turbidites of 0-17 Ma age have REE patterns similar to those of equivalent age ODP Leg 125 ashes. More than 85% of the turbidites studied by Gill et al. (1994) have REE patterns similar to those of DSDP Leg 60 ashes. They do not show any temporal changes during the arc's evolution. Data from the Izu-Bonin subaerial and drilled tholeiitic basement volcanic rocks also support this conclusion (Figure 7-5A; Gill et al., 1994). Within the group characterised by overall flat REE patterns (10 to 30 times chondritic), the REE abundances increase with increase of SiO_2, consistent with a genesis of the spectrum of compositions of arc magmas (volcanic rocks and ashes) by fractional crystallisation.

The majority of the IBM forearc basement volcanic rocks are quite different and belong to a boninitic series (e.g., Pearce et al., 1992; Taylor, 1992). Representative Ba-REE- and N-MORB -normalised patterns are shown in Figure 7-6. Clearly, they have very low Ba, REE and HFSE abundances and the MREE are lightly depleted. Representative trace element data of MORB and the modern IBM backarc basin volcanic rocks are also plotted in Figures 7-3 and 7-7. Compared to the IBM ashes, these MORB and backarc basin samples have lower LILE abundances but similar REE patterns. The majority of IBM volcanic ashes and rocks and MORB have flat, chondrite-normalised REE patterns, indicating that they are derived primarily from similar upper mantle source (with similar spinal peridotite residues) by equivalent percent of melting.

The abundances of relatively hydrous-fluid-immobile HFSE (Zr, Hf, Nb, and Ta) for the IBM ashes and turbidites, IBM arc and backarc volcanic rocks, MORB and adakites from Aleutians (e.g., Kay, 1978; Myers et al., 1985) are shown in Figure 7-8. The IBM ashes have similar HFSE abundance with IBM arc volcanic rocks, and MORB, indicative of a common mantle source. However, the abundances of LILE such as Ba and Pb vary greatly for these volcanic rocks. In general, the Ba and Pb abundances of IBM ashes are within the ranges of the IBM arc volcanic rocks and are higher than those of the back arc basin rocks (Figure 7-8). From Figures 7-1 to 7-8, it is clear that there is a shortage of good quality LILE and HFSE abundance data for arc and backarc basin volcanic rocks. The 29 IBM volcanic ashes, which provide a comprehensive set of good quality trace element data, are representative of the IBM subaerial volcanic activity with the exception of IwoJima. They probably derived from the N-MORB type mantle source.

7.5 Summary

Based on the LILE and HFSE abundance data for bulk ashes and glasses from DSDP Leg 60 and ODP Leg 125, and comparisons of these data with IBM volcanic rocks and MORB, the following conclusions can be drawn:

1. The chemical compositions of six, representative, hand-picked bulk glass shard samples, ranging from basaltic andesite through andesite to dacitic rhyolite, are very similar to their corresponding bulk ash samples, indicating that the major component of these ash layers is glass.

Bulk ashes of homogeneous ash layers can be used to represent the average chemical compositions of island arc volcanic rocks.

2. The 17 representative bulk ashes from DSDP Leg 60 spanning a major portion of the arc's history (0-35 Ma) have very similar REE patterns (relatively flat abundances REE at 10 to 30 times chondrite) and N-MORB-normalised patterns, with peaks at Cs, K, Ba, Pb and similar to that of N-MORB for HFSE. No consistent temporal change is observed. However, some bulk ashes are LREE-enriched (30 to 70 times chondritic at La) and with higher LILE abundances do occur at ~ 2 Ma and 8-11 Ma. The trace element abundances of the 17 bulk ashes are very similar to those of Mariana subaerial volcanic rocks, indicating that they are tholeiitic series derived from common sources through similar petrogenetic processes.

3. The 12 representative bulk ashes from ODP Leg 125, ranging from 0-17 Ma in age, are distinctive when compared with DSDP Leg 60 bulk ashes having lower LREE and LILE abundances. Half of the turbidite samples of the same age range (0-17 Ma) have similar REE patterns to the ashes. More than 85% of the turbidites studied by Gill et al. (1994) have very similar REE patterns with the DSDP Leg 60 ashes and they do not show any temporal changes during the arc's evolution. Data from the Izu-Bonin subaerial and drilled tholeiitic basement volcanic rocks also support this conclusion.

4. The majority of the IBM volcanic ashes and rocks belong to tholeiitic series. Compared to MORB, the IBM bulk ashes and volcanic rocks (excluding IwoJima) have much higher LILE abundances but very similar REE patterns. These data are consistent with the hypothesis that the major source of most of the IBM magmas is in a MORB-type mantle wedge that has been subjected to inputs from the subducted Pacific Plate.

5. On the basis of distinctive characterisation of REE, LILE and HFSE abundances, the IBM bulk ashes are different from the Eocene-Oligocene IBM forearc basement volcanic rocks, the majority of which belong to boninitic series. No boninitic ashes have been found to date.

DSDP Leg 60 Bulk Ashes

Chondrite-normalised Ba-REE patterns
A

N-MORB normalised multi-element patterns
B

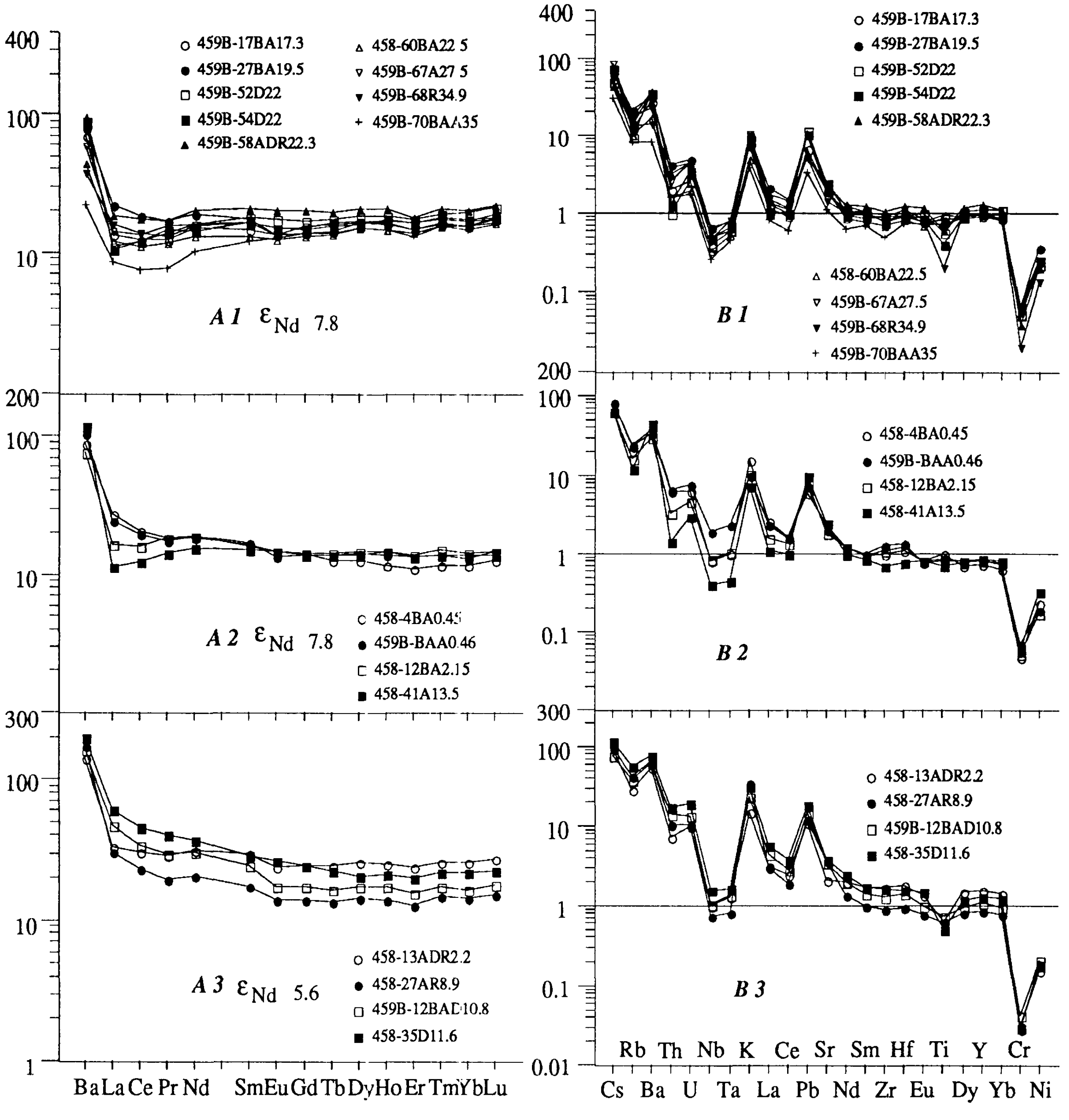

Figure 7-1 Comparison of chondrite-normalised Ba-REE patterns (A1, A2, A3) and N-MORB normalised multi-element patterns (B1, B2, B3) of bulk ashes from DSDP Leg 60 Sites 458 and 459B. Notation by the specific sample symbols is Site number followed by layer number, compositional type (BA-basaltic andesite, A-andesite, D-dacite, R-rhyolite) and age in Ma. The normalising values are from Sun and McDonough (1989). See appendix for samples and text for discussion.

ODP Leg 125 Bulk Ashes and Torishima Volcanic Rocks

Chondrite-normalised Ba-REE patterns *A* N-MORB normalised multi-element patterns *B*

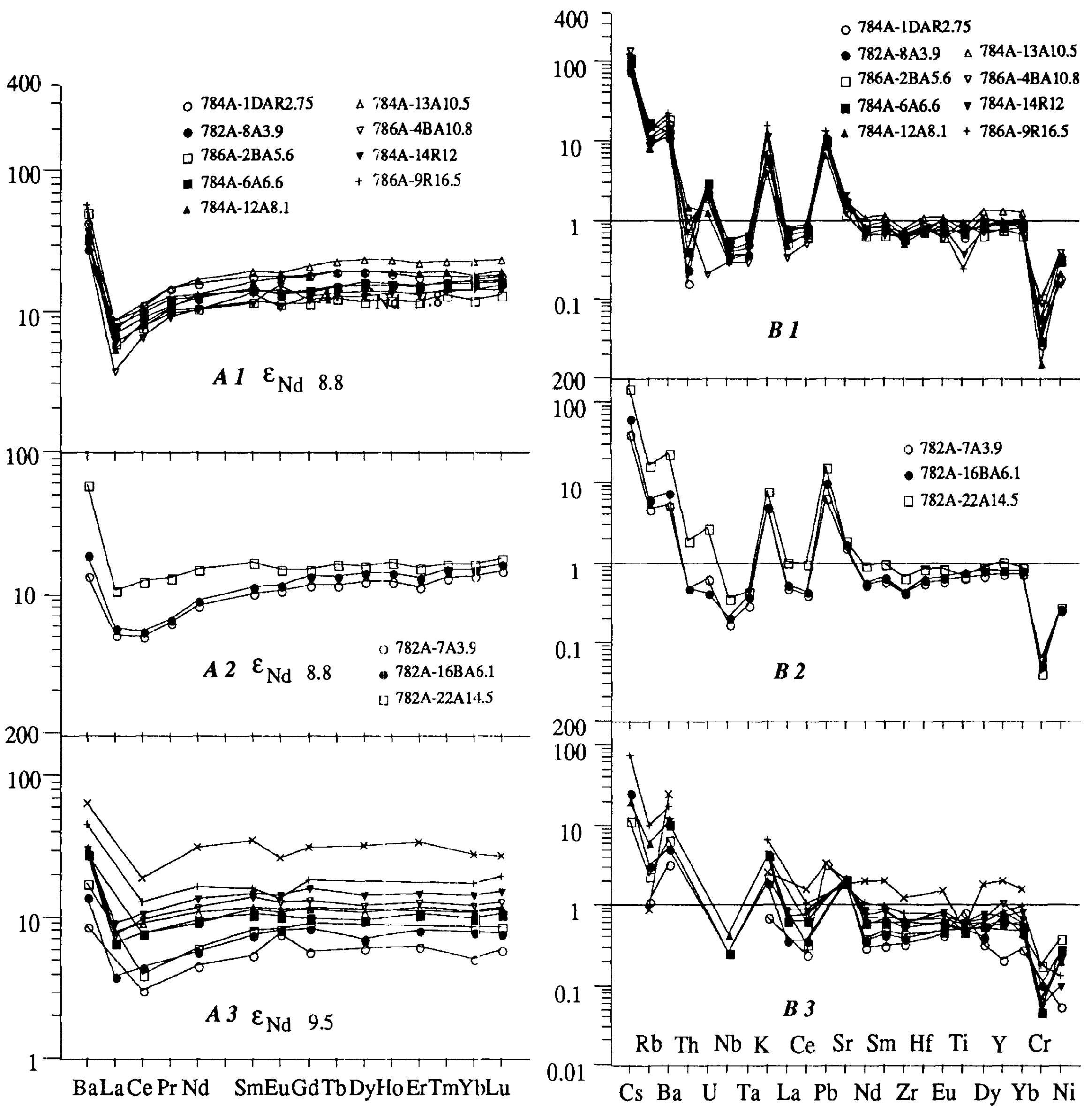

Figure 7-2 Comparison of chondrite-normalised Ba-REE patterns (A) and N-MORB normalised multi-element patterns (B) of bulk ashes from ODP Leg 125 Sites 782A, 784A, and 786A ash layers (A1, A2; B1, B2) and Torishima island arc volcanic rocks (A3, B3) (from Langmuir et al. 1995). Notation by the specific sample symbols is Site number followed by layer number, compositional type (BA-basaltic andesite, A-andesite, D-dacite, R-rhyolite) and age in Ma. The normalising values are from Sun and McDonough (1989). See appendix for samples and text for discussion.

