Journal of Structural Geology, Vol. 13, No. 5, pp. 489 to 500, 1991
Printed in Great Britain

0191-8141/91 $03.00+0.00

The structural evolution of the Timor collision complex, eastern Indonesia

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(*Received* 25 *July* 1990; *accepted in revised form* 7 *November* 1990)

Abstract—The structural style of Timor is consistent with foreland fold belt processes, and zones of frontal accretion and underplating can be recognized in the Australian parautochthonous sequence. The parautochthon is overlain by an allochthonous sequence, which corresponds to the pre-collisional oceanic forearc. In northern Timor the parautochthon has been underplated directly beneath the allochthonous basement. Unlike previous interpretations of Timor in terms of foreland fold belt processes, the Timor foldbelt is here interpreted as having evolved in a fairly straightforward way from the pre-collisional forearc by the sequential addition of thrust slices of Australian continental crust to the front and base of the developing collision complex.

INTRODUCTION

TIMOR island, located in the southern Banda Arc in eastern Indonesia (Fig. 1) forms part of the present-day collision zone between the northwestern margin of Australia and the southeast Asian island arcs. The island is frequently quoted as one of the best examples of active arc–continent collision, and an understanding of its structure and evolution is thus not only of local interest, but can also usefully constrain models of analogous ancient collision zones. However, Timor is still rather poorly known geologically, and although several rather detailed models have been proposed for its evolution, no consensus exists even on such basic questions as the style of deformation on the island. This paper outlines the structural style of a number of better studied areas in Timor, and attempts to reconcile this structural information with a simple model for the evolution of the Timor collision complex.

Timor occupies a forearc location in the southern Banda Arc of eastern Indonesia (Fig. 1). To the south is the outer margin of the Australian Northwest Shelf, a passive continental margin created by the Jurassic breakup of eastern Gondwana (Powell 1976, Veevers 1982). Further west, the Indo-Australian Plate is composed of Jurassic oceanic crust (Larson 1975, Fullerton *et al.* 1989) which is being subducted northwards beneath the Sunda Arc, the westward continuation of the southern Banda Arc. Prior to the Late Neogene deformation in Timor, Indian Ocean crust was presumably also subducted at the Banda Arc in the region of present-day Timor. During the later Neogene (probably Late Miocene–Pliocene), continental crust of the Australian passive margin began to enter the Banda subduction system, leading to the development of the present arc–continent collision complex of the Timor region.

The primary aim of this paper is to develop a structural interpretation of the Timor collision complex by describing the structural style from a few well studied parts of the island. However, before we can consider the structural style in any detail, it is first necessary to discuss briefly two more specific problems. These are the definition of what constitutes the allochthon in Timor, and the origin of the Bobonaro Complex.

THE ALLOCHTHON IN TIMOR

Timor has frequently been described in terms of autochthonous, parautochthonous and allochthonous structural elements (Audley-Charles 1968, 1986a, Carter *et al.* 1976, Barber *et al.* 1977). The parautochthon of Timor, which is the largest component of the island, is generally equated with Australian continental margin material thrust back towards Australia during arc–continent collision. According to Audley-Charles (1986a) the allochthon comprises a series of southward travelling exotic nappes that originated in the hanging-wall of the subduction zone as part of the (pre-collisional) Banda forearc. In papers by Audley-Charles and co-workers up until at least Audley-Charles (1986a), 'allochthonous' is also specifically equated with

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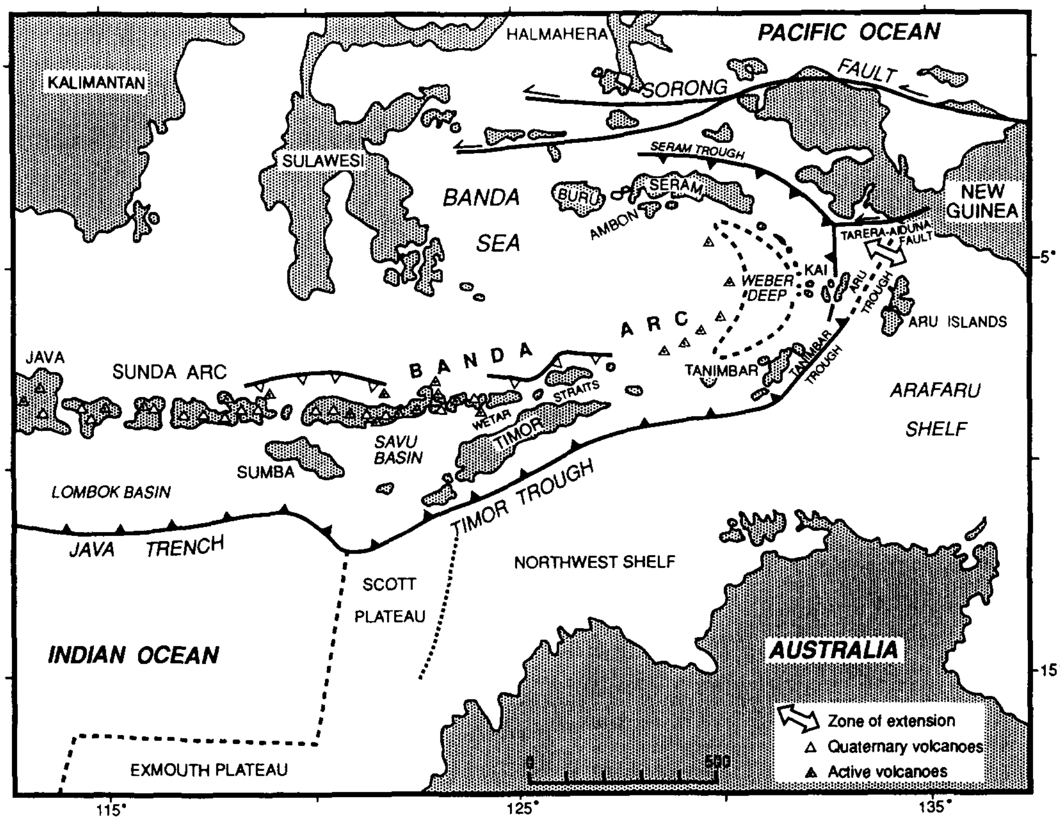

Fig. 1. Tectonic setting of Timor. Triangles mark the Banda-Sunda volcanic arc.

'Asiatic': that is, derived from the margin of southeast Asia rather than from the Australian continent. This frequent but poorly defined linking of the words 'allochthonous' and 'Asiatic' has led to a great deal of confusion as to the origin of various lithotectonic elements on Timor. This is particularly true of the Permian Maubisse Formation and the stratigraphically associated Aileu Formation.

The Maubisse Formation is a predominantly limestone sequence of Permian age, while the Aileu 'Formation' comprises metamorphosed siliciclastic sediments and volcanics ranging from sub-greenschist to upper amphibolite facies (Audley-Charles 1968, Barber & Audley-Charles 1976, Barber *et al.* 1977, Berry & Grady 1981a). The Maubisse Formation outcrops widely in Timor island, whilst the Aileu Formation is restricted to the NW corner of East Timor (Fig. 2). The grainsize of the Aileu siliciclastics decreases southwards, and they pass transitionally into the limestones of the Maubisse Formation. The highest metamorphic grades in the Aileu Formation are attained near the north coast of Timor, and metamorphic grade decreases southward.

