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Crustal reactions resulting from the mid-Pliocene to Recent continent-island arc collision in the Timor region

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The Sunda and Banda Arcs are contiguous surface features associated with the convergent boundary between the Southeast Asian and Australian-Indian Ocean plates, and where these two arcs meet, the tectonic environment changes from oceanic subduction to continent-island arc collision. This area has been investigated in an attempt to recognise and understand some of the effects of the introduction of continental crust into a subduction zone. Depositional environments encountered in Deep Sea Drilling Project (DSDP) hole 262 have been correlated with present environments to determine past horizontal distances between the leading edge of the subduction zone and the DSDP location on the Australian crustal margin. These data have been combined with the apparent plate motion at this margin to derive an estimate of the surface width of the subduction zone through time. The similarity between past width variations and present lateral variations has been used as the basis for proposing a collision model.

Before the collision, the Indonesian subduction zone extended eastwards into the region that is now the southern Banda Arc. The continental edge of Australia first entered this subduction zone about 3 m.y. ago, in the mid-Pliocene. Initially, a wedge of deformed continental margin sediments began to develop at the leading edge of the subduction zone. The tectonic front that separated deformed from undeformed sediments and an associated bathymetric low migrated up the continental slope leaving in their wake a large wedge of deformed continental margin sediments, which produced a southerly bulge in the subduction zone. Ultimately, the deformation wedge began to absorb the near-surface stresses, and relative motion between the front and the southern plate slowed to near zero. Continuing relative plate motion carried the deformation front back towards the volcanic arc. Compression from this has been almost entirely taken up in the subduction zone, and has led to thickening and uplift of the deformation wedge and crust associated with the pre-collision outer-arc ridge.

The proposed collision model explains many of the morphological, geological, and geophysical irregularities in the Timor region.

On a broader regional scale, the evidence that the Southeast Asian plate at Timor is moving eastward at about 60 km/m.y. relative to the Eurasian plate, supports the interpretation that the India/China continental collision is pushing the Southeast Asian plate to the southeast.

Introduction

In a broad sense, the tectonic complexity of the Southeast Asian region results from convergent interaction between the Pacific, Eurasian, and Australian-Indian Ocean plates. One of the effects of this interaction has been the development of a number of small sub-plates which move independently of the major plates as they adjust to regional stresses. One such sub-plate is the Southeast Asian plate, which encompasses most of the Indonesian Archipelago region.

The Southeast Asian plate is separated from the Australian-Indian Ocean plate by the Indonesian subduction zone (Fig. 1), which is bounded to the north by a volcanic arc and to the south by a tectonic front coincident with a bathymetric trench or trough. Since its inception in the Paleogene this subduction zone has had an episodic history. During the Oligocene/Early Miocene, the volcanic arc was associated with intense, andesitic volcanism and uplift. However, volcanic rocks from this period are not known further east than western Flores (van Bemmelen, 1949). During the Middle Miocene, the volcanic arc subsided and volcanic activity was almost absent. The present active period began in the Late Miocene, and volcanism and associated uplift have been fairly continuous since that time.

The Indonesian subduction zone can be subdivided into two portions, the Sunda and Banda Arcs, extending, respectively, west and east of the island of Sumba (Fig. 1). South of the Sunda Arc oceanic lithosphere of the Australian-Indian Ocean plate dips northwards into the Java Trench, where it is subducted beneath the Southeast Asian plate. In contrast to this, the Banda Arc is characterised by having Australian continental lithosphere dipping northwards into the Timor Trough (Bowin & others, 1980). In the region where these two arcs meet there exists a unique opportunity to examine the crustal effects of introducing continental lithosphere into a subduction zone.

Comparison of the Sunda and Banda Arcs

In recent years, many authors have compared the Sunda and Banda Arcs (Fitch & Hamilton, 1974; Audley-Charles, 1975; Hamilton, 1977; Cardwell & Isacks, 1978; Von der Borch, 1979). Some of the more striking similarities and contrasts, which must be considered when attempting to understand the geological development of this region, are discussed below.

The volcanic arc is undoubtedly the best example of continuity between the two arcs. A small circle fit to the active volcanoes between western Java and Pantar emphasises this point (Fig. 1). The pole of the small circle is at 32°N, 120°E. The most notable features of the volcanic arc are the marked decrease from west to east in both subaerial exposure and age of the oldest exposed rocks. Granites in Sumatra suggest a Mesozoic magmatic belt; in western Java and southern Sumatra there is evidence of a Cretaceous volcanic arc which extended across the Java Sea and into Kali-

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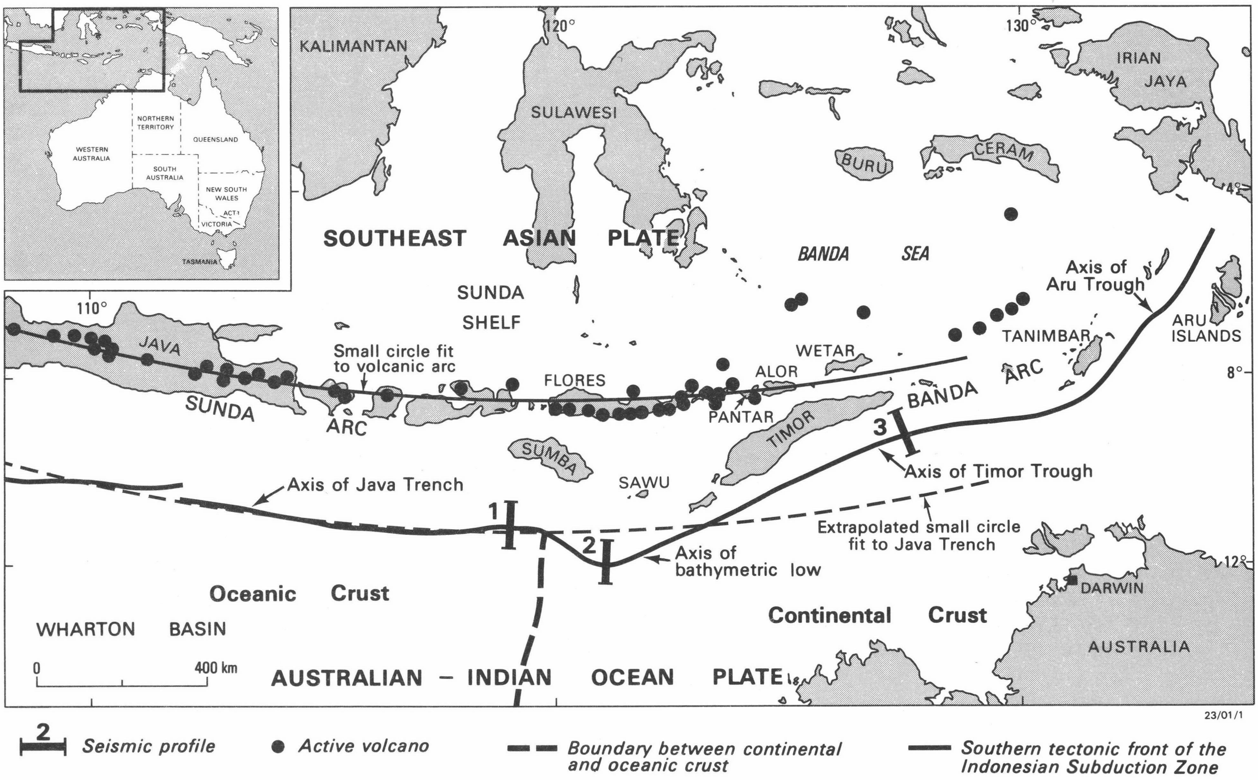

Figure 1. Eastern end of the Indonesian subduction zone.
The continent-ocean boundary between Australia and the Wharton Basin separates a region of oceanic subduction along the Sunda Arc from a region of continental collision along the southern Banda Arc. South of 13°S the continent-ocean boundary is according to Stagg (1978).

mantan; throughout eastern Java and Flores the oldest volcanics are Oligocene to Early Miocene; and east of Flores the volcanics are no older than Late Miocene. It should be noted that the Alor/Wetar area has been volcanically inactive during the last 3 m.y. (Abbott & Chamalaun, 1978). This portion of the arc, however, has undergone differential uplift since volcanism ended (Brouwer, 1942; van Bemmelen, 1949; Katili & Soetadi, 1971; Chappell & Veeh, 1978).

The seismic zone associated with the Indonesian subduction zone extends beneath the Southeast Asian Plate (Cardwell & Isacks, 1978), and appears to be continuous between the Sunda and Banda Arcs.

The Java Trench and Timor Trough are associated with the southern tectonic boundary of the Sunda and southern Banda Arc portions, respectively, of the Indonesian subduction zone (Fig. 1). The Timor Trough is some 3 km shallower than the Java Trench and as such has been considered by some to be a relatively minor feature (CCOP-IOC, 1975). However when compared with adjacent morphological features the relative dimensions of the Timor Trough are seen to be similar to those of the Java Trench. From the top of Timor to the axis of the Timor Trough there is an elevation difference of about 5 km. Similarly, the difference between the outer-arc ridge south of Java and the Java Trench axis is also approximately 5 km. The Australian continental crust is depressed about 3 km at the Timor Trough (Bowin & others, 1980), whereas at the Java Trench the southern oceanic crust is depressed only about 2 km. There is, therefore, no reason to suggest that the Timor Trough is not related to a tectonic boundary just as significant as the generally accepted Java Trench plate boundary.

The axis of the Java Trench (Fig. 2) marks the surface boundary between depressed oceanic crust to the south and the accretionary wedge to the north. Seismic profiles across the trench show an abrupt change from relatively undeformed crustal material south of the axis to highly deformed material to the north. High resolution multi-channel seismic techniques have successfully revealed structural detail beneath the northern flank of the Java Trench south of Java (Beck & Lehner, 1974; Hamilton, 1977). The data show that the southern plate continues to dip northwards beneath an accretionary wedge imbricated by north-dipping thrust planes.

The Timor Trough (Fig. 2) is associated with a similar type of structural boundary, except that north of the trough the structural complexity is even more difficult to resolve. However, the data suggest that the northern flank of the Timor Trough includes both compressional folds and north-dipping thrust planes (Montecchi, 1976; Beck & Lehner, 1974; Von der Borch, 1979).

The Java Trench and Timor Trough are connected via the Roti Basin. This shallow-sided bathymetric low, on the northern side of the Scott Plateau (Fig. 3), also corresponds to a structural boundary, like the Java Trench and Timor Trough (Fig. 2). Thus, there appears to be a continuous bathymetric low, extending from the Java Trench through the Roti Basin and into the Timor Trough, which is both coincident with and related to the southern tectonic boundary of the Indonesian subduction zone.

The usual form for subduction zones is convex towards the plate that is being subducted, as is the case throughout the Sunda Arc. However, the Timor Trough and the outer-arc portion of the Banda Arc in the vicinity of Timor are concave towards Australia, whereas the inner volcanic arc is convex (Brouwer, 1919).

The morphological features associated with the Sunda Arc display lateral continuity and run very nearly parallel with one another, as can be demonstrated by fitting a small circle to the Java Trench centred on the same pole as the small circle through the active volcanoes (Fig. 1). Other small circles centred on this pole could likewise be fitted to the outer-arc ridge and outer-arc basin features of the Sunda Arc. The parallelism of these features extends for more than 1000 km, from western Java to Sumba. The Banda Arc features, on the other hand, display lateral continuity, but their parallelism wanes, resulting in significant variation in both the distance between the volcanic arc and the southern tectonic front (Fig. 1) and the elevation of the surface features of the subduction zone. The point where the uniform dimensions of the Sunda Arc give way to the variable form of the Banda Arc coincides with where the continent-ocean boundary between the northeast Wharton Basin and the Scott Plateau intersects the subduction zone south of Sumba (Fig. 1).

