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Lithosphere structure and dynamics of the Banda Arc collision zone, Eastern Indonesia

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Abstract: Timor and adjacent islands in Eastern Indonesia are the site of a currently active collision between the Australian continental shelf and the volcanic islands of the Banda Arc. Previously published sedimentological and micro-paleontological data from the islands and the subduction trench date the start of this collision at 2.5 to 3 Ma. Previously published work on seismicity in the Banda Arc shows the geometry of the subduction zone to be fairly simple and continuous down to below 650 km depth. In this paper, the geometry of both the top and bottom surfaces of the subducting slab is mapped to a higher degree of accuracy than before. The edge of Australia, which was previously a rifted passive margin, is shown to be markedly thickened in the collision zone itself and has been subducted to a depth of about 200 km. In addition, it appears that the subduction zone has major lateral and vertical discontinuities at depth. It is proposed that these discontinuities reflect slab separation during a previous micro-continental collisional event some 10 to 7 million years ago and that this collision was related to the transfer of continental lithosphere from the Indo-Australian plate to the South East Asian plate.

INTRODUCTION

One of the more fundamental geological problems being addressed by current research is to discover how collisional mountain ranges are constructed. Understanding is hampered by both the geographical remoteness and structural complexity of some of the areas under study. Another approach to the problem is to study a young, active collision zone which has not yet developed to the same degree of complication as a mature mountain range. The Banda Arc in Eastern Indonesia is, arguably, the youngest mountain belt in the world. A collision is presently underway between the northern edge of the Australian continent and the volcanic islands of the Banda Arc (Fig. 1). The collision has progressed to a stage such that a "collision complex" has been built up parallel to and just south of the volcanic arc. The higher parts of the collision complex have risen above sea level to form the islands of Sumba, Timor, Tanimbar and a string of smaller islands.

Timor is the largest island of the chain and it is here that geological research has been historically focused since the late 1800s. The age of onset of this collision has been derived by many workers using a variety of types of evidence at 2 to 3 million years ago in the region of Timor, (Johnston and Bowin, 1981; De Smet *et al.*, 1990; Harris, 1992). The rocks of Timor have traditionally been split into six groups (Audley-Charles, 1968; Barber, 1981; Charlton *et al.*, 1991). The "para-autochthon" forms the core of the island and consists of unmetamorphosed to high grade metamorphosed sedimentary material which has been interpreted as being underplated Late Palaeozoic to Early Mesozoic Australian-derived rocks. The "allochthon" is made up of ultrabasic rocks with some metamorphosed sedimentary cover. This unit has a "tectonic" relationship with the "para-autochthon" and was traditionally regarded as being derived from the Asian plate forearc region, (Barber and Audley-Charles, 1976). However, Sopaheluwakan (1990) has good evidence that the unit was metamorphosed during a period of intra-oceanic thrusting near a spreading centre and was subsequently emplaced against the "para-autochthon" in a collisional event around 38 million years ago. The rocks of the "autochthon" consist of unmetamorphosed Mesozoic to Recent sediments that have been accreted to the southern side of the developing orogen. The remaining three groups are mud diapir deposits, raised reef terraces and Recent alluvium.

SEISMOLOGICAL DATA

Earthquakes are one of the main sources of information on the large-scale structure and dynamics of tectonically active areas and it is with
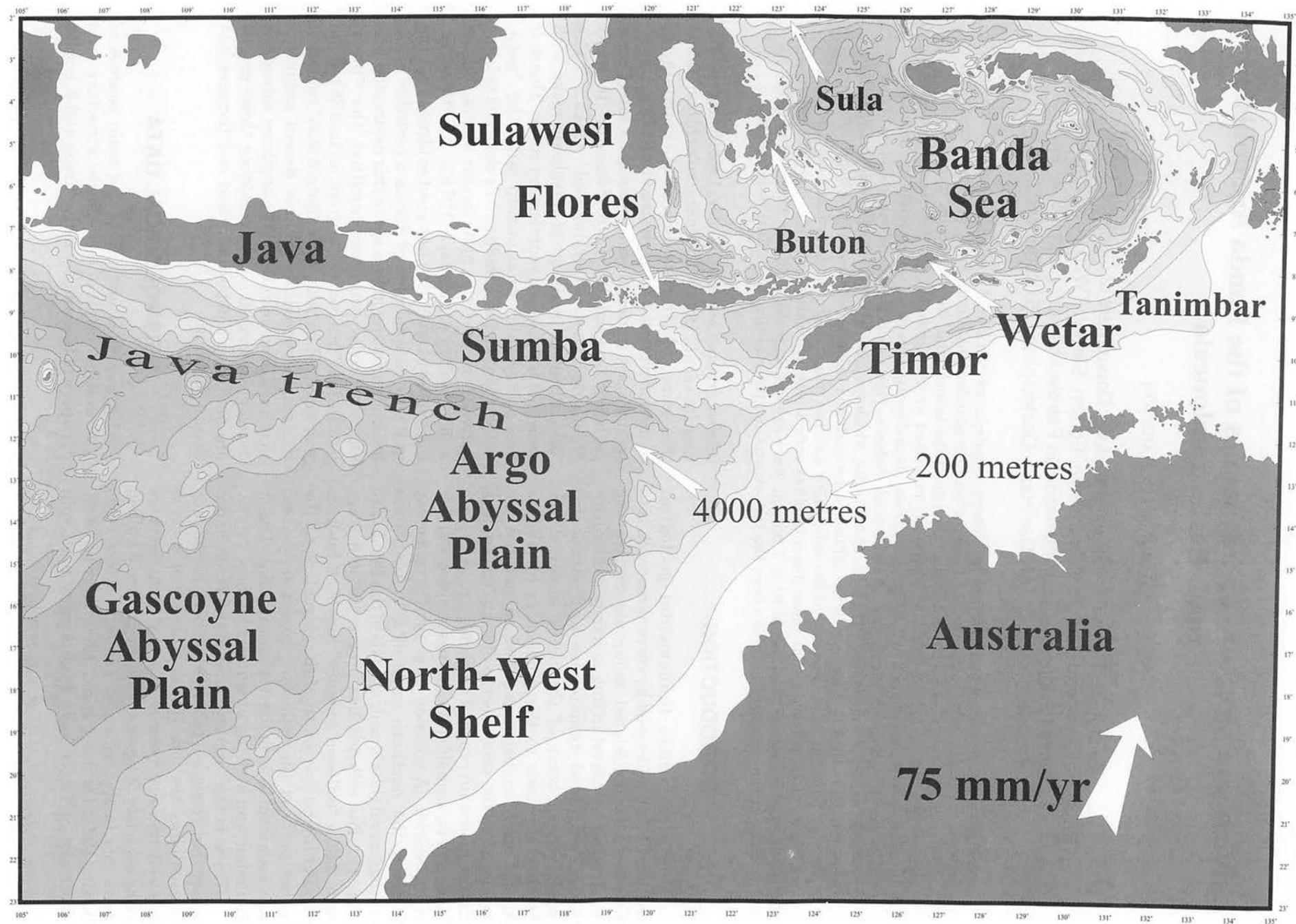
Figure 1. Location map of Eastern Indonesia.

