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Rates of Neogene and Quaternary tectonic movements in the Southern Banda Arc based on micropalaeontology

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Abstract: It is generally considered that the Outer Banda Arc islands are composed in part of strongly deformed sediments that accumulated at the north Australian continental margin. The onset and completion of folding, nappe emplacement, imbrication and uplift that produced the islands of the Outer Banda Arc have been dated by means of planktonic foraminifera. The dating of the onset of uplift of Timor, from a deep submarine position at the end of the Neogene nappe emplacement, to mountains now reaching nearly 3 km high, indicates the rate of post-collision uplift to have been initially 3 mm/yr, then it slowed to about 1.5 mm/yr. Where the Australian continental margin meets the eastern end of the present Java Trench there are indications that the Australian margin has overridden the Trench in the Timor region by 240 km. Micropalaeontological dating of the Neogene collision between the Australian continental slope–proximal rise and the trench provides constraints for checking the overriding hypothesis by calculating rates of convergence derived from plate motions (7.5 cm/yr) against the rates based on the tectonic model (7.4 cm/yr). After nappe emplacement (possibly faster than 6.25 cm/yr) shortening of the continental crust appears to have migrated towards the Australian continent so that the shelf itself has become involved in the imbrication with shortening of the cover rocks between the nappes and the present shelf edge amounting to about 40 km during the last 2 Ma.

The convergent plate boundary between SE Asia and the Indian Ocean is marked by the Java trench, which is the site of underthrusting (subduction) of the oceanic lithosphere beneath the Sunda Arc. At the eastern end of the Java trench all the Indian Ocean appears to have been subducted because the Asian boundary is marked by the collision zone between the volcanic arc and Australian continental margin. The arc morphology, its dimensions and gravity field and the exposed geology of the islands east of Sumba (where the Java Trench ends) are so different from those of the Sunda Arc that this eastern part of the plate boundary is regarded as a separate element called the Banda Arc (Fig. 1).

The Banda Arc comprises an inner arc of volcanic islands, whose eruptive rocks range from early Miocene to currently active (Van Bemmelen 1949; Ratman & Yasin 1978; Koesoemadinata & Kadarisman 1981), and an outer arc of islands, exposing mainly sedimentary (Permian to Quaternary), with some metamorphic (pre-Cretaceous) and few igneous (Permian to Quaternary) rocks.

Seismic refraction and reflection surveys (Jacobson *et al.* 1978; Bowin *et al.* 1980) have demonstrated there is no oceanic crust between the Australian–New Guinea continental shelf and the islands of the Outer Banda Arc. Most marine geophysical surveys have concluded (Hamilton 1979; von der Borch 1979) that the Timor–Tanimbar–Seram troughs, that now separate the islands of the Outer Banda Arc from the continental shelf of Australia–New Guinea, mark the surface trace of the Benioff zone, and that the islands of the Outer Banda Arc comprise a rootless tectonic melange forming part of a forearc accretionary prism (Fig. 2). Earthquake data do not permit the Benioff zone to be traced with confidence in the uppermost 50 km of the crust of the Banda Arc region (McCaffrey *et al.* 1984, 1985). This has been one of the main factors contributing to the controversy concerning the structural configuration and evolution of the region.

The main controversy (Fig. 3) has developed between those placing most weight upon the marine geophysical survey data (Jacobson *et al.* 1978; Hamilton 1979; von der Borch 1979; Bowin *et al.* 1980; Silver *et al.* 1983) and those whose investigations have been based on geological mapping of the Outer Banda Arc islands (Audley-Charles 1968; Grady 1975; Carter *et al.* 1976; Grady & Berry 1977; Barber *et al.* 1977; Brunnschweiler 1978; Audley-Charles *et al.* 1979; Norvick 1979; Rosidi *et al.* 1979). The geological field mapping has failed to find evidence of Timor and the other islands of the Outer Banda Arc being composed of a rootless tectonic melange. Furthermore, because the rocks below the allochthonous nappes (i.e., the parautochthon) accumulated at a passive continental margin far from a volcanic arc they do not resemble a forearc accretionary prism. The results of this geological field work seem to require that the Benioff zone does not come to the surface in the Timor–Tanimbar–Seram trough. This paper attempts to present a new aspect of the late Cenozoic orogenesis by a consideration of the implications of the rates of tectonic movement in the region based on dating of important events by micropalaeontology (Table 1). It also draws attention to the indications of the way the deformation of the orogen appears to have migrated both towards and away from the Australian continent.

Palaeontological evidence for interpreting the Banda Arc structures

As with most if not all Phanerozoic fold and thrust mountain belts the stratigraphy and the structure of the Banda Arc has been worked out on the evidence of the relative age of parts of the geometrically complex pattern of deformed rocks. And, as with so many other fold and thrust mountain belts, the predominating pattern is of flat-lying allochthonous nappes whose rocks are of very similar (often overlapping)

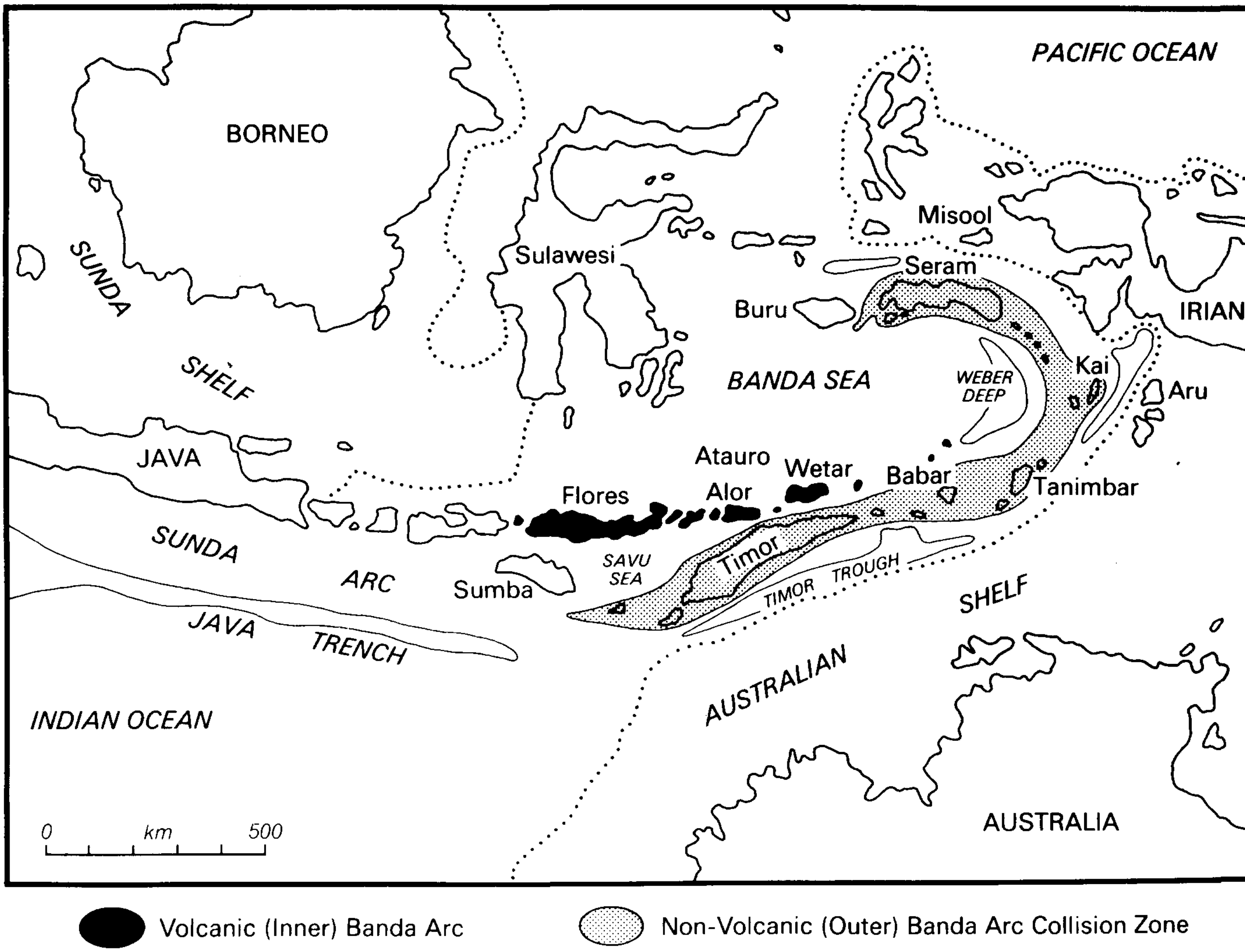

Fig. 1. The volcanic (Inner) Banda Arc is a continuation of the volcanic Sunda Arc, but the Outer Banda Arc is regarded here as the deformed margin of Australia and not a continuation of the Sunda forearc accretionary wedge.

age to the parautochthonous rocks below the nappes, but these contemporaneous allochthonous and parautochthonous elements are of contrasting facies. In the Outer Banda Arc the allochthonous sedimentary rocks are mostly of shallow marine origin while the parautochthonous sediments are nearly all deep marine deposits.

Definition of parautochthon, allochthon and autochthon in islands of the Outer Banda Arc

The three principal structural elements of the main islands of the Outer Banda Arc (Timor and Seram) are not only stratigraphically and palaeontologically distinct, they occupy different topographic and structural positions and display different styles and histories of deformation (Fig. 4).

