Geochemical evolution of magmatism in an arc–arc collision: the Halmahera and Sangihe arcs, eastern Indonesia

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Abstract: The Molucca Sea Collision Zone in eastern Indonesia is the site of an orthogonal collision between two active subduction systems. Both the Halmahera subduction zone, to the east, and the Sangihe subduction zone, to the west, have subducted oceanic lithosphere of the Molucca Sea Plate, which has now been completely consumed. Both volcanic arcs were active since the Neogene and provide a means of probing the element fluxes through the two systems. The geochemistry of Neogene and Quaternary lavas from each volcanic arc is compared to constrain changes in the mass fluxes through the systems and the processes controlling these fluxes at different times during their history. Both arcs show increased evidence for sediment recycling as the collision progressed, but for contrasting reasons. In Halmahera this may represent an increased sediment flux through the arc front, while in Sangihe it may simply reflect a greater opportunity for melting of sediment-fluxed portions of the mantle wedge. In both cases the change in arc geochemistry can be related to the evolving architecture of that particular subduction zone. The Halmahera lavas also record a temporal change in the chemistry of the mantle component that resulted from induced convection above the falling Molucca Sea Plate drawing compositionally distinct peridotite into the mantle wedge.

The geochemistry of magmatism is an important tool for understanding the internal processes of active subduction zones and for providing constraints on the geodynamics of ancient convergent plate margins. Subduction-zone magmas are generated when melting occurs in the wedge of mantle trapped between the lower (subducted) plate and the upper (overriding) plate, onto which lavas are erupted. Geochemical evidence suggests that fluids are released from the subducted plate as pressure increases, causing hydrous mineral phases to break down and release volatiles. This provides a medium for mass transport from the subducted plate into the mantle wedge and may also encourage melting of the wedge by lowering its solidus temperature. Melting of sediment carried down on the surface of the subducted plate may provide another means of transporting subducted material into the source of lavas. Geochemical investigation of well-sampled traverses along and across arcs have shown that spatial changes in mass transfer processes, the material subducted and magma interaction with the overriding plate are all important features of active subduction systems (e.g. Ben Othman *et al.* 1989; Morris *et al.* 1990; Tatsumi *et al.* 1991; Edwards *et al.* 1993; Plank & Langmuir 1993; Vroon *et al.* 1993; Pearce *et al.* 1995; Davidson 1996; Ryan *et al.* 1996; Elliott *et al.* 1997; Peate *et al.* 1997; Turner & Hawkesworth 1997; Macpherson *et al.* 1998; Woodhead *et al.* 1998; Hochstaedter *et al.* 2001; van Soest *et al.* 2002). However, recent magmatic products from subduction systems provide less opportunity for studying temporal changes in these factors, especially on the timescales over which the architecture of subduction zones are likely to change, i.e. millions to tens of millions of years.

This contribution investigates the temporal evolution of two volcanic arcs in Indonesia. The Halmahera and Sangihe arcs are undergoing orthogonal collision after subducting a single piece of oceanic lithosphere (the Molucca Sea Plate) from the east and west, respectively. Neogene volcanic rocks are exposed, to varying degrees, in both arcs and their geochemistry can be compared with more recent lavas from the Quaternary arcs. Therefore, we are able to investigate magmatic systems that are reaching the end of their lifetime as island arcs and are becoming a single collision zone. There are significant differences between the architecture of these systems and the processes operating
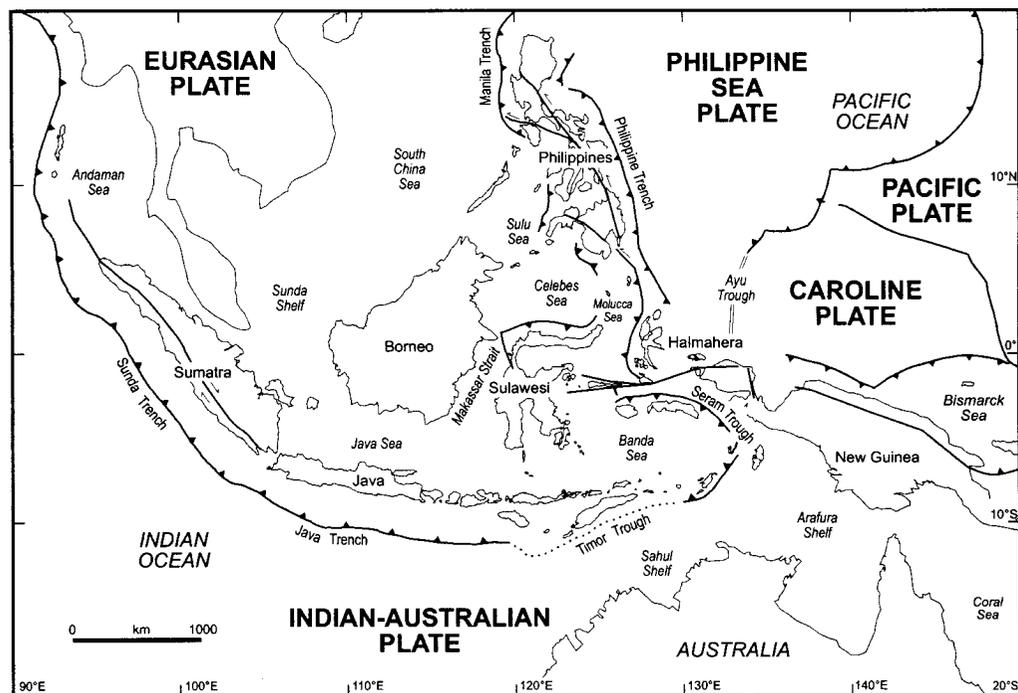
Fig. 1. Map of SE Asia highlighting major tectonic plates and plate boundaries. Plate names are shown in bold type and subduction zones are indicated by lines with barbs on the overriding plate.

within them that have important effects on the composition of the lavas erupted during the Neogene and Quaternary.

