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Temporal distribution of strain in the active Banda orogen: a reconciliation of rival hypotheses

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Abstract—Integration of geological and geophysical data from the active Banda orogen reveals important variations in structural style with time that reconcile rival hypotheses for the tectonic evolution of the Banda arc. These variations indicate the temporal distribution of strain in the collision zone by vertical and horizontal structural restorations of the collision through time.

In the western part of the collision (Sumba and Savu Islands) most plate convergence occurs at a very high strain rate within 20–40 km of the deformation front. This narrow zone of frontal accretion expands eastward toward Savu where it is part of a submarine accretionary pile over 150 km wide.

In West Timor the accretionary wedge is internally shortened and emergent. Uplift of the forearc upper plate during this deformational phase causes its leading edge to detach and form nappes. The remainder of the forearc is overridden along backthrusts by the orogenic wedge. Various sites of intra-wedge shortening and some strike–slip motion may account for as much as 70% of plate convergence in West Timor.

The distribution of plate convergence away from the deformation front into more internal parts of the collision zone is interpreted as a function of increasing frictional resistance at the base of the orogenic wedge. Resistance to orogenic wedge advance is attributed to an abrupt increase in basal decollement slope, decrease in pore–fluid pressures and increase in strength of incoming material. The combination of continued plate convergence and increased coupling in East Timor cause the wedge to move almost entirely with the lower plate along arc-directed backthrusts and backarc thrusts. Backthrusting eventually closes the Banda forearc basin entirely.

These lateral variations in structural style along the strike of the Banda orogen are attributed to the kinematics of oblique collision, and structural and stratigraphic discontinuities of the Australian lower plate. Possible relationships between different stuctural styles and the temporal distribution of strain in the orogenic zone is constrained by structural restorations of the collision. The restorations demonstrate that each of the three different models (imbricate, overthrust and upthrust) used to characterize the structure of the western Banda orogen may be applied at various times during the arc–continent collision.

INTRODUCTION

THE BANDA orogen of eastern Indonesia is the product of complex interaction between the SE Asian, Australian and Pacific plates (Fig. 1). Relative to the SE Asian plate, Australian continental crust moves NNE at between 70 and 80 km/Ma toward oceanic realms of the Pacific plate that move WNW at 100–130 km/Ma (Minster and Jordan 1978, Daly *et al.* 1987, DeMets *et al.* 1990, Smith *et al.* 1990). Shear at the intersection of the three plates is distributed through a complex zone of convergence and sinistral shear between the Terera-Aiduna and Sorong fault systems (Fig. 1). Superposition of the westward and northward plate motions in this zone have detached, rotated and moved westward several continental fragments from the Australian plate (Hamilton 1979).

Three major tectonic elements form the Banda orogen (Fig. 1): (1) the Banda Sea is a complex marginal basin that occupies the interior (concavity) of the Banda arc; (2) the northern Australian–New Guinea continental margin forms the external perimeter of the Banda orogenic arc; and (3) the Banda arc constitutes an orogenic zone between the Banda Sea and Australian continental margin. This orogenic zone has a paired system of arcuate islands; an inner, intra-oceanic magmatic arc and an outer, contractional wedge. The Banda orogen is a consequence of progressive collision of the continent-bearing Australian plate with the Banda Sea (Fig. 2), providing an extensive natural laboratory for discovery and quantification of fundamental orogenic processes.

Australian continental margin

Continental material incorporated into the Banda orogen correlates directly with undeformed laterally equivalent sequences of the present NW Australian margin (Audley-Charles 1986a). This correlation helps in structural restorations of continental margin stratigraphy in the fold–thrust zone of the Banda orogen. The NW Australian passive continental margin formed during Middle–Late Jurassic breakup and Early Cretaceous (Berriasian) sea-floor spreading in the adjacent Wharton Basin (Falvey 1972, Larson 1975). A breakup unconformity separates two major sedimentary sequences found throughout northern Australia (pre- and post-rift sequences).

Pre-breakup sedimentary successions of NW Australia generally fill NW–SE striking grabens (Fig. 3) with two major stratigraphic sequences (Powell 1982). The lower sequence consists of Late Cambrian to Carboniferous clastics, evaporites and carbonates. These rocks unconformably underlie an Early Permian to Early Jurassic sequence of neritic turbidite deposits, carbonates and siliciclastic sediment. Only the Early Permian–Jurassic successions are exposed on platform regions of the Australian shelf and in the Banda orogenic zone. Studies of these rocks in Timor (Audley-Charles 1968,

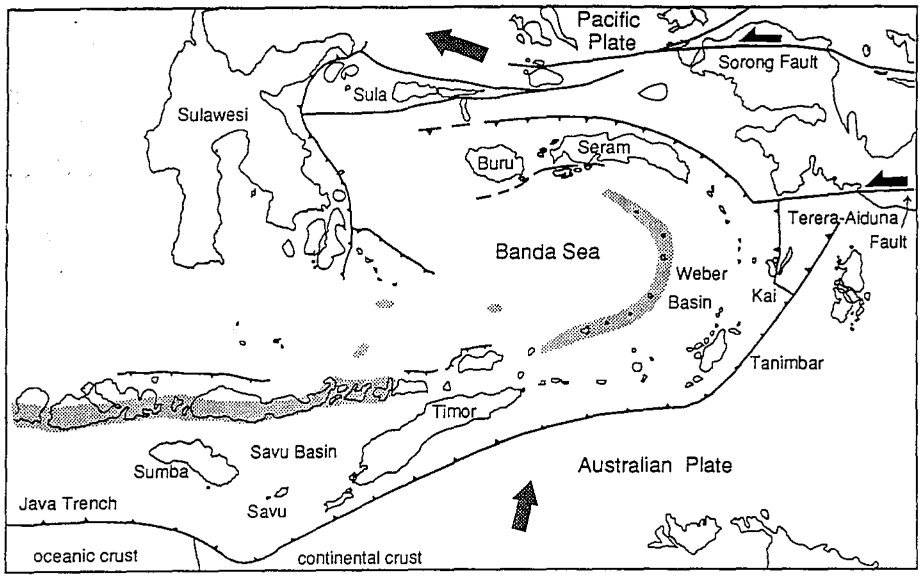

Fig. 1. Tectonic map of Banda arc. Shaded region is zone of active volcanism. Large arrows are relative plate motion directions.

Cook 1986, Bird 1987) indicate an accumulation of around 3000 m in what is interpreted as an intra-cratonic basin of northern Gondwana.

Middle–Late Jurassic continental breakup is characterized in the NW Australian shelf (von Rad and Exon 1983), and orogenic zones of Timor (Charlton 1987) and Seram (Audley-Charles *et al.* 1979), by marine transgression across ENE–WSW trending horsts and grabens (Fig. 3). Thin sedimentary successions from erosion or non-deposition occur on structural highs. Open-ocean passive margin conditions prevailed from Early Cretaceous until Miocene–Present arc–continent collision (Powell 1982).

Post-breakup passive margin deposits encountered by wells and dredge samples from the present NW Australian margin are dominantly pelagic. The margin is starved of terrigenous sediment. Distal slope and rise facies are characterized by 500–1500 m of Late Cretaceous radiolarian chalk and Paleocene–Pliocene, semi-consolidated foraminiferal and nanno chalks (von Rad and Exon 1983). These deposits are identical in age and composition to Early Cretaceous to Pliocene shales, marls and radiolarites found in the orogenic zone of Timor and Seram (Audley-Charles *et al.* 1979). Post-rift shelf facies successions consist of Cretaceous transgressions of sandstone and shale conformably overlain by Cenozoic carbonate (Smith and Ross 1986). The shelf facies is up to 3000–4000 m thick (Balke and Burt 1976).

