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SEISMOLOGICAL CONSTRAINTS AND SPECULATIONS ON BANDA ARC TECTONICS

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ABSTRACT

Fault plane solutions of shallow earthquakes show that the collision of the Australian continent with the Banda Arc shortens the overriding Indonesian plate in the north-south direction and elongates it in the east-west direction by a combination of strike-slip and thrust faulting. The shallow tectonics and the distribution of deep earthquakes beneath the Banda Basin both indicate that two plates subduct beneath the Banda Arc; the Australia-Indian Ocean plate northward beneath the Java Trench, Timor Trough, and Aru Troughs, and the Bird's Head southwestward beneath the Seram Trough. The slab of the Indian Ocean plate forms a westward plunging synform beneath the Banda Basin. Its unusual shape is interpreted to have been caused by subduction beneath the westward moving Pacific plate which transported slivers of New Guinea into the back arc. The lithosphere of the Bird's Head was subducted beneath the Seram Trough and now reaches 300 km depth. At the surface decoupling between Australian and the Bird's Head probably occurs by left-lateral strike slip at the Tarera-Aiduna fault zone in western Irian Jaya and by convergence in the New Guinea fold-and-thrust belt. Seismic quiescence occurs at depths of 50 to 380 km beneath both Timor and the inactive volcanic arc to its north but the efficient propagation of S-waves through the same volume suggests that the lithospheric slab is continuous there. The lack of seismic and volcanic activity may result from removal of part of the Australian continental crust prior to subduction of the lower part of the lithosphere. This crust was stacked up to form the island of Timor.

1. INTRODUCTION

The active tectonics of the Banda Arc are dominated by the northward motion of the Indian Ocean plate, including the Australian continent, and the westward motion of the Pacific plate, with respect to Southeast Asia. As a result, the region is one of the more seismic on earth. In this report I use the seismicity of the Banda Arc region to infer its active tectonics. Fault plane solutions for earthquakes from 1962 to 1986 are compiled and used to infer the geometry of strain due to collision of the Australian continent with the Banda Arc. The configuration of the subducted lithosphere is inferred from the distribution of better-located intermediate and deep earthquakes from 1964 through 1984. The shape of the subducted lithosphere is then used to place constraints on the history of the Banda Arc collision zone.

2. DEPTHS AND MECHANISMS OF SHALLOW EARTHQUAKES

Fault plane solutions for earthquakes whose published depths are listed as less than 75 km are shown in Fig. 1. Before discussing the events in detail I will comment briefly on the various methods used to constrain their depths and fault plane solutions. The mechanisms and depths of events labeled A and M were estimated by body-waveform inversion (BWI) of teleseismic, long period P- and SH-waves recorded on instruments of the World Wide Standardized Seismograph Network (WWSSN) and Global Digital Seismograph Network (GDSN). WWSSN waveforms place strong constraints on the depths of the earthquakes so that BWI depth uncertainties are typically less than 5 km (*e.g.* Fig. 2). With such accuracy we can confidently separate events that occur within the upper plate from those that occur within the subducting lithosphere. Events labeled H are constrained by the centroid-moment tensor (CMT) method of DZIEWONSKI & WOODHOUSE (1983) using GDSN data. For the purposes of tectonic interpretation, the CMT double-couple mechanisms are reliable —strike, dip, and rake angles for the same events are typically within 10° of the BWI solutions (MCCAFFREY, 1988). For shallow earthquakes, GDSN waveforms are less sensitive than WWSSN waveforms to depth; the CMT depths are systematically deeper (13 $\pm$ 17 km) than the BWI depths so that the uncertainty for shallow H events is on the order of $\pm$ 30 km. Depths of the remaining events (labeled C, F, J, and K) are based on P-wave arrival-times or on pP-P differential times and