Geological setting of the Molucca Collision Zone

SE Asia and the SW Pacific are dominated by convergence between the Eurasian, the Indian–Australian and the Pacific plates (Fig. 1). In addition, the Philippine Sea Plate, which lies between the Pacific and Eurasian plates, has played a crucial role in the region's development. There are currently a large number of other small plates and plate fragments, and a similar complexity has probably existed throughout the Cenozoic (Hall 1996, 2002).

The Halmahera and Sangihe arcs form the Molucca Sea Collision Zone, which is itself part of an elongate zone of convergence extending north through the Philippines towards Taiwan (Fig. 1). The polarity and location of subduction varies along the length of this zone, and in the south the Halmahera and Sangihe arcs form the eastern and western margins of an orthogonal

arc–arc collision (Fig. 2). During the Neogene, both arcs consumed oceanic lithosphere of the Molucca Sea Plate (Cardwell *et al.* 1980), which has now been entirely consumed such that the Sangihe arc is presently overriding the Halmahera forearc (Hall 2000) (inset to Fig. 2).

Neogene magmatic rocks in Halmahera overlie ophiolitic basement and arc volcanic rocks that represent an early Tertiary period of subduction (Hall *et al.* 1991). In the Halmahera arc Miocene magmatism is represented by exposures of volcanic rocks in the southern islands of Obi and Bacan, and in the centre of Halmahera itself where its four arms converge (Fig. 2). The oldest Neogene volcanic rocks, dated at about 11 Ma, are found in Obi at the southern end of the arc, but the most extensive areas of Neogene volcanic rocks are the Upper Miocene and Pliocene deposits of Bacan and Halmahera (Hakim & Hall 1991; Baker & Malaihollo 1996). These rocks are mainly andesitic with rare basalts and dacites (Hakim & Hall 1991; Malaihollo & Hall 1996). The active Halmahera arc extends along the north arm of Halmahera Island, through the islands of Tidore and Ternate, but Quaternary cones are present as far
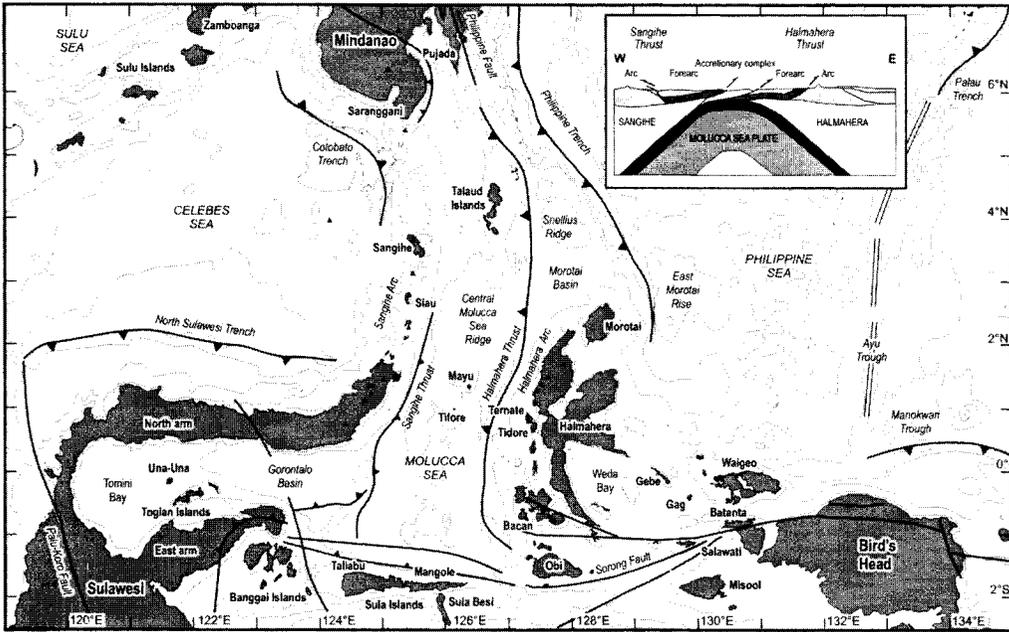
Fig. 2. Geographical features of the Molucca Sea and surrounding regions. Small black filled triangles are volcanoes from the Smithsonian database. Bathymetric contours at 200, 2000, 4000 and 5000 m from the *GEBCO Digital Atlas* (IOC, IHO & BODC 1997). Lines with large barbs are subduction zones and lines with small barbs are thrusts. Note that the direction of surface thrusting in the Molucca Sea is correctly shown. Thrusts on each side of the Molucca Sea are directed outwards towards the adjacent arcs, although the subducting Molucca Sea Plate dips east beneath Halmahera and west below the Sangihe arc. The Halmahera arc is being overridden by the Sangihe arc as shown in the inset figure.

south as Bacan (Fig. 2). Volcanic rocks erupted during the Quaternary range from basalt through to dacite, but are most commonly basaltic andesites and andesites (Morris *et al.* 1983; Malaihollo & Hall 1996).

The basement of the Sangihe arc is thought to comprise pre-Miocene ophiolitic or arc crust (Carlile *et al.* 1990). The arc extends from the northern tip of Sulawesi through the Sangihe islands, but terminates south of Mindanao due to a reversal in subduction polarity where the Cotobato Trench begins (Fig. 2). In the north, the arc is made up entirely of Quaternary volcanic islands and there is significant volcanic and geothermal activity on the eastern tip of the north arm of Sulawesi (Morrice *et al.* 1983; Morrice & Gill 1986) where older portions of the arc are also exposed. The oldest known Neogene volcanic rocks of the Sangihe arc occur on Sulawesi (Elburg & Foden 1998), where Late Miocene–Pliocene magmatism is also recognized (Polvé *et al.* 1997). Like Halmahera, lavas erupted throughout the history of this arc vary from basaltic to dacitic compositions, but

andesitic rocks dominate (Morrice *et al.* 1983; Elburg & Foden 1998).