Evidence for crustal convergence at the Timor Trough

The continuity between the Sunda and Banda Arcs can be interpreted as suggesting that the Timor Trough is merely a shallow equivalent of the Java Trench (i.e. it represents the outcrop of a major thrust boundary

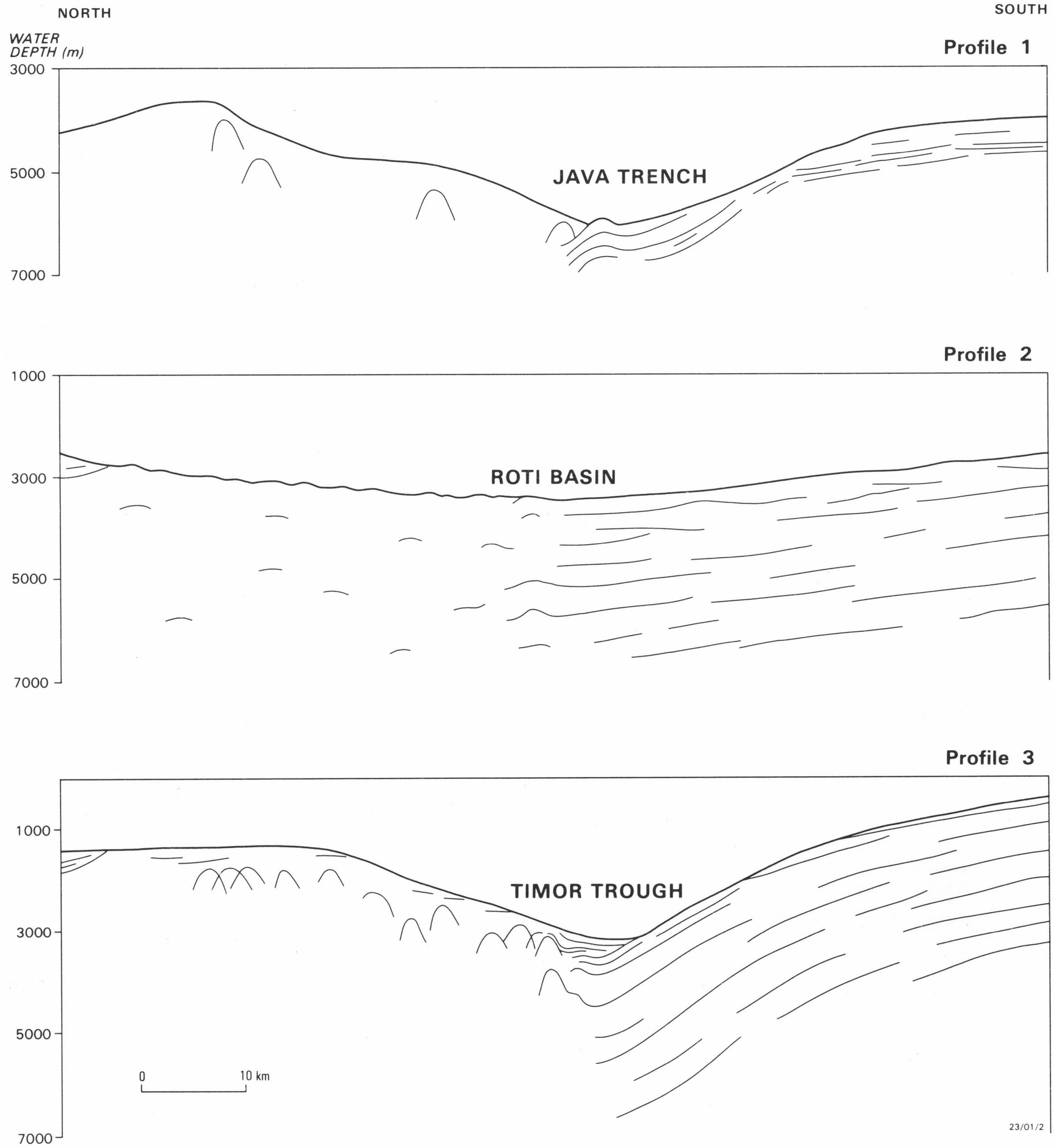

Figure 2. Representative seismic profiling reflectors across three bathymetric features associated with the southern tectonic front of the Indonesian subduction zone.
All profiles have been projected onto planes perpendicular to the tectonic front. For location see Figure 1.

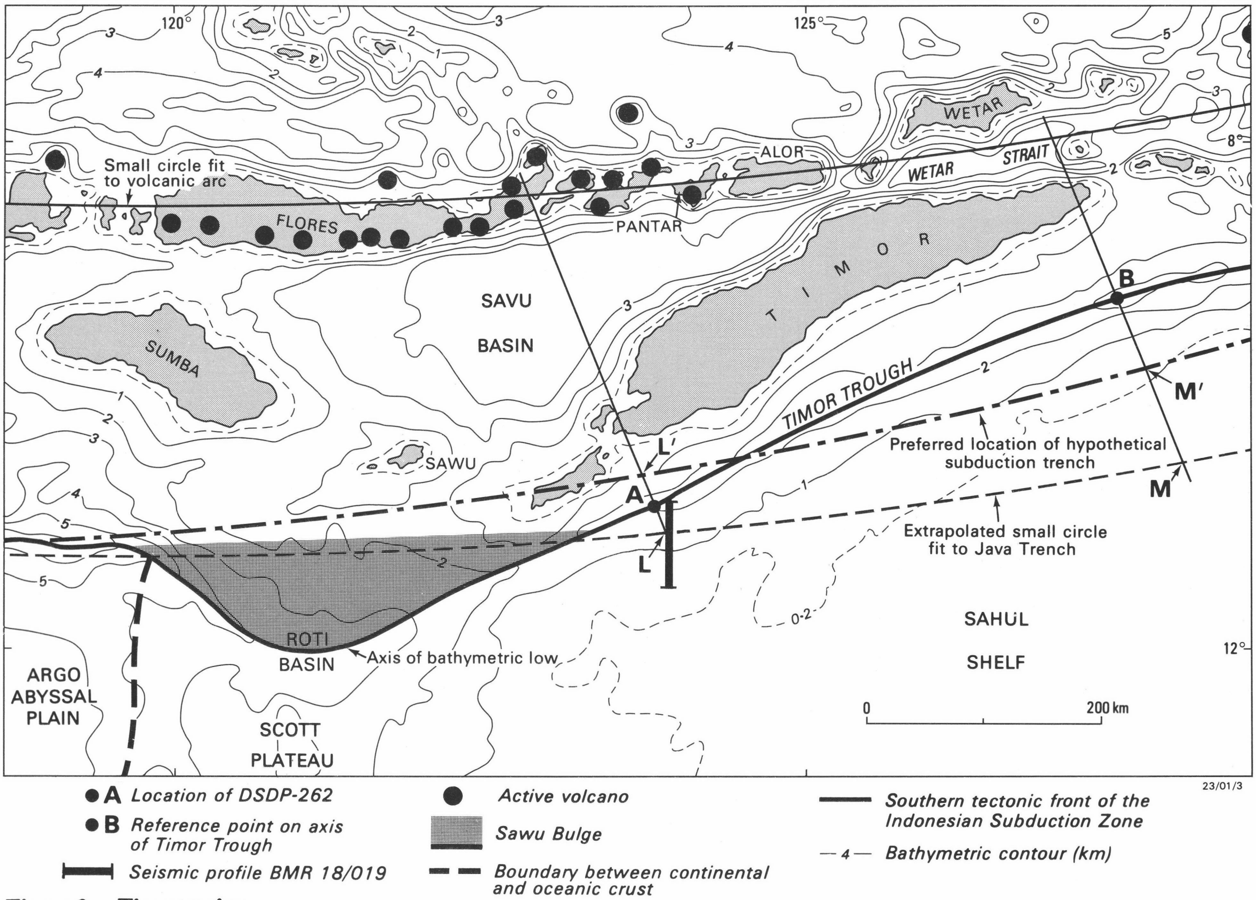

Figure 3. Timor region.
North-northwest lines through points A and B are oriented in approximate direction of plate convergence.

between two converging plates). If this is so, one might reasonably expect the relative motion between the flanks of the Timor Trough to be the same as the apparent motion between the Southeast Asian and Australian-Indian Ocean plates in this region. However, an examination of shallow earthquake activity in the region (Fig. 4) reveals a marked paucity of events associated with the Timor Trough compared to the Java Trench. This contrast has been discussed by both Fitch (1972) and Cardwell & Isacks (1978), who suggest it indicates reduced under-thrusting in the region of the Timor Trough.

Using data from Deep Sea Drilling Project (DSDP) hole 262, at the western end of the Timor Trough (Fig. 3), in conjunction with seismic reflection, sedimentological, and morphological data, we have estimated past separations and, thus, relative motions between the southern tectonic front of the Banda Arc and the Australian crustal sediments penetrated by DSDP 262. Veevers & others (1978) used this approach and concluded that the relative motion in the trough during the Late Pliocene and Quaternary was 5.8 km/m.y. and 0.55 km/m.y., respectively. This marked slowing down appears consistent with the low level of seismic activity at the trough.

DSDP 262 penetrated 442 m of sediment ranging in age from Pliocene to Holocene (Fig. 5). Five general stratigraphic units have been recognised (Veevers & others, 1974). Units 1 and 2 consist of 337.5 m of fairly uniform clay-rich nanno ooze deposited in an environment similar to that which exists in the Timor Trough today. These sediments were mostly formed as a result of pelagic deposition and deposition of mud from bottom currents (Veevers & others, 1978). Unit 3 is 76.5 m thick and consists of nanno-rich and micarb-rich foraminiferal ooze. The top 52.5 m of this unit suggests a depositional environment shallowing down the core. Immediately below this interval at the 390 m level there is a sudden change in the ratio of benthic to planktic foraminifera, suggesting a rapid change in depositional environment. The abundance of shallow-water benthic foraminifera beneath this level suggests an inner shelf environment. Unit 4 (13 m of shallow-water dolomitic mud rich in foraminifera) and Unit 5 (dolomitic shell calcarenite) both indicate a high-energy shallow-water environment. The hole was terminated after penetrating 15 m of Unit 5.

The distribution of microflora and fauna in DSDP 262 have been reviewed by B.U. Haq (Appendix) and several datum levels have been determined (Fig. 5). Those plotted have each been assigned an error bar attributable to a combination of both sampling error and intervals of uncertainty as detailed in the Appendix. By the application of best-fit straight lines to the datum points, rates of deposition have been estimated for the penetrated sediments. The rates vary between 80 m/m.y. towards the base of the hole and 350 m/m.y. for the top 200 m or so of sediment.

Percentages of sand in DSDP 262, determined by G. W. Bode (1974a) and Thayer & others (1974), show a significant change at 337.5 m (Fig. 5). Of the 123 values derived for the bottom trough sediments (Units 1 and 2), 11 values exceed 10 percent. These values are seen as spikes superimposed on a fairly constant low background, and are thought to represent

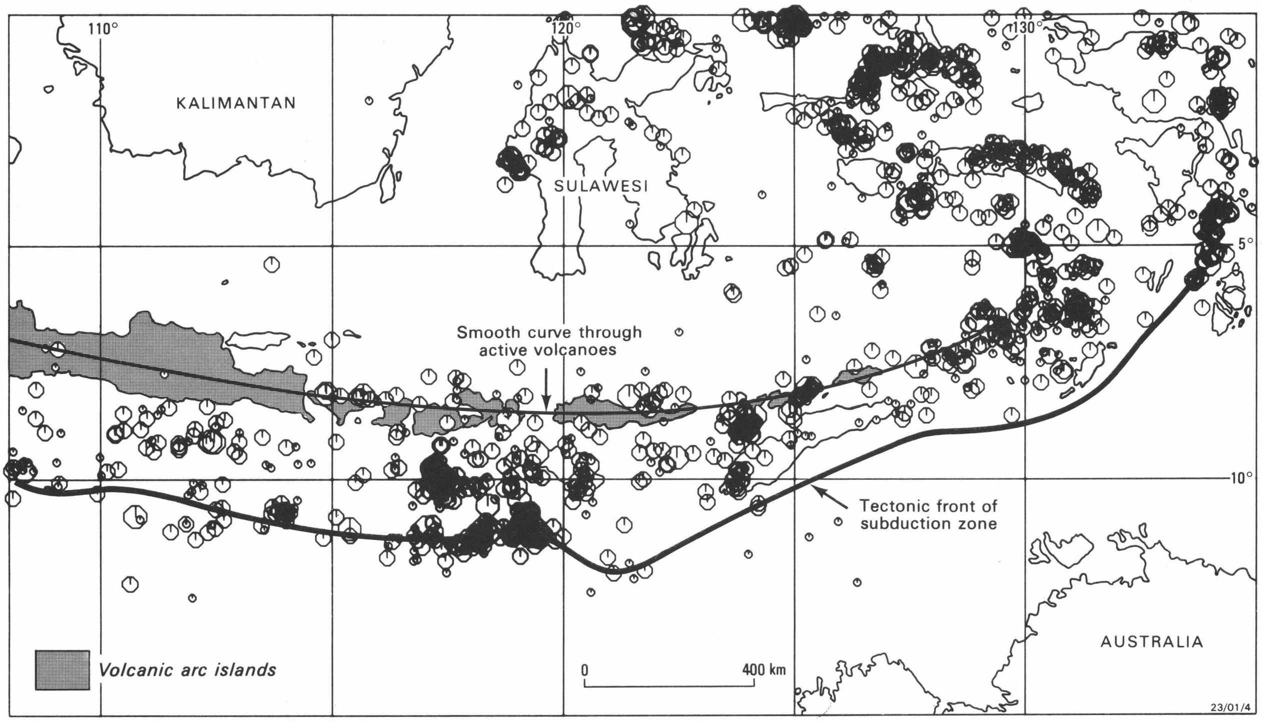

Figure 4. Shallow seismicity (<70 km), showing all events between 1958 and end of 1977 positioned by at least ten seismological stations.