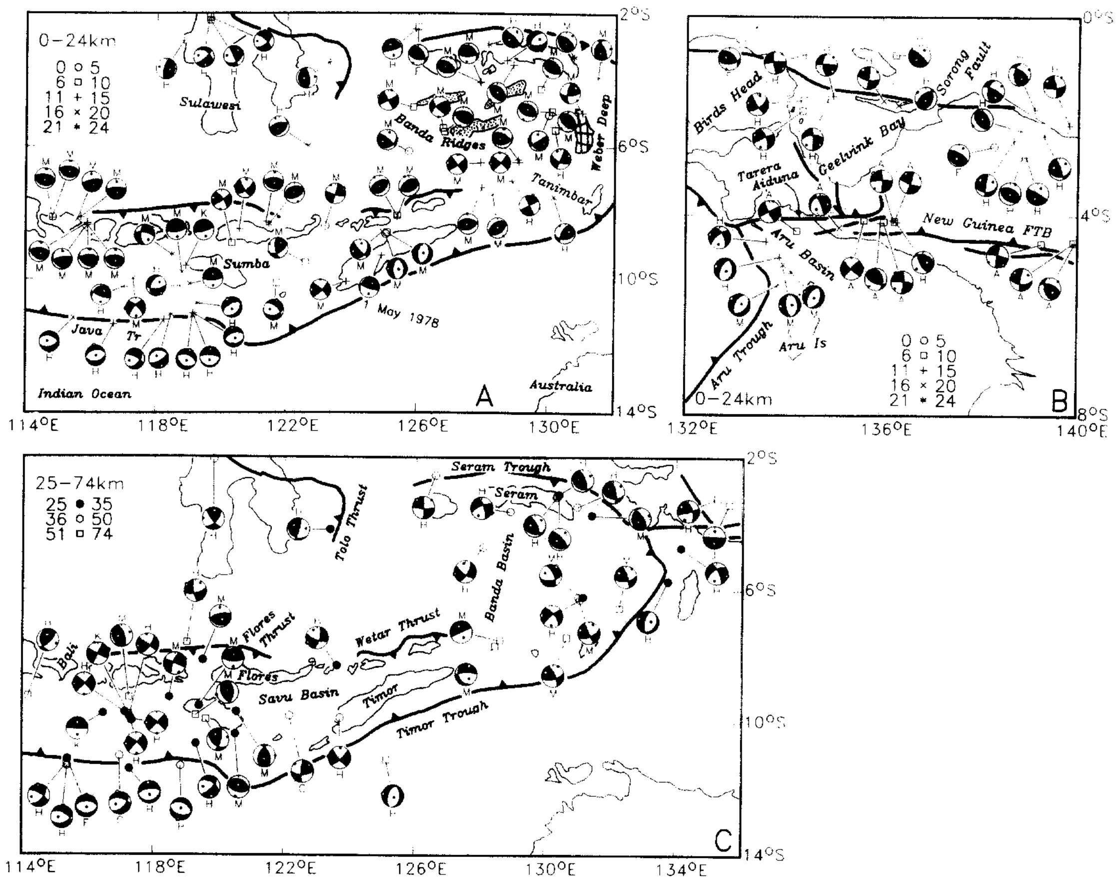

Fig. 1. Map of eastern Indonesia and western New Guinea showing fault plane solutions of earthquakes shallower than 74 km. Compressional quadrants are filled and the P-(closed) and T-(open) axes are shown by circles. Symbols and corresponding depth ranges are given in each figure. Mechanisms are labeled according to their reference as follows: A=ABERS & McCAFFREY, 1988; C=CARDWELL & ISACKS, 1978; F=FITCH, 1972; G=FITCH & MOLNAR, 1970; H=Harvard CMT; J=JOHNSON & MOLNAR, 1972; K=KAPPEL, 1980; and M=McCAFFREY, 1988. CMT solutions with seismic moments less than 10^{17} Nm and aftershocks of the great Sumba earthquake of August 1977 with moments of less than 10^{18} Nm have been ommitted.

have large uncertainties, at least ± 50 km, even when 'pP' is used (McCAFFREY, 1988). Their fault plane solutions are based largely on P-wave first motions so that, in general, steep nodal planes will be constrained well while gently dipping planes will not.

Because of the greater confidence in the depths of the BWI results (A and M events) than of the others, I infer the depths of the other events based on similarity of fault plane solutions. For example, strike-slip solutions labeled H are located at 49 km depth beneath western Timor, at 30 km depth east of Flores, and at 36 km depth beneath the central Banda Basin (Fig. 1c). M strike-slip solutions are found in the same areas (Fig. 1a) but are all shallower than 15 km, I infer then that the H events are also shallower than 15 km. In other words, the constraints on the depths of the non-BWI events, being poor, fail to disprove that these earthquakes have generally the same distribution as the A and M events. In interpreting the fault plane solutions in Figs 1a and 1c, events other than those labeled M can be moved from one map to the other if more consistency is gained by doing so.

Earthquakes occurring at the Java trench display normal faulting and strike parallel to the trench. Several of these are associated with the great Sumba normal-faulting event of 1977 which has been interpreted as due to either plate bending or plate rupturing. Normal faulting events are also seen along the eastern margin of the Aru Basin (Figs 1b and 1c).

Beneath the forearc north of the Java trench and west of the Savu Basin, with one exception, earthquake mechanisms are of three types: 1. strike slip with roughly north-trending P-axes; 2. underthrust with a gently north-dipping fault plane; and 3. thrust faulting on north-striking planes. These earthquake

types occur within the upper plate, between the plates, and within the subducting plate, respectively (McCAFFREY, 1988). Many of the strike-slip events were aftershocks of the 1977 Sumba earthquake. The underthrust events reveal northward convergence between the Indian Ocean plate and the Sunda Arc. Earthquakes with east-trending P-axes are deeper than 50 km (Fig. 1c), with one exception, and occur within the subducting plate.

Earthquakes beneath Timor show strike-slip and normal faulting within the crust of the forearc. Left-lateral strike-slip faults trending at azimuths of 10° and 50° on Timor have been recognized in the field by CHARLTON (1986). Most of the earthquakes beneath Timor probably occurred on such faults and the fatal earthquake that occurred on Pantar Island during the Snellius-II Symposium was likely associated with the westernmost of these faults. Earthquakes suggest that east-west crustal extension now dominates Timor tectonics.

The Timor earthquake of 1 May 1978, to my knowledge, is the first to indicate thrusting of Australia beneath Timor. Although the earthquake is small (m_b=5.5), a CMT solution was determined (Fig. 1a). Using WWSSN long-period P-waveforms, I inverted for the depth and source time function of this event (Fig. 2). By comparing best-fit waveforms at several depths, the depth was estimated to be between 5 and 15 km. The dip angle of the north-dipping plane, presumably the fault plane, is 31°. While this analysis is still preliminary, it suggests that the structure of Timor is that of a thrust package with a basal detachment at around 10 km depth. The normal to the auxiliary plane provides the direction of the slip vector and, if it is correct, a NNE direction of convergence is indicated for Australia with respect to Timor.

Northeast of Timor, in the vicinity of Tanimbar, one thrust and one strike-slip event show NW directed compression (Fig. 1a). Deeper earthquakes near Tanimbar (Fig. 1c) show compression in the lower plate parallel to the trench.

Fault plane solutions for earthquakes occurring in the forearc and arc, excluding those beneath the Savu Basin, reveal a consistent orientation of the T-axes in an E to ENE direction. The predominant deformation mode for the arc and forearc is therefore east-west extension with a smaller amount of north-south shortening, interpreted to be a response to the encroachment of the Australian continent. If the strike-slip earthquakes occur on northeast-trending fault planes then the forearc also undergoes north-south left-lateral shear; *i.e.* Tanimbar moves north-east with respect to Timor. The east-west elongation is accommodated by bending of the arc, particularly near Flores, as it thrusts over the back-arc basin, by east-west shortening of the Savu Basin, and by an

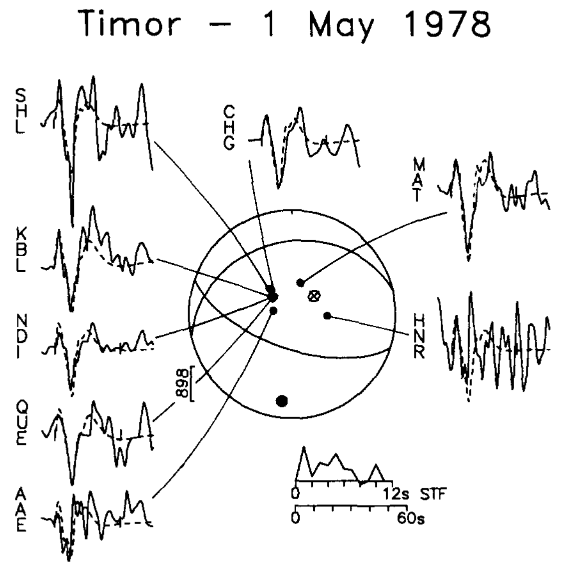

Fig. 2. Fault plane solution for the Timor earthquake of 1 May 1978. Observed (solid lines) and calculated (dashed lines) P-waveforms are shown for the best-fit solution (for the fault plane, strike = 257 ± 18°; dip=31 ± 8° rake=62 ± 10°; depth=9.7 ± 1.0 km; M_0 =3.2 ± 0.5·10^{17}Nm). Tics enclose the portion of the waveform used in the inversion. The larger dots plotted on the lower hemisphere focal sphere show the P- (closed) and T- (open with cross) axes. The amplitude scale is in microns and corresponds to a WWSSN instrument at a distance of 40° with a magnification of 3000. The normalized source time function is shown on the time scale. Assumed source structure is a half-space for all calculations (v_p =6.0 km·s^{-1}, v_s =3.4 km·s^{-1}, ρ=2700 kg·m^3).

eastward component of thrusting over the Australian margin at the Aru Trough.