Data-set

Data are available from the Late Neogene and Quaternary segments of both the Halmahera and Sangihe arcs. Previous studies of both arcs have identified instances of crustal contamination and, for the purposes of this study, we have eliminated any analyses suspected of recording this process. Neogene volcanic rocks from central Halmahera, Bacan and Obi in the Halmahera arc were analysed by Forde (1997), while Morris *et al.* (1983) obtained data from the Quaternary arc. Elburg & Foden (1998) produced data from the entire range of known ages for the Sangihe arc. The Sangihe data-set is necessarily small due to the lack of published data suitable for comparison with the Halmahera data; however, Elburg & Foden's data-set represents the entire suite of analyses available at this time and so we make the assumption that these represent the magmatism of the Sangihe
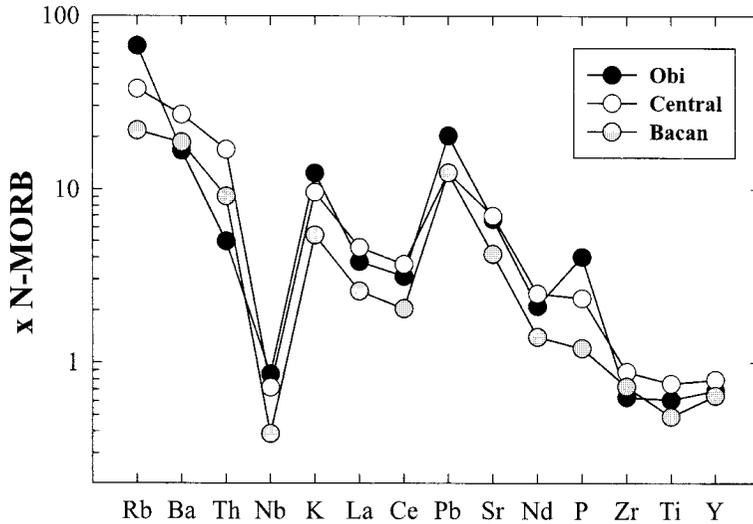
Fig. 3. Incompatible element abundances of the least-evolved Neogene Halmahera arc lavas, from the islands of Obi and Bacan and from central Halmahera, normalized to N-MORB (Sun & McDonough 1989).

arc. Where available, we have used other geochemical data from this arc to provide qualitative support for our conclusions. Conclusions reached below may have to be revised if the existing data-set for the Sangihe arc is shown to be unrepresentative. We have chosen to focus on a small number of key trace element and isotopic ratios to simplify the discussion. This is also forced on us by the less extensive coverage of trace element analyses for the Quaternary lavas from Halmahera, but the wider range of geochemical data for the remaining suites are consistent with the interpretations presented below. Finally, as the Molucca Sea Plate has been largely subducted, it is not possible to sample the crust itself or the sediments it carried. Therefore, we have not attempted to produce detailed geochemical models of particular processes discussed in this paper.

Geochemical evolution of the Molucca Sea Collision Zone

Neogene Halmahera arc

The geochemistry of Neogene magmatism in the Halmahera arc displays typical subduction zone characteristics (Forde 1997). Normalized incompatible element plots (Fig. 3) reveal that, relative to normal mid-ocean ridge basalt (N-MORB), the Neogene arc erupted lavas with elevated ratios of the large ion lithophile elements (LILEs) and the light rare earth elements (LREEs) to the high-field strength elements (HFSEs). Such patterns are considered typical of subduction zones in which the mantle wedge has been contaminated by fluid released from the subducted slab (e.g. McCulloch & Gamble 1991; Davidson 1996). Lead isotope ratios highlight two further important features of the sources contributing to the Neogene arc. First, the rocks with the lowest $^{206}Pb/^{204}Pb$, which are assumed to lie close to the composition of uncontaminated mantle wedge, have $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ ratios that are more elevated than MORB from the Pacific and Atlantic oceans (Fig. 4). This is a trait shared with Indian Ocean MORB (I-MORB) and suggests that during the Neogene the mantle wedge beneath Halmahera was part of the I-MORB domain which is consistent with the source inferred for lavas erupted to the north and west of the Molucca Sea during the Eocene and Oligocene (Hickey-Vargas 1998). Second, the data trend away from the main I-MORB array towards relatively high $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$. This is another feature typical of island arc volcanics; such arrays are usually explained by the incorporation of subducted sediment into the source of the magmas (e.g. Morris *et al.* 1983).