Banda orogenic wedge

The zone of late Neogene contraction of underthrust Australian continental margin material comprises the outer Banda orogenic wedge (Fig. 3). The wedge is bound by basins with water depths usually more than 3000 m in both the foreland outer perimeter of arc, and internally in the forearc region. Within the orogenic zone, Banda forearc basement is uplifted by underthrusting of Australian continental margin sediments (Fig. 4).

Banda forearc basement forms the Banda allochthon or Banda terrane of Audley-Charles and Harris (1990). On Timor Island (Figs 3 and 4), the Banda allochthon occurs as flat-lying, attenuated nappes (Barber and Audley-Charles 1976, Carter *et al.* 1976, Barber *et al.* 1977). These nappes structurally overlie folded and thrust Australian continental margin sequences (Fig. 4c). The Banda terrane is correlative with exposures on 22 other outer Banda arc islands including the larger islands of Sumba, Tanimbar and Seram. The Banda allochthon provides some of the only documented exposures of the forearc basement of an *active* intra-oceanic arc system.

Although nappes were first described in Timor by the field studies of Wanner (1913) and then by Audley-Charles (1968), more recent work (e.g. Fitch and Hamilton 1974, Chamalaun and Grady 1978, von der Borch 1979, Hamilton 1979) challenges the stratigraphic and structural basis for this interpretation. Alternative models characterize structural styles as one of two end members: either as an intensely sheared and chaotic subduction mélange of continental material (Hamilton 1979), or as somewhat undeformed Australian continental margin material uplifted along high angle faults (Chamalaun and Grady 1978). The evidence for each of these models comes dominantly from studies of different parts of the Banda orogenic wedge. Each of these rival hypotheses may actually represent a different instant in time during the evolution of the Banda orogen. If so, then each model may be one of several transitional phases of the tectonic evolution of arc–continent collision. These various deformational phases may provide clues to the temporal distribution of strain throughout the orogenic zone.

The aim of this paper is to: (1) document the transitional nature of variations in structural style along

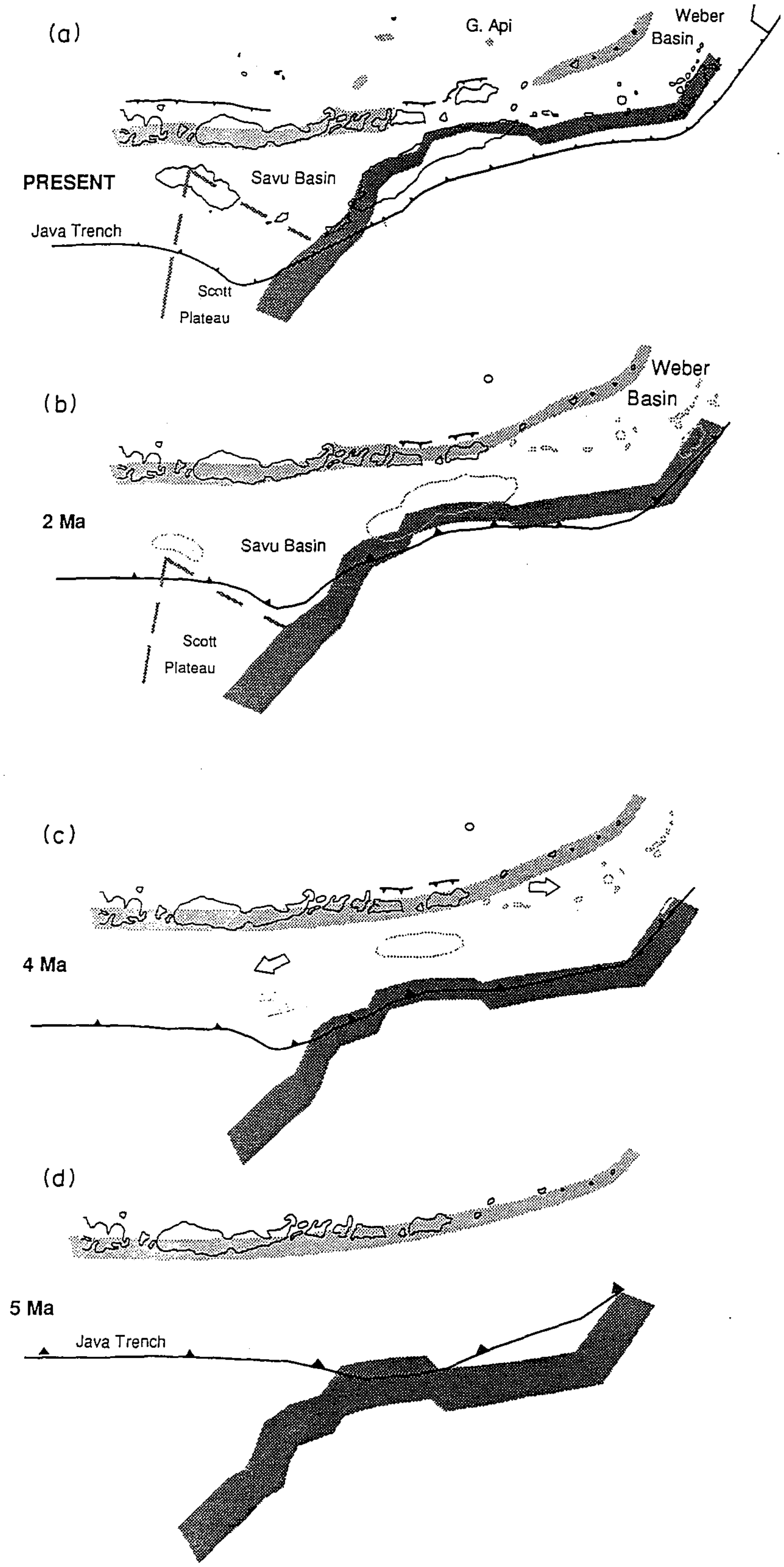

Fig. 2. Horizontal restoration of collision between NW Australian slope (dark grey band) and Java Trench. Initial collision occurs at 4–5 Ma of what is now the central Timor segment of Australian margin. Distribution of plate convergence in collision zone is shown by progressive shortening of Australian margin (reduction in thickness of dark grey band), uplift of orogenic wedge (dashed outlines of islands), closure and possible extrusion of forearc basin, backarc thrusting and northward displacement of orogenic wedge and zone of active volcanism (shaded light grey).

