Chapter 4 Major Element Chemistry of Individual Glass Shards from DSDP Leg 60 and ODP Leg 125 Ash Layers

4.1 Introduction

On the basis of lithologic descriptions presented in Volume 60 of the Initial Reports of the DSDP (Hussong, Uyeda, et al., 1981) and in Volume 125 of Initial Reports of the Proceedings of the ODP (Fryer, Pearce, Stokking, et al., 1990a), a total of 64 representative ash layers from Site 458 and 71 layers from Site 459B (Mariana forearc), 22 representative ash layers from Site 782A, 16 layers from Site 784A, and 15 layers from Site 786A (Izu-Bonin forearc) were selected for study. Biostratigraphic dating and magnetostratigraphy were combined to obtain estimates for the ages of these representative ash layers (see Table A 1-1 and A 1-2). The ages assigned to sediments from DSDP Sites 458 and 459 and ODP Sites 782A, 784A and 786A are from B. Taylor (pers. comm., 1992) and Stabell et al. (1992), respectively. The ages for ash samples from Site 458 range from about 0.35 to 34 Ma; for Site 459B, from 0.25 to 35 Ma; for Site 782A, from about 0.25 to 14.5 Ma and about 42 Ma; for Site 784A, from approximately 0.7 to 14 Ma; for Site 786A, from about 2.5 to 17 Ma and 23.7 Ma. Therefore, these selected ash layers (and volcanic glasses) span the IBM arcs' explosive history from a mid-Eocene inception to the present.

The major element composition of the individual glass shards from all of these Leg 60 and Leg 125 representative ash layers were determined by EDS-EMP. In excess of 1750 major element analyses of individual glass shards were acquired from 184 bulk ash samples (1215 from 133 DSDP Leg 60 ash layers, and 538 from 51 ODP Leg 125 ash layers). All these original data are listed in Appendix 3.1. In order to compare systematically these data with published data of volcanic rocks and glasses, the classification and nomenclature for glass types and rock series adopted for use in this thesis are the total alkali-silica (TAS) diagram recommended by the IUGS Subcommission on the Systematics of Igneous Rocks (LeBas et al., 1986), the K_2O-SiO_2 diagram widely used by Gill (1981) adopted from Peccerillo and Taylor (1976), the FeO*/MgO-SiO_2 diagram suggested by Miyashiro (1974) and the AFM discriminant recommended by Irvine and Baragar (1971). All the major and minor element analyses used in this thesis together with data collected from other publications, have been recalculated to 100 weight per cent (wt%) volatile-free with all Fe being reported or recalculated as FeO* except where otherwise indicated. Most of the data were acquired by EDS-EMP with no detectable P_2O_5. There should be no significant differences for major and minor element chemistry because of the very low abundances of P_2O_5 reported using WDS-EMP for the volcanic glasses and rocks by Arculus and Bloomfield (1992).

In order to evaluate any temporal geochemical changes in the geochemistry of arc magmas, six time period intervals: Quaternary-Pliocene (QP) 0-5.3 Ma, Late Miocene (LM) 5.3-11.2 Ma, Middle Miocene (MM) 11.2-16.6 Ma, Early Miocene (EM) 16.6-23.7 Ma, Oligocene (OL) 23.7-36.6 Ma, and Eocene (EOC) 36.6-57.8 Ma, were selected for use in this thesis, based on the Geological Time Scale recommended by the Geological Society of America (Palmer, 1983) following detailed examination of geochemical changes with times of the ash layers.

4.2 Glass shards of DSDP Leg 60 Sites 458 and 459B ash layers

1200 analyses of individual glass shards from DSDP Leg 60 forearc Sites 458 and 459B are all plotted in Figures 4-1A, 4-1B and 4-3A. The glass shards of the two Sites 458 and 459B seem to form a similar population, physically (see Appendix 2) and chemically as might be expected. They are all subalkaline on the total alkali-silica (TAS) diagram (Figure 4-3A), predominantly low-K to medium-K based on Gill's (1981) division (Figure 4-1B), and tholeiitic series on the basis of Miyashiro' (1974) and AFM diagram (Irvine and Baragar, 1971) (Figures 4-1B and 4-6). The combinations of glass types in different time internals vary. They are predominantly basaltic andesite (64.1%) and andesite (18.8%) during Quaternary-Pliocene times, dominantly andesite (43.3-47.1%), dacite (27.3-24.6%) and basaltic andesite (17.3-21.7%) during Late Miocene to Middle Miocene, almost equal proportions of basaltic andesite (21.9%), andesite (24.3%), dacite (29.7%) and rhyolite (22.5%) during Early Miocene times, and dominantly andesite (50.0%), basaltic andesite (19.8%) and rhyolite (20.9%) during Oligocene times (Figures 4-3C and 4-3D).

The major element compositions of glass shards from the two Sites form a tight continuum from basalt through andesite to dacite and rhyolite (Figures 4-1A, 4-1B and 4-3A). Glasses analysed from Site 458 range from 49.5 to 80.6 wt% SiO_2 and those from Sites 459B range from 49.2 to 79.7 wt% SiO_2. The MgO contents of glasses from the two Sites range from 9.8 to 0.1 (limit of EDS-EMP) wt% in Site 458 and from 9.5 to 0.1 wt% in Site 459B. The K_2O abundances of glasses from Site 458 range from 0.05 (limit of EDS-EMP) to 5.36 wt% and those from Site 459B range from 0.12 to 4.81 wt%. As is evident in these variation diagrams, some oxides such as FeO*, TiO_2, CaO, to a lesser extent Na_2O, and a subset of K_2O vary linearly with silica, but MgO varies nonlinearly, while Al_2O_3 is essentially unchanged. The nonlineality of Al_2O_3 vs. SiO_2 can be attributed to the dominance of fractional crystallisation rather than simple magma mixing processes (e.g., Arculus and Bloomfield, 1992).

The scatter of oxide variation in the case of TiO_2, FeO*, MgO, Al_2O_3 and CaO can also in part be attributed to overlap of the probe beam with plagioclase and/or pyroxene and/or Fe-Ti oxides, because in some cases these minerals are included in host glasses.

Are there any temporal changes in the major element chemistry of glasses from DSDP 60 Sites 458 and 459B? Detailed examination of major element oxides vs. age indicate that the abundances of all major and minor element except K are unchanged, within reasonable error, with time. There is a significant increase however, of K_2O abundance (Arculus et al., 1992, 1995; Chen and Arculus, 1993a, 1994a) from (Eocene) Oligocene through Early Miocene (predominantly low-K tholeiitic series) to Middle and Late Miocene to present (predominantly medium-K tholeiitic series) (Figures 4-4A, B and C). Some high-K but (including medium-K and low-K) glass pulses appear at 20-22 Ma, 8-11 Ma and ~2 Ma (Arculus et al., 1995; Figure 4-4A). Alkalic glasses (TAS discriminant) are not found in any of the ash layers in the Mariana forearc Sites (458 and 459B) (Figure. 4-3A). There is also no report of alkalic glasses from the volcanic ash studies in the Mariana arc-backarc system (see Chapter 3 for a review of IBM volcanic ash studies). Furthermore, boninitic glasses are not recorded in any of Sites 458 and 459B ash layers using the definition of boninite series as: high-SiO_2 (> 55 wt%), low-TiO_2 (< 0.4 wt%), high-MgO (9-15 wt%), lack of plagioclase phenocrysts and existence of Mg-rich olivine and/or low-Ca pyroxene (enstatite or clinoenstatite) (Hickey and Reagan, 1987; Crawford et al., 1989).

However, Warner et al. (1987) reported a brief period of boninitic ash deposition at Site 450 in the Parece Vela Basin at 15-14 Ma, presumably derived from the West Mariana Ridges, but not confirmed by subsequent study (R.J. Stern, pers. comm., 1994). Detailed discussion of the problems of boninitic glasses will be presented in Chapter 9.

In Figure 4-1B, TiO_2 contents against CaO/TiO_2 and Al_2O_3/TiO_2 ratios for all glass data are plotted. There is very strong trend of the data, indicating that as the degree of melting increases (i.e. as TiO_2 decreases) these ratios, especially Al_2O_3/TiO_2, increase. Sun et al. (1979) proposed a method of estimating the degree of partial melting required for MORB formation. They suggested that MORB with 0.7% and 1.5% TiO_2 could represent about 25 and 15 % partial melting (respectively) of MORB-type mantle source based on model calculations on the major element data and plots of Al_2O_3/TiO_2 and CaO/TiO_2 vs. TiO_2. Our volcanic glass data show that there is probably a simple relationship between the degree of partial melting of MORB-type mantle source and the ratio of Al_2O_3/TiO_2 for the MORB and the basaltic (and/or basaltic andesitic) volcanic glasses derived from island arcs. The basaltic (and/or basaltic andesite) glasses with 0.7% and 1.5% TiO_2 from DSDP Site 458 and 459B ash layers are probably derived from about 25 % to 15 % partial melting (respectively) of MORB-type mantle sources and there are no temporal changes during the past 35 Ma (Figure 4-4C) if the method of Sun et al. (1979) is reasonable.

The MgO versus CaO and Na_2O plots of DSDP Leg 60 glasses are shown in Figure 4-3B for the whole Site and in Figure 4-4C for different time intervals. There is a broad positive relationship between MgO and CaO concentrations (R=0.65-0.83) but a rough negative relationship between MgO and Na_2O contents (R=0.19-0.37). The calculated crustal thicknesses for the different time periods OL, EM, MM, LM, and QP are about 15, 25, 15, 22, and 15 km, respectively, based on the Plank and Langmuir (1988) global correlation.

Projections of the glass compositions from Sites 458 and 459B in the olivine-clinopyroxene-quartz pseudoternary phase diagram of Grove et al. (1982, 1993) are shown in Figures 4-5A,B. The glass compositions generally overlap closely the 1 bar (10^5 Pa) cotectics of this projection; thus the overall compositional spread probably results from fractional crystallisation differentiation at low pressures in shallow crustal-level magma chambers. However, the opposing effects of equilibrium pressures of differentiation (> 1 bar) and elevated H_2O activities on the position of the appropriate cotectics means that other conditions are possible, and that this overlap may be coincidental. Quantification of the pristine volatile contents will help to resolve this question.

4.3. Glass shards of ODP Leg 125 Sites 782A, 784A, and 786A ash layers

538 analyses of individual glass shards from ODP Leg 125 Sites 782A, 784A and 786A ash layers are all shown in Figures 4-2A, 4-2B, 4-2C and 4-3A. The glass shards of the three Sites 782A, 784A and 786A appear to be the same population, both physically (see Appendix 2) and chemically (Arculus and Bloomfield, 1992). In order to systematically study the trace element geochemistry of individual glass shards from heterogeneous and homogeneous ash layers, those ODP Leg 125 ash samples studied using WDS-EMP by Arculus and Bloomfield (1992) were reanalysed using EDS-EMP, together with 16 new ash samples to cover a wider age range. These glasses are all subalkaline on the total alkali-silica (TAS) diagram (Figure 4-3A), predominantly low-K based on Gill's (1981) division (Figure 4-2B), and tholeiitic on the basis of Miyashiro's (1974) criterion and AFM diagram (Irvine and Baragar, 1971) (Figures 4-2B and 4-6). The combinations of glass types in different time intervals vary. They are predominantly basaltic andesite (48.0-53.4%) and andesite (27.5-29.1%) during Middle Miocene to Late Miocene and almost equal proportions of basaltic andesite (24.5%), andesite (36.4%), dacite (25.0%) and rhyolite (14.1%) during Quaternary-Pliocene times (Figure 4-3D). Although few data are available, all Eocene glasses are low-K tholeiitic rhyolites (Arculus and Bloomfield, 1992; Figure 4-4A), but only one ash sample is available at present.

The major element compositions of glass shards from the three Sites form a tight continuum from basalt through andesite to dacite and rhyolite (Figures 4-2A, 4-2B and 4-3A). Glasses analysed from Site 782A ranges from 51.6 to 78.6 wt% SiO_2, those from Site 784A range from 50.5 to 80.2 wt% SiO_2, and those from Site 786A range from 51.9 to 79.6 wt% SiO_2. The MgO contents of glasses from the three Sites range from 9.0 to 0.1 (limit of EDS-EMP) wt% at Site 782A, from 8.7 to 0.1 wt% at Site 784A and from 9.51 to 0.1 wt% at Site 786A. The K_2O abundances of glasses from Site 782A range from 0.1 to 3.1 wt%, those from Site 784A from 0.1

to 4.8 wt%, and those from Site 786A range from 0.1 to 2.5 wt%. As is evident in these variation diagrams, some oxides such as FeO*, TiO_2, CaO, to a lesser extent Na_2O, and a subset of K_2O vary linearly with silica, but MgO varies nonlinearly, while Al_2O_3 is essentially unchanged, within a relatively restricted range. These oxide variations are similar to those of DSDP Leg 60 glasses.

As is the same with Leg 60 glasses, there is some scatter in TiO_2, FeO*, MgO, Al_2O_3 and CaO. This scatter can reasonably be attributed to probe beam overlap of glass with plagioclase and/or pyroxene and/or Fe-Ti oxides.

Are there any temporal changes in the major element chemistry of glasses from ODP Leg 125 Sites 782A, 784A and 786A? The abundances of all major and minor element are unchanged (within reasonable error) as a function of an age (Figures 4-4A, B and C). But some high-K (including medium- and low-K) glass pulses appear at Site 784A at ~ 6 Ma, ~3 Ma, and in Site 782A at ~ 3 Ma and present (Arculus and Bloomfield, 1992). Alkalic glasses are not found in any of the ash layers of ODP Leg 125 Sites. However, there are some records for a few alkalic glasses from the extensive volcanic ash studies of ODP Leg 126 Sites (see Chapter 3 for a review of IBM volcanic ash studies). These were probably derived from eruption sites far to the west of the Izu-Bonin arc (i.e. from the Ryukyu arc, Japan) (Fujioka et al., 1992a,b). Boninitic glasses are not recorded in any of the ash layers derived from ODP Legs 125 and 126 Sites.

In Figures 4-2C and 4-4C, TiO_2 contents against CaO/TiO_2 and Al_2O_3/TiO_2 ratios for all glass data are plotted. Strong trends within these data are similar to those of DSDP Leg 60 glasses.

The MgO versus CaO and Na_2O plots of ODP Leg 125 glasses are shown in Figure 4-2C for all Sites and in Figure 4-4C for different time intervals. There is a broad positive relationship between MgO and CaO concentrations (R=0.56-0.72) but a roughly negative relationship between MgO and Na_2O contents (R=0.24-0.40). The calculated crustal thicknesses for the different time periods MM, LM, and QP are about 25, 20, and 15 km, respectively, based on the global correlation in arc magmas between CaO content at 6 wt% MgO ($Ca_{6.0}$) and crustal thickness and about < 10, < 10, and 15 km, respectively, based on the correlation between Na_2O content at 6 wt% MgO ($Na_{6.0}$) and crustal thickness (Plank and Langmuir, 1988) whereas measured thicknesses are ~ 20 km (Shinohara et al., 1992; Takahashi et al., 1993).

Projections of the glass compositions from Sites 782A, 784A and 786A in the olivine-clinopyroxene-quartz pseudoternary phase diagram of Grove et al. (1982, 1993) are shown in Figures 4-5A,B. The data for Leg 125 project at a similar position to those of DSDP Leg 60 glasses. The glass compositions generally overlap closely the 1 bar cotectics of this projection but with a shift into the olivine (+ plagioclase) field alone at higher normative olivine contents; thus the overall compositional spread probably results from fractional crystallisation at low pressures in shallow, crustal-level magma chambers.

4.4 Major element comparison of Leg 60 and Leg 125 glasses

The major element chemistry of glasses from DSDP Leg 60 Sites 458 and 459B ash layers and from ODP Leg 125 Sites 782A, 784A, and 786A ash layers is discussed above. The two groups of glasses share the common chemical characteristics as follows:

1. They are all subalkaline (Figure 4-3A) and predominantly tholeiitic (Figures 4-4A and 4-6), with < 2% of calc-alkaline affinity on the Miyashiro (1974) classification, and < 1% of calc-alkaline affinity in the AFM diagram.

2. There are no consistent temporal changes in the glass (melt) series during the past 35 Ma. No boninitic series, calc-alkaline, or alkalic series with shoshonitic affinity have been erupted during this period (maybe some alkaline rhyolite at the Izu-Bonin and Mariana, Figure 4-2B, and some from 458 and 459, Figure 4-1B).

3. The chemical compositions of both groups of glasses range from basalt through andesite to dacite and rhyolite (Figure 4-3A). Basalt is volumetrically the least significant with < 5 volume % based on number of analysed glass points. Andesite (including basaltic and high-Si andesite) is dominant with > 61% (61-83%) except for Middle Miocene DSDP Leg 60 glasses (~ 46%). High-SiO_2 glasses (dacitic and rhyolitic) vary from 31 to 52% during Oligocene-Miocene times, highest

in Middle Miocene but decreasing to 13% during Quaternary-Pliocene times at DSDP Leg 60 Sites. High-SiO_2 glasses range from 13 to 21% and 39% during Middle Miocene to Quaternary-Pliocene times, with the highest abundances in the Quaternary-Pliocene at ODP Leg 125 Sites (Figures 4-3C,D).

4. The diagram of Al_2O_3/TiO_2 versus TiO_2 in both groups of glasses is almost the same as that of MORB.

5. Major element oxide variations with silica of both groups of glasses are almost the same, indicating that the genesis of the spectrum of glass (melt) compositions sampled is dominated by fractional crystallisation rather than simple mixing processes (e.g. Arculus and Bloomfield, 1992).

6. Projections from plagioclase into the olivine-clinopyroxene-quartz plane (Grove et al., 1982, 1993) for the two groups of glasses are very similar (Figures 4-5A,B). The glass compositions generally overlap closely the 1 bar cotectics of this projection. The overall compositional spread of DSDP Leg 60 and ODP Leg 125 glasses probably results from fractional crystallisation differentiation at low pressures in shallow crustal-level magma chambers.

Although the DSDP Leg 60 glasses and ODP Leg 125 glasses show many common features, they do have their differences as follows:

1. Volcanic ashes spanning a 35 Ma age range were recovered from DSDP Leg 60 Sites 458 and 459B whereas ODP Leg 125 Sites 782A, 784A, and 786A recorded abundant arc volcanism from the Miocene to present (17-0 Ma) (Leg 125 shipboard scientific party, 1989) with few ash layers in the age range from 18 to 45 Ma (Arculus and Bloomfield, 1992; only two ash layers at about 23.7 and 42 Ma are available).

2. No temporal chemical changes are observed in the ODP Leg 125 glasses during 17 Ma. On the other hand, DSDP Leg 60 glasses change from Oligocene-Early Miocene (> 17 Ma), and a low-K tholeiitic series to Middle-Miocene-present (17-0 Ma), predominantly a medium-K tholeiitic series with < 5% exceptions (Arculus et al., 1992; Chen and Arculus, 1993a; Figures 4-4A and 4-

6). Other major and minor element abundances are unchanged significantly (Figures 4-4A,B and C).

3. The average K_2O contents in different time periods for DSDP Leg 60 and ODP Leg 125 glasses are quite different. In general, the highest average K_2O abundances are in Late Miocene relative to other time periods for DSDP Leg 60 glasses, while Oligocene and Early Miocene DSDP glasses have similar K_2O contents, comparable to those of ODP Leg 125 glasses during the 0-17 Ma period (Figure 4-3E).

4. The major element chemistry of ODP Leg 125 glasses in the 0-17 Ma interval is very similar to that of DSDP Leg 60 glasses during 18-35 Ma interval but different to that of DSDP Leg 60 glasses during the 0-17 Ma period (term it as 60B Gl or L60B group). This aspect will be discussed in Chapter 9.

4.5 Comparison of Leg 60 glasses and volcanic rocks of Mariana arc-basin region

As briefly reviewed in Chapter 2, there are extensive published studies of the Mariana arc-backarc system. The published volcanic rock data for major and trace elements, and isotopes, have been compiled. All references used are given here for convenience. Data for Mariana arc volcanic rocks include: 56 Eocene-Oligocene volcanic rocks from Guam and Saipan islands (abbreviated as M.EoOl 56) (Schmidt, 1957; Shiraki et al., 1978; Beccaluva, 1980; Bloomer, 1983; Meijer, 1983; Reagan and Meijer, 1984; Hickey and Reagan, 1987), 121 (Eocene) Oligocene drilled volcanic rocks from the PKR (Site 448 121) (Armstrong and Nixon, 1980; Ishii, 1980; Mattey et al., 1980; Scott, 1980; Wood et al., 1981), 19 Miocene (possibly Middle to Late Miocene) drilled volcanic rocks on the WMR (Site 451 19) (Ishii, 1980; Mattey et al., 1980; Wood et al., 1981), 24 Middle-Late Miocene volcanic rocks from Guam and Saipan islands (M.L-M.M 24) (Schmidt, 1957; Stark, 1963; Shiraki et al., 1978; Hickey and Reagan, 1987; Arculus, unpublished data, 1992), 205 modern Mariana subaerial volcanic rocks (M.QP 205) (Schmidt, 1957; Larson et al., 1974; Dixon and Batiza, 1979; Stern, 1979; Chow et al., 1980; Meijer and Reagan, 1981a; Meijer, 1982; Banks et al., 1984; Hole et al., 1984; White and Patchett, 1984; Woodhead, 1988, 1989), 40 southern Mariana submarine province volcanic rocks (M.SSP 40) (Dixon and Stern, 1983; Stern and Bibee, 1984; Stern et al., 1989), 28 central Mariana submarine province volcanic rocks (M.CSP 28) (Dixon and Stern, 1983: Bloomer et al., 1989a,b; Lin et al., 1989, 1990) and 87 northern Mariana submarine province volcanic rocks (M.NSP 87) (Dixon and Stern, 1983; Bloomer et al., 1989a,b; Lin et al., 1989, 1990; Jackson, 1991; Stern et al., 1993).