More can be learned about the Neogene mantle wedge by considering elements that are likely to be relatively immobile during devolatilization of the slab, such as Nb and Zr, although these may become mobile if slab
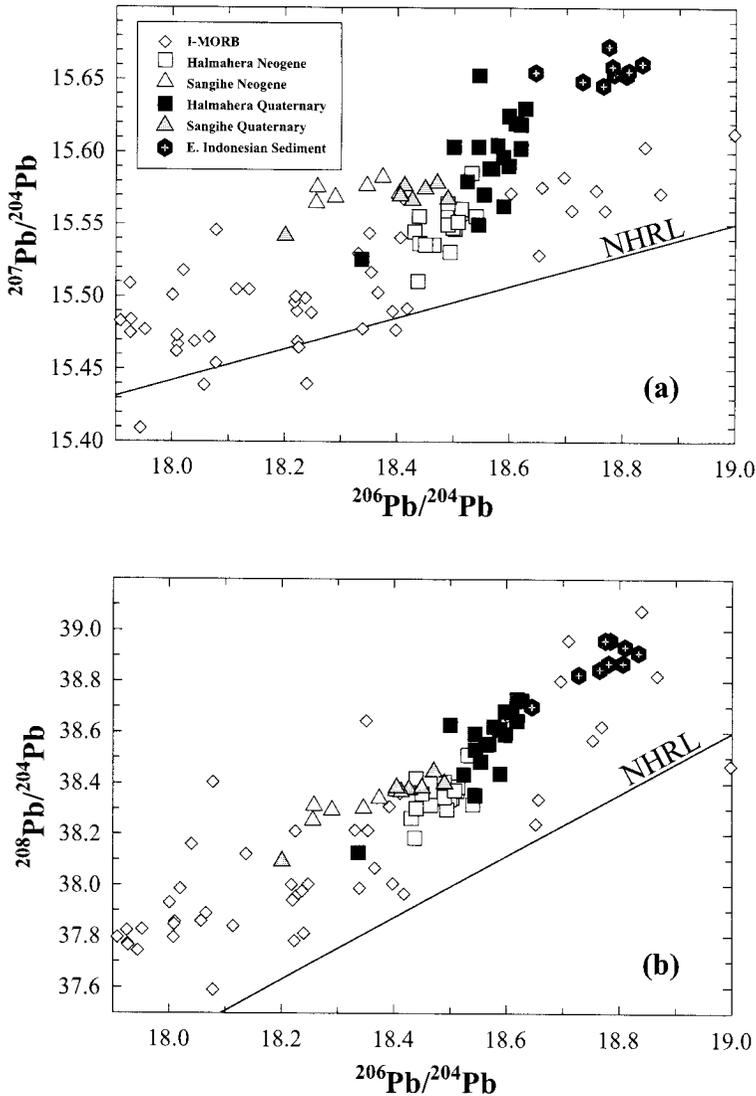
Fig. 4. (a) $^{207}Pb/^{204}Pb$ v. $^{206}Pb/^{204}Pb$ and **(b)** $^{208}Pb/^{204}Pb$ v. $^{206}Pb/^{204}Pb$ in Neogene and Quaternary lavas from the Molucca Sea Collision Zone (Morris *et al.* 1983; Forde 1997; Elburg & Foden 1998). The Northern Hemisphere Reference Line (NHRL; Hart 1984), I-MORB (Michard *et al.* 1986; Dosso *et al.* 1988; Le Roex *et al.* 1989; Mahoney *et al.* 1989, 1992; Danyushevsky *et al.* 2000) and East Indonesia sediments (Vroon *et al.* 1995) are shown for comparison.

components melt (Elliott *et al.* 1997). Most MORB display a restricted range in Zr/Nb in contrast to subduction zone lavas in which Zr/Nb varies up to high values (e.g. McCulloch & Gamble 1991). High Zr/Nb lavas cannot be generated directly by melting MORB-source peridotite (Woodhead *et al.* 1993). Instead, the high Zr/Nb signature is thought to characterize mantle that has previously lost a basaltic melt

fraction, leaving behind a source that is more depleted in the most highly incompatible elements, such as Nb. Furthermore, refractory sources require high fluid fluxes to lower the solidus and assist the melting process, therefore, high Zr/Nb ratios are consistent with fluid fluxing as an important recycling mechanism. Source contamination by sediments, or partial melts derived from sediments, would most

probably reduce the Zr/Nb ratio of the source of arc lavas (Elliott *et al*. 1997).

Neogene lavas from Halmahera display considerable Zr/Nb variation with a strong spatial control (Fig. 5). The southernmost, and oldest, lavas from Obi possess a narrow range in Zr/Nb that is similar to the mean value of MORB. This suggests that the mantle wedge beneath Obi contained relatively fertile mantle similar to the source of MORB from the major ocean basins. The Neogene lavas from Central Halmahera and Bacan also show quite restricted ranges for Zr/Nb, but at progressively higher values with only minor overlap between the different centres. This suggests that during the Neogene the sources of Central Halmahera and Bacan lavas were increasingly depleted relative to the source of MORB. Prior depletion of the mantle wedge is consistent with HFSE concentrations, which are consistently less than N-MORB (Fig. 3). Zr/Nb is similar to, or greater than, N-MORB in rocks from all three sites suggesting sediments made an insufficient contribution to modify this ratio in the source of the Neogene arc. The Central Halmahera and Bacan suites were probably erupted at similar distances from the trench, so their contrasting Zr/Nb implies along-arc variations in the degree of mantle wedge depletion.

The relationship between the mantle wedge and the recycled component in the Neogene Halmahera arc is explored further in Figure 6. There is a broad positive correlation between Ba/Nb and Zr/Nb, with some scatter to higher Ba/Nb at intermediate Zr/Nb. This is consistent with an important role for fluid fluxing of the mantle wedge. Ba is highly mobile in fluids released from both subducted oceanic crust and its sedimentary cover (Brennan *et al*. 1995; Keppler 1996; You *et al*. 1996), so high Ba/Nb ratios represent a high fluid flux. More depleted (higher Zr/Nb) mantle will possess lower concentrations of trace elements, so incoming fluids will be more visible in any mixture, thus producing a broad correlation between Zr/Nb and Ba/Nb (Fig. 6). Scatter to higher Ba/Nb at constant Zr/Nb could represent more variable fluid fluxes at any location. This seems to be particularly true for Central Halmahera lavas, in which Zr/Nb values lie between 30 and 50.