The origin of the Maubisse Formation has recently been reviewed by Barkham (in press), who concluded that the Maubisse Formation is an integral part of the parautochthonous stratigraphy of Timor and not part of the allochthon. In more recent papers by Audley-Charles (e.g. Audley-Charles & Harris 1990), the equating of 'allochthonous' with 'Asiatic' is discarded, and 'allochthonous' is used only to indicate 'far-travelled'. In particular, Audley-Charles & Harris (1990) indicate an Australian margin origin for the Maubisse Formation, in line with most other work on its palaeogeographic location (e.g. Crostella & Powell 1976, Grady & Berry 1977, Chamalaun & Grady 1978, Hamilton 1979, Berry *et al.* 1984, etc.). It now seems widely agreed that the Maubisse Formation originated on, and remained located on, the northwestern flank of Australia up until the Neogene arc–continent collision. It will be treated as such in this paper.

In this paper we take as our definition of the allochthon those sequences that originated in the pre-collisional Banda forearc. This definition follows established usage such as Carter *et al.* (1976), Barber *et al.* (1977), Barber (1979) and Audley-Charles (1986a), but it should be noted that Audley-Charles & Harris (1990) use the term allochthonous in a different way. On the basis of our definition, the allochthon of Timor is now fairly clearly established and not subject to widespread dispute. The Timor allochthon includes the Mutis/Lolotoi Complex which represents the basement of the pre-collisional forearc, and the Palelo Group, Same Formation, Barique Volcanic Formation, Noil Toko Formation, Cablac Limestone Formation, Miomaffu Tuff and Manamas Formation (=Oecusse Volcanics) which form the sedimentary–volcanic cover (Audley-Charles 1968, 1986a, Audley-Charles & Carter 1972, Barber & Audley-Charles 1976, Carter *et al.* 1976, Haile *et al.* 1979, Earle 1981, Rosidi *et al.* 1981, Harris 1989, Tobing 1989). These elements form a stratigraphic sequence entirely separate from the Timor parautochthon.

THE ORIGIN OF THE BOBONARO COMPLEX

The Bobonaro Scaly Clay (Audley-Charles 1965, 1968) or Bobonaro Complex (Rosidi *et al.* 1981) is a scaly clay melange consisting of a wide variety of unsorted angular and subangular blocks set in a scaly clay matrix. The matrix is generally dark reddish brown, but is also commonly green, and less commonly black, grey, yellow and bright red. Contortion structures indicate plastic flow, and are particularly common around the exotic blocks. At outcrop the clay characteristically has a 'popcorn' texture. According to Audley-Charles (1968) the exotic blocks vary in age from Permian to Lower Miocene, although microfossils as young as Upper Miocene were also found. Block sizes range up to 500 m across, and down to silt grade material. Most clasts are angular to subangular, but a few blocks show a remarkable degree of rounding. The blocks are randomly and chaotically distributed throughout the clay matrix, although particular lithologies predominate locally.

Audley-Charles (1965) interpreted the Bobonaro Scaly Clay as a syn-orogenic olistostromal deposit. Based on the age of the youngest included clasts (Lower Miocene) and the age of the oldest overlying sediments (the Viqueque Formation of Upper Miocene age), the age of emplacement of the Bobonaro olistostrome (and the contemporaneous climax of deformation) was determined as Middle or possibly Upper Miocene. Audley-Charles (1968) was unsure if the Bobonaro olistostrome was emplaced as a single event, or as a series of smaller emplacements.

In a later paper (Carter *et al.* 1976), the main period of deformation was re-interpreted as occurring within planktonic foraminiferal zone N20 (mid-Pliocene). It was also recognized that the Bobonaro Complex contained material as young as Plio-Pleistocene. To explain this new data in terms of the olistostromal model, Carter *et al.* (1976) proposed the following sequence of events. The Bobonaro Scaly Clay was emplaced as an olistostrome onto the allochthon during the period N17–18 (Late Miocene), after which it was unconformably overlain by the Batu Putih Limestone during the period N18–19 (Early Pliocene), and was then carried onto Timor on the back of the allochthonous thrust sheets during N20 (mid-Pliocene). Subsequent uplift of Timor caused the Bobonaro Complex to slump southward over southern Timor towards the Timor Trough, incorporating material from the autochthonous (i.e. post-orogenic) Viqueque Formation (re-interpreted as Plio-Pleistocene in age). Thus in addition to 'primary' Bobonaro Scaly Clay (the original olistostrome), there is 'reworked Bobonaro' of post-N20 age which results from landslipping.

Hamilton (1979 and earlier work) reinterpreted the Bobonaro Complex as a tectonic melange. Drawing analogies with geological studies of oceanic forearc complexes such as Nias (e.g. Moore & Karig 1980), and by reference to seismic lines across oceanic forearcs which typically showed a chaotic structure, Hamilton