Data for MORB and backarc basin volcanic rocks from the Philippine Sea Plate consist of 101 representative Pacific MORB (MORB 101) from the 1981 Pacific MORB analyses (Zindler et al., 1984; Dupuy et al., 1987; Le Roex, 1987). 397 MORB glass analyses (MORBGL 397) (from Pacific and Atlantic) (Bryan et al., 1976; Bryan, 1979; Bryan et al., 1981; Sigurdsson, 1981; Bryan and Dick, 1982; Puchelt and Emmermann, 1983; Bender et al., 1984; Christie and Sinton, 1986; Michael and Chase, 1987; Batiza and Niu, 1992), 78 Daito basin volcanic rocks (DTB 78) (Marsh et al., 1980; Nisterenko, 1980), 66 West Philippine basin volcanic rocks (WPB 66) (Armstrong and Nixon, 1980; Mattey et al., 1980; Wood et al., 1980; Zakariadze et al., 1980), 14 Parece Vela basin volcanic rocks (PVB 14) (Ishii, 1980; Wood et al., 1980; Zakariadze et al., 1980), 182 Shikoku basin volcanic rocks (SKB 182) (Marsh et al., 1980; Nisterenko, 1980), 124 Mariana Trough 18°N area volcanic rocks (MT18 124) (Wood et al., 1981; Sinton and Fryer, 1987; Volpe et al., 1987; Hawkins et al., 1990) and 21 Mariana Trough 22°N area volcanic rocks (MT22 21) (Stern et al., 1990). Eocene-Oligocene Mariana forearc basement volcanic rocks were collected from Site 458: 50 analyses (458 base 50) and Site 459B: 37 analyses (459B base 37) (Meijer, 1980; Bougault et al., 1981; Hickey and Frey, 1981; Meijer and Reagan, 1981b; Sharaskin, 1981; Wood et al., 1981).

All the major element data for Mariana arc and backarc volcanic rocks together with MORB and MORB glasses are plotted in Figures 4-3A, B and 4-7 to 4-15 for a comprehensive comparison. All these rocks are subalkaline except some samples from Mariana NSP and a few from the PKR (Site 448) and Leg 60 forearc basement (Site 459B) and some from backarc basins such as the Daito and Shikoku basins (Figures 4-3A,B). Stern et al. (1988), Bloomer et al. (1989b) and Lin et al. (1989, 1990) reported that some volcanic rocks from the NSP are alkalic with strong shoshonlitic affinity, equivalent to those of IwoJima. No other volcanic rocks from the Mariana region are alkalic. A few samples from the PKR (Site 448), Leg 60 forearc basement (Site 459B) and backarc basins such as Daito and Shikoku with abnormal total alkalis probably result from alteration by seawater (e.g., Mattey et al., 1980). The K_2O abundances of all volcanic rocks are mostly low- to medium-K, with very few high-K samples.

From the comprehensive comparisons of chemical compositions between DSDP Leg 60 glasses and the Mariana arc-backarc volcanic rocks (Table 4-1, Figures 4-1A,B; 4-10 to 4-12), it is very clear that some significant differences exist. Taking subaerial Mariana arc andesites as a comparator, these have lower TiO_2 (0.6-1.2%), lower FeO* (9-13%), and higher Al_2O_3 (15-21%), relative to DSDP Leg 60 glasses (TiO_2 0.7-1.8%, FeO* 9-17%, and Al_2O_3 12-17%).

A clear distinction between tholeiitic (TH) and calc-alkaline (CA) series does not exist based on Miyashiro's (1974) and the AFM criterion. The majority of Eocene-Oligocene Mariana arc volcanic rocks are low-K tholeiitic series with some exceptions (Figures 4-7 to 4-9 and 4-15). The volcanic rocks from Guam, Saipan, and Leg 60 forearc Sites are calc-alkaline on the AFM diagram (Figures 4-7 and 4-8) and transitional between TH and CA series on the Miyashiro (1974) diagram (Figures 4-9 and 4-15). The volcanic rocks of the Eocene-Oligocene backarc basins (DTB and WPB) are predominantly medium-K tholeiitic basalts (Figure 4-9) and transitional between TH and CA basalts on the AFM diagram (Figure 4-8). Data for Miocene Mariana arc volcanic rocks are relatively sparse, especially for Early Miocene times. Available data show that these rocks are predominantly medium-K transitional between TH and CA (Figures 4-7 and 4-9). Volcanic rocks of the Miocene backarc basins (PVB and SKB) are predominantly low-K, transitional between TH and CA (Figures 4-8 and 4-9). The data set for the modern Mariana arc is drawn from many samples of Quaternary-Pliocene subaerial and submarine volcanic rocks. These are predominantly medium-K transitional between TH and CA but with more tholeiitic affinity (Figures 4-7 and 4-9). The modern Mariana backarc basin volcanic rocks (MT18 and MT22) are dominantly low- to medium-K, transitional between TH and CA with much more tholeiitic affinity (Miyashiro, 1974; Figure 4-9) but predominantly calc-alkaline on the AFM diagram (Figure 4-8). Interestingly, MORB and MORB glasses are also dominantly low- to medium-K transitional between TH and CA, with greater tholeiitic affinity (Figures 4-8 and 4-9). Note that the relationship between TH-CA series and K_2O abundances of Mariana arc volcanic rocks appears more complex than the DSDP Leg 60 glasses, and there is a higher incidence of CA compositions.

The chemical compositions of the Mariana arc volcanic rocks vary greatly (Figures 4-3A,B) and the distribution of rock types varies, too (Figures 4-3C,D). The Eocene-Oligocene subaerial volcanic rocks range compositionally from basalt through andesite and dacite to rhyolite with almost equal proportions among mafic, intermediate and felsic (30.4% B, 12.5% BA, 30.4% A, 14.3% D and 12.5% R). The drilled Eocene-Oligocene tholeiitic volcanic rocks from Site 448 are predominantly mafic, from basalt to andesite, with 59.5% basalt, 39.7% basaltic andesite and only 0.8% andesite, while the volcanic rocks from the temporally equivalent Mariana forearc drilling Sites 458 and 459B are predominantly basaltic andesite (75.9%) with 21.8% andesite and only 2.3% basalt. The available Miocene volcanic rocks (WMR Site 451) are predominantly mafic with 52.6% basalt, 21.1% basaltic andesite, 21.1% andesite and only 5.3% dacite, and 31.8% basalt, 59.1% basaltic andesite and 9.1% andesite for subaerial (Guam) volcanic rocks. The modern subaerial volcanic arc is very similar to the CSP and SSP, which are predominantly mafic (30-42% basalt and 42-53% basaltic andesite) with 5-16% andesite and 5-13% dacite (none in the CSP) and only 1.4% rhyolite restricted to the subaerial arc. The NSP volcanic rocks have a higher proportion of evolved rocks with 27.6% basalt, 34.5% basaltic andesite, 29.3% andesite and 8.6% dacite. An important overall point emerges from this detailed comparison: it is clear there is a large difference between the abundance of rock types of the Mariana arc and DSDP Leg 60 glasses, with more abundant evolved types such as dacite and rhyolite and fewer basalts in the volcanic ashes.

The rock types of the Mariana backarc basins are very similar to MORB and MORB glasses, predominantly basalt, with < 5% basaltic andesite (45-55% SiO_2) (Figures 4-3B,F). The spectrum of low- (~ 90%) to medium- (~ 7%) to high-K (~ 3%) composition is also similar in these backarc basins to the Pacific MORB populations (Figure 4-3F). The Daito Basin volcanic rocks are 78% medium-K and only 8% low-K while the West Philippine Basin volcanic rocks are 58% medium-K and 41% low-K. The Parece Vela Basin comprises 79% medium-K and only 21% low-K while the Shikoku Basin are dominated by low-K (89%) with only 6% medium-K volcanic rocks. The modern Mariana Trough volcanic rocks are different and evolved to basaltic andesite: MT-18 basalts are 85% low-K and 15% medium-K while MT-22 basalts are only 46% low-K and 54% medium-K; MT-18 have 24% medium-K and 76% low-K basaltic andesites, however MT-22 have 100% low-K basaltic andesites. Therefore, the low-K to medium-K series are persistent, concurrent chemical features of backarc basins and there is no evidence for clear temporal changes.

TiO_2 contents against CaO/TiO_2 and Al_2O_3/TiO_2 ratios for all Mariana arc and basin volcanic rocks with MORB and MORB glasses are plotted in Figure 4-13. There are strong trends in the data, similar to those discovered by Sun et al. (1979). All of the Mariana arc and backarc basin volcanic rocks overlap with MORB, MORB glasses and DSDP Leg 60 glasses in diagrams of wt % TiO_2 vs. Al_2O_3/TiO_2. The basalts and/or basaltic andesites with 0.7% and 1.5% TiO_2 from Mariana arc-backarc region are probably derived from about 25 to 15% partial melting (respectively) of MORB-type mantle sources and there are no temporal changes from the Eocene to present.

The MgO vs. CaO and Na_2O plots for all Mariana arc and basin volcanic rocks, MORB and MORB glasses, are shown in Figure 4-14. There is a broad positive relationship between MgO and CaO concentrations (R=0.40-0.94) but a roughly negative relationship between MgO and Na_2O contents (R=0.12-0.94) for Mariana arc volcanic rocks. The calculated crustal thicknesses ignoring those with limited compositional spreads, based on the Plank and Langmuir (1988) global correlation, are as follows: - Eocene-Oligocene subaerial volcanic rocks ~ 35 km (0.77 correlation coefficient of wt % CaO vs. MgO); drilled Eocene-Oligocene (Site 448) ~ 35 km (0.02); drilled Miocene (Site 451) ~ 15 km (0.44); subaerial Miocene ~ 45 km (0.03); modern subaerial volcanic rocks ~ 18 km (0.66); SSP lavas ~ 15 km (0.79); CSP lavas ~ 25 km (0.80); and NSP volcanic rocks ~ 25 km (0.67). However, when the individual modern arc volcanoes such as Agrigan (14 analyses), Asuncion (8), Guguan (11), Pagan (61) and Sarigan (44) are used, the calculated crustal thicknesses for these five islands are quite different: Agrigan ~ 10 km (0.94); Asuncion <10 km (0.49); Guguan <10 km (0.56), Pagan ~ 15 km (0.40), and Sarigan ~ 25 km (0.93), based on the Plank and Langmuir (1988) global correlation. Compared with those data (15-25 km) from DSDP Leg 60 glasses, the calculated crustal thickness from the Mariana arc volcanic rocks vary largely from <10 to ~ 45 km. Therefore, it is difficult to evaluate the true crustal thickness of island arcs using the method of Plank and Langmuir (1988).

Projections of the volcanic rock compositions from the Mariana arc into the olivine-clinopyroxene-quartz pseudoternary phase diagram of Grove et al. (1982, 1993) are presented in Figure 4-5C. These diagrams are quite different from those of DSDP Leg 60 glasses but similar to those of the Lesser Antilles arc suites (Grove and Kinzler, 1986). The Mariana arc volcanic rocks seem to have been produced at higher crustal-level pressures and higher water contents (Grove and Bryan, 1983; Grove and Kinzler, 1986). Interestingly, the Mariana backarc basin volcanic rocks are similar to MORB glasses in the olivine-clinopyroxene-quartz pseudoternary phase diagram (Figure 4-5D) and quite different from those of DSDP Leg 60 glasses, projecting towards the olivine apex and displaced from the atmospheric pressure cotectics.

4.6 Comparison of Leg 125 glasses and volcanic rocks of Izu-Bonin arc region

In chapter 2 and 3, a brief review of studies on volcanic rocks and glasses (tephras) in the Izu-Bonin region was presented. The collected data include major and trace elements and isotopes. The references are given here again for convenience: - the data set consists of 29 subaerial and submarine IwoJima volcanic rocks (possibly Miocene to present, IwoJima 29) (Macdonald, 1948; Philpotts, et al., 1971; Meijer, 1982; Stern et al., 1984; Bloomer et al., 1989a,b; Lin et al., 1990; Yuasa and Nohara, 1992), 15 subaerial Torishima volcanic rocks (Torishima 15) (Langmuir et al., 1995), 23 other Izu-Bonin subaerial volcanic rocks (IB sub* 23) (Macdonald, 1948; Philpotts, 1971; Nohda and Wasserburg, 1981; Meijer, 1982; Stern et al., 1984; Ikeda and Yuasa, 1989; Takada et al., 1992; Yuasa and Nohara, 1992; Langmuir et al., 1995), 86 Izu-Bonin submarine volcanic rocks (IB subm 86) (Bloomer et al.. 1989a,b; Ikeda and Yuasa, 1989; Lin et al., 1990; Yuasa and Nohara, 1992; Tatsumi et al., 1992), and 59 modern Izu-Bonin rift (backarc basin) volcanic rocks (IB Rifts 59) (Ikeda and Yuasa, 1989; Fryer et al., 1990; Ikeda et al., 1992). In addition, the data set includes 148 Eocene-Oligocene Izu-Bonin forearc basement volcanic rocks from Site 786 (786 base 148) (Arculus et al., 1992; Murton et al., 1992), 16 Oligocene-Early Miocene volcaniclastic turbidites (Turbi A 16) and 8 Middle Miocene-present volcaniclastic turbidites (Turbi B 8) from Gill et al. (1994).

All these major element data of Izu-Bonin arc and backarc volcanic rocks plus turbidites are plotted in Figures 4-3A,B, and 4-8 to 4-15 for comprehensive comparison. These rocks are subalkaline except for IwoJima (Figures 4-3A,B). Stern et al. (1988), Bloomer et al. (1989b) and Lin et al. (1989, 1990) reported that IwoJima volcanic rocks are alkalic with strong shoshonitic affinity. No other samples from the Izu-Bonin region are alkalic. The K_2O abundances of these rocks varies largely from low- to medium- to high-K in the case of Site 786 (a few high-K volcanic rocks are probably caused by strong alteration). A clear classification between tholeiitic (TH) and calc-alkaline (CA) series does not exist based on Miyashiro's (1974) and AFM discriminants. The modern subaerial arc volcanic rocks are predominantly low-K tholeiitic series (Figures 4-8 and 4-9) while the submarine volcanic rocks are low- to medium-K transitional between TH and CA series (Figures 4-8 and 4-9). Volcanic rocks of the modern backarc basins are predominantly low-K tholeiites (Figures 4-8 and 4-9). There is a lack of Miocene volcanic rocks in the Izu-Bonin region, but the turbidites can be used to compare with limited glass data. The Middle Miocene-present turbidites are low-K tholeiitic series, comparable to the ODP Leg 125 glasses, while the Oligocene-Early Miocene turbidites are dominantly medium-K calc-alkaline series (Figures 4-8 and 4-15). The Eocene-Oligocene forearc basement are low- to high-K boninitic series (Arculus et al., 1992; Pearce et al., 1992).

The compositions of the northern Izu-Bonin subaerial and submarine volcanic rocks are similar, ranging from basalt, basaltic andesite through andesite to dacite in almost equal proportions (43-38% B, 38-34% BA, 10-8% A, and 7-12% D) with the latter evolved to rhyolite (8%), while the IwoJima volcanic rocks are homogeneous trachyandesites (Figures 4-3A,B and D). The drilled Eocene-Oligocene basement boninite series from Site 786 are predominantly intermediate, from basalt (1%) through boninite (75%) to dacite (16%) and rhyolite (8%), however the backarc basin volcanic rocks are predominantly basalt with minor felsic derivations. Clearly, the ODP Leg 125 glasses are dominated by intermediate and felsic types, similar to the mode of the drilled basement but different from those of modern northern Izu-Bonin volcanic rocks (dominated by mafic volcanic rocks).

TiO_2 contents against CaO/TiO_2 and Al_2O_3/TiO_2 ratios for all Izu-Bonin arc and basin volcanic rocks with turbidites are plotted in Figures 4-13 and 4-15. Once again, there are strong trends in the data, similar to those discovered by Sun et al. (1979). All the Izu-Bonin arc and backarc basin volcanic rocks overlap with ODP Leg 125 glasses in the diagrams of TiO_2 contents against Al_2O_3/TiO_2. All forearc basement rocks from Site 786 have very low TiO_2 (< 0.4 wt%). They are boninitic series, similar to Site 458 basement volcanic rocks, and quite distinct compared with other Izu-Bonin arc volcanic rocks.

The MgO vs CaO and Na_2O plots of Izu-Bonin arc and basin volcanic rocks with MORB are shown in Figures 4-14 and 4-15. There is a broad positive relationship between MgO and CaO concentrations (R=0.32-0.74) and a roughly negative relationship between MgO and Na_2O contents (R=0.42-0.71) for the Izu-Bonin modern arc. The calculated crustal thicknesses, based on the Plank and Langmuir (1988) global correlation, are as follows: - IwoJima ~ 70 km (0.32 correlation coefficient of wt% CaO vs. MgO); Torishima ~ < 10 km (0.62); other Izu-Bonin subaerial < 10 km (0.65) and Izu-Bonin submarine volcanic rocks ~ 20 km (0.73). The calculated crustal thicknesses of IB Rifts are different and ~ 27 km (0.89) based on the method of Plank and Langmuir (1988). The crustal thickness data (10-25 km) calculated from ODP Leg 125 glasses are similar to those (10-20 km) from the Izu-Bonin arc volcanic rocks but much thinner than those (27-37 km) from the backarc basins.

Projections of the volcanic rock compositions from the Izu-Bonin arc in the olivine-clinopyroxene-quartz pseudoternary phase diagram of Grove et al. (1982, 1993) are presented in Figure 4-5D. Once again, the projection positions in these diagrams are quite different from those of ODP Leg 125 glasses but similar to Mariana arc volcanic rocks. The Izu-Bonin arc volcanic rocks may be produced at higher (crustal-level) pressures and higher water contents (Grove and Bryan, 1983; Grove and Kinzler, 1986).

A comparison of the chemical compositions between ODP Leg 125 glasses and the Izu-Bonin arc-backarc volcanic rocks (Table 4-2, Figures 4-2A,B and C; 4-10 to 4-12, 4-15), reveals some significant differences. The Izu-Bonin arc volcanic rocks (andesite as a comparator) have lower FeO* (8-14%), and higher Al_2O_3 (15-20%), relative to those of ODP Leg 125 glasses (FeO* 10-17%, Al_2O_3 12-17%). Both suites are chemically distinctive compared with the forearc basement boninitic series. These chemical differences between glass shards in ashes, volcanic arc rocks and forearc basement are similar to the Mariana sample set.

4.7 Summary

From the foregoing comparative effort on volcanic glasses from DSDP Leg 60 and ODP Leg 125, and volcanic rocks from the Mariana arc-backarc region and Izu-Bonin arc-backarc area, the following conclusions can be drawn: -

1. The volcanic glasses collected from deep-sea volcanic ash layers nearby the Izu-Bonin-Mariana arc system were derived from island arc volcanism. All these glasses were derived from subaerial rather than submarine sources, and not from backarc basin volcanism.

2. The glass compositions clearly represent melt compositions better than the volcanic rocks, but they cannot represent a single line of liquid descent (Arculus and Bloomfield, 1992).

3. The glass compositions show a narrow overall compositional range, probably caused by the range of degree of partial melting. All these volcanic glasses and rocks with between 0.7% and 1.5% TiO_2 from the IBM arc-backarc region, which is ~ 2400 km long and ~ 2000 km wide, were probably derived from between 25 to 15 % partial melting (respectively) of a MORB-type mantle source (Sun et al., 1979). Thus a MORB-type mantle source may be widely distributed beneath the Philippine Sea Plate.

4. The glasses are dominantly andesitic with < 5-8 % basalt, < 30% dacite and rhyolite, while the arc volcanic rocks are dominantly basaltic and andesitic with < 5% dacite and rhyolite. The variation diagrams and projections from plagioclase into the olivine-clinopyroxene-quartz plane (Grove et al., 1982, 1993) for the DSDP Leg 60 and ODP Leg 125 glasses exhibit more clearly than the volcanic arc suite that these glasses probably result from fractional crystallisation differentiation at low pressures in shallow crustal-level magma chambers.

5. The ODP Leg 125 glasses are predominantly low-K tholeiitic series, similar to the ODP Leg 126 glasses and volcanic rocks of the northern part of the Izu-Bonin arc. There are no systematic chemical changes during the past 17 Ma. The low-K tholeiitic glasses are probably the

products of northern Izu-Bonin arc volcanism. Some medium-K tholeiitic glasses may derived from the nearby Mariana arc.