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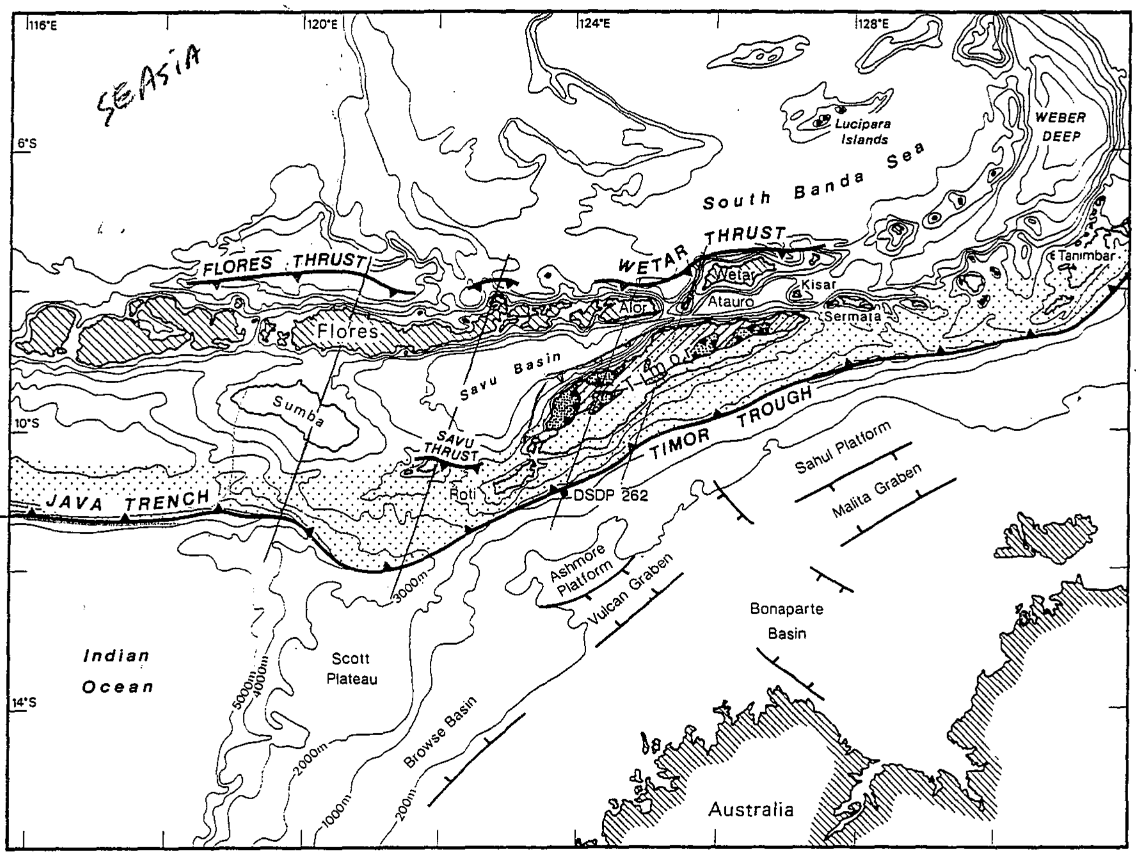

Fig. 3. Detail of western Banda orogen and NW Australian continental margin. Stipples represent frontal accretionary wedge. Closely spaced dots represent Banda allochthon forearc upper plate. Structurally underlying the Banda allochthon is underthrust Australian pre-rift sequence (NE–SW diagonal lines). Given NNE convergence rate of 75 km/Ma and obliquity of convergence angle, collision between Australia and Java Trench propagates WSW at 110 km/Ma along the Australian continental margin. Assuming time–space equivalence, a distance of 110 km along deformation front represents 1 Ma in time. Lines correspond to various structural transects used for restoration of cross-sections (see Fig. 4).

orogenic strike; (2) relate these variations to plate kinematics, and structural and stratigraphic discontinuities of the Australian margin; and (3) discuss possible relationships between different structural styles and the temporal distribution of strain in the orogenic zone.

VARIATION IN STRUCTURAL STYLE

The Banda orogen manifests several episodes, phases and types of deformation that produce a variety of structural styles. The first episode of collisional deformation is difficult to constrain, but is most likely transitional in time and space with the New Guinea orogeny to the NE. The New Guinea orogen marks the initial collision between the proto-Banda allochthon (island arc) and a promontory of NE Australia–northern New Guinea around 30–40 Ma (see Pigram 1991). This collision causes considerable identation and modification of the Australian–Pacific plate margin (Fig. 1). The Banda arc progressively developed as Australia continued to move northward, becoming increasingly more involved in the collision (Fig. 2).

The Australian continental margin near Seram arrived at the collisional front around Middle Miocene (Audley-Charles *et al.* 1979, Jongsma *et al.* 1989). Superposition of northward and westward motions of the respective Australian and Pacific plates in this region also contributes a major component of counter-clockwise (CCW) rotation shown by paleomagnetic studies (Haile 1981). Apart from rotation, geological and geophysical data from Seram suggest its tectonic evolution is very similar to that of Timor Island (Audley-Charles *et al.* 1979, Jongsma *et al.* 1989).

At the Kai and Tanimbar Islands, the Australian continental margin, inner volcanic arc and outer contractional wedge are subparallel to the Australian plate convergence vector (Fig. 2). This geometry may account for the occurrence of steeply dipping strike–slip faults in the hinterland, the relatively small (20–30 km wide) compressional zone and mostly undeformed sedimentary fill in small basins throughout the region (Jongsma *et al.* 1989). Contractional deformation of the Australian margin in this region began shortly after collision in Seram, but the extreme obliquity of arc–continent convergence appears to have limited the extent of shortening.

The western Banda arc is part of an oblique collision zone involving the NW Australian continental margin. Data from marine and onshore geological and geophysical studies document important variations along strike