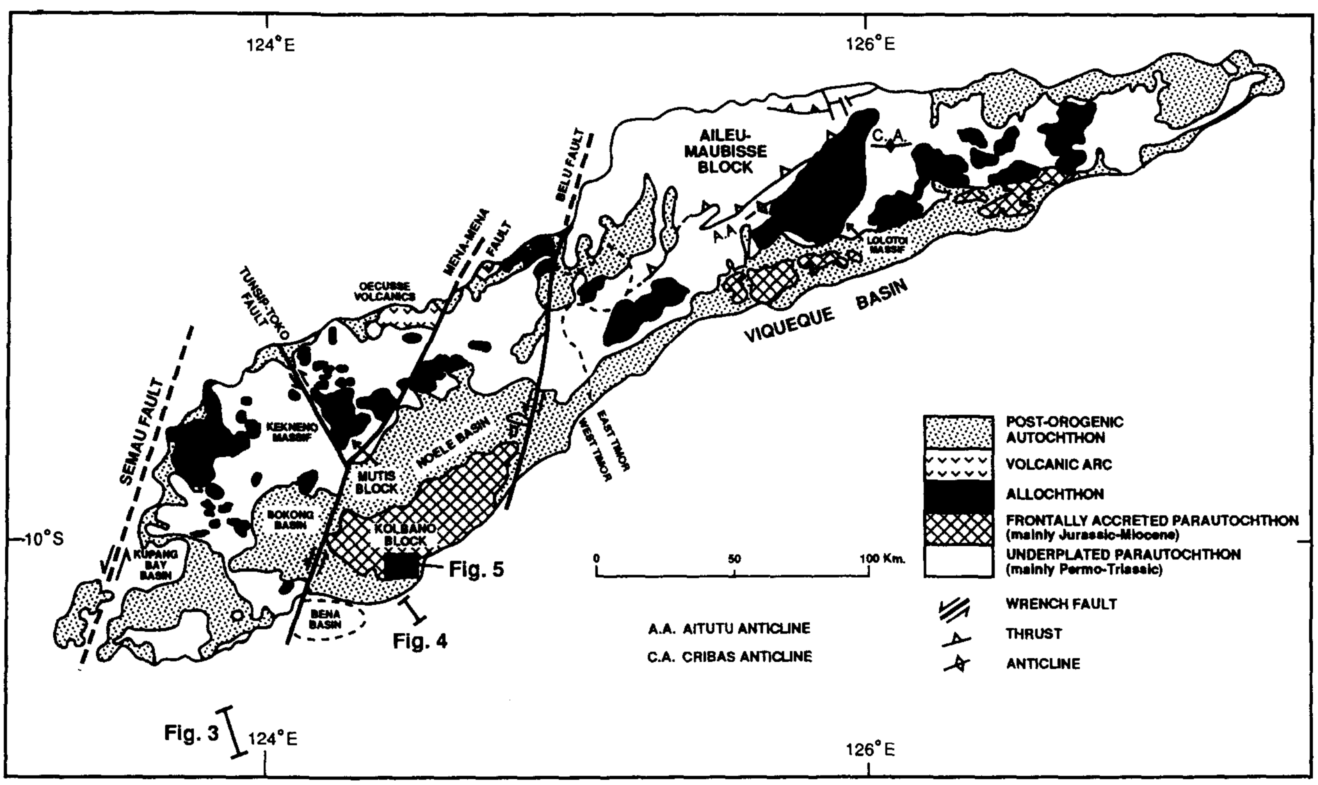

Fig. 2. Structural map of Timor. Adapted from Audley-Charles (1968) and Rosidi *et al.* (1981), with additional data from Kenyon (1974), Berry & Grady (1981a) and Bird *et al.* (1989). The Bobonaro Complex mainly crops out within the areas recorded as the parautochthon, but also locally cuts through the allochthon, and occurs as isolated diapirs intruding the post-orogenic autochthon.

(1979) interpreted the whole of Timor as one very large melange complex in which more or less coherent lithotectonic blocks were distributed through a pervasive scaly clay matrix. The Bobonaro Complex was seen as this melange matrix, resulting from intense shearing by repeated thrusting in a forearc setting.

A third interpretation of the Bobonaro Complex was proposed by Barber *et al.* (1986), who interpreted the complex as resulting from the multiple intrusion of shale diapirs. Mud volcanism is a widely occurring phenomenon in Timor, with at least 27 active mud volcano fields recognized (Barber & Brown 1988). Mud volcanoes are the surface expression of shale diapirs that break through to the ground surface (e.g. Biju-Duval *et al.* 1982). These shale diapirs can have a vertical extent of several kilometres, being sourced from overpressured shale horizons at depth. In Timor the overpressuring of shales is thought to arise from the tectonic loading by thrusting and from hydrocarbon generation. The shale diapirs tend to be located along the lines of wrench faults which cut vertically through the thrust stacks and provide suitable conduits for the intrusion of the shale diapirs. The Bobonaro Complex was interpreted by Barber *et al.* (1986) as the deeper parts of multiple shale diapirs exposed by erosion.

Of the three interpretations, the olistostrome model seems to have the most problems. The necessity of recognizing 'primary' and 'secondary' Bobonaro seems to be particularly suspect. For instance the whole of central West Timor (a distance of 50 km across strike on section 2, fig. 5 of Carter *et al.* 1976) must constitute either a thrust sheet of Bobonaro Complex or 'reworked Bobonaro', with the Neogene Batu Putih Limestone of the Central Basin having ridden passively on the back of the gravity sliding mass of Bobonaro Scaly Clay. As Audley-Charles *et al.* (1974) themselves commented "such a process seems highly improbable".

Other problems with the olistostrome interpretation include a lack of well documented localities where the supposed basal unconformity is seen; lack of bedding or other sedimentary structures apart from ambiguous flowage structures in a sedimentary succession supposedly more than 3000 m thick; and no explanation being given by this interpretation of the characteristic scaliness of the clay matrix (especially problematical as the scaliness is retained in the 'reworked Bobonaro'). Finally there is the more general problem with the olistostrome model in that no recent examples of olistostromes on anything like the scale required in Timor have been documented anywhere in the world.

Hamilton's (1979) interpretation of the Bobonaro Complex as a tectonic melange has more validity as certain scaly clays seen in Timor undoubtedly result from thrust-related deformation. For instance, deformed shales in the Noil Tuke River section of the northern Kolbano area of West Timor are thrusted shales of the Cretaceous Nakfunu Formation. However, these shales are distinct from the true Bobonaro Complex in having a strong planar fabric and in the absence of obvious exotic blocks.

Whilst admitting to an obvious bias, we believe that the shale diapirism model for the Bobonaro Complex (Barber *et al.* 1986) is the most successful interpretation of this unit. Shale diapirs can locally be seen intruding rocks as old as Triassic in the Kekneno area, and as young as Pleistocene in the Central Basin. The diapirs in the Kekneno area occupy a very low structural position, well below the level of supposed olistostrome emplacement, and so it cannot be argued that the diapirism is a secondary reactivation of shales originally emplaced in a collision-related olistostrome. In the Noil Tuke River section mentioned in the previous paragraph, an outcrop of Bobonaro-type shales distinct from the Nakfunu shales can be traced as a linear body some 100 m across for several kilometres parallel to strike. Structural vergence in the surrounding rocks is outward from this inferred diapiric structure (Charlton 1987). The source horizon for the shale diapirism in this region is the Lower Cretaceous Nakfunu Formation, and a similar stratigraphic level sources young diapirs near the thrust front south of Sumba to the southwest of Timor (Breen *et al.* 1986, Masson *et al.* 1991).

STRUCTURAL MODELS OF TIMOR

Three main structural models with numerous variations in detail have been proposed for Timor, which for brevity are usually described as the Imbricate, Overthrust and Rebound models.

Imbricate model (e.g. Fitch & Hamilton 1974, Hamilton 1979)

Timor is interpreted as an accumulation of imbricated and chaotic material at the hangingwall of a subduction zone whose surface trace is the Timor Trough. Hamilton (1979) emphasized what he interpreted to be the chaotic nature of Timor, with a tectonic melange (the Bobonaro Complex) forming a pervasive matrix supporting the more coherent stratigraphic sections.

Overthrust model (e.g. Carter *et al.* 1976, Barber *et al.* 1977, Barber 1979, Audley-Charles 1981, 1986a,b, Price & Audley-Charles 1983, Harris 1989, Audley-Charles & Harris 1990)

Early investigators of Timor (e.g. Wanner 1913) interpreted Timor in terms of Alpine-type nappe tectonics. Subsequently Audley-Charles and his co-workers (Carter, Barber and others) regarded Timor as made up of a series of thrust sheets including both oceanic and continental material which have been thrust onto the Australian continental margin. A clear distinction is made in most overthrust models between parautochthonous units derived from the Australian continent, and allochthonous units of non-Australian origin. Later models by Audley-Charles (1981, 1986a,b) and Price & Audley-Charles (1983, 1987) regard the Timor Trough not as a subduction-related feature equivalent to the Java Trench south of the Sunda Arc, but as a foredeep to a foreland fold belt (Timor), with Timor having been thrust northward over the pre-collisional Banda forearc. Harris (1989) and Audley-Charles & Harris (1990) also infer a foreland fold belt structure, but continue to interpret the Timor Trough as an essentially intracontinental downwarp rather than as the fundamental tectonic break inferred by Hamilton (1979).

Rebound model (Chamalaun & Grady 1978)

This model suggests that the Australian continental margin entered the Banda Arc subduction zone at a trench located in the vicinity of the Wetar Strait which currently separates Timor from the volcanic arc. Subsequently the continental lithosphere separated from the oceanic lithosphere which had been subducted ahead of it, resulting in the uplift of Timor by isostatic rebound controlled by steep faults. The model interprets virtually the whole exposed stratigraphy of Timor as parautochthonous, with only a very minor allochthon emplaced as part of the supposed Bobonaro Scaly Clay olistostrome. The model has been most fully applied to northern East Timor, where it has been used to explain the evolution of the Aileu metamorphic complex and surrounding areas (e.g. Berry & Grady 1981a, b, Berry *et al.* 1984).