6. The DSDP Leg 60 glasses are predominantly low-K to high-K tholeiitic series. They can be divided into two groups (L60A Gl and L60B Gl) on the basis of K_2O contents and time intervals. L60A Gl are predominantly low-K tholeiitic series formed during the Oligocene to the end of Early Miocene (35-18 Ma) times, while L60B Gl are predominantly medium-K tholeiitic series formed during Middle Miocene to present (17-0 Ma) times. Clearly, there is a temporal chemical change of K_2O abundances in the DSDP Leg 60 glasses but no other temporal change such as rock series or other major element abundance variations are apparent. Interestingly, the major-element chemistry of L60A glasses (35-18 Ma) is very similar to that of IB glasses (17-0 Ma). The Mariana arc volcanic rocks have a complicated chemistry. In general, on the basis of major element chemistry and tectonics of the Mariana arc system, the Oligocene Leg 60 glasses are probably the products of the PKR arc: the Miocene glasses are possibly derived from the WMR arc; and the Quaternary-Pliocene glasses are the products of the active Mariana arc.

7. The age of most high-K glasses from DSDP Leg 60 and ODP Leg 125 Sites is Late Miocene (11.2-5.3 Ma). These high-K glasses are termed IBM high-K glasses. They range from basaltic andesite through andesite to dacite and rhyolite. They are all tholeiitic series. They may possibly be derived from the southern Izu-Bonin arc (but not IwoJima, which is alkaline).

8. From the extensive comparative studies of the IBM volcanic glasses and rocks, it is very clear that neither a medium-K nor high-Al_2O_3 content are necessarily synonymous with calc-alkaline. The classifications of calc-alkaline series suggested by Jakes and Gill (1970), Peccerillo and Taylor (1976), and Wilson (1989) may not be appropriate.

9. The calculated arc crustal thicknesses for the IB and Mariana glasses based on the method of Plank and Langmuir (1988) are about 10-25 km, comparable to measured IB thicknesses, ~ 20 km (Shinohara et al., 1992; Takahashi et al., 1993). However, the calculated arc crustal thicknesses from IBM arc volcanic rocks vary greatly from 10 to 45 km. Actually, the $Ca_{6.0}$ and $Na_{6.0}$ values are obtained from the broad correlation between the CaO and Na_2O

contents and MgO contents; particularly, the relationship between $Ca_{6.0}$ or $Na_{6.0}$ values and the thicknesses of the overlying arc crust is roughly negative or positive. It is very difficult to calculate the correct crustal thicknesses by this geochemical method, and it appears meaningless to evaluate crustal growth in arcs using these kind of data.

Table 4-1 The comparison of average major element compositions of Leg 60 glasses and Mariana arc volcanic rocks

Glass/lava	Rock types	Analysis No	SiO_2	TiO_2	Al_2O_3	FeO*	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5
Quat-Plio												
L60 glass	B 3.8%	9	51.19	1.37	14.24	14.96	0.20	4.51	9.96	2.73	0.84	
Mariana subaerial	B 29.7%	43	50.85	0.86	17.93	10.48	0.19	5.22	11.16	2.52	0.64	0.15
Mariana SSP	B 30.0%	12	50.73	0.99	17.43	11.35	0.19	5.07	10.77	2.63	0.69	0.15
Mariana CSP	B 42.1%	8	49.49	0.68	16.57	9.43	0.18	8.44	12.54	2.01	0.54	0.13
Mariana NSP	B 27.6%	16	50.79	0.89	18.02	9.45	0.18	5.80	10.76	2.58	1.28	0.23
L60 glass	BA 64.1%	150	54.46	1.15	14.60	13.00	0.19	4.00	8.78	2.92	0.90	
Mariana subaerial	BA 46.9%	68	53.92	0.86	17.20	9.59	0.18	4.59	9.94	2.82	0.75	0.15
Mariana SSP	BA 52.5%	21	53.77	1.07	16.09	10.72	0.20	4.39	9.31	3.29	0.96	0.20
Mariana CSP	BA 42.1%	8	53.75	0.80	18.18	8.79	0.17	5.34	9.72	2.58	0.56	0.10
Mariana NSP	BA 34.5%	20	55.09	0.86	17.90	8.68	0.12	3.66	9.03	2.91	1.53	0.21
L60 glass	A 18.8%	44	59.36	1.13	14.81	11.02	0.16	2.32	6.83	3.25	1.14	
Mariana subaerial	A 16.6%	24	59.74	0.80	16.75	7.54	0.18	2.86	7.09	3.73	1.17	0.14
Mariana SSP	A 5.0%	2	59.06	0.69	16.29	7.39	0.14	3.63	7.83	3.39	1.41	0.17
Mariana CSP	A 15.8%	3	60.08	0.66	17.14	6.63	0.15	3.61	7.29	3.16	1.14	0.13
Mariana NSP	A 29.3%	17	60.41	1.12	14.97	9.22	0.16	2.97	6.39	3.07	1.55	0.14
L60 glass	D 9.8%	23	66.93	0.82	13.95	7.63	0.13	1.02	4.46	3.24	1.83	
Mariana subaerial	D 5.5%	8	64.80	0.81	16.49	5.87	0.15	1.38	4.71	3.92	1.74	0.14
Mariana SSP	D 12.5%	5	69.85	0.54	14.35	2.83	0.12	1.30	3.74	5.36	1.82	0.09
Mariana NSP	D 8.6%	5	64.91	1.07	14.10	7.69	0.15	2.23	4.80	3.20	1.79	0.06
L60 glass	R 3.4%	8	76.06	0.48	12.22	3.33	0.00	0.13	2.24	2.87	2.66	
Mariana subaerial	R 1.4%	2	76.26	0.44	13.85	2.42	0.12	1.18	2.29	2.07	1.25	0.13
Site 458 base	Boninitic glass	15	58.64	0.10	13.19	8.22		8.20	9.38	1.71	0.55	
Chichijima**	Boninitic lava	3	58.25	0.16	9.97	8.82	0.16	13.71	7.19	1.33	0.39	0.02

Total Fe reported as FeO ; **The data from Shimizu et al. (1992)

All analyses are recalculated to 100 per cent and free of H_2O and volatiles according to LeBas et al. (1986)

Table 4-1 The comparison of average major element compositions of Leg 60 glasses and Mariana arc volcanic rocks (cont)

Glass/lava	Rock types	Analysis No	SiO_2	TiO_2	Al_2O_3	FeO*	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5
Late Miocene												
L60 glass	BA 17.3%	40	54.37	1.24	14.02	13.72	0.20	4.16	8.75	2.38	1.17	
L60 glass	A 43.3%	100	59.90	0.91	15.37	9.80	0.20	2.58	6.64	2.93	1.69	
L60 glass	D 27.3%	63	66.11	0.70	15.21	6.37	0.15	1.10	4.53	3.54	2.31	
L60 glass	R 12.1%	28	74.85	0.42	13.44	3.01	0.17	0.16	2.00	3.03	2.95	
Middle Miocene												
Mariana subaerial	B 31.8%	7	52.08	0.80	17.60	10.30	0.24	6.24	9.06	2.53	1.04	0.12
Mariana subaerial	BA 59.1%	13	54.81	0.67	16.51	8.65	0.16	6.61	8.79	2.70	0.93	0.18
Mariana subaerial	A 9.1%	2	62.21	0.66	15.05	6.58	0.13	3.25	7.65	3.11	1.20	0.17
L60 glass	BA 21.7%	30	55.31	1.08	14.42	13.16	0.19	4.09	8.76	2.22	0.79	
L60 glass	A 47.1%	65	59.01	0.98	14.73	11.22	0.18	2.86	7.30	2.83	0.92	
L60 glass	D 24.6%	34	67.48	0.80	14.56	6.75	0.15	1.01	4.47	3.15	1.64	
L60 glass	R 6.5%	9	74.09	0.40	14.36	3.32	0.00	0.30	2.54	2.98	2.03	
Early Miocece												
L60 glass	B 1.4%	7	50.61	0.83	12.36	13.79	0.25	8.09	12.26	1.52	0.30	
L60 glass	BA 22.0%	112	55.02	1.08	14.48	12.74	0.18	4.36	9.17	2.42	0.55	
L60 glass	A 24.3%	124	60.01	1.04	14.34	10.93	0.17	2.61	7.29	2.88	0.74	
L60 glass	D 29.8%	152	67.44	0.77	13.90	7.44	0.16	1.18	5.23	3.13	0.75	
L60 glass	R 22.5%	115	74.64	0.46	12.97	4.36	0.15	0.40	3.30	2.84	0.90	
Oligocene-Eocene												
Mariana subaerial	B 30.4%	17	49.18	1.30	14.85	10.85	0.19	9.86	10.81	2.41	0.36	0.18
Mariana subaerial	BA 12.5%	7	56.15	0.83	17.47	9.02	0.16	4.56	8.58	2.57	0.57	0.10
Mariana subaerial	A 30.4%	17	59.77	0.59	17.17	7.30	0.12	3.57	7.60	2.96	0.79	0.14
Mariana subaerial	D 14.3%	8	68.25	0.48	15.07	4.71	0.09	2.03	4.89	3.36	1.03	0.09
Mariana subaerial	R 12.5%	7	80.03	0.15	11.12	1.50	0.03	0.27	1.58	3.56	1.69	0.07
L60 glass	BA 19.8%	17	55.71	0.97	15.10	12.20	0.19	4.02	9.69	1.86	0.30	
L60 glass	A 50.0%	43	59.72	0.88	14.90	10.40	0.18	2.69	7.97	2.68	0.58	
L60 glass	D 9.3%	8	63.97	0.81	14.26	8.48	0.00	1.87	6.46	3.45	0.70	
L60 glass	R 20.9%	18	76.49	0.29	12.37	3.06	0.14	0.22	2.80	3.71	0.93	

Total Fe reported as FeO: All analyses are recalculated to 100 per cent and free of H_2O and volatiles according to LeBas et al. (1986)

Table 4-2 The comparison of average major element compositions of Leg 125 glasses and Izu-Bonin arc volcanic rocks

Glass/lava	Rock types	Analysis No	SiO_2	TiO_2	Al_2O_3	FeO*	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5
Quat-Plio												
Izu-Bonin subaerial	B 45.2%	19	50.10	0.83	17.99	11.22	0.22	5.40	11.90	1.96	0.30	0.09
Izu-Bonin submarine	B 38.4%		49.74	0.83	18.28	10.32	0.20	6.15	11.79	2.21	0.37	0.12
L125 glass	BA 24.5%	45	55.23	0.99	14.44	12.33	0.19	4.47	9.52	2.41	0.43	
Izu-Bonin subaerial	BA 38.1%	16	54.88	0.90	17.05	10.36	0.20	3.94	9.49	2.61	0.43	0.13
Izu-Bonin submarine	BA 33.7%	29	54.68	0.89	17.42	9.70	0.19	4.04	9.14	3.07	0.73	0.14
L125 glass	A 36.4%	67	59.28	0.97	14.84	10.69	0.16	2.82	7.80	2.94	0.52	
Izu-Bonin subaerial	A 9.5%	4	60.68	0.71	15.43	7.65	0.17	3.98	7.20	3.39	0.65	0.14
Izu-Bonin submarine	A 8.1%	7	61.06	0.79	16.01	7.76	0.21	2.96	6.31	3.81	0.93	0.17
Iwojima subaerial	A	17	60.38	0.78	17.29	6.23	0.23	1.39	3.49	5.73	4.06	0.41
Iwojima submarine	A	12	61.22	0.74	16.53	5.69	0.19	1.84	3.34	5.74	4.33	0.37
L125 glass	D 25.0%	46	67.57	0.78	14.04	6.97	0.24	1.19	5.08	3.21	0.93	
Izu-Bonin subaerial	D 7.1%	3	68.18	0.59	14.61	5.10	0.08	1.64	4.83	4.27	0.55	0.15
Izu-Bonin submarine	D 11.6%	10	70.55	0.59	14.05	4.22	0.17	1.29	3.74	4.46	0.78	0.14
L125 glass	R 14.1%	26	76.35	0.33	13.02	2.72	0.00	0.17	2.27	3.10	2.05	
Izu-Bonin submarine	R 8.1%	7	74.95	0.32	13.30	2.35	0.12	0.80	2.34	4.69	1.06	0.06
Late Miocene												
L125 glass	B 4.5%	11	51.65	1.22	13.85	14.15	0.14	5.94	10.95	1.78	0.34	
L125 glass	BA 53.4%	132	54.66	1.10	14.47	13.21	0.17	4.21	9.60	2.28	0.33	
L125 glass	A 29.1%	72	58.93	1.07	14.49	11.38	0.16	2.72	7.96	2.86	0.41	
L125 glass	D 4.0%	10	64.91	1.11	13.12	10.16	0.00	1.35	5.97	2.88	0.50	
L125 glass	R 8.9%	22	76.41	0.36	12.66	3.34	0.00	0.20	2.48	3.03	1.54	
Middle Miocene												
L125 glass	B 3.9%	4	51.69	1.04	15.52	13.65	0.23	4.92	10.50	2.06	0.41	
L125 glass	BA 48.0%	49	54.08	0.99	14.31	13.61	0.18	4.59	9.71	2.13	0.42	
L125 glass	A 27.5%	28	59.17	0.91	15.30	10.70	0.16	2.73	7.97	2.53	0.54	
L125 glass	D 3.9%	4	69.09	0.56	14.25	6.32	0.00	0.79	5.15	3.08	0.80	
L125 glass	R 16.7%	17	77.10	0.33	12.08	3.68	0.00	0.23	2.85	2.62	1.12	
Eocene												
L125 glass	R	5	77.79	0.15	13.00	0.83	0.00	0.10	2.52	5.36	0.24	

Total Fe reported as FeO; All analyses are recalculated to 100 per cent and free of H_2O and volatiles according to LeBas et al. (1986)

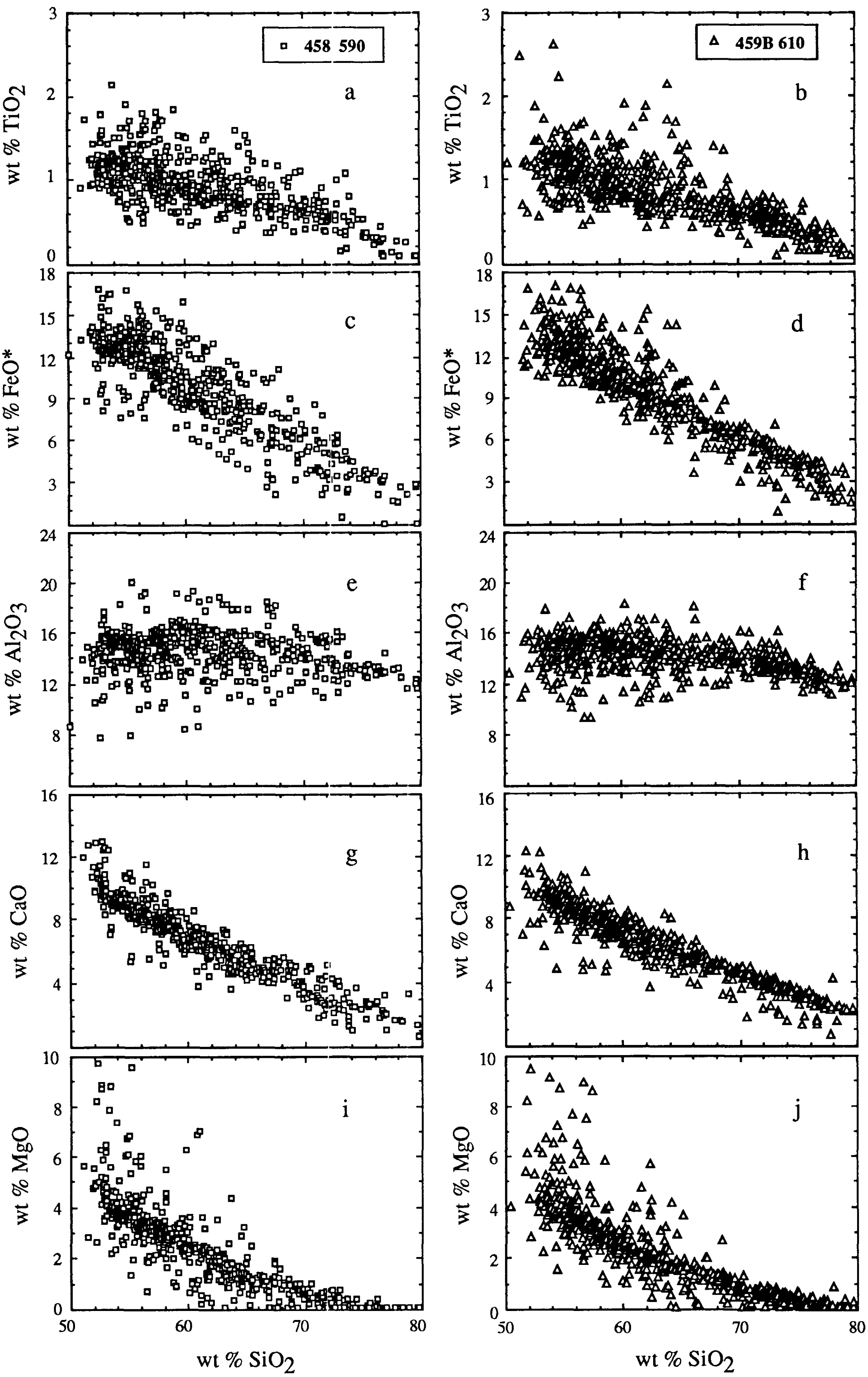

Figure 4-1A Comparison of major element compositions of individual glass shards from DSDP Leg 60 Sites 458 and 459B. The numbers 590 and 610 are the total analyses of glass points for the respective sites.

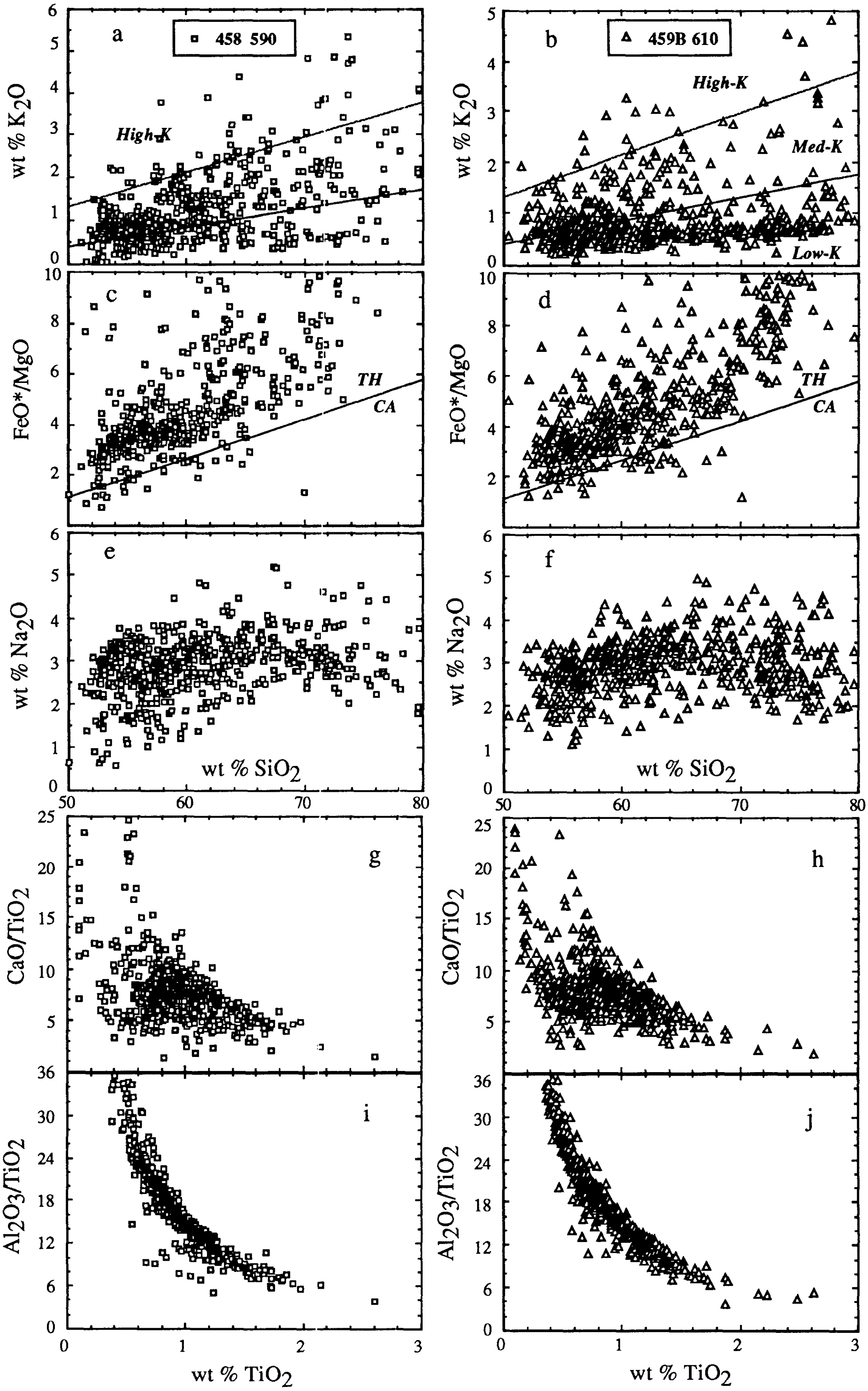

Figure 4-1B Comparison of major element compositions of individual glass shards from DSDP Leg 60 Sites 458 and 459B. See Figure 4-1A caption.