Bulk Volcanic Ashes and Glasses plus MORB and MORB Glasses

Chondrite-normalised Ba-REE patterns N-MORB normalised multi-element patterns

A *B*

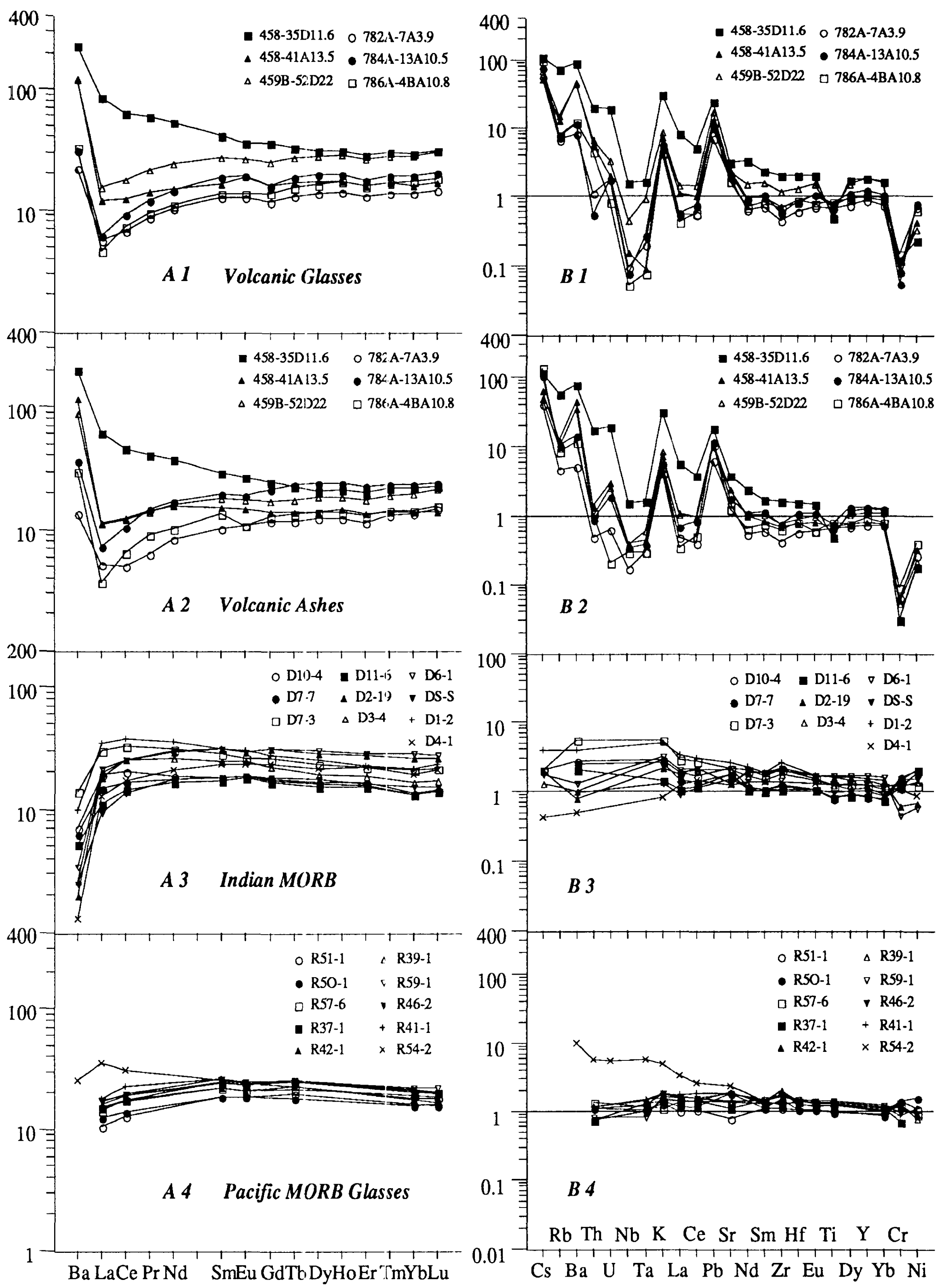

Figure 7-3 Comparison of chondrite-normalized Ba-REE patterns (A) and N-MORB normalized multi-element patterns (B) of representative bulk volcanic ashes (A2 and B2) and their bulk glass shards (A1 and B1) from DSDP Leg 60 and ODP Leg 125 ash layers with Indian MORB(A3 and B3) and Pacific MORB glasses (A4 and B4). The normalizing values are from Sun and McDonough (1989). See Figure 7-1 and 7-2 for notation and text for data sources and discussion.

Mariana Arc Volcanic Rocks (Eocene ~ Miocene)

Chondrite-normalised Ba-REE patterns *A* N-MORB normalised multi-element patterns *B*

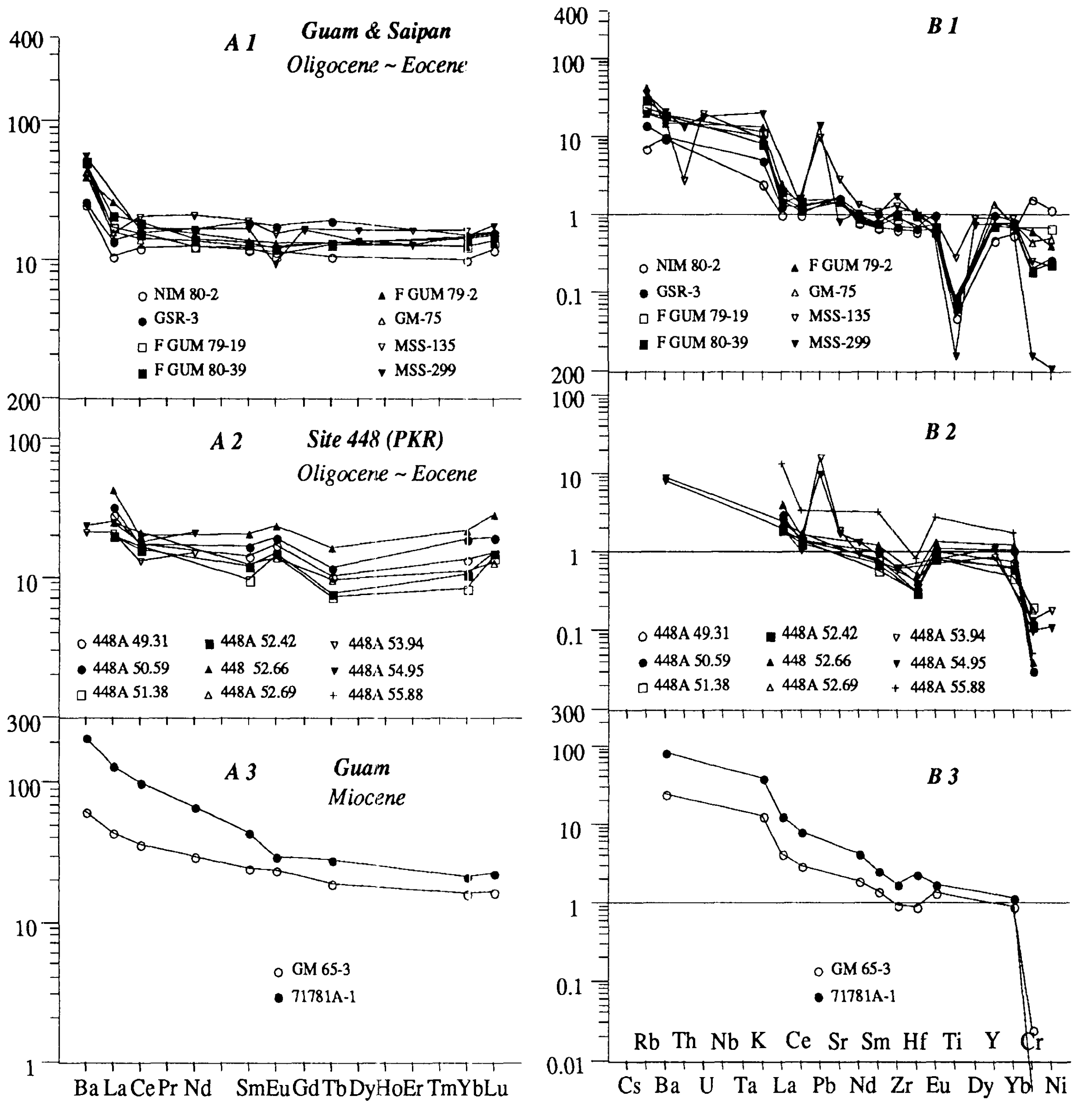

Figure 7-4A Comparison of chondrite-normalised Ba-REE patterns (A) and N-MORB normalised multi-element patterns (B) of representative Mariana arc volcanic rocks: Guam and Saipan arc volcanic rocks (A1, B1), Site 448 drilled volcanic rocks (A2, B2) and Miocene Guam arc volcanic rocks (A3, B3). Notation by the specific sample symbols is taken from original authors however, sample symbols of Site 448 are the Site number followed by SiO_2 contents. The normalising values are from Sun and McDonough (1989). See text for data sources and discussion.

Mariana Arc Volcanic Rocks (Modern Subaerial)

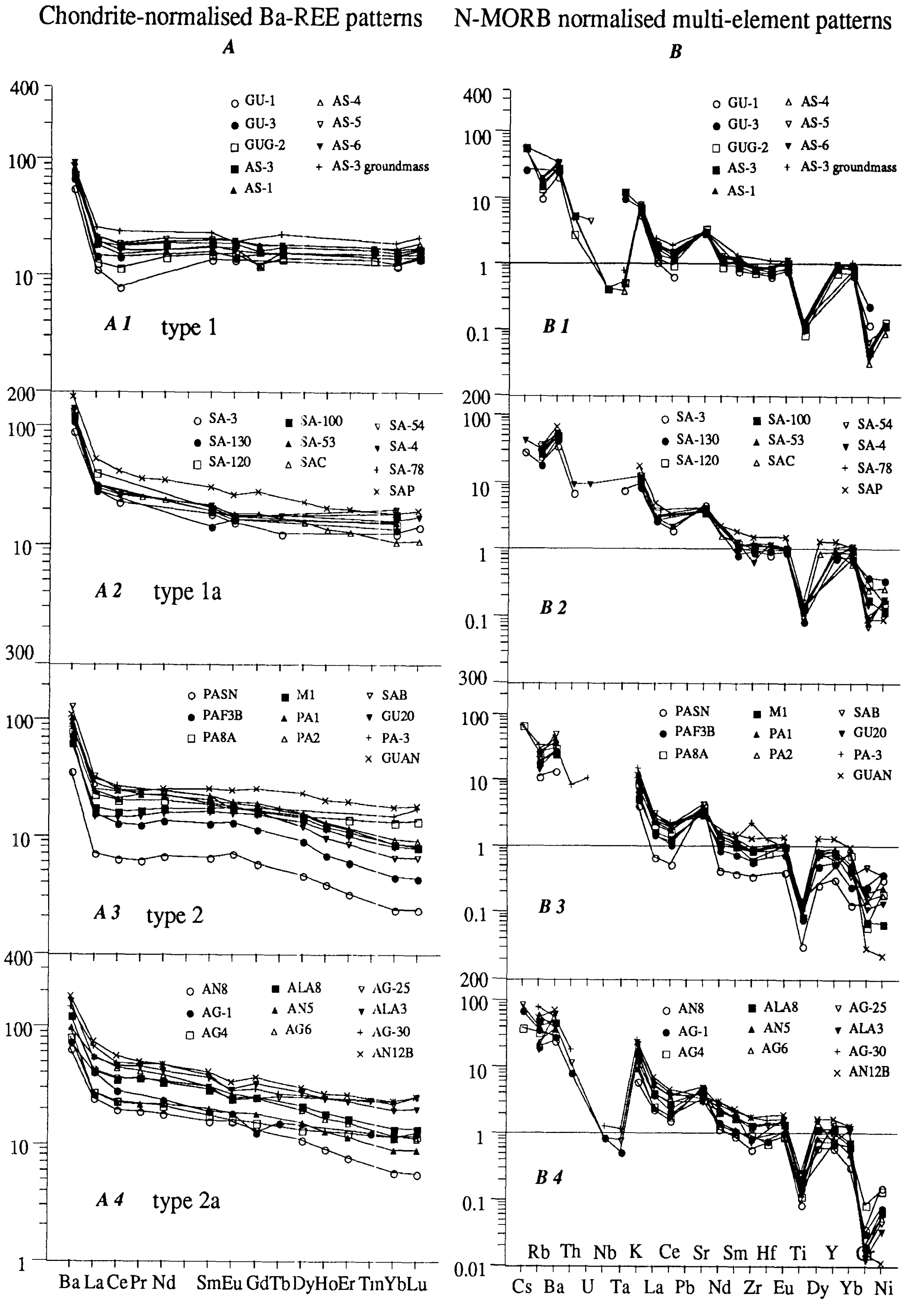

Figure 7-4B Comparison of chondrite-normalised Ba-REE patterns (A) and N-MORB normalised multi-element patterns (B) of representative Mariana arc subaerial volcanic rocks. Notation by the specific sample symbols is taken from the original authors. The normalising values are from Sun and McDonough (1989). See text for type 1, 1a, 2 and 2a, data sources and discussion.