The parautochthon. The parautochthonous strata of Timor range in age from early Permian to early Pliocene (Audley-Charles *et al.* 1979). They display evidence of having accumulated in a deep marine environment. Typically they are turbidites and associated lutites. They include both siliciclastic turbidites of Permian, Triassic and Jurassic age, and calciturbidites and marls of Triassic, Cretaceous, Paleogene and Neogene age. Some bedded cherts of Triassic and Cretaceous age have also been found (Audley-Charles *et al.* 1979; Rosidi *et al.* 1979). The Permian sedimentary rocks with rare volcanics contain a Permian ammonoid fauna 'showing strong affinity with Western Australia and elsewhere in the Tethyan–Uralian region' (H. G. Owen, pers. comm. 1984). The Triassic sedimentary rocks contain palynomorphs remarkably similar to those of the northern Australian shelf (Crostella & Powell 1976), the Jurassic (Oxfordian–Kimmeridgian) *Buchia-Belemnopsis* fauna that is widespread in Australasia is present in Timor (Brunnschweiler 1978). D. J. Carter showed (in Audley-Charles *et al.* 1979) that from Tithonian times until the early Pliocene there is a remarkable biostratigraphical correlation (particularly well displayed by the planktonic foraminiferal microfaunas) between Timor and Seram of the Outer Banda Arc, and the northern Australian shelf (offshore Canning Basin).

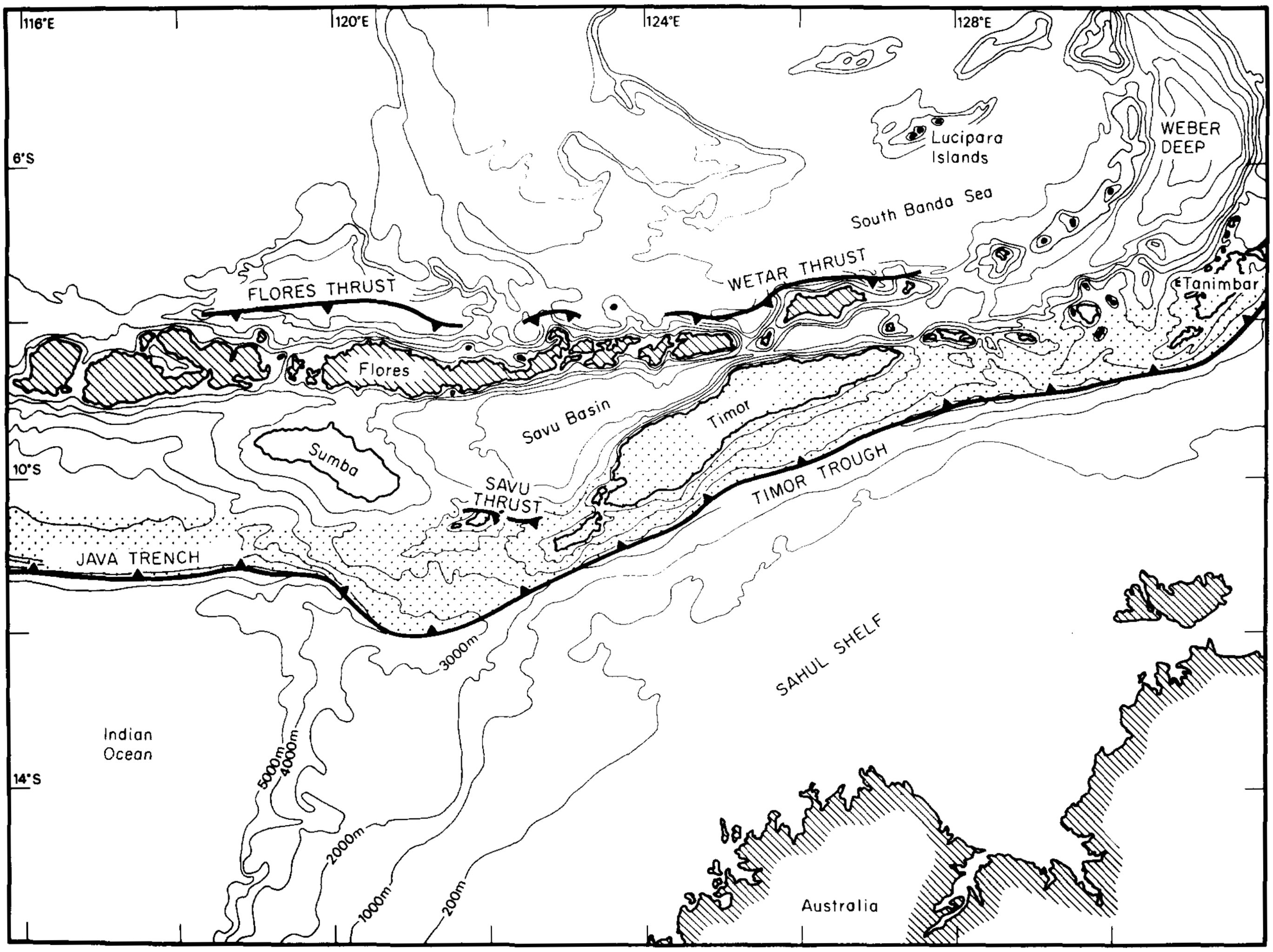

Fig. 2. The accretionary wedge model considers the Sunda forearc continues eastward via Savu, Roti and Timor to Tanimbar. This model regards the Timor Trough (despite it being underlain by 40 km of continental crust) as marking the trace of the Benioff zone.

Topographically and structurally these parautochthonous rocks can be seen and deduced from mapping to be below the very different facies of similar age and also below the metamorphic and igneous rocks that all belong to the allochthonous nappes. There are thrusts *within* the parautochthon so the presence of thrusts alone is not diagnostic of the allochthon (defined later in this paper).

The parautochthon has been strongly deformed with tight small-scale folding typically showing vergence towards Australia–New Guinea. Reverse faults and thrusts occur with this same vergence. Upright folds of varying scales are also present as are a great variety of other faults. Locally, especially in the southern part of Timor and the northern part of Seram, a Cretaceous to Pliocene section of Kolbano facies (Timor) and Nief facies (Seram) display a strong imbrication with vergence towards Australia–New Guinea.

The Allochthon. The range in age of the allochthonous strata (Fig. 5) is very similar to that of the parautochthon (early Permian to early Pliocene) (Audley-Charles *et al.* 1979). There is also an important suite of pre-Cretaceous metamorphic rocks forming high upstanding massifs, usually as distinct nappes with various late Mesozoic and Paleogene to early Miocene shallow marine carbonates and volcanics unconformable on these high to low grade metamorphics known as the Lolotoi Complex and Mutis Complex in Timor (Barber *et al.* 1977).

Another suite of allochthonous metamorphic rocks occurs along the northern part of central Timor, the Aileu Formation of Audley-Charles (1968). These contain Permain ammonoids (Brunnschweiler 1978). The Aileu Formation is essentially a flysch which becomes more sandy northwards until near the N coast metaquartzites and micaschists occur with marbles and metabasic rocks and amphibolites (Barber *et al.* 1977). The Aileu Formation has been multiply deformed with three phases of strong penetrative deformation near the N coast (Berry & Grady 1980). This metamorphism and structural deformation contrasts markedly with the absence of penetrative deformation in the parautochthonous strata adjacent to and below the Aileu Formation in northern Timor as described

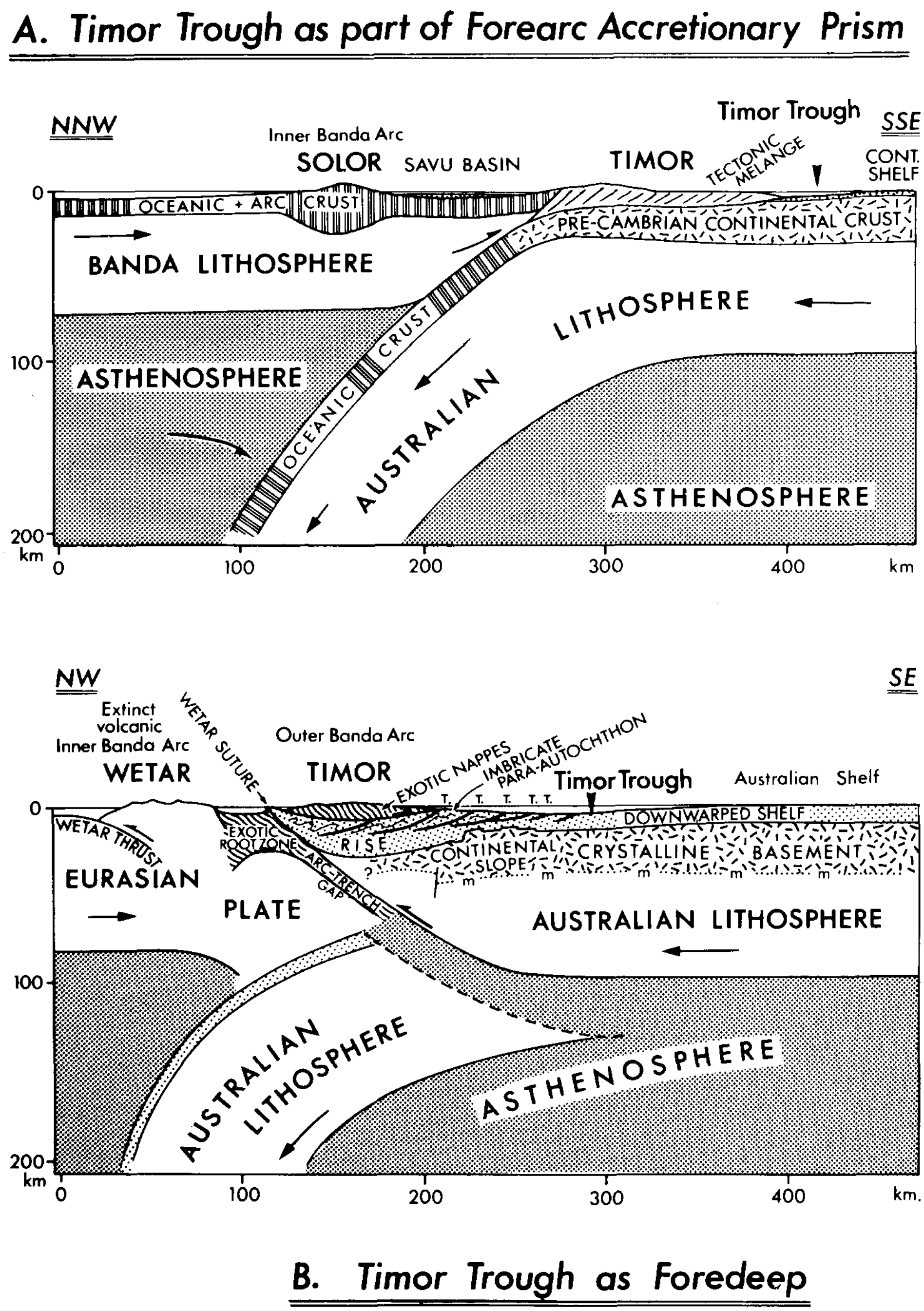

Fig. 3. A. Tectonic Model based mainly on interpretation of marine seismic reflection data (from Hamilton 1979, fig. 78 and von der Borch 1979, fig. 9). B. Model based mainly on surface geological mapping (after Audley-Charles 1983b).

by Barber *et al.* (1977). It indicates that the allochthonous elements must have been strongly deformed before they were emplaced at a high structural level in Timor and Seram.

