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Neogene sutures in eastern Indonesia

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Abstract

Five suture zones are described from the zone of collision between the Eurasian, Indian–Australian and Pacific–Philippine Sea plates within the eastern Indonesia region. These are the Molucca, Sorong, Sulawesi, Banda and Borneo sutures. Each of these sutures has a relatively short history compared to most pre-Neogene orogenic belts, but each preserves a record of major changes in tectonics including subduction polarity reversals, elimination of volcanic arcs, changing plate boundaries, and important extension within an overall contractional setting. Rapid tectonic changes have occurred within periods of less than 5 Ma. Many of these events, although important, would be overlooked in older orogenic belts because the age resolution required to identify them, even when the evidence is preserved, is simply not possible. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: Suture zones; Eastern Indonesia; Tectonic changes

1. Introduction

Eastern Indonesia is situated at the junction of three major plate regions: the Eurasian, Indian–Australian and Pacific–Philippine Sea plates (Fig. 1). The boundary between each pair of plates is a relatively narrow zone of deformation, typically of the order of 100–200 km; although a detailed analysis of each boundary requires description in terms of many other small plates, lithospheric/crustal fragments, or terranes, each is characterised by the presence of subduction zones and major regional strike–slip faults (Fig. 2). The triple junction itself, in eastern Indonesia, is even more complex. It is situated in a zone of long-term subduction, is up to 2000 km wide, and active contractional deformation continues at present. The triple junction can be considered as the site of several sutures, because the recent history of deformation within this region requires description in terms of many small plates or lithospheric fragments whose boundaries have changed as collision has proceeded.

In eastern Indonesia the use of the terms suture and collision is problematical and both have been used at a variety of length and time scales. This is unsurprising since in everyday conversation we use the two words to describe features that could be regarded as ranging from trivial to catastrophic. However, it does create problems when attempting to define sutures and to understand their development, particularly when comparison is to be made with orogenic events much earlier in the history of the Earth when the time resolution may be much less, and when orogenic deformation has clearly finished.

Here we identify five major suture zones in the region of eastern Indonesia, which are arguably all within the single suture zone that will remain after the Australia–Eurasia collision is completed. These are the Molucca, Sorong, Sulawesi, Banda and Borneo sutures (Fig. 2). The Borneo Suture is situated at the political border of Indonesia and extends through Malaysia into the Philippines, but for simplicity we refer to this as eastern Indonesia. The account of the Sulawesi Suture is the work of both authors, whereas the accounts of other sutures are by RH. For each of the suture zones we have tried to identify common features which are summarised below, together with a brief discussion. Table 1 summarises the principal features of each of the sutures. We have also attempted lithosphere-scale cross sections for the sutures, except those of Sorong and Sulawesi. With such a large area to cover, we have tried to limit the number of cited references by including the more important recent papers and those that review older literature. The reader is referred to these, as well as to standard works on the region (e.g. van Bemmelen, 1949; Hamilton, 1979; Hutchison, 1989, 1996; Hall and Blundell, 1996) for more

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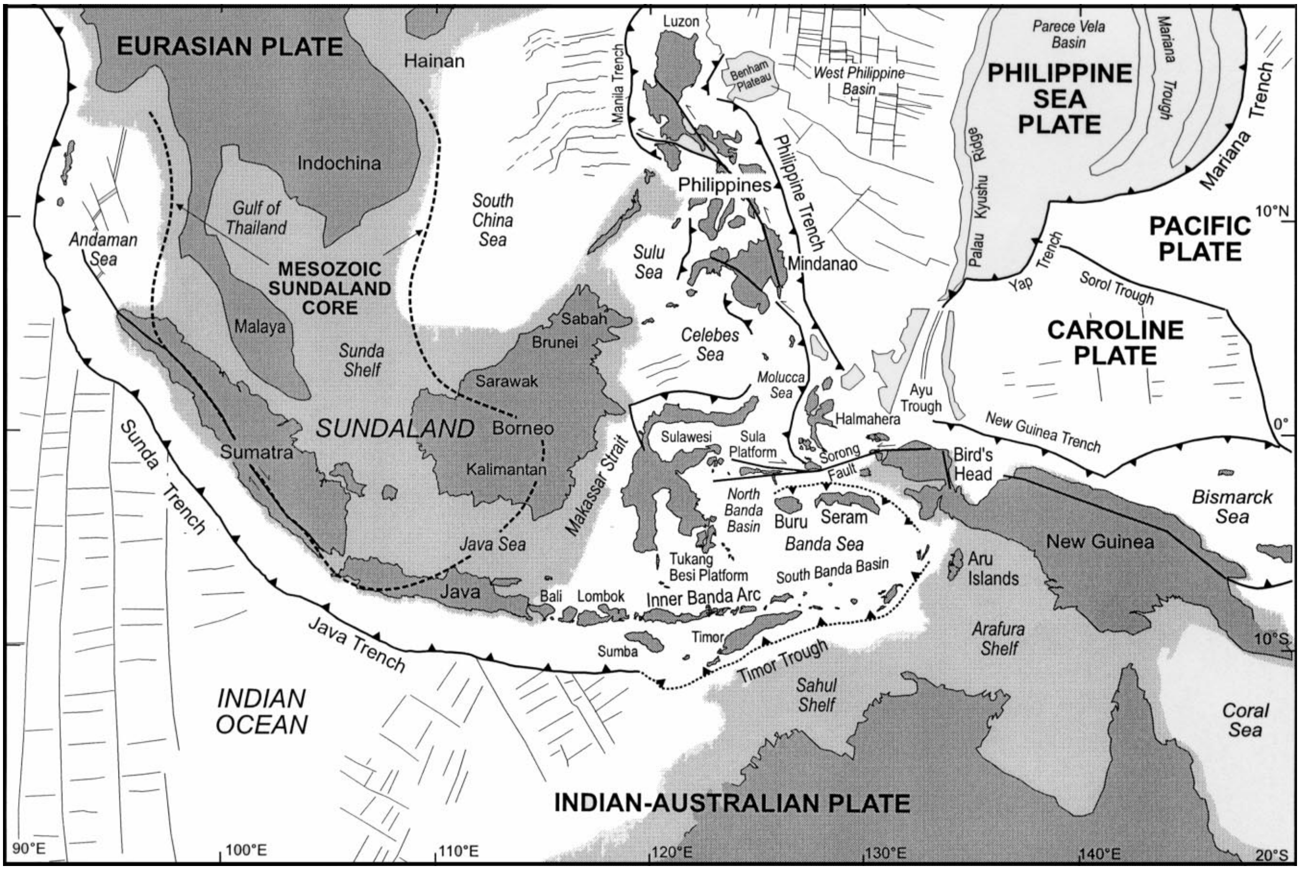

Fig. 1. Principal geographical features of SE Asia. The light shaded areas are the continental shelves of Eurasia and Australia drawn at the 200 m isobath.

detailed information. At the end of the paper we draw attention to some important general features that may be of interest to those studying older sutures, and are relevant to the problems of identifying sutures and collisions.

2. The Molucca Suture

The Philippine archipelago, a complex of modern and ancient island arc and continental fragments, terminates southwards in the Molucca Sea collision zone where the opposed Halmahera and Sangihe arcs are actively converging (Figs. 3 and 4). The Molucca Sea Plate dips east under Halmahera and west under the Sangihe Arc in an inverted U-shape (McCaffrey et al., 1980). Seismicity records subduction of 200–300 km of lithosphere beneath Halmahera, whereas the Benioff zone associated with the west-dipping slab can be identified to a depth of at least 600 km beneath the Sangihe Arc. Tomography suggests that both slabs extend much deeper into the mantle (Spakman and Bijwaard, 1998). At present, on the west of the Molucca Sea the active volcanoes of the Sangihe Arc can be traced from north Sulawesi into Mindanao. In contrast, on the east side of the Molucca Sea volcanic activity in the Halmahera Arc has ceased to the north of Halmahera. Observations offshore and on land can be used to infer the sequence and timing of events that created the double subduction system and led to the now complete subduction of the Molucca Sea Plate (Fig. 5). The Molucca Sea region thus contains a record of the collision between the two arcs of Halmahera and Sangihe–North Sulawesi, which is not yet complete. The essential features of the geology of these two arcs are summarised below.

2.1. Halmahera Arc

Ophiolitic rocks form the basement of east Halmahera (Hall et al., 1988a). They are dismembered and formed in an early Mesozoic intra-oceanic arc. The ophiolitic rocks are overlain by Cretaceous, Eocene and Oligocene arc volcanic rocks. In the western arms Oligocene arc volcanic rocks form the basement. Miocene carbonates unconformably overlie all the older rocks. The Neogene Halmahera Arc became active at approximately 11 Ma (Hall et al., 1995a). Volcanism began earliest in the south and extended northwards producing a volcanic arc similar in position and extent to the present Halmahera Arc. To the west of the arc turbidites and debris flows were deposited below steep west-facing submarine slopes containing material derived from a region of volcanic arc rocks and reef limestones. To the east of the arc an extensive basin developed (Hall, 1987; Hall et al., 1988b; Nichols and Hall, 1991) containing similar

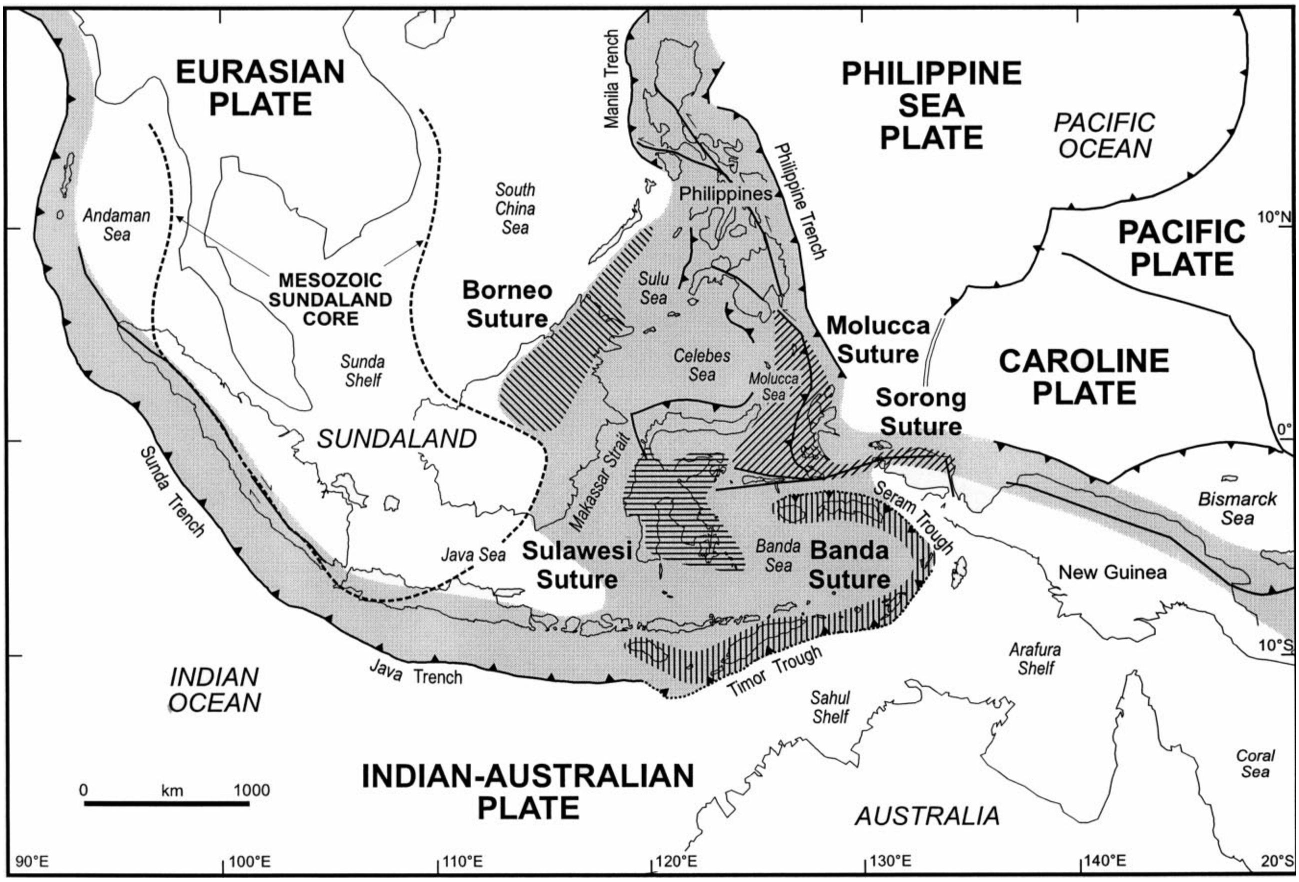

Fig. 2. The five sutures of eastern Indonesia discussed in the text. The lighter shaded area are the zones of collision between the Eurasian, Indian–Australian and Pacific–Philippine Sea plates.