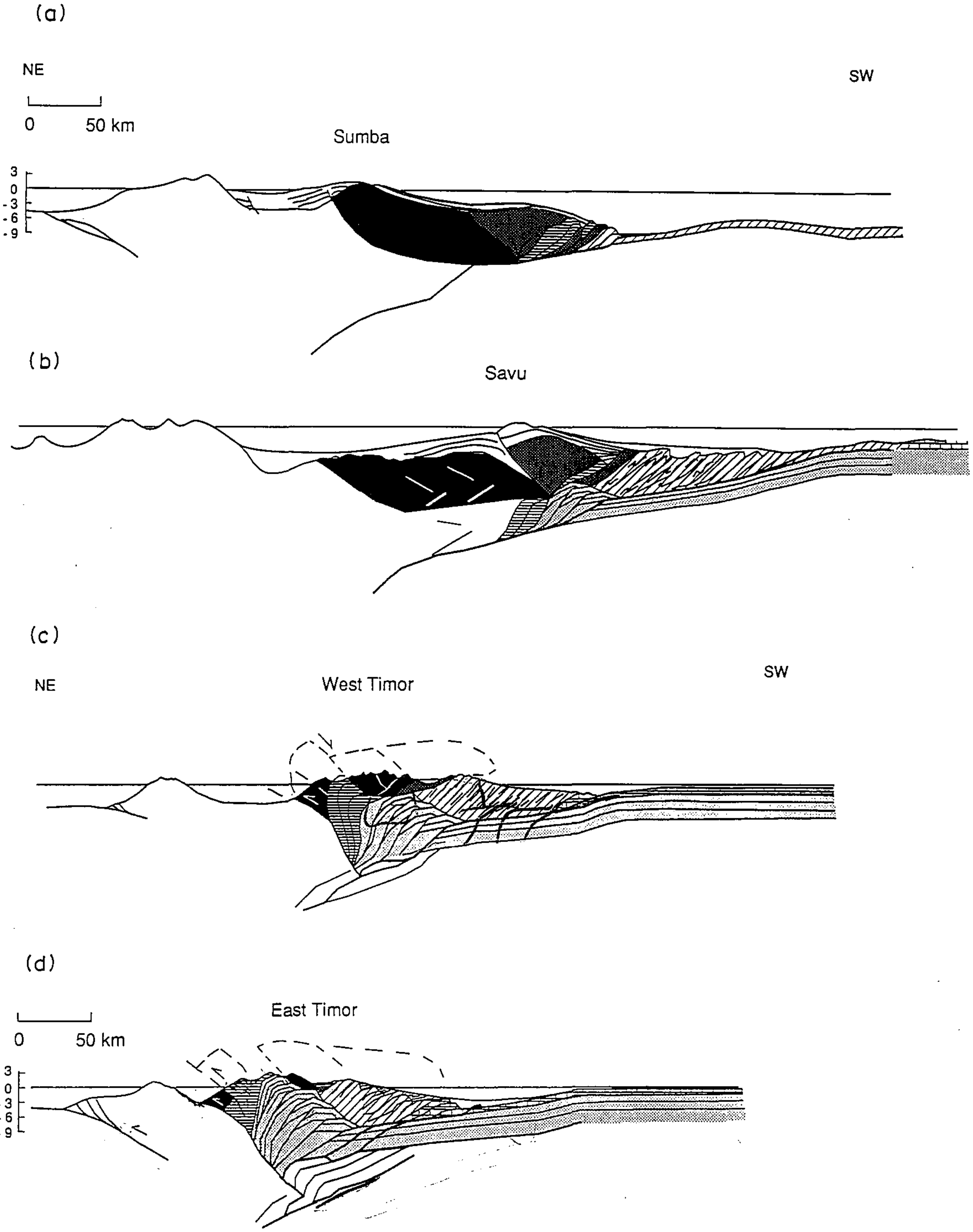

Fig. 4. Restored structural sections of seismogenic layer of Banda orogen at various stages of collisional deformation. Savu documents the initiation of collision of distal continental margin sediments with Java Trench, West Timor represents 3–4 Ma of collisional history and East Timor documents 4–5 Ma of collision (see text for further discussion). Sections are restored using seismic and field data with three times vertical exaggeration. Deep structure is interpretive. Lithotectonic units: *Black*—forearc basement upper plate (Banda allochthon). *Dark grey*—frontal accretionary wedge of Java Trench and mélange. *Horizontal stripes*—Permian to Triassic Aileu–Maubisse Formation (most distal reaches of Australian continent). *Diagonal stripes*—post-rift slope and rise deposits of Australian passive margin. *Brick pattern*—Shelf facies of post-rift deposits. *Light grey*—Permian to Jurassic pre-rift sedimentary sequence. White units underlying light grey are Cambrian to Carboniferous pre-rift sediments or crystalline basement. White overlying orogenic wedge are synorogenic deposits.

in structural style in this region. These variations, and the reconnaissance nature of many studies, are responsible for much of the debate about rival hypotheses for the structural evolution of the western Banda orogen (i.e. Barber 1981). To illustrate and discuss the structural variation, data from marine and onshore investigations is integrated here into four structural transects through Sumba, Savu, West Timor and East Timor (Fig. 4).

Sumba transect

Sumba is a recently uplifted segment of forearc crust near where the Java Trench becomes the Timor Trough. The oldest rocks exposed on the island are Cretaceous–Neogene arc-type volcanic and sedimentary rocks (Audley-Charles 1985). These underlie Miocene–Recent sediments (Reed 1985, Karig *et al.* 1987, Reed *et al.* 1987, van Weering *et al.* 1989). The stratigraphic sequence and lithologic character of these rocks are correlative with the Palelo Group (Audley-Charles 1968), which forms the upper part of the Banda allochthon (Barber and Audley-Charles 1976, Audley-Charles 1985, Audley-Charles and Harris 1990). The lower part of the Banda allochthon has metamorphic complexes that also may underlie the Palelo Group of Sumba.

The Palelo Group in Sumba connects with similar sequences in Timor via the Sumba submarine ridge (Silver *et al.* 1983, Reed 1985, Reed *et al.* 1987, Karig *et al.* 1987). The occurrence of Pliocene deep water facies sediments on the ridge and in Sumba indicate the young age of ridge uplift. The sediments tilt away from the ridge axis causing growth faults, massive slumps and slides, and shale diapirism (van Weering *et al.* 1989). The recent deformation of these sediments and the emergence of multiple Quaternary reef terraces on Sumba (von der Borch *et al.* 1983) show that uplift of the Sumba ridge is still active. The cause of this uplift is most likely due to recent changes in the type of lithosphere underthrusting the region.

South of Sumba is the transition from the Java Trench to the Timor Trough. This transition represents an important change in the character of the lithosphere presently underthrusting Sumba from Jurassic Indian Ocean to continental Scott Plateau (Fig. 2). The uplift of the Sumba ridge, and the progressive widening of the arc–trench gap SE of Sumba, indicate an increase in accretionary influx into the forearc. Where old ocean crust is underthrust only the thin veneer of weak pelagic sediment and possibly igneous basement from upstanding blocks of seamounts accrete to the upper plate. The upstanding and weak continental crust of the Scott Plateau significantly increases the influx of accretable material. Some of this material accretes in front of the Sumba ridge upper plate, which acts as a rigid buttress (bulldozer blade).

Breen *et al.* (1986) describe and interpret frontal accretionary processes from seismic and side scan sonar acquired at the trench–trough transition south of Sumba. The western part of the transition zone, at the edge of the continental Scott Plateau, is characterized by horizontal propagation of short decollements into weak material of the lower plate. This process produces a wedge of small accreted slices that shorten along closely spaced thrusts and conjugate strike–slip faults. Seismic images of the accretion zone are usually chaotic.

To the east, between 120°40′ E and 121°, Breen *et al.* (1986) found that decollements propagate up to 15 km south of the thrust front allowing for the accretion of long slabs of lower plate material. Due to the length/thickness ratio of these slabs, shortening of the wedge most likely involves fold–thrust deformational styles (Breen *et al.* 1986). The thrust front is well defined by a vertical separation along faults and folds 2–4 km long that occur throughout the lower slope. Mud diapirism also produces ridges of mud volcanoes in the lower plate.

The decollement is seen in seismic reflection profiles at the deformation front. Reed (1985) and Karig *et al.* (1987) found a strong to moderate reflector interpreted as the top of shallow marine Cretaceous shale under the decollement. These shales overlie pre-rift sedimentary sequences of the Australian continental margin, indicating the decollement at the toe of the orogenic wedge is near the breakup unconformity.

South of the Sumba region, and in the Java Trench to the west, a sharp boundary exists between the lower and upper slope of the accretionary wedge (Karig *et al.* 1980, Breen *et al.* 1986). Seismic reflection and sonar data show that deformation of recent sediments occurs throughout the lower slope region, around 20–30 km from the deformation front. This implies that in the Java Trench and the westernmost (youngest) Timor Trough, most of the convergence between Australia and SE Asia occurs at a high strain rate within the lower slope region. The only evidence that some strain is distributed to other parts of the orogenic wedge is the development of backarc thrusts north of Flores and perhaps the recent uplift of Sumba.

The uplift of Sumba is associated with normal faulting seismic events including the great 1977 Sumba earthquake (McCaffrey 1989). These stresses are most likely a function of bending forces associated with underplating or subcretion of continental material below the decollement. Gravity data from Sumba (Chamalaun *et al.* 1981) indicate that continental-type crust underlies the forearc basement exposed at the surface. This implies that the continental Scott Plateau, or another continental fragment, extends north under the forearc as far as Sumba Island. According to this scenario the Sumba ridge may trace the rough outline of underplated continental material.

Active backarc thrusting along the Flores thrust north of Sumba shows that some of the stress from collision of the continental Scott Plateau transmits through the entire arc–forearc region. Although Silver *et al.* (1983) estimate only 35 km of convergence along the Flores thrust, active deformation in the backarc region and uplift of Sumba Island both document the extent of collisional strain distribution, even early in the development of the orogenic wedge.

