Geochemical and tectonic relationships in the east Indonesian arc–continent collision region: implications for the subduction of the Australian passive margin

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ABSTRACT


Variations in the isotopic signatures of volcanics along the East Sunda Banda Arc reflect changes in the nature and amount of sedimentary material supplied by the northeast Indian Ocean floor and the adjacent Australian passive continental margin, which form the two major domains of the Indian Ocean plate that approach the arc system. A compilation of isotopic data for 200–500-km-long arc sectors shows that the trend in magmatic signatures follows distinct subduction/collision stages reached by the corresponding oceanic and continental-margin sections entering the trench system. Maximum amounts of magma source contamination are inferred for volcanics near an extinct sector north of Timor, where the Australian continent started to collide with the arc first. Pb-Nd isotopic source mixing models point to contamination by sediments with variations in composition, similar to observed along-arc changes in sediments entering the trench. The results indicate an increasing contribution of subducted continental material in the direction of the collision region. Mass-balance calculations, considering the magmatic output and minimum input of subducted continental material required to generate the composition of the volcanic arc in the collision region, are difficult to reconcile with subduction of ocean-floor sediments alone. Thicknesses of sediments presently covering oceanic crust near the margin are close to calculated thicknesses of the sediments fluxed into the trench and magmatically returned to the arc crust, but cannot account for the additional volumes of material accreted on the overriding plate in the same period of time. It is inferred that leading portions of the Australian continental margin have reached magma generation zones in the easternmost Sunda arc and western Banda arc, which implies subduction to depths greater than 100 km.

Introduction

When a passive continental margin approaches a subduction zone along an island arc or active margin, the resulting collision causes tectonic disturbances which often lead to the cessation of the subduction process. Arccontinent and continent–continent collisions have occurred throughout large parts of the Earth’s history, as for example within the Tethys region from the western Mediterranean to southeast Asia. The extent to which underthrusting/subduction of continental crust proceeds in these settings is not only an important control for tectonic processes at the surface, but also provides fundamental constraints on the budgets of recycled crustal material to the mantle.

The depth reached by a passive margin below the overriding plate before convergence ceases, is
Fig. 1. Map of southeast Indonesia and northwest Australia. Arrows indicate approximate movements of the Indian-Australian and Pacific (Bird's Head) plates relative to the southeast Asia plate. Triangles represent active volcanoes (not shown for Java). Labeled dots indicate locations for which geochemical data on sediment compositions are available (DSDP 261: Cook, 1974; ODP 765: Plank and Ludden, 1992; 1: Ben Othman et al., 1989, DSDP 262 and SN: Vroon, 1992). Tectonic features after Hamilton (1979).
difficult to assess, given the general complexity of collision settings. The discovery of coesite-bearing assemblages in high-pressure metasediments of Alpine regions (Chopin, 1984, 1987; Schreyer et al., 1987) supports the idea that continental crust can be subducted to at least 100 km depth. Physical properties of the subducting slab are not necessarily prohibitive (Molnar and Gray, 1979; Van den Beukel, 1992), and evidence for the presence of continental crust at depths of more than 150 km has been obtained from seismic velocities in the Pamir–Hindu Kush region (Roecker, 1982).

Here we use geochemical signatures of volcanic arc rocks to address the problem of passive margin subduction beneath the Indonesian East Sunda–Banda Arc, which is in collision with the northern margin of the Australian continent (Hamilton, 1979). Isotopic studies have demonstrated the involvement of subducted sedimentary/continental material in magma genesis for various parts of the arc (Whitford et al., 1977, 1981; Whitford and Jezek, 1979, 1982; Hilton and Craig, 1989; Stolz et al., 1990; Hilton et al., 1992; Vroon et al., 1992; Van Bergen et al., 1992). This paper compares along-strike variations in magma-source contamination with subduction/collision-related controls governing the supply of “continental” material. From mass-balance considerations it is suggested that a substantial portion of the Australian margin has been subducted to at least the depths of magma generation beneath the volcanic arc, that is > 100 km.

The east-Indonesian collision setting

The Indian–Australian plate approaches the Sunda–Banda Arc, situated on the Eurasian plate, at a velocity of 7–8 cm/yr in a NNE direction (Minster and Jordan, 1978). While oceanic lithosphere subducts beneath the arc along the Sunda Trench, Australian continental crust has entered the subduction region in the eastern part of the Sunda Arc and the Banda Arc (Hamilton, 1979; Fig. 1). The Banda Arc is also enclosed by continental lithosphere to the east, due to the westward movement of the Pacific plate. This interaction between the Eurasian, Indian–Australian and Pacific plates (and associated microcontinents) has resulted in the complex geological pattern in the Banda Sea region (Hamilton, 1979; Silver et al., 1985), and may have caused the strong curvature of the Banda Arc (Katili, 1975). The Banda Sea floor and fore-arc basins are essentially oceanic (Bowin et al., 1980), but the surrounding troughs are underlain by continental crust, which is up to 40 km thick near Timor (Jacobson et al., 1979).