The models outlined above all have elements of value but also have significant flaws. The Imbricate model is useful in that it draws analogies between Timor and processes documented from other active forearcs, but it implies a greater degree of structural incoherence than is actually the case in Timor. The Overthrust model recognizes the importance of flat-lying thrust structures in Timor, but the implication that the Timor Trough is not directly connected with subduction processes appears to the present authors unreasonable. The Rebound model is useful in recognizing the importance of steep structures in addition to thrusting and can apparently be applied to good effect in northern East Timor, but by downplaying the importance of thrusting and in not recognizing a substantial allochthon the model is not usefully applicable to most other parts of Timor. In the following sections an interpretation will be developed which uses facets of all these earlier models, but in particular the imbricate and overthrust models. The new interpretation will be developed by considering the structural style in a number of areas sequentially across the Timor forearc, starting from the most external parts of the orogen close to the deformation front in the Timor Trough.

Timor Trough north slope

The Timor Trough marks the deformation front of the Timor orogen (Fig. 3). To the south, the outer slope of the Australian Northwest Shelf dips into the trough at an average of 2–3°. The northern trough slope is overall only slightly steeper (3–4°), but is much more rugged topographically, with ridges, topographic lows and plateaus forming prominent features (e.g. von der Borch 1979, Karig *et al.* 1987). Between the northern and southern slopes at the axis of the trough is a flat-lying sedimentary basin of very variable extent and sedimentary thickness (0–15 km wide; 0–1 km thick).

The seismic expression of the axial region of the trough is illustrated in Fig. 3, which shows part of a commercial multichannel seismic line from south of the Kolbano area, West Timor. The seismic reflection pattern in much of the northern trough slope is incoherent higher up the slope, becoming somewhat more coherent in the lower parts of the slope closer to the deformation front. In the lower slope region, a few structures can be identified: these are antiformal culminations over S-directed thrusts. The antiforms are asymmetrical with a long N-dipping limb and a short S-dipping limb truncated by the underlying thrust. The foremost of these thrust–antiform pairs is a simple structure with an across-strike width of about 3 km. Structures further into the northern trough slope are multiply thrusted antiformal stacks. Between these antiformal stacks are minor sedimentary basins.

Crostella & Powell (1976) (Fig. 4) illustrated comparable structures from higher up the northern trough slope. The sketch of a seismic line shows a series of asymmetrical thrust antiforms stacked piggyback fashion with a southward sense of override. The imbricated sequence is interpreted as Cretaceous–Pliocene in age, unconformably overlain by Plio-Pleistocene post-orogenic sediments. The scale of the thrust–anticline structures in Fig. 4 is directly comparable to those shown in Fig. 3.

The style of deformation illustrated in Figs. 3 and 4 is suggestive of foreland fold and thrust belt tectonics. The Timor Trough north slope can be interpreted as a forward propagating thrust sequence in which new thrusts are sequentially developed at the axis of the Timor Trough, adding new thrust slices of the previously undeformed Australian margin to the toe of the northern trough slope. Subsequent to the addition of a new thrust package at the thrust front (such as the frontal thrust package in Fig. 3), internal deformation within the accreted sequence leads to the development of out of sequence thrusts within the thrust stack, producing the complex antiformal stacks seen further north in the accretionary prism (Fig. 3). Similar out of sequence thrusting can be inferred in Fig. 4 where there is a marked difference in scale between what can be interpreted as the original in-sequence thrust and the subsequent smaller out of sequence thrusts. This rather small-scale out of sequence deformation can be interpreted as the internal shortening within the fold belt/ accretionary prism necessitated by the Coulomb wedge or critical taper model (e.g. Davis *et al.* 1983).

The Kolbano area

The Kolbano area (Fig. 2) is located on the south coast of West Timor, immediately onshore from the Timor Trough northern slope. The Kolbano area has been studied in detail by Barber *et al.* (1977) and by Charlton (1987). The stratigraphy has been summarized in Charlton (1989) and Charlton & Suharsono (1990). Figure 5 shows a detailed geological map of a small part of the Kolbano area, around a Jurassic inlier at the core of the Kolbano structure. The most striking structural feature