An important adjustment to collision is the development of extensive back-arc thrust zones, marked by trenches, accretionary prisms, and shallow thrust earthquakes at the southern margins of the back-arc basins (Fig. 1). Earthquakes on the Flores thrust indicate north-south convergence whereas those on the Wetar thrust show more NNW convergence. South of Seram, thrust earthquakes suggest the presence of another back-arc thrust zone and show a NNE direction of slip.

The deepest earthquake on the Flores thrust zone that can be documented is at only 26 km depth (Fig. 1c). Thus, while thrusting penetrates the entire thickness of the crust, the lack of conclusive evidence for deeper earthquakes leaves the inference of subduction polarity reversal unproven. Moreover, the extensive deformation of the Banda Basin demonstrates that polarity reversal is not the only possible outcome of arc-continent collision; strike-slip faulting and crustal thickening are important mechanisms.

Earthquakes beneath the Banda Basin with well-constrained depths are very shallow (5 to 15 km below sea level) and show NNE-trending P-axes. Despite the change in structural trend to north-south at the eastern end of the volcanic chain, the consistency of the P-axes, showing north to NNE shortening, suggests that the earthquake mechanisms are reliable indicators of the direction of maximum compressive stress within the crust. Thrust earthquakes indicate that the Banda Basin is closing and the strike-slip events reveal that the basin elongates in the easterly direction as it shortens but does so without an increase in its surface area.

Two underthrust earthquakes west of the Tolo thrust show that it is an active thrust zone with westward thrusting of the north Banda Basin beneath Sulawesi. Eight thrust earthquakes west of the Seram Trough demonstrate active WSW thrusting of the Bird's Head beneath Seram. Earthquakes in western New Guinea show a complex combination of thrust and strike-slip faulting distributed between the Sorong fault in the north and the fold-and-thrust belt in the south (Fig. 1b). The presence of both fault types is a manifestation of oblique convergence between the Pacific and Australian plates.

3. GEOMETRY OF THE SUBDUCTED LITHOSPHERE

Previous studies of the geometry of the subducted lithosphere beneath the Banda Basin have led to conflicting views of the shape of the slab(s) beneath the Banda Basin due largely to the lack of well-recorded deep earthquakes available when those studies were made (CARDWELL & ISACKS, 1978; HAMILTON, 1974; HATHERTON & DICKINSON, 1969). More well-located events are available now owing largely to the installation of seismograph stations on Ambon, Timor, Sumba, and Sulawesi in the mid 1970's.

The configuration of the subducted lithosphere is inferred from earthquake hypocenters listed by the ISC for the years 1964-1984. Events used are those that meet the criteria outlined in the caption to Fig. 3. The filter used closely reproduces the set of earthquakes culled by CARDWELL & ISACKS (1978), who examined the residuals and station distributions for each event. The ISC depths of earthquakes in the upper 100 km have large uncertainties so the 100-km contour (Fig. 3) is uncertain. Orthogonal cross-sections were plotted every 1-2° for north-south profiles (Fig. 4) and every 1° for east-west profiles (Fig. 5).

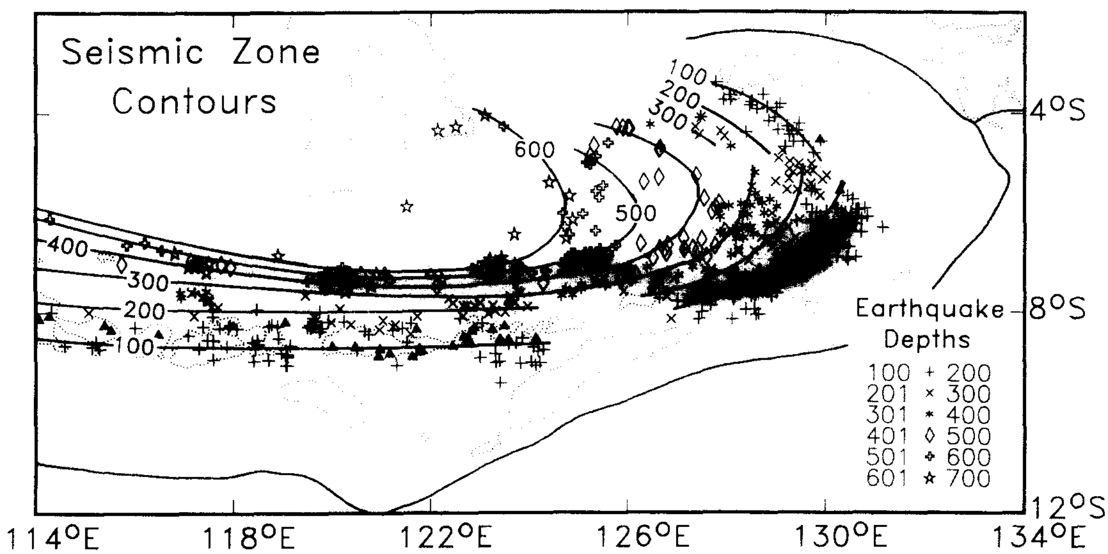

Fig. 3. Map of selected earthquake epicenters and contours of the top of the seismic zone in kilometers. Only earthquakes deeper than 100 km are shown. Hypocenters were selected from ISC bulletins by the following: number-of-stations is >15; root-mean-square (rms) of the arrival-time residuals is ⩾0.8s but ⩽2.0s; and standard errors in depth and epicenter are >0 but ⩽25 km. These criteria were selected by examining the dependences among the number of stations, magnitude, rms, and standard errors in depth and epicenter, and between each of these and hypocentral depth for the 6564 events in the region; 2081 events met the criteria. Limiting values were chosen to remove events that either lie outside the majority of events in these distributions or whose locations are likely coupled to the velocity structure (*e.g.* small rms and few stations). The number-of-stations criterion provides that the rms and standard errors are based on a sufficient number of samples; a large number-of-stations alone does not guarantee a good location, particularly in depth (McCAFFREY, 1988).