Seismically, the slab of the Indian–Australian plate can be followed down to more than 600 km (Cardwell and Isacks, 1978; McCaffrey, 1988, 1989). It has a steep dip at depths greater than 200 km in the Eastern Sunda Arc (60–70 degrees) and flattens towards the eastern end of the Banda Arc. According to these authors a separate slab enters the Seram Trough with a relatively shallow southwestward dip.

Absence of earthquake foci at relatively shallow depth near Timor, one of the large islands in the non-volcanic outer arc (Fig. 1), coincides with the stretch of the arc where collision probably began first. The exact locus, style and timing of the collision, the distribution of deformation, and hence the extent to which subduction has proceeded after the onset of collision, have been the subject of considerable debate (see Barber, 1981; Charlton et al., 1991). Contrasting views stem from structural interpretations of the complex geology of Timor and other islands in the outer arc, and from marine geological/geophysical observations in the bordering fore-arc basins and troughs. Imbricate or accretionary wedge models are favoured by several authors (e.g., Hamilton, 1979; Silver et al., 1983; Karig et al., 1987), and contrast with overthrust (Carter et al., 1976; Barber et al., 1977; Audley-Charles et al., 1979) and upthrust models (Chamalaun and Grady, 1978). Harris (1991) suggested that much of the controversy can be reconciled when temporal differences in the deformational stages of the structural evolution along the orogen are taken into account. Important factors causing these differences in the East Sunda–SW Banda outer arc are the oblique convergence angle and the presumed outward “bulge” of the original Australian mar-
Fig. 2. Map of the arc-continent collision region in east Indonesia. Oblique lines parallel to plate movement vectors (arrows) are drawn to distinguish the Bali-Sumbawa, Flores-Adonara-Pantar (F-A-P), Alor-Romang (A-R) and southwest Banda Arc (SW B-A) sectors in the volcanic arc, which are approached by different oceanic and continental parts of the Indian-Australian plate in front of the subduction system. The northeast Banda Arc (NE B-A) sector is probably underlain by a separate slab (Cardwell and Isacks, 1978; McCaffrey, 1988), attached to continental lithosphere entering the Seram Trough. Positions of the Australian margin are indicated by heavy dotted lines for the present situation (subducted beneath Timor) and during the initial collision (together with the position of the trough), according to Harris' (1991) interpretation (references to alternative ideas on the timing and nature of collision are given in the text). Major tectonic features and approximate area of the accretionary wedge (grey) after Hamilton (1979) and Silver et al (1983).
gin where Timor is situated now (Fig. 2; cf., Harris, 1991).

Geological arguments against subduction/underthrusting have emphasized the importance of crustal shortening and deformation in the fore-arc, arc and back-arc (e.g., Audley-Charles, 1981), but several observations suggest that the continental crust has reached at least the inner margin of the outer arc (cf. Hamilton, 1979):

1. The strong recent uplift in the outer arc (Chappell and Veeh, 1978; De Smet et al., 1989) which can be interpreted to reflect the presence of buoyant subducted continental material.

2. From seismic evidence McCaffrey et al. (1985) suggested that continental crust could have been subducted down to 150 km.

3. Gravimetric interpretations which point to the presence of subducted continental crust below Timor and the adjacent oceanic Savu Sea, while the presence of thin crust to depths of more than 100 km cannot be excluded (Chamalaun et al., 1976; McBride and Karig, 1987).

4. Geometric considerations based on the convergence rate of 7–8 cm/yr and the time elapsed since the collision started. If this occurred about 3 Myr ago (e.g., Abbott and Chamalaun, 1981), more than 200 km of continental crust could have entered the subduction zone, whereas if collision events began 5 Myr (e.g., Harris, 1991) or even 8 Myr ago (Berry and McDougall, 1986), a much greater length is conceivable (McCaffrey, 1989; and see McCaffrey, 1988 for a discussion of additional mechanisms accommodating (part of) the northward motion of Australia). Charlton et al. (1991) associated the presence of Australian margin sediments on Timor with two periods of collision. During the Late Miocene, the basal Palaeozoic–?Mesozoic parts of distal sequences were added to the collision complex by underplating. Proximal parts of the margin covering continental crust entered the trench during the Early Pliocene collision, as witnessed by exposed frontally accreted and underplated sequences.

5. Detachment of the old oceanic part of the slab from the buoyant continental part (Eva et al., 1988); if the latter had been subducted to a depth of at least some 100 km, rebound forces could explain the rapid recent uplift and extension of the fore arc (Charlton, 1991). Although unequivocal evidence is lacking, several of these points would imply that the continental crust has reached the magma generation zone in some parts of the eastern Sunda and southwestern Banda Arc.

To the west of Timor collisional deformation decreases (Harris, 1991). South of Flores the continental-type Scott Plateau is colliding with the arc. Here the transition occurs from the continental margin to the Jurassic Indian Ocean floor of the Argo Abyssal plane. The oceanic crust becomes younger to the west. South of Bali–Sumbawa, a few hundred meters of pelagic sediments cover the oceanic basement, and an imbricate melange wedge is present along the trench (Hamilton, 1979). Close geological similarities exist between Seram, at the northeastern end of the arc, and Timor (Audley-Charles et al., 1979). According to Hamilton (1979) the geology of Seram can be accounted for largely by subduction of the New Guinea continental shelf.