The other members of the allochthon in Timor are nearly all shallow marine deposits. For example, there is a great contrast in facies between the allochthon and parautochthon in the Permian Maubisse Formation (highly fossiliferous shallow marine limestones, shales and vesicular lavas) in contrast with siliciclastic turbidites of the Atahoc and Cribas Formations. Grady (1975), Grady & Berry (1977) and Chamalaun & Grady (1978) have challenged the concept of there being any allochthon in Timor and in particular have claimed the allochthonous and parautochthonous Permian facies interdigitate, a point supported by Crostella & Powell (1976). Carter *et al.* (1976), Barber *et al.* (1977) and Audley-Charles *et al.* (1978 & 1979) have pointed to the evidence of the mapping as clearly demonstrating the allochthonous nature of the Permo–Triassic Maubisse Formation. There is a similar contrast in the Triassic rocks of Seram where shallow marine allochthonous reefal carbonates of the Asinepe Limestone

Table 1. *The micropalaeontological biozonation and dating of the Viqueque Group*

Local zonation (D. J. Carter)	Planktonic zonation (Blow 1969)	Age	Important Benthoic spp.
Not differentiated on planktonics	N.23	Holocene	*Hyalinea baltica*, *Bolivinita quadrilatera*, *Hoeglundina elegans*, *Valvulineria jauana*, *Ceratobulimina pacifica*, *Cassidulinoides inflatus*, *Burseolina sp. 2*
Gl. truncatulinoides Zone	N.22	Pleistocene and Holocene	
Up. *Gl. oides quadrilobatus fistulosus* Zone	N.21	Late Pliocene	
Lr			
Sphaeroidinellopsis-*Sphaeroidinella* Zone	Late N.19 (? + N.20)	Early (and Mid-) Pliocene	*Favocassidulina favus*
G. nepenthes-*Sphaeroidinella* Zone	Early N.19	Early Pliocene	
G. nepenthes-*Sphaeroidinellopsis* Zone	N.18	Late Miocene Early Pliocene	

The biostratigraphical zonation used in this paper is based upon the work of D. J. Carter who used the scheme of Blow (1969), as his framework. Carter modified this scheme for the local zonation as outlined above. The relationship between this zonation and the chronometric data follows Harland *et al.* (1982).

contrast with the deeper water fine-grained *Halobia* and radiolaria-bearing carbonates of the Saman-Saman Limestone (Audley-Charles *et al.* 1979). Many, if not all, the criticisms of Berry *et al.* (1984) of the overthrust hypothesis are invalidated by their inaccurate references to earlier workers who, despite the claims by Berry *et al.*, did recognize both Permian and Triassic elements of the Maubisse Formation (e.g. Audley-Charles 1978). A palaeogeographical reconstruction of the original sites of accumulation of these Permian and Triassic members of the parautochthon and allochthon has been put forward by Audley-Charles (1983*a*). Other examples of contrasting contemporaneous facies being juxtaposed structurally exist in the Cretaceous and Palaeocene. Palelo Group siliciclastic

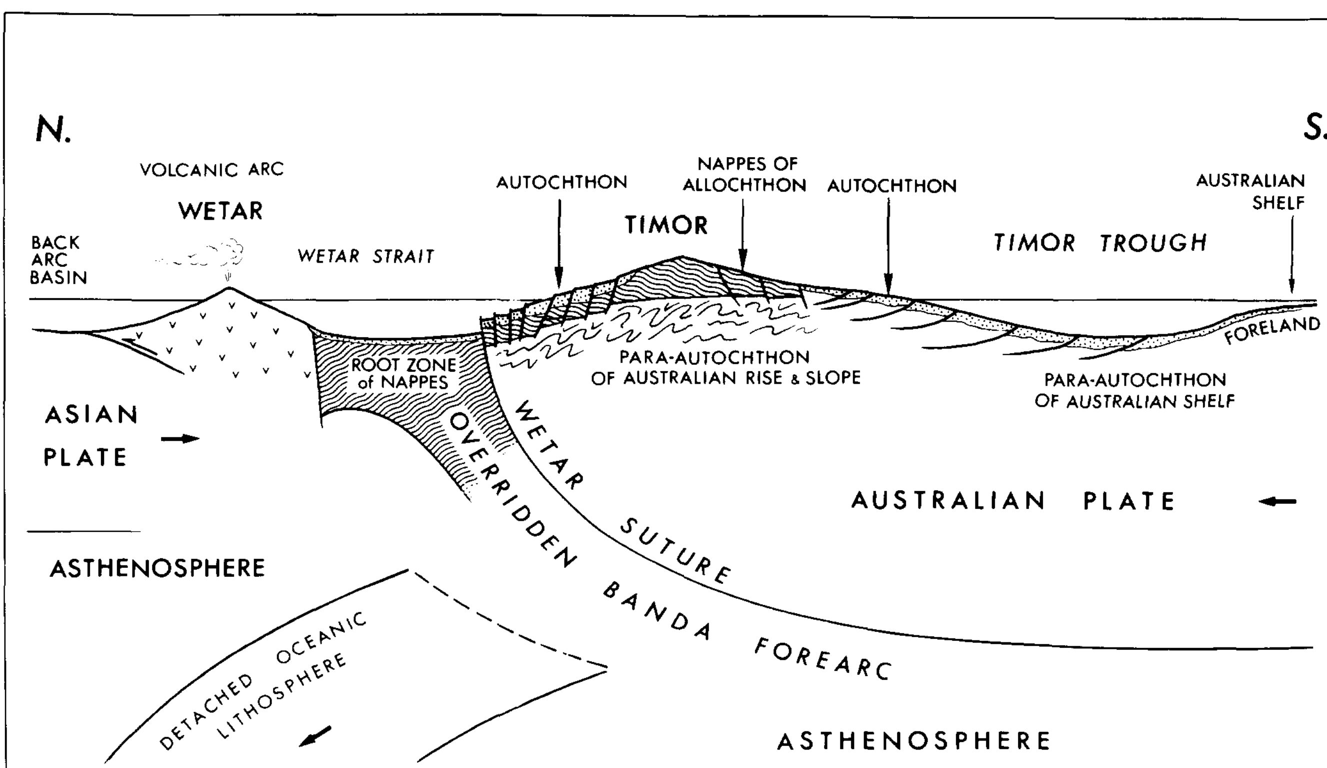

Fig. 4. Diagrammatic cross-section showing parautochthon–allochthon–autochthon. Model based on Price & Audley-Charles (1983).

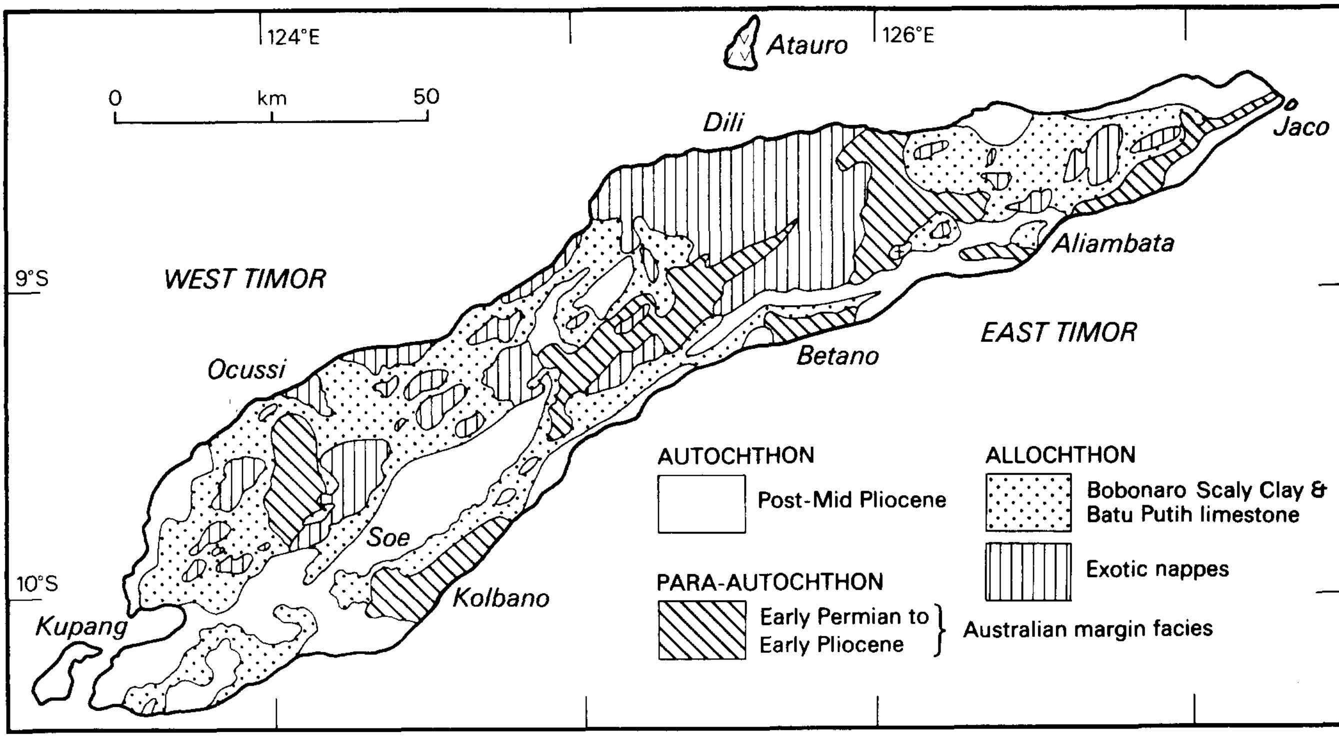

Fig. 5. Geological sketch map of parautochthon, allochthon and autochthon in Timor.