debris but deposited in much shallower water. There is an unconformity dated as ~3 Ma between older Neogene and overlying upper Pliocene sedimentary rocks. In SW and central Halmahera sedimentary rocks of the backarc region were thrust westward over the Neogene arc and forearc. The present Halmahera Arc is built unconformably upon Neogene arc rocks and adjacent sedimentary basins.

2.2. Sangihe Arc

Most of the north arm of Sulawesi has a basement of oceanic basalts, basaltic andesites and pelagic sediments, thought to be of Eocene to early Miocene age (Pearson and Caira, 1999). The basement is overlain by calc-alkaline arc volcanic rocks of early to middle Miocene age (Effendi, 1976; Apandi, 1977). Dow (1976) records late Miocene quartz-diorites intruding older Miocene intermediate and volcanic rocks. Ar–Ar and K–Ar dates from the north arm indicate magmatism from the early Miocene to the Pleistocene (Pearson and Caira, 1999). Further north, the Sangihe Arc is largely submarine with a relatively small number of emergent and some submarine volcanic islands between Sulawesi and Mindanao. In the Sangihe forearc on Talaud there is a sedimentary sequence, of middle Miocene to Pleistocene age, which includes probable mid-Miocene volcanic rocks and volcaniclastic turbidites (Moore et al., 1981) suggesting volcanic activity since the middle Miocene.

2.3. Age of suture

Collision between the two arcs in the Molucca Sea region is still continuing (Fig. 5). The first contact between the two arcs probably occurred in the late Pliocene. Suturing is at different stages in different places in the Molucca Sea region. It is most advanced in the north at the latitude of Talaud where most of the Halmahera forearc and arc has been subducted. Further south and on the west side of the present arc, the Halmahera forearc is being thrust eastwards over the Halmahera Arc.

2.4. Ocean-floor basalts, deep marine sediments, ophiolites and obduction

Ophiolites have been exposed by the collision process but they are probably not fragments of the subducted ocean crust of the Molucca Sea Plate. The Talaud ridge at the centre of the Molucca Sea has been interpreted to include an obducted slice of Molucca Sea lithosphere (Silver and Moore, 1978; McCaffrey et al., 1980). However, the Molucca Sea Plate is now deep in the mantle and sinking

Table 1
Principal geological features of each of the eastern Indonesian region sutures discussed in the text

Suture	What is/was colliding?	Age of suture	Ocean floor basalts, marine sediments and ophiolites	Mélanges	High-pressure metamorphism	Collisional/post-collisional plutons	Syn-collisional geochemical changes	Age of deformation related to collision	Notes
Molucca Suture	Two arcs: Halmahera and Sangihe-North Sulawesi arcs	Pliocene and ongoing. Collision more advanced in north	Ophiolites have been exposed due to collision process, but probably not fragments of subducted Molucca Sea plate	Melange wedge or collision complex in Molucca Sea, between arcs. No mélanges exposed onshore	None	None	Increase in amount of subducted sediment in younger arc volcanics of North Sulawesi and Halmahera	Pliocene thrusting and overthrusting of Halmahera arc. Uplift and minor backthrusting of Sangihe arc	Double subduction system. Complete subduction of Molucca Sea plate
Sorong Suture	Varies. Essentially boundary between Australian-origin continental crust and arc/oceanic crust of the Molucca Sea, Philippine Sea and Caroline plates	Estimates of initiation of strike–slip motion vary from late Oligocene through to mid-Pliocene	Probable Mesozoic ophiolites exposed along strike–slip system	Melange of locally derived fragments and exotic blocks in strands of Sorong Fault. Strongly deformed	None	None	No significant Neogene volcanism associated with suture. Evidence for continental contamination in Neogene volcanics on Bacan from at least 8 Ma.	Began early Miocene. Left-lateral strike slip faulting of Birds Head dominantly occurred in late Miocene-Pliocene, continues at present day	Clearest junction between Australian- origin continental rocks and younger arc and ophiolitic rocks
Sulawesi Suture	Continent–continent collision between Sundaland and fragments of Australian continental margin. In reality, very complex accretion of ophiolitic, arc and continental fragments	Oldest dated events — late Oligocene to early Miocene (may be intra-oceanic thrusting rather than obduction ages of ophiolite). Deformation related to accretion continues	Ophiolites in E, SE and S arms of Sulawesi. Ages and tectonic setting of formation of ophiolites unclear. Cretaceous to early Oligocene marine sediments associated with ophiolite of east arm	Mélanges of Central Sulawesi between ophiolite and western Sulawesi contain fragments of ophiolite and broken formations. Mélanges also known from contacts of the microcontinental blocks of Banggai-Sula and Buton	Blueschist facies metamorphism associated with the suture is Oligo-Miocene in age in central Sulawesi. Similar HP overprint of ophiolitic sole in E arm	Large granitic plutons in western Sulawesi date from c. 12–4 Ma. Rapid uplift during late Miocene and possibly some thrusting	Paleogene calc-alkaline volcanic activity in S arm ceased by the early Miocene. Resumption of high-K volcanic activity in W Sulawesi (began c. 11 Ma), may be related to extension	Deformation began at least in Miocene (possibly Oligocene) and continues to present day. Thrusting, uplift and strike–slip faulting at present day	At least three phases of accretion associated with suture. Most complex suture zone in region
Banda Suture	Arc–continent collision zone between Banda volcanic arc and Australia, may also be microcontinental fragments involved	Late Neogene age for the beginning of arc–continent collision, although some authors suggest may be older	Volcanic rocks and peridotites on Timor, thought to represent part of the Banda volcanic arc and forearc, thrust southward onto Timor in the Pliocene. Unusual ophiolites. Possibly some Miocene obduction of young oceanic crust	Controversial. Melange present on Timor, but not clear how much and of what origin. Mud volcanoes suggest mélanges may be forming at present day	No high pressure metamorphic rocks associated with the modern collision have been reported	None	Volcanics enriched in incompatible elements, suggesting involvement of continental crust. Modern arc — evidence for both shallow crustal assimilation and for a subducted continental component	The age of the first orogenic deformation in the outer Banda arc resulting in nappe emplacement — latest Miocene on Seram (may be extensional) to post-mid Pliocene on Timor. Vertical movement associated with accretion	Position of suture controversial. Subduction reversal may be in progress. Slab break-off may be cause of rapid uplift
Borneo Suture	Passive continental margin of South China with the active north Borneo margin (Sundaland margin). Laterally arc–continent collision in Cagayan/Palawan area	Early to middle Miocene	No Tertiary ocean floor basalts or deep marine sediments thought to represent parts of subducted ocean. Age of ophiolites on Borneo uncertain, probably Cretaceous	Predominantly early Miocene and older mélanges. Mainly subduction-related mélanges, including olistostromes, mud-rich diapirs, and tectonic mélanges	Blueschists have been reported but they are very rare. Possibly more abundant than reported?	Few plutonic rocks with the exception of the Mt Kinabalu granitic body (cooling ages of c. 10 Ma)	Little data available yet	Accretionary deformation in south Sabah until early Miocene. Further north accretion continued to middle Miocene. Thrusting, possibly some strike–slip component	Difficulties in dating and subdividing sedimentary rocks due to monotonous character

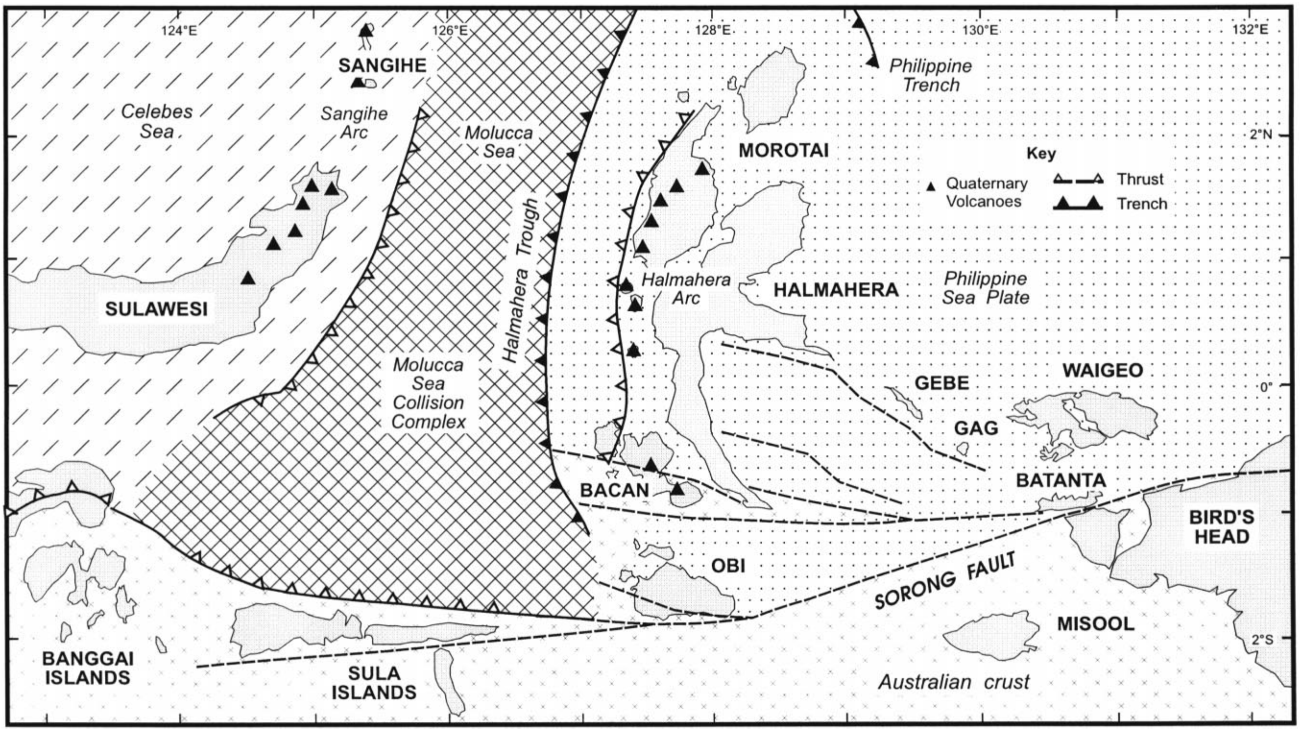

Fig. 3. Simplified tectonic summary map of the Molucca Sea and Sorong sutures in east Indonesia.