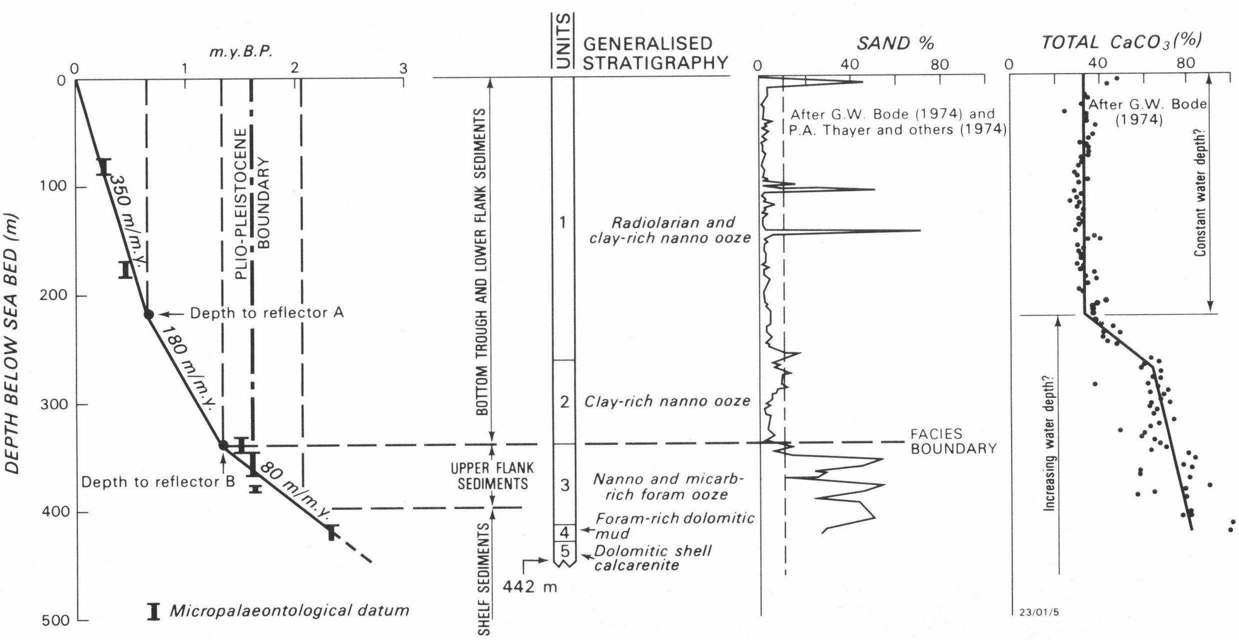

Figure 5. Information from DSDP 262 used to define depositional environments.
Micropalaeontological datums are indicated (see Appendix for details) together with approximate sediment deposition rates.

irregular deposits of material such as turbidity sands (Veevers & others, 1978) or volcanic ash layers (Veevers & others, 1974) which are volumetrically unimportant to the bottom trough sediments as a whole. If these eleven values are rejected, the remainder average 2.42 percent and have a standard deviation of 2.15 percent, whereas the values below 337.5 m vary widely and average 35 percent.

Total calcium carbonate percentage for DSDP 262 (Bode, 1974b) shows a gradual decrease up the hole (Fig. 5) across the 337.5 m mark, and can be interpreted as suggesting continued deepening of the depositional environment. Van Andel & Veevers (1967, fig. 8.1) showed a uniform gradient of calcium carbonate percentage, derived from surface sediments, which decreases with increasing water depth down the southern flank of the Timor Trough. The sudden decrease (up the hole) in the DSDP calcium carbonate percentage at 270 m appears to reflect a corresponding increase in non-carbonate or mud deposition. The per-

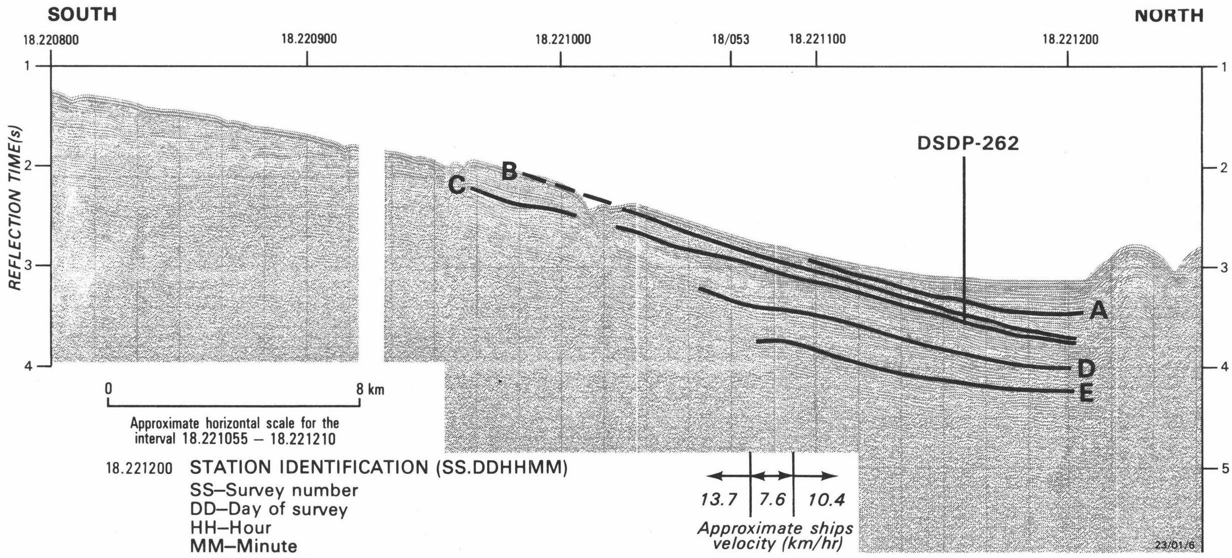

Figure 6. Portion of seismic profile BMR 18/019, showing bottom trough sediments and projected position of DSDP 262.
For location see Figure 3.

centage remains at 30-35 percent above 220 m, suggesting that water depth was fairly constant during the deposition of these sediments.

The deepening of the depositional environment, previously observed in Unit 3 (Veevers & others, 1974), appears to continue through Unit 2 and into the lower part of Unit 1. For this reason, in Figure 5, Unit 3 has been classified as 'upper flank sediments', and Units 1 and 2 as 'bottom trough and lower flank sediments'.

The change in rate and depth of deposition indicates a range of different depositional environments at the DSDP location. Using other local data, it is possible to define boundaries for the major depositional environments encountered in the hole, which can then be used to infer horizontal surface displacements throughout the last 2 m.y. or so.

A north-south seismic profile across the Timor Trough passes within 3 km of the DSDP 262 location (Fig. 3), and a tie was established betwen the two by projecting the hole location along the bathymetric strike onto the seismic line (Fig. 6). The accuracy of the tie was maximised by processing the seismic line navigation data according to Garnett (1975).

The seismic section shows that there is approximately 0.5 s of ponded sediments in the bottom of the trough. North of the trough axis these become progressively deformed, the boundary between deformed and undeformed sediments being quite distinct. South of the trough axis the ponded sediments onlap a sedimentary sequence that has an apparent northward dip of 2.6°. Beneath the ponded sediments are several unconformities (Fig. 6, Seismic Horizons C, D, and E).

The interval between seabed and Seismic Horizon A is seen to thicken towards the trough axis. A similar thickening is also apparent between Seismic Horizons A and B, whereas beneath Horizon B there is no such thickening. In fact, the interval between Horizons B and C apparently thickens slightly up the southern flank, away from the trough axis, suggesting that the lower boundary of the ponded sediments lies near seismic Horizon B. If the 337.5 m thick bottom trough sediments (Units 1 & 2) at the DSDP location are correlated with the seismic interval between seabed and Horizon B, an interval velocity of 1750 m/s is obtained. This is in good agreement with the interval velocity range of 1650-1900 m/s suggested by Veevers & others (1978) for the surface layer beneath the southern flank and axis of the Timor Trough.

Using the 1750 m/s velocity for the ponded sediments, Horizon A intersects the DSDP location at approximately 220 m below seabed. The sediments between the seabed and Horizon A thin onto the southern flank until, in the vicinity of Station 18.221100, Horizon A merges with the seismic wavelet generated by the seabed reflector. From the micropalaeontological datums (Fig. 5) Horizon A can be dated at approximately 0.6 m.y. On the assumption that Horizon A is isochronous, or at least approximately so, rates of deposition can be determined across the bottom of the Timor Trough for the interval between seabed and Horizon A. These deposition rates, which have been determined at approximately 1 km intervals between seismic stations 18.221100 and 18.221200, vary significantly along the line (Fig. 7). They appear to approach, asymtotically, constant values, both on the southern flank and at the trough axis. The depo-

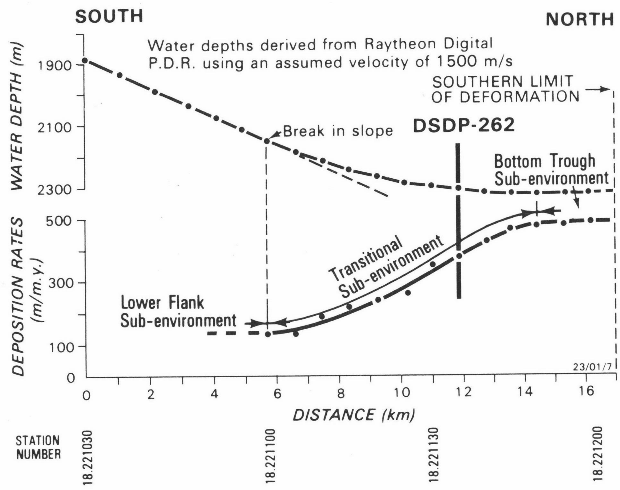

Figure 7. Deposition rates across the bottom trough, showing three depositional sub-environments.
Station numbers as in Figure 6.

sition rates thus appear to define three sub-environments associated with the bottom trough sediments: a trough axis sub-environment, with average deposition rate about 480 m/m.y. during the last 0.6 m.y.; a southern lower flank sub-environment, average deposition rate about 120 m/m.y. over the same period; and a transitional sub-environment within which the average deposition rate has varied smoothly between 120 and 480 m/m.y.

The boundary between the lower flank sub-environment and the transitional sub-environment corresponds to a distinct break in seabed slope, as recorded by a Raytheon digital PDR echo-sounder (Fig. 7), and appears to be the result of the higher sedimentation rate in the transitional sub-environment.

Any recent movement of the tectonic front and associated trough axis should be apparent from a comparison of the rates of deposition for the DSDP sediments and lateral variations in the deposition rates across the trough. The DSDP data (Fig. 5) suggest that the deposition rate during the last 0.6 m.y. (i.e. above Horizon A) has been very nearly constant at about 350 m/m.y. When this is compared with the deposition rates across the trough axis during this time, it appears that, throughout the last 0.6 m.y., the DSDP location has been stationary relative to the bottom trough sub-environments. The average deposition rate 5 km to the south of the DSDP location is approximately 150 m/m.y., and it seems most unlikely that a deposition rate as low as this has existed at the DSDP location at any time during the last 0.6 m.y. The simplest and most likely explanation for this is that, during this time, the DSDP location, and thus the Australian continental crust, has not moved any significant distance relative to the axis of the Timor Trough. The only other explanation is that the depostion rates at the trough axis have changed through time in such a way as to maintain a constant deposition rate at the DSDP location. This seems a most unlikely possibility.

We conclude, therefore, that during the last 0.6 m.y. the relative displacement between the southern tectonic front of the Indonesian subduction zone and the Australian continental crust in the vicinity of DSDP 262 has almost certainly been less than 5 km, and has probably been very close to zero. Thus, the corresponding relative motion between these two features during this time has been less than 10 km/m.y.

Between Units 2 and 3 (337.5 m) there is a change from ponded bottom trough sediments to shallower flank sediments, and it has already been shown that this 337.5 m boundary is closely associated with seismic Horizon B (Fig. 6). Horizon B can be followed up the southern flank of the Timor Trough to a point near station 18.221020, where it merges with the seabed reflector. Extrapolation up the slope suggests that this horizon crops out near station 18.220950. The outcrop is located about 18 km south of the trough axis, in approximately 1500 m of water.

The percentages of sand from the DSDP hole (Fig. 5) have been compared with values from six surface sediment sampling profiles extending across the Timor Trough (van Andel & Veevers, 1967). These data (Fig. 8) show that along the trough axis the percentage of sand is less than 5 percent and along the southern flank of the trough it varies widely, but averages 36 percent. Using an arbitrary value of 5 percent sand for separating the ponded from flank sediments it can be seen that, despite the large separation (approximately 20 km) between the surface sediments sampling stations, ponded bottom trough sediments all lie less than 30 km from the trough axis, in water deeper than about 1500 m. This agrees very favourably with the outcrop position for seismic horizon B, the boundary between ponded bottom trough sediments and shallower flank sediments in DSDP 262.