these data that this paper is largely concerned. This part of Indonesia is one of the most seismically active areas in the world. The International Seismological Centre (ISC) currently records about 5 earthquakes per week within the area of the map in Figure 1. A number of papers have already been published about the seismicity of the Banda Arc area (Fitch and Molnar, 1970; Cardwell and Isacks, 1978; Hamilton, 1979; McCaffrey et al., 1985; Eva et al., 1988; McCaffrey, 1988, 1989; Ritsema et al., 1989). All of these works regard the geometry of the Wadati-Benioff zone to be a simple concave bowl shape to the east and a steeply dipping single surface to the west penetrating to below 600 km depth; see, for instance, Figure 5 of Cardwell and Isacks (1978). The Wadati-Benioff zone contours in all the above works are only rough approximations through the data at depth intervals of 100 km.

The data set for this study is an extract from the ISC catalogue from 1 January 1964 to 31 August 1988 and the USGS Preliminary Determination of Epicenters Bulletin from 1 September 1988 to 31 December 1991. Also included are earthquakes recorded by temporary regional networks (McCaffrey et al., 1985), giving a total of about 8500 events. Undefined depth events that had been assigned a default depth of 33 km were discarded but all other events down to the smallest recorded magnitudes were retained.

The aim of this work was to create a three-dimensional model of the structure of the lithospheric components of the Banda Arc region. Locations of earthquake hypocentres were initially plotted on maps. The plotted earthquakes were then grouped into horizontal slices 10 km in thickness. The surface curvature of the earth was ignored. The depth error for any given teleseismically located earthquake is of the order of 10-20 km (Dziewonski et al. 1981). The sample group is large enough, however, for the statistical errors to have no impact on the overall distribution of events. With the aid of maps and sections, the outer surfaces of the envelope of active seismicity were contoured by hand with a contour interval of 10 km. The resulting contour maps are rather complicated since, in many regions, the contoured surfaces are almost vertical and the contours lie on top of each other. The results are therefore displayed in isometric view (Figs. 2, 4 and 5). The main assumption implicit for interpretation of these data is that anything within the envelope of active seismicity is lithospheric material while anything outside may be either seismically quiescent lithosphere or asthenosphere material.

INTERPRETATION

The "Top of Envelope" plot (Fig. 2) is interpreted as showing the geometry of the active part of the Wadati-Benioff zone since the top of a subduction slab is relatively cold and brittle. This is in keeping with many other works, for instance those referred to above. The shallow portions (< 200 km depth) to the west and to the east of Timor are seismically very active and define a fairly smooth surface. The high activity in the eastern region is largely due to stresses within the plate near the region of greatest curvature. Most events for which fault plane solutions have been calculated in this region are north-east directed thrusts whose orientation is parallel to the direction of motion of the Australian plate. In contrast, there is little shallow seismic activity under eastern Timor. The probable explanation for this observation is that subduction under eastern Timor has now ceased. Eastern Timor is the location of the highest mountains and has the smallest arc-orogen cross-strike width and is therefore the most developed part of the collision zone. Inactivity of this segment of the subduction zone is in accord with the work of Johnston and Bowin (1981) on sediments in the trench to the south of eastern Timor which indicates that subduction in this region has been inactive for the last 600 000 years. Continuing deformation in this segment of the collision zone is being accommodated by a high rate of uplift (Johnston and Bowin, 1981; Milsom and Audley-Charles 1986; De Smet et al. 1989; De Smet et al.; 1990) and back-arc thrusting north of Alor and Wetar Islands (Nabelek and McCaffrey, 1983; Silver et al., 1983; McCaffrey and Nabelek, 1984, 1986; McCaffrey, 1989).

The deeper portion of the subduction zone is more difficult to contour confidently because of the relative scarcity of events. Nevertheless, it is clear that to the west of Timor, the seismic zone descends vertically to below 650 km depth. To the west of Timor and to the west of Sumba, there appear to be large gaps in the vertical portion of the seismic zone.