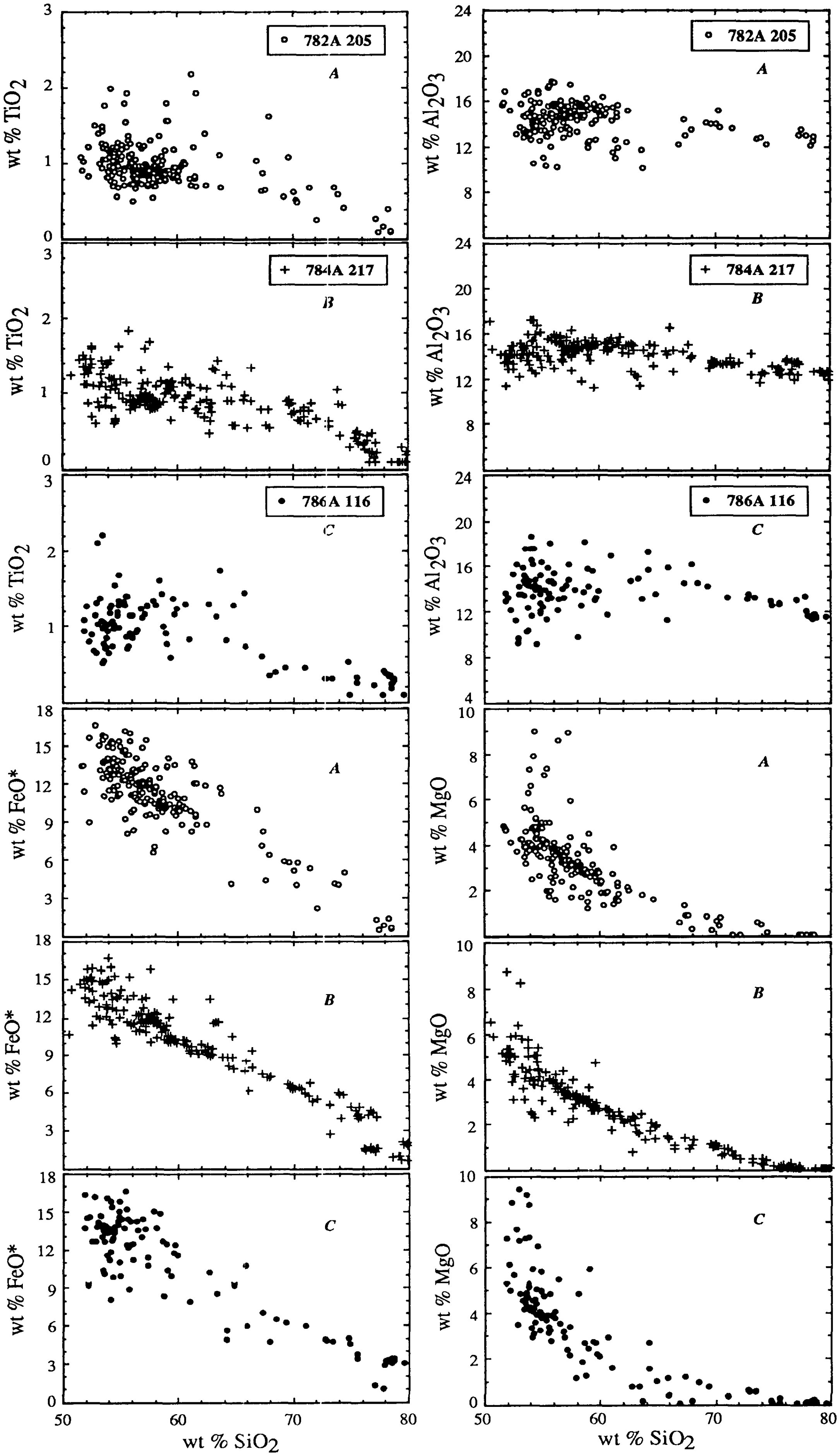

Figure 4-2A Comparison of major element compositions of individual glass shards from ODP Leg 125 Sites 782A, 784A and 786A. The numbers 205, 217 and 116 are the total analyses of glass points for the respective sites.

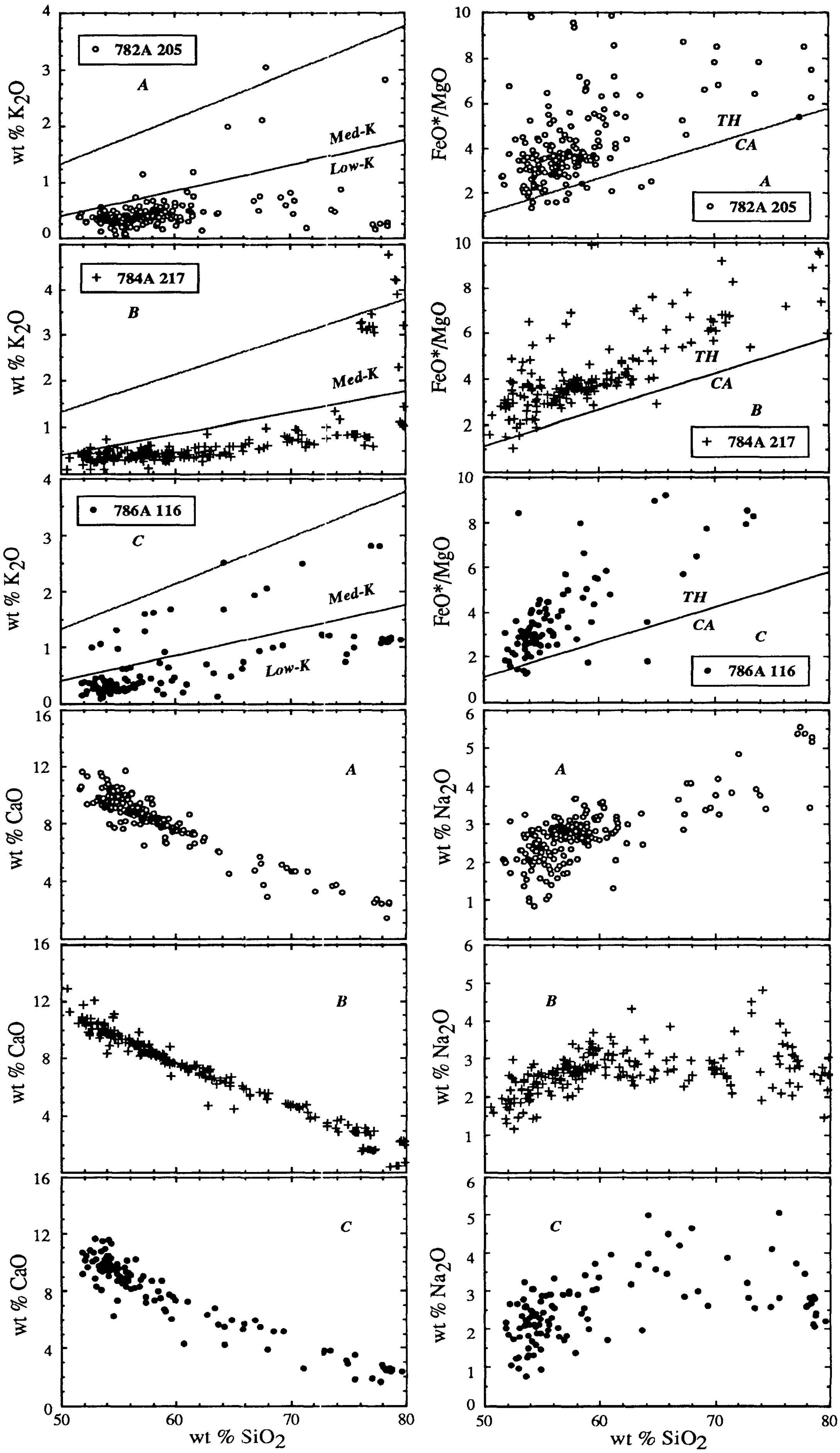

Figure 4-2B Comparison of major element compositions of individual glass shards from ODP Leg 125 Sites 782A, 784A and 786A. See Figure 4-2A caption.

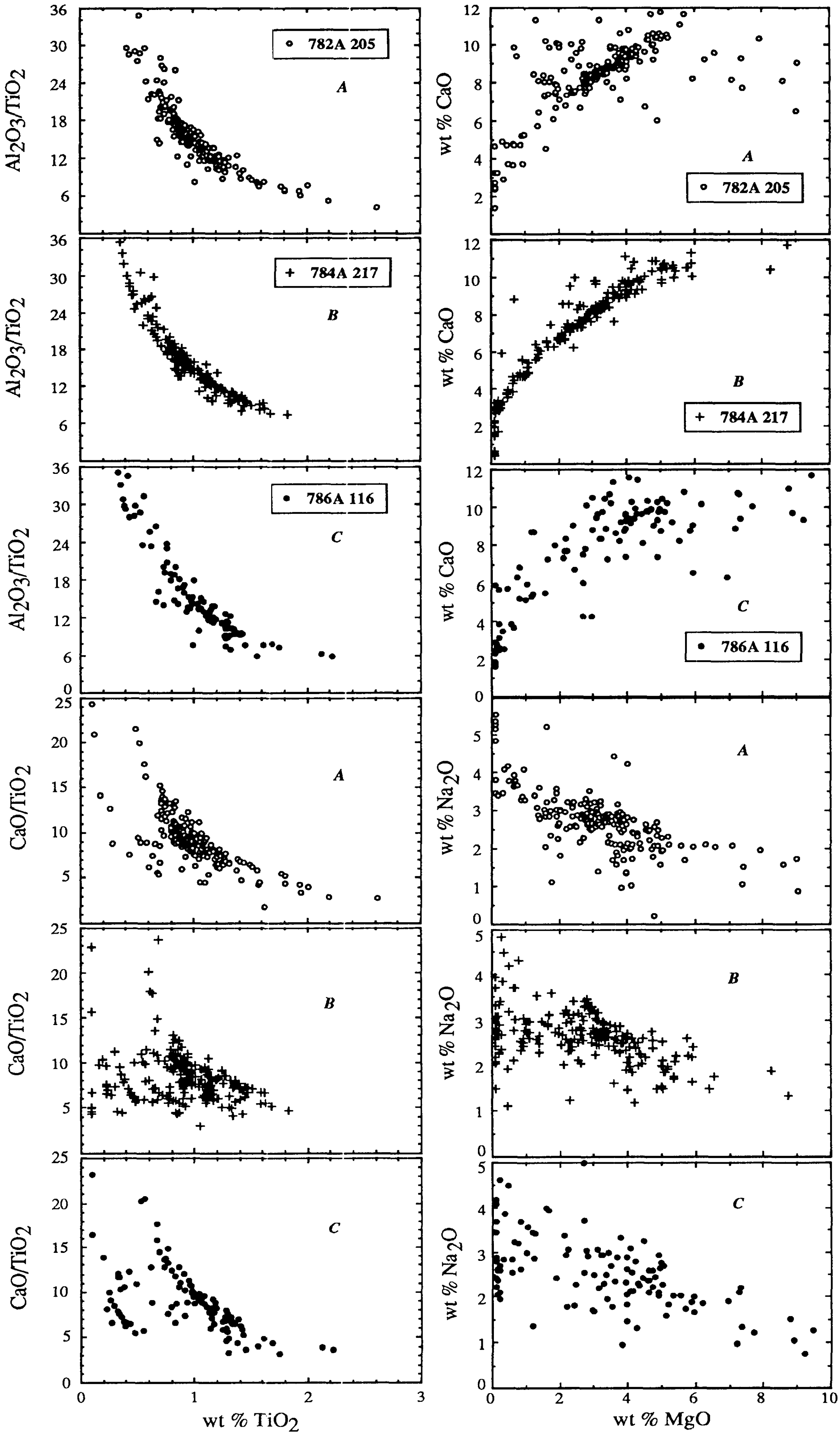

Figure 4-2C Comparison of major element compositions of individual glass shards from ODP Leg 125 Sites 782A, 784A and 786A. See Figure 4-2A caption.

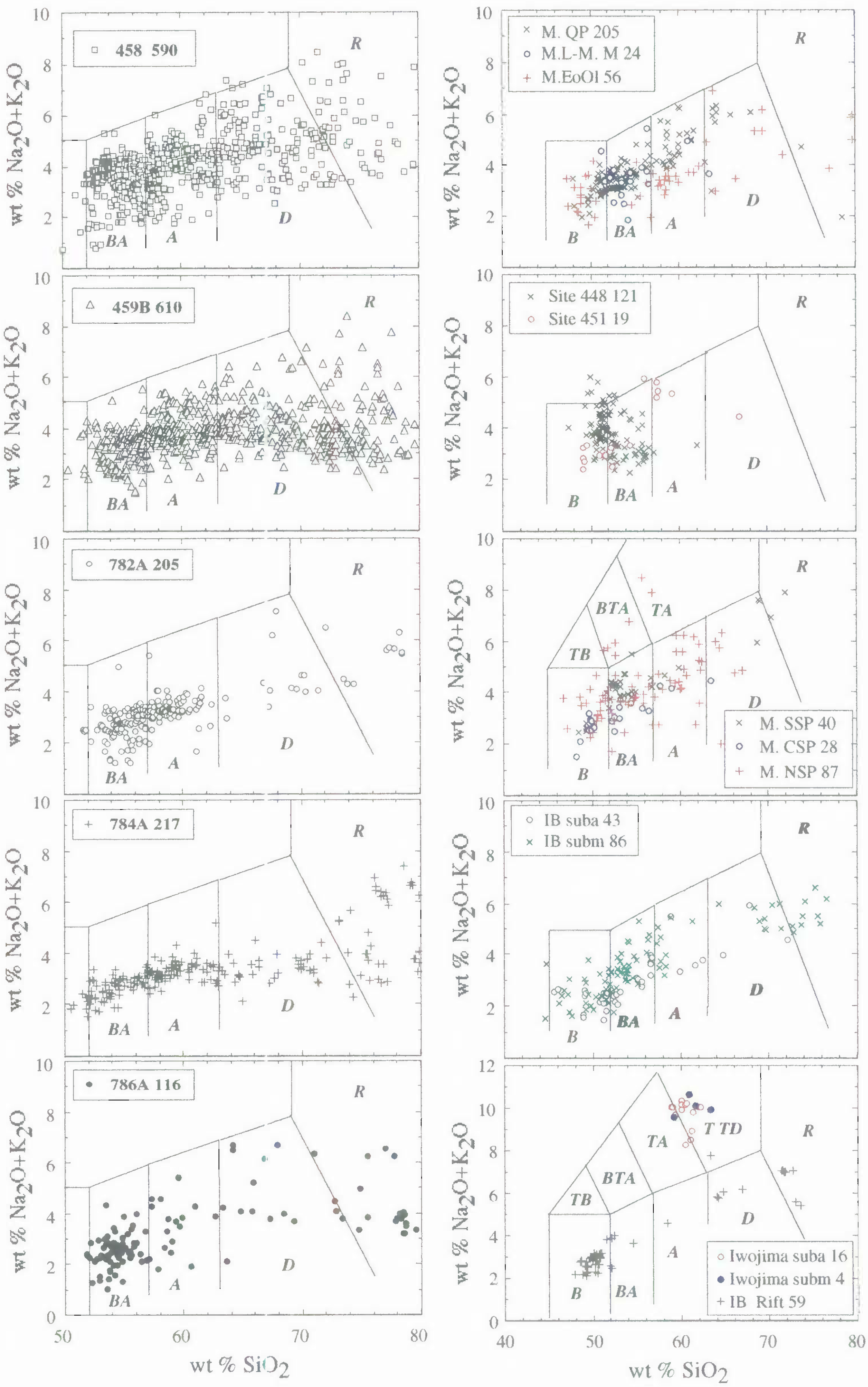

Figure 4-3A Comparison of rock types of individual glass shards from Sites 458, 459B, 782A,784A and 786A compared with the IBM arc volcanic rocks. The numbers after the Site or arc name are the total number of analyses of glass points or collected rock analyses. Suba and subm means subaerial and submarine, respectively. The classification of rock types is taken from LeBas et al. (1986). See text for data sources and legend interpretation.

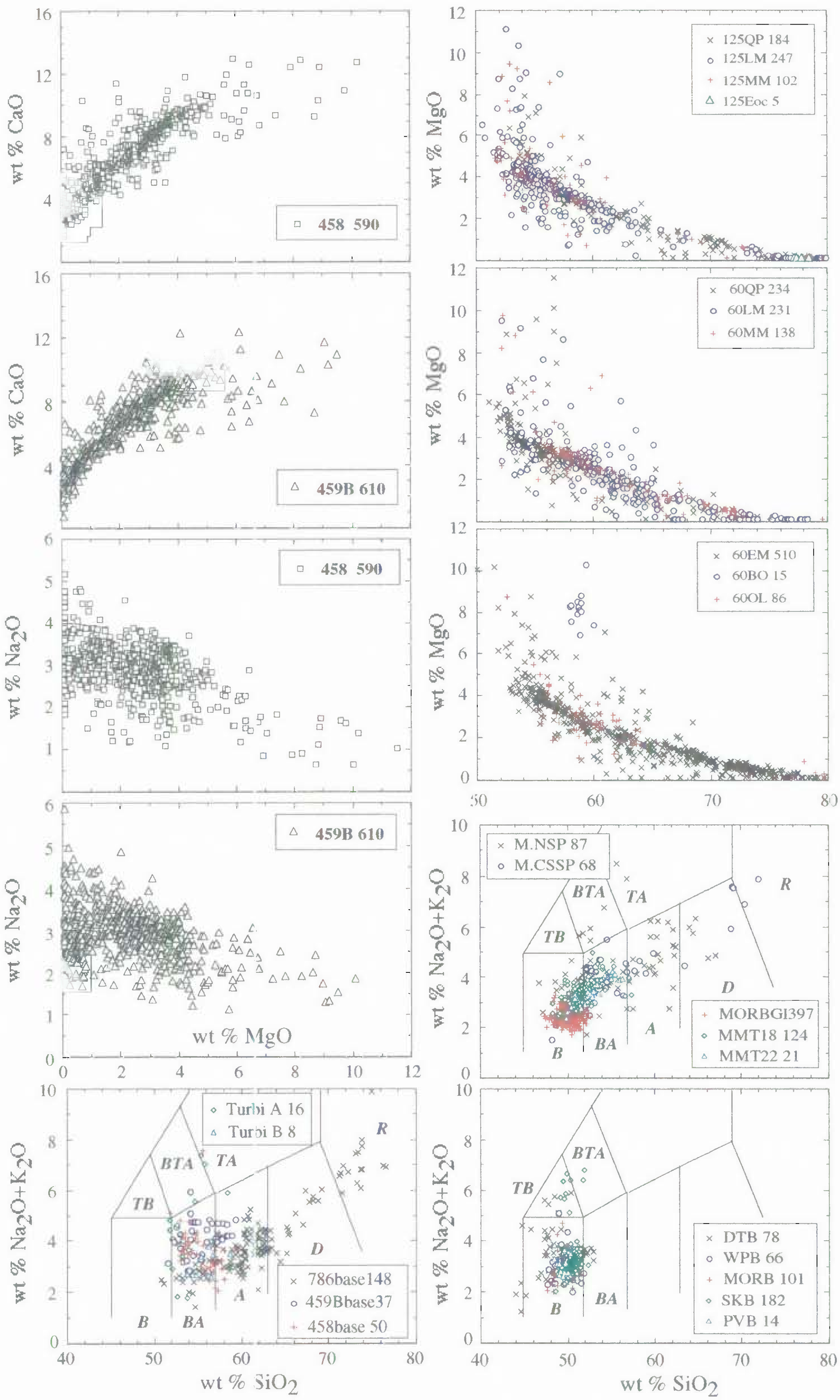

Figure 4-3B Comparison of major element compositions of individual glass shards from Sites 458 and 459B; different age group glasses from Legs 60 and 125; rock types of the IBM forearc drilled volcanic rocks and turbidites compared with the IBM backarc basin volcanic rocks; and MORB and its glasses. 60BO 15 means 15 point analyses of individual boninitic glass shards from Site 458. The classification of rock types is taken from LeBas et al. (1986). See text for data sources, age groups and interpretation.