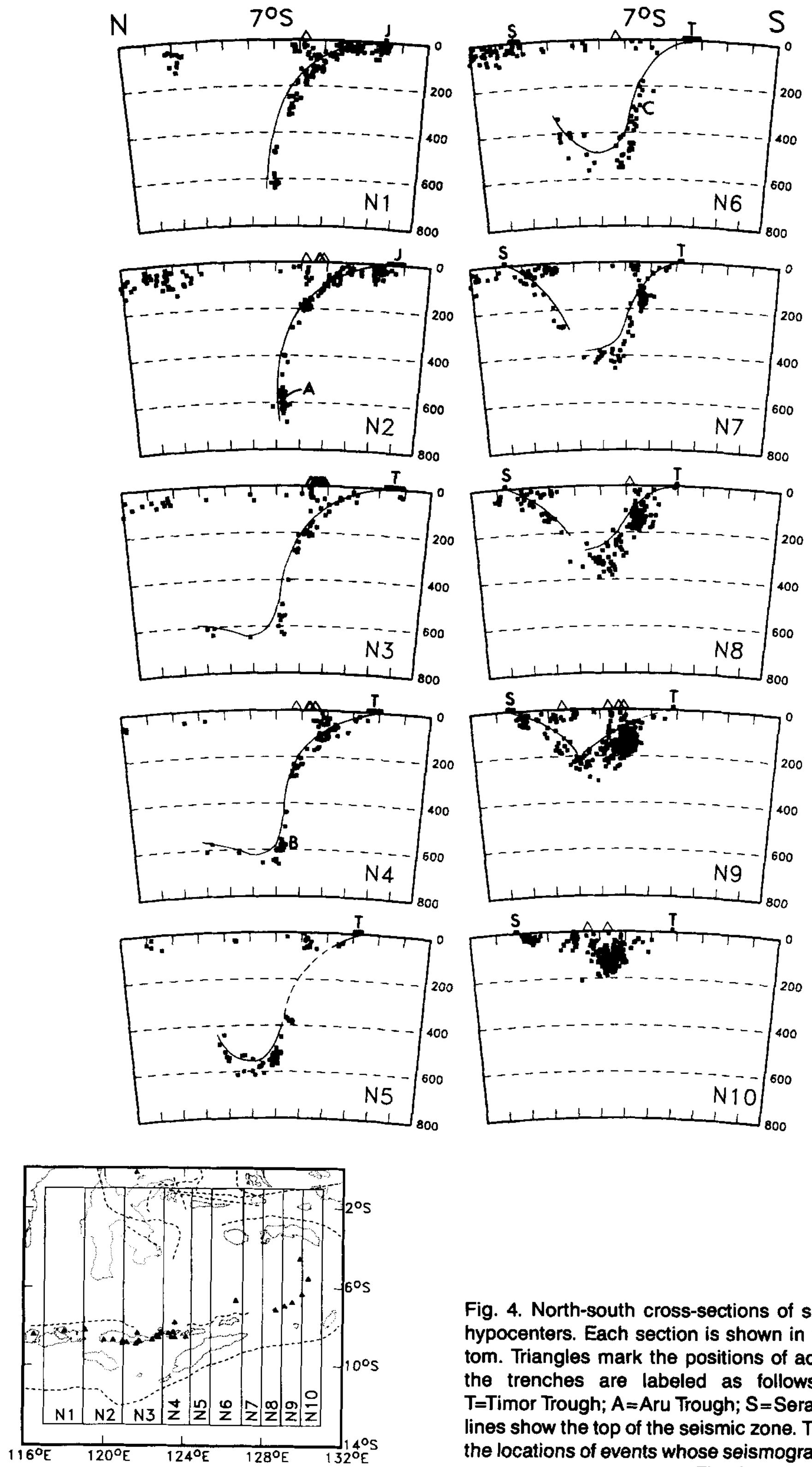

Fig. 4. North-south cross-sections of selected earthquake hypocenters. Each section is shown in the map at the bottom. Triangles mark the positions of active volcanoes and the trenches are labeled as follows: J=Java Trench; T=Timor Trough; A=Aru Trough; S=Seram Trough. The light lines show the top of the seismic zone. The letters A-C show the locations of events whose seismograms are displayed in Fig. 6.

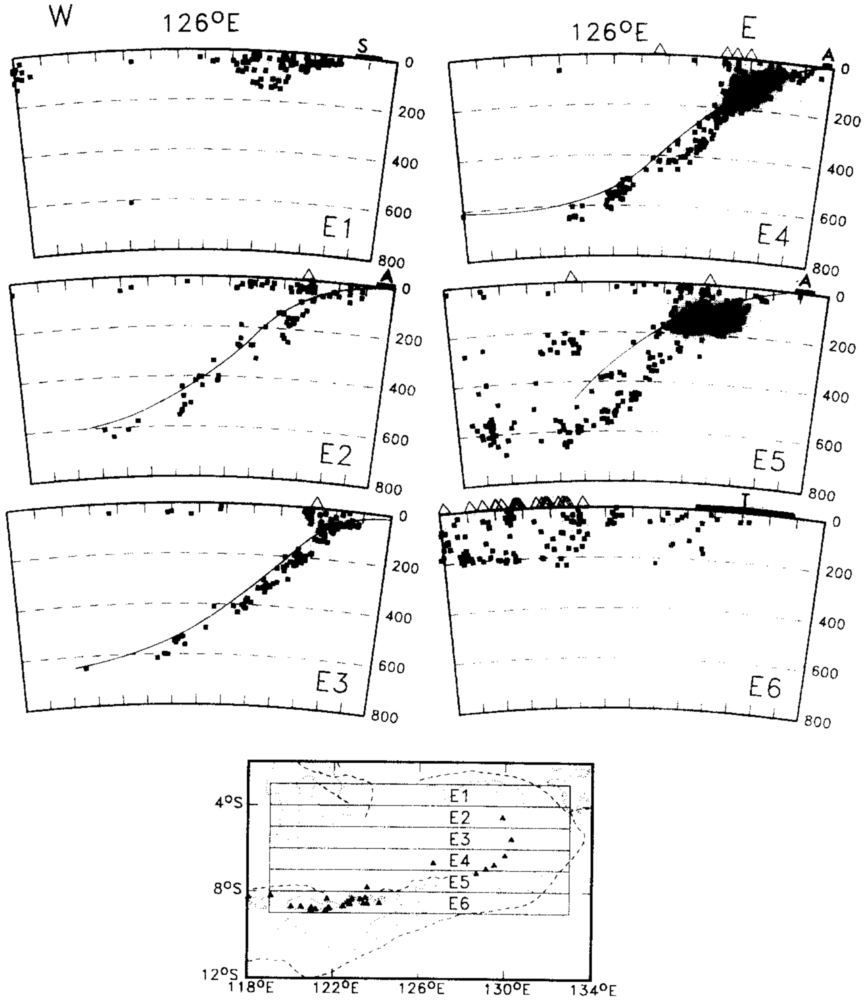

Fig. 5. East-west cross-sections of selected hypocenters. Each section is shown in the map at the bottom. See Fig. 4 for details.