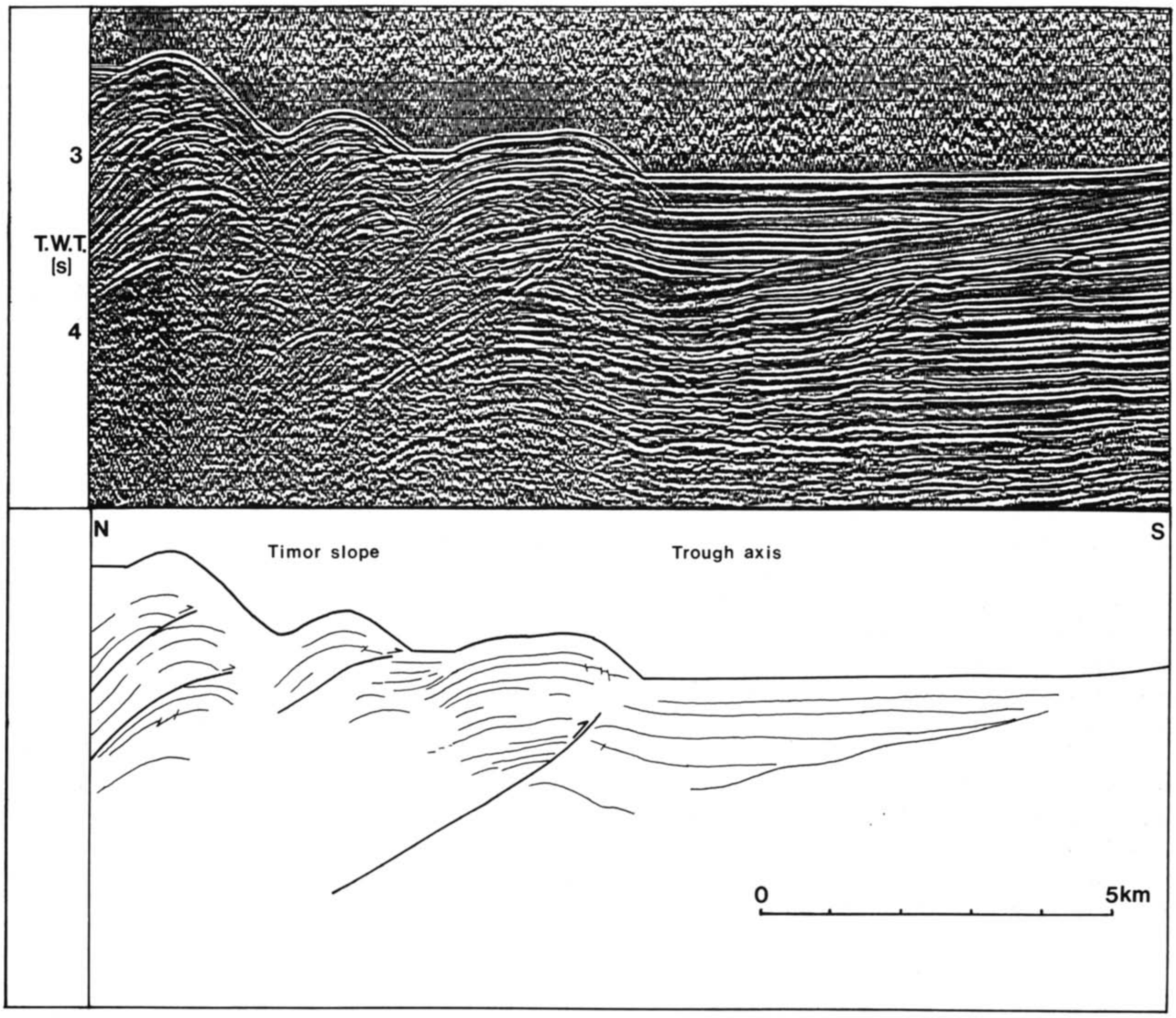

Fig. 3. Detail of a commercial multichannel seismic line across the axis of the Timor Trough. The north slope of the trough is interpreted as a thrust stack, with a number of anticlinal culminations located over southward directed thrusts. The culminations are in part diffractions, but nevertheless discrete packages can be recognized, separated by basal thrusts. The ridge on the left of the diagram is a multiply thrusted antiformal stack, whilst the right-hand thrust ridge is a simple anticlinal culmination. The small central ridge appears to be a minor thrust developing within the larger frontal thrust slice, and probably shows an early stage in the development of a complex antiform like that in the ridge to the left. See Fig. 2 for location.

of the Kolbano area is imbrication by high-angle reverse faults with a predominant S-vergence. The imbricated sequence generally ranges from Cretaceous to Miocene in age, but locally Jurassic, Triassic and possibly even Permian rocks are seen.

Imbrication structures in the southern Kolbano area occur on two important scales (Fig. 5). Firstly there is a gross repetition of sequences on a scale of 2–4 km across strike. Most of Fig. 5 consists of such a structural package, bounded by outcrops of the synorogenic Sonalete Formation (Charlton & Suharsono 1990) near Buni village in the south and in the Oe Baat river valley in the north. Within these larger packages, there are smaller reverse fault repetitions on a scale of a few hundred metres. Internally within these smaller imbricate slices, asymmetrical folds with a long northern limb and a short southern limb terminated by the reverse fault are sometimes seen. The folding is of a fairly open style, and bedding inversion is only rarely recognized. The style of deformation in the southern Kolbano area appears to be identical to that imaged by seismic sections across the Timor Trough inner slope immediately to the south, and the area is clearly a simple northward continuation of this structural province.

In the northern Kolbano area, the structural style is somewhat different (Barber *et al.* 1977, Charlton 1987). Instead of repeatedly imbricated slices of essentially homoclinal strata as seen in the southern Kolbano area, large recumbent anticlines predominate. These anticlines have a comparable size range (2–6 km) to the main thrust packages further south, and have a similar S vergence. We interpret them as comparable structures, with the different structural style resulting from a northward change in rock-type. The southern Kolbano area is dominated by decimetre-bedded hard calcilutites with thin intervening shales which have deformed in a brittle fashion without much folding. In contrast, the northern Kolbano area is dominated by shaly sequences, and folding rather than thrust-imbrication is the preferred mode of deformation. However, both the recumbent folding and the thrust imbrication are probably responses to the same necessity for internal shortening within the thrust stack.

The Viqueque and Central basins

Crostella & Powell (1976, fig. 10) also illustrated a seismic line across the Viqueque Basin offshore from southern East Timor (Fig. 2). This basin rests unconformably on the deformed sequences of the Timor Trough north slope, and the sedimentary fill consists of turbidite-deposited conglomerate, sandstone, siltstone and mudstone of Late Pliocene–Pleistocene age (Audley-Charles 1968, Crostella & Powell 1976). The basin fill is locally more than 2 km thick near its northern margin, and thins progressively southward over a distance of about 20 km. The seismic line shows a progressive downward rotation of the northern basin fill, suggestive of accumulation in a basin controlled by synsedimentary listric normal faulting. The basin fill is essentially unfaulted, and is clearly post-orogenic with respect to the main phase of deformation.

The Central Basin, located immediately north of the Kolbano area, is the West Timor equivalent of the Viqueque Basin (Kenyon 1974). The Central Basin can be divided into a number of sub-basins including the Bokong, Noele and Kupang Bay sub-basins. Sediments within both the Noele and Bokong sub-basins are estimated by Kenyon (1974) to be about 1500 m thick, whilst the actively subsiding Kupang Bay Basin may be only tens to several hundreds of metres thick (Kenyon 1974). It will be suggested subsequently that the post-orogenic Viqueque and Central basins are controlled by late-stage wrench faulting.

The Mutis–Kekneno area

The Mutis–Kekneno area of north-central West Timor (Fig. 2) is the highest part of West Timor. The structure of the Kekneno area and the adjacent western part of the Mutis massif has been studied in particular by Bird (1987). The Kekneno massif is an area of about 40 × 25 km composed entirely of Permian and Triassic rocks of Australian affinity (Bird *et al.* 1989, Cook *et al.* 1989). The structural style of the Kekneno area is dominated by bedding-parallel thrusts with locally well-developed imbrication structures. Folding and imbrication by high-angle reverse faults also occur, but are of lesser importance here than in the Kolbano area to the south. Compared to the Kolbano area, the Kekneno structures are in general larger and more coherent.

The Kekneno massif is bounded to the east by an important zone of wrench faulting which will be considered in more detail subsequently. To the east of this wrench fault is a block of Maubisse Formation, here interpreted as a further part of the parautochthon. The Maubisse Formation is separated from the Mutis massif by a zone of serpentinites (Rosidi *et al.* 1981). The

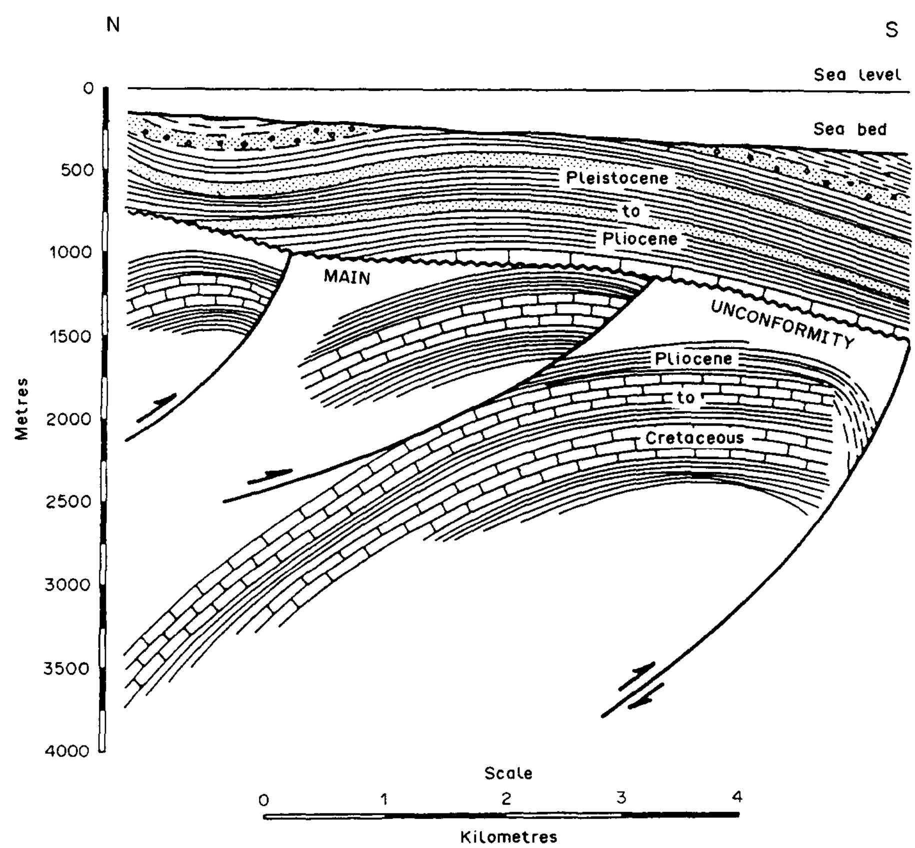

Fig. 4. Interpretation of a seismic line shot offshore from the Kolbano area, southern West Timor (Crostella & Powell 1976). The central thrust slice is directly comparable in scale to the small central thrust ridge in Fig. 3, and may have had a similar origin by out of sequence thrusting. See Fig. 2 for location.