In summary, Neogene Halmahera arc magmatism was generated from a mantle wedge that was part of the I-MORB domain. This mantle had experienced prior melt extraction and there is evidence that the amount of depletion varied along the strike of the arc. Slab dehydration added fluid-mobile elements to the source and may have helped promote melting. Lead isotope
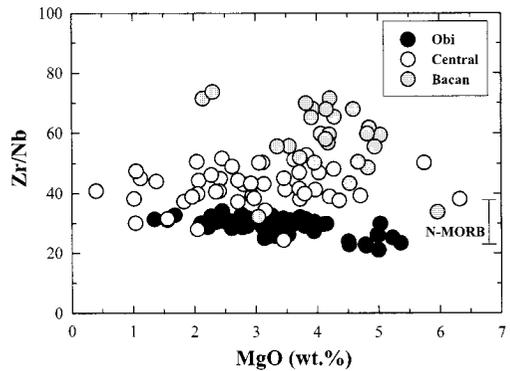

Fig. 5. Zr/Nb v. MgO for Neogene lavas from the islands of Obi and Bacan and from central Halmahera, in the Halmahera arc (Forde 1997).
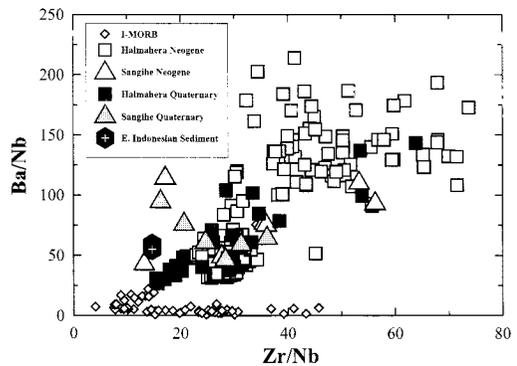

Fig. 6. Ba/Nb v. Zr/Nb for Molucca Sea Collision Zone lavas, with I-MORB and sediment from eastern Indonesia for comparison (see Fig. 4 for data sources).

ratios indicate that relatively modest quantities of sediment were also incorporated into the source of the lavas.

Quaternary Halmahera arc

Quaternary lavas from the Halmahera arc (Morris *et al*. 1983) differ from the Neogene arc in their lead isotope and trace element ratios. One Quaternary lava lies at the low $^{206}Pb/^{204}Pb$ end of the Neogene array, but still within the I-MORB field, and represents our best estimate of uncontaminated mantle presently lying beneath Halmahera (Fig. 4). The majority, however, are displaced to higher $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ values, and extend the Neogene array well beyond the I-MORB field. This

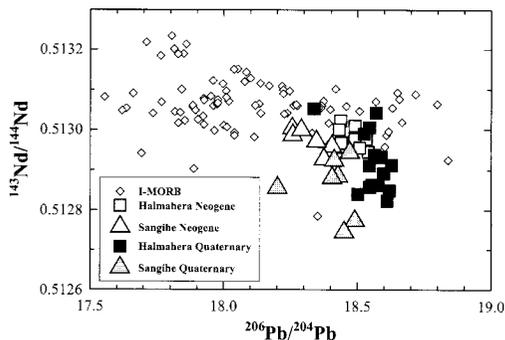**Fig. 7.** $^{143}Nd/^{144}Nd$ v. $^{206}Pb/^{204}Pb$ for Molucca Sea Collision Zone lavas and I-MORB. Data sources as in Figure 4 plus Rehkämper & Hofmann (1997) and references therein.

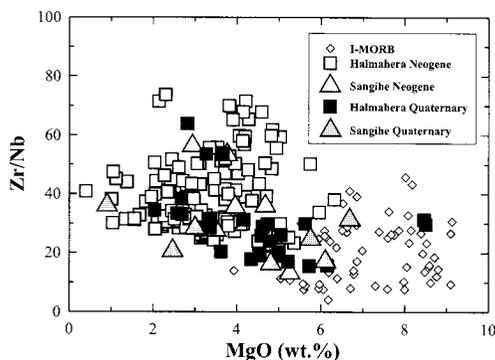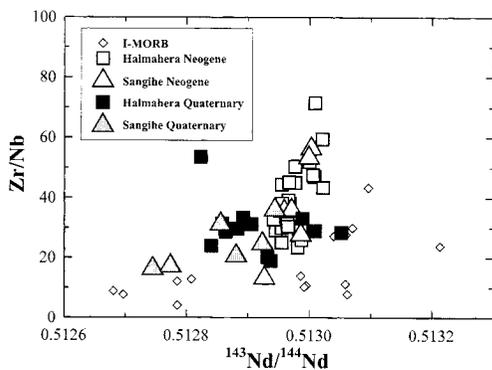**Fig. 8.** Zr/Nb v. MgO for Molucca Sea Collision Zone lavas and I-MORB (see Fig. 4 for data sources).

Fig. 9. Zr/Nb v. $^{143}Nd/^{144}Nd$ for Molucca Sea Collision Zone lavas and I-MORB. Data sources as in Figure 4.

suggests that the components recycling Pb into the sourse of the Halmahera arc were similar from the Neogene until the present day, but this process contributed a greater fraction to the source of Quaternary lavas. As noted above, such arrays are commonly interpreted as reflecting an increased sediment input to the source of lavas. An important role for sediment recycling can also be inferred from Nd isotope ratios as $^{143}Nd/^{144}Nd$ is substantially lower in the high-$^{206}Pb/^{204}Pb$ Quaternary lavas, which again extend beyond the vast majority of I-MORB rocks (Fig. 7). Hochstaedter *et al.* (2001) observed Pb isotope variations resembling the Halmahera arrays in Figure 4 in transects across the Izu–Bonin arc. These were explained as the result of contamination of variably depleted mantle wedge by fluids derived at different stages of slab devolatilization. An important conclusion of their work was that the ratio of material derived from subducted oceanic crust and sediment remained constant in all slab-derived fluids. If this were true in Halmahera the strongly increased $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ (Fig. 4) and decreased $^{143}Nd/^{144}Nd$ (Fig. 7) values of the Quaternary suite, relative to the Neogene, would require a substantial increase in either the fluid flux through the arc or the depletion of the mantle wedge to make the recycled signature more visible. Neither scenario is supported by the trace element data leaving the alternative explanation; that the extent of sediment recycling increased from the Neogene to the Quaternary.