The East Sunda-Banda volcanic arc

The volcanic Sunda–Banda arc east of Java is constructed on a basement which becomes progressively more oceanic in nature and thinner towards the Banda Sea (Jacobson et al., 1979). The oldest igneous rocks cropping out in the East Sunda Arc and in the extinct sector between the active East Sunda and Banda arcs are Miocene in age (cf. Van Bemmelen, 1949; Katili, 1975; Abbott and Chamalaun, 1981). No such ages are known from the much smaller islands of the volcanically active Banda Arc which probably have a more recent origin. With a few exceptions, the active volcanoes are situated on Wadati-Benioff zone depth contours between 100 and 200 km (Hamilton, 1979). Volcanoes in the Adonara–Pantar sector form an across-arc array (h = 100–250 km) which allows detecting the penetration of continental material from down-dip changes in the contributions of subducted components to magma sources (Hilton et al., 1992). According to the seismic interpretation of McCaffrey (1989).
the volcanoes in the NE Banda sector, are situated on contours of less than 100 km.

Rock types of active and Quaternary volcanoes in the East Sunda–Banda Arc show typical island-arc characteristics. In the Banda Arc they range from low-K tholeiitic in the NE to high-K calcalkaline in the SW (Jezek and Hutchison, 1978; Whitford and Jezek, 1979; Van Bergen et al., 1989; Vroon, 1992). Volcanics of the East Sunda Arc show a large compositional variation (Whitford et al., 1979; Foden and Varne, 1980; Varne and Foden, 1986; Wheller et al., 1987; Stolz et al., 1988, 1990). An exceptional wide range is found in the across-arc array mentioned above: from low-K tholeiitic at the front to ultra-potassic behind the arc (Varekamp et al., 1989; Van Bergen et al., 1992). Acidic intrusives occur on Wetar in the inactive sector, where they are associated with predominantly extrusive and pyroclastic rocks (Van Bemmelen, 1949). The igneous activity lasted from 12 to 3 Myr ago (Abbott and Chamalaun, 1981). It should be noted, however, that dredging has revealed the presence of only 400-kyr-old high-Mg diabase rocks off the north coast of Wetar (Schwartz et al., 1984; Silver et al., 1985). In a puzzling position behind this island, a small active volcanic island (Gunung Api North of Wetar) rises from the 5000-m-deep ocean floor. The depth to the Benioff zone \( h \) is some 400 km, but its relation to the subduction process is not evident (e.g., Silver et al., 1985).

**Magma-source contamination**

The East Sunda–Banda arc is particularly suitable to study contamination of magma sources by subducted material. The transition from an oceanic to a continental character of the subducting plate is coupled with changes in the nature and quantity of sediments that enter the trench along the arc. Moreover, the supply of detrital sediments by the erosion of ancient (Precambrian) rocks of the Australian craton, facilitates detection in the volcanics, given their highly radiogenic Sr and Pb, and unradiogenic Nd isotopic ratios. Absence of continental crust in the overriding plate east of Java minimizes the chance that primary signatures of mantle-derived magmas were modified by contamination at shallow depths. Finally, the spatial distribution of volcanoes is favourable for geometrical considerations based on along- and across arc systematics.

Using isotopic evidence, Whitford and co-workers were the first to point out the differences between the western and eastern parts of the arc system, and proposed that magma sources in the easternmost Sunda Arc and Banda Arc were contaminated by subducted continent-derived material (Whitford and Jezek, 1979, 1982, and references therein). Subsequent work established the view that the Banda Arc is isotopically perhaps the world’s most “continental” island arc (e.g., Magaritz et al., 1978; Morris, 1984; Vroon et al., 1992). Compelling evidence for sediment subduction was recently provided by the along-arc parallelism in isotopic variations of volcanics and sediments in front of the arc (Vroon, 1992; Vroon et al., 1992).

A significant degree of source contamination has also been documented in the easternmost part of the Sunda Arc (Whitford et al., 1977; Stolz et al., 1990; Vroon et al., 1990; Van Bergen...
GEOCHEMICAL AND TECTONIC RELATIONSHIPS IN THE EAST INDONESIAN ARC-CONTINENT COLLISION REGION

Bali-Sumbawa Flores AP Alor-Romang SW-BA S NE-BA

$^{87}Sr / ^{86}Sr$

$^{206}Pb / ^{204}Pb$

$^{208}Pb / ^{204}Pb$

$^{143}Nd / ^{144}Nd$

Rc / Ra

Distance along arc (km)
accr. wedge volume (km³/km of trench)

arc trench gap (km)

$^{206}\text{Pb}/^{204}\text{Pb}$ sediments

sediment thickness (km)

crust thickness (km)

stress ($\sigma_\perp$) Ind.-Austr. plate (Kbar)

Distance along trench (km)
et al., 1992). Further west, the situation is less unambiguous. For the Bali–Sumbawa part of the arc, situated outside the collision area, arguments against contributions from recently subducted upper-crustal sialic material have been discussed by Varnes and Foden (1986) and Wheller et al. (1987). Based on the systematic deviation of several isotope systems from mantle values, and on analogies with the more eastern parts of the arc, we believe that recent source contamination cannot be ruled out. It should be noted, however, that the involvement of different mantle components in the East Sunda Arc, probably including an enriched type (e.g., Stolz et al., 1990), poses limits on the detection of small amounts of sediments.