There is still great debate about the actual mechanism of deep earthquakes (Davies, 1980; Goto et al., 1985, 1987; Frohlich, 1987). Nevertheless, it appears from hypocentre plots that earthquakes at or near the base of the Australian lithosphere do occur. It is unlikely therefore that they are all spuriously located shallow events. Although the base of a lithospheric slab is hot, its viscosity is still generally considered to be much higher than the convecting asthenosphere underneath. Perhaps
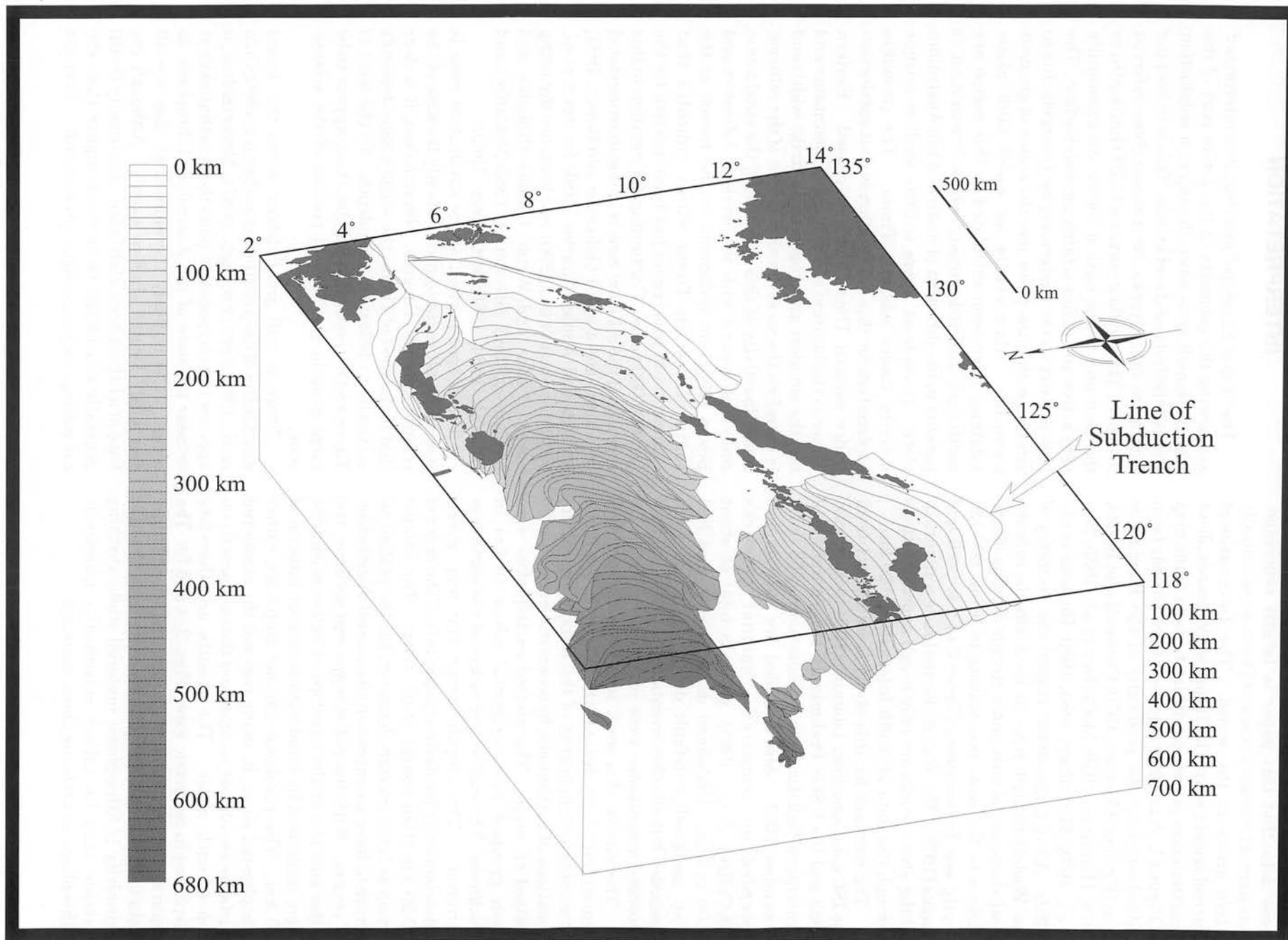
Figure 2. Banda Arc seismic zones: isometric view of the top of the envelope of activity.
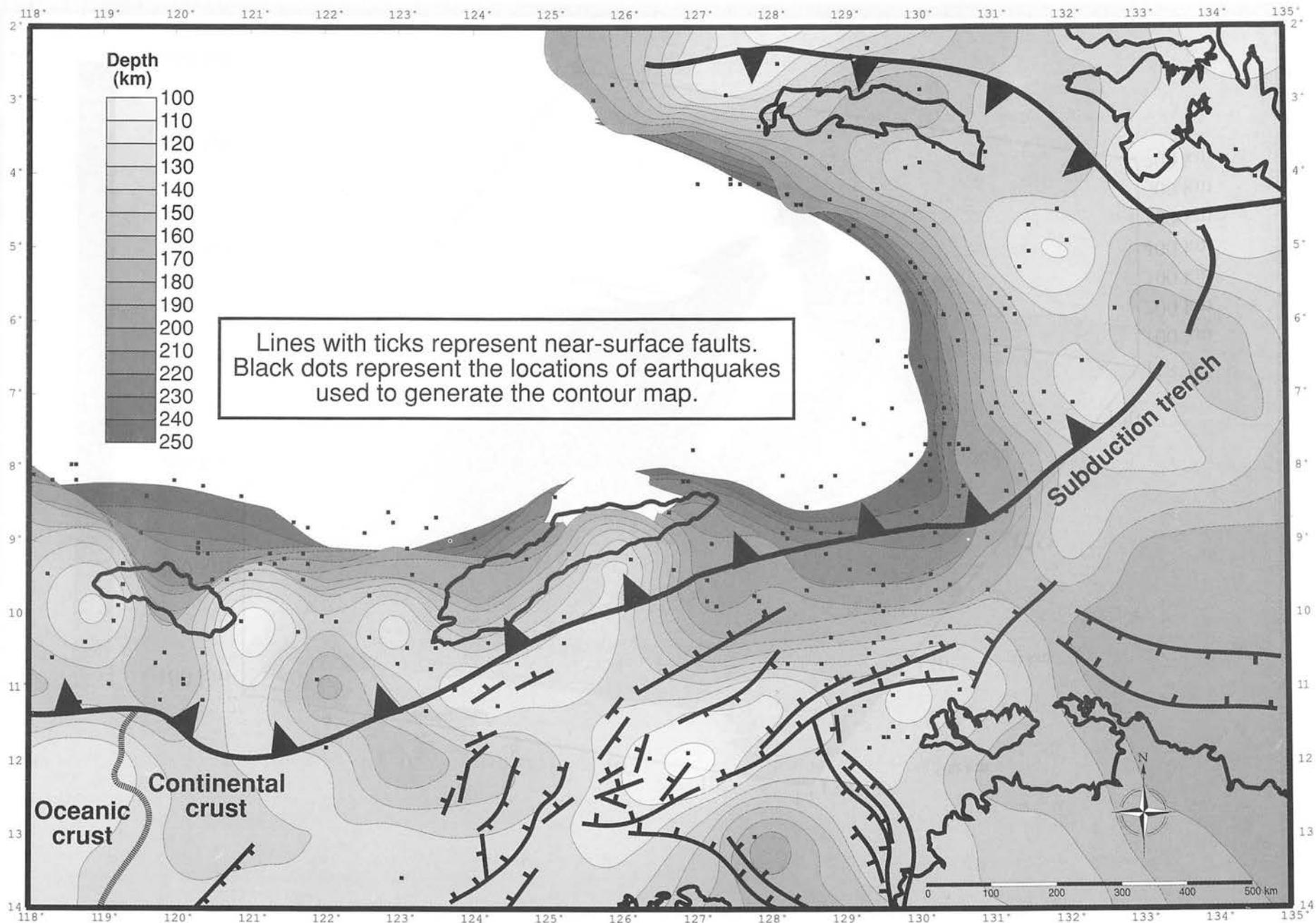
Figure 3. Banda Arc seismic zones: map view of the base of the envelope of activity.
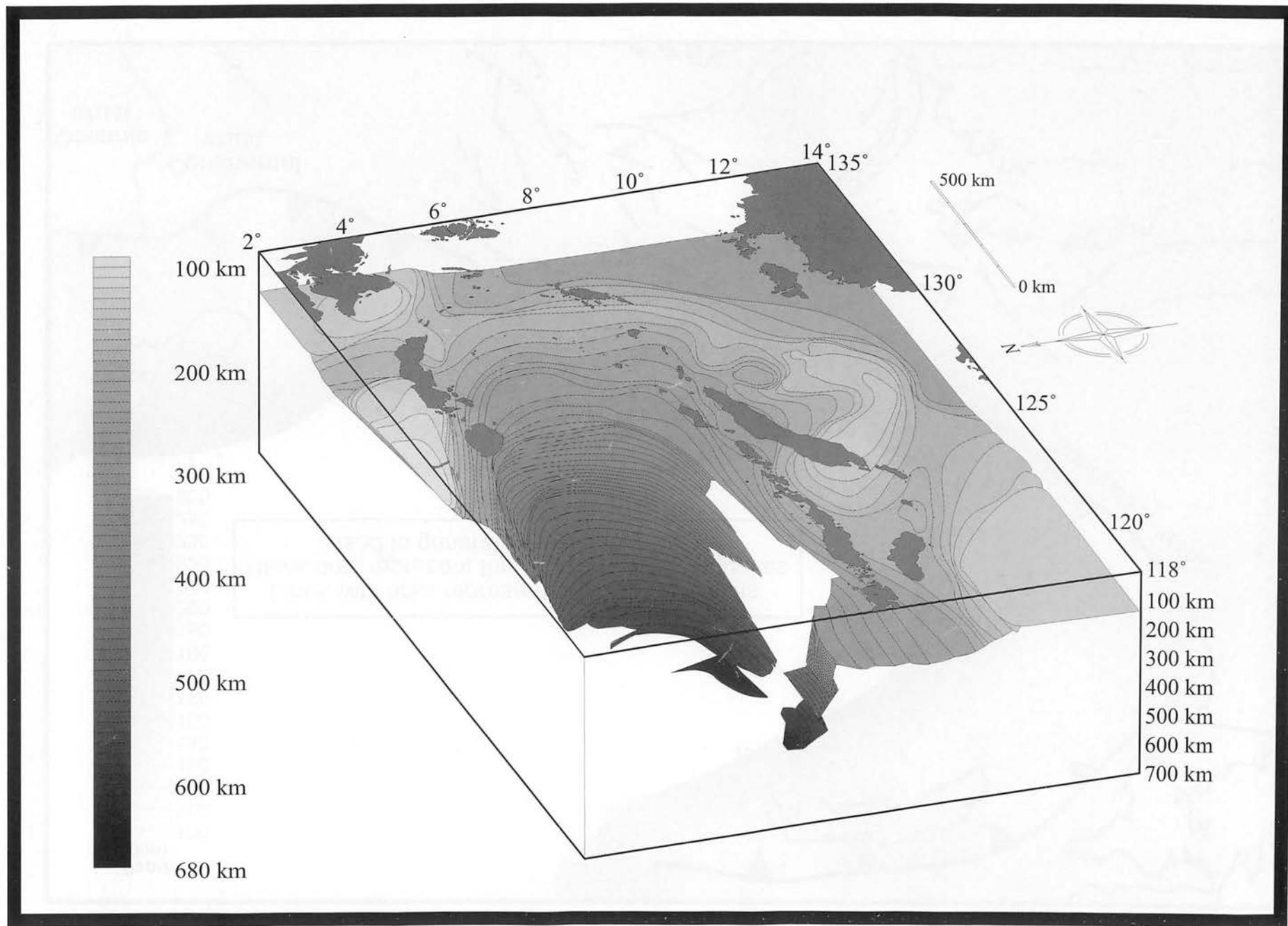
Figure 4. Banda Arc seismic zones: isometric view of the base of the envelope of activity.