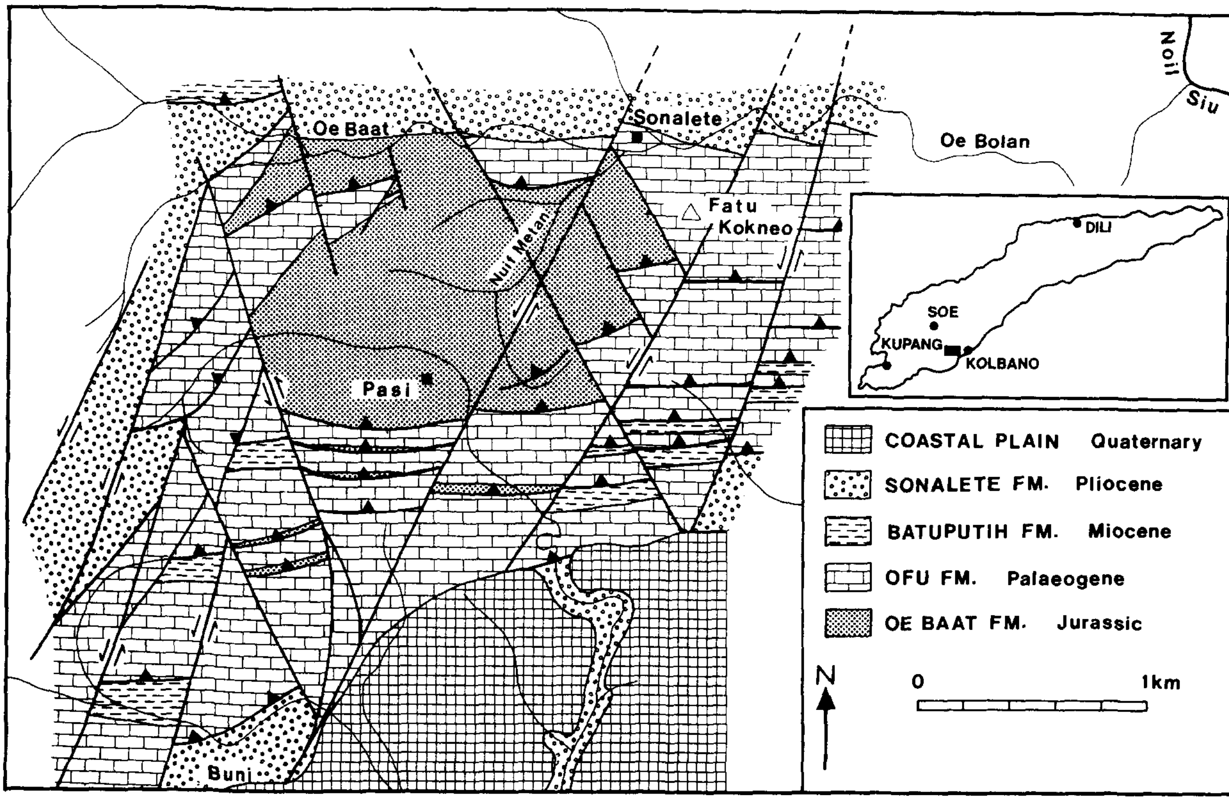

Fig. 5. Geological map of the Pasi Jurassic inlier at the core of the Kolbano structure, southern West Timor (Charlton & Suharsono, 1990). See inset map and Fig. 2 for location.

serpentinites probably mark a basal thrust plane to the Mutis block, which comprises part of the allochthonous basement. Earle (1981) and Sopaheluwakan *et al.* (1989) described the Mutis Complex as comprising distinct ophiolitic and metasedimentary parts. In the Mutis massif, the ophiolitic part consists primarily of peridotites, and these structurally overlie the metasediments. The metasediments have an inverted metamorphic gradient, interpreted (Sopaheluwakan *et al.* 1989) as a metamorphic sole beneath a hot overthrust peridotite body. In other allochthonous klippen, metamorphics of the Mutis Complex are overlain unconformably by the Palelo Group, an unmetamorphosed sedimentary–volcanic sequence of Late Cretaceous–Palaeogene age (e.g. Rosidi *et al.* 1981). Another member of the allochthon, the Miocene Cablac Limestone Formation, forms an isolated klippe resting directly on the Kekneno massif (Bird *et al.* 1989).

The allochthon of Timor is interpreted as representing the pre-collisional Banda forearc (e.g. Audley-Charles 1986a). Tectonometamorphic events restricted to the allochthon, such as the metamorphic inversion described above, can be interpreted in terms of events occurring prior to arc–continent collision. Ophiolite complexes in intraoceanic forearc settings, such as the East Halmahera Ophiolite of NE Indonesia, have been interpreted as resulting from extreme extension and ocean-like spreading within a forearc setting (e.g. Ballantyne 1990). Thus one possible interpretation of the metamorphic inversion in the Mutis massif might be that it occurred in the pre-collisional forearc complex, with the metasediments representing material underplated beneath a supra-subduction zone (forearc) ophiolite. However, this may be an oversimplification, as radiometric dating of pelitic metasediments in the Mutis Complex suggests a peak of prograde metamorphism at about 118 ± 38 Ma (Earle 1981), with a possible retrograde metamorphic event at about 38 Ma (Sopaheluwakan & Helmers 1990). More likely these radiometric dates correspond to events occurring on the 'Asiatic' plate margin before the Mutis rocks occupied their eventual forearc position (e.g. Brown & Earle 1983). For instance, the approximate 118 Ma date (mid-Cretaceous) may correspond to an important phase of deformation recognized in SE Kalimantan and western Sulawesi (Sukamto 1975, van Leeuwen 1981, Sikumbang 1986). The 38 Ma (Late Eocene) retrogressive event may correspond to a phase of uplift and erosion recognized in western Sulawesi (van Leeuwen 1981). Both SE Kalimantan and western Sulawesi show distinct stratigraphic similarities with the allochthon of Timor (Haile *et al.* 1979, Earle 1981, Audley-Charles 1985).