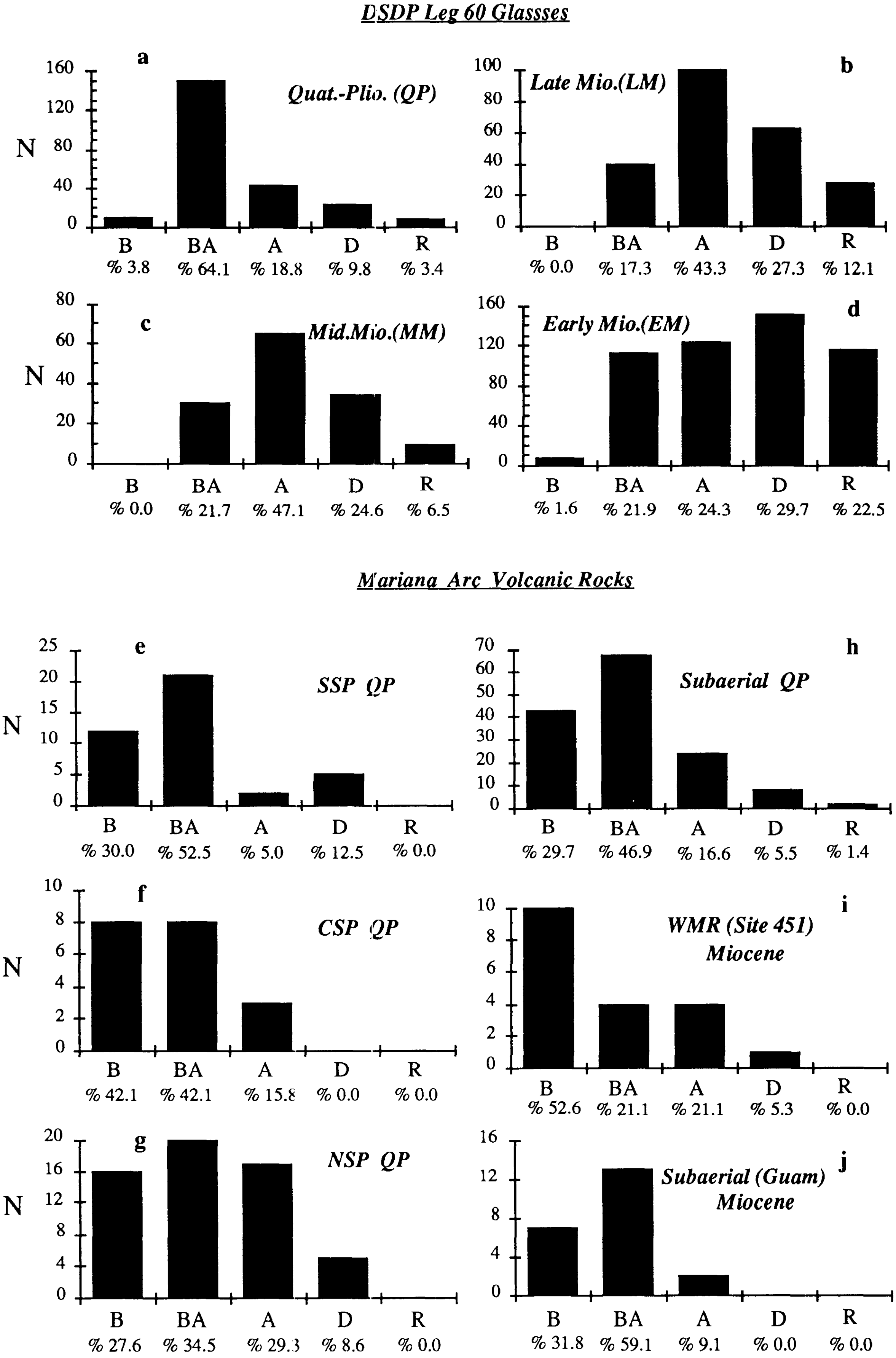

Figure 4-3C Comparison of rock types of DSDP Leg 60 glasses in different age groups (a,b,c,d) compared with the Mariana subaerial and submarine volcanic rocks in the similar time periods (e,f,g,h,i,j). See text for the sample data sources and classification of rock types.

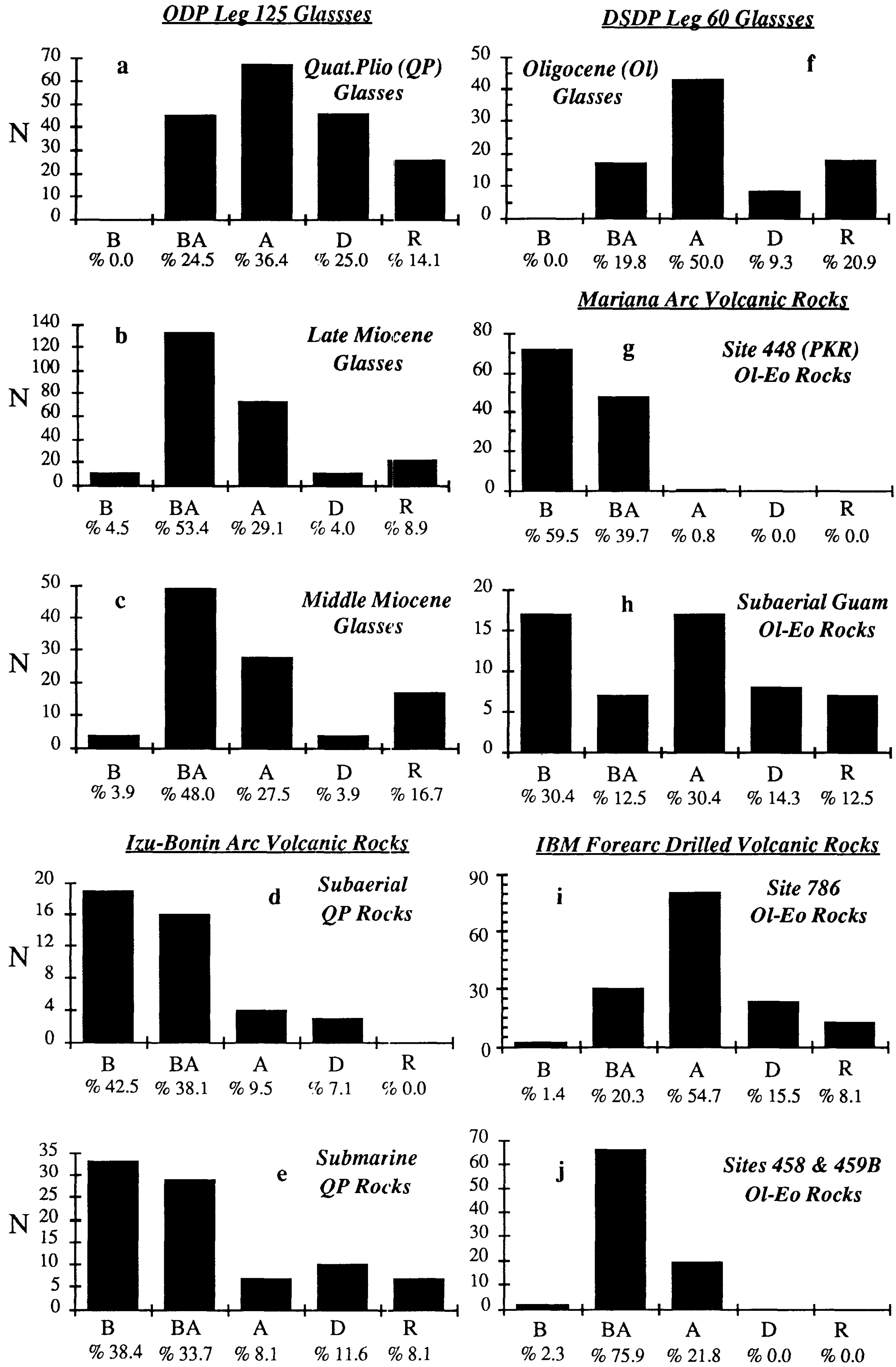

Figure 4-3D Comparison of rock types of Leg 125 glasses (a,b,c) and Leg 60 glasses (f) in different age groups compared with the Izu-Bonin arc rocks (d,e), the Mariana arc rocks (g,h) and IBM forearc drilled rocks (i,j) in the similar time periods. See text for the sample data sources and classification of rock types.

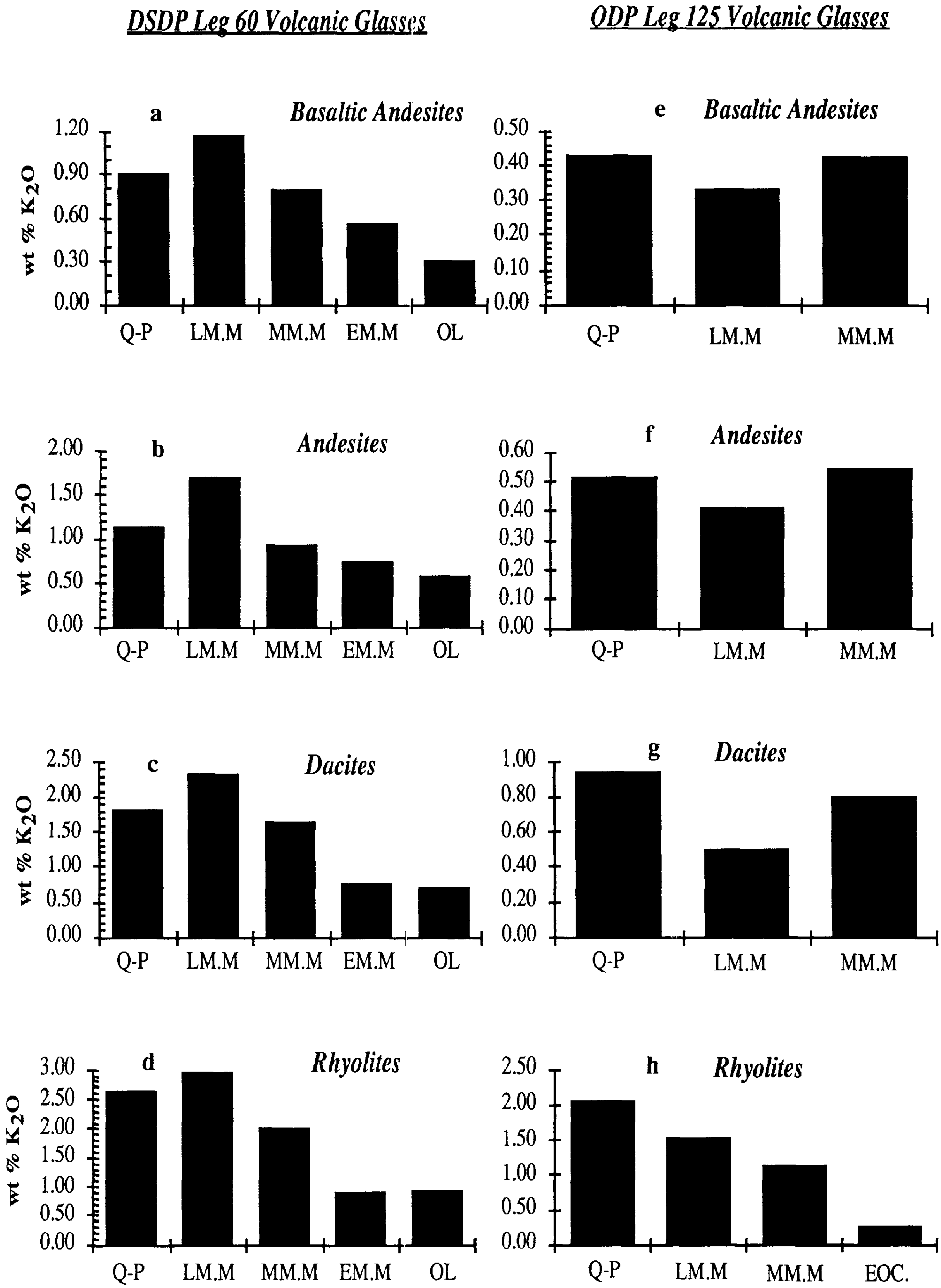

Figure 4-3E Comparison of variation diagrams of K_2O for DSDP Leg 60 volcanic glasses (a,b,c,d) and ODP Leg 125 glasses (e,f,g,h) in different age groups during the IBM arc's evolution. The classification of rock types is taken from LeBas et al. (1986). See text for description and discussion.

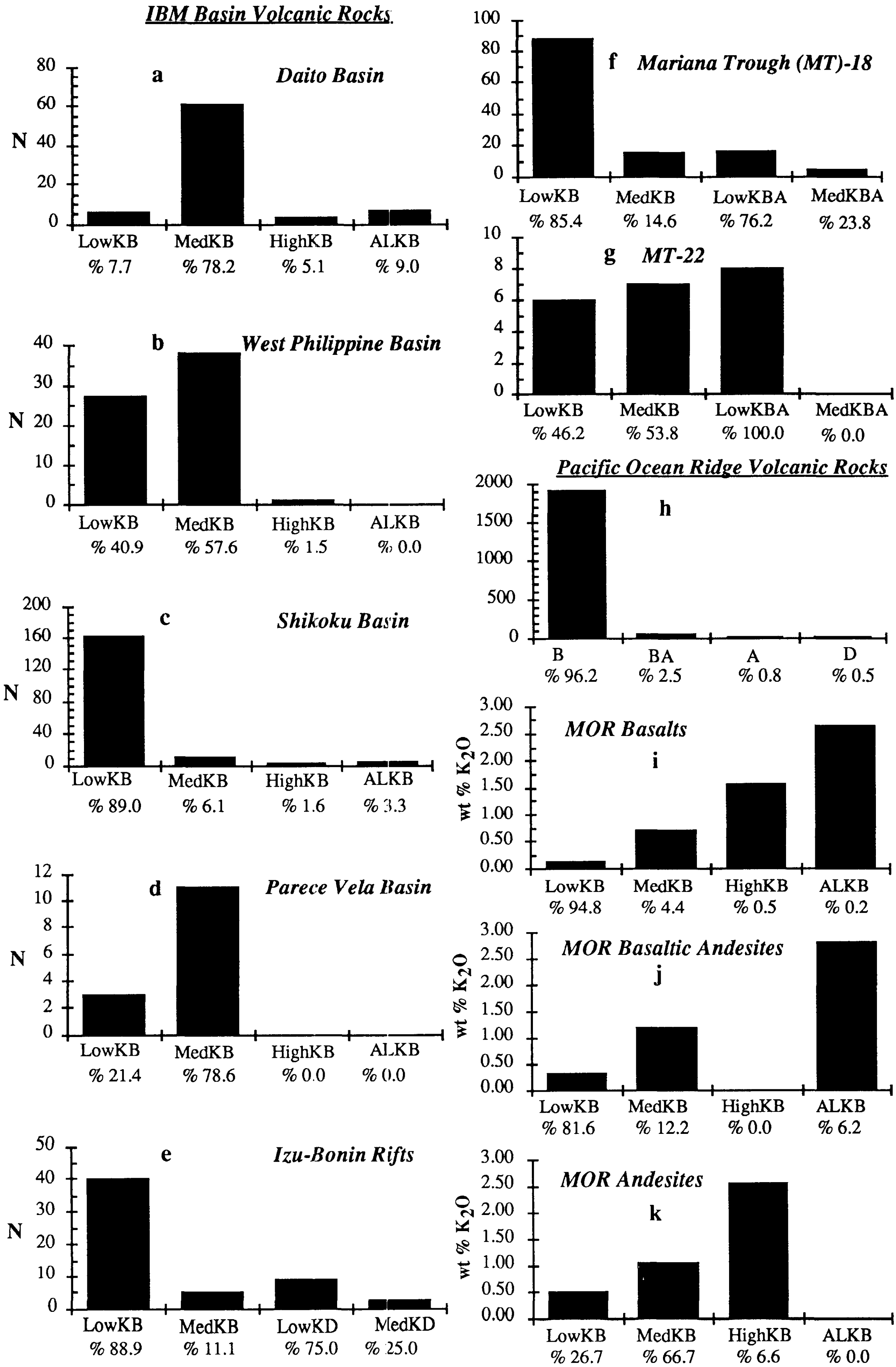

Figure 4-3F Comparison of rock types of Izu-Bonin-Mariana basin volcanic rocks (a,b,c,d,e,f,g) compared with Pacific Ocean Ridge volcanic rocks (h,i,j,k). The division of K-types is from Gill (1981). The classification of rock types is taken from LeBas et al. (1986). See text for data sources and discussion.

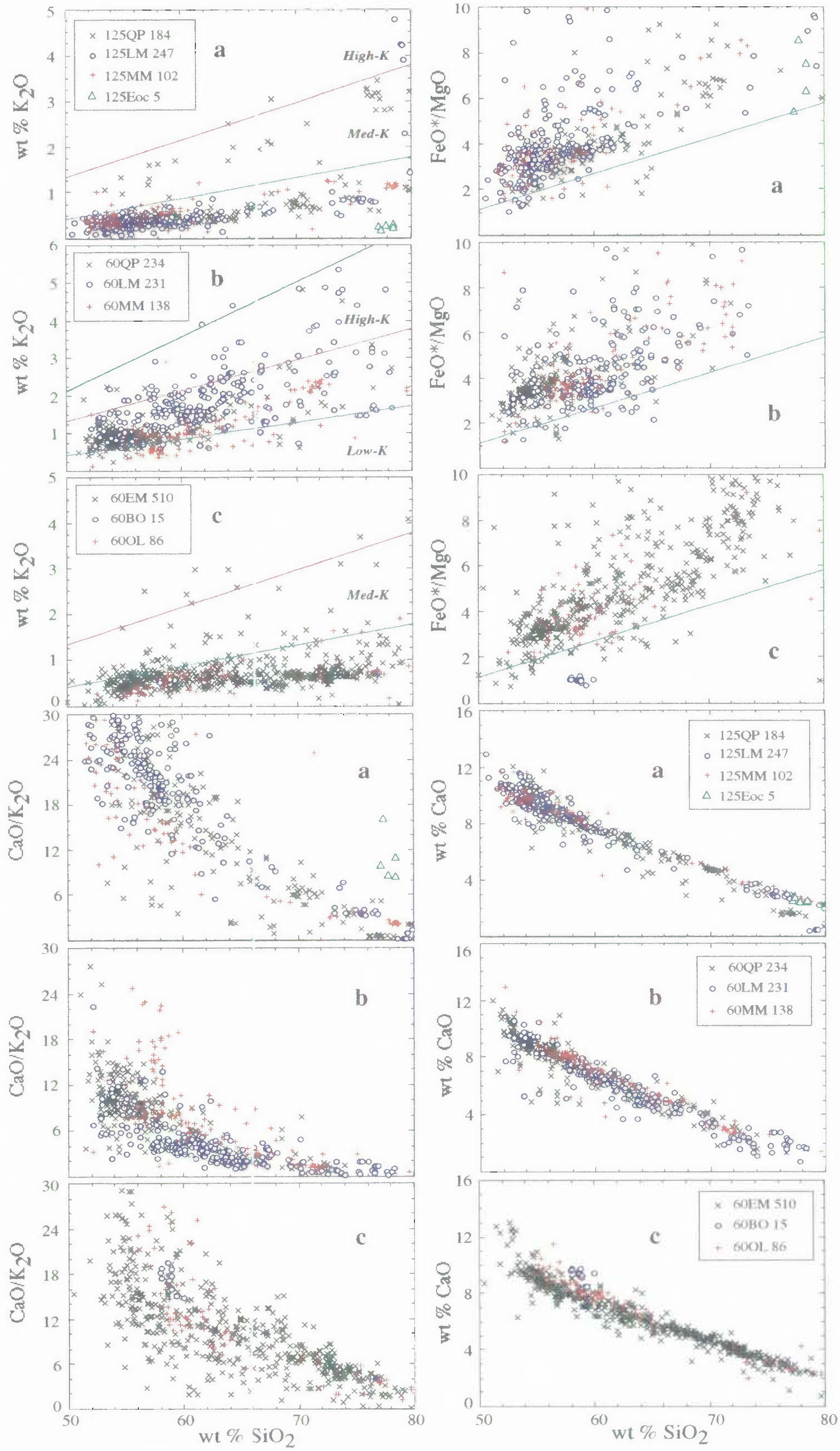

Figure 4-4A Comparison of major element compositions of different age group glass shards from Leg 60 and Leg 125 ash layers. See text for age groups and interpretation.