these deep events relate to the "plate drag" force often mentioned when plate driving forces are considered (Forsyth and Uyeda, 1975; Chapple and Tullis, 1977). The "Base of Envelope" plot was drawn using the deepest earthquakes only and ignoring shallower ones. Where the subducting slab plunges vertically the "Base of Envelope" contours were drawn using the southernmost events of the seismic zone although they were few and far between. In spite of being derived from far fewer events than the "Top of Envelope" plot, the "Base of Envelope" plot shows some interesting features.

Firstly, the surface is, to the first order, parallel to the surface that represents the top of the lithosphere. Secondly, the surface is much shallower in the south-west corner of the map (Fig. 3) than the south-east. This is consistent with the transition westwards from Archean continental lithosphere to oceanic lithosphere. Thirdly, an L-shaped arch is evident to the south of Timor (Figs. 3 and 4). The eastern leg of this arch is parallel to the pre-existing rifting structures on the Australian North-West Shelf (Mollan et al., 1970). The northern part of this arch strikes normal to the motion of the Australian continent i.e. NNE. Also, the northern end of the arch is located under central Timor where the subduction zone is inactive. Fourthly, the deep gaps in seismicity are more-or-less in the same place as those for the "Top of Envelope" plot (Fig. 5). For these reasons the "Base of Envelope" plot is interpreted tentatively as representing the base of the lithosphere.

DISCUSSION

The existence of gaps in seismicity creates a problem and begs the question: are they real gaps in the subducting slab or merely a seismic portions of a continuous slab? Uncertainty in the density of a slab at this depth makes the errors inherent in gravity studies larger than the actual effect under investigation and therefore unresolvable. The seismic tomography technique could be a future possibility for investigating this type of phenomenon but current global three-dimensional tomographic models do not show structures to the necessary resolution (Dziewonski and Woodhouse, 1987).

Geochemical techniques are the only other way of looking at material from deep in the mantle. The Sunda and Banda volcanic arcs have been bringing this material to the surface for millions of years. Because of their geographical remoteness, there are rather few geochemical data or accurate isotopic dates already acquired from these volcanic islands; certainly not enough to monitor the change in geochemistry of volcanic rocks over the course of the last few million years. A number of studies

have, however, investigated rocks from a few locations and have found some to be anomalous in a number of ways. For example, the high $^{87}Sr/^{86}Sr$ ratios in Recent calk-alkaline lavas from the Banda Arc investigated by Whitford and Jezek (1979) are interpreted to result from mixing of a sialic component with a mantle derived component. The sialic component must come from continental material that has been subducted to a depth of over 100 km. Morris and Hart (1980) looked at lead isotopes in volcanic rocks from the Banda Arc and concluded that they were the most radiogenic of any island arc due to entrainment of continental material. Morris et al. (1984) reported the recovery of 400 000 year old basalt dredged from north of the Wetar thrust to the north of East Timor. These samples also showed high $^{87}Sr/^{86}Sr$ ratios, LIL enrichment and other trace element concentrations similar to those from the southern Banda Arc (Schwartz et al., 1984). Thus it appears that subducted continental material does underlie eastern Timor but that actual subduction in this segment of the collision zone is presently inactive. In contrast, the $^{87}Sr/^{86}Sr$ ratios in lavas presently erupting from the volcanoes Rinjani on Lombok and Tambora on Sumbawa are similar to the lowest derived from the Sunda Arc where purely oceanic lithosphere is currently subducting (Foden and Varne, 1980). Hutchison (1981) noted that the decrease in $^{87}Sr/^{86}Sr$ ratio in volcanic rocks from West Java to Bali suggested an upper plate basement transition from continental to oceanic material.