Savu transect

The island of Savu is mostly composed of mixed clay mélange similar to the Bobonaro mélange of Timor (Audley-Charles 1968). Blocks in the clay mélange consist of pre- and post-breakup sequences of the Australian continental margin (Audley-Charles, unpublished maps). Possible origins for the mélange are: (1) tectonic disruption of underthrust material; (2) accretion of mass waste deposits from the Australian continental margin; (3) mass wasting of over steepened accretionary wedge material; and (4) diapirism and stratal disruption by high fluid pressures.

Uplift of Savu Island is most likely a function of an increase in accretionary influx into the orogenic wedge by the encounter of the Java Trench with Australian rise and slope deposits. Seismic reflection profiles (Hamilton 1979) document frontal accretion at the trench and backthrusting on the north coast of Savu. Jurassic blocks extruded from mud volcanoes on the island may suggest that the decollement for transfer of sediment from the lower to the upper plate is most likely located near the breakup unconformity.

The Savu forearc basin north of Savu Island (Fig. 3) is filled with more than 3000 m of relatively undeformed sediment (Karig *et al.* 1987). Some of these sediments are overridden by the Savu backthrust, but no other evidence of shortening exists in the basin. The active volcanic island of Flores bounds the Savu Basin to the north. No evidence exists for backarc thrusting north of Flores Island as in the Sumba transect. The development of the Savu backthrust may prevent the transmission of collisional stresses into the arc region.

Nappe emplacement

The Savu backthrust forms the southern flank of the Sumba ridge. The thrust carries an assemblage of mélange and broken formation (Savu Island) over the Sumba ridge and its sedimentary cover (Fig. 4). The position of the Savu backthrust suggests it is related to the closure of the Savu Basin. East of Savu the Banda forearc basin begins to decrease in width from 200 km north of Savu to 5 km north of central Timor. Demise of the forearc basin is partly a function of vertical movements associated with progressive uplift as in the Sumba transect. Horizontal shortening between the accretionary wedge and the arc are also necessary to completely close the Banda forearc north of Timor.

Uplift of the forearc basin occurs throughout the western Banda arc in Sumba, Timor, Kisar, Leti and several other islands (Barber and Audley-Charles 1976, Audley-Charles 1985, Audley-Charles and Harris 1990). Underthrusting of low density continental material of the Australian margin is a likely cause of the uplift. Although vertical displacement alone may account for uplift of the western and eastern Savu Basin, it cannot explain the progressive eastward decrease in the width of upper plate rocks. Assuming an initial forearc width of 200 km north of Savu, the uplifted forearc in Timor decreases to a width of 80–100 km in East Timor. The extensive exposure of Australian margin sequences on the north coast of Timor, between nappes of the upper plate and their forearc roots, is also difficult to explain by only vertical motion of the upper plate. Uplift alone of the wedge-shaped forearc upper plate predicts that the hinterland of the collision zone (north coast of Timor) should be overlain by the thickest part of the forearc slab (i.e. cross-sections of Timor in Hamilton 1979). This model is inconsistent with the geology of Timor Island (Fig. 3), where in several places Australian margin material outcrops on the north coast (Leme and Coelho 1962, Audley-Charles 1968, Rosidi *et al.* 1979, Harris 1989). The map geometry indicates that the forearc nappes are detached from their roots and thin both to the north and south.

Price and Audley-Charles (1983, 1987) suggest the Savu backthrust is part of the much larger "Wetar suture", which they infer to track along the break in slope between Timor and the Savu and Wetar forearc basins. The suture zone is drawn as a south dipping lithospheric thrust where Australian continental material overrides forearc basement. Seismic lines show no evidence of shortening in the interior of the Savu Basin (Karig *et al.* 1987), but the inferred position of the fault zone, along the north coast of West Timor, is unexplored. A recently published seismic line across the north slope of central Timor shows some evidence of shortening at the base of the accretionary wedge, which led Breen *et al.* (1989) to also infer a south dipping fault in the "Wetar suture" zone. My recent field studies of the north coast of central Timor also document several north vergent structures including arc-directed backthrusts.

Uplift and erosion of the accretionary wedge in West Timor expose several large massifs of the Banda allochthon along strike of the submerged Sumba ridge to the west. The allochthon is detached from its roots and forms the roof of a growing wedge of accreted and underplated continental material. Because the slice is detached, continued underthrusting and accretion of Australian margin sequences lifts it passively to a structurally high position where it occurs as isolated nappes throughout Timor. In contrast, the forearc roots of the nappes become progressively buried by arc-directed thickening in the collision zone (Fig. 3c, d). Analysis of the steep gravity gradient in northern Timor (Kaye 1990) shows that dense crustal material occurs beneath the north coast of Timor in a similar geometry to Fig. 3c, d).

Substantial subaerial erosion of the upper plate nappe most likely causes the progressive eastward thinning of nappe thickness from estimates of 6–8 km in Savu and Sumba, 3–4 km in West Timor and 1–2 km in central Timor (Figs 3 and 4). Subaerial erosion rates in Timor may be high due to moderate to high uplift rates. Estimates of uplift rates in Timor vary from 0.5 km/Ma along the perimeter of the island (Chappell and Veeh 1978) to an average of 2 km/Ma in the central basin of West Timor (Audley-Charles 1986b), suggesting a domal uplift pattern. Microfaunal studies by DeSmet *et al.* (1989) provide an estimate of uplift rates in central West Timor as high as 10 km/Ma averaged over the past 0.2 Ma. Evidence from vertebrate fossil studies also suggest that during the Quaternary a land bridge existed between Timor and the Banda volcanic arc (Audley-Charles and Hooijer 1973). The island of Sumba may provide a good modern analog of what Timor may have looked like before the forearc upper plate was fractured and overthrust.

West Timor transect

West Timor consists mostly of two lithotectonic units separated by the east–west trending Central Basin. The northern part of the island consists of the Banda allochthon, which forms resistant peaks that protrude through a blanket of mélange. The Central Basin fills a flexural depression in front (south) of the Banda allochthon massifs. This basin represents a perched remnant of an early phase of foreland basin development. Synorogenic deposits of the Central Basin overlap the Banda allochthon, mélange and the accretionary prism of Australian continental material.

South of the Central Basin, an erosional window through synorogenic detritus exposes an accretionary prism of mostly Cretaceous–Late Miocene pelagic sediments, known as the Kolbano sequence (Carter *et al.* 1976). The Kolbano sequence represents Australian slope deposits (Charlton 1987) that are shortened and repeated by frontal accretionary processes (Fig. 4). Shelf facies equivalents to the Kolbano sequence are notably lacking in the uplifted parts of the accretionary wedge suggesting that the collision of the orogenic wedge with the Australian shelf is a recent phenomenon.

The Late Jurassic age of the oldest rocks included in the accretionary wedge reinforce interpretations along the Sumba and Savu transects that the decollement at the front of the wedge is near the Late Jurassic breakup unconformity of the Australian continental margin. This indicates that only post-rift sequences are involved in the frontal accretionary phase of initial collision. Synorogenic sediments unconformably overlying the Kolbano sequence and the upper slope of the accretionary prism show little evidence of recent crustal shortening.