Mariana Arc Volcanic Rocks (Modern Submarine)

Chondrite-normalised Ba-REE patterns N-MORB normalised multi-element patterns
A *B*

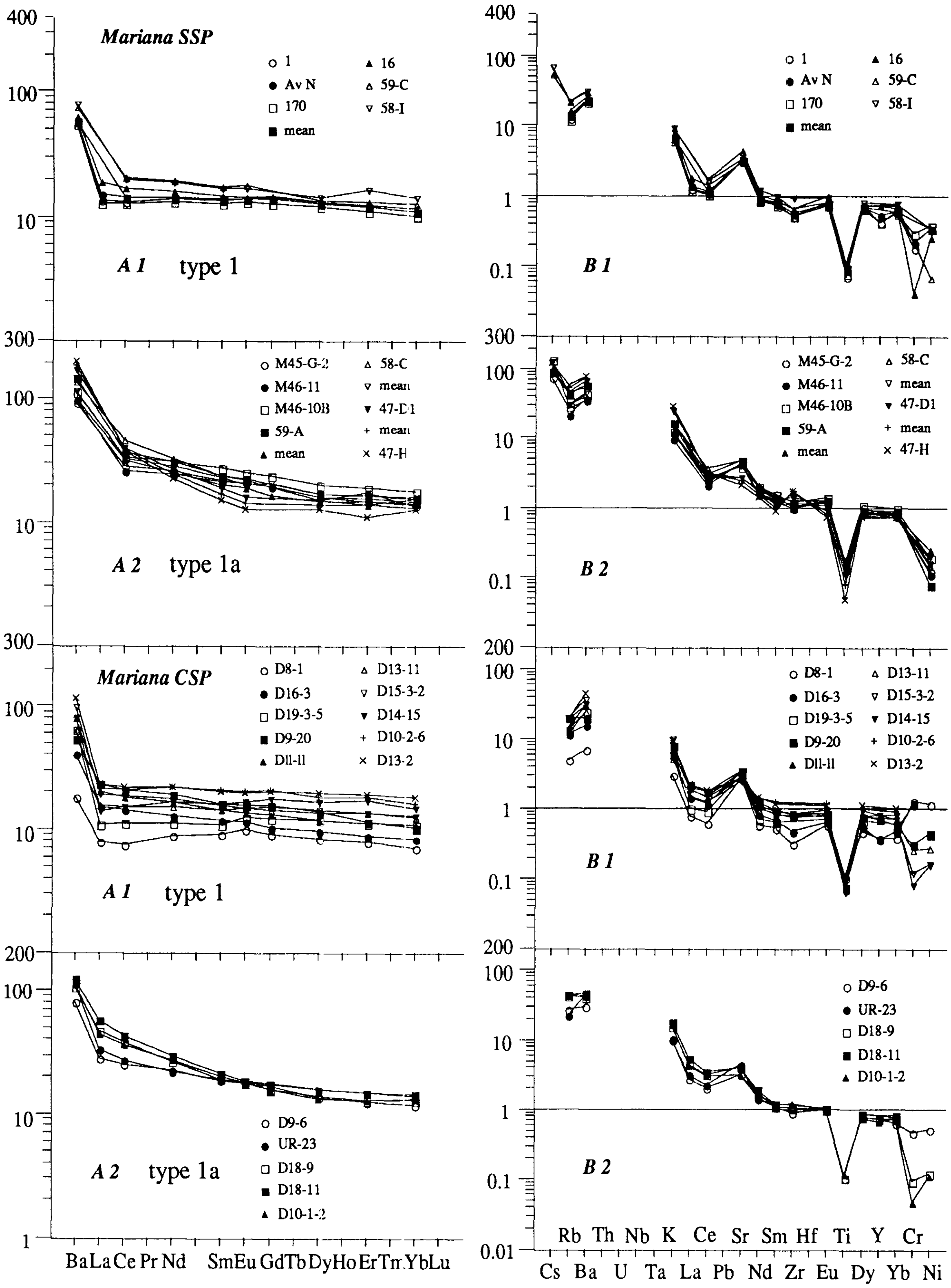

Figure 7-4C Comparison of chondrite-normalised Ba-REE patterns (A) and N-MORB normalised multi-element patterns (B) of representative Mariana modern submarine arc volcanic rocks (SSP and CSP). Notation by the specific sample symbols is taken from the original authors. The normalising values are from Sun and McDonough (1989). See text for type 1, 1a, data sources and discussion.

Mariana Arc Volcanic Rocks (Modern Submarine)

Mariana NSP

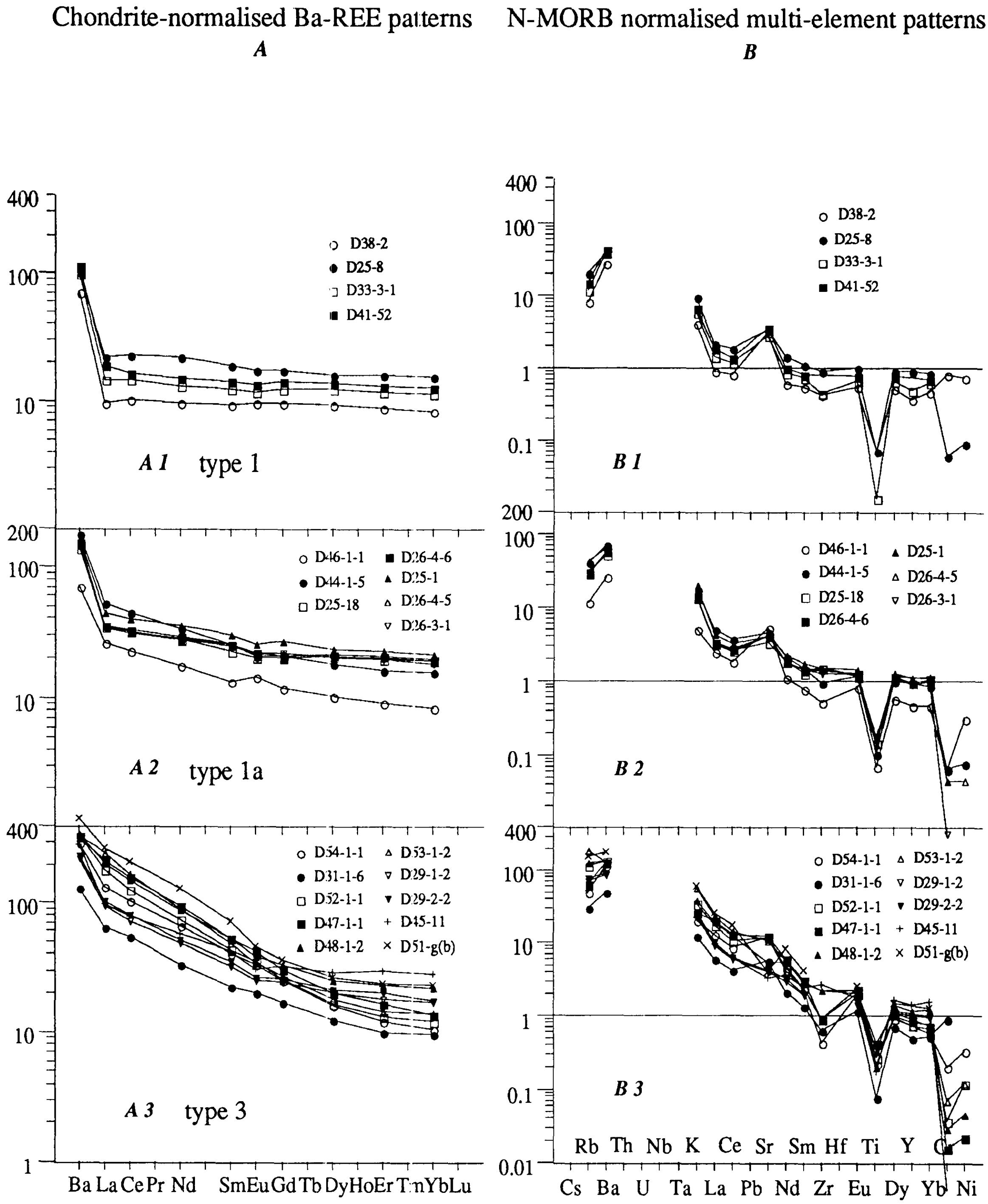

Figure 7-4D Comparison of chondrite-normalised Ba-REE patterns (A) and N-MORB normalised multi-element patterns (B) of representative Mariana modern submarine arc volcanic rocks (NSP). Notation by the specific sample symbols is taken from the original authors. The normalising values are from Sun and McDonough (1989). See text for type 1, 1a and 3, data sources and discussion.

Izu-Bonin Arc Volcanic Rocks (Subaerial & Submarine)

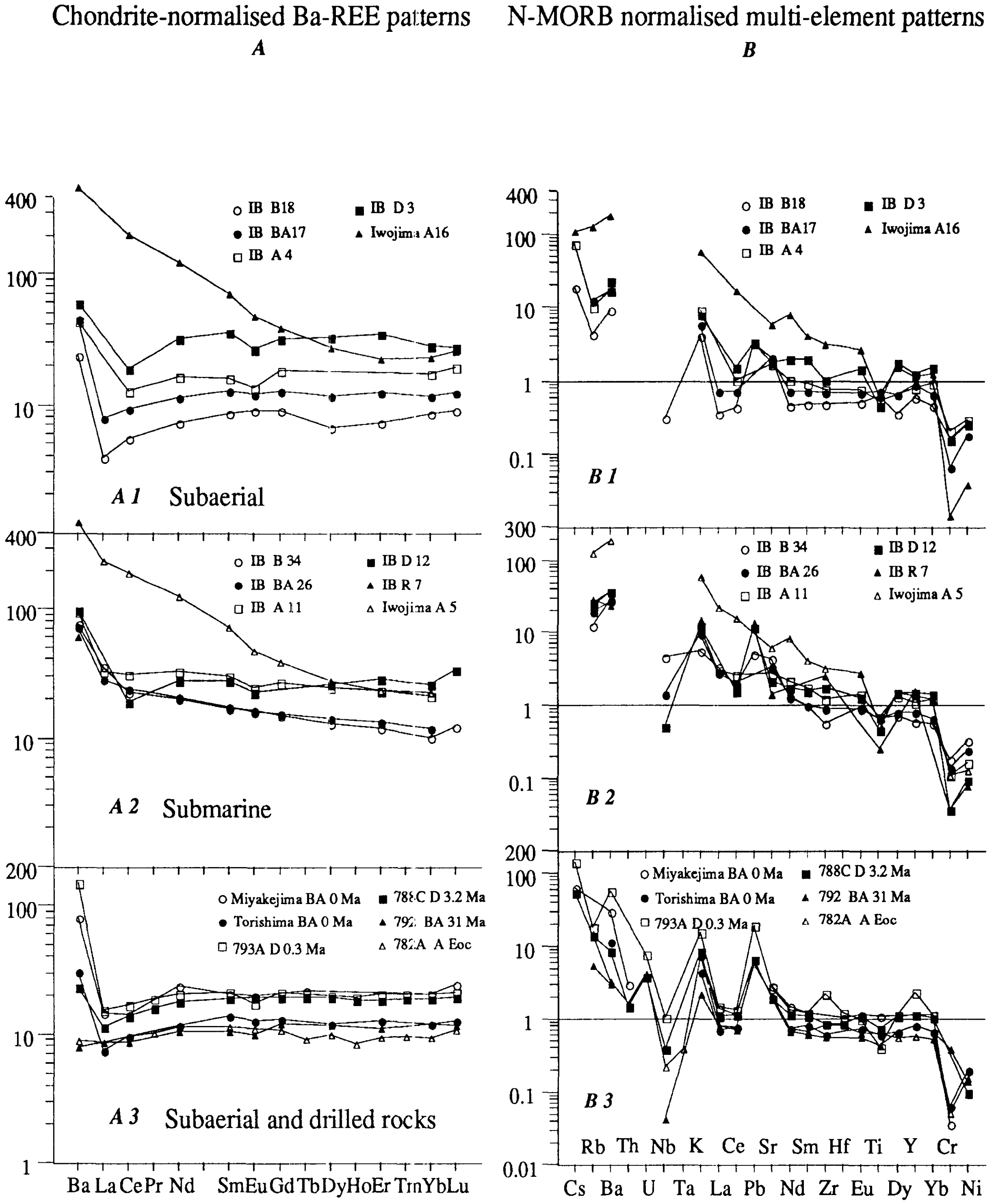

Figure 7-5A Comparison of chondrite-normalised Ba-REE patterns (A) and N-MORB normalised multi-element patterns (B) of representative Izu-Bonin arc volcanic rocks (subaerial, A1 and B1; submarine, A2 and B2, and subaerial and drilled ODP Leg 126 volcanic rocks, A3 and B3). Notation by the specific sample symbols is arc name or Site number followed by compositional type (B-basalt, BA-basaltic andesite, A-andesite, D-dacite, R-rhyolite) and analysis number for average or age in Ma. The normalising values are from Sun and McDonough (1989). See text for data sources and discussion.

ODP Leg 126 Forearc Sites Turbidites

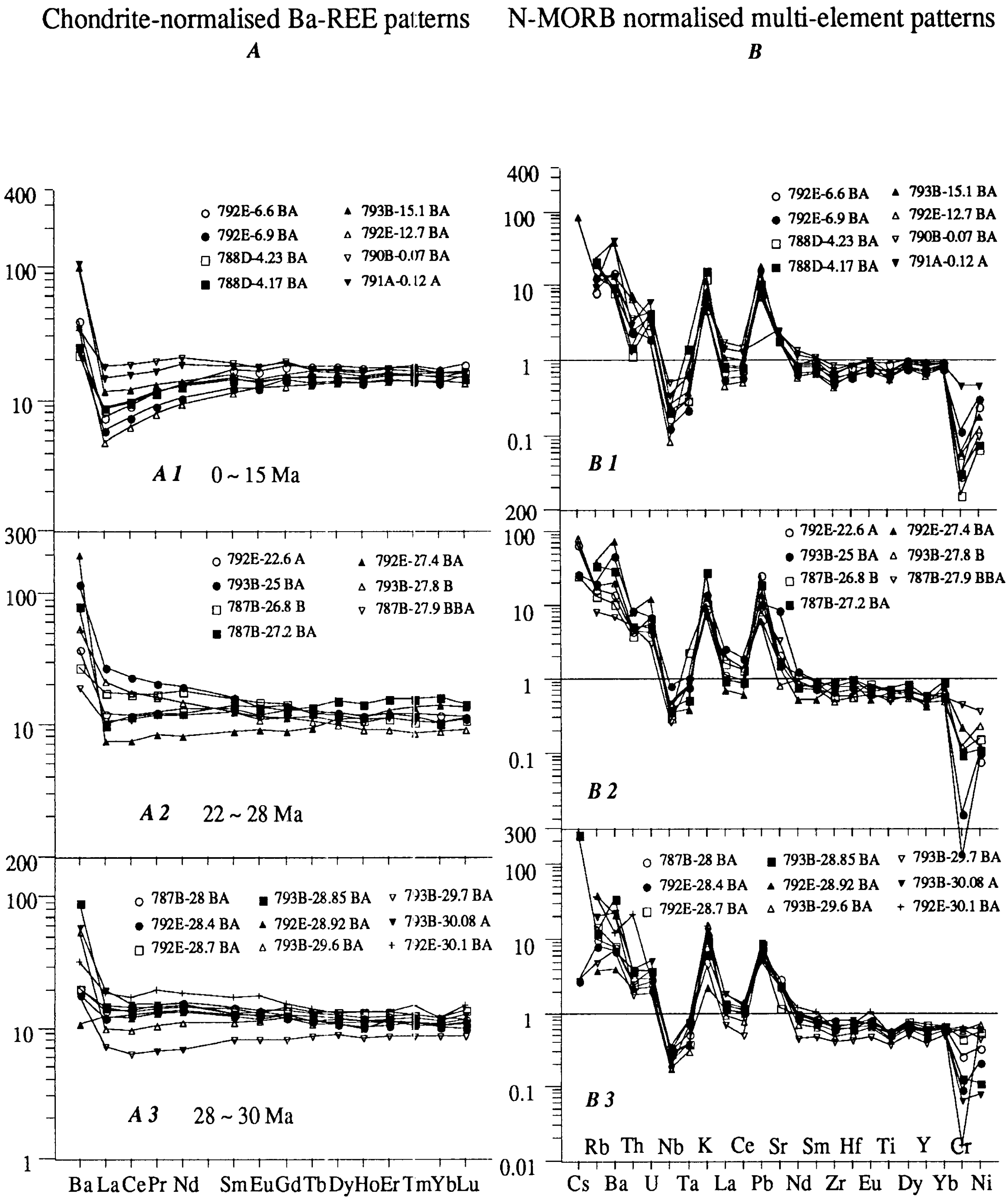

Figure 7-5B Comparison of chondrite-normalised Ba-REE patterns (A) and N-MORB normalised multi-element patterns (B) of representative turbidites recovered from ODP Leg 126 forearc Sites (0-30 Ma, A1, A2 and A3, from Gill et al. 1994). Notation by the specific sample symbols is Site number followed by age in Ma and compositional type (B-basalt, BA-basaltic andesite, A-andesite). The normalising values are from Sun and McDonough (1989). See text for discussion.