turbidites and volcaniclastics of the Timor allochthon (Earle 1983) contrast with calciturbidites and marls of the parautochthonous Kolbano facies (Audley-Charles *et al.* 1979, table 2). Dramatic contrasts are also found in the Cenozoic of Timor where the allochthonous Eocene and early Miocene very shallow marine carbonates with their calcareous algae and large benthonic forams contrast with the deep water calciturbidites and marls containing planktonic microfaunas of the Kolbano facies parautochthon. These facies, 55 km apart in W Timor, are only separated by 10 km in the Cablac–Betano region of E Timor.

The Autochthon. The autochthonous rocks are defined here as those that accumulated where they are exposed. All were deposited after the allochthonous nappes were emplaced. This includes all the post-N.20 (i.e. post mid-Pliocene) deposits of Timor and post-N.18 (i.e. latest Miocene) deposits of Seram (Audley-Charles *et al.* 1979).

In Timor these autochthonous rocks are of three main kinds: raised terraces of fringing coral–algal reefs and alluvial terraces of Quaternary age and turbidite facies of late Pliocene and Quaternary age (Kenyon 1974). The autochthonous rocks are found overlying the nappes and the parautochthon. Usually in Timor they rest on the underlying Bobonaro Scaly Clay interpreted as an olistostrome belonging to the allochthon emplaced in the mid-Pliocene (Carter *et al.* 1976). The coral–algal reef terraces and alluvial terraces are generally either horizontal or gently tilted by normal faulting. The turbidite facies has locally been folded and faulted, a few reverse faults have been mapped. These folded turbidites have been penetrated and locally disturbed by the diapiric behaviour of the underlying Bobonaro Scaly Clay (Audley-Charles 1968; Kenyon 1974).

The age of the main orogenic phase in the Banda Arc

The presence in Timor of the series of allochthonous nappes having a stratigraphy, metamorphism and deformation distinct from that of the underlying parautochthon (summarized above) indicate that there was a major orogenic phase that both folded and faulted the parautochthon and emplaced the allochthonous nappes above. This Ramelauean orogenic phase (Audley-Charles 1968) has been dated in Timor by Carter *et al.* (1976) as mid-Pliocene (N.20) on the basis of the micropalaeontological age of the Batu Putih Limestone, which is the youngest member of the allochthon (N.18–N.19), and the Sabaoe Limestone which is the oldest member of the autochthon (N.21). Confirmation of this age is suggested by the age of the youngest member of the parautochthon in the Kolbano region being very similar (N.18) to that of the youngest part of the allochthon. This also suggests the main phase was a short-lived (N.20) event. In Seram this orogenic event was dated as late Miocene (N.18) by Carter *in* Audley-Charles *et al.* (1979) and the equivalent in Sulawesi is middle Miocene (Sukamto & Simandjuntak 1983). Before dealing with the details of these various stratigraphic elements it is necessary

to discuss the stratigraphical and the structural status of the Bobonaro Scaly Clay and the overlying lower part of the Batu Putih Limestone because they are critically important deposits in any consideration of the age of this orogen.

The stratigraphical and structural position of the Bobonaro Scaly Clay

The Bobonaro Scaly Clay is a generally brown but locally variously coloured and flow-banded soft scaly clay that in places is more than 2 km thick (Ossulari well in SE Timor). Its composition is variable owing to the varying proportion of derived constituents of all sizes ranging from clay and silt size to blocks more than 0.5 km long. Samples of the clay matrix from east Timor were found to contain up to 35% montmorillonite. Some samples from W Timor showed no detectable amounts of montmorillonite (A. J. Barber, pers. comm. 1985). The outstanding feature of this scaly clay with its wide variety of exotic blocks is that the exotic blocks consist almost entirely of recognizable members of the allochthon and parautochthon of pre-Pliocene age. There is a tendency for particular formations locally to dominate the exotic blocks. This is seen laterally in the field and vertically in wells. This derivation of either all or nearly all its constituents from the exposed allochthonous and parautochthonous elements in Timor is compatible with the presence of the Bobonaro Scaly Clay sitting throughout Timor directly on all the pre-Pliocene members of the allochthon and parautochthon forming a most dramatic unconformity (Fig. 6). There must be considerable relief on this unconformity amounting to more than 3 km. This is illustrated by the geological map of E Timor. The Bobonaro Scaly Clay crops out in the Lari Guti Pass between Venilale and Ossu where it can be seen sitting on the Cablac Limestone at about 1000 m above sea level. Its base occurs at more than 2 km below sea level (not reached) in the Ossulari well (20 km SSE of Ossu and 4 km NE of Beaco) near the south coast. Just 2 km inland, near the northern coast of E Timor, the base of the Bobonaro Scaly Clay can be seen in contact with the parautochthon on the road section near Laleia less than 100 m above sea level.

Both exposure mapping and well site sampling along the southern part of E and W Timor have yielded exotic blocks and microfaunas derived from the allochthonous Cablac Limestone and Maubisse Limestone as well as blocks of Lolotoi metamorphics that crop out between 10 km and 30 km farther north. This is a strong argument in favour of the southward movement of the Bobonaro Scaly Clay as a gravity slid mass. This, together with its strongly unconformable basal surface, has led to its interpretation as an olistostrome that was emplaced in Timor on the back of southward travelling nappes.

The age of the Bobonaro Scaly Clay was originally (Audley-Charles 1968) said to be of middle Miocene age although paradoxically it contained *Globorotalia truncatulinoides, Pulleniatina obliquiloculata, Sphaeroidinella dehiscens* and '*Globigerina*' *subcretacea* which indicate an N.22 (Pleistocene age). This apparent contradiction, which has confused other workers (e.g. Hamilton 1979, p. 130), arises from two factors: (a) the Bobonaro Scaly Clay is overlain stratigraphically by the late Pliocene–Quaternary Viqueque Group (Kenyon 1974), and (b) where erosion has partially removed this Viqueque cover the underlying Bobonaro is vulnerable, where the Viqueque is exposed upslope with the Bobonaro in the valley sides downslope, to contamination by hillwash moving down slope from the Viqueque during monsoons. This results in microfossils being washed out of the up slope Viqueque down slope into the exposed Bobonaro. Repeated landslipping of the Bobonaro then incorporates the subaerially derived microfossils into the Bobonaro matrix. Detailed microscopic examination (D. J. Carter, per. comm.) revealed the post-Miocene forams in the Bobonaro to be derived from the Viqueque Group. Local topographic relationships have suggested this mechanism of derivation. This led to the concept of primary Bobonaro Scaly Clay distinguished from reworked Bobonaro Scaly Clay in south Timor containing the forams derived from the Viqueque (Carter *et al.* 1976).

In an unpublished report D. J. Carter (1970) noted that despite the intensive study of hundreds of samples no species of Oligocene or Miocene age (except those in exotic fragments of the allochthonous Cablac Limestone) have been found in the Bobonaro. However, middle Eocene planktonic assemblages are abundant: *Globorotalia centralis, Globigerina ampliapertura intermediata, Globigerina parva, Globigerina venezuelana, Globigerinatheka barri, Catapsydrax echinatus, Aragonella dumblei, Hantkenina alabamensis,* '*Globigerapsis index*', *Globorotaloides suteri, Truncorotaloides topilensis, Hastigerina micra, Globigerina yeguaensis* and *Chiloguembelina martini.*

The Bobonaro Scaly Clay is overlain by the Batu Putih Limestone, whose lower part is described below with its characteristic foraminifera assemblage indicative of uppermost Miocene to lowermost Pliocene (N.18 to N.19) age. This was determined from the assemblage present in each of more than 50 samples.

The presence of the latest Miocene or earliest Pliocene (N.18–N.19) lower part of the Batu Putih Limestone sitting stratigraphically on the Bobonaro, although usually with a sheared contact (Kenyon 1974), brackets its age of emplacement in Timor as post-youngest member of the allochthonous nappes (Miomaffu tuff of N.17 age) and pre-Fatu Laob Member which is the upper part of the Batu Putih Limestone (Kenyon 1974) of N.21 age (determined by D. J. Carter—*in* Audley-Charles *et al.* 1979). Kenyon described an interesting single locality transition from the Bobonaro Scaly Clay up into the lower part of the Batu Putih Limestone as the Tanah Runta Member of late Miocene age (N.15). This suggests that although much of the Bobonaro Scaly Clay is composed of rocks derived from the submarine erosion of allochthon and parautochthon, by the southward-moving olistostrome, a brownish clay, which is the most pervasive material of the matrix dated as middle Eocene (see above) and late Miocene (Tanah Runta), accumulated during the pre-Pliocene in part of the deep water zone north of the advancing Australian margin. It seems most likely this was associated with the volcanic forearc.