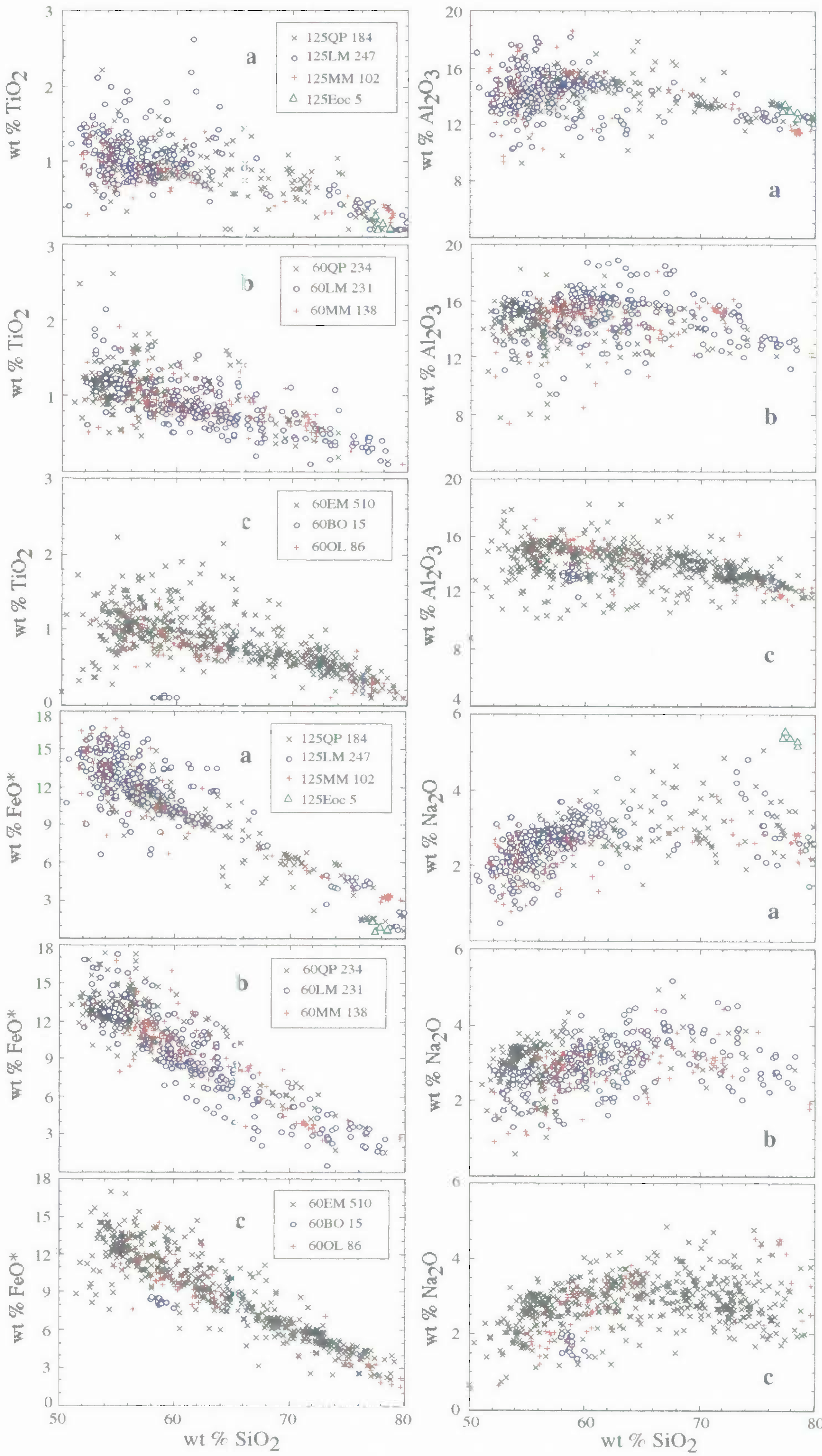

Figure 4-4B Comparison of major element compositions of different age group glass shards from Leg 60 and Leg 125 ash layers. See text for age groups and interpretation.

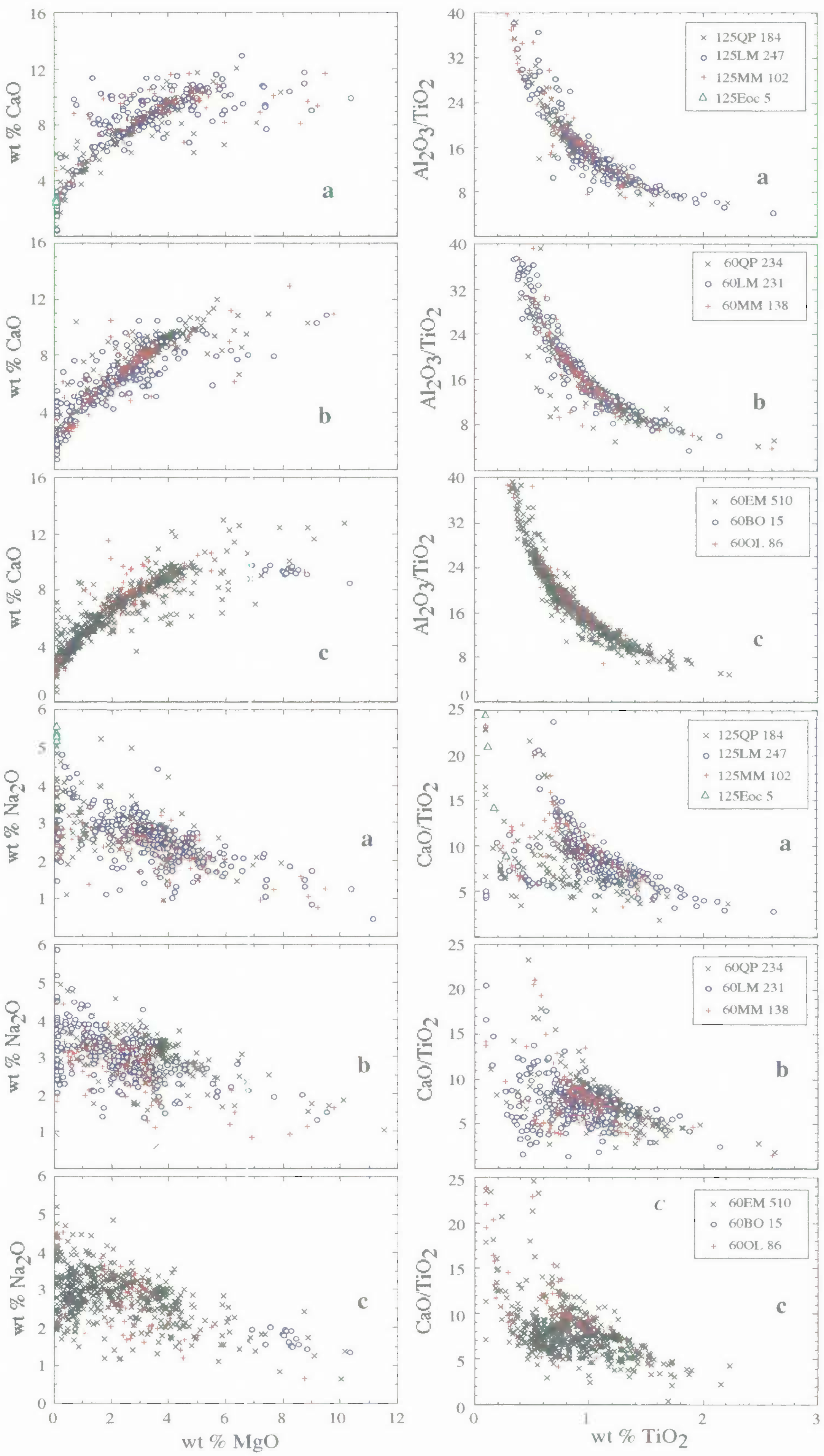

Figure 4-4C Comparison of major element compositions of different age group glass shards from Leg 60 and Leg 125 ash layers. See text for age groups and interpretation.

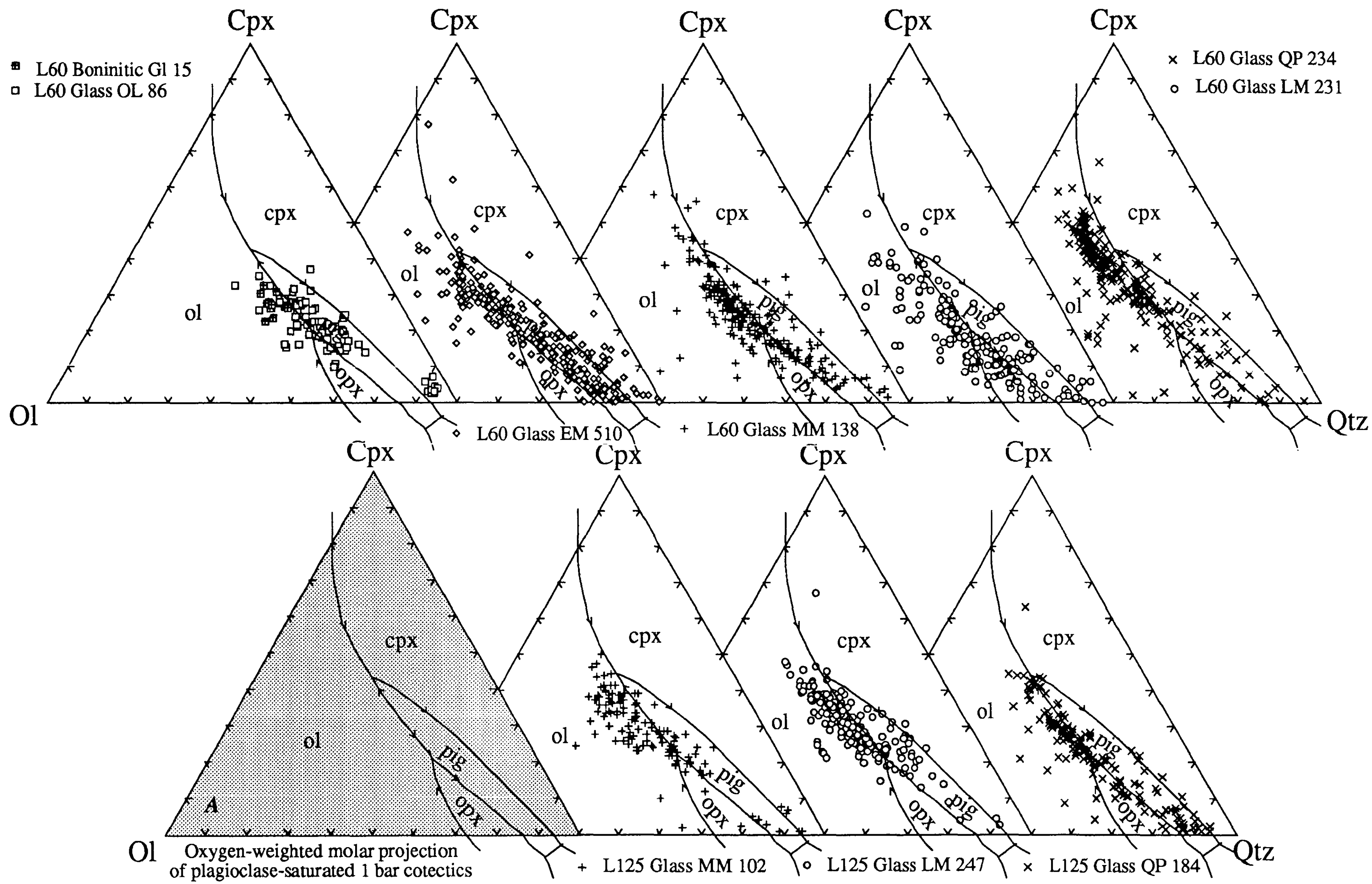

Figure 4-5A Comparison of oxygen-weighted molar projections (from plagioclase) of DSDP Leg 60 and ODP Leg 125 glass compositions in the system olivine (Ol)-clinopyroxene (Cpx)-SiO_2 (Qtz) with the experimentally-determined atmospheric pressure cotectics (A) after Grove et al. (1982, 1993). See text for samples.

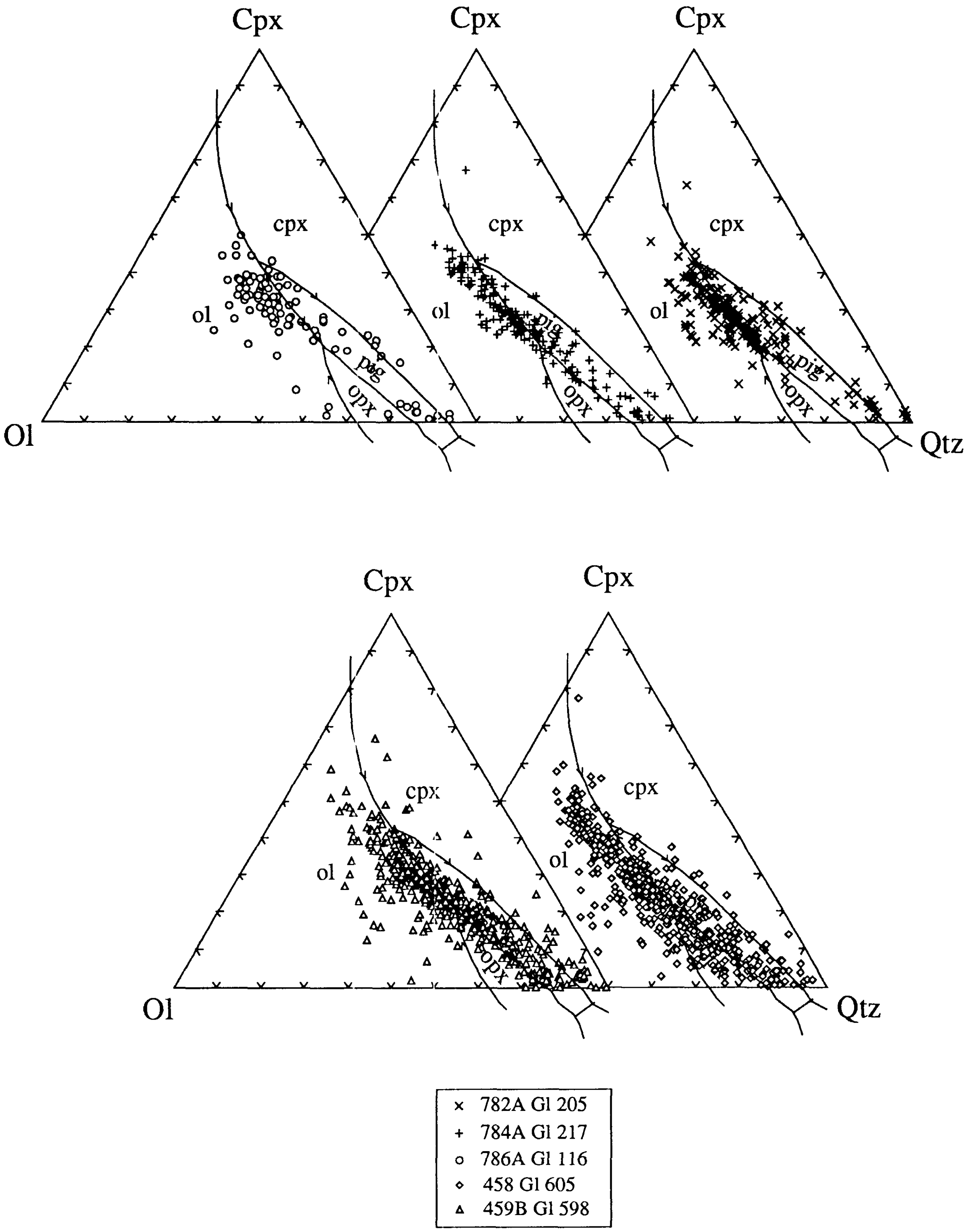

Figure 4-5B Comparison of oxygen-weighted molar projections (from plagioclase) of compositions of glasses from DSDP Leg 60 Sites 458 and 459B and ODP Leg 125 Sites 782A, 784A, and 786A ash layers in the system olivine (Ol)-clinopyroxene (Cpx)-SiO_2 (Qtz) with the experimentally-determined atmospheric pressure cotectics after Grove et al. (1982, 1993). See text for samples.

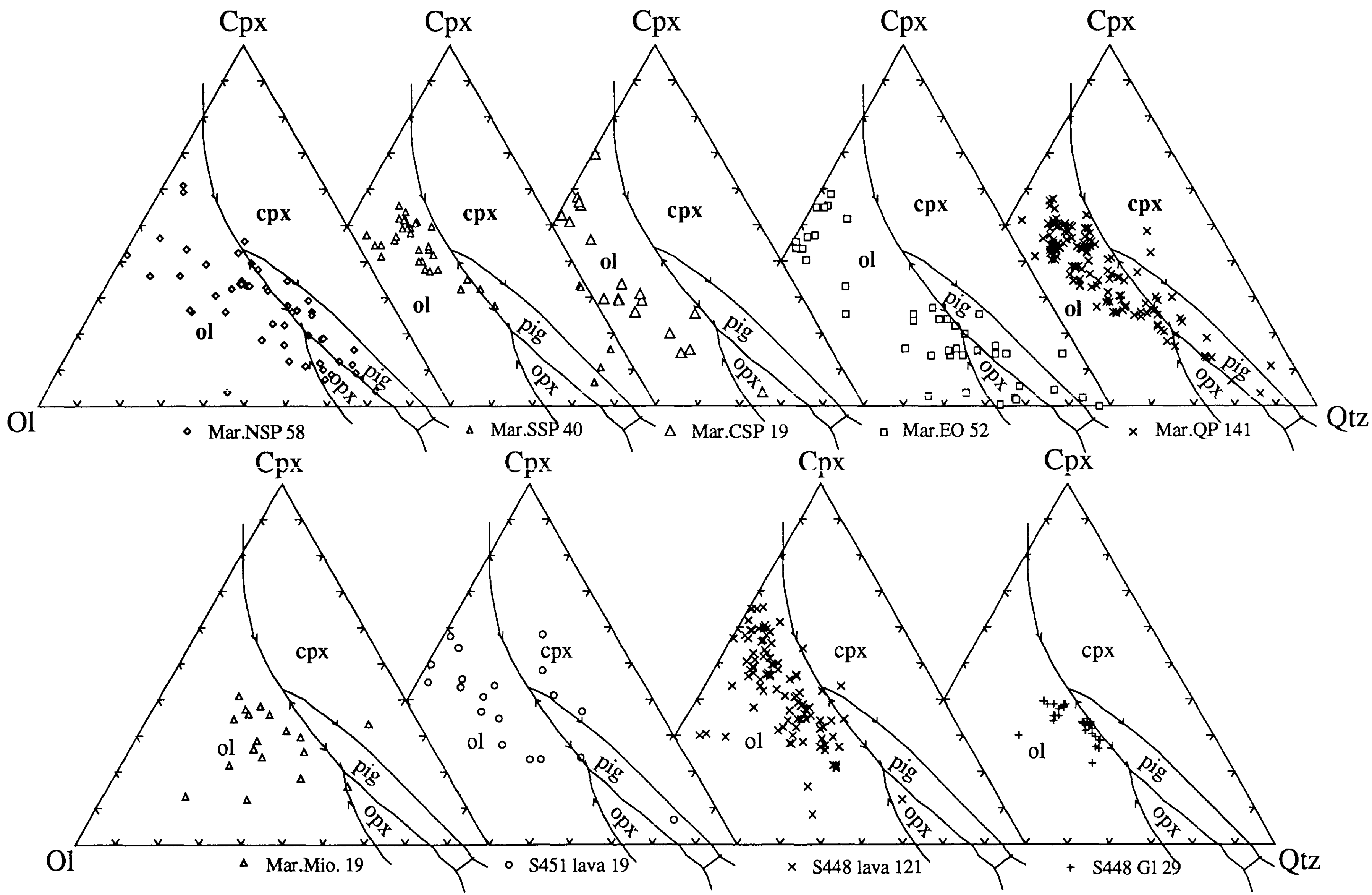

Figure 4-5C Comparison of oxygen-weighted molar projections (from plagioclase) of the Mariana arc volcanic (subaerial and submarine) compositions in the system olivine (Ol)-clinopyroxene (Cpx)-SiO_2 (Qtz) with the experimentally-determined atmospheric pressure cotectics after Grove et al. (1982, 1993). See text for sample data sources.

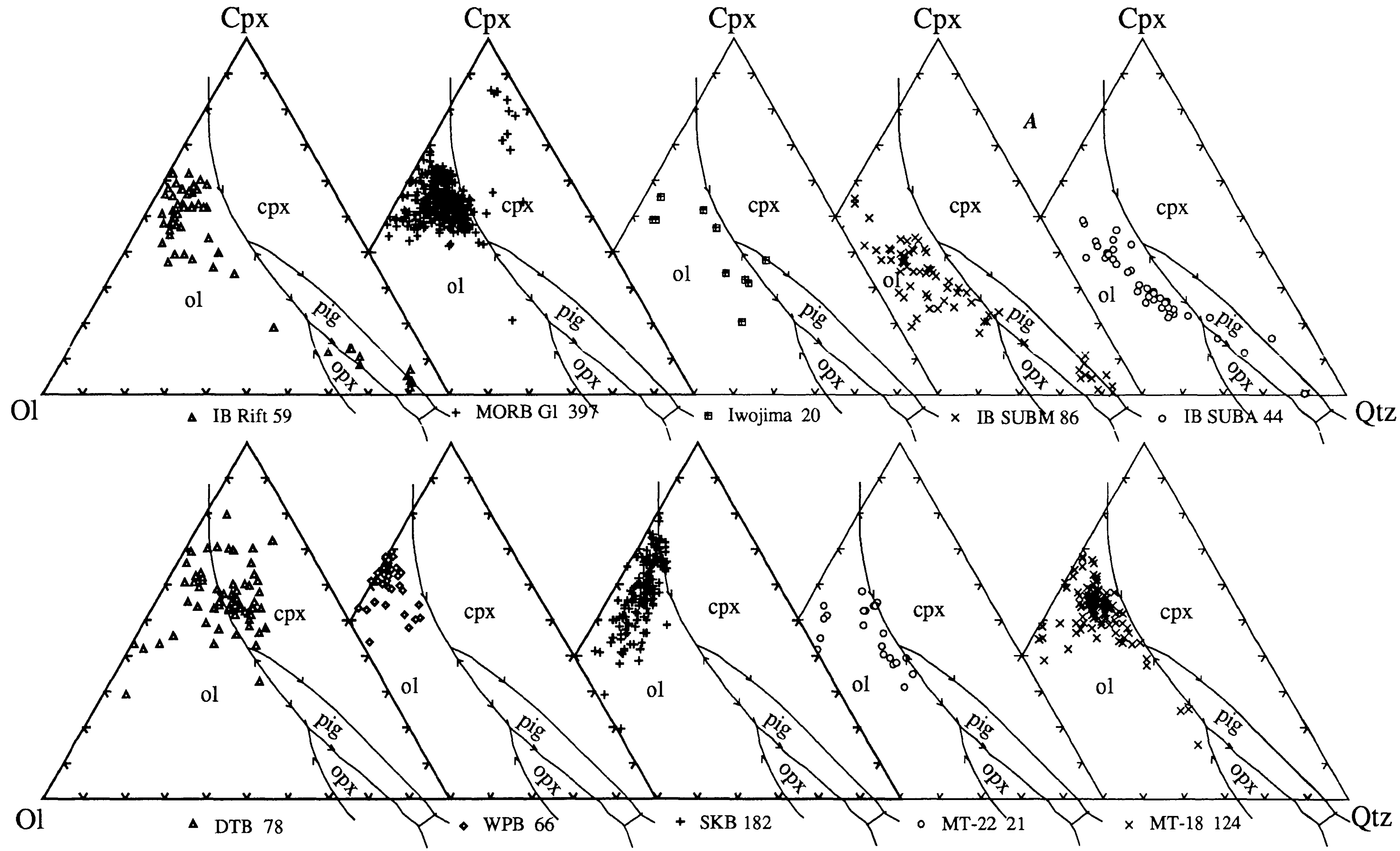

Figure 4-5D Comparison of oxygen-weighted molar projections (from plagioclase) of the Izu-Bonin arc volcanic (subaerial-SUBA and submarine-SUBM) compositions compared with IBM basin volcanic rocks and MORB glasses in the system olivine (Ol)-clinopyroxene (Cpx)-SiO_2 (Qtz) with the experimentally-determined atmospheric pressure cotectics after Grove et al. (1982, 1993). See text for data sources.