Drilled Basement Volcanic Rocks in the IBM Forearc

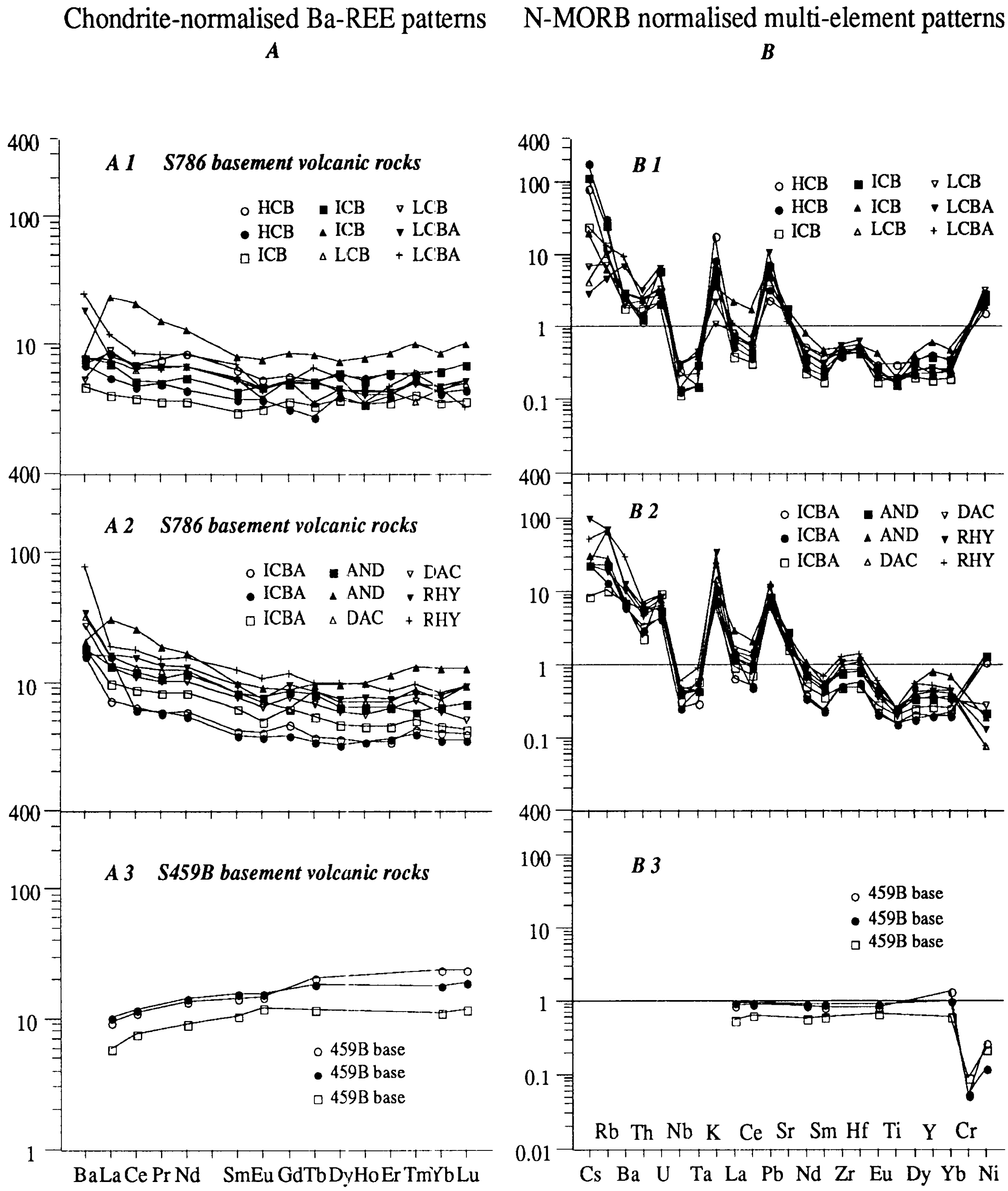

Figure 7-6 Comparison of chondrite-normalised Ba-REE patterns (A) and N-MORB normalised multi-element patterns (B) of representative basement volcanic rocks recovered from ODP Leg 125 Site 786 (A1, A2 and B1, B2) and DSDP Leg 60 Site 459B (A3 and B3). Notation by the specific sample symbols is taken from the original authors. The normalising values are from Sun and McDonough (1989). See text for data sources and discussion.

IBM Backarc Basin Volcanic Rocks and MORB

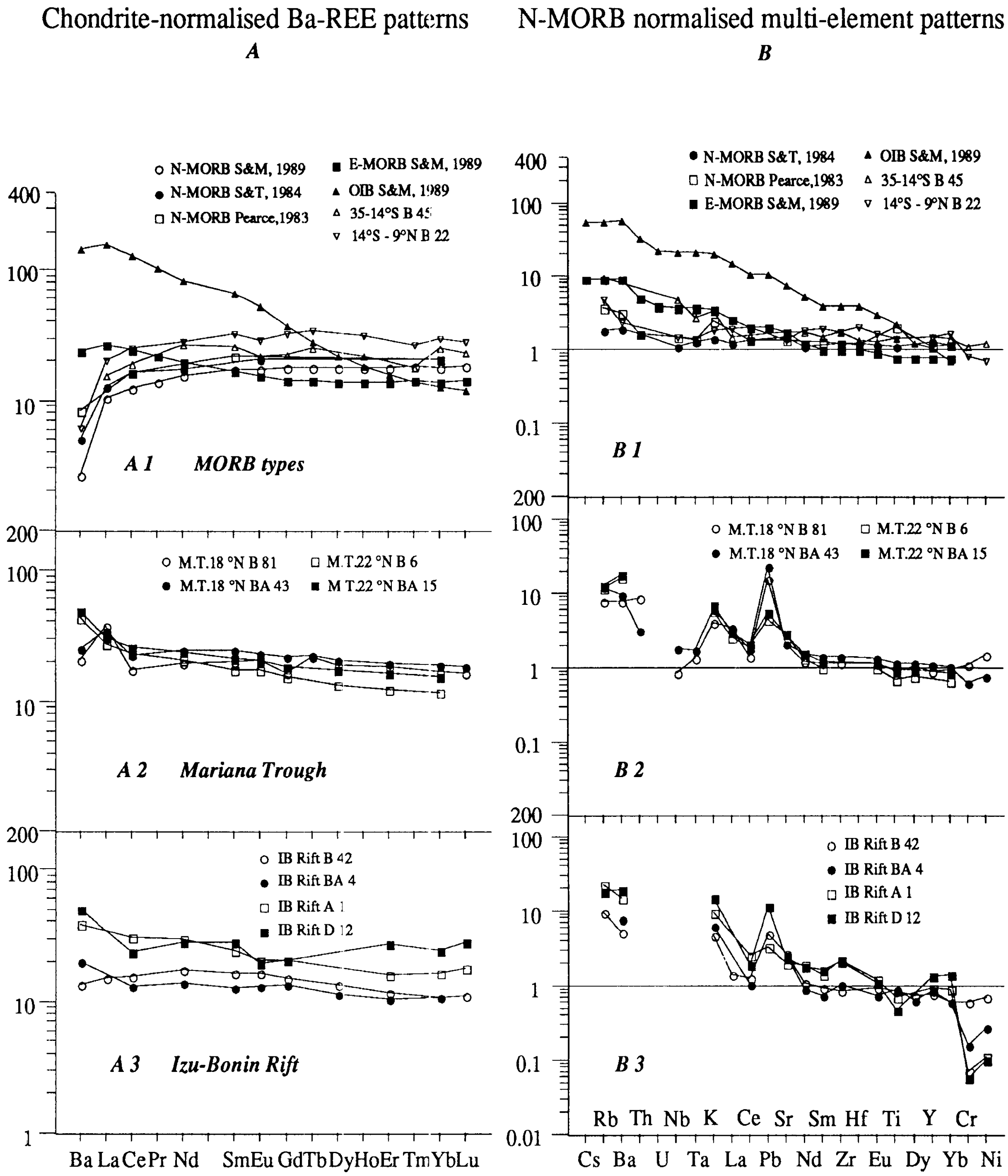

Figure 7-7 Comparison of chondrite-normalised Ba-REE patterns (A) and N-MORB normalised multi-element patterns (B) of representative volcanic rocks of MORB types (A1 and B1), Mariana Trough (A2 and B2) and Izu-Bonin rift (A3 and B3). Notation by the specific sample symbols is location followed by compositional type (B-basalt, BA-basaltic andesite, A-andesite, D-dacite) and analysis number for average. S &M is Sun and McDonough, S & T, Saunders and Tarney, 35°S-14°S and 14°S-9°N are from the Pacific ocean. The normalising values are from Sun and McDonough (1989). See text for data sources and discussion.

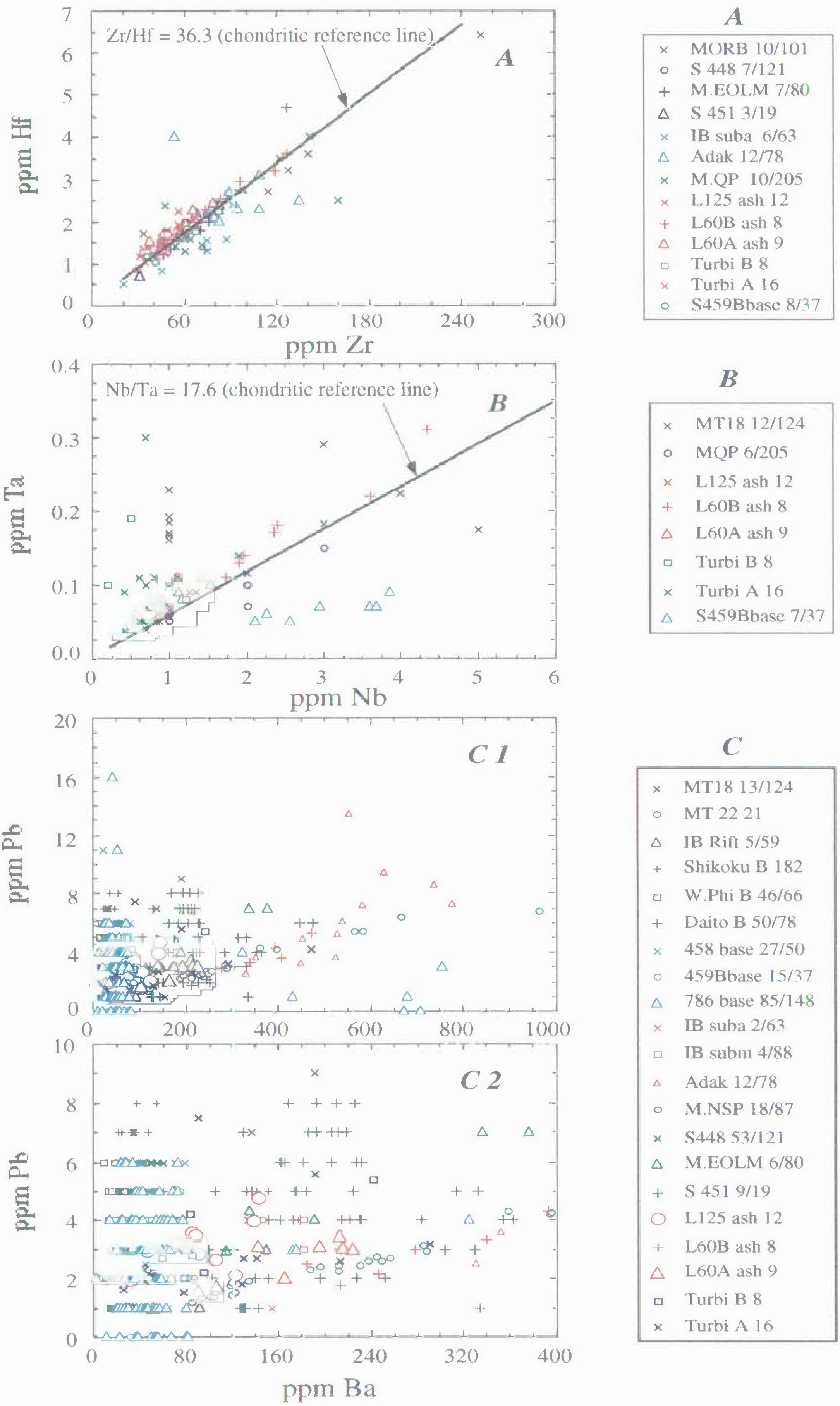

Figure 7-8 Comparison of trace element compositions (A: Hf vs. Zr, B: Ta vs. Nb, and C1 & C2: Pb vs. Ba) of representative bulk ashes from DSDP Leg 60 and ODP Leg 125 with IBM arc and backarc volcanic rocks (subaerial and submarine), turbidites, MORB and Adak volcanic rocks from Aleutian arc. The reference lines of Zr/Hf = 36.3 and Nb/Ta = 17.6 are from Sun and McDonough (1989). See text for data sources and discussion.