The Zr/Nb data also differ through the history of the Halmahera arc. Quaternary lavas have ratios that are, for the most part, similar to or lower than N-MORB (Fig. 8). As mentioned above, addition of a subducted sedimentary component can lower Zr/Nb levels of arc sources (Elliott *et al.* 1997). However, a comparison of the isotopic and trace element data for the Quaternary arc does not provide convincing support for this. For example, there is no clear correlation between Zr/Nb and $^{143}Nd/^{144}Nd$ (Fig. 9), suggesting either that sediment addition has not influenced trace element ratios or that some additional factor has influenced the source of the Quaternary arc.

Ba/Nb data also suggest that a distinctive component has affected the Quaternary lavas. There is a global correlation between the Ba flux entering a particular subduction zone in sediment and the Ba contents of arc lavas erupted by that subduction zone (Plank & Langmuir 1993; Peate *et al.* 1997). Therefore, we assume, as a broad approximation, that Ba partitioning during partial melting of sediment varies relatively little

between arcs. If increased sediment recycling is the main control on the changing trace element inventory of the Halmahera arc sources, the Quaternary array in Figure 6 requires any sedimentary component added to their source to have relatively low Ba/Nb. Pelagic clays and volcaniclastic sediment are two possible low Ba/Nb sediments (Elliott *et al.* 1997; Peate *et al.* 1997). As the Molucca Sea Plate cannot be sampled, we have no way of estimating the proportion of these relative to other types of sediment that were subducted beneath Halmahera. However, we note that the volcaniclastic sediments are unlikely to possess sufficiently low $^{143}Nd/^{144}Nd$ to produce the isotopic shift apparent in the Quaternary lavas (Fig. 7). Therefore, pelagic clay, similar to that found in the western Pacific (Elliott *et al.* 1997), appears to provide the most likely sedimentary contaminant.

An alternative explanation for the Zr/Nb and Ba/Nb characteristics of the Quaternary arc is that the composition of the mantle wedge beneath Halmahera may have changed. The trace element characteristics of the youngest Halmahera lavas include a tendency towards more enriched mid-ocean ridge basalt (MORB) compositions (low Ba/Nb, relative to other arc lavas, and low Zr/Nb; Figs 6 and 8) found in various parts of the Indian Ocean (Le Roex *et al.* 1989; Mahoney *et al.* 1989, 1992). In addition to the change in the recycled component, the mantle wedge composition may have changed in the Halmahera arc with the introduction of enriched I-MORB. Over the lifetime of an arc, peridotite is cycled through the mantle wedge as a result of convection induced by 'slab rollback' (Andrews & Sleep 1974; Hamilton 1995). Volcanic rocks erupted at spreading centres in the Indian Ocean (Fig. 6) demonstrate that the I-MORB mantle domain contains low-Ba/Nb, low-Zr/Nb portions, which could be drawn into the mantle wedge as a source for the Quaternary lavas. Plate reconstruction of the Molucca Sea region suggests that Halmahera was particularly susceptible to this type of mantle wedge circulation due to the large amount of rollback associated with the arc between the Neogene and Quaternary (see Macpherson & Hall 2002, figs 4 and 7). Therefore, the Quaternary arc appears to have experienced a greater flux of recycled sediment than the Neogene arc, but the mantle wedge may also have sampled compositionally distinctive parts of the I-MORB domain. Using the possible sediment components suggested by Elburg & Foden (1998) and our best estimate of the mantle wedge, the estimated sediment contributions are 0.3–1% during the Neogene and 0.1–2.2% during the Quaternary.

Sangihe arc

Elburg & Foden (1998) studied changes in the geochemistry of Sangihe arc lavas from the Neogene to Recent. They demonstrated a characteristic subduction zone signature with elevated LILE/HFSE and LREE/HFSE ratios and distinctive isotope ratios. Like Halmahera, Elburg & Foden (1998) identified an I-MORB affinity for the mantle wedge beneath Sangihe and suggested that low concentrations of HFSE and the heavy rare earth elements (HREEs) indicate that the mantle wedge had previously experienced partial melting. There are also differences between the trace element and isotopic characteristics of the Neogene and Quaternary Sangihe arcs. Elburg & Foden (1998) attributed these changes to (i) a decrease in the extent of prior depletion with time coupled with (ii) a change from fluid-dominated to sedimentary melt-dominated recycling from the Neogene to the present day.

Elburg & Foden (1998) interpreted lower Zr/Nb, lower $^{143}Nd/^{144}Nd$ and higher Pb isotope ratios as evidence that partial melt from sediment became the dominant recycling mechanism in the Sangihe arc during the Quaternary. Like Halmahera, the isotope ratios changed with time (Figs 4 and 7). Furthermore, decreasing $^{143}Nd/^{144}Nd$ in the Quaternary lavas correlates well with decreasing Zr/Nb (Fig. 9), which is consistent with adding a partial melt of subducted sediment to the source of the younger lavas (Elliott *et al.* 1997; Elburg & Foden 1998). In contrast to Halmahera, low Zr/Nb ratios are associated with higher Ba/Nb (Fig. 6) in the Sangihe arc, which could also be generated by partial melting of sediment with moderate Ba/Nb, such as East Indonesian sediment (Fig. 6).