Hypocenters and contours of the top of the seismic zones are shown in Fig. 3. In map view, we see a very narrow zone of deep seismicity beneath the Sunda Arc that broadens considerably beneath the Banda Basin. Note the change in the seismicity pattern at 124°E, quiescence north of Timor, and the sharp cutoff in earthquakes deeper than 200 km along 4°S.

From Sumbawa to western Flores (N1 and N2; Fig. 4), earthquakes extend from the Java trench northward to greater than 600 km depth, forming a nearly vertical zone below 400 km. To the east, profiles N3 and N4 are similar but the seismic zone appears to flatten at 600 km depth. East of 124.4°E, where the volcanic arc becomes inactive, earthquakes are absent between 70 and 380 km depth and form a U-shaped seismic zone below 380 km (N5). Farther east (N6) the limbs of the seismic zone become longer and form a J shape, but still do not appear to continue to the surface at either end. The south-dipping limb in this profile is not continuous with the Seram Trough. A south-dipping seismic zone extending from the Seram Trough to nearly 300 km depth is first visible in N7, but does not continue to 400 km depth, where the north-dipping zone ends. In N8 and N9, both zones are evident but the separation between them is not. At the far eastern end, the two zones merge into a cloud of seismicity in the upper 200 km (N10).

In the northernmost of the east-west projections (E1; Fig. 5), seismicity occurs only to about 150 km depth and appears to deepen westward away from the Seram Trough. The contrast between E1 and E2, where a well-defined seismic zone extends to 600 km depth, shows that the west-dipping, deep seismic zone ends abruptly in an east-west trend near 4°S. This termination is interpreted as evidence that the

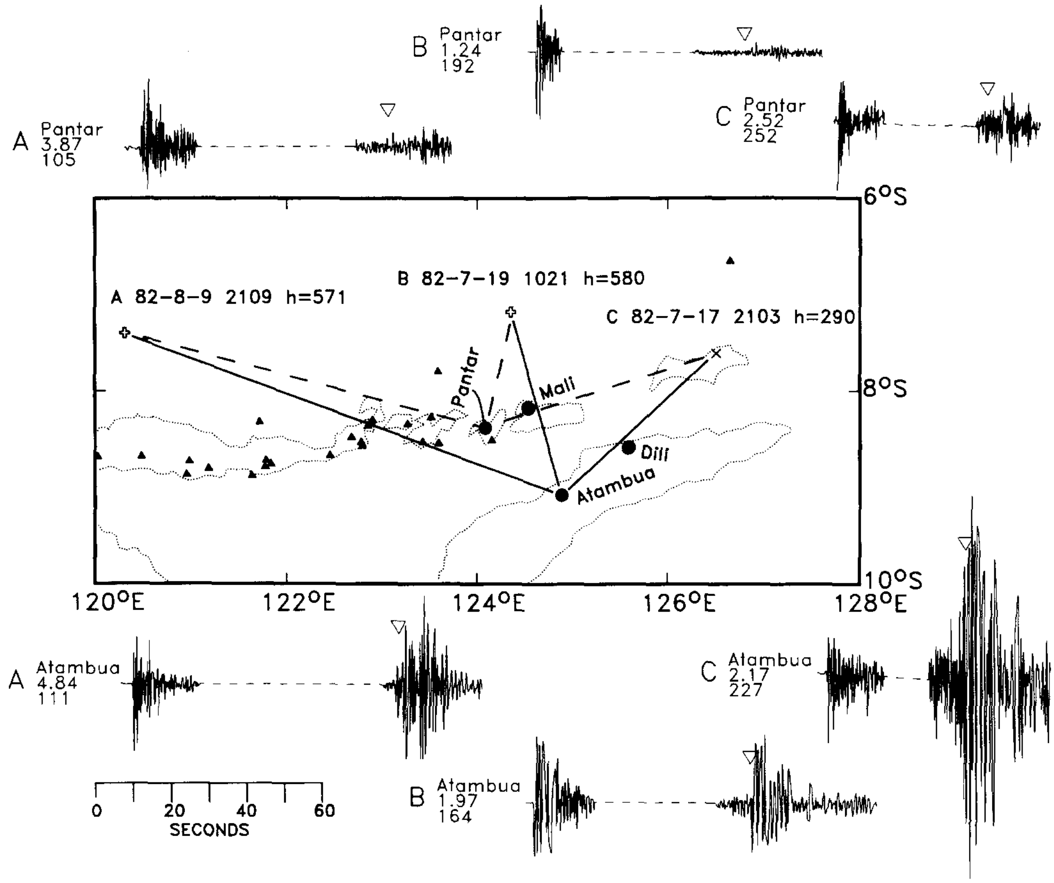

Fig. 6. Short-period, vertical component seismograms from deep earthquakes beneath the Flores Basin recorded at stations along the East Sunda Arc (dashed where data were not digitized). Descriptions of the seismograph network and earthquakes are given in McCaffrey *et al.* (1985) and locations of events are shown in Fig. 4. Amplitudes are normalized by the maximum amplitude in the P-waves. Next to each seismogram are the event letter, the station name, and the epicentral distance and azimuth in degrees. The inverted triangle shows the expected arrival of the S-wave. On the map, events A, B, and C are labeled by their year-month-day, hour, minute, and depth (h). Large dots show locations of seismograph sites and dashed lines show paths where S-waves were small.

lithosphere subducting at the Seram Trough is not continuous with the slab at 600 km depth beneath the Banda Basin. The northern slab, which dips SW to about 300 km depth beneath Seram, is bounded by the Seram Trough in the north and east, by 127° in the west (it is seen in N7 but not in N6), and by 4°S in the south.