The Bobonaro Scaly Clay and lower part of the Batu Putih Limestone thought to have been emplaced in Timor on the back of the southward-travelling nappes are regarded as part of the allochthon (Carter *et al.* 1976; Barber *et al.* 1977). The rapid change in facies above the lower part of the Batu Putih Limestone to a mainly regressive pattern of turbidites, developed as Timor emerged from the sea to become a mountain island, together with the much gentler state of deformation in the post-Batu Putih Limestone

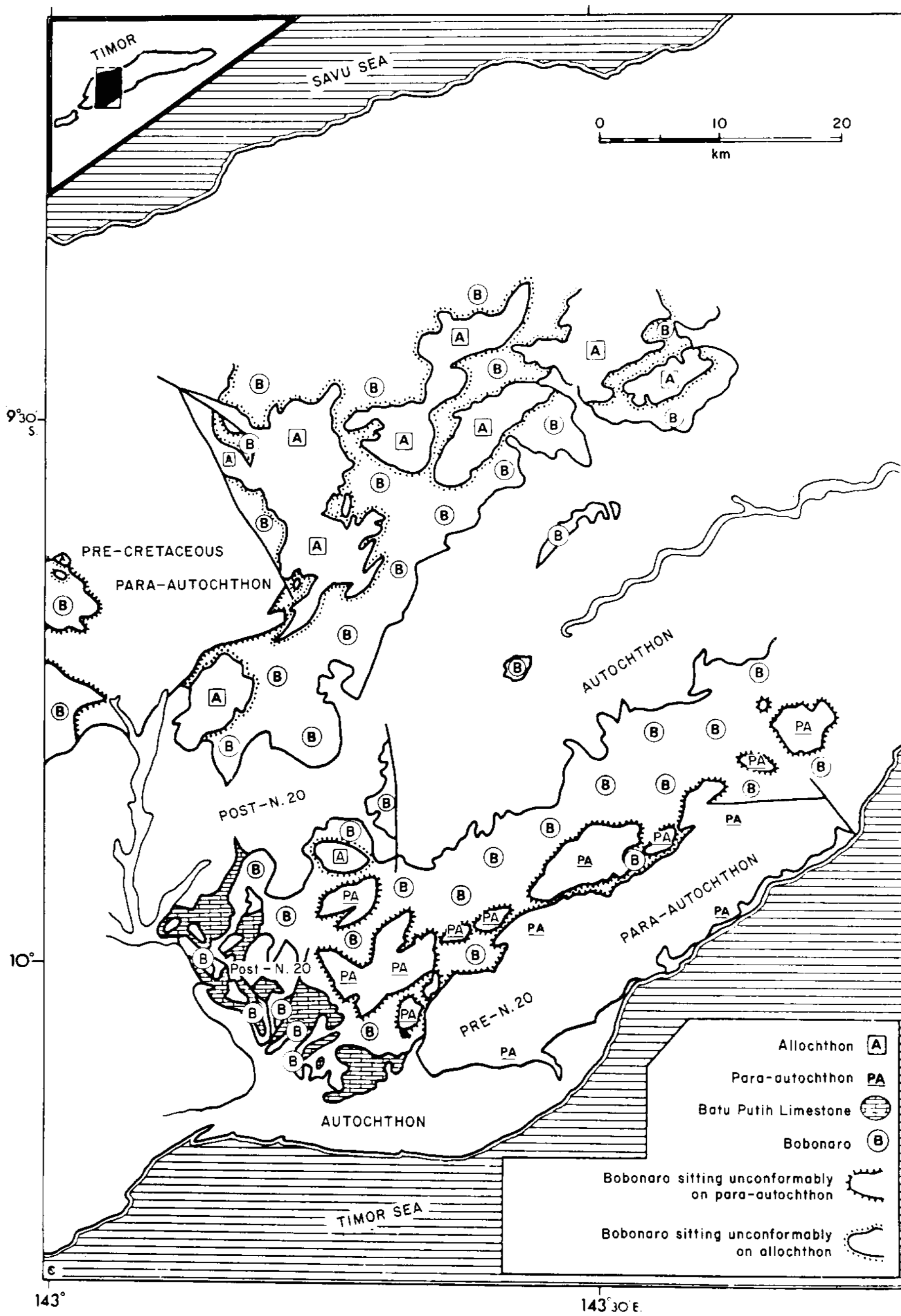

Fig. 6. Geological map (after Rosidi *et al.* 1979) showing relation of Bobonaro Scaly Clay and the Viqueque Group to parautochthon and allochthon. Note the terrane linking unconformity at the base of the Bobonaro. Note too that the imbricated pre-N.20 parautochthon includes slices of N.18 lutites of the same age as the Batu Putih Limestone.

sequence helps to confirm the allochthonous nature of the Bobonaro and Batu Putih and the autochthonous status of all those rocks that overlie them.

Indications that the allochthon was emplaced in very deep water

The allochthonous nappes are overlain unconformably by the Bobonaro Scaly Clay throughout Timor. The youngest sub-Bobonaro member of the allochthon is the deep marine Miomaffu tuff of N.17 age determined by Carter *et al.* (1976). The lower part of the Batu Putih Limestone (that is the oldest rock that sits on the Bobonaro Scaly Clay in Roti, W Timor and E Timor) is composed of foraminiferal calcilutites, vitric tuffs and occasional turbiditic lithic arenites (Kenyon 1974). These rocks contain an abundance of planktonic foraminifera and thin shelled bivalues. The low percentage of clay material and the very low content of benthonic organisms suggest an open marine environment subject to incursions of turbidity currents. D. J. Carter

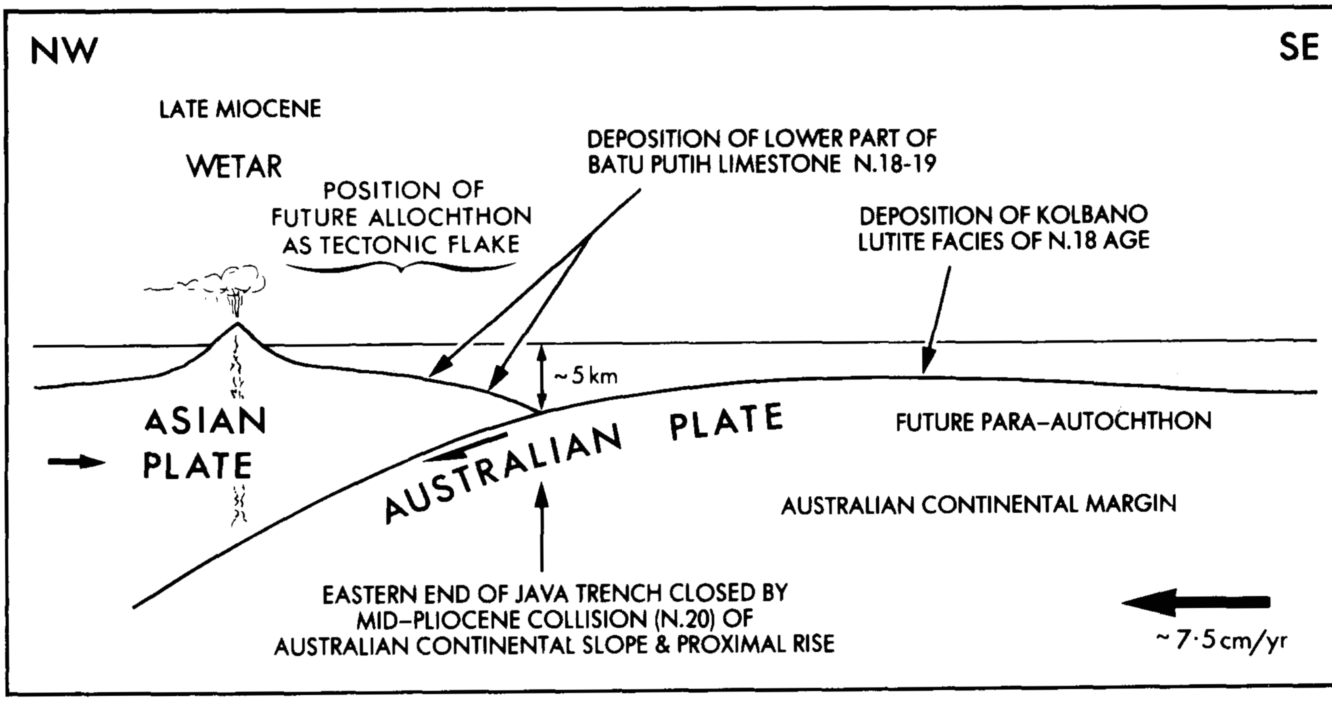

Fig. 7. Late Miocene palinspastic reconstruction of allochthon (Asia) and parautochthon (Australia) immediately prior to collision.

(unpublished report, 1970) recorded the following microfauna: Planktonics: *Globorotalia cultrata menardii*, *G. tumida tumida* (sinistral), *G. cultrata cultrata*, *Globigerina nepenthes*, *Pulleniatina primalis*, *Globigerinoides gomitulus*, *G. ruber*, *G. conglobatus*, *G. quadrilobatus* sp., *G. obliquus obliquus*, *Sphaeroidinellopsis subdehiscens subdehiscens*, *Sphaeroidinellopsis seminulina kocki* and *Sphaeroidinellopsis subdehiscens paenedehiscens*. Benthonics: *Textularia* spp., *Cibicides* spp., *Spiroplectammina* spp., *Uvigerina* spp. Miliolacea, *Bulimina* spp., Nodosariacea, *Planularia* spp. and *Oridorsalis* spp.

The whole aspect of this deposit is one of quiet deep water. D. J. Carter (pers. comm.) considered it likely to have been in excess of 2 km.