Foden and Varne (1980, 1981) also studied the geochemistry of volcanic rocks from extinct Miocene to Pliocene rocks of Lombok and Sumbawa. At the time, the only work on the geometry of the Wadati-Benioff zone was that of Fitch and Molnar (1970) and Cardwell and Isacks (1978) showing simple continuous slabs to great depth. In spite of this, Foden and Varne (1980) concluded that *"We must invoke inhomogeneities in the source region to explain mineralogy and chemical composition ... We suggest that LIL-rich (K, Rb, Sr) component is progressively added to the source regions ... If this component occurs deep within the mantle, it might gain passage to shallower regions either by percolating up the down-going slab to yield the familiar arc magma zonation, or up substantial cross-arc fractures."* The "substantial cross-arc fractures" referred to by Foden and Varne could be the large gap in the vertical portion of the subducting slab.

Several authors (Goto et al., 1985) have pointed out that a minimum of seismic activity can be observed between 300 and 350 km depth in "normal" oceanic slabs as they subduct. This is because the
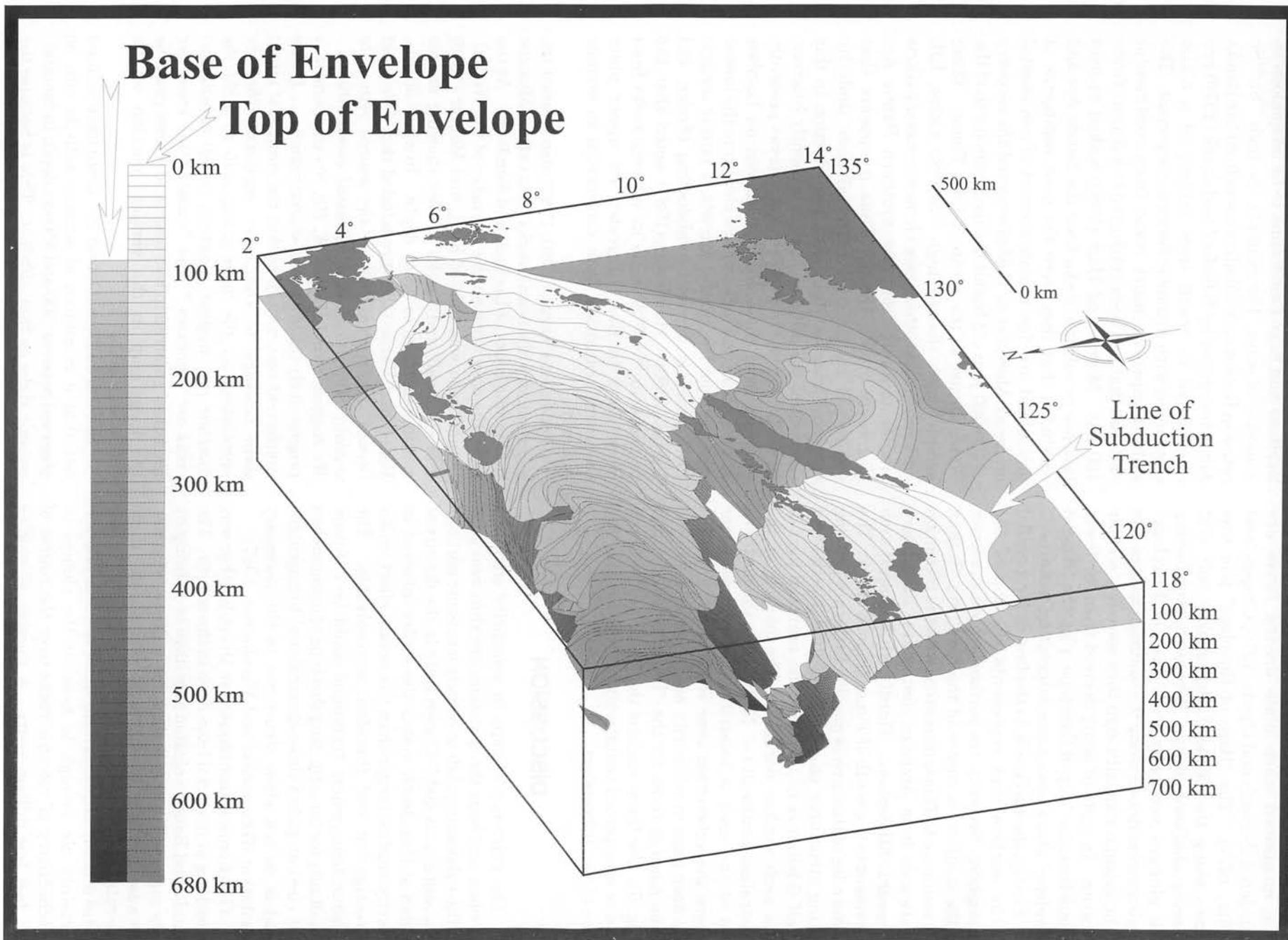
Figure 5. Banda Arc seismic zones: isometric view of the both the top and base of the envelope of activity.

down-dip tension in the upper part of the slab is cancelled out by down-dip compression in the lower part of the slab forming a mid-depth zone of neutral stress. In fact, the slab section at 120.5°E in Figure 6 and other slab sections across the oceanic slab subducting under Java appear (Eva *et al.*, 1988) to be consistent with this. Nevertheless, the seismic zone to the east of Timor is continuous down to 650 km and was, presumably, part of the same slab before subduction. Also, to the west of the gap, at 117°E, the seismic zone is also continuous down to about 650 km depth (Eva *et al.*, 1988). In view of the above evidence, I argue that the gaps in the seismicity genuinely represent asthenosphere filling breaks in the lithospheric slab. The lower portion of the lithospheric slab, below the gap, must have become detached at some time in the past as has been previously proposed by others (Nur and Ben-Avraham, 1982; Price and Audley-Charles, 1987).