Chapter 8 Sr-Nd Isotopic Characteristics and Significance of Ba/Rb of Volcanic Ashes from DSDP Leg 60 and ODP Leg 125

8.1 Introduction

In the preceding chapters, it has been shown that the trace element abundances of IBM ashes are very similar to those of IBM subaerial volcanic rocks with the exception of IwoJima and the IBM forearc basement boninitic series. A number of isotopic studies of IBM volcanic rocks, including back-arc samples, have been published (e.g., Notsu et al., 1983; Lin et al., 1990; Hickey-Vargas, 1991; Stern et al., 1993; Langmuir et al., 1994). However, isotopic data for volcanic ashes are rare. Egeberg et al. (1992) reported 26 Sr and Nd isotopic ratios of bulk glass shards from megascopic tephras recovered from ODP Leg 126 site 792. Chen and Arculus (1993a, 1994a) reported briefly Sr and Nd isotopic ratios of bulk ashes recovered from ODP Leg 125 and DSDP Leg 60 in the IBM forearc. In this Chapter, Sr and Nd isotopic characteristics of bulk ashes are presented in detail and compared with available data for IBM volcanic rocks. These data are used in answering the questions: - "are there any significant differences between IBM bulk ashes and volcanic rocks; and are there any temporal isotopic changes during the IBM arcs' evolution?". In addition, the most highly incompatible (in mantle melting) elements (Ba and Rb) Ba/Rb values of island arc volcanic rocks are reviewed and are systematically compared with those of mantle sources, subducted slab and oceanic sediments. The significance of Ba/Rb ratios for the genesis of island arc volcanic rocks is also discussed.

8.2 Sr and Nd isotopic ratios of bulk ashes from studied ash layers

On the basis of ~ 1750 major element data of individual glass shards from 184 bulk ash samples (133 DSDP Leg 60 ash layers and 51 ODP Leg 125 ash layers), 24 ash layers from DSDP Leg 60 and 22 ash layers from ODP Leg 125 were selected for Sr and Nd isotopic analysis. Among these 46 samples, 26 are relatively homogeneous and 11 are heterogeneous. Significant dilution of the ash component with nannofossil marls, chark and clay is present in 4 of the homogeneous and 4 of the heterogeneous layers. These samples were selected to indicate the possible trends of contamination in the erstwhile pure ash layers. One additional sample was taken from the boninitic basement of Site 458. These ash samples span the IBM arcs' explosive history from a mid-Eocene inception to the present and cover the spectrum of glass compositions ranging from basaltic andesite through andesite to dacite and rhyolite (Table A 3-17 of Appendix 3). Isotopically, the 45 ash samples are representative of the deep-sea volcanic ash layers studied.

All Sr and Nd isotopic data are listed in Tables A 3-17 of Appendix 3 and shown in Figure 8-1. The detailed sample treatment and isotopic analytical techniques are reported in Appendix 2. The Mariana ash samples have uniform $^{87}Sr/^{86}Sr$ ratios from 0.70350 to 0.70397. The Izu-Bonin ash samples have uniform $^{87}Sr/^{86}Sr$ ratios from 0.70339 to 0.70379. The average $^{87}Sr/^{86}Sr$ ratios for the Izu-Bonin ashes is slightly lower (0.70361) than that of the Marianas (0.70376) but may not be significant given the analytical errors. The $^{87}Sr/^{86}Sr$ ratios for Izu-Bonin and Mariana ashes are essentially constant over 2400 km of arc strike length, and all range between the relatively narrow limits of 0.70339 and 0.70397 throughout the arcs' explosive history from a mid-Eocene inception to the present, regardless of the nature of the rock types (Figures 8-1A and 8-2). However, the boninitic basement has significantly higher $^{87}Sr/^{86}Sr$ ratio (0.70468). The pore water collected from 784A-13# bulk ash has a very high $^{87}Sr/^{86}Sr$ ratio 0.70774 (Table A 2-1 of Appendix 2), similar to that of interstitial water of Site 784A (0.70703-0.70853, Haggerty and Chaudhuri, 1992) and sea water (~ 0.7090, Hess et al., 1986). The 8 ash samples containing about 2-90 volume percent sediments show that the $^{87}Sr/^{86}Sr$ ratios generally increase from 0.70390 to 0.71108 with an increase in amount of sediment from ~ 2 vol % to 90 vol % (Table A 3-17 and Figure 8-1C).

The $^{143}Nd/^{144}Nd$ reported as ε_{Nd} - deviation in parts per 10^4 of the $^{143}Nd/^{144}Nd$ of the sample compared with a present day value of 0.512638 for a chondritic uniform reservoir for the Izu-Bonin and Mariana ashes have similar ranges from +9.5 to +5.3 during the arcs' explosive history (Table A 3-17 and Figure 8-1B). In detail however, the Nd isotopic ratios are more distinctive than the Sr isotopic characteristics. There are three different and specific ranges of the ε_{Nd} values: 8.8±0.7, 7.8±0.7, and 5.6±0.3 corresponding respectively to three types of REE patterns for the IBM volcanic ashes: LREE-depleted to flat (5 to 10 times chondritic at La) Izu-

Bonin ashes, LREE-flat (10 to 30 times chondritic at La) Mariana ashes, and LREE-enriched (30 to 70 times chondritic at La) IBM ashes. The boninitic basement has a still lower ε_{Nd} value of 4.3±0.3. The ε_{Nd} values of the 8 ash samples containing significant proportion of sediments generally decrease from +8.4 to +0.4 with an increase of about 2 to 90 vol % sediment. It is clear that ε_{Nd} values are good indicator for LILE including LREE enrichment in island arc magmas. The lower ε_{Nd} values may indicate that sediments are involved into these volcanic ashes.

Relationships between the Sr-Nd isotopic ratios and bulk chemical compositions of the ashes are shown in Figure 8-2. The major element compositions of the bulk ashes are taken from the average compositions of all individual glass shards analysed by EMP in each ash layer. The trace elements (Rb, Sr, Sm, Nd) and element ratios (Rb/Sr and Sm/Nd) were determined by ICP-MS (Tables A 3-15 and 3-16). The $^{87}Sr/^{86}Sr$ ratios of IBM ashes are relatively uniform ranging from 0.7034 to 0.7040, regardless of rock type, Sr abundance (100 to 350 ppm), and Rb/Sr (0.02 to 0.09). Although L60B ashes (0-17 Ma) have higher Sr contents (170-350 ppm) and higher Rb/Sr ratios (0.05-0.09) than those of L60A (18-35 Ma) and L125 ashes (0-17 Ma), the $^{87}Sr/^{86}Sr$ of all these ash samples is in the same range from 0.7034 to 0.7040. There were no temporal changes in $^{87}Sr/^{86}Sr$ during the IBM arc's evolution. This indicates that all the IBM ashes were derived from a source with limited spread in $^{87}Sr/^{86}Sr$ and the genesis of the spectrum of ash compositions was dominated by fractional crystallisation without concurrent assimilation or contamination by extraneous components.

There is some important structure to the ε_{Nd} characteristics of the IBM ashes. For example, within a range of ε_{Nd} from +9.5 to +5.3, there seems to be some persistent differences. Generally, L125 ashes and L60A ashes have very similar ε_{Nd} values, +9.0 to +7.8, regardless of rock type from basaltic andesite to rhyolite. On the other hand, L60B ashes range from ε_{Nd} = +7.8 to +5.3 with two subgroups: +7.8 to +7.0, and +5.9 to +5.3. The former belongs to low-K ashes, and the latter belongs to high-K ashes, possibly from the IwoJima region. There is a pronounced negative correlation between ε_{Nd} values and Nd contents, with the L60B ashes having higher Nd contents (7-18 ppm), and a positive relationship between ε_{Nd} values and Sm/Nd (0.25-0.32) (Figures 8-2 E,F). From the Figures 8-2 C and F, it may be concluded that: - 1). there is a high mobility of Sr compared with Nd establishing homogeneity in the arc magma sources; 2). Sm/Nd vs. $^{143}Nd/^{144}Nd$ may have age significance - it could be interpreted as "pseudochron" of 255 Ma of heterogeneity in Sm/Nd in the wedge; and 3). Sm/Nd vs. $^{143}Nd/^{144}Nd$ could be a mixing array between ≥ two sources: a. with high La/Yb (low Sm/Nd), b. with low La/Yb (high Sm/Nd) and lack of homogeneity of wedge. The subgroup of L60B ashes with lower ε_{Nd} values has LREE-enriched REE patterns (see Figure 7-1), and appeared mainly at ~ 2 Ma and 8-11 Ma (Figure 8-1B). Therefore, unlike the case for $^{87}Sr/^{86}Sr$, there are temporal and spatial changes for Nd isotopic ratios of IBM ashes. The fact that a general positive correlation of Sm/Nd and $^{143}Nd/^{144}Nd$ exists implies long-term source heterogeneities exist rather than the development of variable LREE enrichments just prior to arc magma generation in a common source.

8.3 Isotopic comparison of IBM bulk ashes, IBM igneous rocks and MORB

There are extensive separate and combined isotopic studies of the IBM arc-backarc systems (Pushkar, 1968; Meijer, 1975,1976; DePaolo and Wasserburg, 1977; Masuda et al., 1977; Armstrong and Nixon, 1980; Nohda and Wasserburg, 1981; Stern, 1981, 1982; Dixon and Stern, 1983; Notsu et al., 1983; Stern and Ito, 1983; Stern and Bibee, 1984; White and Patchett, 1984; Woodhead and Fraser, 1985; Ito and Stern, 1986; Hickey-Vargas and Reagan, 1987; Woodhead et al., 1987; Hickey-Vargas, 1989; Woodhead, 1989; Lin et al., 1990; Hickey-Vargas, 1991; Pearce et al., 1992; Tatsumi et al., 1992; Yuasa and Nohara, 1992; Stern et al., 1993; Gill et al., 1994; Langmuir et al., 1995). There are fewer combined element and isotopic data sets. In order to understand more clearly the nature of island arc-backarc magma sources, elemental abundances together with Sr and Nd isotopic ratios have been collected to compare the IBM bulk ashes with IBM arc-backarc volcanic rocks and MORB.

Available Sr and Nd isotopic data of the IBM arc-backarc basin volcanic rocks, IBM volcanic ashes and MORB are shown in Figures 8-1D,E and F. Of major importance is the fact that all IBM arc volcanic rocks, including the IwoJima region have relative uniform $^{87}Sr/^{86}Sr$ ratios (0.7032 - 0.7040) over a strike length of ~ 2400 km and ~ 2000 km width. This is true, regardless of rock type (from basalt through andesite to rhyolite), or K series (low- through medium- to high-K and alkalic) and time: - Eocene-Oligocene Mariana rocks (Sites 296 and 448 on the PKR, Guam and Saipan volcanic rocks); Miocene volcanic rocks (IwoJima and Guam); to modern IBM subaerial and submarine volcanic rocks (e.g., Meijer, 1975,1976; DePaolo and Wasserburg, 1977; Masuda et al., 1977; Armstrong and Nixon, 1980; Stern, 1981, 1982; Notsu et al., 1983; Woodhead and Fraser, 1985; Hickey-Vargas and Reagan, 1987; Stern et al., 1989; Lin et al., 1990; Hickey-Vargas, 1991; Tatsumi et al., 1992; Yuasa and Nohara, 1992; Gill et al., 1994; Langmuir et al., 1995). The Sr isotopic composition of IBM ashes are also all within this range of $^{87}Sr/^{86}Sr$ ratios from 0.7034 to 0.7040. Magma genesis processes, including source input components and potential lithosphere interactions en route to the surface are similar in the whole region. Within this small range of $^{87}Sr/^{86}Sr$ however, there seems to be some fine-scale structure that has been attributed to small differences in magma genesis processes, or to changes in the mode of subduction of the Pacific plate or to mantle heterogeneity (e.g., Notsu et al., 1983; Stern and Ito, 1983; Lin et al., 1990; Yuasa and Nohara, 1992; Stern et al., 1993).

There are fewer Nd than Sr isotopic data for the IBM arc system. Reported ε_{Nd} varies from +9.7 to +2.3 (DePaolo and Wasserburg, 1977; Nohda and Wasserburg, 1981; White and Patchett, 1984; Hickey and Reagan, 1987; Woodhead, 1989; Lin et al., 1990; Hickey-Vargas, 1991; Tatsumi et al., 1992; Stern et al., 1993; Gill et al., 1994; Langmuir et al., 1995). Generally, ε_{Nd} values are correlated with the REE patterns (and Sm/Nd). The volcanic rocks of the northern part of the Izu-Bonin arc have high ε_{Nd} values (+9.7 to +8.0), corresponding to LREE-depleted to REE-flat patterns. The Eocene-Oligocene Mariana volcanic rocks also have high ε_{Nd} values (+8.9 to +7.6), corresponding to unfractionated REE patterns within 10 to 30 times chondrite abundances. The majority of modern Mariana subaerial and submarine volcanic rocks (except NSP) are characterised by ε_{Nd} = +8.2 to +6.3, coupled with unfractionated to slightly enriched LREE patterns. The IwoJima region, Mariana NSP and Mariana Miocene high-K series, however, have lower ε_{Nd} values from +6.0 to +2.3, corresponding to LREE-enriched to highly enriched at 50 to 100 times chondrite abundances. The ε_{Nd} values of L125 volcanic ashes, like those of L126 turbidites (+9.4 to +7.4, Gill et al., 1994), are very similar to those characteristic of northern part of the active Izu-Bonin subaerial arc, indicating that they are probably derived from similar sources and processes. The majority of L60 ashes have ε_{Nd} values similar to most Mariana arc volcanic rocks. However, a subgroup of L60 ashes have lower ε_{Nd} values, 5.6 ± 0.3, similar to those associated with the IwoJima region and Mariana Miocene high-K volcanic rocks.