As previously discussed, the DSDP calcium carbonate percentages (Fig. 5) suggest that when the depositional environment changed from flank to bot-

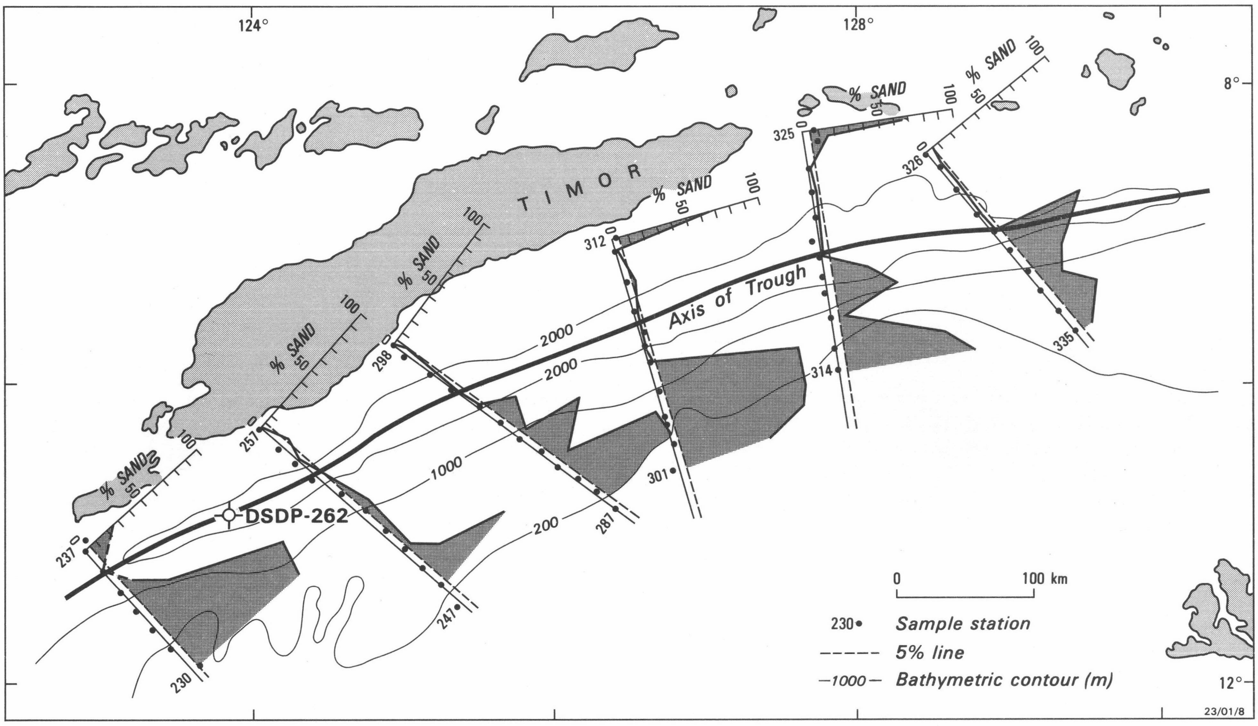

Figure 8. Percentage of sand in surface sediments across the Timor Trough (after van Andel & Veevers, 1967).

tom trough at 337.5 m, the DSDP location was in shallower water than it is today.

The above observations can be interpreted as suggesting that, when bottom trough sedimentation commenced at the DSDP site some 1.3 m.y. ago, the DSDP sediments were located approximately 15-30 km south of a bathymetric trough and, since that time, they have moved north to their present position on the axis of the trough.

The change from flank to shelf sediments is another obvious environmental boundary within the DSDP sediments. This boundary at 390 m below seabed is defined by a rapid increase, down the hole, in benthic foraminifera coupled with a corresponding decrease in planktic forms. This is assumed to indicate a change from an open deep-water environment, seawards of the shelf edge, to a shallow-water shelf environment with its more restricted water circulation. A similar present-day boundary has been observed along the top of the southern flank of the Timor Trough by van Andel & Veevers (1967, fig. 9.4), where the percentage of planktic foraminifera compared to the total number of foraminifera changes by 30 percent over a distance of about 15 km. The present-day boundary is approximately 90 km south of the trough axis and is closely associated with the seaward edge of large reef banks lying seaward of the shelf break. These banks almost certainly have a considerable influence on the local environment, including water circulation, the distribution of sedimentary facies either side of the banks, and the distribution of planktic and benthic foraminifera.

The growth of fringing reefs beyond the shelf break in this area appears to have been a recent development, since there are no known examples of drowned reefs further down the southern flank of the Timor Trough. Therefore, it is suggested that the planktic/benthic foraminiferal boundary in the DSDP sediments was probably more closely associated with the location of the shelf break than is the present foraminiferal boundary. The present shelf break is approximately 120 km south of the trough axis (van Andel & Veevers, 1967; Veevers & others, 1978).

Very shallow water benthic foraminifera were found in DSDP 262 at the base of Unit 3 and throughout Units 4 and 5 (Veevers & others, 1974). If the DSDP foraminiferal boundary was associated with a past shelf break in a similar position to the present shelf break, then the very shallow water environment evident in the DSDP sediments 2-2.5 m.y. ago (<30m) would be in approximately 100 m of water on today's shelf. This large apparent discrepancy can be accounted for by the low sea levels that existed during the Plio-Pleistocene transition (Galloway, 1970; Vail & others, 1977).

From what is known about depositional environments in the Timor Sea today, plus the assumption that flexural characteristics of the continental lithosphere have not varied significantly, either laterally or as a function of time, it would appear that, when the DSDP sediments passed from a shelf to a flank environment about 2.1 m.y. ago (Fig. 5), they were probably 100-140 km south of a bathymetric low, and, since that time, they have moved north, relative to that bathymetric low, to their present position.

The three apparent displacements between the Timor Trough tectonic front and the Australian continent represented by the DSDP 262 location have been plotted on Figure 9a. They have been interpolated with a smooth curve to provide a continuous estimate of relative displacement through time. The relative motion function derived from this displacement curve is plotted on Figure 9b. Over the 2 m.y. period there has been a continuous decrease in relative motion from about 160 km/m.y. to zero.

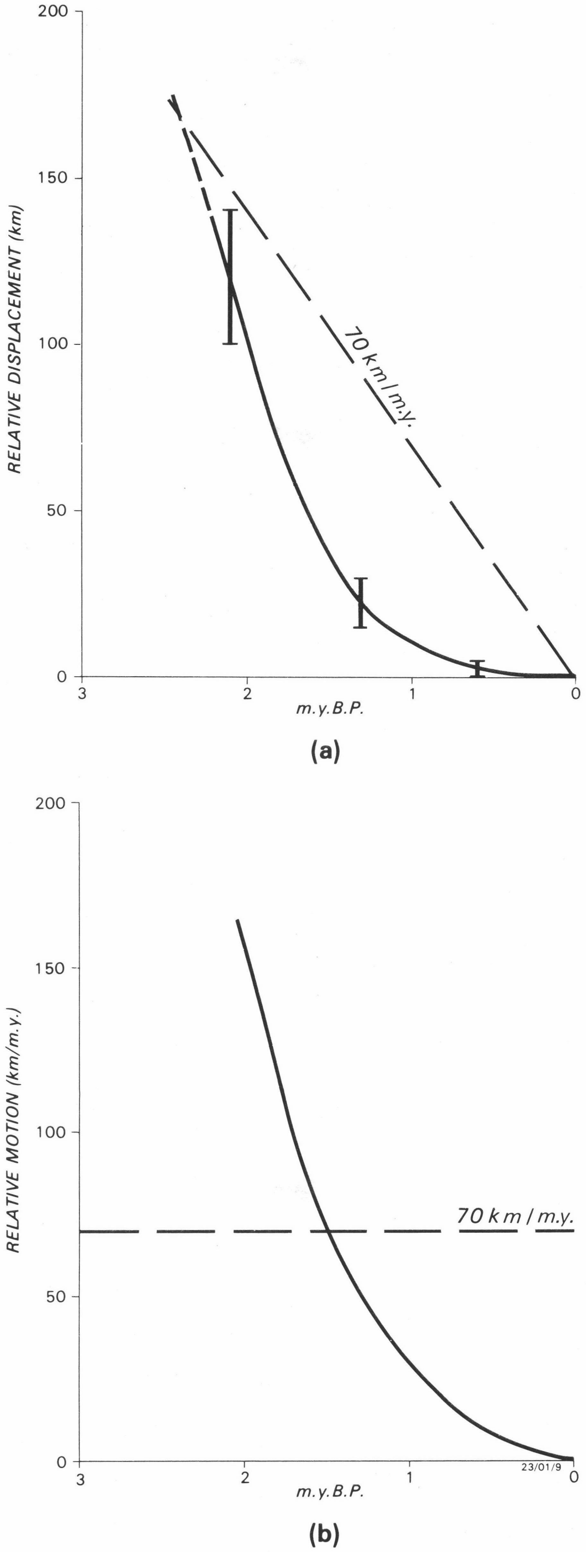

Figure 9. **(a) Horizontal displacement and (b) corresponding motion between the tectonic front of the subduction zone and the DSDP location on Australian continental crust in the vicinity of western Timor.**

An evolutionary link between the Java Trench and Timor Trough

The global solution for relative plate motions derived by Minster & others (1974) predicted that the relative motion at the eastern end of the Indonesian subduction zone in the vicinity of Timor is approximately 70 km/m.y. Isacks & others (1968) have shown empirically that the length down dip of a seismic zone is approximately equivalent to the amount of lithosphere subducted at the plate margin during the last 10 m.y. In the Timor region the down dip length of the seismic zone, as mapped by Cardwell & Isacks (1978), is approximately 800 km, suggesting an average relative plate motion during the last 10 m.y. of about 80 km/m.y. This is in general agreement with the estimate of Minster & others (1974).

The motion we have derived for the Timor Trough appears to have little in common with that derived by Minster & others (1974) (Fig. 9b) except that whichever value is used to calculate the total movement over the last 2.4 m.y., the results are very similar (Fig. 9a).

Could the present near-zero crustal motion at the Timor Trough be explained by absorbing the relative plate motion in some other way apart from simple thrusting at the leading edge of the subduction zone?

If the morphological differences between the Sunda and Banda Arcs, which have already been discussed, are related to the different types of lithosphere that dip into these two regions then it may be proposed that, prior to the collision, the Banda Arc would have been similar in form to the Sunda Arc. If this was the case, the extrapolated small circle fit to the Java Trench (Fig. 1) can be considered as a first approximation for the position of a hypothetical oceanic subduction trench that would exist if continental lithosphere had not entered the eastern end of the Indonesian subduction zone.

Volcanic arcs associated with subduction zones are distinctive features which, over a limited period, can be regarded as fixed on the superposed plate. Therefore, they can be used as fixed points from which to relate horizontal plate and crustal movements associated with the subduction zone.

A number of authors have speculated that the direction of convergence between the two plates in this region is north-northwest (Cardwell & Isacks, 1978; Katili, 1970; Vening Meinesz, 1954; Brouwer, 1919). This apparent convergence direction has been used to construct a diagram of relative displacements through time for this active plate margin (Fig. 10). Point A in Figure 3 lies on the axis of the Timor Trough at the same location as DSDP 262. In Figure 10 horizontal displacements relative to the volcanic arc are plotted for a north-northwest line passing through Point A. As previously discussed, the relative plate motion in this region is about 70 km/m.y. This is portrayed in Figure 10 as a straight line passing through Point A. Therefore, on the assumption that the relative motion has been constant for the last 2-3 m.y., this line represents the location through time of a point on the Australian crust that now lies at the axis of the Timor Trough; i.e. it represents the location of the DSDP sediments.

Point L lies on the extrapolated small circle fit to the Java Trench, (Fig. 3) which, as already discussed, can be considered as a first approximation to the hypothetical location of an oceanic subduction trench. A

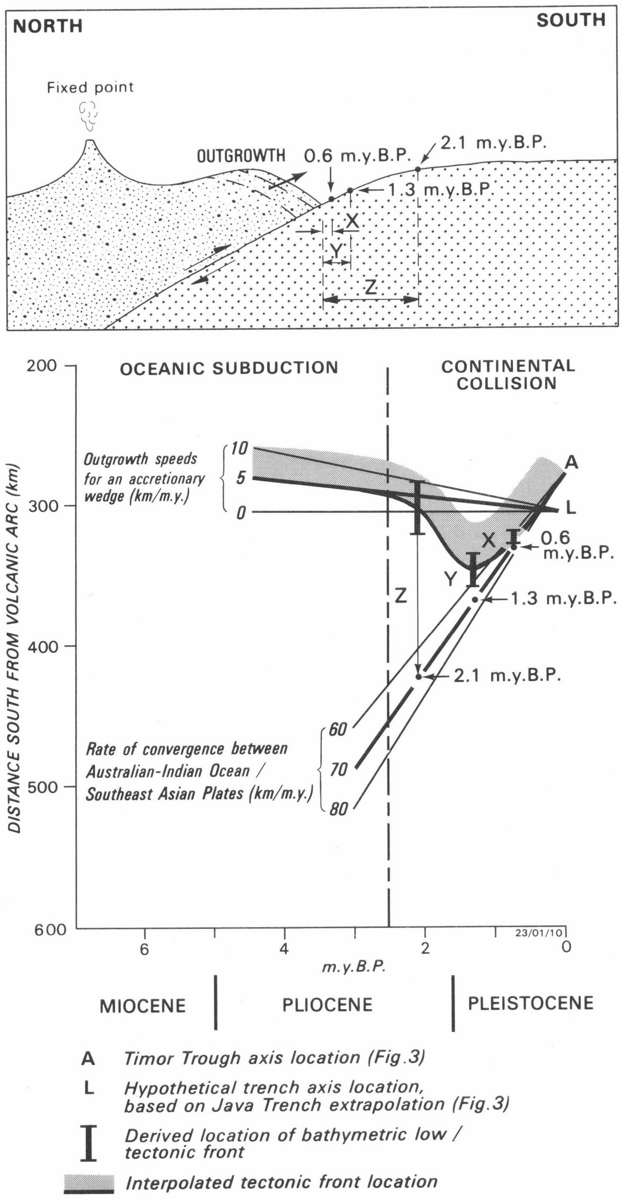

Figure 10. Horizontal displacement between the northern volcanic arc and the southern tectonic front of the Indonesian subduction zone in the vicinity of western Timor.
Derived by combining the apparent relative plate motion, the displacements from Figure 9 and the approximate location of a pre-collision subduction trench.

line representing the approximate outgrowth speed of an oceanic accretionary wedge has been drawn from Point L to indicate the position of this hypothetical subduction trench through time. The proposed outgrowth rate of 5 km/m.y. is based on a paper by Karig & others (1980) in which an Early Miocene (~20 m.y. ago) trench along western Sumatra is located 100 km to the northeast of the Java Trench. Outgrowth rates of 0 and 10 km per m.y. are also indicated on Figure 10. Any value within these limits could well apply equally to the present discussion with little consequence to the results.