At the toe of the West Timor orogenic wedge Karig *et al.* (1987) document a simple, strongly convex-upward lower slope region where acoustically opaque trough fill strata are accreted. Local disruption of this pattern forms a low angle sloping zone 15–20 km wide that is broken by several ridges of north dipping strata. These ridges are around 7–10 km in breadth and most likely represent accreted material from the Australian continental shelf. Structural lows between the ridges form slope basins of various sizes and structural histories. Most of these basins, including others further upslope, have growth faults against which strata dip progressively steeper to the north with depth.

The Timor Trough is also variable along strike where up to 1000 m of sediment fill it in places. These sediments onlap the depressed continental shelf of Australia, which forms the outer slope. DSDP 262 penetrated to 442 m in the trough, encountering very fine grained clastic and carbonate deep water deposits underlain by shelf and upper flank facies carbonate of the outer slope (Heirtzler *et al.* 1974). The outer slope dips into the trough at near 2° and becomes progressively buried by trough fill toward the inner slope (Karig *et al.* 1987). Industry seismic lines show steep normal faults with large displacements offsetting the Australian continental margin sequence down to the NW. Some of these fault blocks have large-scale slumps into the trough. Locally these slumps are seen in Industry seismic lines to involve the entire post-rift sequence of the lower slope. Large slump scars also occur on the inner slope (Karig *et al.* 1987).

Interpretations of the amount of active deformation in the Timor Trough differ. Karig *et al.* (1987) interpret seismic reflection profiles crossing the trough to show "a progression of sedimentation and deformation that extends to the surface, indicating continuing deformation in this setting". In contrast, Johnston and Bowin (1981) and Charlton (1988) show through analysis of sedimentation patterns in the Timor Trough near DSDP 262 that convergence at the deformation front has ceased. This implies that crustal shortening in the West Timor region is more distributed throughout the orogen zone. Possible effects of the distribution of collisional strain away from the toe of the orogenic wedge are: (1) the rapid uplift rates of West Timor evidenced by Quaternary coral reefs raised to 1300 m (Rosidi *et al.* 1979) and Late Pliocene deep water microfauna in synorogenic deposits now at over 1000 m elevation (De Smet *et al.* 1989); (2) the increasing indentation of the deformation front toward central Timor; and (3) active backarc thrusting (Fig. 4).

In the hinterland of the West Timor transect small erosional windows through massifs of the Banda allochthon expose Permian–Jurassic pre-rift sequences that have underthrust and uplifted the leading edge of the forearc upper plate. During frontal accretion this material was below the decollement allowing it to underthrust deeper into the accretionary prism before transfer from lower to upper plate. Volume accountability is difficult for the forearc upper plate if it is thrust intact over the shortened wedge of pre-rift Australian continental material. At the north coast of West Timor, where continental rocks are exposed, the forearc upper plate should be at least 20 km thick. No evidence exists for overthrusting of a slab this thick. Most of the pre-rift sediments on the north coast of Timor were deformed at very low temperatures and yield vitrinite reflectance values of less than 1.0 (unpublished data of the author). Where the forearc narrows to only 10 km north of central Timor, the problem is even more acute.

If the forearc has not completely overridden the underthrust Australian margin then its closure must be accounted for in part by underthrusting, strike–slip extrusion or tectonic erosion. The only structural restoration of the Banda orogen that accounts for forearc volume is presented by Price and Audley-Charles (1987). Their restoration models the closure of the Banda forearc by whole lithosphere rupture of the lower plate allowing it to override the forearc. The existence of lithospheric ruptures is difficult to test without deep seismic images of central Timor, but the mechanism of forearc wedging into continental material merits serious consideration. It is important to note that backthrusting of continental material over colliding arc terranes also occurs in Taiwan and other orogens (Mitchell 1983, Harris and Audley-Charles 1987). In Taiwan, Suppe and Liou (1979) propose that the forearc acts as a wedge between the lower plate basement and its cover allowing the cover to override the forearc via arc-directed backthrusts.

The possibility of strike–slip extrusion of forearc material away from the closing gap between Australia and the Banda arc is difficult to support. Some large vertical faults are found south of the volcanic arc near Flores, but it is uncertain how much extrusion this may accommodate.

The possibility of tectonic erosion of the forearc is also highly probable due to the low angle nature of the underthrust Australian margin. Subduction erosion structurally thins the upper plate as the dip of a subduction zone decreases (von Huene 1986). A decrease in the dip of the basal decollement from 4–8° along the Java Trench to 2° in the Timor Trough is noted by Karig *et al.* (1987). Crustal stretching and thinning during allochthon emplacement also may cause considerable fragmentation of the nappes. Extensional detachment faults are common throughout the Banda allochthon (Harris 1989).

East Timor transect

East Timor provides a perspective of Banda orogen structural style that is not found in any other part of the Banda arc with the possible exception of Seram. Orogenic wedge structure in other parts of the Banda arc is mostly obscured by blankets of synorogenic detritus and reef deposits that usually overlie thick massifs of the Banda allochthon. Uplift and erosion in East Timor have removed most of the synorogenic detritus and forearc nappes, forming windows into the internal parts of the orogenic wedge. These erosional windows correspond to antiformal culminations, with wavelengths of several km, that lift underthrust pre-rift sequences of the Australian margin to an elevation of nearly 3000 m.

The deformed wedge of East Timor surprisingly shows only localized effects of intense deformation and has a very low temperature thermal history. Microstructures are dominantly compactional in origin with only faint traces of compressional deformation at the deepest structural levels and near the basal decollement of overthrust nappes. Paleotemperature indicators yield maximum paleotemperatures of 150–200°C. The low temperature deformation of these rocks requires a shallow orogenic path that limits the depth to which Australian margin sediments are underthrust beneath the forearc upper plate before emerging again to the surface.

South of the structural culminations, isolated klippen of the Banda allochthon are all that remains of the extensive upper plate overthrust that caps the orogenic wedge of West Timor. The klippen structurally overlie Permian–Jurassic pre-rift sequences along a fault that now dips toward the foreland (Fig. 4). Accreted post-rift slope and rise material is piled up south of the Banda allochthon klippen as in the Kolbano region of West Timor.

North of the basement culminations of East Timor are multiple repetitions of Permian–Triassic strata. The compressed sequence verges to the north toward the Banda arc instead of continentward like most of the orogenic wedge. Near the capital city of Dili, metamorphosed Australian basement is thrust to within 10–20 km of the Banda arc island of Atauro. These metamorphic rocks rapidly decrease in grade to the south where conodonts (Grady and Berry 1977) and vitrinite (unpublished data of the author) indicate paleotemperatures of less than 150–200°C.

PLATE KINEMATICS OF WESTERN BANDA OROGEN

Relative plate motion vectors between Australia and Asia, calculated from both geological (Minster and Jordan 1978, DeMets *et al.* 1990) and satellite laser ranging (Smith *et al.* 1990) data bases, indicate an Australian plate convergence rate of 70–80 km/Ma and direction of N20–30E. The extent to which the Banda Sea plate is kinematically part of greater Asia is not known. Various rotations with respect to Asia are proposed for the region, but are poorly constrained. The few kinematic indicators available from the western Banda arc are consistent with a NNE convergence vector for Australia. Fault plane solutions of earthquakes in the orogenic wedge (McCaffrey 1988, 1989) show northward convergence along the Java Trench and NNE convergence near Savu. The 1978 event in central Timor shows a NNE direction of convergence of Australia with respect to Timor. A fault plane solution of the event indicates thrusting at a depth of about 10 km and an angle of around 30°. Left-lateral transcurrent faults in the contractional wedge, similar to lateral ramps in thrust belts, are also oriented NNE (Audley-Charles 1985, Charlton 1986).