Figure 6 shows four vertical sections (located in Fig. 1) drawn across the seismicity envelope contour maps. The surfaces of the deeper portions of the slabs appear rather jagged because they are less well defined. Deviations in the surface with wavelengths less than about 20 km, the average error in teleseismic earthquake depth locations, could justifiably be smoothed out. However, the unsmoothed data are displayed to minimize bias. Note that the top surface of the descending slab appears much smoother in the 125.5°E section than the others. This is because the shallow portion of the Wadati-Benioff zone is inactive in this area and its geometry has been derived by extrapolation. The true geometry is probably more like that at 127.5°E than that at 123.5°E but since there is so little seismic activity, there are no real data to substantiate this claim.

Figure 6 shows marked variations in the thickness of the slabs. The sections clearly show that the Australian continental lithosphere is over 200 km thick under the Archean part of the continent which is consistent with other work (Lerner-Lam and Jordan, 1987). The previously rifted margin of the Australian lithosphere becomes thinner towards the north, to the south of the point of inflection where it plunges down the subduction zone. The sections show the lithosphere becoming thicker towards the north but a sharp decrease in thickness at a depth of about 200 km. These sections cross East Timor which is the site of the highest mountains, the narrowest cross-arc width and is therefore the most mature segment of the collision zone. The sharp decrease in thickness probably denotes the boundary between sinking oceanic
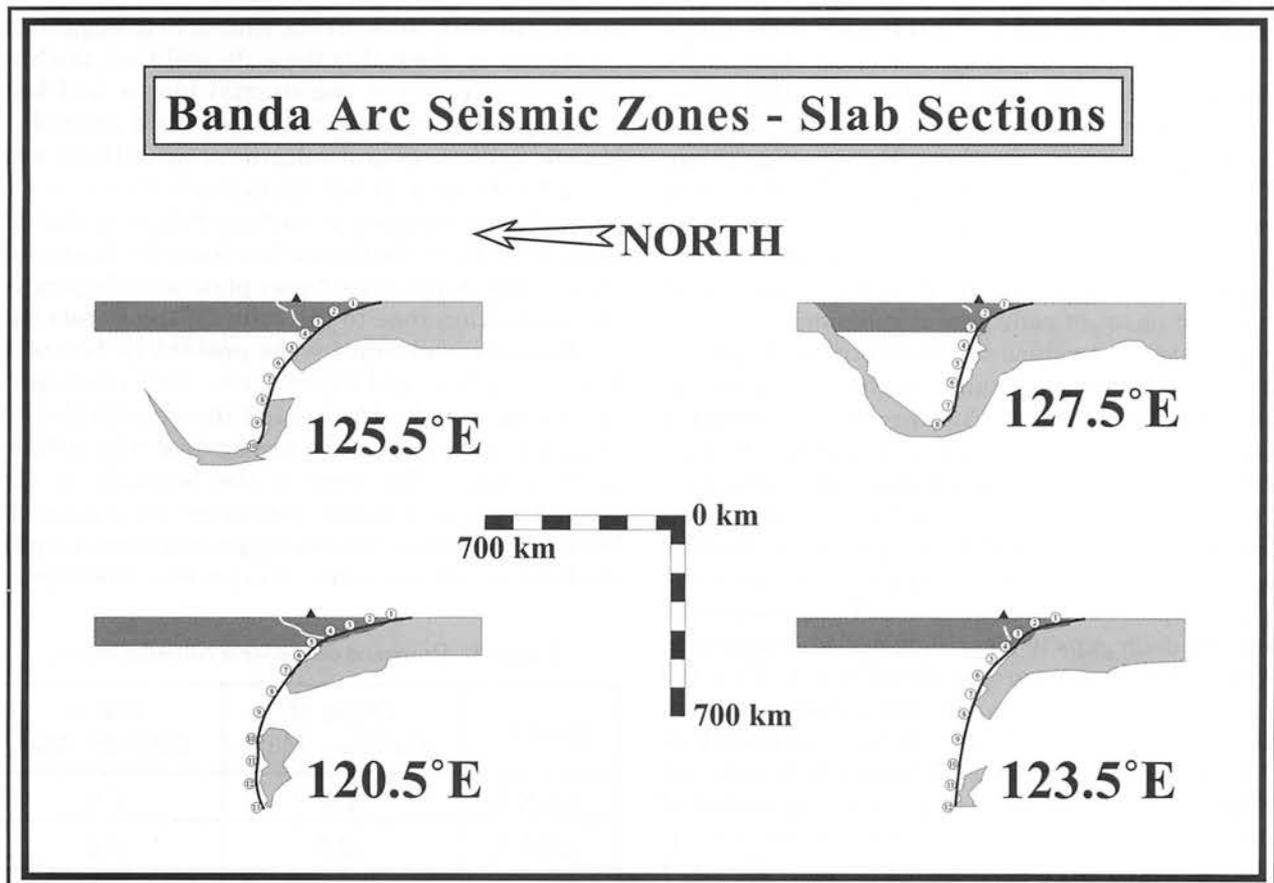

Figure 6. Banda Arc seismic zones: sections through the lithosphere located in Figure 1.

material below and continental material above, which thickens, being too buoyant to be subducted (McKenzie, 1969).

In Figure 6, the numbers in circles represent the time in millions of years since the portion of the slab adjacent to the number entered the subduction zone. The values were derived by calculating the constant plate motion velocity inferred by the magnetic lineations between Australia and Antarctica. Retaining a constant velocity for the slab during and after detachment is undoubtedly a simplification but the values are probably of the right order.

It is presumed that slab detachment results from an event that inhibits subduction such as continental collision where the continental material is too buoyant to subduct (McKenzie, 1969). The oceanic lithosphere that has already subducted is too dense to remain static in the mantle. During the course of a continental collision, therefore, the oceanic slab ahead of the continent continues to sink into the asthenosphere. Thrusting of continental material along the shallow portion of the subduction zone first slows and then disrupts subduction completely. Continued compressive deformation is accommodated by thickening of the continental lithosphere, uplift at the surface and strike-slip expulsion. As it continues to sink, the descending oceanic slab first thins to a narrow neck (Agnon and Eidelman, 1991) and then parts company. An upper mantle section derived by seismic tomography appears to show this same process of thinning and necking of the African plate as it descends under Southern Europe (Spakman, 1990, Fig. 2b). If the "subduction age" of the top of a separated slab can be calculated (that is the time that part of the slab entered the subduction zone) it is possible to obtain an approximate indication of the age of onset of continental collision.