further with time. The ophiolitic rocks are middle Eocene or older, are overlain by Miocene turbidites (Moore et al., 1981), and may once have been a former part of the Celebes Sea (Hall, 1996); but most recently it formed the basement of the Sangihe forearc. These rocks are now being thrust towards the east in the Sangihe forearc (Fig. 5) and onto the collision complex (Rangin et al., 1996). On Halmahera, ophiolites thrust westward during the Pliocene deformation

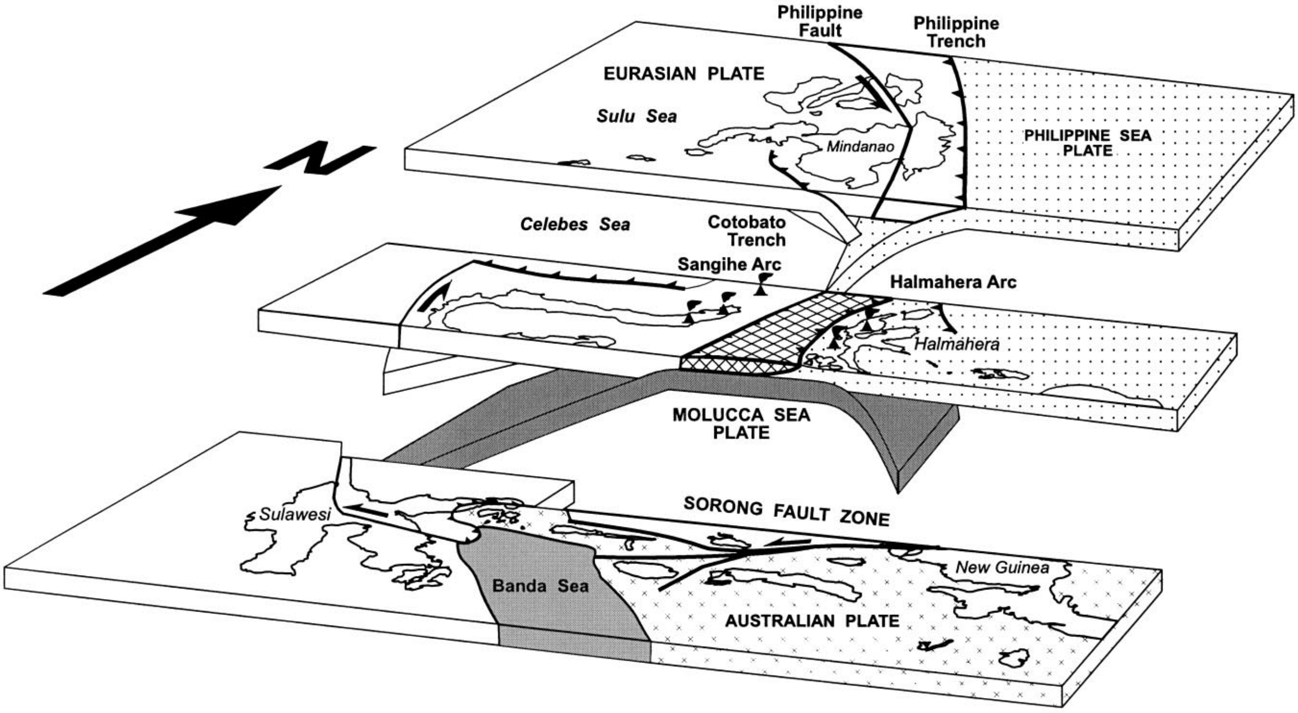

Fig. 4. The Molucca Sea and Sorong sutures shown in a 3D diagram, which represents in simplified form the geometry of the converging plates in east Indonesia.

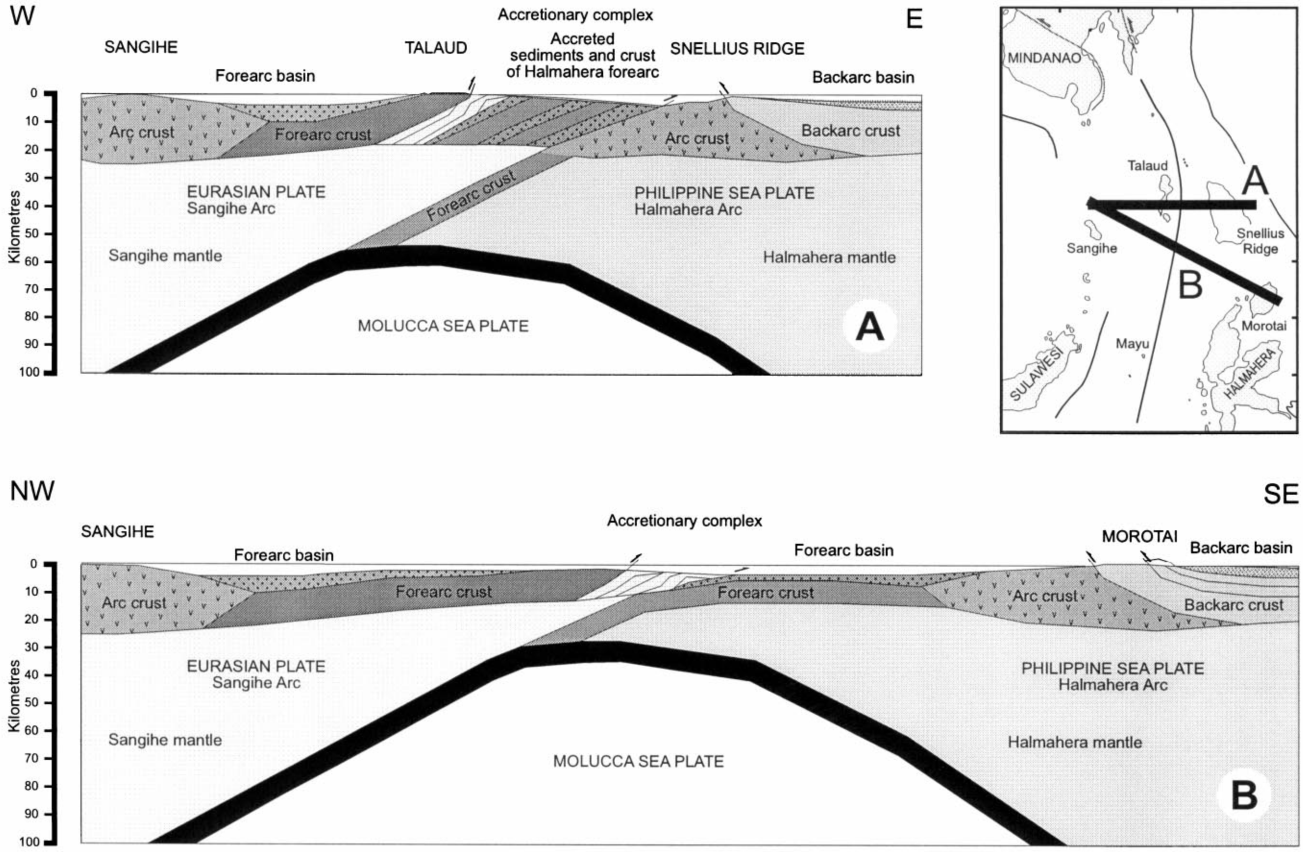

Fig. 5. Cross sections across the Molucca Sea drawn at same vertical and horizontal scales showing the present status of convergence of the Halmahera and Sangihe arcs in the northern Molucca Sea. In section A at the latitude of Talaud the entire arc and forearc of the Halmahera Arc has been over-ridden by the Sangihe forearc. Ophiolites of the Sangihe forearc basement are exposed in the Talaud Islands. Further south (section B) only part of the forearc has been overridden, but the Halmahera Arc in Morotai was overridden by its own backarc in an earlier thrusting episode.

are probably Jurassic, and definitely older than Late Cretaceous, and formed part of the east Halmahera basement.

2.5. Metamorphism and igneous activity

There is no record of HP-LT metamorphism associated with the Neogene-Recent collision. Volcanic arc rocks are widely exposed but there are no collisional or post-collisional plutons as erosion has not yet removed the volcanic cover. On Halmahera the oldest arc rocks are ophiolites of supra-subduction zone origin and are probably Jurassic. There was arc activity in the Late Cretaceous, Eocene, late Eocene-Oligocene, late Miocene-Pliocene, and Quaternary. The polarities of the older arcs are not clear. The Mio-Pliocene and Quaternary Halmahera arcs were erupted above an east-dipping subduction zone.

The north arm of Sulawesi has probably been the site of almost continuous arc activity since the Eocene. In the Sangihe−North Sulawesi region there was arc activity above a west-dipping subduction zone from early Miocene until the present.

Elburg and Foden (1998) report geochemical changes in late Miocene to Recent subduction-related volcanic rocks in northern Sulawesi, which they attribute to collision between the Halmahera and Sangihe arcs. The geochemical character of older volcanic rocks is dominated by fluids derived from altered MORB whereas younger rocks show an increase in a subducted sediment component. A similar, but less extreme, change in magma geochemistry has been noted in Neogene and Quaternary lavas from the Halmahera Arc (Forde, 1997; Macpherson and Hall, 1999).

2.6. Melanges

Collision is creating a high central ridge in the Molucca Sea, formed between the two colliding forearcs. This central zone, marked by intense shallow seismicity and a low gravity is the Molucca Sea ‘melange wedge’ or ‘collision complex’ (Silver and Moore, 1978; Hamilton, 1979; Moore et al., 1981). However, although mélanges may have formed during collision they are not yet exposed onshore. Those on Talaud and Mayu were not formed during the present collision but are part of the pre-Neogene basement of the Sangihe forearc. The presumed mélanges of the modern collision complex are all submarine and constitute part of the bathymetrically shallow and seismically incoherent volume of sediment in the central Molucca Sea. Accretionary material from both forearcs has contributed to this melange wedge. On the Sangihe side the sediments in the accretionary complex date from the middle Miocene. On the Halmahera side they probably date from the late Miocene.

2.7. Palaeomagnetic data

Palaeomagnetic evidence indicates the Halmahera Arc has been situated at equatorial latitudes for most of its history (Hall et al., 1995a,b). Data from the Halmahera islands define two areas: an area forming part of the Philippine Sea Plate north of the Sorong Fault, and an area within the Sorong Fault system. The area within the fault zone records local rotations due to deformation at the plate edge. In contrast, the area north of the fault records a long-term clockwise rotation history; since 25 Ma there has been about 40° of clockwise rotation with northward movement of about 15°. Rotations of up to 90° are recorded by Eocene rocks (Hall et al., 1995a,b).