Along-arc systematics

A large data set on volcanics and sediments is currently available (see Fig. 3 for references), which allows evaluating along-arc systematics from Bali to the NE Banda Arc for various isotope systems in considerable detail. For convenience, we distinguish a number of sectors which roughly coincide with changes in nature and volume of sedimentary/continental material currently present in front of the arc, or with changes in the extent to which collision has proceeded; from west to east: Bali–Sumbawa (B-F), Flores (F), Adonara–Pantar (A-P), Alor–Romang (A-R), SW Banda Arc (SW BA), central Banda Arc and NE Banda Arc (NE BA). Each sector contains a number of active volcanoes, except for the Alor–Romang sector, where volcanism is probably extinct since 3 Ma, the youngest age of dated rocks from Wetar (Abbott and Chamalaun, 1981).

The variations in isotope ratios of the sectors along the volcanic arc are shown in Figure 3, and can be compared with changes in relevant sedimentary and geophysical parameters along the trench in Figure 4. The Sr, Nd, Pb, He isotope ratios show a roughly symmetrical pattern with the most extreme values near the extinct Alor–Romang sector. Here $^{87}\text{Sr}/^{86}\text{Sr}$, $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ reach the highest values and decrease on both sides, while $^{143}\text{Nd}/^{144}\text{Nd}$ and $^{3}\text{He}/^{4}\text{He}$ are lowest and increase on both sides. These isotopic systematics indicate maximum deviations from uncontaminated mantle values near Timor, and are consistent with a progressively increasing role of subducted continental material in magma genesis towards the extinct sector. The following additional observations are worthwhile to note:

1. The extinct sector shows a wide range in isotopic signatures (Whitford et al., 1977; McCulloch et al., 1982; Hoogewerff and Vroon, unpubl. data), which encompasses much of the variation in the other sectors of the East Sunda and Banda Arcs. The data from the latter are from active and Quaternary volcanoes only, while the range in the extinct sector might reflect changes in subduction-related controls with time, in view of the up to 12-Myr-old ages (Abbott and Chamalaun, 1981).

2. The volcanics at the eastern end of the Banda Arc do not fall back to the “least contaminated” values of the Bali–Sumbawa sector in the East Sunda Arc.

3. Assimilation of arc crustal material in the SW and central Banda–Arc sectors may have modified Sr- and Nd isotope signatures obtained at greater depth to some extent, but cannot explain the overall “continental” compositions nor a slight deviation from the along-arc trends in the central sector (Vroon et al., 1992).

4. Some of the variations within individual active sectors can be attributed to across-arc effects. For example, volcanoes in the Adonara–Pantar sector show a trend of increasing $^{3}\text{He}/^{4}\text{He}$.
away from the trench, which can be explained by
deviations from uncontaminated mantle values in
the Banda Arc and easternmost sectors of
the active Sunda Arc (e.g., Stolz et al., 1990;
Vroon et al., 1992). Changes in quantity seem
the most obvious explanation for the overall along-arc
trend. However, variations in the isotopic signa-
tures of co-eval volcanics along an arc-continent
collision zone may also be caused by changes in
the composition of subducted sediments. Hypo-
thetically, this can be predicted when the sedi-
ments display:

(a) Lateral compositional variations, which
may be controlled by the provenance of clastic
terrigenous material supplied by erosion, or by
variations in the relative amounts of terrigenous
and biogenic fractions.

(b) Vertical compositional variations, com-
bined with along-arc changes in subduction/collis-
ion-related controls (e.g., frontal accretion,
underplating, delamination) determining how “in-
complete” stratigraphic sequences arrive at mag-
ma source regions.

(c) Compositional variations with distance to
the passive margin (e.g., differences between
shelf, slope and rise facies), combined with along-
arc temporal variations for each sediment facies
to become involved in magma genesis.

All three options may be applicable in the East
Sunda–Banda Arc. Lateral changes in sediment
compositions (a) have been documented, but can-
not account for the isotopic variations alone
(Vroon, 1992; and see below). Options (b) and
(c), which require an oblique convergence or ir-
regularities in the geometry of the continental
margin (outward bulges, embayments) and/or of
the arc (e.g., strong curvature) prior to collision,
are potentially valid as well, but are more difficult
to verify.