For the structurally underlying parautochthon, the greater structural coherence of the Kekneno area compared with the Kolbano area is here interpreted to be the result of a somewhat different tectonic history for the two areas. The Kolbano area, consisting primarily of Jurassic–Miocene strata, was imbricated into the Timor thrust stack by the process of frontal accretion. In contrast, the Kekneno massif, consisting exclusively of

Permian and Triassic strata, was underplated to the base of the thrust stack. The underplated thrust packages of the Kekneno area are generally larger, structurally more coherent and are bounded by longer, flatter thrust planes than the frontally accreted packages of the Kolbano area. The absence of post-Triassic strata from the Kekneno area is explained by the originally overlying sequences having been stripped off the deeper units in an earlier phase of frontal accretion. Considering their relative positions and their broadly complementary age ranges, it is likely that the Kolbano and Kekneno area originally formed part of the same stratigraphic pile (as originally suggested by van Bemmelen 1949), with the two sequences having become separated during sequential imbrication into the Timor thrust stack.

Whilst the uppermost (i.e. youngest) sediments of the colliding continental margin were added to the nascent fold belt by frontal accretion, the deeper parts of the outer slope stratigraphy would have been initially thrust below the former forearc complex before being added to the base of the thrust stack by underplating. This underplating would thus have taken place directly beneath the former forearc basement, resulting in the present situation in the Mutis–Kekneno region with the Mutis Complex directly overlying the Permo-Triassic parautochthon, separated by a zone of serpentinites which mark the basal decollement to the pre-collisional forearc.

Although this relatively simple thrust belt interpretation is sufficient to explain the emplacement of allochthonous basement onto the Permo-Triassic parautochthon, it is not sufficient to explain the presence of allochthonous cover (i.e. the Cablac Limestone Formation) directly on the parautochthon. Harris (1989) inferred a late-stage phase of low-angle normal faulting on Timor, which has locally excised the former allochthonous basement, resulting in the present superposition of allochthonous cover directly on the parautochthon.

Northwestern East Timor

Northwestern East Timor is occupied by the Aileu Formation, a metamorphic complex ranging from subgreenschist to upper amphibolite grade (Barber & Audley-Charles 1976, Barber *et al.* 1977, Berry & Grady 1981a). Overall the Aileu Formation grades northward from essentially unmetamorphosed and undeformed Maubisse Formation, through stylolitized limestones with slates, to refolded slates with folded and lineated limestones, and finally to multiply deformed schists at the north coast (Barber *et al.* 1977). According to Barber & Audley-Charles (1976) and Barber *et al.* (1977), the Aileu Formation forms the northern half of the Aileu–Maubisse nappe, which forms one of the highest structural units on Timor. In a detailed study of the high-grade schists near the north coast east of Dili, Berry & Grady (1981a) found no evidence of internal thrusting or imbrication within the Aileu Formation. These authors recognized the following metamorphic history (with additional radiometric dating by Berry & McDougall 1986).

(1) Production of widespread layer-parallel schistosity without recognizable folding, followed by a peak of prograde metamorphism (pre-70 Ma).

(2) Tight folding with axial planar schistosity, associated with gradual cooling (approximately 8 Ma).

(3) Two phases of minor folding under greenschist conditions.

(4) A further phase of open, macroscopic folding probably synchronous with strike-slip faulting parallel to the north coast.

(5) Juxtaposition of the Aileu Formation with essentially unmetamorphosed Permian and Mesozoic rocks by dip-slip faulting.

The Aileu metamorphic complex originally comprised a mixed sedimentary and basic igneous succession (Barber & Audley-Charles 1976, Barber *et al.* 1977, Berry & Grady 1981a). In the south where the complex grades into the Maubisse Formation, the Aileu Formation is presumably of Permian age. Elsewhere the protolith probably extends up into the Mesozoic and possibly down into the older Palaeozoic (Barber & Audley-Charles 1976). The Hili Manu Lherzolite (Berry 1981), which occurs in faulted contact with the rocks studied by Berry & Grady (1981a) has been interpreted by Harris (1989) as the basement to the Aileu Formation. The petrology of the lherzolite suggested to Harris (1989) an origin close to the continent–ocean transition. The gradation of the Aileu Formation into the parautochthonous Maubisse Formation suggests that this continent–ocean transition was the outermost margin of Australia.

The metamorphic history of the Aileu Formation outlined above can be interpreted as follows.

(1) The development of layer-parallel schistosity without folding may suggest an extensional mode of formation. Taken with the subsequent prograde metamorphic peak dated as pre-70 Ma, and considering the likely Palaeozoic–?Mesozoic age of the Aileu protolith, this extensional event can probably be correlated with the Late Jurassic rifting of the northwestern margin of Australia.

(2) The approximately 8 Ma phase of tight folding and associated gradual cooling is the major tectonic event recorded in the Aileu Formation (Berry & Grady 1981a, b). These authors interpreted this as the main arc–continent collision event in this area. The Late Miocene deformation pre-dates the Pliocene deformation consistently recorded by sedimentary sequences elsewhere in Timor (e.g. Carter *et al.* 1976, Audley-Charles 1986a, Charlton 1987). Considering the location of the Aileu Formation in the extreme north of Timor, the Late Miocene deformation may record the very first phase of collision between the most distal parts of the Australian continent and the island arc system.

(3) The relatively minor post-collisional structural events recorded in the Aileu Formation may correspond to the main structuring (by thrust-imbrication) in the rest of Timor.

(4) and (5) As elsewhere on Timor, the main deformation related to imbrication by thrusting is succeeded by a phase of wrench faulting and finally by late-stage

normal faulting (Audley-Charles 1985, Charlton 1987, Bird *et al.* 1989, Harris 1989, Barkham in press).

Wrench faulting in Timor

As was mentioned in the previous section, a characteristic pattern of thrusting followed by wrench faulting is recognized throughout Timor. The wrench faulting is often of great importance, locally as important as thrusting in controlling structural relationships. This section will briefly discuss some examples of well documented wrench faulting in Timor.

Figure 5 shows a geological map of the Jurassic inlier at the core of the Kolbano structure (Charlton & Suharsono 1990). In addition to the reverse faults with a predominant E–W strike and S vergence, there are two prominent sets of steep faults oriented NNE–SSW and NNW–SSE. The NNE–SSW set are left-lateral wrench faults. The NNW–SSE set were originally interpreted as a conjugate set of right-lateral wrench faults (e.g. Tjokrosapoetro 1978, Rosidi *et al.* 1981), but following detailed fieldwork in the Kolbano area these have been reinterpreted as both left-lateral wrench faults and normal faults (Charlton 1987). The NNW–SSE wrench faults generally have small offsets compared with the NNE–SSW set, and are interpreted as secondary features. In many cases these may be normal faults originating from extension related to wrenching on the NNE–SSW set reactivated subsequently as wrench faults. No indisputable right-lateral wrench faults have been recognized in the Kolbano area (Charlton 1987).

In northern West Timor, Rosidi *et al.* (1981) recognized an important fault lineament with a NNW–SSE trend bounding the eastern edge of the Kekneno massif. Bird (1987) recognized this as a left-lateral wrench fault which he named the Tunsip-Toko fault zone (Fig. 2). The fault cuts sharply across the E–W-striking structures associated with earlier thrusting, and is marked in addition to the near vertical wrench fault strands by reverse faults subparallel to the fault lineament which apparently root into the fault zone (Bird 1987).