Farther south, in profile E3, the deep seismic zone dips westward much as in profile E2 but is displaced about 100 km to the E, indicating that the slab bends. The narrowness of the seismic zone suggests that this profile is nearly perpendicular to the strike of the slab. Profile E4 is similar to E3.

In profile E5, along the eastern end of the Timor Trough (7 to 8°S), the west-dipping seismic zone is still evident, though somewhat broader than in the north (but comparable to E2 in breadth). It merges with more scattered foci west of 124°E, where seismicity in the steeply-dipping slab north of the Java Trench intersects the projection. The aseismic triangular region, also apparent in E6, bounded by 124°E in the west and by the west-dipping seismic zone in the east, is where lithosphere recently subducted at the Timor Trough should be. The lack of intermediate depth seismicity east of 124°E was observed also in the distribution of microearthquakes recorded by a seismograph network operating for 3 months in 1982 (McCaffrey *et al.*, 1985) indicating that the pattern seen here in the ISC hypocenters is not due to poor sampling. Either the subducted slab in that region is aseismic or there is none.

The propagation of S-waves from deep earthquakes to seismograph stations along the arc and forearc support the presence of a high-Q lithospheric slab beneath Timor (Fig. 6). Small S-waves (relative to P) in seismograms recorded at stations along the

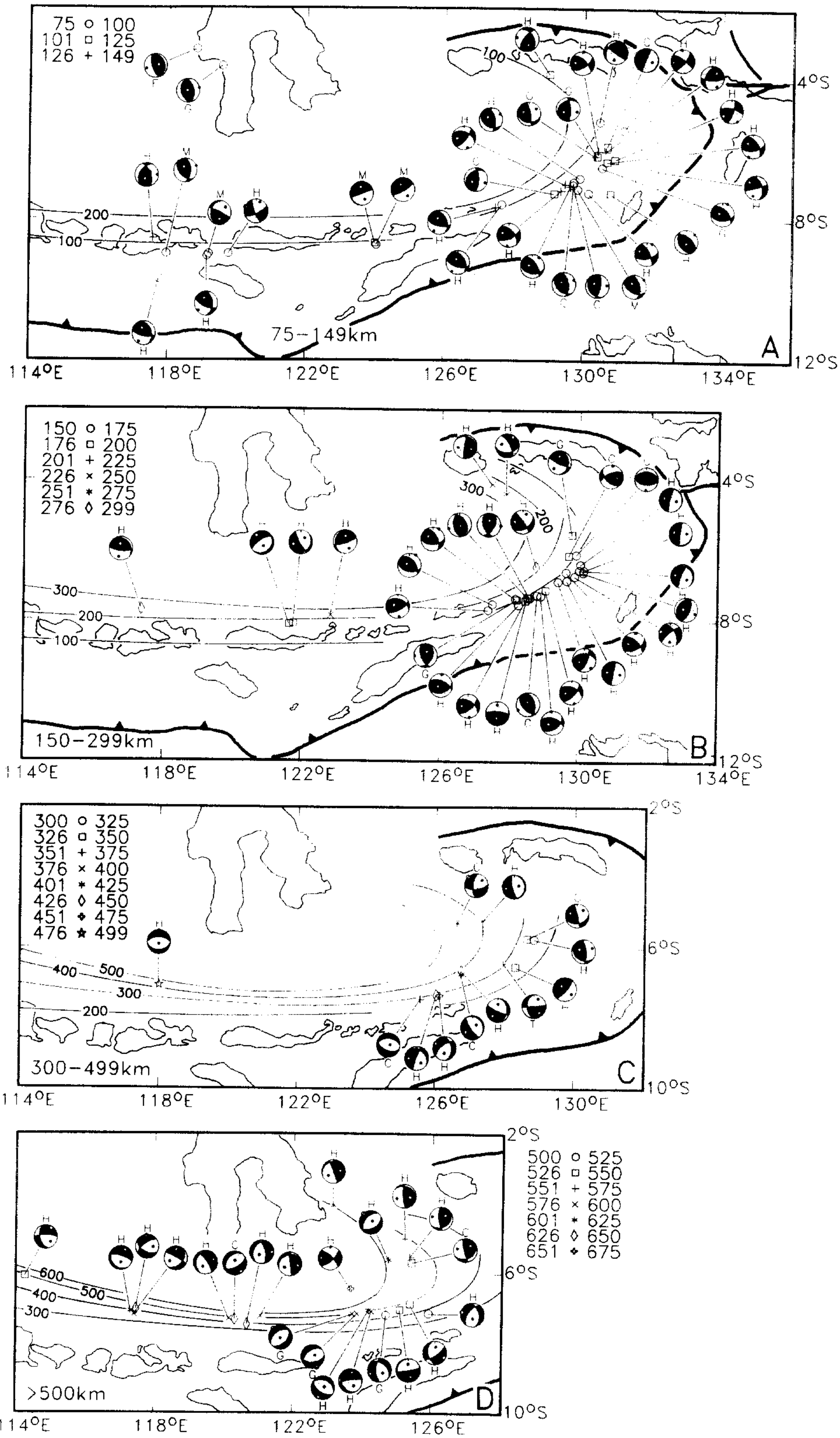

Fig. 7. Fault plane solutions for intermediate and deep earthquakes. See Fig. 1 for explanation. The thin lines are selected contours of the top of the seismic zone labeled in km.

active volcanic arc (*e.g.* Pantar) reveal inefficient propagation and thus the sensitivity of the S-waves to short ($\approx$100 to 200 km) paths within the asthenosphere. By comparison, S propagates efficiently to the station at Atambua in central Timor. Similar differences in S-wave propagation were noted between the stations at Mali (small S-waves), on the extinct portion of the volcanic arc, and Dili (large S-waves), in northern Timor (Fig. 6). S-waves are also small in seismograms of these earthquakes recorded at MKS in southwestern Sulawesi; their paths traversed the upper mantle but did not go below the volcanic arc. Earthquakes that occurred south of Pantar (near 9°S and 124°E) at 100-km depth displayed large S-waves at both Pantar and Atambua, suggesting that the attenuating region is probably north of the volcanic arc and not in the crust. These preliminary observations support inferences that the lithospheric slab is continuous from Timor to 600 km depth and that some part of the Australian continental lithosphere is, or has been until recently, subducting beneath Timor.