Alternative explanations for the isotopic varia-
tion could be inhomogeneity of the mantle com-
ponent, or assimilation of arc crust material by
magmas en route to the surface. Involvement of
different mantle components in the East Sunda-Banda Arc is likely (e.g., Wheller et al., 1987; Stolz et al., 1990; Vroon et al., 1992; Van Bergen et al., 1992), but the strong contrast between sedimentary/continental material and most mantle types in terms of Sr, Nd, Pb contents and isotope ratios makes magma signatures more susceptible to the subducted component. It would further be very coincidental if the along-arc changes in uncontaminated sub-arc mantle would independently follow the same trend as the tectonically controlled supply of sedimentary/continental material approaching the arc. Assimilation at shallow levels is visible in some of the Banda Arc volcanoes, but its effect seems less important than source contamination (Vroon et al., 1992).

**Subducted continental crust or continent-derived sediments?**

\[ ^{143}\text{Nd} / ^{144}\text{Nd} - ^{206}\text{Pb} / ^{204}\text{Pb} \text{ bulk mixing models and estimates of sediment fluxes} \]

The contaminating components involved in magma genesis must originate from the passive margin of the NW Australian continent, which formed by rifting during the Middle–Late Jurassic and subsequent ocean floor spreading in the adjacent parts of the NE Indian Ocean (Veevers and Heirtzler, 1974; Larson, 1975). Precambrian basement rock is thought to underlay pre- and post-rift sediment sequences of the outer slope of the Timor Trough. Pre-rift sediments, found in grabens running roughly parallel to the present margin, include Cambrian to Jurassic sequences rich in siliciclastics. Post-rift sequences are up to 1500-m-thick distal slope and rise facies chalks of Late Cretaceous–Pliocene age, and up to 4000-m-thick shelf sediments consisting of Cretaceous sandstone and shale which are covered by Cenozoic carbonates (Powell, 1982; Von Rad and Exxon, 1983).

Using Sr-Nd-Pb isotope and trace-element compositions it is difficult to assess whether subducted continent-derived sediments covering oceanic lithosphere or continental crust contributes to magma genesis. It has been shown that the terrigenous fraction of sediments of the Australian shelf around the Banda Sea (Vroon, 1992) and in ODP core 765 (Plank and Ludden, 1992) is compositionally close to average Australian upper crust. The following mass-balance considerations provide constraints on the amount of continental material that must have been subducted. The approach is based on the requisite that estimated volumes of sedimentary/continental material which contributed to the formation of the arc crust through magmatic recycling correspond to minimum volumes of material that must have been supplied to the trench. We assume that sediments of the Argo Abyssal Plain, the Scott Plateau and the adjacent shelf are volumetrically and compositionally equivalent to the sediments of the leading ocean floor and portions of the margin that have entered the subduction/collision zone to the north. From a comparison between the thicknesses of these sediments and the calculated minimum thicknesses of subducted material required to generate the isotopic signatures of the arc volcanics, it can be inferred how much of the continental margin has been subducted.

Time-averaged minimum thicknesses of the sedimentary/continental sequence that has reached magma source regions in the distinct arc sectors were estimated as follows (cf.. White and Dupré, 1986). We first calculated the total volume of contaminated mantle source from which the total volume of the arc crust has originated since the onset of volcanism. The arc-crust was assumed to consist entirely of volcano-plutonic complexes with a total volume twice that of the volume above the sea floor. A melting percentage of 10% was adopted, based on trace-element models for magma genesis in the Banda Arc (Vroon, 1992). Subsequently, the share of Subducted Continental Material (SCM) in this volume was calculated from \[ ^{143}\text{Nd} / ^{144}\text{Nd} - ^{206}\text{Pb} / ^{204}\text{Pb} \text{ bulk-mixing models for source contamination, assuming that the density of the mantle is twice that of SCM. Finally, the SCM volume was converted to an average thickness, depending upon the convergence rate, the period of subduction during which the arc sector was built (approximate age of the sector), and the length along...} \]
TABLE 1
Sediment and mantle compositions used as end members in $^{143}$Nd/$^{144}$Nd-$^{208}$Pb/$^{204}$Pb mixing models of Fig. 5. For the Bali-Sumbawa sector, values are based on averaged compositions of pelagic sediments from Ben Othman et al. (1989). Other isotopic data for sediments are based on DSDP262 (average of five samples for Flores and A-P; one selected sample for A-R), SN3 (one selected sample for SW BA) and SN1 (average of 5 samples) from Vroon (1992). Concentrations of Pb and Nd were calculated on a carbonate-free average of SN1-2-3 and DSDP262 sediments, and represent values of the continental crust. MORB-source mantle is a local mantle composition, taken from Vroon (1992) who used isotopic data from Morris et al. (1984).