From Figure 8-1D,E and F, it is clear that the IBM backarc basin volcanic rocks are distinctive compared with the arc having higher ε_{Nd} and lower $^{87}Sr/^{86}Sr$. The isotopic characteristics of lava from the IBM backarc basins (Mariana Trough and Izu-Bonin rifts, Parece Vela and Shikoku basins, and the West Philippine) have been intensively studied (Volpe et al., 1987, 1990; Ikeda and Yuasa, 1989; Hochstaedter et al., 1990a,b; Stern et al., 1990; Hickey-Vargas, 1991; Ikeda et al., 1992; Hickey-Vargas et al. 1995). They have very similar $^{87}Sr/^{86}Sr$ ratios ranging from 0.70267 to 0.70332 and $^{143}Nd/^{144}Nd$ ratios ranging from 0.51315 to 0.51300 (ε_{Nd} values +10.0 to +7.1). Their Sr and Nd isotopic features correspond to their lower LILE abundances and LREE-slightly depleted to REE-flat within 10 to 30 times chondritic abundances (see Chapter 7).

Representative Sr and Nd isotopic data for MORB are also shown in Figure 8-1D. The data are from White and Hofmann (1982), Zindler et al.(1984), MacDougall and Lugmair (1986), Ito et al. (1987), and White et al. (1987). $^{87}Sr/^{86}Sr$ ratios of N-MORB range from 0.70244 to 0.70318 and $^{143}Nd/^{144}Nd$ ratios range from 0.51320 to 0.50300 (ε_{Nd} values +11.0 to +7.1). Compared to N-MORB, the IBM backarc basin volcanic rocks have the same range of ε_{Nd} values from +11.0 to +7.1 and slightly higher $^{87}Sr/^{86}Sr$ ratios (0.70267 to 0.70332), but still within the range of E-MORB (0.7028 to 0.7035) (e.g.. Zindler and Hart, 1986; Saunders et al., 1988). The IBM ashes and arc volcanic rocks have a slightly lower range of ε_{Nd} values from +9.5 to +5.3 (to +2.3) and higher $^{87}Sr/^{86}Sr$ ratios (0.7032-0.7040) than those of IBM backarc basin volcanic rocks and MORB. Specifically, at a given ε_{Nd} value, $^{87}Sr/^{86}Sr$ ratios of IBM arc volcanic rocks including ashes are significantly higher than those of the IBM backarc basin, and both are again significantly higher than those of MORB (Figures 8-1D,E and F). All these features are consistent with the possibility that a small amount of oceanic sediment, altered basalt or sea water component that accompanies the subducting slab, has been contributed to the source regions of arc and backarc magmas which originate primarily however, from a partially melted, N-MORB-type mantle wedge (e.g., Stolper and Newman, 1994).

The comparison between Sr and Nd isotopic compositions and chemical compositions for representative IBM arc-backarc basin volcanic rocks, IBM ashes and MORB is shown in Figures

8-3A,B and C. Combined data sets including major element, trace element and isotopic ratios are fewer than those of major element or trace element or isotopes individually. Generally, Sr and Nd isotopic ratios are relatively uniform in rock type ranging from basalt to dacite and rhyolite. For the IBM ashes and arc volcanic rocks, $^{87}Sr/^{86}Sr$ are 0.7032 < 0.7040, regardless of Sr abundances from 100 to 1100 ppm, and Rb/Sr from 0.02 to 0.27. The IBM basin volcanic rocks and MORB have Sr abundances in the range 80-300 ppm and Rb/Sr < 0.05. There is negative correlation between ε_{Nd} values and Nd abundances: - MORB and backarc basin volcanic rocks with the highest ε_{Nd} values (+11 to +7) compared with lowest Nd contents (5-15 ppm), and IwoJima and northern NSP volcanic rocks having lowest ε_{Nd} values (+5 to +2) and highest Nd contents (15-60 ppm). There is also a positive relationship overall between ε_{Nd} values and Sm/Nd ratios. To some extent therefore, there is overlap between the IBM ashes and arc volcanic rocks (except IwoJima and NSP) with MORB and backarc basin volcanic rocks, indicating some commonality of sources.

8.4 Ba/Rb ratios: indicator of sediment incorporation in island arc magmas

It has long been controversial whether sediments are subducted beneath island arcs and subsequently incorporated into arc lavas, and what kinds of subduction components are involved in arc magmas. 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. In general, it is not easy to distinguish island arc basalts from oceanic island basalts (OIB) in terms of Sr and Nd isotopic compositions, K/Rb, K/Ba, and K/Sr ratios, and K, Rb, Ba and Sr contents. The Hf-Sr-Nd isotopic data alone can still be explained by melting of an OIB-type source to produce island arc magmas (e.g., Stern, 1981; Morris and Hart, 1983). Although the cosmogenic isotope ^{10}Be provides compelling evidence for sediment recycling for some arcs, interpretation of ^{10}Be data for arc lavas is subject to its own limitations. For many arcs including Izu-Bonin-Mariana, ^{10}Be cannot be reliably detected (e.g., Tera et al., 1986). Pb isotope data do provide much stronger evidence for involvement of subducted sediment in some island arc sources (e.g., Hickey et al., 1986). However, only a minority of the available data (out of major database) have radiogenic Pb signatures consistent with recycled sediment involvement (e.g., Meijer, 1976; Woodhead et al., 1985). Is there any other way to evaluate the role of recycled sediment in island arc magmatism? On the basis of elemental abundances (major and trace) and isotopic studies of the IBM volcanic glasses (ashes) and volcanic rocks, the systematic variations of Ba/Rb are suggested to be indicative of sediment incorporation in island arc magmas.

Many high quality analyses of Ba and Rb in fresh basalts from mid-ocean ridges and oceanic islands (e.g., Hofmann and White, 1983) and many standard average compositions (e.g., Sun and McDonough, 1989) for primitive mantle, N-MORB, E-MORB, and OIB, completed in the past 25 years, demonstrate that the most highly incompatible element ratio of Ba/Rb is constant within reasonable error (11 ± 3). That is, Ba/Rb is independent of the degree of partial melting of the mantle, similar to the behaviour observed for Nb/U and Ce/Pb (e.g., Hofmann and White, 1983; Hofmann 1986) (Figures 8-4A1 and B1).

For the IBM arc volcanic rocks, the majority are basaltic andesites and andesites and not primitive basalts as discussed in Chapter 4. Is there any change of Ba/Rb with fractionation of arc magmas? As shown in Chapter 6, about 220 individual glass shards from DSDP Leg 60 and ODP Leg 125 ash layers were analysed for major element and selected trace element (Rb, Ba, Sr, Zr and Y) abundances. These data show that the Ba/Rb of most individual glass shards are in the range 15 to 40 (Figure 6-2B), regardless of SiO_2 content. The average Ba/Rb for the Izu-Bonin glasses and the Mariana glasses are within the same range (20 ± 4), as that reported previously by Chow et al. (1980), and significantly higher than the mantle value (11 ± 3). In fact, the majority of Ba/Rb of arc volcanic rocks are also within the range of 20 ± 4 (e.g., Sinha and Hart, 1971; Chow et al., 1980; McCulloch and Perfit, 1981; Morris and Hart, 1983; Myers et al., 1985; Romick et al., 1990). Clearly, arc magmas are significantly different from MORB- and OIB-type mantle magmas in terms of Ba/Rb.

The problem then is to explain the large difference of Ba/Rb between the mantle ratio of 11 ± 3 (from MORB and OIB) and arc magma ratio (20 ± 4). Clearly, arc magmas can not be directly derived from the partial melting of MORB- or OIB-type mantle sources alone. One possible explanation is that oceanic sediments with higher Ba/Rb ratios must be involved in the genesis of arc magmas. There are at least two ways to explain the Ba/Rb difference: 1. an N-MORB type mantle source mixes with Ba-rich siliceous fluids or melts; 2. OIB-type or OIB 'plums' in a MORB-type 'pudding' mantle source (Morris and Hart, 1983; Stern et al., 1993) mixes with Ba-rich siliceous fluids or melts. However, the nature of Ba-rich siliceous fluids or melts is unclear and the mixing process is also uncertain (e.g., Arculus, 1994; Pearce and Peate, 1995).

The detailed chemical composition of oceanic sediments is moderately complicated. Oceanic sediments consist mostly of combinations of terrigenous components (red clay), biogenic phases (oozes) and about 10-33% water (seawater) (e.g., Nichols et al., 1994). Published average chemical compositions of Pacific oceanic sediment types, altered oceanic crust (AOC), and upper, bulk and lower continental crust (CC) (e.g., Sinha and Hart, 1971; Gill, 1976; Kay, 1980; Stern and Ito, 1983; Hole et al., 1984; Taylor and McLennan, 1985; Ben Othman et al., 1989; Lin, 1992; Plank and Langmuir, 1993) are shown in Figure 8-4. Relative to mantle Ba/Rb, oceanic sediments can be divided into three groups: high (140-600), medium (20-44), and low Ba/Rb (1-10). The average lower continental crust has medium Ba/Rb (28) while the bulk and upper continental crusts have low Ba/Rb (7.8-4.9) (Taylor and McLennan, 1985). The AOC has higher LILE especially Cs, Rb and K (and $^{87}Sr/^{86}Sr$) and low Ba/Rb of about 2 to 7 (e.g., Hole et al., 1984).

Subducted lithosphere can be divided into two parts: altered oceanic crust with sediments (AOCSS) and ultramafic lithosphere (UL). AOCSS can supply water and LIL elements in the form of siliceous fluid and/or melt to the zone of arc magma genesis. The residue of AOCSS and UL can be subducted deeply into the mantle. The nature of subduction zone processes and the transfer of components from the subducted AOCSS to the mantle wedge is poorly understood. Even if the composition of subducted AOCSS is locally heterogeneous, it is possible that bulk siliceous fluids or melts derived from this source are relatively homogeneous. The fact that island arc magmas have high Ba/Rb whereas Ba is reportedly less mobile than Rb in slab - to - wedge transfer processes (Tatsumi et al, 1986) requires that sediments with higher than mantle Ba/Rb must be involved in arc magma genesis. The involvement of sediments with low Ba/Rb (1-10) proposed by Kay (1980), Stern and Ito (1983), Lin (1992), and Plank and Langmuir (1993) in subduction zone magmatism may be unreasonable. For example, Lin (1992) used the bulk western Pacific sediment (BWPS) (Ba/Rb ~11, Ba/La ~13, Sr/Nd ~10) to propose a mixing model for the petrogenesis of Mariana arc magmas. He suggested multiple episodes of fluid fractionation to explain the high Ba/La ratios in Mariana lavas. But this model fails to explain the high Ba/Rb ratios in Mariana lavas unless the chemical mobility of Rb relative to Ba is < 1, a feature unsupported by available evidence.

Taking into account the existence of different types of oceanic sediments (limited to the collected Pacific Oceanic sediment compositions, see Figure 8-4) and AOC, it may be meaningful to calculate an average composition of bulk subducted altered oceanic crust with sediments (BSAOCSS) as follows: Cs 2.13, Rb 34.8, Ba 1735, K 10584, La 45.7, Sr 512 (ppm), Ba/Rb 50, Ba/La 38, Rb/Cs 16. Assuming simple mixing of two end-members: a MORB-type mantle and BSAOCSS, on the basis of Ba/Rb, about 10-30% BSAOCSS is inferred to be involved in the IBM arc magma source. This proportion is similar to that proposed by Plank and Langmuir (1993) (about 20% of subducted sediments are recycled to volcanic arcs). Considering the mobility of 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 (not bulk) is incorporated in IBM arc magmas, identical to the proportion advocated on isotopic grounds by Woodhead (1989).

8.5 Summary

From detailed Sr and Nd isotopic studies of the bulk ashes from DSDP Leg 60 and ODP Leg 125, coupled with systematic comparisons of ashes with IBM volcanic rocks and MORB, and preliminary examination of Ba/Rb of mantle sources, oceanic sediments, altered oceanic crust and arc magmas, the following conclusions can be drawn:

1. The $^{87}Sr/^{86}Sr$ of IBM Legs 60 and 125 ashes are uniform from 0.7034 to 0.7040 and within the same range (0.7032 to 0.7040) as IBM arc volcanic rocks, regardless of rock type from basalt to rhyolite, low- to high-K series, time and space within the arcs' explosive history, and the whole region of some ~ 2400 km length and ~ 2000 km width. The ε_{Nd} values of IBM ashes range mostly from +9.5 to +5.3 and are within the range of IBM subaerial and submarine volcanic rocks (+9.5 to +2.3). The ε_{Nd} values are correlated with the degree of LREE enrichment. Generally, the lower ε_{Nd} values (+5 to +2) characterise high-K to alkalic volcanic rocks of IwoJima and Mariana northern NSP volcanic rocks, with strong LREE enrichment (> 80 times chondritic La). The medium ε_{Nd} values, +8.0 to +6.0, are typical of Mariana arc volcanic rocks

(active arc, SSP, CSP, southern NSP, and Eocene-Oligocene arc), accompanied by LREE-enriched to flat (10 to 50 times chondritic La) patterns. Higher ε_{Nd} values (+9.5 to +8.0) are typical of the northern portion of the Izu-Bonin arc, corresponding to LREE-depleted to flat (5 to 10 times chondritic La) patterns. The similarity of Sr and Nd isotopic ratios among IBM arc, backarc basin, and MORB indicates that IBM arc and backarc basin volcanic rocks share a common mantle source and that a small amount of sediment and altered oceanic crust are involved in the genesis of IBM arc magmas.

2. Although L60B ashes (0-17 Ma) have higher Sr contents (170-350 ppm) and higher Rb/Sr ratios (0.05-0.09) than those of L60A ashes (18-35 Ma) and L125 ashes (0-17 Ma), the $^{87}Sr/^{86}Sr$ ratios of all these ash samples are in the same range from 0.7034 to 0.7040, and there are no temporal changes for $^{87}Sr/^{86}Sr$ ratios during the IBM arcs' evolution. This indicates that the IBM ashes are derived from common source(s) and the genesis of spectrum of ash compositions are dominated by fractional crystallisation rather than simple mixing processes. However, a subgroup of L60B ashes with lower ε_{Nd} values and LREE-enriched patterns appears mainly at ~ 2 Ma and 8-11 Ma. Therefore, there are temporal and spatial changes for Nd isotopic ratios of IBM ashes, indicating involvement of either different source types or blends of sources.