2.8. Deformation associated with collision

The earliest indications of arc–arc collision are of Pliocene age. The Halmahera Arc failed at the site of the active volcanic arc, and there was westward thrusting of the region behind the arc towards the forearc. In Obi the arc was thrust onto the forearc. In south Halmahera the backarc region was thrust onto the forearc, in places entirely eliminating the Neogene arc. After this episode of west-vergent thrusting, volcanism in the Halmahera Arc resumed between Bacan and north Halmahera. On Obi and from Morotai northwards volcanism ceased. In the northern Molucca Sea the Sangihe forearc was then thrust eastwards onto the Halmahera forearc and arc. In the region between Morotai and the Snellius ridge, parts of the Neogene Halmahera Arc and forearc have now disappeared (Fig. 5). Further south this east-vergent thrusting carried the Halmahera forearc onto the flanks of the active Halmahera Arc, and now pre-Neogene rocks of the Halmahera forearc basement are exposed in islands of the Bacan group and off the coast of northwest Halmahera.

Where the Halmahera forearc and arc have been significantly overthrust the Sangihe forearc has been jacked up (Fig. 5). The wide Molucca Sea collisional complex is composed of the accretionary wedges of both arcs. The forearc basement of the Sangihe Arc is exposed where it thrusts over this wedge. The present Halmahera trench or trough broadly represents the frontal thrust of the Sangihe forearc, which is overriding the Halmahera forearc and arc. Locally there is backthrusting of the Sangihe forearc towards the Sangihe arc at the Sangihe trench or trough, but this is a relatively minor feature.

2.9. Conclusions

In the northern Molucca Sea the Halmahera Arc has been entirely overridden by the Sangihe forearc and it seems probable that in a few million years time the entire Halmahera Arc will have disappeared with almost no trace. During collision the active volcanic arc has repeatedly proved to be the weak point of the entire forearc-arc-backarc section, presumably reflecting its quartz-rich rheology at depth, and relatively high temperature at shallow depth. In the islands of Halmahera and Obi much of the Neogene arc has been overthrust by backarc and forearc crust. During arc–arc collision one of the arcs must be overridden and presumably by chance this has proved to be the Halmahera Arc.

3. The Sorong Suture

The Sorong Fault Zone (Figs. 3 and 4) is the southern boundary of both the Molucca Sea and the Philippine Sea plates with the Australian Plate. It includes the region from the Bird's Head to East Sulawesi where there are fragments of crust of continental, arc and oceanic origin. The Sorong Fault is part of one of the world's major fault systems and forms the western end of a zone of left-lateral strike–slip faulting resulting from the oblique convergence of Australia and the Philippine Sea, Caroline, and Pacific plates (e.g. Hamilton, 1979; Dow and Sukamto, 1984; Hall, 1996, 1998). It is a segment of the northern New Guinea fault system, first interpreted as a left-lateral megashear by Carey (1958). The Sorong Fault has its type locality in the northern Bird's Head region of New Guinea (Visser and Hermes, 1962; Tjia, 1973; Dow and Sukamto, 1984). West of the Bird's Head the fault system splits into Pliocene-Recent fault splays including the Molucca–Sorong Fault, the North Sula–Sorong Fault (Hamilton, 1979) and the Buru fracture (Tjokrosapoetro and Budhitrisna, 1982).

The Sorong Fault system is therefore part of a suture zone that juxtaposes arc and continental crust in islands of the North Moluccas and in the Bird's Head of New Guinea. The Sorong suture is essentially the boundary between Australian-origin continental crust and arc/oceanic crust of the Molucca Sea Plate, Philippine Sea Plate and Caroline Plate (Fig. 3). What was and is colliding is different in different places, and has changed with time as displacement on the strike–slip system has occurred.

3.1. Halmahera Arc and Sorong splays

To the north of the Sorong Fault Zone is the crust of the Philippine Sea Plate in Halmahera and other islands such as Gebe, Gag, Waigeo and Batanta. These have a basement of ophiolitic rocks overlain by, and imbricated with, Cretaceous-Oligocene arc volcanic and sedimentary rocks. This phase of arc activity in the Sorong Fault Zone region ceased in the earliest Miocene. Later Neogene arc activity started earliest in the south, on Obi, beginning in the late middle Miocene and terminating at the beginning of the Pliocene.

Within strands of the Sorong Fault system are several islands which include arc and Australian continental crust.

On Obi fragments of continental crust derived from the Australian margin include high-grade metamorphic rocks of probable Palaeozoic or greater age and Jurassic sedimentary rocks, representing the cover to the metamorphic basement (Brouwer, 1924; Hall et al., 1991; Agustiyanto, 1995). On Bacan similar high-grade metamorphic rocks are present (Malaihollo and Hall, 1996) and geochemical studies of Neogene volcanic rocks indicate the arrival of continental crust in the region by 8 Ma (Forde, 1997).

3.2. Bird's Head

The Sorong Fault also cuts the Bird's Head. Accounts of the geology are given in Visser and Hermes (1962), Dow and Sukamto (1984) and Dow et al. (1988). The main part of the Bird's Head is assigned to the Kemum Block. The oldest rocks are lower Palaeozoic greywackes, which have suffered low-grade metamorphism and are intruded by upper Palaeozoic granites. A largely continuous sequence of unmetamorphosed sedimentary rocks then overlies these rocks with an angular unconformity at the base. This sequence ranges from upper Carboniferous to upper Cenozoic. The lower part includes terrestrial and shallow marine strata, and the upper part is almost entirely marine. Most of the Cenozoic is represented by the widespread New Guinea Limestone Group, which is essentially shelf carbonates. The Palaeozoic-Cenozoic sequence is typical of a passive continental margin. Thick clastic sequences date from the latest Miocene. These were derived from the north or west and record uplift and erosion of the northern Bird's Head.

North of the Sorong Fault in the Bird's Head are three principal fault-bounded blocks or terranes: the Tamrau Block, the Netoni Block and the Tosem Block. The Tamrau Block is found in the northern Bird's Head and northern Salawati Island. It consists of Middle Jurassic to lower Cretaceous bathyal shale and minor sandstone metamorphosed in places to slates, phyllites and schists. There are upper Cretaceous quartz sandstones, Neogene limestones and middle Miocene calc-alkaline Moon Volcanics and volcaniclastic sediments. The Netoni Block consists entirely of Triassic intrusive igneous rocks. The Tosem Block consists of upper Eocene to lower Miocene Mandi volcanics, which are basaltic to andesitic pillow lavas with volcaniclastic sediments. It is interpreted as a late Eocene to Miocene island-arc complex built on an oceanic basement, and resembles the Eocene-Oligocene arc rocks of Halmahera.

3.3. Age of suture

Estimates for the initiation of strike–slip movements vary considerably. They include Oligocene (Pigott et al., 1982), late Oligocene-early Miocene (Hermes, 1968; Hall, 1996), early Miocene (Tjia, 1973), early-mid Miocene (Hamilton 1979), post-mid Miocene (Visser and Hermes, 1962), late Miocene (Charlton, 1996), early Pliocene (Dow and Sukamto, 1984) and mid Pliocene (Froidevaux, 1977). The range of ages partly reflects our incomplete knowledge of difficult and remote regions. It also reflects the complex juxtapositions of rocks of different ages due to late Oligocene-early Miocene arc–continent collision, followed by strike–slip movements on different strands of the fault system at different times since the early Miocene.

3.4. Ocean-floor basalts, deep marine sediments, ophiolites and obduction

The ophiolites to the north of the fault (Gag, Waigeo) are the equivalents of those found in east Halmahera. Similar ophiolites are found within strands of the fault on Obi. Their age is probably Jurassic.

3.5. Metamorphism and igneous activity

There is no record of HP-LT metamorphism associated with the suture. There are no collisional or post-collisional plutons, nor is there significant Neogene volcanic arc activity associated with the fault. The Moon Volcanics (Bladon, 1988; Dow et al., 1988; Pieters et al., 1989) are andesitic lavas and pyroclastic rocks associated with minor intrusive bodies which are found within the Tamrau Block of the northern Bird's Head. They are middle-late Miocene in age. If they are subduction-related there is no indication of their polarity. They may correlate with the oldest volcanic rocks from the southern end of the Neogene Halmahera arc found on Obi, and could therefore be related to the east-dipping subduction of the Molucca Sea Plate.

Fragments of continental crust have been incorporated in the collision zone at the south end of the Halmahera Arc by strike–slip movements associated with the Sorong Fault Zone. A sharp change in the character of Quaternary volcanic rocks was reported by Morris et al. (1983) within Bacan, marking a change from an arc segment with oceanic calc-alkaline character to a segment built on continental crust. The geochemistry of Neogene volcanic rocks shows a continental crustal involvement from about 8 Ma (Forde, 1997). Quaternary volcanic rocks along the Sorong Fault Zone have an alkaline character and Sr and Pb isotope compositions distinct from the other two segments (Morris et al., 1983).

3.6. Mélanges

The Sorong Fault (Pieters et al., 1989, 1990) contains a melange of locally derived and exotic rock fragments with widely different compositions, ages, tectonic styles and origins. The fault zone ranges in width from a few hundred metres to 10 km and contains a wide range of fragments ranging in size from a few centimetres to several kilometres across, ranging in age from Late Cretaceous to middle Miocene. The matrix is not described. Pieters et al. (1983) mention sheared and crushed rock, and a strongly deformed mixture of various types of mudstones, and it is therefore inferred to be a fault gouge derived from different rock

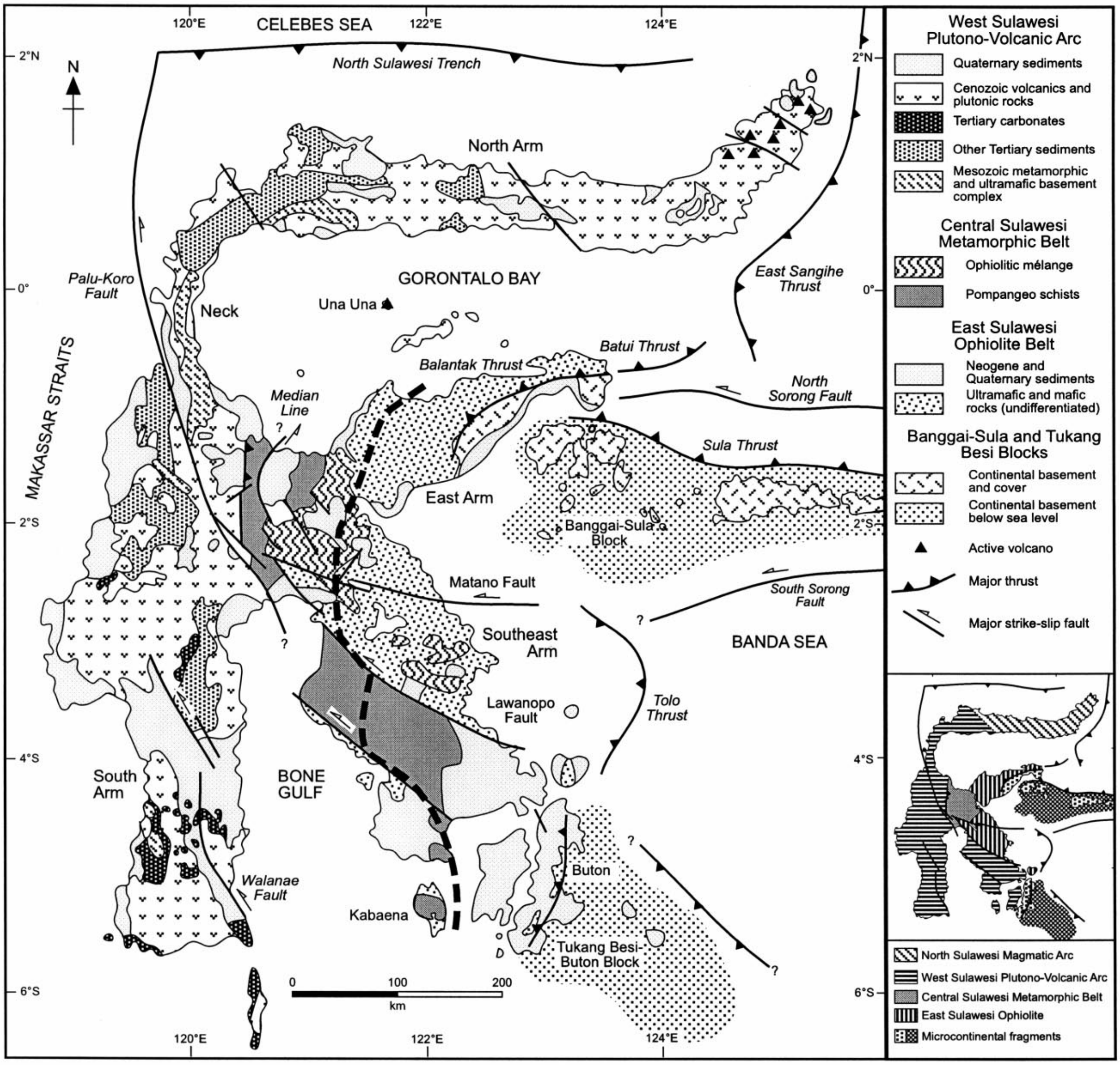

Fig. 6. Summary of the geology of Sulawesi. Inset map shows the principal tectonic provinces. The heavy dashed line shows an estimate of the position of the early Miocene suture, although the trace of this suture has been considerably modified and displaced by later Miocene and younger episodes of contraction, extension and strike–slip faulting.