In order to produce the geometry in Figure 6, subduction would have had to begin again after the collision. Mueller and Phillips (1991) concluded that the only forces large enough to initiate subduction were those generated during continental collision. So if after a collisional event subduction then resumes, the "subduction age" of the leading edge of the subducting slab indicates the age of the end of the preceding continental collisional episode. Thus the deep gaps in the subducted slab shown in Figure 6 may be interpreted as in Table 1. That the geometry of the gaps in the lithospheric slabs in this part of the world is therefore envisaged as evidence for a continental collision which occurred in the recent geological past. A short period of subduction resumed before the onset of the current collision which began 2.5 to 3 Ma ago. Figure 7 summarizes this evolution in cartoon form.

Is there any other evidence for a short-lived collision preceding the current one? An extremely detailed study was made by Berry and Grady (1981) of the deformation and metamorphism of the rocks near Dili in Timor (124.5°E). These rocks are traditionally described as the "para-autochthon" and form the core of the island. Using radiometric dating, they concluded that there were two periods of prograde metamorphism; the first probably relating to Mesozoic rifting and the second occurring after 11 Ma ago but which was finished before 6 Ma. These ages fall neatly around the dates proposed above for a collisional event in Table 1.

How does this event tie in with the tectonic scenario of the surrounding region? The most recent interpretations of magnetic anomaly data in the Banda Sea and Argo Abyssal Plain (Powell and Luyendik, 1982; Silver *et al.*, 1985; Fullerton *et al.*, 1989; Prasetyo, 1989, pers. comm.; Hartono, 1990) tend to support the proposal that the Banda Sea was originally continuous with the Argo Abyssal Plain and part of the Indian Ocean on the Australian plate. If this was the case, the Banda Sea must have become detached from the Australian plate by some sort of tectonic event involving a change in location of the subduction zone. Figure 8 is a reconstruction of the position of the Australian plate 11 Ma ago. It is apparent that the magnetic anomalies in the Argo Abyssal Plain come into alignment with those in the Banda Sea, suggesting continuity at about this time. In addition, the Sula Platform and Buton continental blocks had been colliding with eastern Sulawesi since around 15 Ma and collisional and volcanic activity there were at a maximum at 11 Ma (Parkinson, 1991). It was probably the collision at eastern Sulawesi that led to the transfer of the Banda Sea from the Australian plate to the South East Asian plate and the jump of the subduction zone to the south of the Banda Sea.

Intrusive volcanics were present in Wetar 12 Ma ago (Abbott and Chamalaun, 1981) indicating that subduction had begun in this area by this time and that there existed an arc against which Timor could collide. The gaps in the lithospheric slab opened by the collision remained geographically linked to the Timor-Sumba region and hence identify the former collision zone. It is unclear whether the

Table 1: Proposed dates for a collision event.

Section	Onset of Collision (Ma)	End of Collision (Ma)
120.5°E	9.0	7.5
123.5°E	10.0	8.0
125.5°E	8.0	5.5

rest of the late Miocene arc underlies the present day arc or was incorporated into the collision zone. The present day arc consists of only younger rocks at the surface but outcrops of late Miocene volcanics have been noted on both Timor (Abbott and Chamalaun, 1981) and Sumba (Chamalaun *et al.*, 1981). Subduction subsequently resumed along the southern edge of the Banda Sea. Perhaps it is significant that all the volcanic islands to the east of Timor are less than 5 Ma old (Bowin *et al.*, 1980), decrease in size eastwards and were probably only built following the change in location of subduction.

CONCLUSIONS

Evidence presented in this paper suggests that a micro-continental collision took place between 10 and 7 Ma preceding the current collision event. This was the second accretion event of a young mountain belt. The first was the emplacement against the micro-continent of the ultrabasic rocks at 38 Ma in the Eocene. These two units together formed a composite micro-continent trapped within oceanic crust a few hundred km north of the Australian continental margin. It appears that "untidy" rifted continental margins may be very common (Nur and Ben-Avraham, 1982). Similar situations have been documented many times when a continental margin with many inherent weaknesses has rifted to leave a collage of rifts, failed rifts and isolated continental fragments. Analogues in the Circum-Pacific region are the
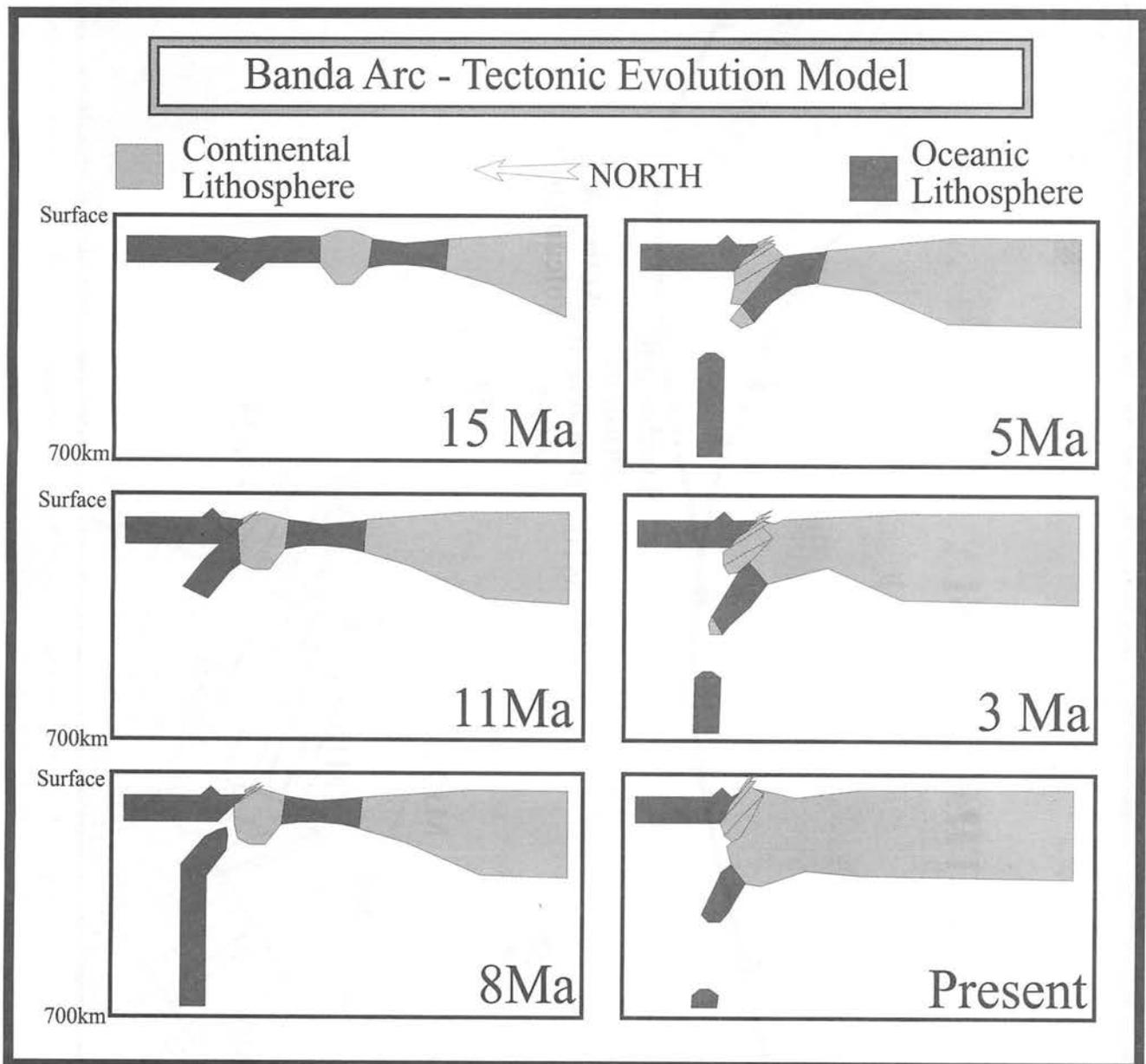