3. 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 DSDP Leg 60 and ODP 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).

Sr-Nd Isotopic Compositions

Bulk Ashes, IBM Volcanic Rocks and MORB

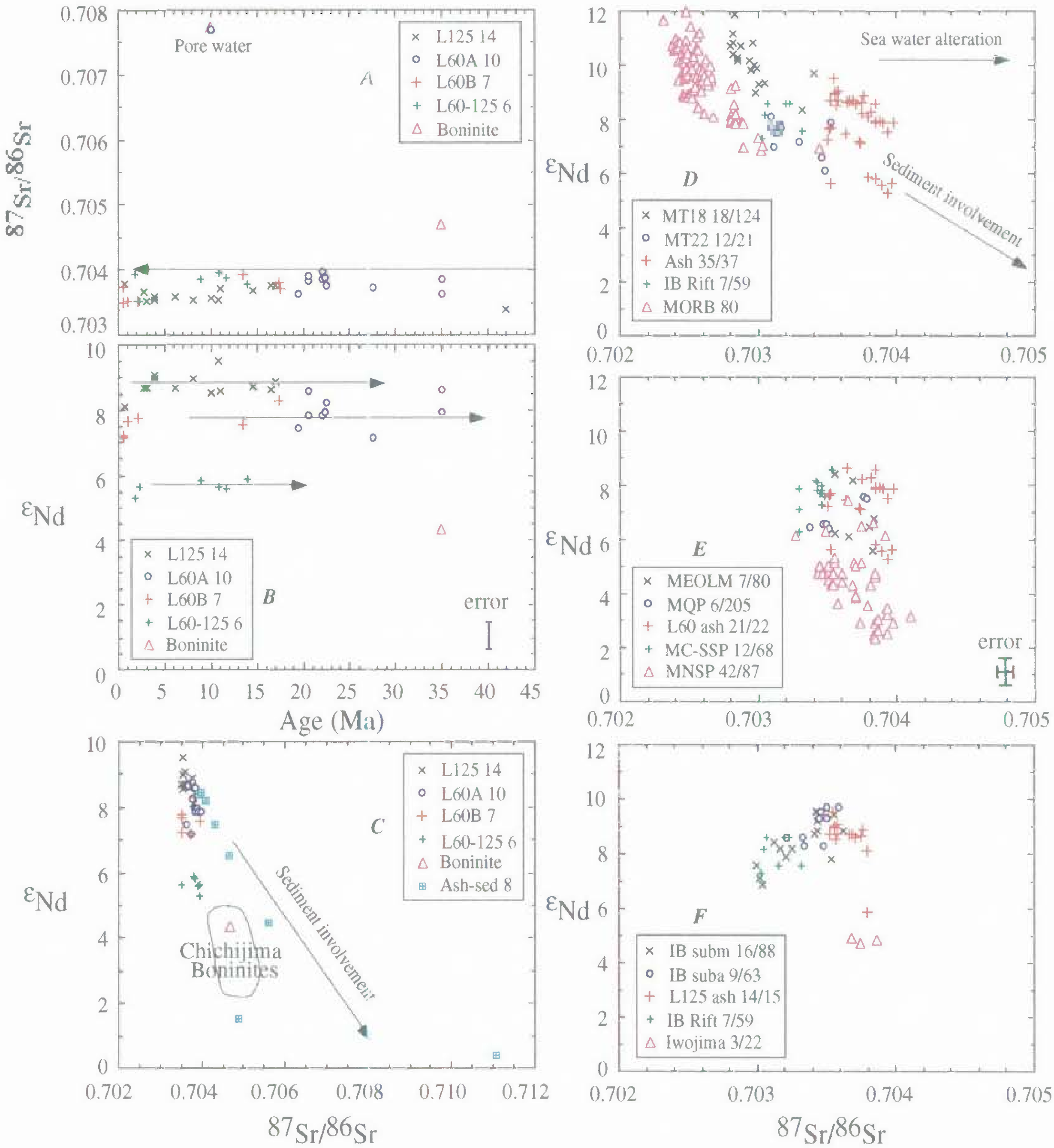

Figure 8-1 Comparison of Sr and Nd isotopic compositions of representative bulk ashes from DSDP Leg 60 Sites 458 and 459B and ODP Leg 125 Sites 782A, 784A, and 786A ash layers (A, B, C) with backarc basin volcanic rocks and MORB (D), Mariana arc volcanic rocks (E) and Izu-Bonin volcanic rocks (F). A and B also show the relationships between Sr-Nd isotopic ratios and the IBM arcs' evolutionary history. Notation by the specific sample symbols is Leg number or location name followed by number of Sr-Nd isotopic ratios analysed. Ash 35/37, total analysis number for bulk ashes in this work; Ash-sed, bulk ash samples containing sediments; Boninite, a sample derived from DSDP Leg 60 Site 458 basement volcanic rocks; IB, Izu-Bonin; MC-SSP, Mariana CSP and SSP; MEOLM, Mariana Eocene-Oligocene and late-Middle Miocene volcanics; MNSP, Mariana NSP; MORB, including Pacific, Atlantic and Indian MORB; MQP, Mariana Quaternary-Pliocene volcanicrocks; MT, Mariana Trough; Pore water, washed HCl solution from an original bulk ash layer of ODP Leg 125 Site 784A; suba, subaerial; subm, submarine. The data of Sr and Nd isotopic ratios of the Chichijima boninites are from Cameron et al. (1983), Shimizu et al. (1992) and Taylor et al. (1994). See appendix for ash samples and text for data sources and discussion.

Sr-Nd Isotopic Compositions

Bulk Volcanic Ashes from DSDP Leg 60 and ODP Leg 125

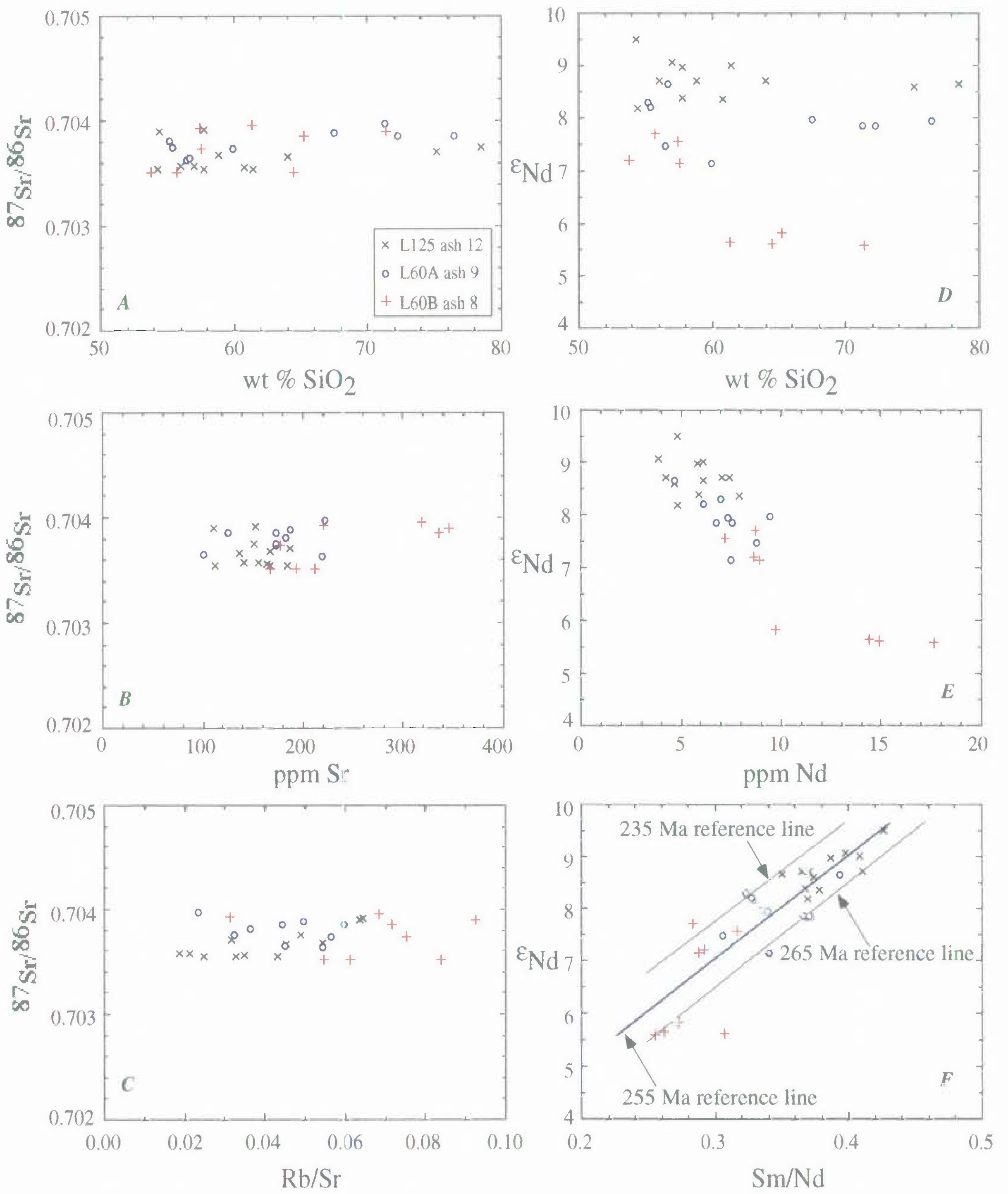

Figure 8-2 Comparison of Sr and Nd isotopic compositions with chemical compositions of representative bulk ashes from DSDP Leg 60 Sites 458 and 459B, and ODP Leg 125 Sites 782A, 784A, and 786A ash layers. SiO_2 content of bulk ash samples is taken from the average content of individual glass shards measured by EMP. See appendix for ash samples and text for discussion.

Sr-Nd Isotopic Compositions

Bulk Ashes, IBM Volcanic Rocks and MORB

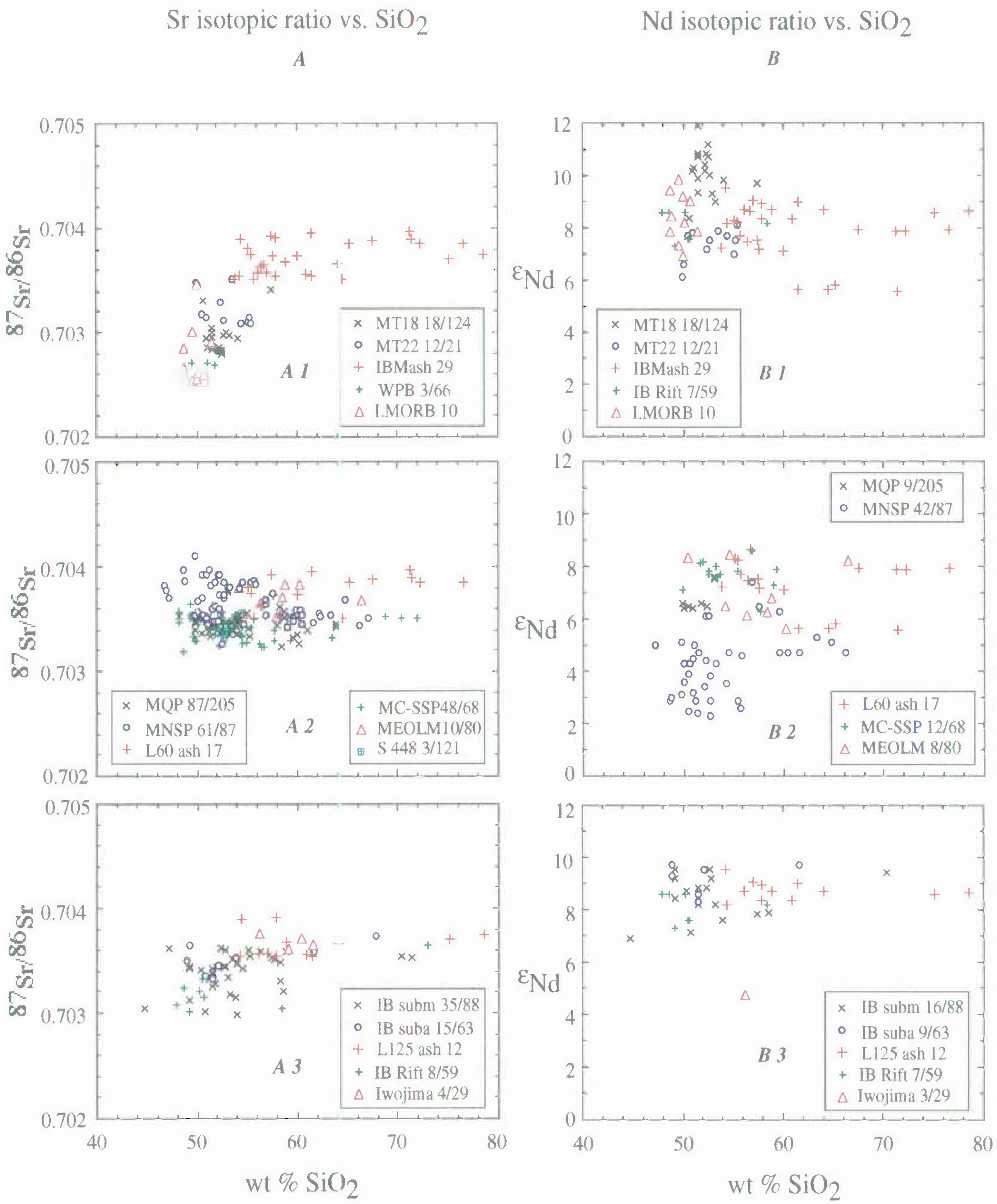

Figure 8-3A Comparison of Sr isotopic compositions vs. SiO_2 (A) and Nd isotopic compositions vs. SiO_2 (B) of representative bulk ashes from DSDP Leg 60 Sites 458 and 459B, and ODP Leg 125 Sites 782A, 784A, and 786A ash layers, with backarc basin and Indian MORB (A1 and B1), Mariana volcanic rocks (A2 and B2) and Izu-Bonin volcanic rocks (A3 and B3). IBM ash 29 = 29 bulk ash samples for ICP-MS analysis in this work; S 448 = DSDP Leg 59 Site 448 (PKR); WPB = West Philippine Basin. See Figure 8-1 for other notation. See appendix for ash samples and text for data sources and discussion.