types. Many of the blocks may be derived from adjacent terranes. Rock types, which are mappable as large blocks, include lower to middle Miocene limestones, quartz sandstones, volcanic rocks and serpentinites. Some of the movements on the fault are therefore middle Miocene or younger.

3.7. Palaeomagnetic data

Rocks of Philippine Sea Plate origin are found within and north of the Sorong Fault Zone. North of the fault zone palaeomagnetic results indicate clockwise rotation and northward latitude shift of about 15° since 25 Ma, considered to represent the motion of the Philippine Sea Plate (Hall et al., 1995a,b). Within the Sorong Fault Zone similar latitude shifts are indicated but there are both counter-clockwise and clockwise rotations, interpreted as local rotations due to deformation at the plate edge (Ali and Hall, 1995). Palaeomagnetic results from the Bird's Head are difficult to interpret due to overprinting. Giddings et al. (1993) suggested a small Neogene counter-clockwise rotation of the Bird's Head. They also interpreted displacement of poles from the Australian Apparent Polar Wander Path as indicating independent movement of the Bird's Head with respect to Australia during the Palaeozoic and Mesozoic. There is continuing debate about whether the Bird's Head was an independent microcontinent that originated far to the east (e.g. Pigram and Panggabean, 1984) or was always close to its present position relative to Australia (e.g. Dow and Sukamto, 1984).

3.8. Age of deformation

Palaeomagnetic data (Hall et al., 1995a,b) and regional reconstructions (Hall, 1998) suggest the strike–slip system has been active since the early Miocene. According to Pieters et al. (1989), the dominantly strike–slip phase of movement in the Bird's Head probably lasted from late Miocene to Pliocene. A phase of dip–slip movement followed, and was succeeded by Plio-Quaternary left-lateral strike–slip motion producing stream offsets. Between the Bird's Head and East Sulawesi the fault strands are mainly submarine and appear to be active (Letouzey et al., 1983; Masson, 1988). GPS measurements indicate that left-lateral motion of the northern Bird's Head continues at the present day, although motion may be occurring on faults other than the Sorong Fault (Puntodewo et al., 1994).

3.9. Conclusions

The Sorong Suture displays the clearest junction between old Australian-origin continental rocks and younger arc and ophiolitic rocks in the region. It originated after the arc–continent collision between the Philippines–Halmahera arc system and the Australian continental margin in the late Oligocene-early Miocene (Hall, 1996, 1998). Subsequently, the former subduction zone boundary changed character to become a strike–slip fault zone. Therefore, unlike all the other sutures the Sorong Suture has a long strike–slip fault history and is not simply the product of a single collision event.

4. The Sulawesi Suture

Sulawesi is a region of Cenozoic collision between continental, ophiolitic and island arc fragments (Fig. 6). The apparently simple tectonic configuration in Sulawesi of arc–ophiolite–continent is not the result of a single arc–continent collision (e.g. Silver et al., 1983a) but is a consequence of multiple events. Emplacement of ophiolite in SE Sulawesi occurred in the early Miocene and was followed by a change in plate boundaries. Since the early Miocene there have been at least two further collisions, in SE and east Sulawesi, as fragments of continental crust have been sliced from the Bird's Head microcontinent and transported west for brief periods on the Philippine Sea Plate along the Sorong Fault system.

4.1. Geological background

Sulawesi has been divided into several tectonic provinces (Sukamto, 1975; Hamilton, 1979) which are, from west to east, the West Sulawesi plutono-volcanic arc, the Central Sulawesi metamorphic belt, the East Sulawesi ophiolite and the microcontinental blocks of Banggai-Sula and Buton-Tukang Besi (Fig. 6).

The Western Sulawesi plutono-volcanic arc, comprising the north and south arms of Sulawesi, is composed of thick Cenozoic sedimentary and volcanic sequences overlying pre-Cenozoic, tectonically intercalated, metamorphic, ultrabasic and marine sedimentary lithologies (Sukamto, 1975; van Leeuwen, 1981). In the Lariang and Karama regions the northern part of the south arm includes Paleogene and Neogene shallow marine clastic sediments. Further south the Eocene to upper Miocene is represented by an extensive carbonate platform. These rocks were deposited on shallow marine shelves around the margins of the deep marine Makassar Straits basin, which formed by rifting during the Eocene (van de Weerd and Armin, 1992; Cloke et al., 1999; Moss and Chambers, 1999). The north arm is formed essentially of Cenozoic arc volcanic rocks described above with the Molucca Suture. Van Leeuwen et al. (1994) separate the eastern part of the north arm as a distinct tectonic province because of differences in lithologies and geochemistry of the igneous rocks.

Central Sulawesi and parts of the SE arm of Sulawesi are composed of sheared metamorphic rocks and in the east a highly tectonised melange complex is present, together comprising the Central Sulawesi metamorphic belt (Sukamto, 1975; Hamilton, 1979; Parkinson, 1991). Similarities between the pre-Cenozoic rocks and some potassium–argon dates from the metamorphic rocks have been used to suggest that these regions, which include microcontinental fragments, had been accreted onto the eastern margin of Sundaland before the Cenozoic (Sukamto, 1975; Hasan, 1991; Wakita et al., 1996). However, data from the Central Sulawesi metamorphic belt, particularly from the SE arm, is sparse, and the timing of its accretion is poorly constrained. Throughout the SE arm and parts of central Sulawesi are rocks that suggest much of this region are underlain by continental type crust. Mesozoic rocks are typically deep water carbonate sequences similar to those of the Australian margin (van Bemmelen, 1949; Kündig, 1956; Audley-Charles, 1978; Cornée et al., 1999). However, peridotites are the most common rocks in the east and SE arms (Silver et al., 1978; Simandjuntak, 1986; Monnier et al., 1995) and are interpreted as fragments of a dismembered ophiolite, known as the East Sulawesi Ophiolite, interspersed with smaller masses of Mesozoic and Cenozoic sediments. The ophiolite includes a full suite of ophiolite lithologies, tectonically intercalated with Mesozoic pelagic sedimentary rocks. However it is not clear that these rocks formed part of a single ophiolite, and it seems likely that ophiolites in different parts of the island may have been emplaced at different times in the Neogene.

On the islands of Buton-Tukang Besi and Banggai-Sula, metamorphic and igneous lithologies of continental origin are exposed or are thought to underlie shallow and deep marine sediments of Palaeozoic and Mesozoic ages. The

Palaeozoic lithologies have Australian–New Guinea affinities, and shallow and deep marine sedimentary rocks were deposited during drifting of the fragments since Mesozoic rifting (Audley-Charles et al., 1972, 1988; Audley-Charles, 1978; Hamilton, 1979; Pigram and Panggabean, 1984; Garrard et al., 1988; Davidson, 1991).

In Sulawesi there is now a continent–continent collision between the Eurasian Sundaland margin and fragments of the Australian continental margin. A popular representation of the island is of a late Oligocene to early Miocene collision between west and east Sulawesi, and collision in Sulawesi is often suggested to have caused many tectonic events further west, for example in Borneo. However, the situation is more complex than this simple model, and which fragments were colliding, as well as the timing and location of collision, are uncertain. West Sulawesi certainly represents the margin of Eurasia, and included a typical subduction-related volcanic arc during the Paleogene. In the Neogene volcanism ceased and then resumed, and its character changed in the south arm. Ophiolites were emplaced on the continental margin in SE Sulawesi and the eastern side of the south arm. Australian micro-continental fragments were probably derived from the Bird's Head microcontinent, which may have been separated from the Australian continent. These micro-continental fragments have thrust contacts with the ophiolite and appear to have collided independently and at different times with Sulawesi.

4.2. Age of suture

The oldest dated events related to accretion and/or suturing are late Oligocene-early Miocene. The ages are from ophiolite-related metamorphic rocks (Parkinson, 1991; Parkinson, 1998a) and date intra-oceanic detachment of the ophiolite. In parts of SE Sulawesi ophiolitic rocks are unconformably overlain by lower Miocene conglomerates, and the ophiolites are interpreted to be thrust over Australian-type crust. Kündig (1956) inferred a regional middle Miocene orogenic episode on the basis of widespread post-collisional clastic sediments said to be upper Miocene and younger. Buton is thought to have collided with eastern Sulawesi during the early (Davidson, 1991) or middle Miocene (Smith and Silver, 1991), but latest Miocene or early Pliocene collision with the east arm of Sulawesi is inferred for Banggai Sula (Garrard et al., 1988; Davies, 1990). Fortuin et al. (1990) and Davidson (1991) suggest that Tukang Besi was a separate microcontinental block, which was accreted to Buton in the Plio-Pleistocene, although not all authors recognise this as a separate micro-continental fragment.

The older collision features are evident only in the eastern parts of Sulawesi. In western Sulawesi there are no significant breaks in marine deposition (Wilson et al., 2000; Calvert, 2000), lack of regional angular unconformities, absence of significant orogenic detrital sediment, and isotopic and fission track ages indicate thrusting, uplift and erosion dates from the late Miocene or later. Seismic lines across Bone Gulf also indicate late Miocene deformation and uplift (Sudarmono, 2000). Active deformation throughout Sulawesi, mostly along strike–slip faults, continues to the present day.