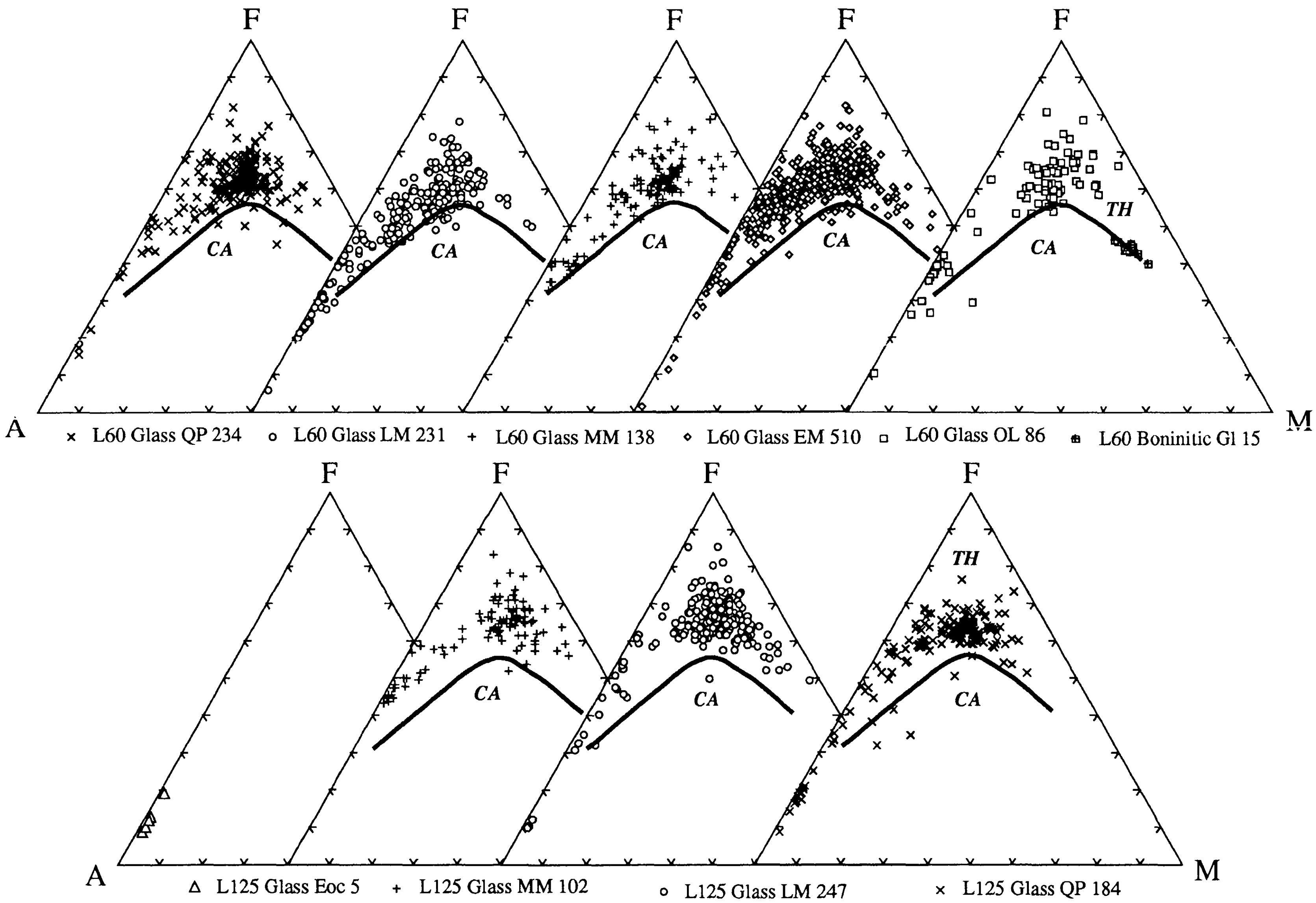

Figure 4-6 AFM diagrams for different age group glass shards from DSDP Leg 60 and ODP Leg 125 ash layers. BO means boninitic. See text for interpretation of age groups and division line of TH and CA.

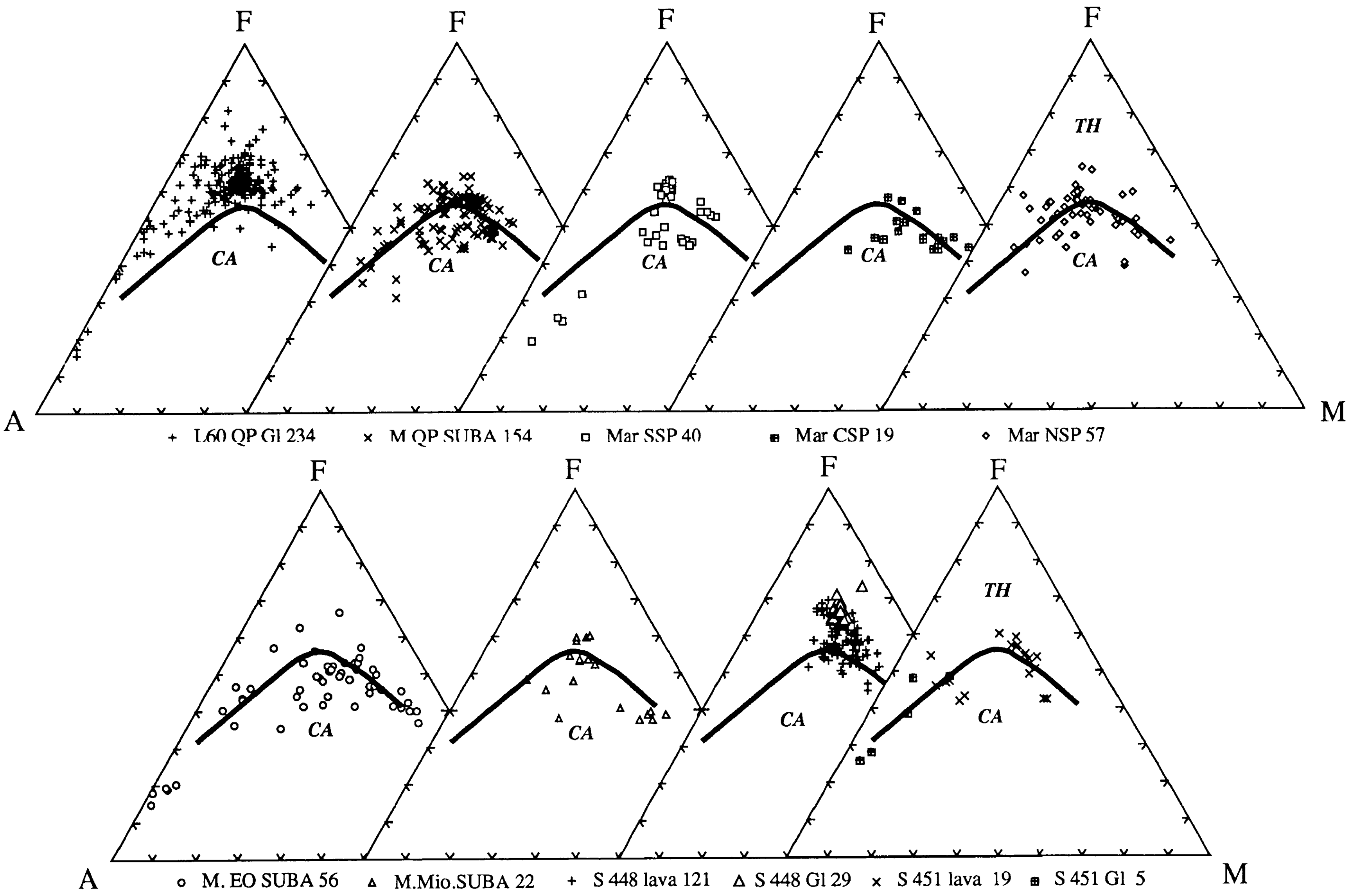

Figure 4-7 Comparison of AFM diagrams for different age group Mariana arc volcanic rocks and Leg 60 Sites 448 and 451 volcanic rocks with their glasses. SUBA means subaerial rocks. See text for interpretation of age groups and division line of TH and CA.

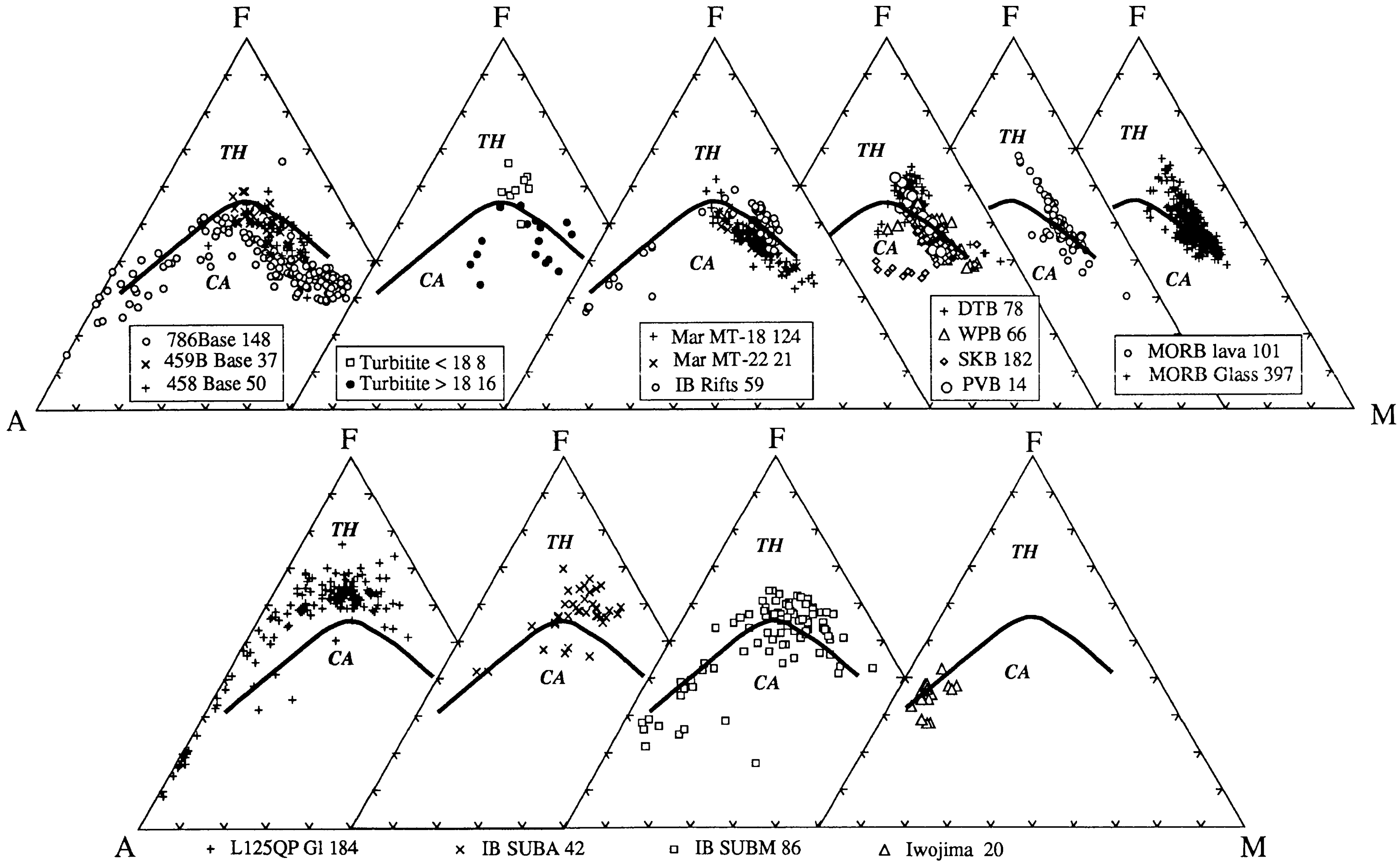

Figure 4-8 Comparison of AFM diagrams for representative Izu-Bonin arc volcanic rocks, IBM drilled basements, IB turbitites and IBMbasin volcanic rocks compared with Leg 125 QP glasses and MORB and MORB glasses. SUBA and SUBM means subaerial and submarine rocks, respectively. See text for interpretation of age groups, IBM volcanic sample data sources and division line of TH and CA.

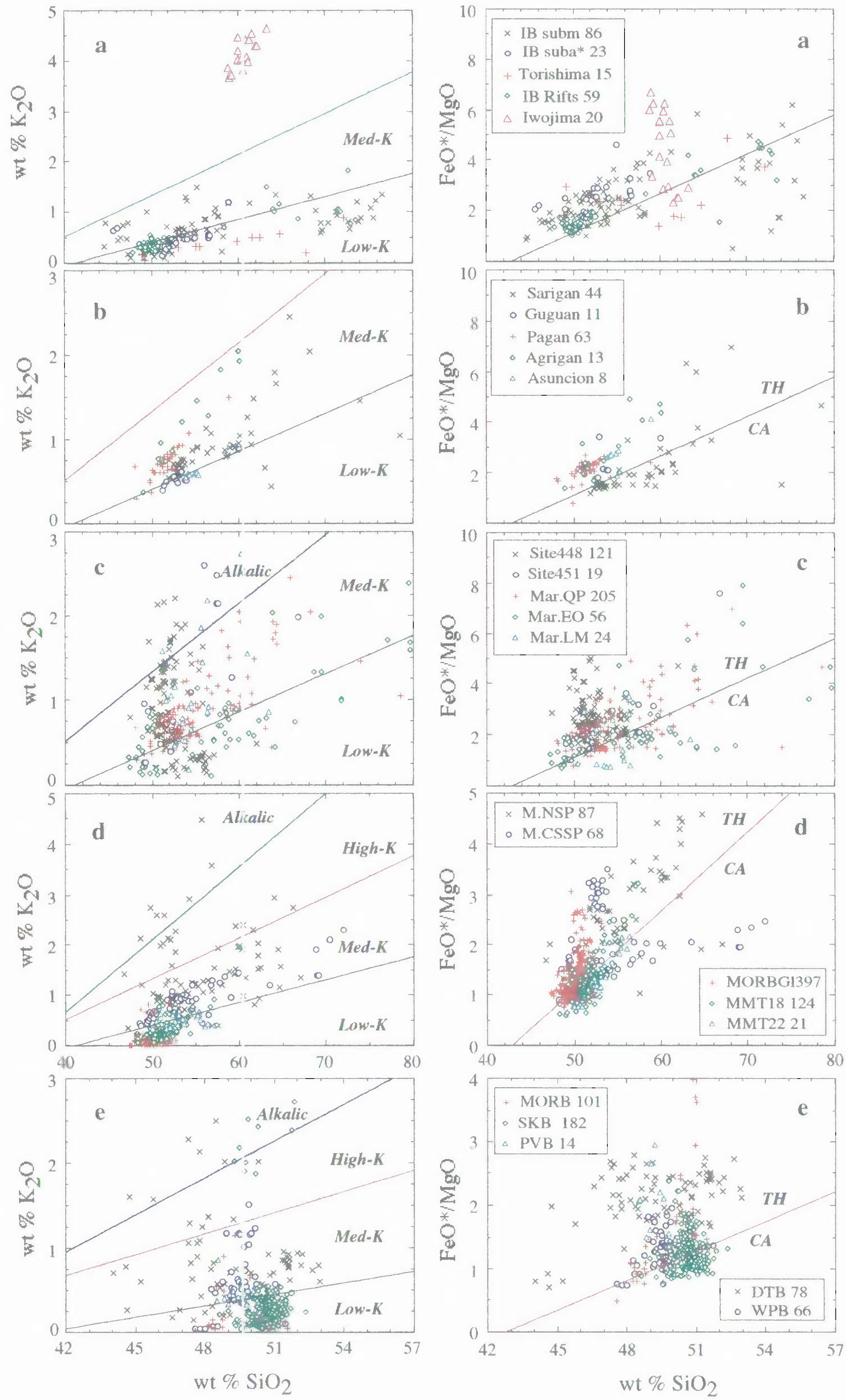

Figure 4-9 Comparison of major element compositions of the IBM arc (subaerial and submarine) volcanic rocks, backarc basin volcanic rocks, Leg 60 Sites 448 and 451 volcanic rocks compared with MORB and its glasses. See text for the sample data sources and classifications of K_2O (Gill, 1981) and TH ~ CA (Miyashiro, 1974).

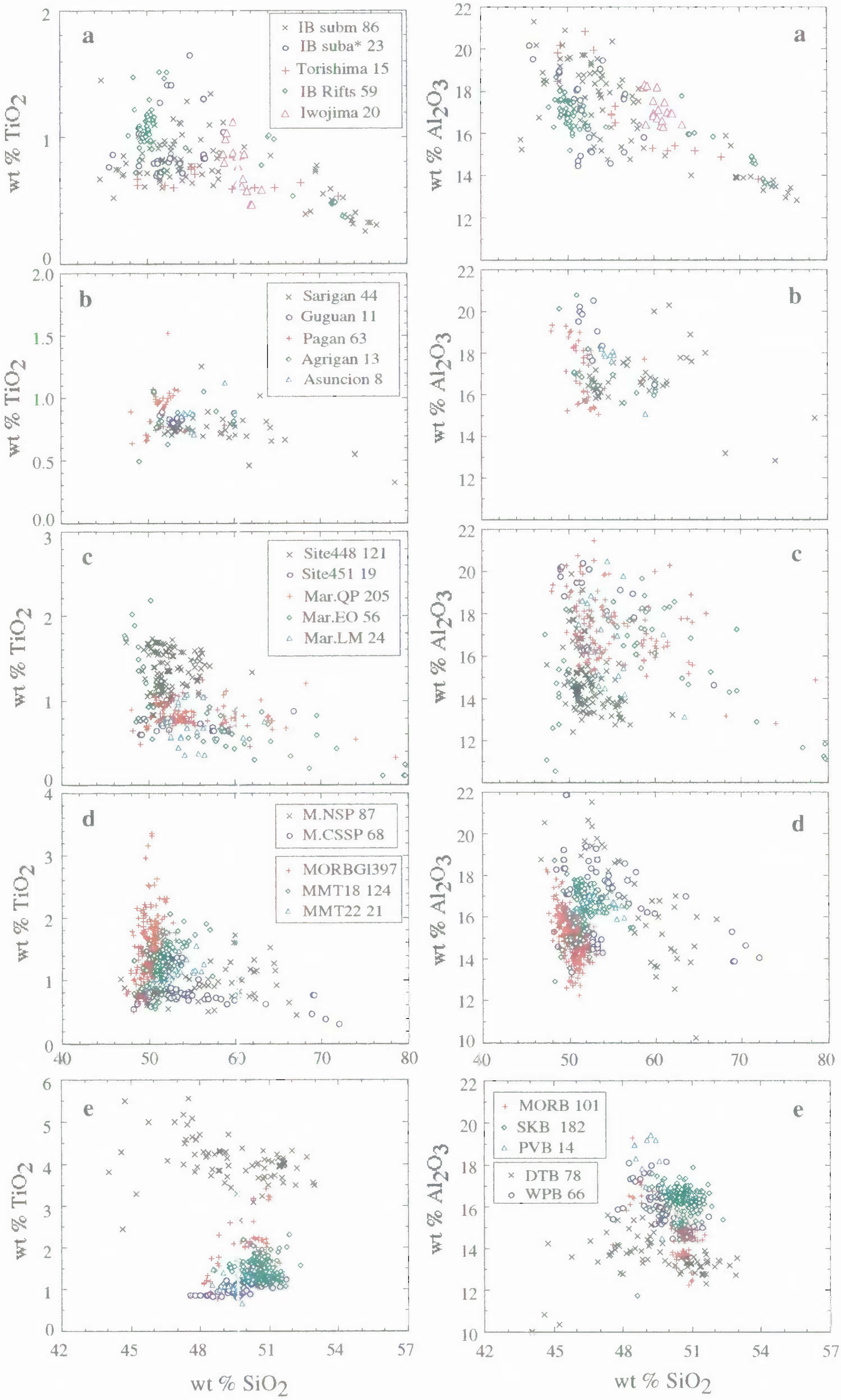

Figure 4-10 Comparison of major element compositions of the IBM arc (subaerial and submarine) volcanic rocks, backarc basin volcanic rocks, Leg 60 Sites 448 and 451 volcanic rocks compared with MORB and its glasses. See text for the sample data sources and interpretation.