From the derived displacements between the DSDP sediments and the southern tectonic front of the Indosian subduction zone, approximate positions can be calculated for the tectonic front relative to the volcanic arc. These have been interpolated to give a curve representing the position of the front through time (Fig. 10). The curve shows that 2.1 m.y. ago the position of the front was nearly the same distance south of the volcanic arc as was the hypothetical subduction trench, suggesting that the Timor Trough and Java Trench share a common origin.

At present, the tectonic front in the Sunda Arc region is at a near-constant distance from the volcanic arc. Eastwards, the front passes the continent/ocean boundary on the western side of the Scott Plateau and begins to move away from the volcanic arc, being furthest from it south of the island of Sawu. Further east the front gradually swings back toward the volcanic arc and is closest to it at the eastern end of Timor.

The similarities between the theoretically derived width for the subduction zone through time at the western end of the Timor Trough (Fig. 10) and the observed variation in width of the present subduction zone (Fig. 1) suggest to us that the southerly bulge in the subduction zone south of Sawu is related to the introduction of continental margin sediments and crust into the subduction system. The implication of this suggestion is that large quantities of continental margin sediments first entered the Indonesian subduction zone near western Timor about 2.5 m.y. ago.

The bulge in the subduction zone south of Sawu, the 'Sawu Bulge', projects approximately 100 km south of the Java Trench trend. It should be noted, however, that the theoretically derived bulge (Fig. 10) is only about half this size. This discrepancy is discussed further on.

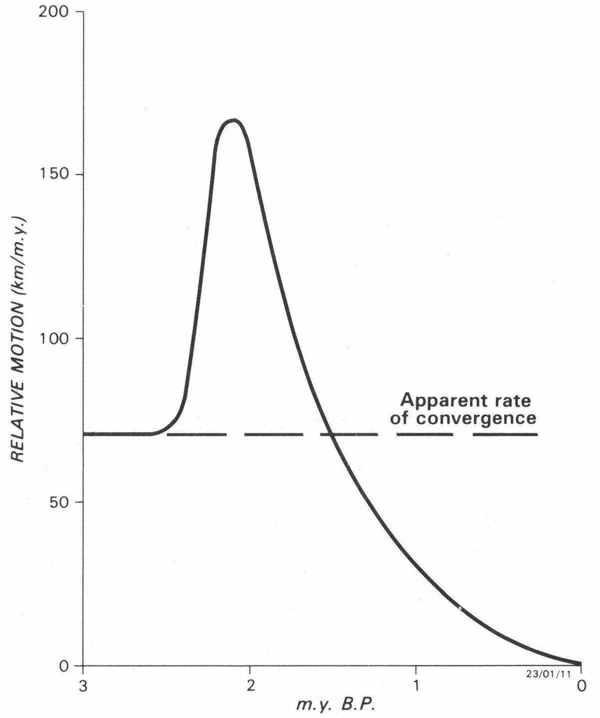

Figure 11. Motion for western Timor region between the southern tectonic front of the Indonesian subduction zone and the DSDP location on Australian continental crust, since pre-collision times.

Development of the 'Sawu Bulge'

To obtain a better understanding of the reasons for the development of the 'Sawu Bulge' (Fig. 3) a curve depicting the relative motion between the Australian continental crust and the leading edge of the subduction zone in the vicinity of western Timor has been derived (Fig. 11) from Figure 10. For the interval 0-2 m.y. ago the relative motion is identical to that depicted on Figure 9b. It can be seen from Figure 11 that, about 2.5 m.y. ago, there was a substantial increase in relative motion, which reached a maximum of about 160 km/m.y. about 2.0 m.y. ago. Since then, the relative motion has been decreasing and has been less than 10 km/m.y. during the last 0.3 m.y.

Figure 12a shows, diagrammatically, the oceanic subduction zone before continental collision. The subduction zone dimensions and crustal thicknesses are based on the Sunda Arc (Curray & others, 1977; Hamilton, 1977). A melange wedge is indicated, and the approaching Australian continental margin is shown as a rifted margin. High-resolution seismic profiles across oceanic subduction zones have permitted some understanding of the development of accretionary wedges (Hamilton, 1977; Talwani & others, 1977): as subducting lithosphere dips into the subduction zone at a trench, some or all of its sediments and possibly some basement material also are accreted to the toe of the wedge, whereas deeper sediments and basement rocks are either thrust beneath the toe and accreted to the wedge from below or are carried even deeper into the subduction zone. The stresses associated with these near-surface processes are absorbed by complete decoupling of surface material from the subducting lithosphere. When a continental margin, similar to the one shown on Figure 12a, first comes into contact with the subduction zone, then, in a manner similar to oceanic subduction, the near-surface sediments are added to the toe of the accretionary wedge, whilst the deeper more coherent sediments are thrust beneath the wedge and accreted to it from below. However, owing to their increased thickness and rigidity compared to oceanic sediments, continental sediments are not easily stripped from the underlying crust, and, as a result, the near surface stresses increase, causing a basic change in the near-surface processes.

Montecchi (1976) pointed out that, the greater the thickness and rigidity of sediments, the better their ability to transmit compressive stresses laterally. Therefore it seems reasonable to expect that following the start of collision, increasing near-surface stress would cause the crustal deformation front to move forward onto the subducting plate (Fig. 12b), resulting in the formation of a large deformation wedge of continental margin sediments at the leading edge of the subduction zone, and explaining the movement of the tectonic front away from the volcanic arc. With time it would become increasingly difficult for near-surface stresses to be transmitted through the growing wedge of deformed sediments along the leading edge of the subduction zone, and, consequently, the advance of the tectonic deformation front over the subducting plate would slow. This effect is evident on Figure 11 where the relative velocity begins to decrease from about 2.1 m.y. ago. Plate interaction at depth in the subduction zone between the continental lithosphere, which resists subduction, as a consequence of its buoyancy (McKenzie, 1969), and the superposed plate might also contribute to this reduction in the rate of advancement of the deformation front.

As the tectonic front slows, continuing plate motion would result in increasing near-surface compressive stress. This stress appears to be absorbed within the

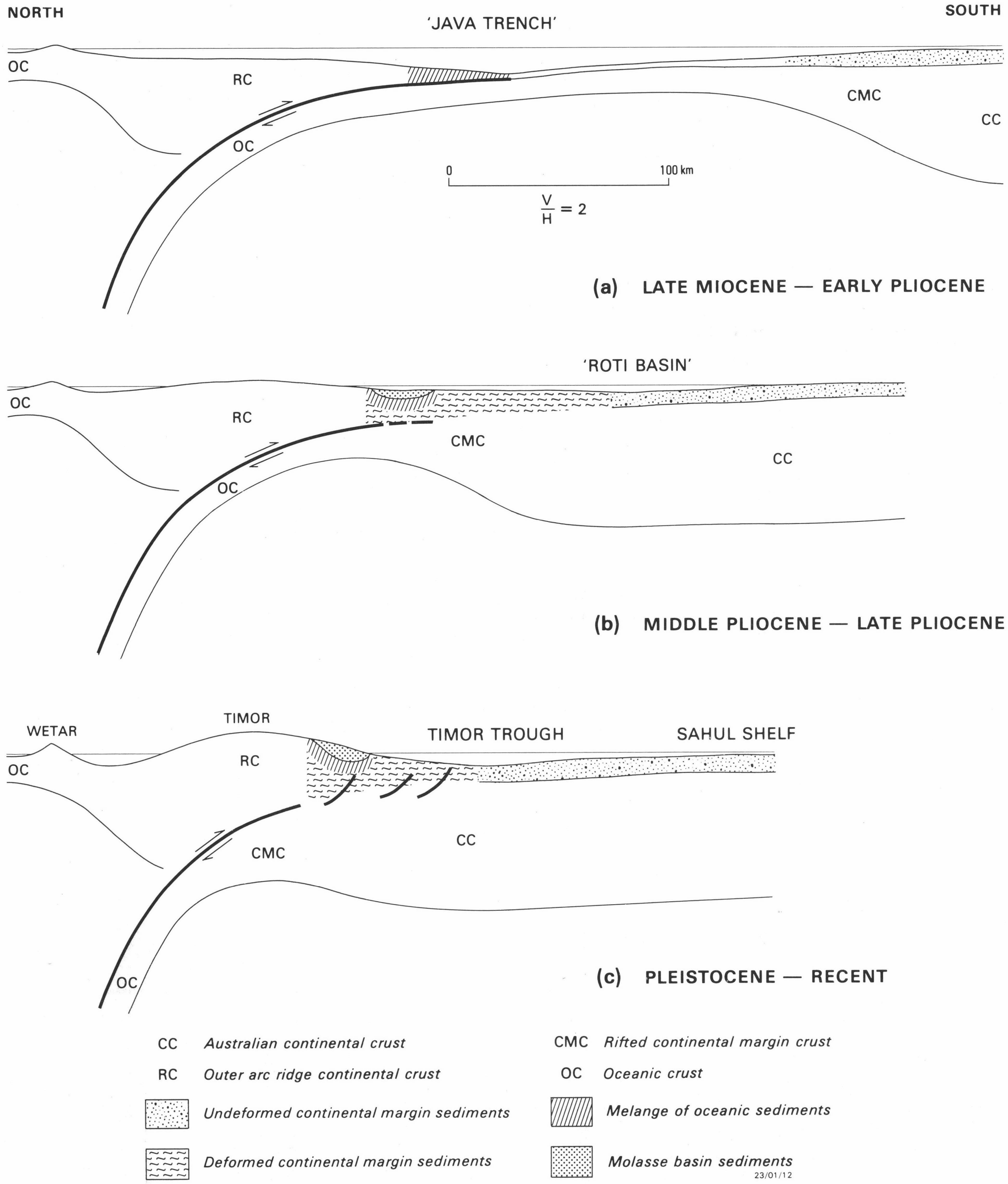

Figure 12. Cross-sections depicting the continent-island arc collision in the Timor region.

subduction zone. Once the advance of the deformation front drops below the actual plate convergence rate, the tectonic front together with its associated bathymetric low is carried by the subducting plate back towards the volcanic arc, compressing the subduction zone and reducing its surfaces width. The increase in stress caused by this change is presumably absorbed by increasing the crustal thickness of both the deformation wedge and the leading edge of the superposed plate (Fig. 12c). In the vicinity of western Timor the surface width of the subduction zone has been decreasing throughout the last 1.5 m.y.

Free-air gravity data show distinct elongated low anomalies of approximately 100 mGals over the northern flank of both the Java Trench and the Timor Trough, presumably reflecting the depression of the southern lithosphere into the subduction zone (Indian Ocean Atlas, 1975; Bowin & others, 1980). However, south of Sawu, where the subduction zone bulges southwards, there is a gap in this distinct gravity trend, with the free-air anomaly values being around zero. A possible explanation for this is that growth of the wedge of deformed continental margin sediments has uplifted the oceanic accretionary wedge and filled the subduction trench, thus masking the gravity anomaly caused by depression of the subducting lithosphere. This hypothesis was tested by computing the gravity effect of an elongated wedge of sediments with the cross-section of an inverted isosceles triangle 100 km wide and 2 km thick at its apex. The top of the sediments was assumed to be 1 km below sea level and the density contrast compared to sea water was 1.17 t/m^3. The resulting sea-level free-air anomaly has a maximum value of 86 mGals. Clearly, a wedge of sediments of approximately these dimensions and density contrast is capable of masking the negative anomaly normally associated with the leading edge of an active subduction zone. Subsequent compression of the subduction zone, following the reduction in growth of the deformation wedge, would result in further depression of the leading edge of the continental lithosphere and the re-establishment of a free-air gravity low along the northern flank of the Timor Trough.

Tectonic developments in the vicinity of Eastern Timor

Point B is located on the axis of the Timor Trough near the eastern end of Timor (Fig. 3). An evolutionary curve similar to that derived at Point A can be constructed for the development of the Timor Trough at this location (Fig. 13). This is accomplished by using the width of the subduction zone at point B together with the hypothetical subduction trench position at this point (M) plus the same relative plate motion and accretionary wedge outgrowth rate as were used for western Timor (Fig. 10). The general shape of the curve derived for Point A was then fitted to these data resulting in a curve depicting the evolutionary position of the tectonic front and associated bathymetric low for the subduction zone at Point B. This curve is shown on Figure 13 as a dashed line.