4.3. Ocean-floor basalts, deep marine sediments, ophiolites and obduction

Ophiolites are known from the east, SE and south arms of Sulawesi but their ages are still poorly known. Complete ophiolite sequences (top of the structural pile towards the east) containing ultramafics associated with gabbros, sheeted dykes and pillow basalts are confined to the east arm (Simandjuntak, 1986). Cretaceous pelagic sediments are imbricated with the ophiolite in this region and K–Ar dates on basaltic rocks range from Cenomanian to early Oligocene. Further south in central Sulawesi, Eocene (47–37 Ma) ages have been obtained from magmatic hornblendes in ophiolitic gabbros interpreted to have formed in a back-arc basin (Monnier et al., 1995). Cretaceous to Miocene K–Ar (Yuwono et al., 1988) and Ar–Ar (Bergman et al., 1996) dates have been obtained from mafic and ultramafic rocks (Lamasi Complex) in eastern South Sulawesi interpreted as an ophiolitic sequence. Bergman et al. (1996) suggest the Cenozoic ages represent obduction ages of the ophiolite sequence but they could represent later intrusions into the ophiolite (A.J. Barber, personal communication, 2000). It seems highly likely, from the complexity of geochemistry, ages and structural relations, that the Sulawesi ophiolite is composite. It may include components representing the forearc basement of the Cenozoic Sundaland margin (Bergman et al., 1996), MORB formed at an Indian Ocean spreading centre (Mubroto et al., 1994), and marginal basins (Monnier et al., 1995; Parkinson, 1998a).

The age of metamorphism of the sub-ophiolite metamorphic sole, obtained by K–Ar analysis, suggests that the East Sulawesi Ophiolite was detached in an intra-oceanic setting during the late Oligocene (28–32 Ma, Parkinson, 1991). These rocks show a blueschist overprint indicating that they were subducted after this. The oldest-known ophiolitic debris in the 'molasse' sequences of Sulawesi is found in lower Miocene conglomerates in SE Sulawesi (Surono, 1995). Ophiolitic debris is reported from middle Miocene sequences in Buton. Elsewhere the timing of ophiolite obduction is uncertain. Thrusting of the East Sulawesi Ophiolite onto the western edge of the Sula platform occurred at the end of the Miocene (Davies, 1990).

4.4. Metamorphism and igneous activity

Most of the famous blueschists from Sulawesi are Mesozoic in age. However, Wijbrans et al. (1994) reported 29–21 Ma Ar–Ar ages on phengites in blueschists from SE Sulawesi. Parkinson (1991, 1998a)) reported K–Ar ages of 33–28 Ma from phengites and Ca–Na amphiboles from central Sulawesi. There, the sub-ophiolite sole experienced a blueschist overprint after the 32–28 Ma date on high-T amphiboles on the sub-ophiolite sole. Thus, blueschist facies metamorphism associated with the suture appears to be late Oligocene-early Miocene in age.

Calc-alkaline volcanic activity is known from the north arm from the Eocene onwards. This arc extends eastward into the Sangihe Arc. Subduction was north-dipping (actually west-dipping when later rotations taken into account). The west Sulawesi calc-alkaline volcanic arc was also active from the late Eocene to the early Miocene and was formed above a west-dipping subduction zone.

In the north arm of Sulawesi all arc volcanism was calc-alkaline. In the south arm, Paleogene volcanic rocks are calc-alkaline but this activity ceased by the early Miocene. Resumption of volcanic activity in western Sulawesi began at about 11 Ma but was probably not related to active subduction but rather to extension (Yuwono et al., 1988; Priadi et al., 1994; Polvé et al., 1997). Elburg and Foden (1998) refer to these rocks as syn-collisional and observe that they are isotopically more enriched and relatively potassium rich, which they attribute to a larger contribution of subducted sediments. Neogene magmatism is commonly high-K and includes shoshonites and leucitites. While the trace element patterns in these lavas record subduction zone recycling they are more typical of post-subduction extensional environments such as those of the SW United States (Macpherson and Hall, 1999).

A number of large granitic plutons in western Sulawesi date from c. 12–4 Ma and geochemical evidence suggests extensive lower crust and upper mantle melting (Priadi et al., 1994; Bergman et al., 1996). Rapid uplift of these plutonic bodies, indicated by fission track data, took place in the late Miocene (Bergman et al., 1996; Bellier et al., 1998). Schematic cross-sections of Coffield et al. (1993) and Bergman et al. (1996) imply syn-collisional granitic magmatism and westward-thrusting of some of the plutonic bodies.

4.5. *Mélanges*

The eastern part of the Central Sulawesi Metamorphic Belt is composed of a melange of tectonised and metamorphosed ophiolite fragments and variably disrupted broken formations (Parkinson, 1991; Parkinson, 1998b). Within the melange area the western lower part is composed of ophiolitic clasts in a sheared matrix of red phyllite, whereas the eastern upper part has a serpentinite matrix and components have suffered Oligo-Miocene blueschist recrystallization. The broken formations, tectonically intercalated within the melange, include upper Cretaceous bathyal limestones and chert, and siltstones, sandstones and conglomerates of Jurassic or Cretaceous age (Rutten, 1927; Koolhoven, 1932; Sukamto and Simandjuntak, 1983). Blocks within the melange, derived from the ophiolite, range from pebble size to several hundreds of metres across, whilst those of the broken formations may be up to hundreds of metres across. Mélanges are also known from contacts of the microcontinental blocks of Banggai-Sula and Buton (Koolhoven, 1930; Kündig, 1956; Silver et al., 1983a; Simandjuntak, 1986).

4.6. *Palaeomagnetic data*

Palaeomagnetic work supports suggestions that Sulawesi is composed of geographically distinct components. The lavas of the East Sulawesi Ophiolite have a southern hemisphere origin (Mubroto et al., 1994) and formed at a latitude of 17 ± 4°S. The palaeolatitude is similar to Cretaceous palaeolatitudes for Sula (Ali and Hall, 1995) and Misool (Wensink et al., 1989). Work by Haile (1978b) on rocks from the south and SE arms showed that these arms were in different regions during the Late Jurassic-Early Cretaceous. South Sulawesi was close to its present latitude in the Late Jurassic (Haile, 1978b) and late Paleogene (Sasajima et al., 1980) but rotated clockwise by about 45° between the late Paleogene and late Miocene (Mubroto, 1988). This is very similar to results from Borneo (Fuller et al., 1999).

4.7. *Palaeobiogeography*

Sulawesi is of great importance in the biogeography of SE Asia. Wallace's (1869) line, originally thought to separate regions of Asiatic and Australian flora and fauna, runs between the islands of Bali and Lombok and north through the Makassar Straits. This line is now taken as the western boundary of a transitional area, Wallacea, between Asiatic and Australian biotas, which includes Sulawesi, the Moluccas and the Lesser Sunda islands. The present biota of Sulawesi shows affinities with those of both Australia and Asia, although far fewer families are represented compared with Borneo or New Guinea and there is an extremely high degree of endemism.

The origin, significance and age of these biogeographic regions is still not clear. Many authors have discussed this problem and only a few examples are listed here. Audley-Charles (1981) identified the formation of the Makassar Straits, possible temporary land links across this seaway, and the juxtaposition of different tectonic fragments in Sulawesi, particularly those in the east with Australian affinity, as major influences. Burrett et al. (1991) related rifting of fragments away from Australia and their subsequent convergence and collision with mainland SE Asia to biogeography. Michaux (1994) interpreted Wallace's line in terms of the suture between Sundaland and Australian-derived fragments. Morley (1998) showed that elements of a Sundanese flora were stranded to the east of Wallace's Line after the opening of the Makassar Straits in the late Eocene. Most recently, Moss and Wilson (1998) summarised the principal features of the present biogeography of Sulawesi and their links to tectonic development of the island.

The distribution of Australian and Asian plants and animals reflects a complex history of isolation and dispersal, with important modifications imposed by glacially-related sea level and climatic change in the Quaternary (Hall, in press). Since the early Miocene Australia and Sundaland have moved closer together, but as land emerged and mountains rose in some areas, new deep basins developed. Wallace's line is partly an ancient deep water barrier to dispersal, partly a dynamic boundary marking a migration front, but also a relic of Neogene patterns that have been tectonically disrupted and modified by Quaternary climate change, and physical conditions such as altitude and soil types.

4.8. Celebes Molasse

One key to dating tectonic events in Sulawesi lies in the clastic sediments deposited after collision. Such sediments were first described by Sarasin and Sarasin (1901) in the SE arm of Sulawesi and were named the Celebes Molasse because of their supposed similarity to the molasse of the Swiss Alps. Wanner (1910) correlated similar rocks of the east arm with the molasse of the SE arm. van Bemmelen (1949) used the term Celebes Molasse for the clastic sediments of young Neogene age that are found all over Sulawesi, though never as large areas of outcrop. Many subsequent authors have referred to Celebes Molasse and it is often assumed that its age is similar throughout the island. In fact, the Celebes Molasse is not well dated. The work of Kündig (1956) is widely cited in support of a Miocene collision. In the SE arm there are definite lower Miocene rocks within the conglomerate sequence, which unconformably overlies the ophiolite (Kündig, 1956; Surono, 1995, 1996). Elsewhere on the island, rocks assigned to the Celebes Molasse are predominantly continental rocks, which are poorly fossiliferous and where dated they are no older than upper Miocene. In the east arm Kündig (1956) cited earlier reports of upper Miocene and Pliocene clastic sediments termed Celebes Molasse. More recent drilling for hydrocarbons indicates thrusting between 5.2 and 3.8 Ma and shows that the clastic (molasse) rocks are Plio-Pleistocene (Davies, 1990). In the northern part of the south arm thick sequences of coarse clastic sediments are also Plio-Pleistocene. Further south in the south arm, shallow marine carbonate deposition continued into the late Miocene and early Pliocene (Ascaria, 1997). The molasse therefore appears to indicate ophiolite emplacement and collision events during the early Miocene in the SE arm. However, in the east and west arms uplift and erosion seems to be much younger and probably occurred in the late Miocene or even later. This is also indicated by young fission track ages on plutonic rocks in western Sulawesi (Bergman et al., 1996; Bellier et al., 1998).

4.9. Deformation associated with collision

Deformation associated with collision dates from the late Oligocene-early Miocene. The oldest events are recorded by ophiolitic rocks, and ages of sub-ophiolitic metamorphic rocks imply intra-oceanic thrusting at this time. Ophiolites were clearly obducted in SE Sulawesi during the early Miocene, and unconformable contacts indicate early Miocene thrusting. Deformation continued throughout the Neogene. In western Sulawesi the evidence for collision-related deformation is less clear and seems to be much younger. Coffield et al. (1993) and Bergman et al. (1996) imply that contraction was broadly continuous from the early Miocene, and westward-directed thrusting seen on seismic lines in the Makassar Straits is the Mio-Pliocene expression of the westward-propagating orogenic event. However, the absence of evidence for significant breaks in marine deposition, lack of regional angular unconformities, absence of significant orogenic detrital sediment, and isotopic and FT ages indicate thrusting, uplift and erosion dates from the late Miocene or later in western Sulawesi. Late Neogene K-rich magmatism suggests an interval of extension during the Neogene, which may be linked to the extension in Bone Gulf.

The eastern margin of the Central Sulawesi metamorphic belt is interpreted by some authors as overthrust by the East Sulawesi Ophiolite from the east (Brouwer et al., 1947; Parkinson, 1991). However, a Bouguer gravity high at the melange/ultramafic contact close to Malili led Silver et al. (1978) to suggest that the eastern margin of the East Sulawesi Ophiolite dips westward under Central Sulawesi. Monnier et al. (1995) suggested that the East Sulawesi ophiolite was part of the palaeo-Celebes Sea and that there was north to south obduction of the southern margin of the palaeo-Celebes Sea. These first two interpretations are incompatible, whilst the third surmise has little geological or geophysical evidence to support it, and is based on geochemical similarities between lithologies in the East Sulawesi Ophiolite, the north arm of Sulawesi, and the Celebes Sea. There has clearly been considerable post-emplacement deformation of the ophiolites and older lithologies, structural contacts and the present day configuration of the ophiolite may differ significantly from those during emplacement. At the eastern end of the east arm, the contact of the Banggai-Sula microcontinental block with the East Sulawesi ophiolite is a northwest dipping, highly imbricate complex (Koolhoven, 1930; Kündig, 1956; Silver et al., 1983a,b; Simandjuntak, 1986).