Geodynamic evolution of the Molucca Sea Collision Zone

Geochemical evidence has resulted in similar conclusions regarding the evolution of the Halmahera and Sangihe arcs. Both appear to have experienced an increase in the amount of sediment incorporated into their sources and both have seen an evolution in the composition of the mantle wedge. Because it is not possible to sample either the oceanic crust of the Molucca Sea Plate or its sedimentary cover, the processes discussed above have not been modelled in detail. Nevertheless, there are significant differences between the geochemistry of the lavas erupted in the two arcs that provide clues as to the tectonic processes that have affected

each. First, the Halmahera and Sangihe datasets form oblique arrays in plots of $^{207}Pb/^{204}Pb$ v. $^{206}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ v. $^{206}Pb/^{204}Pb$ (Fig. 4). This indicates that each arc sampled isotopically distinct mantle wedges and that these were contaminated by different recycled components. The wedge beneath Halmahera has higher $^{206}Pb/^{204}Pb$ values than Sangihe, while the sediment incorporated beneath Halmahera has higher $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ at a given $^{206}Pb/^{204}Pb$ value (similar to the least radiogenic East Indonesian sediment, Fig. 4). The difference is also apparent in Figure 7, where the whole Halmahera array is displaced to higher $^{206}Pb/^{204}Pb$. Second, the Quaternary Halmahera lavas display less coupling between $^{143}Nd/^{144}Nd$ and trace element ratios than contemporary Sangihe magmatism (Fig. 9), indicating that the former may not have experienced a simple increase in the amount of recycled sediment. Finally, the Quaternary arcs show divergent arrays in Ba/Nb v. Zr/Nb sapce. As discussed above, the latter two observations may reflect distinctive mantle wedges and recycled sedimentary components beneath the two arcs. In this section we shall discuss the geodynamic controls that were responsible for this contrasting evolution in the different parts of the collision zone.

Halmahera

In the Halmahera arc, the increased $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$, and decreased $^{143}Nd/^{144}Nd$, are found at centres along the entire length of the arc interspersed with, or even at the same centres as, rocks containing a weaker sedimentary imprint. This suggests that the increase in sediment fluxing is a ubiquitous feature of the arc and requires a mechanism to increase the sediment flux close to the volcanic front. Following the models of Elliott et al. (1997), this can be achieved by compressing the distance between the parts of the mantle wedge where fluid fluxing and sediment melting dominate mass transfer. Steepening of the subducted slab provides a mechanism whereby this compression could occur. Hall et al. (1988) proposed that localized deformation and tilting of fault-bounded blocks throughout the main island of Halmahera, and an unconformity in the Weda Basin to the southeast of Halmahera, resulted from steepening of the eastern limb of the Molucca Sea Plate during the Pleistocene. The dip of the Molucca Sea slab may have increased due to a downward force from the Philippine Sea Plate at the newly formed Philippine Trench to the north, or through westward motion of

continental fragments along splays of the Sorong Fault at the southern end of the arc (Hall et al. 1988). As slab dehydration and sediment melting are thought to be pressure-dependent, slab steepening would bring the locus of sediment melting closer to the arc front during the Quaternary than it had been during the Neogene, therefore increasing the flux of recycled sediment in volcanic arc lavas. Steepening of the slab would also increase the effects of slab rollback in the mantle, in turn increasing the rate of replenishment of the mantle wedge. Therefore, slab steepening can also explain the way in which peridotite with distinctive trace element characteristics (Fig. 6) could be incorporated into the Halmahera mantle wedge.

Sangihe arc

Elburg & Foden (1998) argued that the low $^{143}Nd/^{144}Nd$ and high $^{206}Pb/^{204}Pb$ of the Quaternary Sangihe lavas are consistent with the input of a component derived from subducted sediment, and proposed two mechanisms to explain the increased sedimentary contribution to younger lavas in their data-set. First, they suggested that as the two arcs collided their accretionary wedges may have overlapped and thickened, thus increasing the likelihood of sediment being subducted. Recent models of the Molucca Sea Collision Complex have suggested that segments of the Halmahera forearc may have penetrated to depth approaching the magma genesis zone beneath the northern Sangihe arc (Lallemand et al. 1998; Hall 2000), but whether this is the case in the south is not clear. Second, they suggested that subduction of the Molucca Sea Plate may have slowed down and stopped as the arcs collided, allowing sediment on its upper surface to heat up and melt. However, this assumes that the downward velocity of the Molucca Sea Plate became negligible when the collision occurred or, for subduction more generally, that the motion of overriding plates drives the descent rate of subducted plates. An alternative perspective is that subduction is driven largely by 'slab pull' (e.g. Hamilton 1988, 1995) so that the descent of subducted lithosphere is controlled by the weight of the slab, with the extreme case that overriding plates move passively (or deform) in response to their subducting neighbours. This process must be invoked for models that interpret isolated seismic and tomographic anomalies in the mantle up to 400 km beneath Mindanao, which is thought to be a northern, more advanced extension of the Molucca Sea Collision Zone, as slabs of oceanic lithosphere (Lallemand et al.
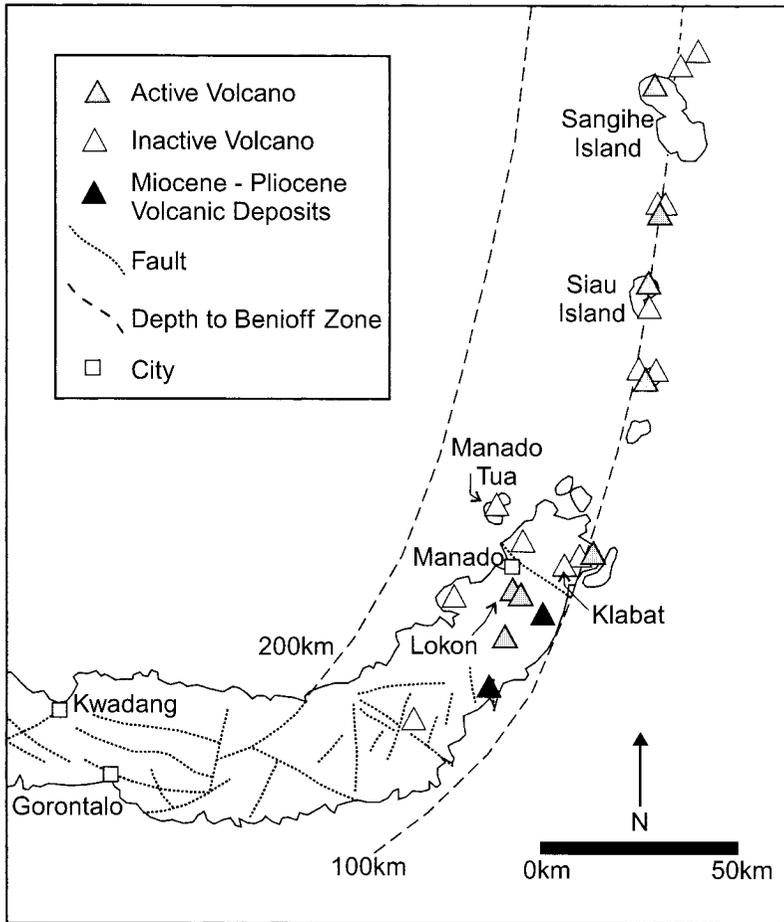
Fig. 10. Map of the southern Sangihe arc collated from Morrice *et al.* (1983), Carlile *et al.* (1990) and Kavalieris *et al.* (1992). Locations of active and inactive Quaternary cones are shown along with the locations of Miocene and Pliocene volcanic rocks sampled by Elburg & Foden (1998).