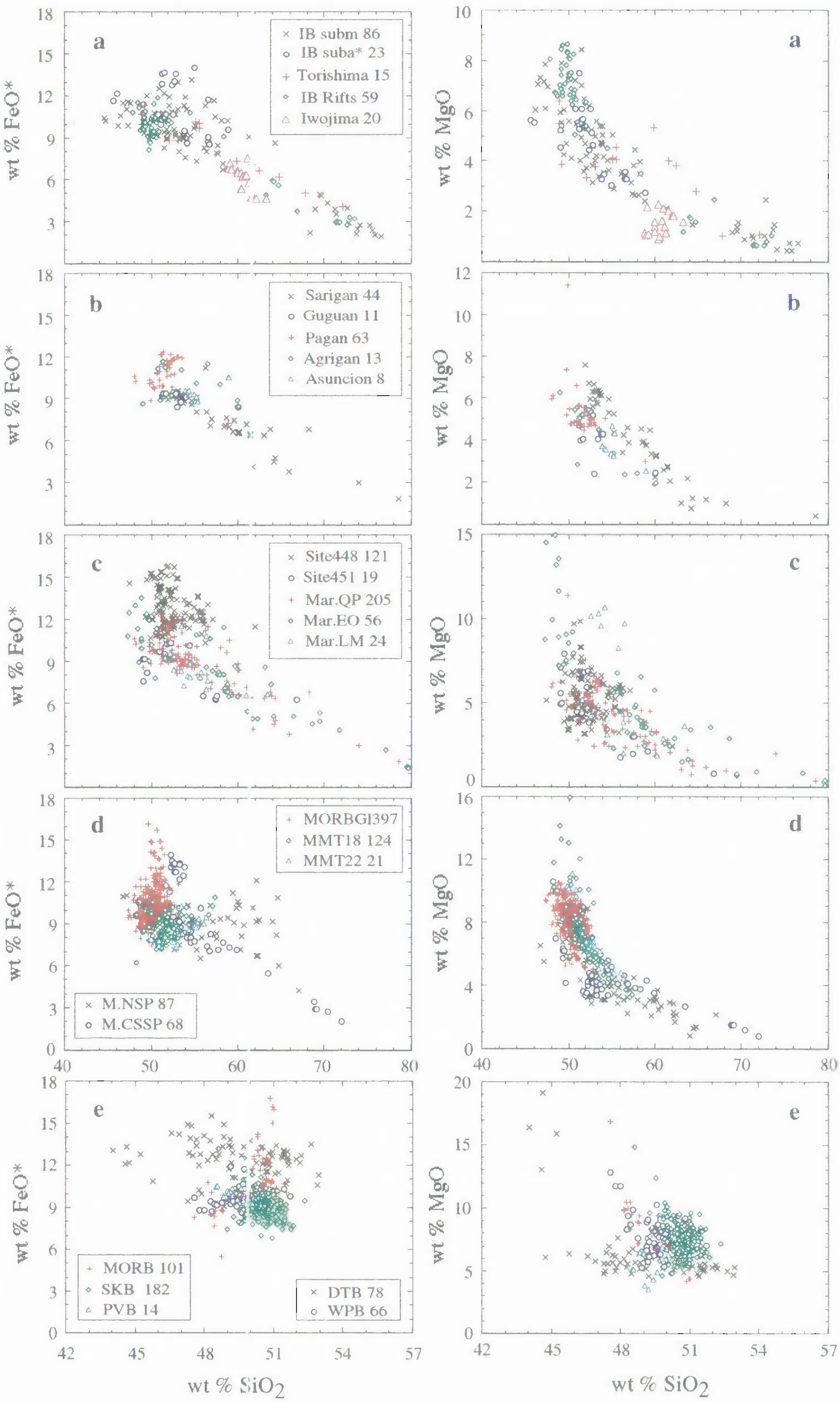

Figure 4-11 Comparison of major element compositions of the IBM arc (subaerial and submarine) volcanic rocks, backarc basin volcanic rocks, Leg 60 Sites 448 and 451 volcanic rocks compared with MORB and its glasses. See text for the sample data sources and interpretation.

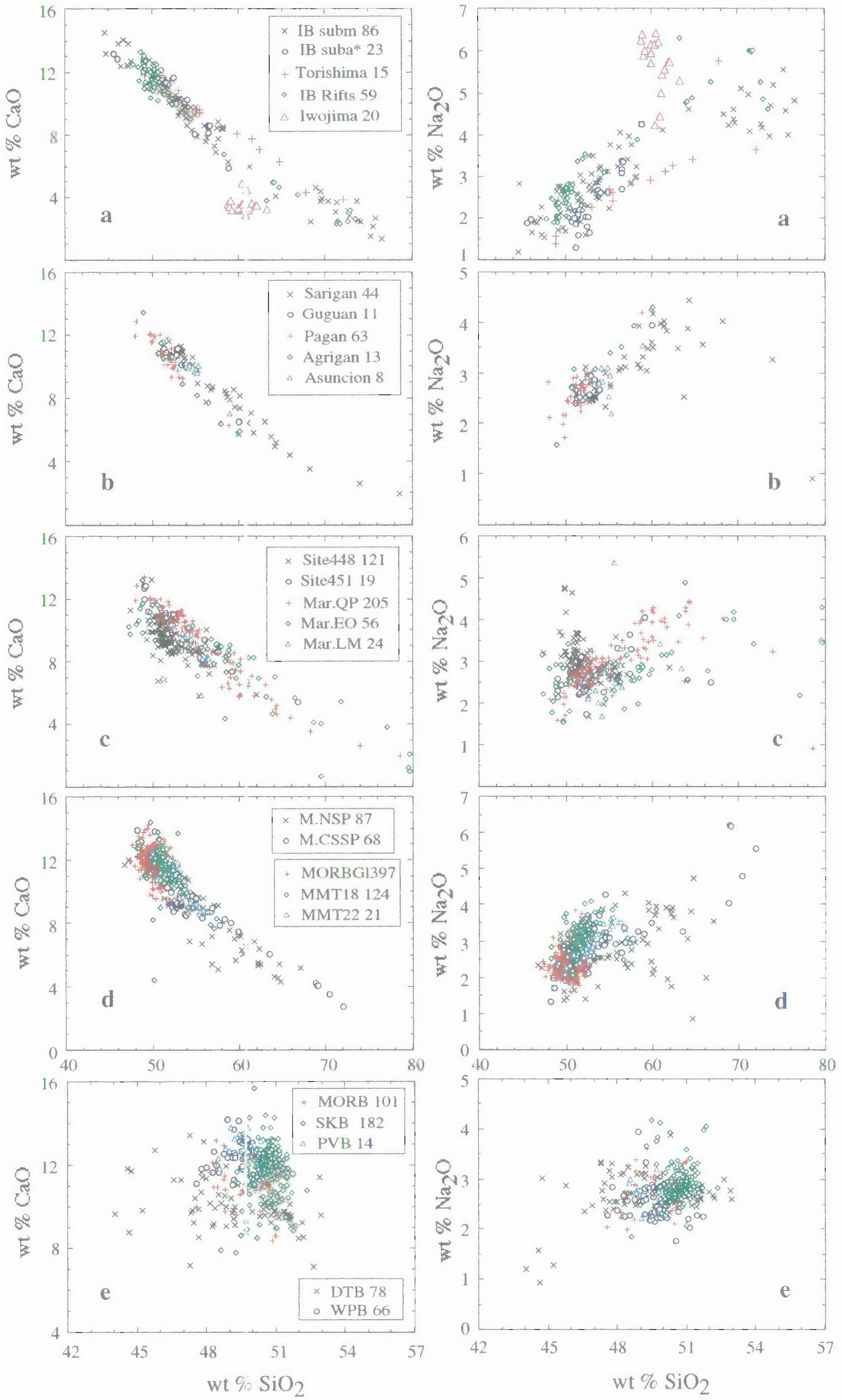

Figure 4-12 Comparison of major element compositions of the IBM arc (subaerial and submarine) volcanic rocks, backarc basin volcanic rocks, Leg 60 Sites 448 and 451 volcanic rocks compared with MORB and its glasses. See text for the sample data sources and interpretation.

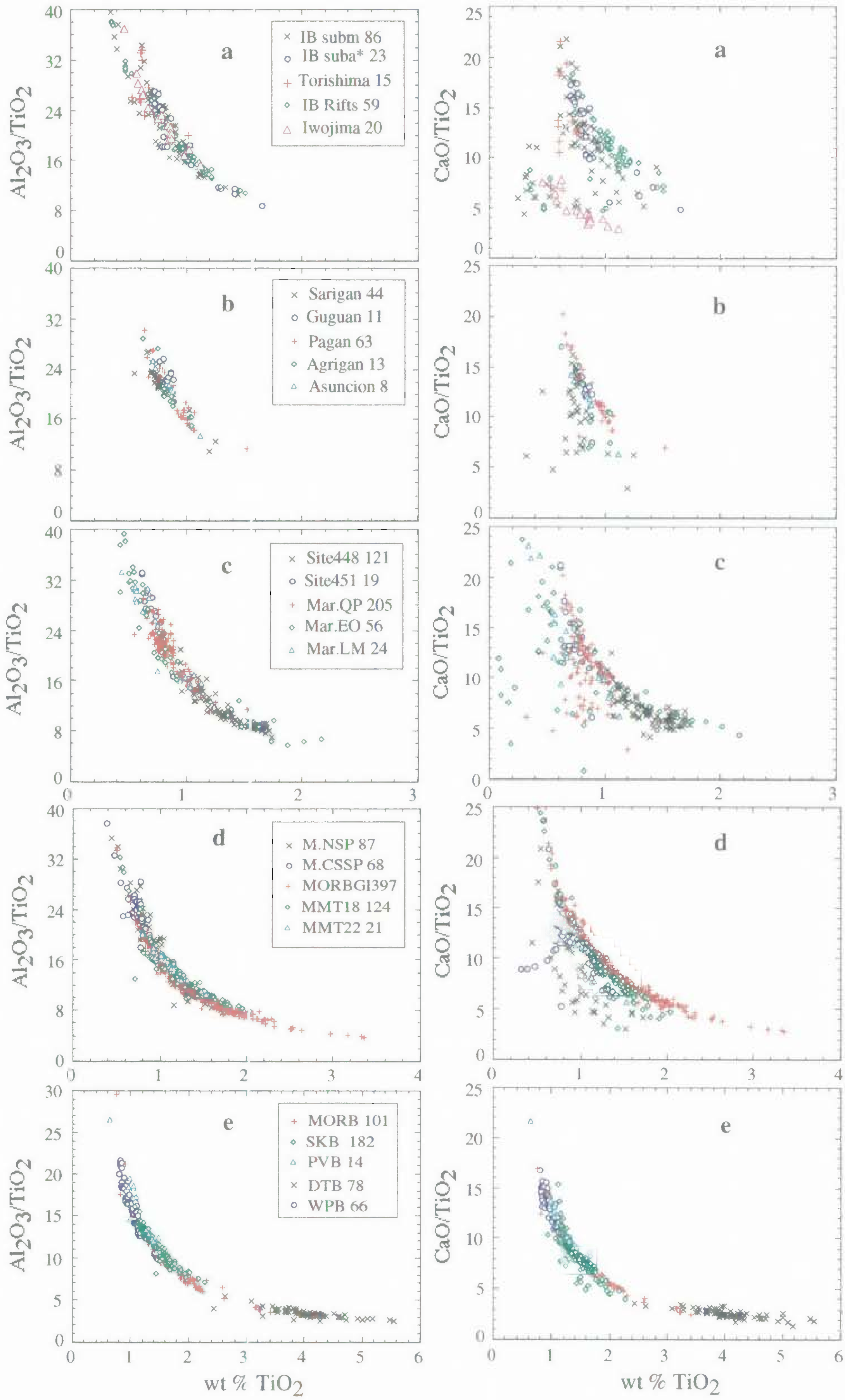

Figure 4-13 Comparison of major element compositions of the IBM arc (subaerial and submarine) volcanic rocks, backarc basin volcanic rocks, Leg 60 Sites 448 and 451 volcanic rocks compared with MORB and its glasses. See text for the sample data sources and interpretation.

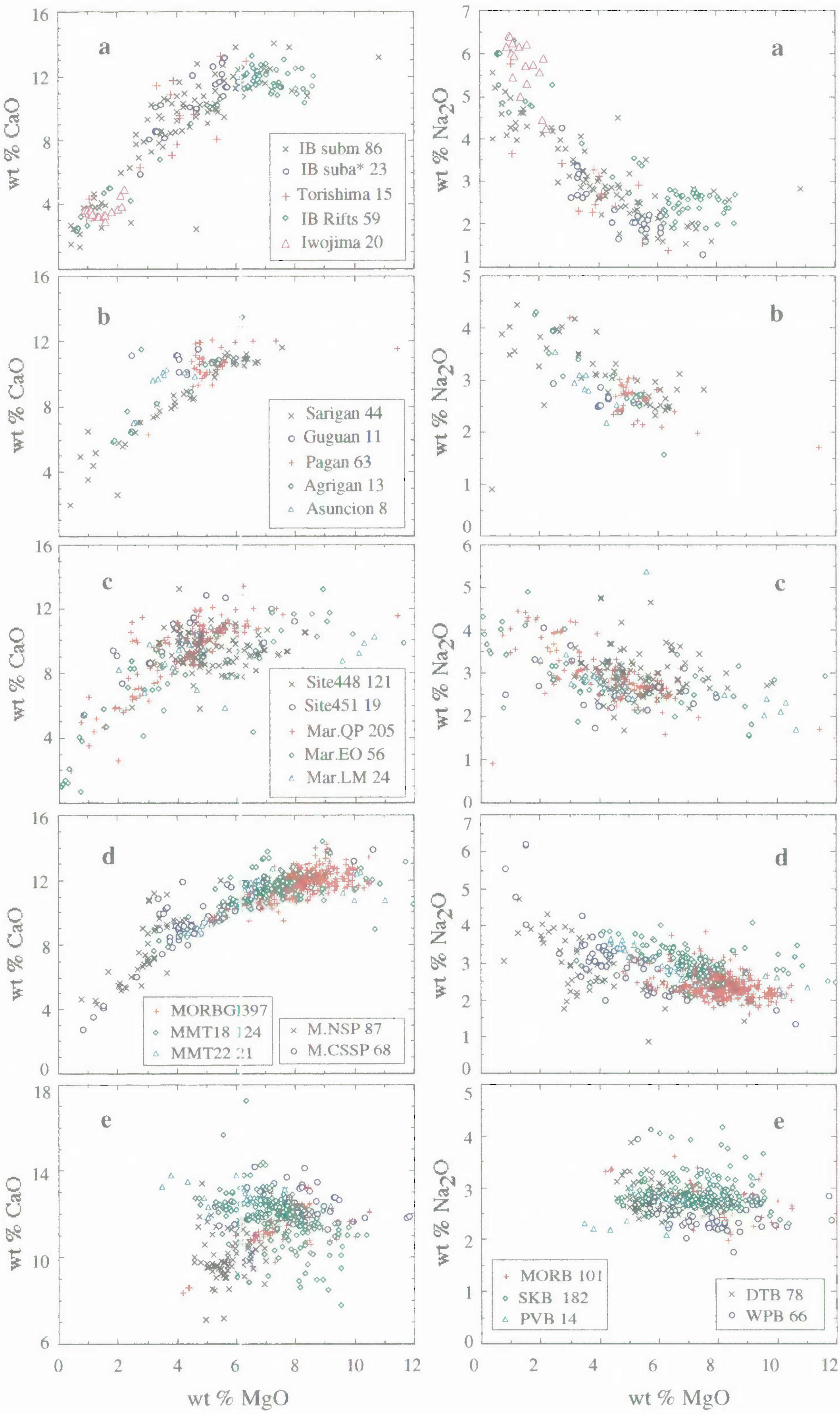

Figure 4-14 Comparison of major element compositions of the IBM arc (subaerial and submarine) volcanic rocks, backarc basin volcanic rocks, Leg 60 Sites 448 and 451 volcanic rocks compared with MORB and its glasses. See text for the sample data sources and interpretation.

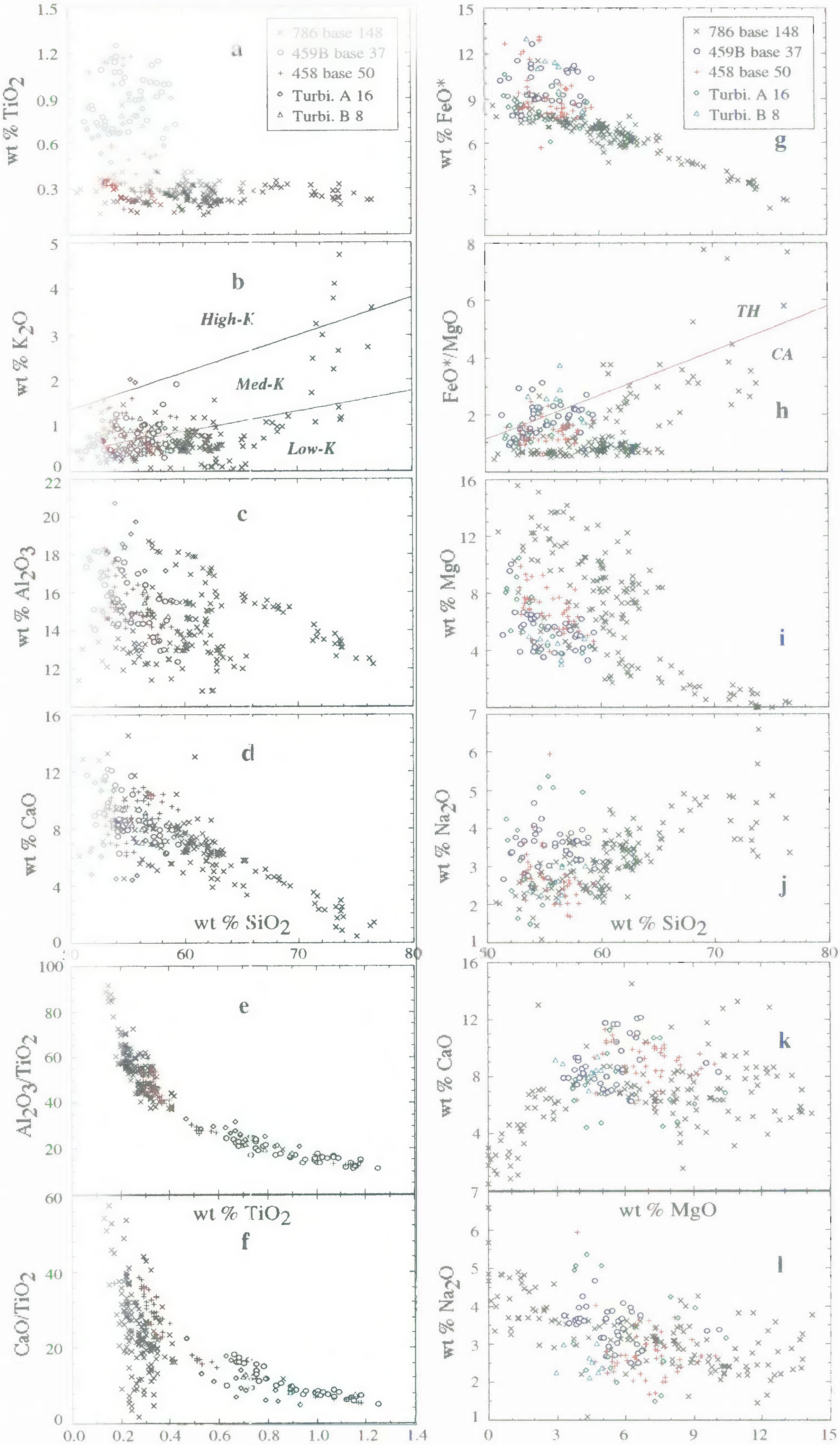

Figure 4-15 Comparison of major element compositions of the IBM forearc drilled volcanic rocks compared with Izu-Bonin turbidites. See text for the sample data sources and divisions of K_2O and TH ~ CA.