Regional reconstructions suggest that there may have been a significant strike–slip component to convergence before collision of the earliest fragments in the early Miocene (Hall, 1996). Subsequently, internal rotation of fragments within Sulawesi is thought to have occurred via a linked system of strike–slip and thrust faults (Hamilton, 1979; Silver et al., 1983b). There are a number of structures interpreted as strike–slip features, mostly with an inferred sinistral motion, such as the Palu-Koro Fault system, the Walanae Fault, the Poso Fault System, the Matano and Lawanopo Faults. The timing of movements and displacements on these faults are still contentious. For example, for the Palu-Koro fault, Tjia (1973) suggested sinistral strike–slip movements with displacements of more than 750 km; whereas Silver et al. (1983b) inferred movements of only 250 km. Ahmad (1975) suggested that 20–25 km of sinistral

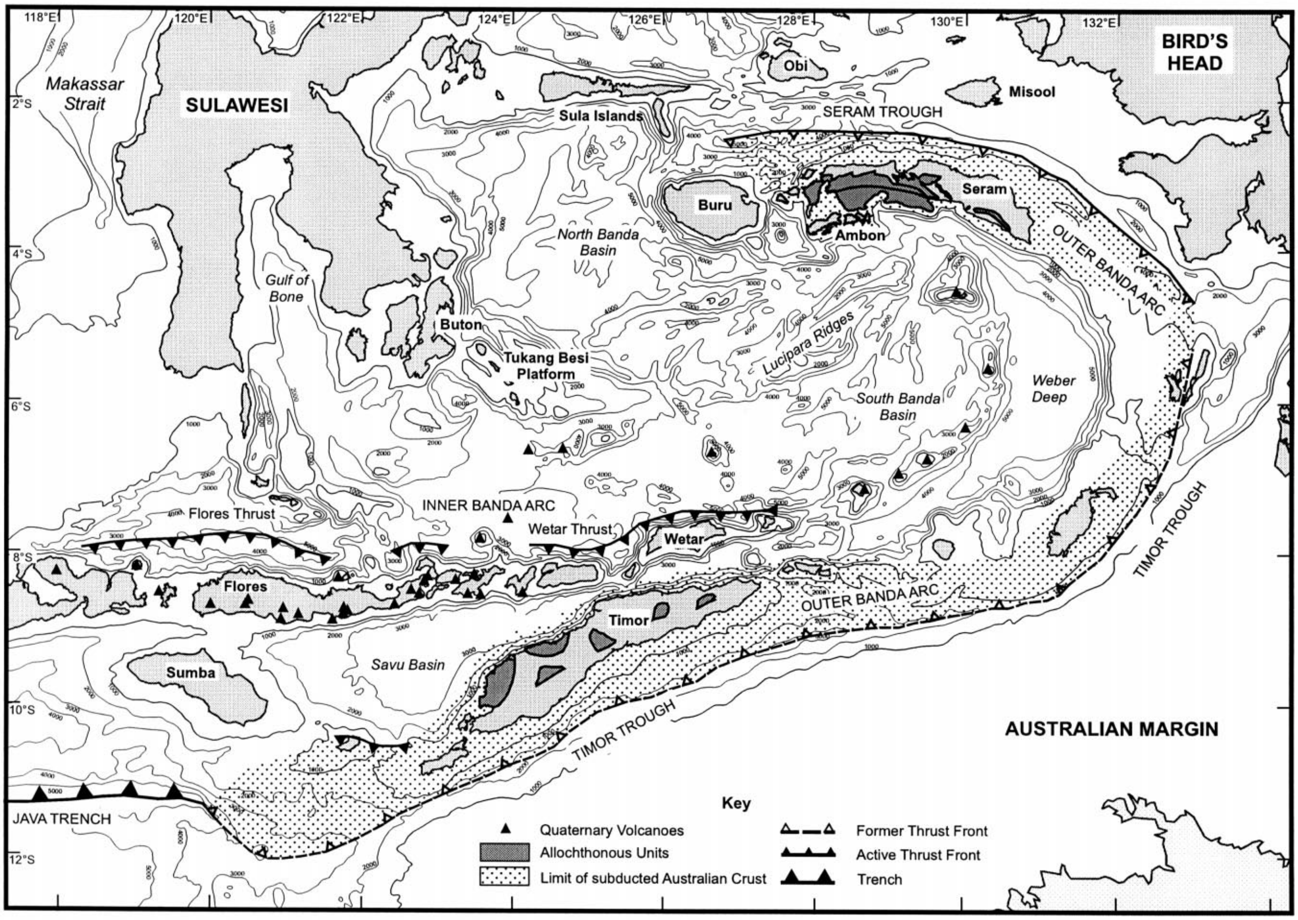

Fig. 7. The Banda arc and Banda Sea basins and principal geographical features. Bathymetric contours are in metres.

strike–slip motion had taken place along the Matano Fault since the mid Cenozoic but fault plane solutions from recent earthquakes in the Matano region suggest north-striking normal faulting (McCaffrey, 1983). The Walanae Fault has a Neogene extensional history prior to Pliocene reactivation as a strike–slip fault (van Leeuwen, 1981). Recent GPS results (Walpersdorf et al., 1998; Stevens et al., 1999) indicate slip rates of up to 4 cm/year on the Palu-Koro Fault, consistent with palaeomagnetic estimates for rotation during the last 4–5 Ma, and implying that rotation and strike–slip motion is linked to contraction in the convergent zone between eastern Indonesia and Sundaland.

4.10. Conclusions

The Sulawesi Suture is the most complex in the region and illustrates the problems of oversimplification of the collision processes. The geology of Sulawesi and surrounding basins is still inadequately known and therefore the exact timing of events is still not well understood. Within the present area of Sulawesi, continent–continent collision and uplift began in the early Miocene, related to west-dipping subduction and arrival of fragments derived from the Australian margin. However, it is not clear where to draw a suture between west Sulawesi, representing the Eurasian margin, and Australian-origin crust of east and SE Sulawesi. There is no obvious foreland basin and the Makassar Straits, which are now receiving sediment from the Sulawesi mountains, represent a rifted margin formed in the Eocene, are floored by oceanic crust in the north, and have been affected by thrusting only recently.

The earliest evidence of collision is a little younger than 25 Ma. Intra-oceanic thrusting just before 25 Ma is indicated by isotopic ages from sub-ophiolite metamorphic sole rocks. Blueschist metamorphic ages indicate subduction continued until about 20 Ma. The Celebes Molasse of SE Sulawesi contains evidence of erosion of ophiolites in the early Miocene. However, there is no evidence in west Sulawesi of collision and most of western Sulawesi appears to have remained close to or just below sea level during this period. This evidence indicates collision between the ophiolitic forearc of East Sulawesi and the leading edge of the Bird's Head microcontinent. Thus, the principal suture lies within the ophiolite of East Sulawesi. However, continued convergence has resulted in the development of several other major thrusts within Sulawesi, each active in different parts of the island and at different times since the early Miocene. Thrusting was active in SE Sulawesi in the early and middle Miocene, and in east and central Sulawesi from the late Miocene. Much of Sulawesi was not emergent until the late Miocene or later, and the present high mountains of west Sulawesi rose only in the Pliocene.

Active deformation continues at the present day, and geological mapping and GPS measurements indicate a complex pattern of block rotations, strike–slip faulting linked to subduction at presently active trenches. Curiously, this has a relatively subdued expression in terms of seismicity and volcanic activity.

5. The Banda Suture

The collision zone of the Banda Arc (Fig. 7) is of major interest because very early stages in the collision of a continental margin and an arc can be observed. More geological literature has probably been generated from this region than any other part of SE Asia, and with it considerable controversy. There is disagreement about the position of the suture, the timing of collision, the origin of mélanges, the style and importance of structures, and the evolution of the region. In the short space here it is not possible to do justice to all of this work but reviews of some of the principal features of the geology, discussion of the literature, and different interpretations are to be found in Hamilton (1979); Barber (1981); Audley-Charles (1986a,b) and Harris (1991).

5.1. Geological background

The Banda Arc consists of an inner volcanic arc and an outer non-volcanic arc of islands formed principally of sedimentary, metamorphic and a few igneous rocks of Permian to Quaternary age (Fig. 7). The inner volcanic arc has been active since the late Miocene (Abbott and Chamalaun, 1981; Barberi et al., 1987; Honthaas et al., 1998). The outer arc is much more complex. Although there have been some dissenters from this view, the outer arc islands are now regarded as formed of nappes thrust over a parautochthonous sequence. Chamalaun and Grady (1978) argued that there were no large-scale thrusts on Timor and that the most important structures are essentially vertical faults. This view was vigorously challenged when proposed (e.g. Barber, 1981) and is now discredited by many unpublished and published (e.g. Reed et al., 1996) seismic lines. Timor is the largest and best known of the outer arc islands and illustrates most of the key problems of this suture zone. Most of the discussion here is based on Timor. Seram is the second largest of the outer arc islands and has a similar structure and stratigraphy to Timor and has been interpreted as essentially a mirror image of Timor (Audley-Charles et al., 1979).

Barber (1981) and Audley-Charles (1988) have summarised the principal stratigraphic features of the outer arc. The parautochthonous strata range from lower Permian to lower Pliocene and are predominantly deep water sedimentary rocks. Typically they are siliciclastic turbidites and calciturbidites with associated mudstones. There are significant biostratigraphical similarities between these Mesozoic and Cenozoic rocks of Timor and Seram and sequences of the NW Australian shelf. The parautochthonous rocks have been strongly deformed with tight folds, reverse faults and thrusts typically showing vergence towards the south (on Timor) and NE (on Seram). According to Barber (1981), all workers on the geology of Timor agree that the Australian continental shelf sediments extend north from the Sahul Shelf, beneath the Timor Trough, to reappear further north where they are uplifted and folded on Timor. The parautochthonous strata are therefore the deformed distal parts of the former Australian continental margin.

The parautochthonous units are overlain by overthrust allochthonous units. In his original interpretation, Audley–Charles (1968) considered that the Maubisse-Aileu unit composed of limestones, volcanics and flysch-type lithologies, passing into metaquartzites and mica-schists, associated with marbles, metabasites and amphibolites (Barber et al., 1977; Audley–Charles, 1988) on the north coast of east Timor, was part of this allochthon; but it is now considered to be the distal part of the Australian margin sequence (e.g. Charlton et al., 1991).

Overthrust allochthonous rocks (the Banda allochthon) include pre-Cretaceous metamorphic rocks, principally of continental origin (Lolotoi and Mutis Complexes of Timor of Barber et al., 1977) overlain by cherts, limestones and flysch deposits of upper Jurassic to Eocene age and then by shallow water carbonates ranging up to the Lower Pliocene. The youngest rocks of the allochthonous sequences of Timor, in Audley-Charles's interpretation (e.g. Carter et al., 1976), belong to the Bobonaro Scaly Clay, which includes deformed clay-rich rocks containing blocks of rocks of many types and ages. On Seram a similar but thinner sequence is known as the Salas Block Clay.