Figure 7. Cartoon of the tectonic development of the Timor region since the mid-Miocene.

SOUTHEAST ASIA

COLLISION

M0 **?**

M8

M10

M14

COLLISION

**Trench Propagates
to East**

**Southward
Jump of
Subduction
Zone**

M10

**Active Arc
Volcanism ?**

?

300+ km

?

?

M10

M0

M10

M16

M22

M25
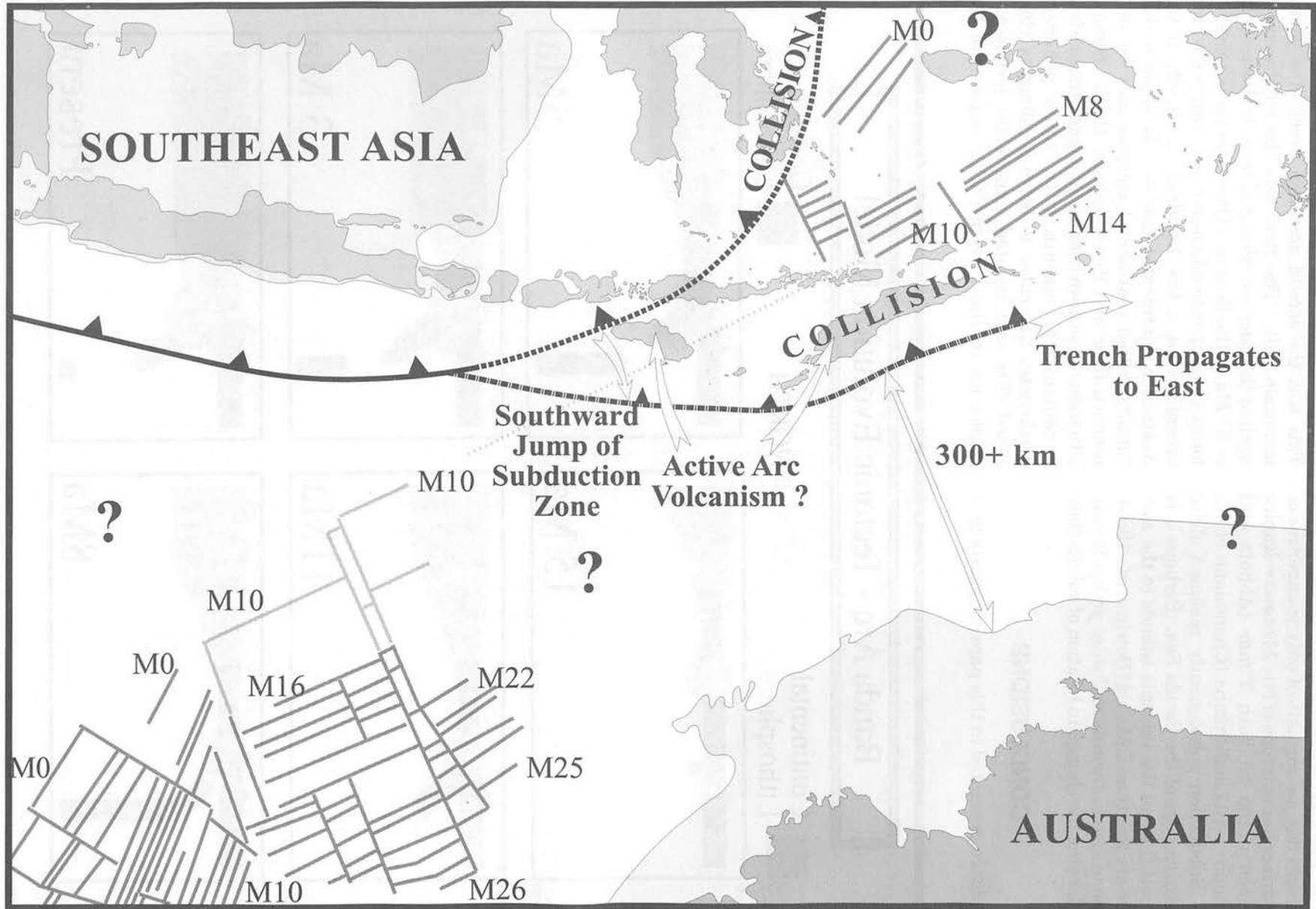
M0

M10

M26

AUSTRALIA

Figure 8. Tectonic reconstruction of Eastern Indonesia about 10 Ma ago. Present day coast-lines are shown for reference only. Magnetic lineations from Hartono (1990).

Yamato bank in the Sea of Japan (Tamaki, 1988) or the Macclesfield Bank in the South China Sea (Taylor and Hayes, 1980). When continental fragments such as these arrive at a subduction zone, collisions take place in discrete steps. Eventually, this ends up as an extremely complicated region of geology such as Alaska (Silver and Smith, 1983) or the Himalayas (Coward *et al.*, 1986). Subduction has now ceased at the narrowest and most uplifted part of the collision zone at eastern Timor. Continued deformation is being transferred to other sites, such as the back-arc region (Silver *et al.*, 1983), that are more favourable for the new stress regime. The entire lithosphere is deformed as the multiple collisions progress.

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