The presence above the allochthonous Bobonaro of such a deep water deposit, together with the indications of the Bobonaro having been emplaced on the back of the nappes as a gravity sliding olistostrome, all suggest the nappes were moving down slope into deep water. One candidate for this environment is the trench slope. This seems especially likely given that the orogenic phase involved collision between the Banda volcanic arc and the northward moving continental margin of Australia. The most obvious site of the collision zone would be the subduction trench into which the Australian margin was being thrust under the Banda forearc (Figs 7 and 8) during the Early and Middle Pliocene N.19–N.20.

History of vertical movement of the Banda orogen

The Banda orogen can be considered to be comprised of the three tectonic elements discussed above.

The allochthon—a series of southward travelled exotic nappes that originated in the hanging wall of the subduction zone as part of the original Banda forearc (Carter *et al.* 1976; Price & Audley-Charles 1983). The allochthon is now found sitting directly above the highly folded, thrust and locally imbricated parautochthon.

The parautochthon with its long lithostratigraphical and palaeontological affinity with the northern margin of Australia is regarded as being composed of the Australian continental margin facies wherever it has been seen cropping out in the islands of the Outer Banda Arc. However, seismic reflection profiles especially those of the Tanimbar–Kai region, that have achieved the greatest degree of penetration (Schlüter & Fritsch, 1985), indicate that the region between the islands of the Outer Banda Arc and the present Australian shelf has (at least locally) been thrust towards the Australian continental margin so that locally the shelf too forms part of the parautochthon.

The autochthon has been defined here as representing those sedimentary rocks that accumulated in the Banda orogenic zone after the thrust sheets of the allochthon were emplaced.

In discussing the history of vertical movements of the Banda orogen we need to consider the indications of vertical movements of the rocks that originated on the Asian side of the Java Trench (i.e., the allochthon), those that came from the Australian side of the Java Trench (the parautochthon) and those that were deposited only after the allochthon was emplaced above the parautochthon in the collision zone. This involves the history of vertical movements of the autochthon which can only have occurred after the destruction of the Java Trench by the collision of the Australian continental margin with the hanging wall accretionary wedge on the Asian side of the Trench (Figs 4 & 7). These movements of the autochthon must have affected equally the allochthon and parautochthon which are overlain unconformably by the autochthon.

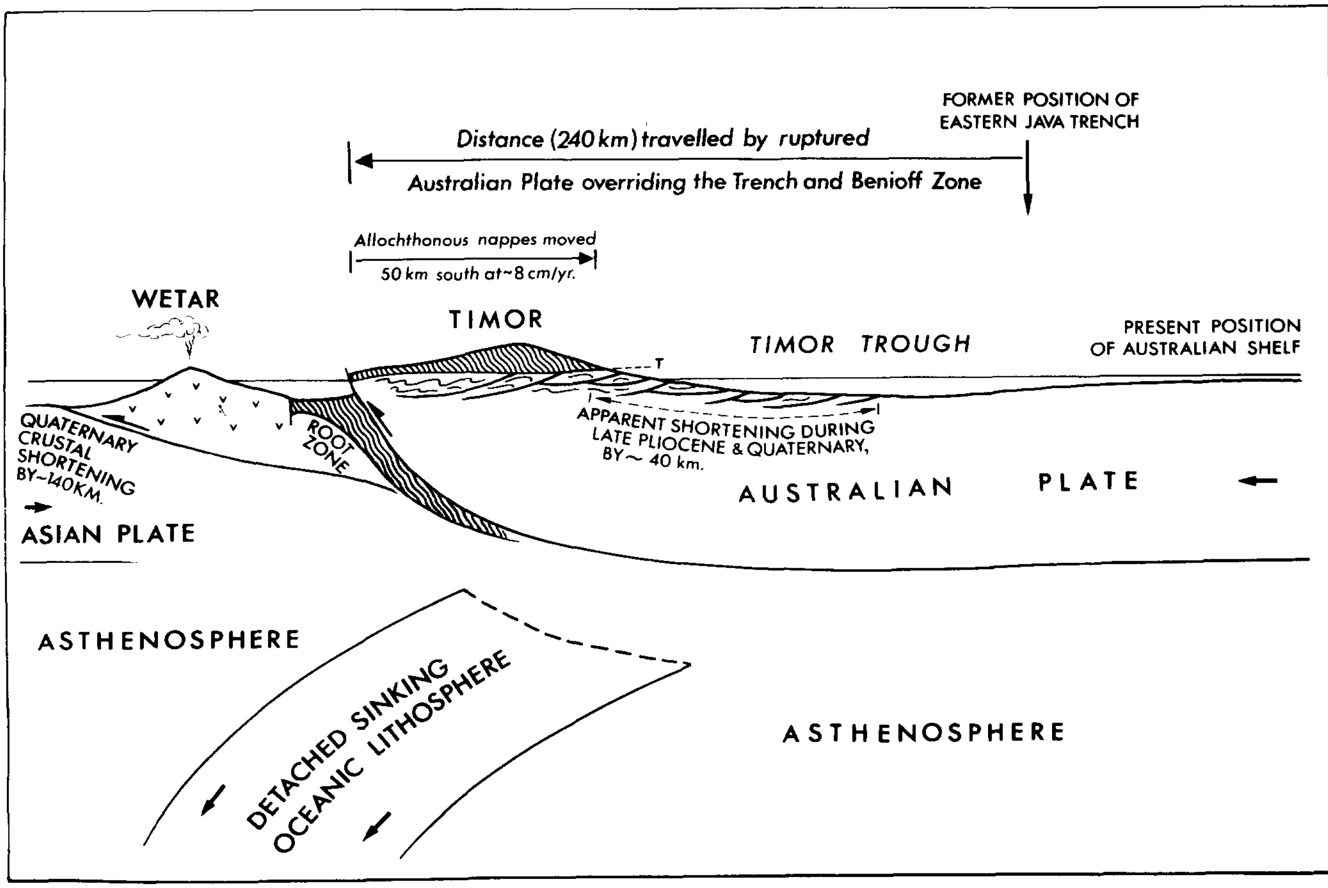

Fig. 8. Diagrammatic cross-section showing overthrusting by nappes and Australian lithosphere and the post-nappe-emplacement shortening of the cover rocks in the foredeep.

Events prior to emplacement of allochthonous nappes (pre-N20)

A great change in depth of sediment accumulation appears to have taken place in the allochthon after the deposition of early Miocene (N.7) shallow marine limestones. The evidence of N.17 Miomaffu tuff is, however, the only indication we have of subsidence affecting the post-N.7 sediments in the allochthon except for the presence of the Bobonaro Scaly Clay, interpreted as an olistostrome that slid under gravity southwards on the backs of the nappes. However, the evidence of the Batu Putih Limestone sitting directly on the Bobonaro Scaly Clay is that during latest Miocene and earliest Pliocene (N.18–N.19) very deep marine conditions prevailed which D. J. Carter has estimated as at least 2 km deep.

The parautochthonous deep water lutites tell a story of deep, open marine deposition from late Jurassic times until early Pliocene (Audley-Charles *et al.* 1979). Thus, the indications are that the rocks which accumulated on the Asian side and as well as those that accumulated on the Australian side of the Java Trench in late Miocene–early Pliocene time just prior to the collision were deposited under deep marine conditions, possibly greater than 2000 m depth (Fig. 7). It seems that the emplacement of the allochthonous nappes in Timor took place under these conditions during the mid-Pliocene N.20 interval of which we have no fossiliferous record despite analysis of many hundreds of samples of Bobonaro and Viqueque.

Post-collisional uplift of Banda Orogen

The evidence we have of vertical movements after the allochthonous nappe emplacement is all from the autochthonous rocks. Kenyon (1974) described the Fatu Laob member of the upper part of the Batu Putih Limestone as a regressive facies. A non-sequence exists at the base of Fatu Laob Member (zone N.20 is missing) and this suggests it should be classified not as a Member of Batu Putih but as a distinct formation. The Fatu Laob Member was dated by D. J. Carter (*in* Kenyon 1974) as late Pliocene (N.21) on the basis of *Globoquadrina dehiscens dehiscens, Sphaeroidinellopsis seminula seminula, Globigerina decoraperta* and *Pulleniatina obliquiloculata praecursor.*

The Batu Putih Limestone and its Fatu Laob Member are overlain stratigraphically by the Sabaoe Limestone Formation described by Kenyon (1974) as a series of shallow marine and marginal marine calcarenites and marls. Locally the base of the formation is conformable; elsewhere it is unconformable upon steeply dipping Batu Putih Limestone. Kenyon interpreted the lower part of the thin Sabaoe

Limestone Formation as having been deposited in intertidal, barrier bar and lagoonal conditions. This implies that this part of Timor had been uplifted (from about 2000 m depth of water) to just about sea level during the time represented by possibly part of N.19 zone, N.20 zone and part of N.21 zone. If we accept that the Pliocene lasted from 5.1 until 2.0 Ma. (Harland *et al.* 1982) then, assuming the nappes were all emplaced by the end of N.20, the rate of uplift can be estimated to have been 3 mm/yr if the time taken for the Fatu Laob Member and the lower part of the Sabaoe Limestone to accumulate was about half of N.21 zone, i.e., 700,000 y. This is twice the average rate of uplift for the whole of the late Pliocene and Quaternary in Timor estimated by Milsom & Audley-Charles (1985).

Kenyon (1974) interpreted the vertical movements of the late Pliocene and Quaternary from his study of the stratigraphy and sedimentology of the Plio-Pliocene deposits of Timor in terms of the following.

(1) The Fatu Laob uplift (which Kenyon regarded as lasting from N.15 to N.21) should be revised in the light of later work by Carter *et al.* 1976; Barber *et al.* 1977. This uplift phase is now regarded as beginning immediately after the nappes were emplaced in the middle Pliocene N.20 and lasting until the early part of the Sabaoe Limestone deposition in late Pliocene N.21.

(2) The Bidjeli subsidence of middle–late Pliocene (N.21) affected the central basin of Timor. Minor, very local folding occurred during this phase. This subsidence lasted until middle N.22 (i.e., middle Early Pleistocene). While this subsidence of the central Basin of W Timor and the southern part of E Timor was taking place the northern part of W Timor and central and northern parts of E Timor were being uplifted. This was a time of steep fault movements throughout Timor.