When interpreted the same way as was done for point A the evolutionary development of the bathymetric low at point B suggests that collision with the Australian continental lithosphere began about 4 m.y. ago. However, it can be seen from a series of crustal profiles constructed perpendiular to the subduction zone to depict various stages of such a collision (Fig. 12), that the degree of crustal shortening needed to allow for continuing relative plate motion after collision cannot be accommodated in the present subduction zone (Fig. 12c) without requiring the subduction of considerable quantities of continental lithosphere into the mantle; this suggestion is untenable to us. This problem can be resolved, simply, by reducing the assumed width of the hypothetical subduction zone at point B by approximately 100 km (Fig. 3). The prefered hypothetical trench position for point B is indicated as M′, and it can be seen that, by maintaining linear continuity with the Java Trench, the hypothetical position assumed for point A is probably in error by about 50 km. The preferred offset at point A (L′) increases the size of the evolutionary southerly bulge to a size similar to that of the present Sawu bulge. In Figure 13 point M′ represents the revised trench offset and the solid curve represents the corresponding evolutionary position of the tectonic front at this location. This curve suggests that the continental collision commenced about 3 m.y. ago.

At point B (Fig. 3) the southern flank of the Timor Trough is seen to dip north at approximately 5°. This is about twice the dip observed south of point A. Also at point B the water depth to the top of the northward-dipping continental margin sediments is about 3300 m, some 500 m deeper than the equivalent at point A. According to Cardwell & Isacks (1978), the 100 km depth contour on the subducted lithosphere in this region is almost directly beneath the volcanic arc. Since point B is closer to the volcanic arc than point A, the steepening and deepening of the top of the Australian continental lithosphere at point B may reflect the increased northerly tilt of the subducting plate required to maintain continuity with the previously subducted lithosphere at depth.

A collision model for the Timor region

By combining the convergent plate motion for the eastern Indonesian arc with apparent horizontal surface motions from the western Timor Trough, a model for continent-island arc collision in the Timor region has been developed.

Figure 12 depicts three stages for the development of this model. These cross-sections have been drawn to scale, in an attempt to ensure that the model can account for the relative plate motion that has occurred since the start of the continental collision. This is an important requirement, for, with the continuity that exists between the subduction zone features of the Sunda and Banda Arcs, it is difficult to conceive how there can be any significant difference in the relative plate motions associated with these two portions of the same plate boundary. This plate motion has been taken up within the subduction zone bearing in mind the following constraints: pre-collision subduction trench location (Fig. 3); pre-collision topographic levels within the subduction zone (Kenyon, 1974); present topographic levels; established crustal thick-

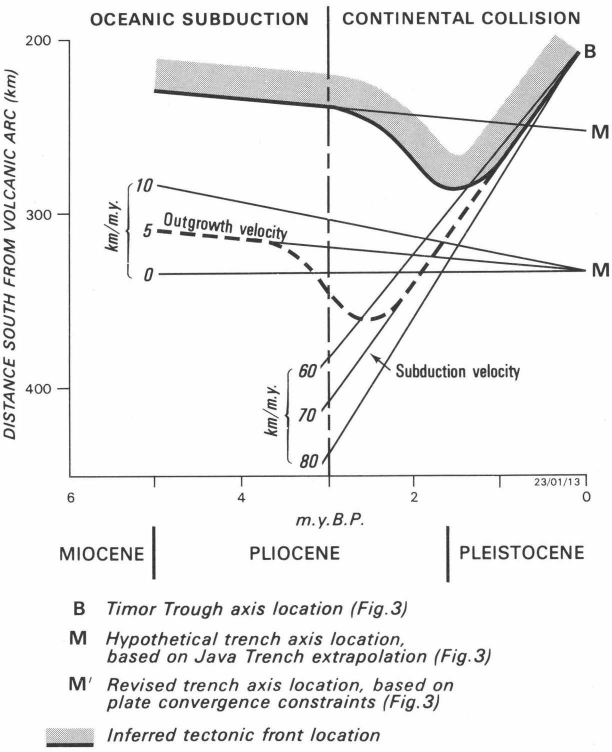

Figure 13. Horizontal displacement between the northern volcanic arc and the southern tectonic front of the Indonesian subduction zone in the vicinity of eastern Timor.

nesses either side of the subduction zone (Bowin & others, 1980); approximate crustal thickness within the pre-collision subduction zone (Curray & others, 1977), and the requirement that subduction of continental crust into the mantle is not acceptable (McKenzie, 1969).

The model suggests that the Australian continental crust first entered the eastern end of the Indonesian subduction zone approximately 3 m.y. ago or mid-Pliocene. The resulting influx of thick, coherent continental margin sediments into the subduction zone initiated a change in the sediment accretion processes. A deformation or tectonic front, separating deformed from undeformed continental margin sediments, moved rapidly up the continental slope. In this way a large wedge of deformed continental margin sediments formed along the leading edge of the superposed plate on top of the subducting continental margin. At the same time as the deformation wedge was developing the previously rifted margin of the Australian continental lithosphere was gradually being depressed into the subduction zone, as it followed the oceanic lithosphere that had been subducted ahead of it.

Ultimately, the sheer size of the deformation wedge which appears to have developed to a maximum width of about 100 km, resulted in it acting as a stress barrier, gradually slowing the southwards advance of deformation further onto continental Australia. When the movement of the deformation front decreased to less than the relative plate motion the front began to be carried northwards on top of the Australian-Indian Ocean plate. At present the southward motion of this deformation front, which is coincident with the Timor Trough, is less than 10 km/m.y. in the vicinity of western Timor compared to 70 km/m.y. for the estimated relative plate motion in this region. Most of the stress resulting from continuing convergence between the two plates has been absorbed within the subduction zone by crustal shortening. This shortening has been accommodated principally by thickening of the deformation wedge and possibly the southern edge of the superposed plate.

In accordance with our model, the Timor Trough coincides with a tectonic boundary separating a wedge of deformed, but autochthonous, continental margin sediments from the depressed margin of Australia. It cannot be regarded as a shallow equivalent of a classical subduction trench, since it no longer represents the surface trace of an active thrust boundary separating two lithospheric plates. Such a boundary no longer crops out within this collision zone. Despite its developmental link with a subduction trench it may now be regarded as an intracontinental feature.

A plot of shallow seismic events in the region, whose computed depths are less than 70 km, is shown in Figure 4. It was produced from the BMR data file and includes all events between 1958 and 1977 that have been positioned by at least 10 seismological stations. The BMR data file includes events compiled from the International Seismological Summaries (1918-1963), the United States Coast & Geodetic Survey (and its successors), the Bulletins of the International Centre, and the Australian seismological network. In the production of this plot there has been no rejection of events on the basis of azimuthal coverage, as was done by Cardwell & Isacks (1978).

In considering the distribution and intensity of events, it should be remembered that the relative plate movement during the period in which these events were recorded has been about 1.4 m only. This being so, the distribution of events should only be used for regional analysis, for there is probably little that can be inferred from local variations. The first point to notice is that, clearly, the events are concentrated along the Banda and Sunda Arcs, with little difference in the overall intensity of events associated with the two arcs. Secondly, there have been many more events along the Java Trench than along the Timor Trough (Fitch, 1970; Cardwell & Isacks, 1978). This observation is in accord with our model, which suggests that little if any relative motion is currently occurring at the trough. The seismic events beneath Timor and beneath the region between Timor and the volcanic arc probably result from a variety of crustal and upper mantle stresses. These stresses include those in and associated with the subducted oceanic lithosphere and those resulting from compression of the subduction zone.

Oceanic lithosphere is still descending into the mantle beneath Timor, and the Banda Arc can in one sense still be regarded as an active subduction zone. However, the amount of additional plate motion that the model can accommodate without requiring the extension of continental margin crust into the mantle is extremely limited (Fig. 12c). Therefore, it appears that simple compression of the subduction zone, as a means of absorbing the relative plate motion, is approaching a crisis point and that when this is reached northward subduction will cease and new tectonic processes will evolve to accommodate the plate motion.

Brouwer (1942) interpreted certain morphological features in the vicinity of Wetar as indicative of a northwards displacement of this island relative to the other inner-arc islands to the west. Northeast of Alor and north of Wetar, there is an elongated free-air gravity low and associated bathymetric low that parallel the volcanic arc (Bowin & others, 1980), and seismic reflection data indicate deformation of shallow crustal material in this region. It is interesting to note that the smooth curve through the volcanic arc (Fig. 15) passes south of Wetar and thus also supports the possibility of a northwards displacement for this island. In accordance with the model these data are interpreted as suggesting recent crustal shortening along the northern side of Alor and Wetar, which again implies that the proposed subduction zone compression model is approaching a crisis point.

Geological and geomorphological support for a mid-Pliocene start of collision

During recent years there have been a number of publications on the geology of Timor which differ widely in their broad interpretations of this complex island. Fitch & Hamilton (1974) proposed that Timor can be regarded as a chaotic complex of imbricated and mainly allochthonous rocks and melange derived from Australia's continental margin during the collision and forming an outer-arc ridge within the subduction zone. In addition, they regarded the Timor Trough as a shallow subduction trench. Carter & others (1976) viewed the geology as representing a deformed Australian continental margin overthrust from the north by several allochthonous units. Crostella (1977) interpreted the Timor rocks without the requirement for a continental collision. Instead, he suggested that the Timor Tertiary orogenies occurred in a geosynclinal trough along the northwest margin of Australia.

Finally, Chamalaun & Grady (1978) suggested that prior to a mid-Miocene collision all the Timor rocks belonged to the Australian continental margin, and following the collision, the continental lithosphere separated from the previously subducted oceanic lithosphere, giving rise to the Late Pliocene to Recent uplift of Timor by isostatic rebound.

Despite the conflict of ideas concerning the origin of Timor's geology, there are a number of specific geological observations which, when combined with our model, result in a simple and comprehensive picture of the development of this region during the Neogene.

The Kolbano Unit, which is found along the south coast of Timor, consists of bathyal radiolarites, calcilutites, and cherts, ranging from Cretaceous to Early Pliocene. It is folded recumbently, and contains many thrusts and imbricate faults, and now overlies less-deformed Australian continental sediments (Barber & others, 1977). In a general sense, these sediments become younger, less siliceous, and more calcareous to the south (Carter & others, 1976), and may well represent deep-sea equivalents of similar sediments found on the northwest shelf of Australia (Chamalaun & Grady, 1978). Carter & others, (1976) interpreted them as having been scraped from oceanic crust and imbricated into an accretionary prism prior to the continental collision.

The Late Miocene Bobonaro Olistostrome is widespread on Timor, having been emplaced as a huge gravity slide that moved from north to south. It consists of exotics within a clay matrix. The exotics, which range from pre-Permian to Late Miocene, have been derived from all the underlying continental rocks on Timor (Carter & others, 1976b). The high percentage of montmorillonite within the matrix suggests that the clay was derived from submarine weathering of volcanic ash (Audley-Charles, 1968). It appears that the olistostrome developed in response to southward tilting of Timor. On the southern side of Timor it contains rafts of deep-sea red clays of Cretaceous age. These contain manganese nodules similar to those now found in water 3500-5000 m deep (Audley-Charles, 1972; Margolis & others, 1978).

The Viqueque Group represents the most recent sedimentary sequence on Timor. It overlies the Bobonaro Olistostrome and is Late Miocene to Recent. The Late Miocene to Late Pliocene Batu Puti Limestone at the base of the Viqueque Group is widely distributed and appears to have been deposited over most of the island. The calcilutite sediments which make up the bulk of this formation suggest a deep water depositional environment during the Late Miocene and Early Pliocene (Kenyon, 1974). However, in the mid-Pliocene, the environment shallowed significantly and, in the south, the Batu Puti Limestone Formation is terminated by a strong unconformity, the result of a period of compressive folding in the Late Pliocene. The influence of this deformation phase diminishes northwards, and in the centre of the island the depositional sequence throughout this period is conformable (Audley-Charles & others, 1972; Crostella & Powell, 1976). The Viqueque Group turbidites, which were deposited on top of the Batu Puti during the Late Pliocene and Pleistocene, are restricted to elongate basins which parallel the strike of the island and are located in the southern half.

The fact that the Batu Puti Limestone Formation is present over most of the island suggests that, apart from a few possible isolated areas, Timor did not become emergent until the Late Pliocene (Kenyon, 1974). Since that time the island has been uplifted by about 3 km. This uplift is also evidenced by the raised Pleistocene reef terraces at altitudes as high as 1300 m (Katili & Soetadi, 1971). The uplift has given rise to intensive, near-vertical faulting, including reversed faulting, and some minor folding, which add considerably to the complexity of the island geology.