On a larger scale, Charlton (1987) recognized three important zones of NNE–SSW left-lateral wrench faults cutting through West Timor (the Semau, Mena-Mena and Belu faults: Fig. 2). The Tunsip-Toki fault zone is a splay from the Mena-Mena Fault, joining the larger fault where the latter has a marked dogleg in central Timor. These major faults have offsets of a few tens of kilometres, and are characterized by low topography fault zones with abundant outcrops of the Bobonaro Complex. The Bokong and Noele sub-basins of the Central Basin are offset by the Mena-Mena Fault, whilst the actively subsiding Kupang Bay Basin is associated with the seismically active Semau Fault (Tjokrosapoetro 1978, McCaffrey 1989). The evolution of the Timor postorogenic basins is probably related to transtension on these late-stage wrench faults. Wrench faults with similar orientations and left lateral displacement but with probably smaller offset, also occur in East Timor (Audley-Charles 1985), and may similarly control the Viqueque post-orogenic basins.

Perhaps the largest of the three NNE–SSW-trending wrench faults in West Timor is the Belu Fault which approximately follows the border between East and West Timor, and bounds the Aileu–Maubisse Block on its western margin. According to Audley-Charles (1968) and Barber *et al.* (1977), the Aileu–Maubisse Block is thrust onto the Lolotoi Complex along its southeastern margin (Fig. 2). If this is correct, then according to the interpretations outlined in this paper, the parautochthon has been thrust onto the allochthon. This requires a late-stage thrusting event. The thrust front of the Aileu–Maubisse Block has a NE–SW orientation compared with the earlier thrusting oriented more nearly E–W, and a possible explanation of this late deformation event is that it resulted from transpression on the Belu Fault. Similarly the late-stage low-angle normal faulting inferred by Harris (1989) might be related in general terms to local transtension on these wrench fault systems.

STRUCTURAL EVOLUTION OF THE TIMOR COLLISION COMPLEX

The structural style of Timor suggests interpretation in terms of a foreland fold belt model. However, unlike the models proposed by Price & Audley-Charles (1983, 1987), Audley-Charles (1986a,b), Harris (1989) and Audley-Charles & Harris (1990) which clearly distinguish between a pre-collisional oceanic subduction trench and a post-collisional foredeep (the Timor Trough) with the two being essentially unconnected, the interpretation developed here sees a simple structural progression from the pre-collisional forearc and trench to the present foreland fold belt and associated foredeep. The predominant structural style of Timor can be related to the processes of frontal accretion, underplating and subsequent out of sequence deformation. The main (parautochthonous) part of Timor has evolved by the sequential addition of imbricate thrust slices of the Australian continental margin to the front and base of the former forearc complex. After the main phase of deformation related to thrusting, Timor was cut by left-lateral wrench faults with a predominant NNE–SSW trend, and finally by a phase of normal faulting. The overall structural style of Timor is summarized in a cartoon cross-section in Fig. 6.

The first portion of the Australian continental margin to interact with the Banda Arc subduction zone was the most distal part: i.e. the Aileu sequence. Radiometric dating (Berry & McDougall 1986) indicates that collision commenced during the Late Miocene at about 8 Ma. The youngest sedimentary cover of this distal Australian sequence was probably stripped from the deeper units by frontal accretion, and cannot now be recognized. The deeper Palaeozoic–?Mesozoic parts of the Aileu sequence were thrust beneath the former forearc complex and soon after were accreted by underplating into the nascent collision complex. Rapid uplift and

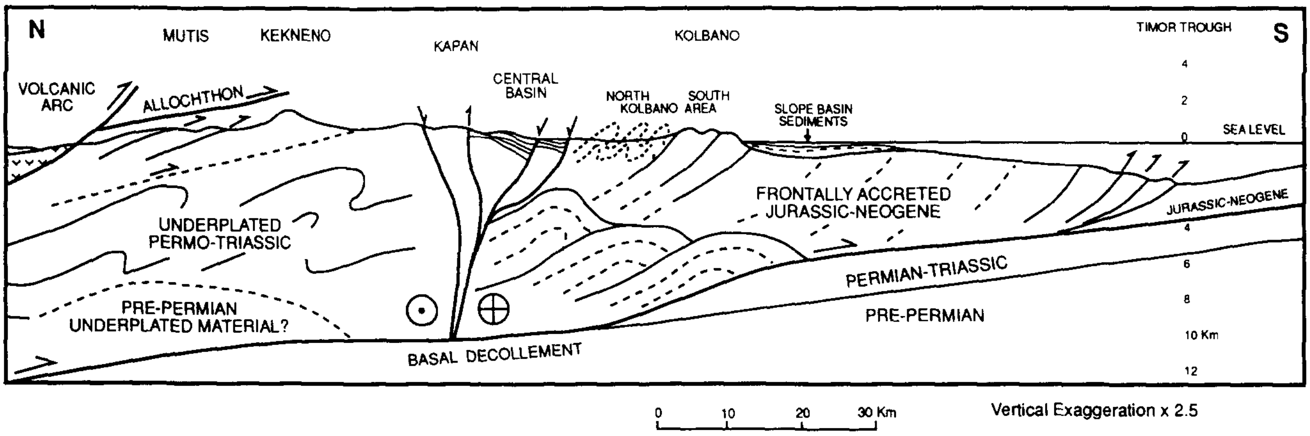

Fig. 6. Cartoon structural cross-section through the Timor fold belt in West Timor. The deeper structures are purely schematic.

deformation at this time produced the main phase of structuring and the retrograde metamorphism in the Aileu Formation.

The second stage of collision commenced in the Early Pliocene (Carter *et al.* 1976, Audley-Charles 1986a) when the more proximal parts of the Australian continental margin overlying true continental crust began to enter the subduction system. Again the younger, uppermost sediments were accreted to the collision complex by frontal accretion giving rise to the Kolbano area in West Timor, whereas the deeper stratigraphic levels (such as the Kekneno sequences) were initially subducted beneath and then underplated into the base of the collision complex. In East Timor, the frontally accreted equivalents of the Kolbano area are less extensive, being restricted to small localities along the south coast at Betano, Aliambata and Iliomar (Barber *et al.* 1977; Fig. 2). The underplated zone in East Timor includes the Cribas and Aitutu anticlines (Audley-Charles 1968). As with the Mutis–Kekneno area described earlier, the older parautochthonous strata seen in these anticlines were underplated directly beneath the Lolotoi–Mutis allochthonous basement, and hence the close geographical association between the Lolotoi massif and the Cribas and Aitutu anticlines.

The subsequent phase of left lateral wrench faulting was primarily taken up on three major faults in West Timor (the Semau, Mena-Mena and Belu faults), but smaller-scale left-lateral wrench faulting also pervasively affects regions such as the Kolbano area. Transtension associated with these faults has controlled sedimentation in the postorogenic Viqueque and Central Basins, whilst transpression on the Belu Fault may have emplaced the Aileu–Maubisse thrust block onto the Lolotoi allochthon. The wrench faults also permitted the release of overpressuring in shales involved in the earlier thrusting. This release of overpressure produced intrusive shale diapirs, which are represented by the extensive Bobonaro Scaly Clay (Barber *et al.* 1986).

Acknowledgements—We are grateful to the staff of the Geological Research and Development Centre, Bandung, Indonesia, with whom we have collaborated during our studies of Timor; in particular Dr R. Sukamto (Director), Dr T. Simandjuntak, Suharsono and S. Tjokrosapoetro (M.G.I.). We are also grateful to Prof. M. G. Audley-Charles and Dr R. Berry for useful comments made in review of an earlier version of this paper. Fieldwork in Timor was primarily financed by a group of oil companies sponsoring the University of London geological research programme in southeast Asia.

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