(3) Noele uplift lasted from the middle of N.22 until early N.23 zone of the Pleistocene. It seems to have affected the whole island and was associated with the Mataian phase of folding that was accompanied by wrench faulting.

(4) Soe subsidence was a (early–middle N.23) phase of relative subsidence (it may have been in part a reflection of a eustatic sea level rise) that affected the whole island. It resulted in the widespread reef limestone deposition over the eroded Viqueque Noele Marl Formation.

(5) Noilbesi uplift lasted from the middle of N.23 to the present. This renewed uplift of Timor deposited conglomerates and braided river gravels. It has been accompanied by minor tilting and normal faulting.

If, in estimating the rate of vertical uplift of Timor after the nappe emplacement in N.20, we include the figure of 2000 m for the depth of sea below which the Batu Putih Limestone accumulated, then the gross uplift between the end of N.20 and the present is 5000 m. If the end of N.20 is taken as 3.4 Ma BP (Harland *et al.* 1982) then average rate of uplift has been 1.47 mm/yr.

Rates of overthrusting in Banda Arc

The presence in Timor of flat-lying nappes of the allochthonous elements: Lolotoi–Mutis metamorphic Complex; Permo–Trias Maubisse–Aileu Formation, Palelo Group, Dartollu Limestone, Cablac Limestone with Bobonaro Scaly Clay and Batu Putih Limestone as well as similar elements in Seram occupying a comparable structural setting is incompatible with the concept of these islands of the Outer Banda Arc being composed of a tectonic melange of a forearc accretionary prism. The mapping of these nappes in Timor and Seram (Audley-Charles 1968; Audley-Charles *et al.* 1979; Rosidi *et al.* 1979) allows their rate of emplacement above the parautochthonous Australian continental margin facies to be estimated. Of these allochthonous nappes those that travelled farthest southwards are the metamorphic rocks of the Lolotoi Complex (E Timor) and Mutis Complex (W Timor). In both cases they appear to have travelled at least 50 km across the exposed parautochthonous element. The maximum time taken for that journey can be estimated from the age of the youngest member of the allochthon that sits on the Lolotoi–Mutis Complex and the age of the youngest member of the overridden parautochthon checked against the age of the oldest member of the autochthon that sits on both the allochthon and parautochthon. We are for the allochthon thus dealing with the age of the lower part of the Batu Putih Limestones (N.19) or, it might be argued, we should use the age of the Miomaffu Tuff (N.17). Using the Batu Putih Limestone (N.18–19) produces an age ranging from 5.1 to 3.8 Ma. The youngest part of the overrridden parautochthon is the N.18 lutite of 5.1 to 4.7 Ma. The oldest member of the overlying autochthon is the Fatu Laob Member of the Batu Putih of N.21 (ca. 3.4 to 3 Ma). These figures produce an estimate for the duration of nappe overthrusting of 0.4 to 0.8 Ma. This suggests a rate of between 12.5 cm/yr and 6.25 cm/yr for the emplacement of the allochthonous nappes. Of course the distance moved must have been greater than 50 km so that real rate of overthrusting was likely to have been about 8 cm/yr.

Rates of overthrusting implied by the lithospheric rupture model

Price & Audley-Charles (1983) proposed a model for the origin of this Banda Arc–Australian margin collisional orogen that involved the Australian lithospheric plate rupturing after the continental margin had been subducted below the Banda forearc accretionary wedge (Fig. 3B). This model involves the eastern end of the Java Trench and its associated Benioff zone in the region east of Sumba (Fig. 1) being overridden by the Australian lithosphere (Figs 8 & 9). The field geological mapping requires that this rupturing and overriding began in early Pliocene (N.18–19) times and was completed by the end of the middle Pliocene (N.20). By that time the northern margin of the ruptured Australian plate had achieved a position relative to the Banda volcanic arc islands of Wetar, Alor and Atauru (Figs 1 & 9) not significantly different from the present position. I assume that the Java Trench in early Pliocene time (i.e., before collision) occupied a position relative to the volcanic Banda Arc similar to its present position relative to the volcanic Sunda Arc, although I have allowed a gentle narrowing of the arc-trench gap eastwards as the volcanic islands becoming progressively smaller (and possibly younger).

The pre-collision position of the Java Trench opposite the Banda volcanic arc has been reconstructed on this basis in Fig. 9. The maximum distance travelled by the Australian margin across the Benioff zone (Java Trench trace) is 240 km. However, that includes the distance travelled down the Benioff zone before rupture. One difficulty in these calculations is knowing how far below the Banda forearc the Australian continental margin (that we now see exposed in

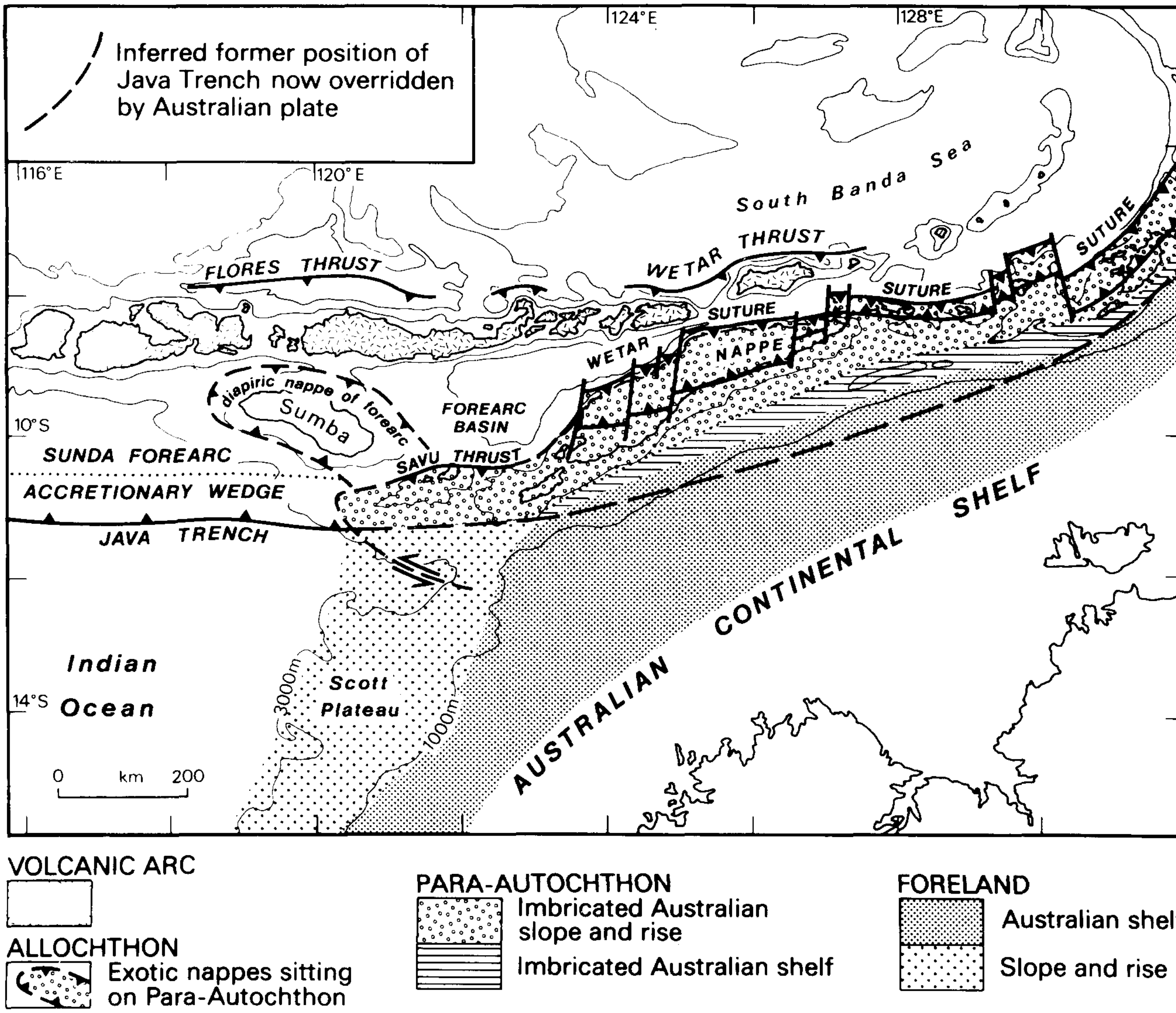

Fig. 9. Southern Banda Arc tectonic map showing the allochthonous nappes and the parautochthon in relation to the undeformed Australian margin. Interpretation of the Sumba region is after Audley-Charles (1985). Compare this model with the forearc accretionary wedge concept of Fig. 2.

northern Timor) had travelled before this lithospheric plate was ruptured. We can be guided by the very low state of metamorphic alteration of these Australian continental margin rocks exposed in northern Timor to indicate that the maximum depth of cover was 5 km and that therefore the maximum distance travelled beyond the trench before rupture was 40 km. This allows the rate of postulated overthrusting of this eastern part of the Java Trench by the ruptured Australian margin during the mid-Pliocene collision to be estimated. The minimum northward distance travelled by Australian lithospheric plate across the Java Trench after it ruptured is 200 km. The time taken to travel that distance is the time between the onset of dislocation of the forearc nappes (which overrode the Australian continental margin) and the onset of uplift of these allochthonous thrust sheets in northern Timor. Our nearest estimate for disruption of the allochthonous forearc nappes is the age of the youngest members of these nappes, *viz.* Miomaffo Tuff of N.17 (6.1 Ma) age. The onset of the uplift of the allochthonous thrust sheets in northern Timor was late N.20 (3.4 Ma). Thus the ruptured lithospheric plate travelled 200 km in 2.7 Ma. This gives a rate of overthrusting by the ruptured lithosphere of 7.4 cm/yr which compares closely with the rate of plate convergence (Minster & Jordan 1978) given as 7.5 cm/yr (Fig. 8).