Using the NNE plate motion vector, and approximate trends of the deformation front and NW Australian continental slope, a velocity triangle predicts a lateral westward propagation rate for the Banda orogen of around 110 km/Ma (Fig. 3). Assuming the NW Australian continental slope is straight and laterally continuous to the first approximation (discussed below), various phases of the collision should be similar at each time, only shifted in space (Bowin *et al.* 1980, Suppe 1984). Therefore, to move 110 km along the collisional front is equivalent to moving 1 Ma in time. Independent evidence from stratigraphic relations in Timor confirms this reconstruction. The distance along the strike of the orogen from Timor, where stratigraphic evidence suggests the collision began 3–5 Ma ago, to where the slope–trench collision is now starting (south of Savu) is 300–500 km.

Time–space equivalence provides an important method for understanding variations in structural style of the Banda orogen. For example, past perspectives of the early evolution of Timor are provided by more western parts of the orogen, and future perspectives of the geologic evolution of Savu are found to the east in Timor. Each major island in the outer orogenic arc characterizes a different, but transitional phase of Australian continental margin contraction. If the collision is a continuum process that varies systematically along strike due only to the obliquity of continent–trench collision, then cross-sections at regularly spaced intervals should provide a serial representation of the temporal distribution of strain in the Banda orogen.

STRUCTURAL RESTORATION

Figure 4 illustrates in cross-section structural restorations at regularly spaced intervals through the Banda orogen. Sections through Sumba, Savu and West Timor are 300 km apart, which corresponds to time intervals of approximately 3 Ma. The East Timor section is 170 km from the West Timor section corresponding to 1.5 Ma of elapsed time. The sections incorporate available field, seismic and gravity data, and use classical area balancing techniques (Gougel 1962, Dahlstrom 1969). The general scarcity of data in the region, particularly the lack of onshore seismic control, allow for a number of possible balanced solutions. The solutions that honor the data most are used.

The cross-sections illustrate the progressive distribution of strain away from the toe of the orogenic wedge with time. Shortening of the Australian margin becomes increasingly partitioned between frontal accretion, subcretion and backthrusting. At the Java Trench west of Sumba very little evidence of shortening exists throughout the arc–trench system except in the lower slope region, within 20–40 km of the deformation front. It is estimated that at least 80% of the 70–80 km/Ma of Australia–Asia plate convergence occurs in this region.

The Sumba transect shows continued evidence of high strain rates at the toe of the orogenic wedge in addition to recent uplift of the forearc basin and backarc thrusting. To account for the uplift by bending forces requires the addition of a minimum of 125 km^2 of underplated material. Backarc thrusting can account for a maximum of 30 km of convergence (Silver *et al.* 1983). The development of backarc thrusts and the northward indentation of the arc is most likely a consequence of stress transmission through the forearc suggesting buckling forces also may be an important component of the deformation in Sumba. Due to the recent nature of uplift and backarc thrusting in the Sumba region it is estimated that a maximum of 40–50% of plate convergence over the past 1 Ma has occurred at the toe of the wedge. This distribution of strain throughout the arc–forearc region is enigmatic for the westernmost and youngest part of the Banda orogen. According to the calculated rate of westward propagation of the Banda orogen, Sumba should represent a position 3 Ma before collision with Australia. This inconsistency, and the difference between Sumba and the steady-state Sunda arc to the west, is attributed to lateral discontinuity of the Australian margin in the Scott Plateau region.

In the Savu region the subduction rate of the lower plate exceeds the plate convergence rate by at least 30 km/Ma due to outgrowth of the accretionary wedge. Some plate convergence occurs by internal shortening along the Savu backthrust and other structures contributing to uplift of the island. The ramping of Australian continental material over the Savu forearc basin provides a way for accreting material to reach the surface via a shallow deformation path.

It is very likely that the accretionary prism outgrowth seen south of Savu also occurred previously to the east where the collision is older. This implies that the accretionary prism has experienced considerable internal shortening between Savu and Timor. The increase in surface slope angle of the inner slope of the wedge, from less than 2° south of Savu to a slope of more than 4° between Roti and central West Timor, is consistent with a minimum average of 30 km/Ma of internal shortening of the wedge over the past 3 Ma. Rapid uplift of part of the lower slope to form the Kolbano Mountains in southern West Timor is consistent with these rates of internal shortening.

Inferred backthrusts near the north coast of West Timor may also contribute a total of 30–40 km of internal shortening of the orogenic wedge. Backarc thrusts north of Alor also take up a total of 30–40 km of plate convergence. These various sites of intra-wedge shortening could account for as much as 70% of plate convergence in West Timor. Not included in this estimate is the possible extrusion of material out of the collision zone. These results limit the convergence at the deformation front south of West Timor to a maximum average of 20 km/Ma over the past 3 Ma. Present motion at the deformation front is probably much less than this average.

The orogenic wedge in East Timor comprises the entire forearc region, which is half the size of the Savu forearc and twice the structural relief. At the toe of the orogenic wedge the underthrust rate is significantly less than the convergence rate. The decrease in outer slope angle from 4° to 2° and submergence of the Kolbano high suggest the frontally accreted part of the wedge has collapsed. The axis of uplift, where long wavelength culminations form, is now far north of any other parts of the orogenic wedge.

The formation of structural culminations in East Timor is diagnostic of increasing amounts of internal shortening, verses advance, of the orogenic wedge. A possible cause of this shortening may be continued underthrusting of the steep basement ramp that marks the Australian shelf–slope inflection. Paleogeographic reconstructions (Fig. 2) indicate that the orogenic wedge of central Timor encountered the basement ramp about 2–3 Ma ago. As the orogenic wedge interacts with the shelf–slope break, the dip of the basal detachment may increase suddenly from around 2–3° to as much as 10–15°. This rapid change in slope could act as a major barrier for the orogenic wedge. To advance over the basement ramp the wedge must shorten and thicken internally to restore its critical taper (Davis *et al.* 1983, Platt 1986).

Internal deformation of orogenic wedges involves step down of the decollement zone to deeper levels (underplating) and out-of-sequence thrusting. This process eventually leads to involvement of deeper continental material in the orogen (Jamieson and Beaumont 1988). Internal deformation in Timor is evidenced by the increased lower slope angle and involvement of pre-rift sequence rocks. The collapse of the toe of the orogenic wedge in East Timor suggests it has probably overridden the shelf and now has a supercritical taper. The remainder of the orogenic wedge is compressed between inward dipping buttresses of the underthrust forearc to the north and continental basement ramp to the south (Fig. 4).

The pattern of shallow seismic events throughout the western Banda orogen show a trend of northward displacement of active seismic strain release (Eva *et al.* 1988, McCaffrey 1988, 1989). This trend develops into a conspicuous lack of seismic events east of the structural discontinuity between West and East Timor. The aseismic nature of East Timor suggests that presently most of the collisional strain is transmitted to the hinterland region. Backthrusting and backarc thrusting in this region may account for the bulk of northward Australian plate motion in East Timor. It is also likely that internal shortening of the orogenic wedge in East Timor may occur episodically at a frequency undetected by the available seismic record of the region.