<table>
<thead>
<tr>
<th>Sediments</th>
<th>$^{206}$Pb/$^{204}$Pb</th>
<th>$^{143}$Nd/$^{144}$Nd</th>
<th>Pb (ppm)</th>
<th>Nd (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bali-Sumbawa</td>
<td>18.84</td>
<td>0.51226</td>
<td>37</td>
<td>48</td>
</tr>
<tr>
<td>Flores</td>
<td>19.04</td>
<td>0.51212</td>
<td>21</td>
<td>27</td>
</tr>
<tr>
<td>Adonara-Pantar</td>
<td>19.04</td>
<td>0.51212</td>
<td>21</td>
<td>27</td>
</tr>
<tr>
<td>Alor-Romang</td>
<td>19.23</td>
<td>0.51200</td>
<td>21</td>
<td>27</td>
</tr>
<tr>
<td>SW Banda Arc</td>
<td>19.57</td>
<td>0.51195</td>
<td>21</td>
<td>27</td>
</tr>
<tr>
<td>NE Banda Arc</td>
<td>18.75</td>
<td>0.51219</td>
<td>21</td>
<td>27</td>
</tr>
<tr>
<td>MORB-source mantle</td>
<td>18.28</td>
<td>0.51297</td>
<td>0.03</td>
<td>0.73</td>
</tr>
</tbody>
</table>

the trench over which SCM was subducted. Convergence rates used are 20 km/Myr for the NE Banda Arc sector, derived from a discussion in McCaffrey and Abers (1991), and 75 km/Myr for the other sectors (Minster and Jordan, 1978).

Results of the source-mixing models from Nd-Pb isotopes, based on end-member compositions of Table 1, are illustrated in Figure 5. An important point to note is that isotopic variation in the sedimentary end member has to be invoked in order to model the volcanics along the entire East Sunda-Banda arc (cf. Ben Othman et al., 1989; Vroon et al., 1992). The shift in isotopic compositions of the volcanics corresponds with that of the sediments entering the trench, which is considered as compelling evidence for source contamination by recent subduction. White and Dupré (1986) documented a similar relation for the Lesser Antilles. According to Vroon (1992) the variations along the Banda Arc reflect differences in provenance of detrital components from Australia and New Guinea. Sediments at ODP site 765 in the Argo Abyssal Plain still contain detrital Australian components (Plank and Ludden, 1992), but in general the distal end of clastic deposits, derived from the NW Australian margin, remains relatively close to the continental slope (Hamilton, 1979). The mixing models further indicate an increasing contribution of sedimentary material in the direction of the inactive sector, which is consistent with evidence from the other isotopic systems shown in Figure 3. Acidic rocks from Wetar in the Alor-Romang sector have isotopic compositions falling in the sediment field, which suggests that they may represent almost pure SCM melts.

The calculated average thicknesses of SCM and of the Total volume of Sedimentary Material (TSM) fluxed into the trench (contributing to SCM and the formation of the accretionary wedge) are given in Table 2 and are schematically illustrated in Figure 6. In the absence of suffi-
GEOCHEMICAL AND TECTONIC RELATIONSHIPS IN THE EAST INDONESIAN ARC–CONTINENT COLLISION REGION
cient chronological constraints, different ages for each sector were assumed. The older ages are preferred for the western sectors and the younger for the eastern sectors (Van Bemmelen, 1949, Katili, 1975). Taking uncertainties into account, the calculated thicknesses serve to assess which portions of the margin have subducted to depths greater than 100 km, corresponding to the front of the volcanic arc.

For this purpose, a comparison is made with the sediment sequences covering the oceanic crust of the Argo Abyssal Plain in front of the trench just west of the collision zone, which are 500–900 m thick (DSDP Site 261, Veevers et al., 1974; ODP Site 765, Gradstein et al., 1992; Dumoulin and Bown, 1992). Lithologies are diverse, but a reasonable estimate of maximum thicknesses of the continent-derived fraction is some 400 m, the

<table>
<thead>
<tr>
<th>Sector</th>
<th>Length along trench (km)</th>
<th>Wedge volume (km³)</th>
<th>Wedge volume (km³/trench km)</th>
<th>Arc volume (km³)</th>
<th>% SCM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bali–Sumbawa</td>
<td>520</td>
<td>85000</td>
<td>163</td>
<td>564000</td>
<td>0.5</td>
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<tr>
<td>Flores</td>
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<td>186000</td>
<td>465</td>
<td>370000</td>
<td>1</td>
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<td>Adonara–Pantar</td>
<td>205</td>
<td>137000</td>
<td>668</td>
<td>102000</td>
<td>2</td>
</tr>
<tr>
<td>Alor–Romang</td>
<td>510</td>
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<td>541</td>
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<td>576</td>
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<th>SCM thickness (m)</th>
<th>1 My</th>
<th>5 My</th>
<th>10 My</th>
<th>20 My</th>
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</tr>
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<tr>
<td>Bali–Sumbawa</td>
<td>290 (60–870)</td>
<td>145 (30–435)</td>
<td>70 (15–220)</td>
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<td></td>
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<tr>
<td>Flores</td>
<td>490 (250–1500)</td>
<td>245 (125–745)</td>
<td>120 (60–370)</td>
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<tr>
<td>Adonara–Pantar</td>
<td>530 (270–800)</td>
<td>265 (135–400)</td>
<td>130 (70–200)</td>
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<td>425 (85–8400)</td>
<td>210 (40–4200)</td>
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<tr>
<td>SW Banda arc</td>
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<td>300 (150–370)</td>
<td>150 (75–185)</td>
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<tr>
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<td>480 (50–720)</td>
<td>240 (25–360)</td>
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<th>TSM thickness (m)</th>
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<th>5 My</th>
<th>10 My</th>
<th>20 My</th>
<th>SCM/TSM (x 100)</th>
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<td>360 (250–650)</td>
<td>180 (125–325)</td>
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<td>Flores</td>
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<td>870 (740–1400)</td>
<td>430 (370–680)</td>
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<td>670 (500–4700)</td>
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<td>870 (800–900)</td>
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<td>NE Banda arc</td>
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<td>6200 (5800–6500)</td>
<td>3100 (2900–3250)</td>
<td>8 (1–11)</td>
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average non-carbonate content in the ODP hole being some 60% (Plank and Ludden, 1992). Both sites are situated close to the Scott Plateau, probably already a continental crustal mass where sediment thicknesses rapidly increase (Hamilton, 1979). Thicknesses of pelagic sediments at abyssal depths decrease in westward direction.