Post-Pliocene plate convergence: southward migration of deformation zone

Considering here only the southern part of the Banda Arc, i.e., Timor to Kai, we can apply the Price & Audley-Charles

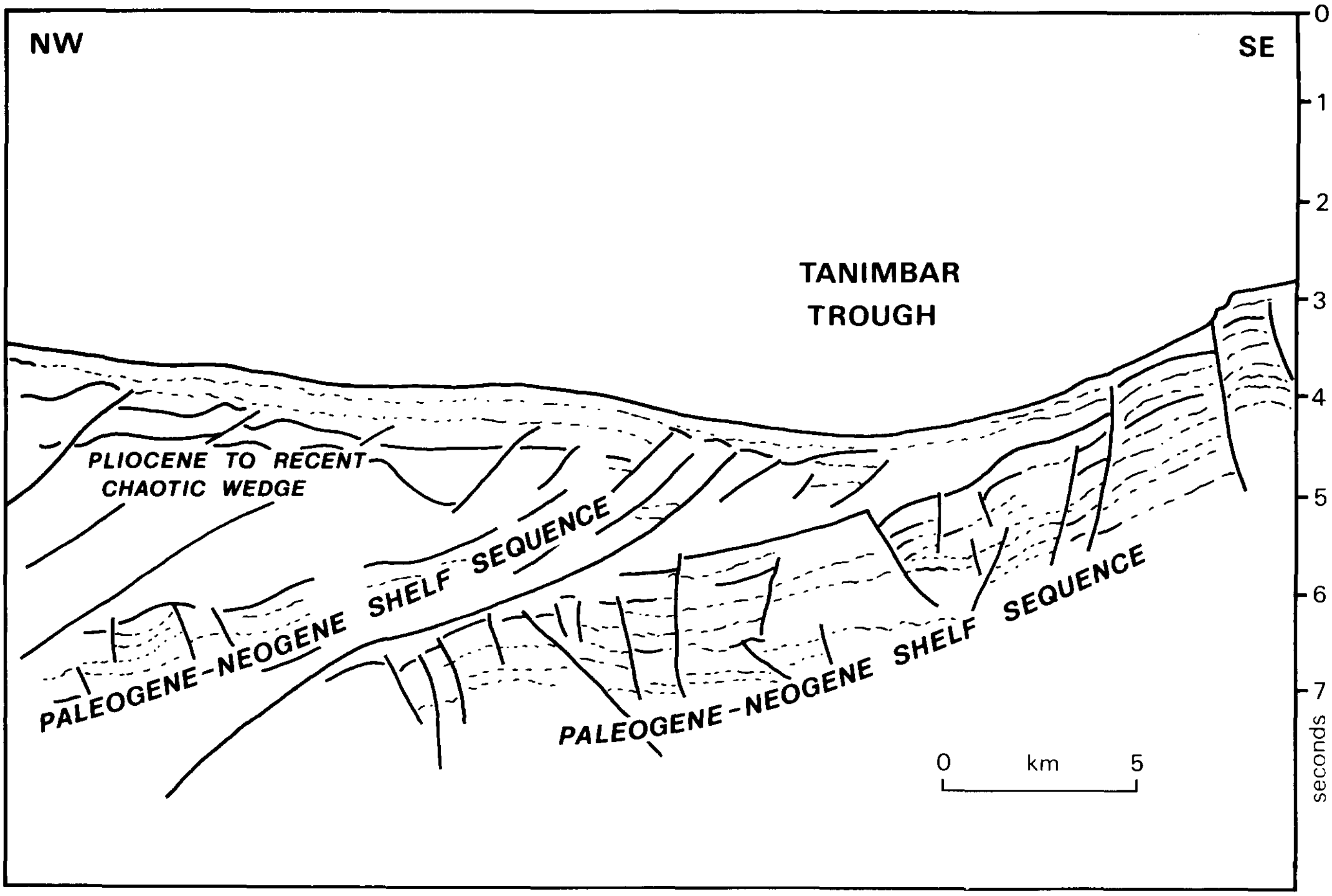

Fig. 10. Overthrusts of Australian continental shelf appear to have moved southwards on to the present shelf in the Tanimbar region (after Schlüter & Fritsch 1985).

(1983) plate rupture model to the Timor region where the biostratigraphy has been studied in some detail. This involves the rate of postulated collisional movement during the Pliocene only. Since the end of the Pliocene plate convergence is thought to have proceeded at 7 cm/yr (Johnston & Bowin 1981). Two million years of Pleistocene implies 140 km of shortening in the collision zone. In a search for evidence of this strain in the rocks of the Timor sector of the Arc three main points seem to emerge.

(1) The back arc thrusting on the north side of the inner volcanic arc described by Silver *et al.* (1983) is relatively young, probably Pleistocene. This could account for 140 km of shortening. Silver *et al.* (1983) estimated their accretionary wedge model could account for 30–60 km of convergence on this back arc thrust.

(2) The Pleistocene Mataian folding phase in Timor (N.22) was a relatively gentle, widespread event accompanied by uplift. This may have been associated with plate convergence strain. It is difficult to estimate crustal shortening because the folded Viqueque is nearly everywhere found overlying the soft plastic Bobonaro Scaly Clay, which has complicated the geometry by behaving diapirically with respect to the overlying Viqueque Group. In addition the possible role of downslope mass movement under gravity to the subsiding Timor–Tanimbar Trough in this Mataian folding phase cannot be ignored.

(3) Some of the shortening required to balance the 140 km of plate convergence might be accommodated in the deformation by thrusting and imbrication of the parautochthon in the region between the Outer Banda Arc islands and the Australian shelf. Charlton (submitted) estimates 90 km of shortening based on strain ellipse modelling and Veevers *et al.* (1978) estimated 80 km of shortening. In particular, the region south of Tanimbar (Schlüter & Fritsch 1985) provides evidence for Quaternary overthrusting of the Australian shelf in a series of thrust slices in the cover rocks that moved southwards towards Australia (Fig. 10).

The accretionary wedge model for the Outer Banda Arc

This model is so well known and has been so widely applied to the Banda Arc (Jacobson *et al.* 1978; Hamilton 1979; von der Borch 1979; Bowin *et al.* 1980; Silver *et al.* 1983) that it has only been discussed here in the introductory paragraphs (Figs 2 & 3A). The strength of the model's application to the Banda Arc is the undoubtedly highly characteristic features seen on the seismic reflection profiles from the region between the Outer Banda Islands and the Australian shelf, particularly from the southern slope of Timor and Tanimbar islands down to the axis of the Timor–Tanimbar

Trough. These seismic profiles show a very close resemblance to those from forearc accretionary prisms such as that associated with the Java Trench (Bally 1983). A weakness of the argument for applying this model to the Banda Arc is that it overlooks the fact that imbricate faulting in very different tectonic regimes will produce this same pattern. For example, the foothills of the southern Canadian Rockies (Bally, Gordy & Stewart 1966) provides a similar pattern of structures but we can be confident that there it was generated by thrusting over the continent without oceanic crust being involved. No Benioff subduction zone has been destroyed in that foothills zone. This problem of the close similarity between the seismic reflection picture across foreland thrust belts and across forearc accretionary prisms has been discussed by Seeber (1983).

While recognizing the important contribution that marine seismic reflection surveying has made in the Outer Banda region by demonstrating the youthfulness (Pliocene to Recent according to Schlüter & Fritsch 1985) of the imbrication of sediments in the southern slope of the Outer Banda Arc and especially in demonstrating the way that slices of the Australian shelf have been thrust southwards over the shelf (Fig. 10) it must be pointed out that this does not imply these features have been generated in forearc accretionary prisms rather than in a foredeep or foothills fold and thrust belt (Fig. 3). The presence of the widespread, flat-lying nappes above the deformed Australian continental margin in Timor and Seram and probably in some of the other islands of the Outer Banda Arc together with the indications that these nappes were derived from the forearc of the Banda volcanic arc, seem to be incompatible with the forearc accretionary wedge model for the present structure of the Outer Banda Arc. Similarly, the post-Middle Pliocene stratigraphy and structure of Timor seems very difficult to reconcile with such a model. The indications that the shortening of the cover rocks by thrusting and imbrication in the Australian parautochthon (Figs 8 & 9) migrated from the slope deposits (seen in Timor and Seram) to the shelf deposits seen in the seismic reflection profile south of Tanimbar (Schlüter & Fritsch 1985) are compatible with the foredeep, foothills structure.

Recent mapping of Tanimbar (Sukardi & Sutrisno 1981) as well as older reports (van Bemmelen 1949), and of Kur island of the Kai group (Achdan & Turkandi 1982), suggest that rocks very similar to those of the Timor allochthon are present. This, together with the interpretation of the structure of Tanimbar from recent seismic reflection survey data (Schlüter & Fritsch 1985), suggests that the Australian lithospheric rupture extends along all the southern side of the Banda Arc to beyond Kai. The interpretation on the basis of seismic refraction and reflection data of the Weber Deep structure by Bowin *et al.* (1980) as a zone of detached lithospheric slab would seem to be compatible with the application of the Price & Audley-Charles (1983) model to the Tanimbar-Kai-Weber Deep region.

D. J. Carter provided all the micropalaeontological analyses on which the stratigraphy has been built. He also contributed to the elucidation of the stratigraphy in the field and to discussion over many years. Both F. T. Banner and C. G. Adams subsequently gave guidance in the use of micropalaeontological data. I would also like to thank Neville Price for discussion, Janet Baker and Colin Stuart for the art work, Hans Schlüter for a pre-print of his paper with Jurgen Fritsch, and Tim Charlton and Tony Barber for a preprint of their paper on wrench tectonics in Timor.

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