An increasing component of anti-vergent translation of orogenic wedge material along backthrusts is associated with an increase in frictional resistance or coupling along the basal decollement. Possible causes of increased coupling of the East Timor orogenic wedge are the abrupt increase in basal decollement slope, decrease in pore–fluid pressures and increase in strength of incoming material. High pore-fluid pressures in an orogenic wedge are usually manifest at the surface by mud volcanism. The distribution of mud volcanism throughout the western Banda orogen is very similar to the distribution of recent shallow seismicity. The lack of both shallow seismic events and mud volcanism in the central part of Timor are consistent with an increase in coupling at the base of the orogenic wedge due to a decrease in pore–fluid pressures. The recent underthrusting of thick (> 3000 m) and relatively strong (Jaeger and Cook 1979) shelf carbonates in the East Timor region may also increase frictional resistance to sliding at the base of the orogenic wedge.

Continued plate convergence during a phase of increased coupling of the orogenic wedge can cause the wedge to move with the lower plate along arc-directed backthrusts and backarc thrusts like the Wetar thrust (Silver *et al.* 1983). Northward displacement of the Timor Trough in the East Timor transect is consistent with up to 100 km of arcward motion of the orogenic wedge. How this motion is distributed between backthrusts and backarc thrusts is difficult to constrain.

Other features to note in the series of cross-sections are: (1) detachment of the leading edge of the forearc and the passive nature of its emplacement above the growing accretionary wedge; (2) progressive delamination of Australian margin material by the roots of the forearc allochthon, allowing only dense and dry parts of the lower plate to subduct; (3) cessation of volcanic activity above delaminated lower plate; and (4) northward displacement of the volcanic arc by backarc thrusting.

LATERAL DISCONTINUITY OF AUSTRALIAN LOWER PLATE

Assuming time–space equivalence for the Banda orogen is only valid to the degree that the deformation front and continental slope of Australia lack major lateral discontinuities. For the most part, the deformation front is laterally continuous, except for the "Sumba enigma" of Audley-Charles (1985). Where the deformation front is laterally continuous (East Timor to Savu), underthrusting of a more or less continuous continental lower plate is assumed. Although much of the original structural and stratigraphic variation in the underthrust lower plate is obscured by collision, it is possible to compare undeformed segments that have not yet reached the trench (western Australian margin).

The western continental margin of Australia is characterized by protrusion of a series of large continental plateaus separated from one another by intervening abyssal plains. The plateaus are rectangular masses of thinned continental crust that extend 300–500 km beyond the continental edge. From south to north these features are the Naturaliste, Cuvier, Exmouth and Scott Plateaus. Spaced at minimum intervals of around 500 km, the plateaus form significant and abrupt lateral discontinuities in the western Australian margin.

The Scott Plateau is colliding now with the Java Trench south of Sumba. How much of the plateau region has underthrust the forearc is not known. The gravity profile of Sumba shows that continental material extends beneath the island (Chamalaun *et al.* 1981). Recent underthrusting of this material is most likely the cause of the recent uplift and active seismicity of Sumba Island, and backarc thrusting. The present axis of uplift in Sumba and along the Sumba ridge to the east may provide a rough estimate of the northern extent of the underthrust plateau. The presence of the plateau explains much of the enigmatic aspects of Sumba including its departure from time–space equivalence predictions for the western Banda orogen.

Structural and stratigraphic variations along the NW Australian margin also occur in association with NW–SE trending grabens formed during earlier unsuccessful rift events (Fig. 3). The orthogonal nature of these features with respect to the present NE–SW trend of the margin provide another significant discontinuity along passive margin strike. One major pre-breakup feature affecting the western Banda orogen is the Bonaparte Basin. Pre- and post-rift sequences in this basin may achieve a thickness of 10,000 m near the Timor Trough, compared to 4000–6000 m outside the basin. Pre-Permian sediments also accumulate to great thicknesses in the Bonaparte Basin and are often missing outside the basin. The Pre-Permian section includes substantial deposits and diapirs of salt (Edgerly and Crist 1974). It is very likely that the thickened sedimentary section of the Bonaparte Basin influences the development of the Banda orogen by providing an abrupt change in the rheology of material entering the collision zone.

The Bonaparte Basin collides with the Banda arc in the Timor region. The extrapolated width of the basin is nearly the same as the island length. Although little data is available from the northwestern part of the Bonaparte Basin to compare with stratigraphic relations in Timor, the possible effects of this interaction on the development of the Banda orogenic wedge need serious consideration.

TECTONIC CONTROVERSY

Some major phases of deformation in the Banda orogen (frontal accretion, allochthon emplacement and culmination development) are similar to different models (imbricate, overthrust and upthrust) relating to an apparent controversy over the tectonic evolution of the Banda orogen (Barber 1981).

Imbricate or accretionary wedge models proposed by Fitch and Hamilton (1974) are mostly based on marine seismic data from submerged parts of the orogen. This model is popular among researchers who rely mostly on data from marine geology and geophysics (von der Borch 1979, Silver *et al.* 1983, Karig *et al.* 1987). Most of the submarine segments of the Banda arc are deforming primarily by frontal accretionary processes.

The overthrust model initially proposed by Wanner (1913) and later championed by Audley-Charles (1968) is dominantly based on field data from Timor where overthrust nappes of the Banda allochthon are well exposed. Subsequent field-based studies of the islands of Timor and Seram also support this model (Carter *et al.* 1976, Barber *et al.* 1977, Audley-Charles *et al.* 1979, Haile *et al.* 1979, Brown and Earle 1983).

The upthrust model proposed by Chamalaun and Grady (1978) results from detailed field mapping near the Cribas anticline (basement culmination) in central East Timor. Extensional unroofing above, and associated with, culmination development significantly modifies structural relations from earlier deformational processes in this region.

Each of these models focuses on a different deformational phase in the evolution of the Banda orogen. Integration of geological and geophysical data from throughout the Banda orogen demonstrates that each model applies at certain times during arc–continent collision.

CONCLUSION

The Banda orogen of eastern Indonesia is an arcuate mountain system comparable in scale, structural style and tectonic evolution to other arcuate orogenic belts such as the Alpine, Carpathian, Apennine, Aegean, Cyprian, Betic–Rif, Caribbean and Yukon–Koyukuk arcs. Many of these arcs form orogenic loops where mountain belts change strike by up to 180°. Extensional basins form in the interior of the loops with much of the extension occurring simultaneously with radially directed contraction at the orogenic front. The present extension of the Weber Basin, which is surrounded on three sides by active radially directed contraction of the Banda arc, is a type example. Whether these orogenic processes are a result of the relative motions of larger bounding plates or the product of body forces that act independent of plate kinematics is controversial (Dewey 1988). The arcuate geometry of the Banda orogen is interpreted here as a product of superimposed NNW Australian and WNW Pacific plate motion.

The Banda arc collided with the NW Australian continental margin at the end of the Miocene. The collision began in central Timor and migrates to the SW at about 110 km/Ma. The transition from subduction to collision initially involves increased frontal accretion of a thickening layer–wedge of distal continental margin sediments. Collision of the continental slope with the expanding accretionary prism increases the slope angle of the basal decollement, which causes considerable internal shortening and uplift of the wedge. This uplift forms large wavelength culminations that detach the leading edge of the forearc upper plate from its roots as nappes. Underthrusting of relatively strong continental shelf material and a decrease in pore–fluid pressure further increases frictional resistance to orogenic wedge advance. Increased coupling causes the orogenic wedge to move more with the lower plate along backthrusts, backarc thrusts and wrench faults.

The temporal distribution of strain in the Banda orogen shows that rival hypotheses for the structural style of the Banda arc–Australia collision each focus on a different deformational phase of collision.

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