This 400 m estimate is close to what can be accounted for by subducted and magmatically recycled continental material alone, in the sectors east of Bali–Sumbawa for ages less than 20 My and more than 1 My (Table 2, Fig. 6). However, the actual thicknesses of sediments fluxed to the trench must have been much greater, considering the additional volumes required to build the wedge system in the same period of time. These average TSM thicknesses are in the order of one to several kilometres, exceeding the 700 m average of the complete DSDP261 and ODP765 sequences. Maximum SCM and TSM values are found for the extinct Alor–Romang sector.

The absolute values of calculated thicknesses should be considered with care, given their sensitivity for several input parameters, but it should be noted that, except for the extreme values, the results listed in Table 2 are conservative estimates for the following reasons:

(a) Volumes lost by erosion of the islands have not been incorporated in the volume estimates for the arc and the emerged parts of the accretionary wedge. Therefore, thicknesses may have been significantly greater than calculated for the sectors near Timor, where uplift rates are high. On the other hand, the volumes of any rock

![Graph](image-url)  
Fig. 6. Schematic illustration of along-arc variations in calculated thicknesses of subducted continental material (SCM) and of the total volumes of sedimentary material (TSM) having entered the trench (see Table 2 for details on calculations, assumptions and comments). Ranges are based on the variation in the inferred contribution of SCM to magma sources in each arc sector. Shown for comparison is the average thickness of DSDP 261 and ODP 765 sediments (Dumoulin and Bown, 1992) which cover oceanic crust (1 = complete sequence; 2 = carbonate-free). Ages were arbitrarily selected in accordance with an eastward decrease. Note that SCM thicknesses east of the Bali–Sumbawa sector are close to (2), but that TSM thicknesses even exceed (1), indicating sediment fluxes to the subduction/collision system which imply involvement of the continental parts of the margin. Extreme thicknesses in the A–R (Alor–Romang) and NE BA (northeast Banda Arc) sectors are probably too large (see text).
types, present in the outer arc for reasons other than accretion, could not be corrected for.

(b) Total volumes of igneous rocks in the arc sectors could be larger than assumed if intrusives in the deeper parts of the arc are more voluminous than the volcanics above the ocean floor.

(c) The unknown amount of subducted material which was not returned to the upper plate but was recycled to the upper mantle, is not accounted for.

(d) The convergence rate of 7.5 cm/yr adopted is probably an upper limit. If it has slowed down since collision(s) started (e.g., by more than half, cf. Hamilton, 1979), sediment thicknesses must have been proportionally larger.

(e) The Australian shelf sediments contain substantial amounts of carbonate. These carbonate sediments are included in the estimates of accreted volumes but not in the SCM estimates, as these were calculated on a carbonate-free basis, and thus yield thicknesses of the detrital continent-derived fraction only. Hence, TSM values lack the possible portion of subducted carbonate.

(f) If a mantle more enriched in incompatible trace-elements than MORB-source mantle is locally involved, the amount of sediment required to generate isotopic shifts by source contamination must be higher (see Vroon et al., 1992).

We conclude, therefore, that the thickness of Argo Abyssal Plain-type sediments is insufficient, and that the subduction of Scott Plateau-type continental crust down to magma-source regions is more likely for the arc sectors in the collision region near Timor. When taking the maximum estimates of SCM and TSM (Table 2), involvement of the shelf may be required.

For the Bali–Sumbawa sector, the estimated total thickness of accreted and subducted sediments is less than 200 m for an age of 20 Myr, which corresponds with the sediments currently covering the ocean floor in front of the trench. For the NE Banda sector, the lower convergence rate and shorter subduction period yield large average SCM thicknesses, despite a lower SCM contribution to magma sources. The calculated TSM thickness is extremely high, but the results are probably biased by an overestimate of the accreted volume, since continental slices, rifted from Australia and New Guinea and tectonically emplaced in this area, may form part of the basement of Seram and other islands in the outer arc (Silver et al., 1985).