Sr-Nd Isotopic Compositions
Bulk Ashes, IBM Volcanic Rocks and MORB

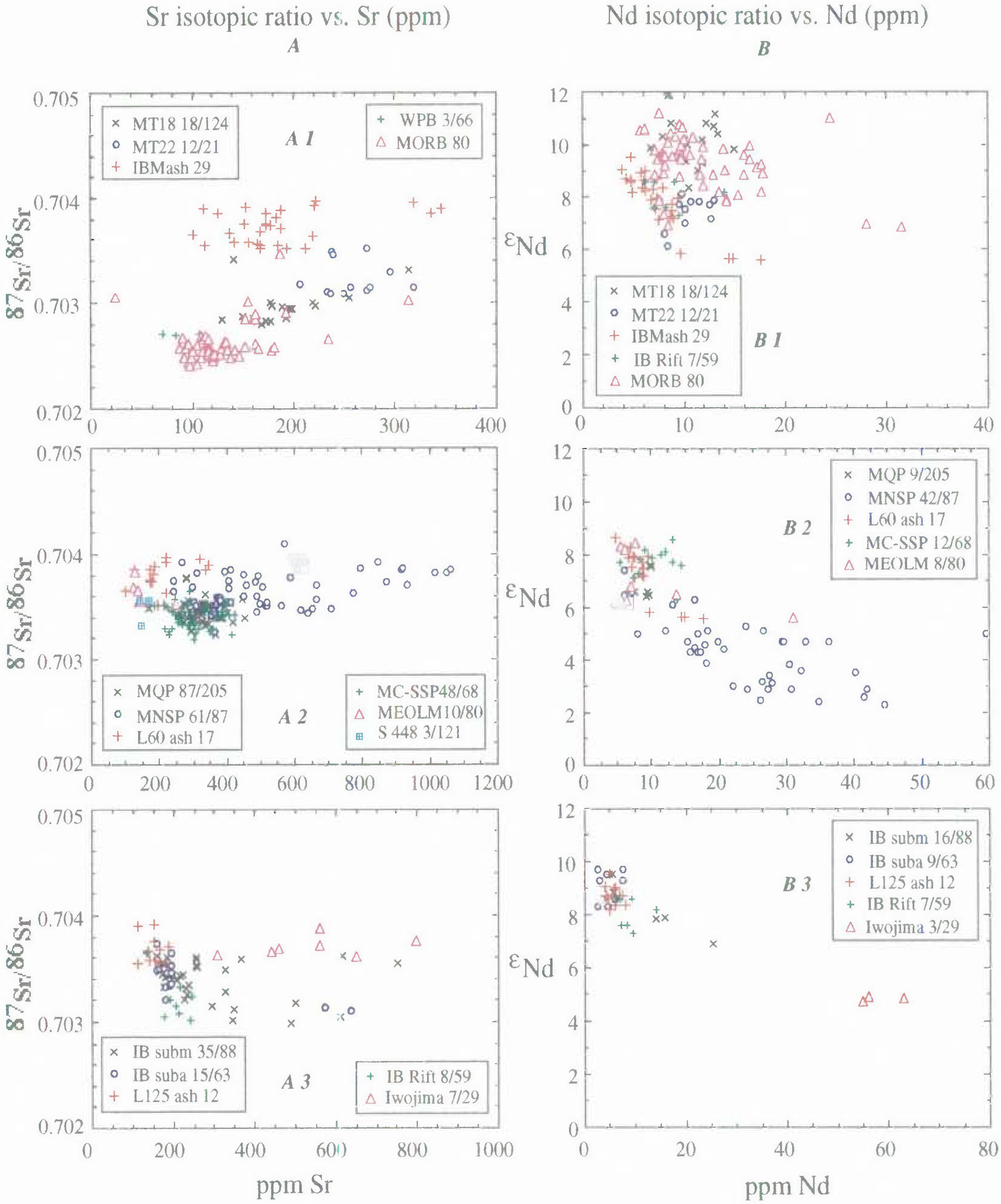

Figure 8-3B Comparison of Sr isotopic compositions vs. Sr (ppm) (A) and Nd isotopic compositions vs. Nd (ppm) (B) of representative bulk ashes from DSDP Leg 60 Sites 458 and 459B, and ODP Leg 125 Sites 782A, 784A, and 786A ash layers, with backarc basin and MORB (A1 and B1), Mariana volcanic rocks (A2 and B2) and Izu-Bonin volcanic rocks (A3 and B3). IBM ash 29 = 29 bulk ash samples for ICP-MS analysis in this work; S 448 = DSDP Leg 59 Site 448 (PKR); WPB = West Philippine Basin. See Figure 8-1 for other notation. See appendix for ash samples and text for data sources and discussion.

Sr-Nd Isotopic Compositions

Bulk Ashes, IBM Volcanic Rocks and MORB

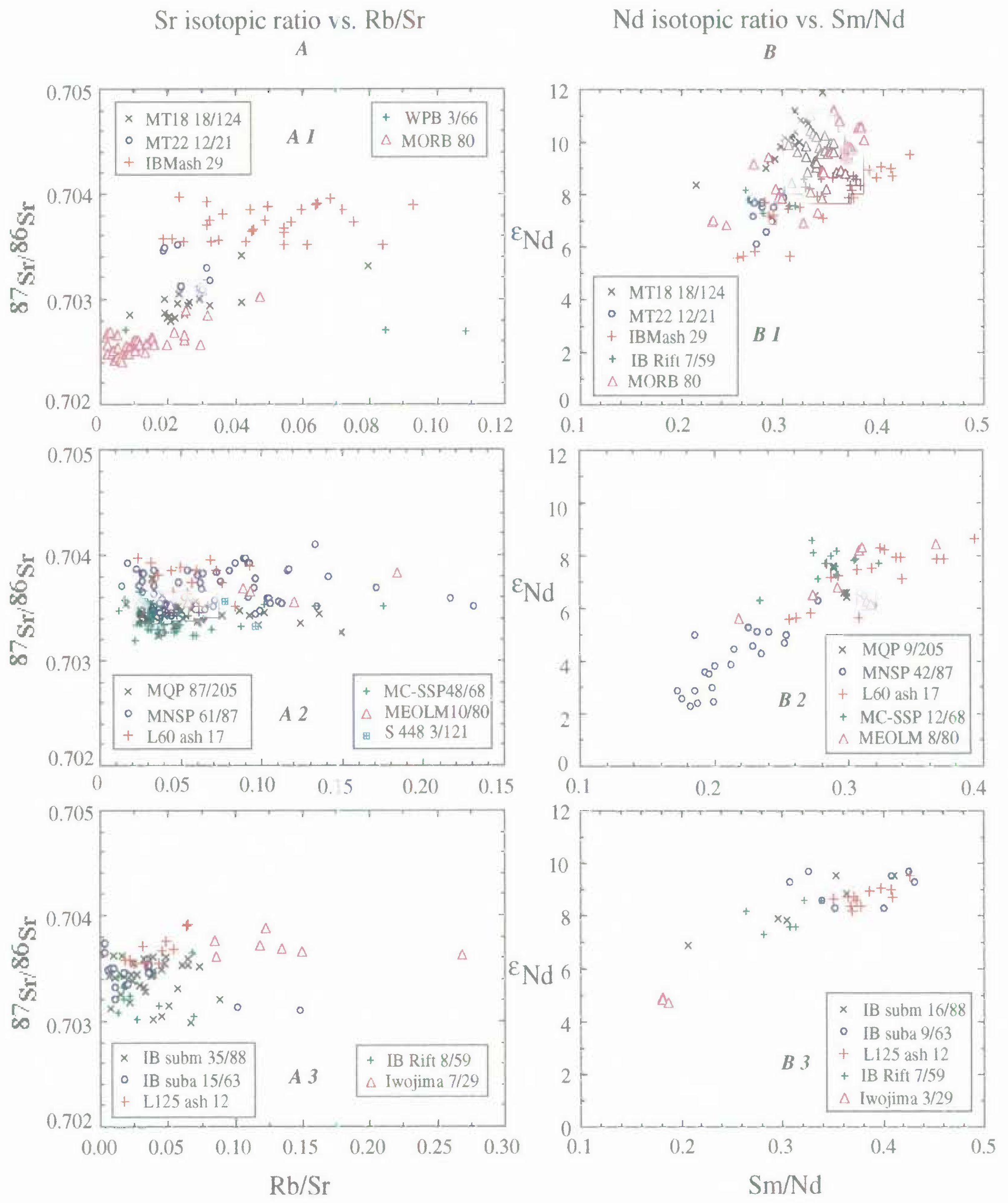

Figure 8-3C Comparison of Sr isotopic compositions vs. Rb/Sr (A) and Nd isotopic compositions vs. Sm/Nd (B) of representative bulk ashes from DSDP Leg 60 Sites 458 and 459B, and ODP Leg 125 Sites 782A, 784A, and 786A ash layers, with backarc basin and MORB (A1 and B1), Mariana volcanic rocks (A2 and B2) and Izu-Bonin volcanic rocks (A3 and B3). IBM ash 29 = 29 bulk ash samples for ICP-MS analysis in this work; S 448 = DSDP Leg 59 Site 448 (PKR); WPB = West Philippine Basin. See Figure 8-1 for other notation. See appendix for ash samples and text for data sources and discussion.

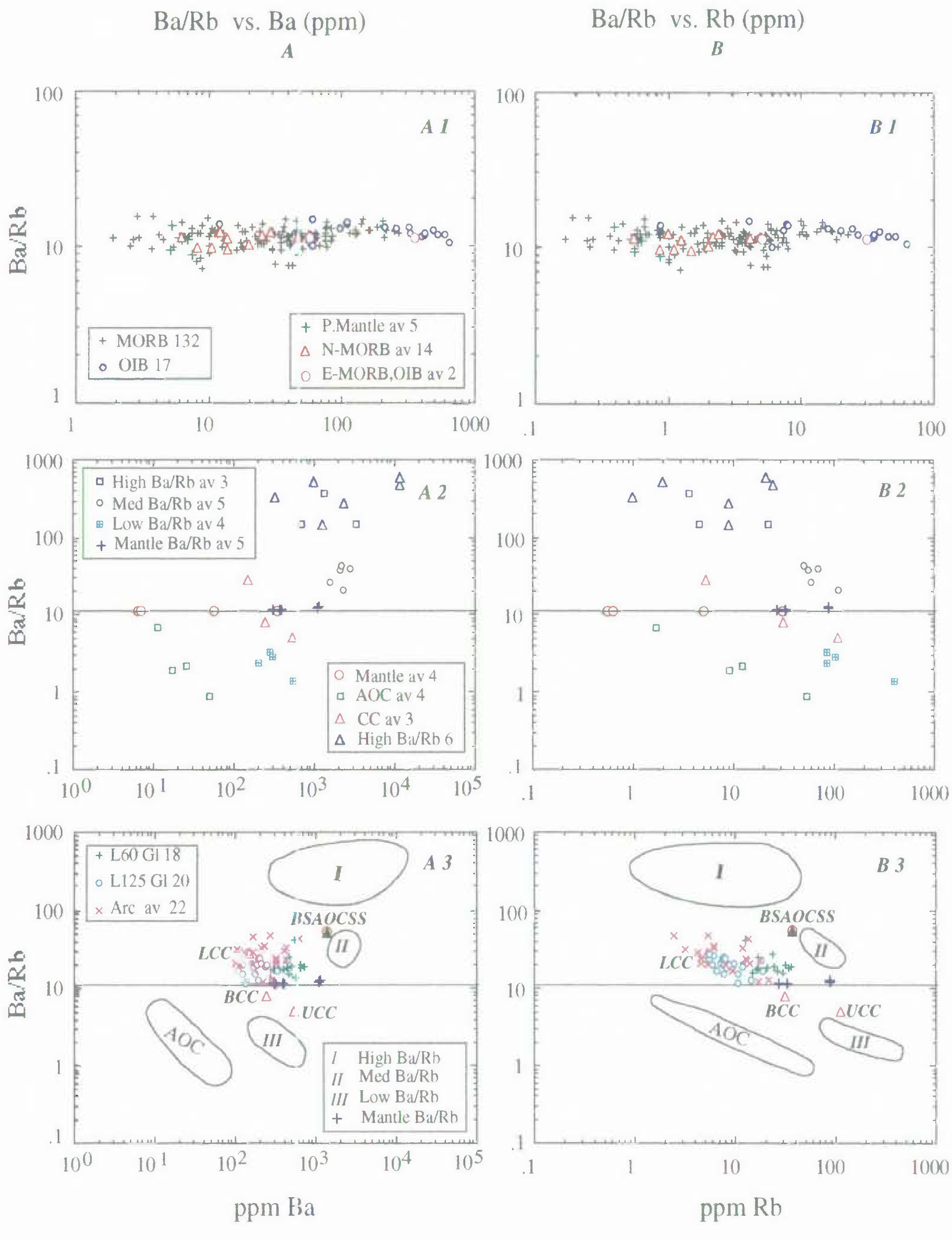

Figure 8-4 Comparison of Ba/Rb vs. Ba (ppm) (A) and Ba/Rb vs. Rb (ppm) (B) of collected MORB, OIB and recommended Primitive mantle, N-MORB, E-MORB and OIB (A1 and B1) with collected Pacific Ocean sediments (high, medium, low and Mantle Ba/Rb type), average upper, lower and bulk continental crust (UCC, LCC and BCC), and altered oceanic crust (AOC) (A2, A3 and B2, B3). The representative individual glass shards from DSDP Leg 60 and ODP Leg 125 ash layers, average compositions of island arc volcanic rocks and the average Bulk Subducted Altered Oceanic Crust with Sediments (BSAOCSS) are illustrated in A3 and B3. See appendix for ash samples and text for data sources and discussion.