The above geological observations fit our model in the following way. During the Late Miocene, the Bobonaro Olistostrome began to develop when Timor tilted sharply to the south in response to the onset of rapid subduction along the eastern end of the Indonesian subduction zone (Johnston, 1981). At the southern edge of this subduction zone, sediments were scraped from descending Cretaceous oceanic crust and incorporated into the olistostrome. For the remainder of the Miocene and the Early Pliocene, almost all the Timor rocks formed part of an outer-arc ridge or basin associated with an oceanic subduction zone. The Batu Puti Limestone Formation and the Noil Toko Formation (Barber, 1979) were deposited in this subduction zone as outer-arc basin, outer-arc ridge, or inner-slope basin sediments. Some of these sediments are stratigraphically equivalent to the Upper Miocene to Pleistocene deep-water limstones and marlstones of the Savu Basin (Crostella, 1977). Prior to the mid-Pliocene, the Kolbano Unit developed as an accretionary wedge of oceanic sediments at the leading edge of the subduction zone (Fig. 12a). These sediments were probably largely derived from the region of thickest sediment adjacent to the Australian margin. The Bobonaro Olistostrome contains exotics derived from these deep water sediments (Carter & others, 1976b), suggesting that olistostrome deposits continued to develop during the Early Pliocene.

In the mid-Pliocene, the continental margin of Australia entered the subduction zone, the Kolbano Unit was uplifted by the underthrusting of the Australian continental margin sediments and crust, and a wedge of deformed continental margin sediments began to develop (Fig. 12b). The stresses associated with these initial collision reactions gave rise to the middle to late Pliocene Timor uplift to about sea-level and the folding orogeny throughout southern Timor (Carter & others, 1976; Crostella & Powell, 1976).

Continuing plate motion during the early part of the Late Pliocene formed molasse basins in the vicinity of the pre-collision plate suture line. The structural bond between the deformed wedge and the underlying continental crust resulted in the wedge material on the southern side of the suture line being depressed and tilted towards the north as it moved northward on top of the continental lithosphere. North of the suture line the uplifted outer-arc ridge acted as both a northern boundary and sediment source for the developing molasse basins. This development accounts for the northern growth-fault boundary of the molasse basins which contrasts with the southern onlap boundary (Crostella, 1977).

With the decrease in motion at the Timor Trough during the Late Pliocene and Pleistocene, the subduction zone was compressed. This resulted in the rocks that originally formed the pre-collision outer-arc ridge being further elevated by crustal thickening or underthrusting or both. The deformed wedge along southern Timor was also compressed and thickened during this period. However, these rocks were simultaneously being depressed into the subduction zone along with the Australian margin. Therefore, the resultant rate of uplift for southern Timor was less than for northern Timor. Southern Timor did not become emergent until the late Pleistocene.

Audley-Charles & Hooijer (1973) produced zoological evidence for the existence of a subaerial connection between Timor and the inner volcanic arc in the Early to mid-Pleistocene. They suggested that the Wetar Strait, which is approximately 3 km deep, was formed during mid-Pleistocene to Recent times. This is clearly possible, using our model (Fig. 12): although no subaerial connection is shown, considerable crustal subsidence in the region of Wetar Strait is suggested for Pleistocene to Recent times. Mid to Late Pleistocene subsidence for the Wetar Strait has also been proposed by Kenyon (1974) from his study of the Viqueque sediments.

During Late Pliocene to Recent times the Alor/Wetar portion of the volcanic arc was differentially uplifted with respect to the rest of the volcanic arc. This is evidenced by the cropping out of both Miocene and Pliocene submarine volcanics and the elevation of Pleistocene reef terraces in this region (van Bemmelen, 1949; Katili & Soetadi, 1971; Chappell & Veeh, 1978). This differential uplift of approximately 1 km followed the cessation of volcanism in this portion of the arc approximately 3 m.y. ago (Abott & Chamalaun, 1978). Two other Neogene continent-island arc collisions have been studied: the Early Miocene New Guinea collision (Jaques & Robinson, 1977) and the Late Miocene Taiwan collision (Bowin & others, 1978). It is significant to note that in both cases volcanism ceased at the time of collision and the volcanic arc was subsequently uplifted.

In 1917 Brouwer (1919) mentioned several peculiarities of the Timor region that are relevant to our model. He drew attention to the fact that the outer arc is concave towards the Australian continent, whereas the inner arc is convex in this direction. He recognised that the outer arc appeared to have adapted itself to the shape of the Australian continental block, and hypothesised that this implied relative movement of the volcanic arc towards continental Australia, resulting in the mountain-building processes evident on Timor. These processes, he suggested, intensified in the Plio-Pleistocene and probably still continue. He also noted the absence of active volcanism along that portion of the inner arc which is closest to the Australian continent (Fig. 1), and suggested it is the result of compression of the inner arc brought about by the continental collision, which severed the connection between the magma chamber and the surface. Compression and uplift of the Alor/Wetar portion of the inner arc is consistent with our model and is suggested as the reason for the absence of active volcanism on these islands.

Whitford & others (1977) have produced evidence that the inner arc volcanics throughout the southern Banda Arc have been contaminated by continental crust. Their preferred explanation is that the contaminant was subducted and incorporated into the magma at a depth of about 100 km below the volcanic arc. It is unlikely that the time-lag associated with the process of subduction, magma genesis, and the upwelling of this magma to the surface could be less than 6-10 m.y. Therefore, any suggestion that this contamination process occurred subsequent to collision is incompatible with our model. A possible explanation consistent with our model is that the contaminant was derived from the continental outer-arc ridge by tectonic erosion during or after, or both during and after, the onset of rapid subduction in the Late Miocene, and carried into the mantle with the oceanic lithosphere.

Tectonic implications for Northern Timor continental rocks

Probably the most significant implication of our model concerns the origin of rocks lying north of both the accretionary melange rocks of the Kolbano Unit and the molasse sediments of the Viqueque Group. According to the model, these northern Timor rocks formed part of the basement of the outer-arc basin and outer-arc ridge of the oceanic subduction zone that existed before the start of the continental collision in the mid-Pliocene (Fig. 12a). The outer-arc ridge of the pre-collision subduction zone was approximately 20 km thick and 100 km wide. Its existence is postulated from the preferred location of the hypothetical subduction trench (Fig. 3), the required continuity of the subducting plate with the seismic zone beneath and north of the volcanic arc (Cardwell & Isacks, 1978; Johnston, 1981), and the interpretation of the geology of southern Timor (Carter & others, 1976; Kenyon, 1974).

The northern Timor rocks, which are mostly indicative of continental crust, display considerable evidence of having been associated with an active plate margin well before the start of the continental collision, possibly since Late Cretaceous times. The Late Miocene Bobonaro Olistostrome (Carter & others, 1976) contains clasts, some of which are several metres in diameter, derived from the underlying continental rocks. These exotics are mixed with volcanic ash and deep sea lutites and were clearly formed in an extremely active tectonic environment. In addition, there are Palaeocene and Eocene tuffs and volcanics, and the Late Cretaceous to Palaeocene flysch sequences, containing coarse boulder conglomerates with clasts of Permian limestone and volcanics (Carter & others, 1976), which suggest an active tectonic environment during the Late Cretaceous and early Tertiary. This contrasts sharply with the stable deep-water environment in which Kolbano Unit sediments of southern Timor were deposited during the same period.

During the Cretaceous and early Tertiary, the Australian continental margin gradually subsided, following Late Jurassic rifting (Heirtzler & others, 1978). The Cretaceous and lower Tertiary rocks of northern Timor have no similarity to rocks of equivalent age on the Australian continental margin. Carter & others (1976) attempted to explain the northern Timor Cretaceous to lower Tertiary rocks by having them emplaced as part of several thin thrust sheets derived from the north. However, the work of Grady (1975), Chamalaun & others (1976), Grady & Berry (1977), and Chamalaun (1977a, b) has disputed the existence of low-angle thrust sheets in northern Timor. Their work suggests that there are structural, stratigraphic, and palaeomagnetic links both between the various 'thrust' units and between the 'thrust' units and the underlying rocks. The suggestion of a common origin for the northern Timor rocks is consistent with the model proposed in this paper. However, crustal shortening since the onset of collision, as required by the model (Fig. 12), does not preclude some low-angle thrusting with a maximum horizontal displacement of a few tens of kilomertes.

There is one disconcerting aspect of the continental rocks of northern Timor, and that is that the pre-Cretaceous components appear to have a close affinity to northern Australian rocks of the same age. The relationship has been inferred from stratigraphic, palaeontological, and palaeomagnetic evidence (Crostella & Powell, 1974; Chamalaun, 1977a,b), and has been accounted for in two different ways, both consistent with our model: Bowin & others (1980) have suggested that the Australian continental rocks were derived from a 'Greater Sula' spur, which moved into the region after the Palaeogene continent-island arc collision in New Guinea. Johnston (1981), on the other hand, has suggested that they were rifted from northwest Australia in the Late Jurassic and have formed part of the Southeast Asian complex since the Cretaceous. This Late Jurassic rifting is reflected in the stratigraphic section from both north and south Timor, where the depositional environment underwent a major change from restricted to open marine conditions (Audley-Charles, 1968; Audley-Charles & others, 1979). Earle (1979) suggested that the ophiolite-spilite complex of the Lolotoi Unit, lying north of the accretionary wedge, was emplaced during Middle to Late Jurassic rifting from the Australian continental margin, and that subsequent metamorphism, producing greenschist facies, occurred during the accretion of this continental block onto the leading edge of the Southeast Asian plate.

The island of Sumba, located towards the northern side of the subduction zone, in a position that would normally be occupied by an outer-arc basin (Fig. 1), clearly forms part of the leading edge of the Southeast Asian plate. Sumba, like northern Timor and other outer-arc islands further east, has an origin linked to the Australian margin (Audley-Charles, 1975) and is believed to have formed part of the outer Banda Arc prior to the continent/island-arc collision (Bowin & others, 1980).

Relative plate motions and the pre-collision Australian continental edge in the Timor region

For reasons already discussed, a relative plate motion of 70 km/m.y. was assumed for the purpose of deriving our model. Cardwell & Isacks (1978) studied and mapped the seismic zone associated with the Banda Arc, and concluded, with the aid of a specially constructed subduction model, that the direction of convergence between the Australian-Indian Ocean plate and the Southeast Asian plate is north-northwest. This was suggested also by Brouwer (1919), Vening Meinesz (1954), Katili (1970), and Bowin & others (1980).

Using the magnitude of 70 km/m.y. and a north-northwest direction for plate convergence in the Timor region, a velocity vector diagram has been constructed (Fig. 14). Included in this is a vector based on a derivation of the motion between the Eurasian and Australian-Indian Ocean plates by Minster & others (1974). The east-west resultant vector implies that, in this region, the Southeast Asian plate is moving eastward at about 60 km/m.y. relative to the Eurasian plate, which is in general agreement with the qualitative study of plate motions in the Southeast Asian region by Terman (1977), who suggested that the Southeast Asian plate is rotating anticlockwise relative to Eurasia, about a pole located east of Taiwan in the Philippine Sea. Molnar & Tapponnier (1975) suggested also that the India/China continental collision is causing much of Southeast Asia to move southeast along numerous transcurrent faults.

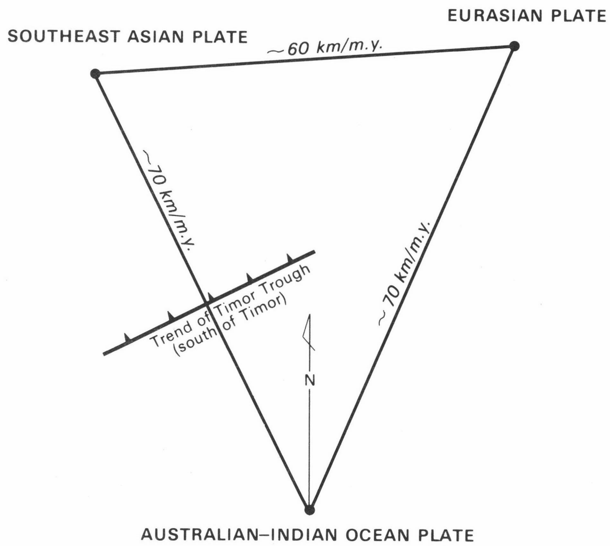

Figure 14. Vector diagram depicting the motion of the Southeast Asian plate relative to both the Eurasian and Australian-Indian Ocean plates in the Timor region.

The apparent relative velocity vector between the two plates at Timor and our collision model have been used to locate the approximate pre-collision Australian continental edge to the north-northwest of points A and B in the Timor Trough (Fig. 15). These edge locations (shown as asterisks on Figure 15) were positioned from the preferred hypothetical subduction trench axis, using the amount of plate convergence that has occurred since the start of collision. In conjunction with the continent-ocean boundary west of Scott Plateau, the positions give an indication of the pre-collision shape of the continental edge of Australia. East of Timor, little is known about this pre-collision shape. However, preliminary evaluation of a gravity profile west of the Aru Islands suggests that the continental crust does not extend beyond the eastern flank of the Weber Deep (Bowin & others, 1980). Therefore, east of Timor the continental edge has been tentatively oriented along an east-northeast trend.

The location of the 3 m.y. old subduction trench axis has also been plotted on Figure 15. The relation between this axis and the continental edge implies that the continent-island arc collision began in eastern Timor and subsequently spread east and west.