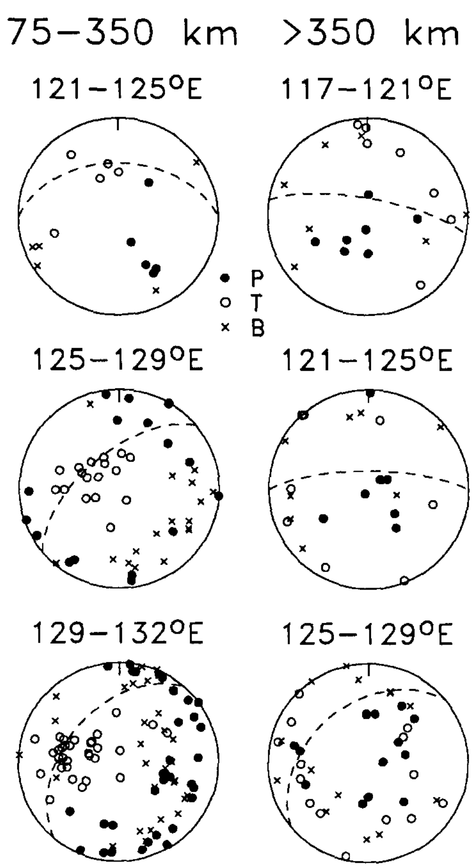

Fig. 8. P, T, and B axes for events between 5°S and 9°S and within the specified longitudes and depths. Axes are plotted on lower hemisphere projections. The lines are the rough projections of the seismic zone in each region.

Beneath the eastern Sunda Arc fault plane solutions for earthquakes from 50 to 150 km depth show P-axes aligned east-west, parallel to the contours of the seismic zone, and down-dip T-axes (Figs 1c and 7a). Below 480 km, earthquakes display P-axes aligned roughly with the dip of the seismic zone (Figs 7d and 8). From 150 to 480 km no pattern is obvious and there are few events (no mechanisms have been found for the 300-480 range; Fig. 7c).

The pattern is more complex beneath the Banda Basin. In the 75 to 350 km depth range most mechanisms have their T-axes aligned with the dip of the seismic zone (Fig. 8) while the P- and B-axes tend to align in a plane normal to the seismic zone. As the seismic zone changes strike east of 125°E, the trends of the T-axes change accordingly. Below 350 km the P-axes tend to align weakly in the down-dip direction. The single mechanism in the flat part of the seismic zone below 600 km shows horizontal P- and T-axes (Fig. 7d). Three mechanisms at 100-275 km depth in the Seram seismic zone show P-axes that align with the down-dip direction; at similar depths in the southern seismic zone the T-axes are alinged down-dip (Fig. 7b).

4. DISCUSSION

The eastern Indonesia deformed zone accommodates the relative convergence between the Southeast Asian (SEA), Pacific (PAC), and Indian Ocean-Australian (AUS) plates and is broken into several smaller plates (Fig. 9). The relative motions of the microplates are constrained by the slip vectors of the shallow earthquakes but rates have few independent constraints.

Deformation within the Banda Basin, inferred from shallow earthquake mechanisms, indicates convergence between Timor and Seram. Since there is a component of north-south convergence between Australia and Timor at the Timor Trough and also between the Bird's Head (BH) and Seram at the Seram Trough, then Australia and BH must converge across the Banda Basin. Hence they are not now part of the same plate. Thrust earthquakes at the Seram Trough indicate that Seram moves at an azimuth of about 50° with respect to BH so that, if Timor and Seram converge in a north-south direction, then BH is moving SSW to SW with respect to AUS. The most likely sites for such motion are the New Guinea fold-and-thrust belt and the Tarera-Aiduna fault zone (Fig. 1). The history of the Tarera-Aiduna is poorly known, but large, left-lateral strike-slip earthquakes east of its mapped trace suggest that it extends into the Highlands of New Guinea (Fig. 1b). Alternatively the Geelvink Bay has been cited as a possible site for slip (DOW & SUKAMTO, 1984) and has some strike-slip earthquakes (Fig. 1b). Undoubtedly the geometry is

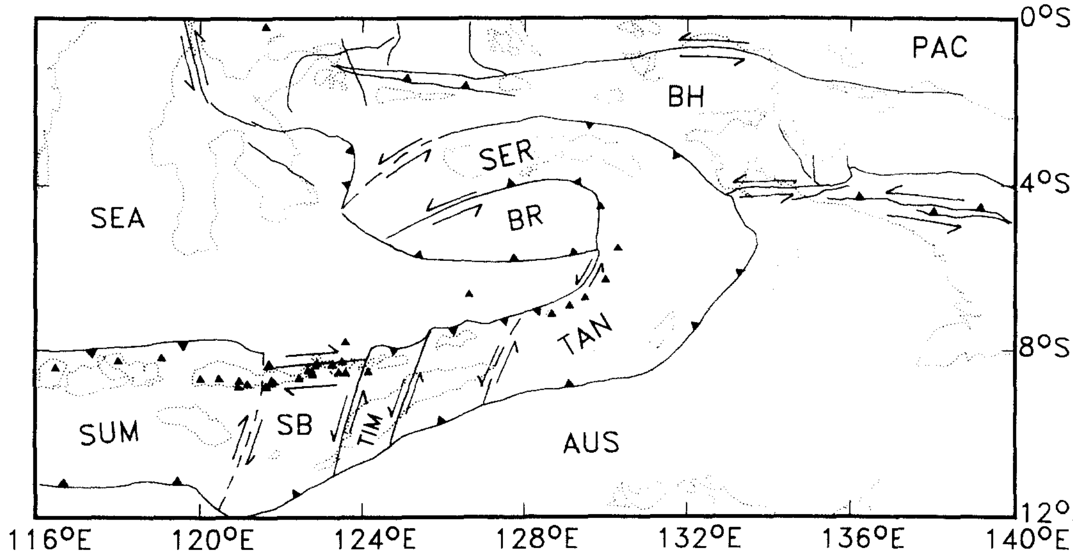

Fig. 9. Interpretative tectonic map of the Banda Arc region. The regions that are inferred to behave as semi-rigid blocks are: SEA=Southeast Asia; SER=Seram; BH=Bird's Head; PAC=Pacific; BR=Banda Ridges; SUM=Sumba; SB=Savu Basin; TIM=Timor; TAN=Tanimbar; and AUS=Australia.

quite complicated. In any case the Aru Basin contains a trench-trench-transform triple junction, named the Snellius-II Triple Junction (JONGSMA *et al.*, 1988), which is a stable configuration since both trenches accommodate subduction beneath the same plate.