1998; Rangin *et al.* 1999). If slab pull drove subduction in the Molucca Sea Collision Complex the ever increasing mass in the two limbs of subducted lithosphere acting on the diminishing area of the Molucca Sea Plate at the Earth's surface (Fig. 2, inset) may actually have accelerated the descent rate of the subducted portions. Note also that this may also have contributed to increasing the slab dip beneath Halmahera (see above).

We note that Gill & Williams (1990) used ^{226}Ra- and ^{238}U-excesses to demonstrate the importance of fluid fluxing of the mantle wedge in the very youngest lavas from the Sangihe arc, and Vroon & van Bergen (2000) have also questioned the importance of sedimentary signal at

the active Sangihe arc front. This raises the possibility that the change in recycling mechanism may have a spatial, rather than temporal, control as the strongest sediment signature is found in lavas from Manado Tua Volcano, which lies at a considerably greater depth to the Benioff zone than most of the arc (Fig. 10). In this case, the appearance of recycled sediment in the Quaternary Sangihe arc would not be due to an increase in the amount of recycling but to a greater opportunity for melting of the parts of the mantle wedge containing recycled sediment.

Elliott *et al.* (1997) proposed two models in which slab fluid and sediment melts are added to the mantle wedge at different times, in different parts of the wedge. In one of these models

sediment melting occurs at greater depth than, and therefore to the backarc side of, the dehydration process that initiates melting beneath the volcanic front. This could provide a means of generating a gradient in the intensity of the sediment signal, decreasing from the backarc region to the arc front. Sediment-modified mantle encountering the zone of fluid-fluxed melting would contribute to the main volcanic arc, as envisaged by Elliott *et al.* (1997). However, without some external process to extract melt from the backarc mantle there would be little magmatism bearing a stronger recycled sediment signature. Manado Tua lies just north of an inferred NW–SE strike-slip fault that crosses the north arm of Sulawesi from Manado to Bitung (Fig. 10). Mt Klabat lies a similar distance north of the same fault where it crosses the Sangihe arc front, and Kavalieris *et al.* (1992) indicated the presence of a further young cone in an intermediate position between Manado Tua and Klabat. Young strike-slip faulting generated in a collision zone may provide a pathway for melts in the back-arc region to reach the surface and be erupted. Alternatively, older strike-slip faults may have been reactivated as the stress field changed during the collision between the Halmahera and Sangihe arcs (Pearson & Caira 1999). In these circumstances new zones of compression and dilation may occur, the latter providing the opportunity for decompression and melting of mantle wedge modified by sedimentary melts (Macpherson & Hall 1999).

Summary

The Molucca Sea Collision Zone magmatism reveals several similarities but a number of differences between the two arc systems involved. These findings have implications for understanding the dynamics of subduction systems and for using geochemistry as a tectonic probe in ancient collision zones.

Magma geochemistry evolved through time in both Halmahera and Sangihe. The mantle wedge beneath both arcs was peridotite from the I-MORB domain that had experienced variable depletion, probably by melting, prior to the onset of Neogene arc magmatism. Both wedges were contaminated by fluid derived from the oceanic crust of the subducted Molucca Sea Plate. In both subduction zones Quaternary magmatism displays an increase in the amount of sediment incorporated into the source of arc lavas. There are geochemical differences between the Quaternary arcs that can be related to the composition of the mantle wedge, the composition of subducted sediment and the processes causing the increased sediment flux. Distinctive peridotite, with enriched I-MORB trace element chemistry, became incorporated into the source of the Quaternary Halmahera arc as a result of induced convection in the mantle wedge. Halmahera arc lavas were contaminated by a sediment with elevated $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ at a particular $^{206}Pb/^{204}Pb$ value relative to the sediment affecting Sangihe. Finally, the increased sediment flux at Halmahera appears in arc front lavas and is interpreted as reflecting a change in the dip of the subducted plate and a decrease in the horizontal separation between the locus of slab dehydration and sediment melting. In Sangihe the sediment signature is predominantly found in back-arc Quaternary lavas suggesting that deformation of the upper plate (North Sulawesi) provided a pathway for these melts to reach the surface and/or induced decompression melting in the underlying, sediment-enriched mantle.

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