In accordance with our model, compression of the subduction zone and the associated uplift of the outer-arc ridge largely depends on the development of a wedge of deformed continental margin sediments along the leading edge of the superposed plate. As this wedge grows, it becomes an increasingly effective barrier to

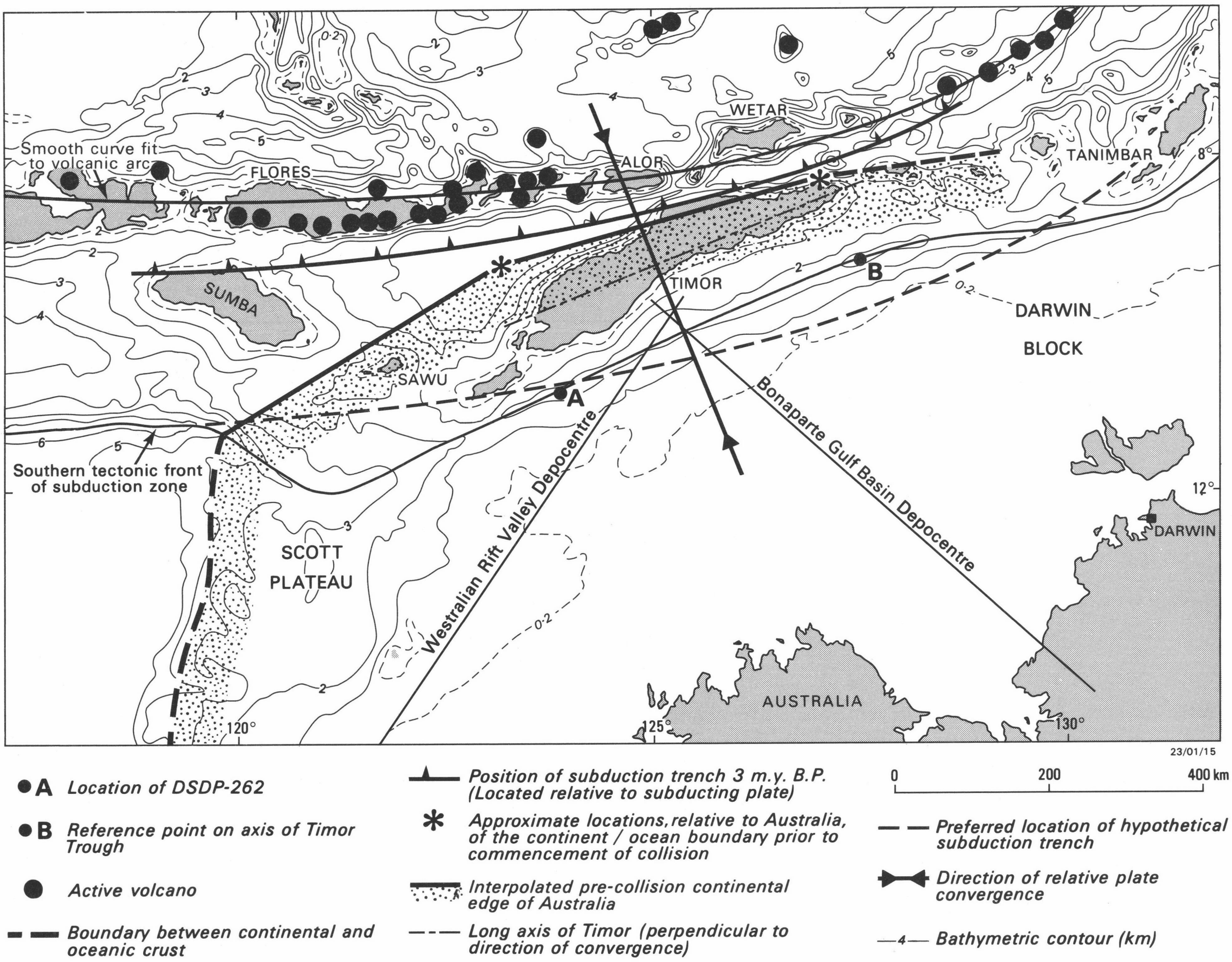

Figure 15. Pre-collision extent of continental Australia in the Timor region.
The north-northwest direction of plate convergence is indicated together with the location of the oceanic subduction trench relative to the subducting plate at the start of collision.

the passage of near-surface plate margin stresses. The more sediment on the continental margin, the quicker this stress barrier will form, and compression and uplift begin. The pre-collision Australian margin in the Timor region lay at the junction of two major depocentres (Warris, 1973) (Fig. 15). Therefore, in this region, the collision entered the compressive phase quickly, giving rise to the rapid emergence of Timor with its long axis oriented approximately perpendicular to the direction of convergence (Fig. 15).

West and east of Timor, the collision began somewhat later, and the Australian margin in these regions, lying north of Scott Plateau and the Sahul Ridge/Darwin Block, respectively, was probably covered by smaller quantities of sediment. Thus, in the Sawu and Tanimbar regions, the compression and uplift phase of the collision has not developed to the same extent as in the Timor region.

Conclusions

The structural and morphological continuity between the Java Trench and Timor Trough can be accounted for by the gradual change from a major crustal thrust boundary at the Java Trench to an intracontinental tectonic front at the Timor Trough. This change results from the massive influx of coherent sediments associated with the Australian continental margin.

Estimates of movements of the tectonic front at the western end of the Timor Trough suggest that, during the last 3 m.y., the surface width of the subduction zone between the volcanic arc and tectonic front has varied significantly. We have compared these width variations with present variations along the southern Banda Arc, and have suggested a model to explain the tectonic developments following the introduction of continental lithosphere into the subduction zone. The main implication of this model is that continental lithosphere first entered the subduction zone about 3 m.y. ago in the mid-Pliocene, giving rise to a collision that is still active.

Before the mid-Pliocene the southern Banda Arc was indistinguishable in form from the Sunda Arc. Oceanic lithosphere that separated Australia from this subduction zone entered the system from the south at a trench and was subducted into the mantle beneath the Southeast Asian plate. At the eastern end of this pre-collision subduction zone, in the vicinity of Timor, the trench and volcanic arc converged. This convergence corresponded to a marked decrease in the size of the volcanic arc. The outer-arc ridge associated with this eastern end of the subduction zone included a sliver of Australian continental crust, which appears to have been part of a larger block of continental crust that was rifted from northwest Australia in the Late Jurassic and which collided with and became attached to southeast Asia during the Cretaceous.

In the mid-Pliocene, the Australian continental margin entered the subduction zone south of Wetar. The influx of vast amounts of sediments associated with this led to marked changes in the near-surface subduction processes. The melange of oceanic sediments that had developed along the southern margin of the subduction zone was underthrust and uplifted by the continental margin sediments. However, unlike oceanic sediments, the continental sediments were not so easily stripped from their underlying continental crust, and a sedimentary deformation front or boundary replaced the cropping out thrust boundary that had previously separated the two converging plates. The deformation front and an associated bathymetric low migrated rapidly up the Australian continental slope, leaving in their wake a large wedge of deformed continental margin sediments. The development of this deformation wedge produced a southerly bulge in the subduction zone. Ultimately, the deformation wedge began to absorb the near-surface stresses and, therefore, to limit the southerly propagation of the stress, and the relative motion between the deformation front and the southern plate gradually slowed to near zero. However, continuing relative plate motion carried the deformation front and its associated bathymetric low back towards the volcanic arc. Continuing compression from this has been almost entirely taken up within the subduction zone and has led to both thickening and uplift of the deformation wedge and crust associated with the pre-collision outer-arc ridge.

As the entry of continental lithosphere into the subduction zone spread laterally, the bulge of deformed continental sediments divided and moved east and west away from the point of intial contact. These bulges now occupy positions south of Tanimbar and Sawu, respectively.

The near-surface processes that we have interpreted as resulting from the introduction of continental crust and sediments into the eastern end of the Indonesian subduction zone can help explain many of the morphological, geological, and geophysical irregularities in this region. Some of the local irregularities are listed below together with a summary of their suggested development:

— Variations in the surface width of the southern Banda Arc can largely be explained by the rapid growth of the wedge of deformed continental margin sediments and the subsequent compression of the subduction zone.

— The absence of shallow seismic activity associated with the Timor Trough can be explained by the fact that movement between the deformation front and the Australian continental crust has almost ceased.

— The absence of a marked gravity low along the southern side of the subduction zone south of Sawu can be accounted for by the masking effect of the wedge of deformed continental margin sediments.

— The continental contamination of inner-arc volcanics can be explained by tectonic erosion of the continental outer-arc ridge either during or after, or both during and after, the onset of oceanic subduction in the Late Miocene.

— The cessation of volcanic activity immediately north of Timor appears to be associated with the mid-Pliocene start of collision, when the connection between the magma source and the surface was severed in response to crustal compression and uplift.

— The Late Miocene olistostrome found throughout Timor formed in response to the southward tilting of Timor during the onset of rapid subduction.

— The deep-sea melange sediments along the southern side of Timor were derived from oceanic crust subducted before the continental collision started in the mid-Pliocene.

— The post mid-Pliocene molasse sediments along the southern side of Timor developed in elongate basins, formed as a result of depression and northward tilting of the Australian continental margin into the subduction zone together with the corresponding uplift of the leading edge of the Southeast Asian plate to the north.

— The overall uplift of Timor since the mid-Pliocene can be accounted for by underthrusting by the Australian continental margin and compression of the subduction zone, producing crustal thickening.

The geological developments that have occurred in the vicinity of Timor since the mid-Pliocene imply that the relative motion between the Southeast Asian and Australian-Indian Ocean plates is probably still continuing. We think that oceanic lithosphere is still being subducted into the mantle beneath the Southeast Asian plate and, therefore, the Banda Arc must be regarded as a site of active subduction despite the changes that have occurred in the near-surface tectonic processes.

On a broader regional scale, the evidence that the Southeast Asian plate is moving eastward at Timor, at about 60 km/m.y. relative to the Eurasian plate, supports the interpretation that the India/China continental collision is pushing the Southeast Asian plate to the southeast (Molnar & Tapponier, 1975).

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Appendix

Micropaleontological Datums and the Plio-Pleistocene Boundary in DSDP 262

*B. U. Haq**

Pleistocene Datums

Two well-dated calcareous nannoplankton biochronologic events occur within the Pleistocene at Site 262. The older of these events is the Last Occurrence Datum (LOD) or the extinction level of the coccolithophore *Pseudoemiliania lacunosa.* Correlation with oxygen isotope records in numerous tropical to subpolar deep-sea cores (Thierstein & others, 1977) has shown this event to be globally synchronous at about 0.46 m.y. B.P. At Site 262 this LOD occurs from about 173 m to 182 m depth. Below 182 m, *P. lacunosa* shows a fairly continuous occurrence (Proto-Decima, 1974). whereas above this depth the species becomes sporadic and is interpreted as having been reworked.

The second of the well-dated biochronologic levels is the First Occurrence Datum (FOD) of the coccolithophore *Emiliania huxleyi,* which appears at about 78 m depth (Proto-Decima, 1974). This FOD has also been shown to be globally synchronous (Thierstein & others, 1977) and is dated at about 0.27 m.y. B.P.

Pliocene Datums

In the Late Pliocene interval, four calcareous nannoplankton and planktic foraminifera datum levels prove to be useful in age assignment. Proto-Decima (1974) showed the continuous first occurrence of the coccolithophore *Gephyrocapsa producta* at 413.5 m depth. However, the illustration of this species as produced in Proto-Decima's Plate 1, figs. 1 and 2 (p. 603) shows it is probably another Late Pliocene gephyrocapsid, i.e. *G. aperta.* The FOD of this species has been recently dated at approximately 2.3 m.y. B.P., based on paleomagnetic stratigraphy in the deep-sea cores (Haq & others, 1977).

The second datum level is the FOD of the gephyrocapsid *G. oceanica,* which first occurs in rare numbers at 366 m depth, but begins to occur in larger numbers and more continuously at 347 m depth (Proto-Decima, 1975, p. 597). The FOD of *G. oceanica* has been shown to occur consistently very close to the top of the *Olduvai* paleomagnetic event. This FOD is dated at about 1.57 m.y. B.P. (Haq & others, 1977). This is corroborated by the LOD of the foraminifer *Globigerinoides obliquus* (Rögl, 1974, p. 757) just below this interval, at about 391 m depth. This datum has been dated at about 1.62 m.y. B.P. (Haq & others, 1977).

The fourth datum level occurs at about 337.5 m depth, namely the LOD of the foraminifer *Globigerinoides fistulosus* (s.l.) (see Rögl, 1974, p. 757). This extinction level has been dated at about 1.6 m.y. B.P. in the paleomagnetically-dated deep-sea cores (Haq & others, 1977).

Plio-Pleistocene Boundary

On the basis of the above biochronologic information the Plio-Pleistocene boundary can be placed at about 366 m depth at Site 262. This boundary has been shown by Haq & others (1977) to correspond closely to the top of the *Olduvai* paleomagnetic event (dated at about 1.6 m.y. B.P.). Haq & others (1977) studied the stratotype sections of the Plio-Pleistocene boundary and established a calcareous plankton biochronology by comparison with paleomagnetically-dated deep-sea cores.

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