The predominantly thrust mechanisms of shallow earthquakes within the Banda Basin crust are strong evidence against the spreading hypothesis proposed by HAMILTON (1979) for the eastward migration of the Banda Arc. Migration of the arc is suggested by both the young age of the eastern volcanoes and the eastward decrease in the length of the subducted slab beneath the Banda Basin. Deformation of the Banda Basin and Banda forearc in part by NE-trending left-lateral strike-slip faults (Figs 1 and 9) produces eastward migration of the arc and forearc without sea-floor spreading.

The shape of the subducted lithosphere beneath the Banda Basin is in part an asymmetric synform with an axis along 6°S that plunges 35° to the west. The deep seismic zone does not appear to be continuous with either the Timor or Seram Troughs, but at its eastern end it projects toward the Aru Trough and in the west it projects southward toward the Java Trench. Despite the lack of seismicity beneath Timor, continuity of the deep slab with the Australian lithosphere at the Timor Trough is suggested by the efficient propagation of S-waves from deep earthquakes to Timor. The U-shape of the seismic zone in its deepest parts, shown by north-south cross-sections, demonstrates that the slab contours must bend more than the 90° indicated by CARDWELL & ISACKS (1978). The inference that the slab subducted at the Timor Trough is separate from the one subducted at the Seram Trough is supported by the depth to which each has been subducted; the Seram slab extends to at most 300 km while the Indian Ocean slab is continuous to well over 600 km so that they record different histories of subduction.

The J-shape of the Indian Ocean slab beneath the Banda Basin (Fig. 4) is unusual and will require more detailed study to see if the distribution of deep earthquakes is real or only apparent. Assuming for the time being that the distribution is real, I propose the following explanation. It is likely that this part of the Indian Ocean plate was moving northward with respect to Indonesia while it was subducting (MINSTER & JORDAN, 1978). A mechanism in which the slab follows a fixed path into the mantle and its shape remains constant over time could not produce the J-shaped lithosphere because it would require that the slab ascend to the north after reaching its deepest point beneath the Banda Basin. Presumably slabs are more dense than the surrounding mantle, so that such ascension is not possible if slab motion is driven by gravity alone. It is more likely that the subducted lithosphere changed shape after subduction and that the observed slab geometry was caused by different parts of the slab sinking at different rates. I suggest that the counter-clockwise bends in the slab contours were caused by the injection of the subducting lithosphere beneath the westward-moving Pacific plate that formed the back arc when this subduction took place.

A popular mechanism for the aggregation of slivers of continental material that compose much of eastern Indonesia is by slicing them from the northern margin of New Guinea and transporting them westward by strike-slip faulting (KATILI, 1974; VISSER & HERMES, 1962), probably driven by the motion of the Pacific plate. This process is seen today along the Sorong fault. The southernmost of these slivers so far recognized are the Tukang-Besi Plateau and the Banda Ridges, that sit only 250 km north of the modern volcanic arc. The Banda Ridges were probably separated from Irian Jaya at 5 to 10 Ma and were emplaced sometime after that (SILVER *et al.*, 1985). The inference then is that at 5 Ma, when the lithosphere now at about the 300 km contour was being subducted (assuming a rate of 80 $mm \cdot a^{-1}$), a left-lateral shear zone was active in the back arc but within a few hundred km of the volcanic arc. The subducting slab may have extended below and north of the shear zone and bent westward by the motion of the asthenosphere entrained in the motion of the northern (Pacific?) plate. When the Banda Ridges were finally emplaced, the shear zone moved northward (relative to the subducting plate) to the Seram Trough. The westward shear on the subducted slab ceased, so that the shallower parts of the plate were not bent like the deeper part (Fig. 3).

The lack of intermediate depth earthquakes beneath both Timor and the extinct volcanic arc to its north (Fig. 4; N5) and the efficient propagation of S-waves through the area indicates that the lithospheric slab, though present, is aseismic. Australia and the eastern Indian Ocean form a single rigid plate and, west of Timor, the subducted lithosphere of the Indian Ocean forms a 1000-km long, continuous seismic zone that reaches depths in excess of 600 km (Fig. 4). A similar length of lithosphere must have entered the Timor Trough. What is not known is whether this lithosphere was oceanic or continental; most likely oceanic lithosphere led the continental lithosphere into the subduction zone so that the slab is a combination of both types. The lengths of each type depend on the amount of convergence that occurred after the Australian continental margin entered the Timor Trough, which can be constrained only broadly because of the uncertainties in both the rate of convergence and timing of the collision. Using a rate of 80 $mm \cdot a^{-1}$ and a middle Pliocene start of collision (AUDLEY-CHARLES *et al.*, 1979; ABBOTT & CHAMALAUN, 1981), roughly 250 km of continental lithosphere has entered the trench. This amount could be as much as 800 km if a middle Miocene start is correct (BERRY & GRADY, 1981).

Arguments based on geometry can give a minimum estimate of the amount of continental underthrusting. If the Timor Trough south of Timor was at the same latitude as the Java Trench prior to collision, at 11°S, then the presence of Australian margin rocks now in northern Timor, at 8.5°S, suggests that at least 280 km of crustal shortening has occurred. Internal thrusting of the continental rocks within the forearc accounts for more shortening. If the crust of Timor is now on the average 40 km thick (CHAMALAUN *et al.*, 1976)—mountains on Timor reach elevations of 3000 m—then it is 10 km thicker than the Australian crust south of the Timor Trough (JACOBSON *et al.*, 1979). Thickening can therefore account for 30% more shortening: another 80 km. The gap in the seismic zone at 125°E extends from about 50 to nearly 400 km depth (N5), a length in accord with the estimates of convergence given above and so is consistent with, though does not prove, the inference that the Australian continental crust remained at the surface rather than being subducted.

My interpretation is that some thickness of the continental crust and perhaps upper mantle entering the Timor Trough was detached from its underlying lithosphere and was stacked up to form the island of Timor. Metamorphic rocks are ubiquitous on Timor and comprise cordierite and sillimanite bearing biotite-garnet gneisses and metamorphosed gabbroic rocks and peridotite. Analyses of pelitic gneiss from the Boi Massif in western Timor suggests a pressure of 7 kbar and temperature of 670°C (EARLE, 1981) indicating that these rocks may have been at lower crustal depths ($\approx$25 km) and may represent continental basement that has been lifted up tens of kilometers. The mantle portion of the lithosphere continued to subduct but is now aseismic and without associated volcanic activity, as a consequence of leaving much of its colder and lighter crust at the surface.

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