Concluding remarks

Acknowledging that uncertainties are inherent to mass-balance approaches of material fluxes at subduction systems, we believe that modelling the SCM flux from isotopic signatures of the East Sunda–Banda Arc magmas yields sufficiently robust results to pose constraints on the subduction of continental margin material. The magmatic signals not only correspond to the large-scale along-arc change from an oceanic to a continental supply to the trench, but also tend to follow the geometry of the margin on the scale of 200–500-km-long arc sectors.

Sediment fluxes in East Indonesia are larger than in the Lesser Antilles, where subduction of approximately 90-m-thick sediments would be required to account for about 1% contamination in the arc magmas, while some 250 m is being underthrust beneath the large Barbados Ridge accretionary prism (White and Dupré, 1986). Within-section decollements above the igneous basement confirm that portions of non-accreting sediment may bypass this prism (Von Huene and Scholl, 1991, and references therein) and reach deep levels in the upper mantle.

Charlton et al. (1991) have suggested that the basal decollement of the Timor fold belt is underlain by Pre-Permian rocks, and that the prism above the decollement for a large part consists of underplated Permo-Triassic sequences and Jurassic–Neogene frontally accreted material. The SCM in the region of the inactive sector may thus consist of Palaeozoic sediments or even older (Precambrian?) crystalline basement.

Accretion of the younger sediments, which on average contain more carbonate than the older sequences, may explain why volcanic gases in the SW Banda Arc and easternmost Sunda Arc do not contain anomalously high CO₂ contents, despite the amount of sediment involved in magma genesis. CO₂/³He ratios do not deviate signifi-
cantly from other island arcs, while the carbon isotope signatures are probably not sufficiently sensitive to detect subducted carbonate (Poorter et al., 1991; Varekamp et al., 1992; Van Bergen, 1992).

Supporting evidence for this mechanism is provided by $^{10}$Be data of volcanics from Java and Bali. This isotope is a powerful tracer to detect recently subducted young sediments, but there is a lack of $^{10}$Be enrichment in the volcanics along the Sunda trench (Tera et al., 1986) despite the evidence for sediment subduction from Pb isotopes (Whitford and Jezek, 1982; Fig. 5). As Plank and Ludden (1992) have pointed out, this may be due to the fact that only sediments older than Neogene (in which any $^{10}$Be must have decayed) are being subducted.

This effect of combined off-scraping and subduction is feasible along the entire length of the Sunda-Banda Arc, given its accretionary-wedge forming character (Von Huene and Scholl, 1991). According to these authors 20–30% of sediments entering subduction zones with accretionary prisms is frontally accreted, whereas the remaining 70–80% subducts and may either underplate older parts of the prism or bypass it entirely. Our crude estimates for the Bali-Sumbawa sector suggest that the volume fraction of bypassed sediments (carbonate-free) returned to the arc crust (SCM) is some 40% of the total sediment influx (Table 2), assuming the latter to be the sum of the accreted volume and SCM. The SCM share in the total volume tends to decrease eastward, which seems consistent with the structural change towards the collision regime (cf., Harris, 1991).

The inferred subduction of continental crust agrees with He isotope results (Hilton et al., 1992) and trace-gas compositions of fumaroles (Poorter et al., 1991) of the Eastern Sunda and Banda Arcs. Hilton et al. (1992) explained the unusually low $^{3}$He/$^{4}$He ratios of the volcanics in the Adonara-Pantar sector by the degassing of the subducted continental crust, since fine-grained sediments are probably not capable of retaining sufficient helium after entering the subduction zone. The $^{3}$He/$^{4}$He ratio increases in the Banda Arc but remains lower than is common in island arcs, whereas to the west the first “normal” values are found in the Bali-Sumbawa sector (Hilton and Craig, 1989), apparently after crossing the transition to the oceanic environment. In the Adonara-Pantar sector, the $^{3}$He/$^{4}$He ratios increase from extremely radiogenic values in the south to higher values in the north. Still, they remain relatively low as far as Batu Tara, an ultrapotassic volcano situated behind the arc. Using the Wadati-Benioff zone depth contours of Hamilton (1979), this may imply that pieces of solid crystalline crust have been subducted down to about 250 km. From seismological evidence for slab pull forces in this area (Spence, 1986), it can be speculated that the down-dip leading portion of old oceanic crust has facilitated the penetration of relatively buoyant continental material into the mantle. Indications for slab detachment (Charlton, 1991) would imply that the limits of margin subduction have been reached.

The significant volumes of subducted continental material, inferred to have reached the magma sources in the volcanic arc, support the view (e.g., Betti and McDougall, 1986) that collision(s) near Timor started before, rather than during the Pliocene. Potentially, the timing of collision(s) and the kinematics of the Australian margin subduction can be further constrained by detailed studies of the older rocks in the East Sunda Banda volcanic arc, which focus on changes in isotopic signals of subducted continental material with time.

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References