The parautochthonous and allochthonous strata are overlain by rocks which accumulated where they are now exposed. These rocks include Quaternary raised coral–algal reefs, Quaternary alluvial terraces and Pliocene-Quaternary turbidites. The terraces are either horizontal or gently tilted. The turbidites are locally folded and faulted and cut by diapirs of Bobonaro Scaly Clay.

Most authors describe the region as an arc–continent collision zone in which the Banda volcanic arc is colliding with Australia. Barber (1981) drew attention to the presence of Asian continental crust within the arc in the models of Audley-Charles (1968) and colleagues (Carter et al., 1976; Barber et al., 1977). Richardson (1995) proposed that a collision between a microcontinent, forming part of an extended passive margin and an Asian arc preceded collision of the volcanic arc and the Australian margin. Linthout et al. (1997) proposed that several microcontinental fragments collided with the Australian margin before the very young arc–continent collision.

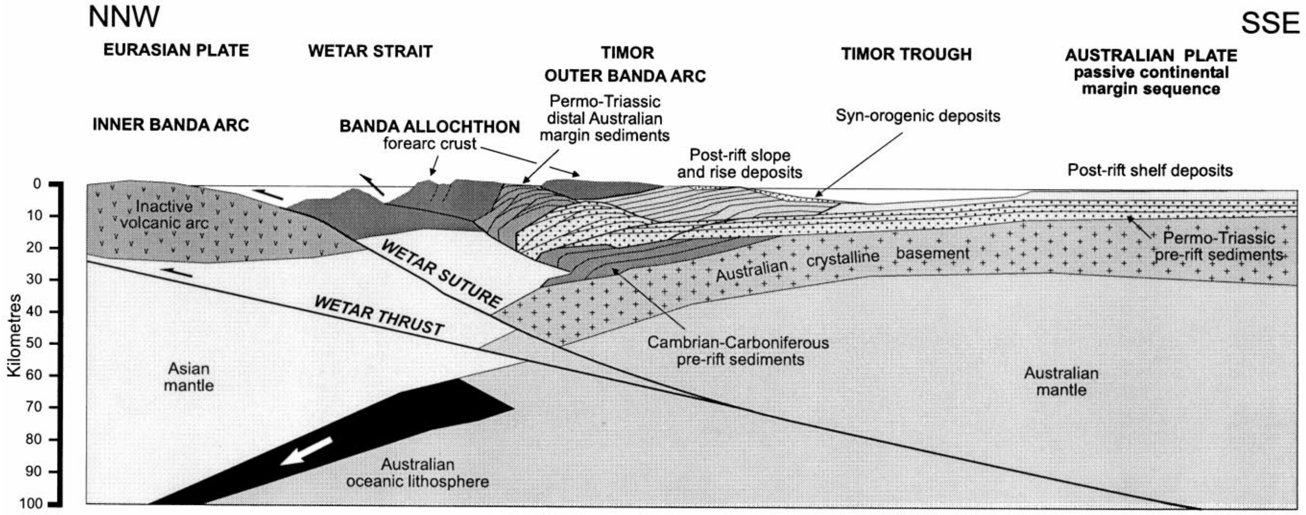

Fig. 8. Schematic cross section across the Banda Suture at the same vertical and horizontal scales based on Price and Audley–Charles (1988) and Harris (1991) but modified from them. The Wetar Thrust is interpreted as the active plate boundary between the Australian and Eurasian plates. Suggested positions for the suture at different stages in the collision are: (1) the base of the Banda allochthon; (2) the deformation front in the Timor Trough (now inactive); (3) the Wetar suture (Audley-Charles, 1986a,b, 1988; now inactive); and (4) the Wetar Thrust.

5.2. Age of suture

Almost all authors concur on a late Neogene age for the beginning of arc–continent collision. However, a few authors have proposed more complex tectonic models with older collisional events dating from the Eocene (Reed et al., 1996), early Miocene (Linthout et al., 1997) and middle Miocene (Richardson, 1995). Some of the older events appear to stem from difficulties in distinguishing events that affected the Asian margin before collision, from those associated with the collision of the Asian and Australian margins.

5.3. Where is the suture?

A particular cause of controversy has been the position of the suture. Many authors (e.g. Hamilton, 1979; Bowin et al., 1980; Silver et al., 1983c) have considered the Timor Trough to be a subduction trench and the site of the suture. Carter et al. (1976) and many others (e.g. Audley-Charles, 1986b) have maintained that the present Timor Trough is not a trench and the suture must therefore be buried or lie to the north of the Timor Trough. Audley-Charles (1986a, 1988) has advocated that there was a south-dipping suture in the Wetar Strait. Cases can be made for all these suggestions (Fig. 8). The base of the Banda allochthon is the boundary between the former Asian Plate and underlying deposits of the former Australian passive margin. The base of the parautochthon is the deformation front and represents the boundary between completely autochthonous deposits of the Australian margin and those that have been displaced. The thrust north of Wetar can be interpreted as the new boundary between the Asian and Australian plates formed after subduction ceased south of Timor, and perhaps in response to slab break-off. Audley-Charles (1986a) summarises in diagrammatic form the contrast between the principal models. Harris (1991) suggested that each of the different models may be appropriate for different sections through the developing orogen, and each may apply at different stages in the collision process.

5.4. Ocean-floor basalts, deep marine sediments, ophiolites and obduction

Some volcanic rocks and peridotites, the Ocussi Unit and Atapupu Unit on Timor, are generally interpreted to represent part of the Banda volcanic arc forearc, thrust southward onto Timor in the Pliocene. However, further controversy results from interpretation of metamorphic rocks associated with ultramafic rocks in the Banda Arc. Sopaheluwakan (1990) suggested that the metamorphic rocks of the Mutis Complex mark high temperature intra-oceanic thrusting in the Cretaceous and Eocene-Oligocene ophiolite obduction onto the Australian margin. These and other similar rocks in parts of the Banda Arc have some unusual features for ophiolites and related rocks. There are no complete ophiolite sequences and the peridotites are lherzolitic. The interpreted sub-ophiolite metamorphic sole rocks are composite, like other metamorphic soles, but are much thicker (up to 1 km) and include lithologies such as sillimanite–mica, staurolite–kyanite and garnet–mica schists (Sopaheluwakan 1990; Linthout et al., 1996, 1997). They are also associated on Seram with cordierite-bearing granites interpreted as partial melts produced by obduction. In contrast to Sopaheluwakan (1990), Linthout et al. (1996, 1997)) interpreted very young metamorphic ages (10–5 Ma) from some of these rocks as indicating Miocene obduction of young oceanic lithosphere. The significance of these unusual rocks is not clear. However, they do not resemble other ophiolites and related metamorphic rocks and some features suggest involvement of sub-continental mantle and overlying continental crust. The 10–5 Ma metamorphic ages are the same as the ages suggested for initiation of volcanic activity in the Banda volcanic arc, and suggest that they may be related to extension rather than obduction in the Banda Sea region.

5.5. Metamorphism and igneous activity

Blueschists are known from Mesozoic rocks on Timor and were produced during collision of a microcontinental block with Sundaland in the Cretaceous (Earle, 1979). No high pressure metamorphic rocks associated with the modern collision have been reported.

In the inner and outer Banda arcs there are volcanic rocks of Eocene to Mio-Pliocene age formed in an arc setting. There are no collisional or post-collisional plutons. The older volcanic rocks of the Banda allochthon seem likely to have formed at a north-dipping subduction zone, which was active from the Mesozoic until the early Miocene. These were part of the Asian margin at the time of their formation. They have been thrust onto Australian margin material on Timor since the Miocene. The young Banda volcanic arc became active in the late Miocene, again associated with north-dipping subduction. The young arc, now inactive, is north of Timor, although separated from it only by the narrow Wetar Strait.

The volcanic rocks of the Banda Arc are well known for enrichment in incompatible trace elements and radiogenic isotopes such as Sr, Pb and Nd, and for the presence of the unusual cordierite-bearing dacites on Ambon (ambonites and cordierite-sanidine-albite rhydites on Wetar (van Bemmelen, 1949)). These features have been widely interpreted as indicating involvement of continental crustal material in magma genesis either by assimilation of arc crust or by addition of subducted continental material. There is an extensive literature on this subject (see for example, Whitford et al., 1977, 1981; Whitford and Jezek, 1979; Vroon et al., 1993, 1995; and references therein). In the modern arc there is evidence for both shallow crustal assimilation and for a subducted continental component. Isotopic studies show that variation in the composition of sediment along the arc can be correlated with variations in volcanic compositions and can be matched to different sediment provenances of the north Australian margin (Vroon et al., 1995).

In the Plio-Quaternary arc there is a low- and a high-K suite of volcanic rocks. The high-K rocks, notably the ambonites, are restricted to the North Banda segment of the arc and are absent in the southern part of the arc (Honthaas et al., 1999). These require assimilation of continental crust, and Honthaas et al. propose this was achieved by subduction at the Seram Trough. An alternative is that the contamination occurred during extension, which occurred as the Banda Arc propagated east in the period before spreading in the Banda Sea (Hall, 1996).

5.6. Mélanges

Mélanges have been another source of controversy. Fitch and Hamilton (1974) and Hamilton (1979) considered all of Timor to be a chaotic melange analogous to those of subduction settings, and this view has been followed by many subsequent authors. Barber (1981) summarised the arguments that suggested Timor had a more coherent structure than this melange concept implied, and it is now widely accepted that Timor is not simply a melange. However, melange is clearly present on Timor. Audley-Charles (1965, 1968) proposed that much of this melange, the Bobonaro Scaly Clay, was a middle Miocene olistostrome formed during the developing collision. Later workers have suggested different ages and other interpretations of the melange. Barber et al. (1986) interpreted the Bobonaro Scaly Clay as the product of shale diapirism formed by over-pressuring in an accretionary complex at a subduction zone. Harris et al. (1998) accepted a subduction setting, but suggested that different melange types (broken formations, matrix-rich mud injections, blocks-in-clay) represent different melange facies formed at different structural positions in the developing orogenic wedge. Harris et al. (1998) also made a detailed study of melange ages based on the contained fossils. Many of the fossils are reworked from older strata, some of which may be present as blocks in the melange, but some of which may have provided Permian to Quaternary fossils to the melange matrix. They suggested that in Timor the age of Bobonaro melange formation changes across orogenic strike from NE to SW, and ranges from late Miocene-early Pliocene in the north to present day at the deformation front. The presence of active mud volcanoes implies some mélanges may be forming at the present day, even in areas where active convergence has ceased (Barber et al., 1986).

5.7. Palaeomagnetic data

Palaeomagnetic evidence indicates that parautochthonous Timor formed part of the Australian margin in the Late Permian (Chamalaun, 1977) although Wensink and Hartosukohardjo (1990a) argued that some displacement within the margin may have occurred since the Permo-Triassic. Wensink et al. (1987) showed that parautochthonous pelagic sedimentary rocks of the Kolbano sequence have moved north by about 10° since the Early Cretaceous. Palaeomagnetism has also been used to support suggestions that Timor also contains SE Asian elements and that Eocene volcanic rocks formed in the northern hemisphere (Wensink and Hartosukohardjo, 1990b). However, the hemisphere is not certain and the palaeolatitude (17 ± 4°) could be southern and still be consistent with an origin on the SE Asian margin as shown in recent reconstructions (Hall, 1996).

The shape of the Banda Arc has provoked suggestions that the arc acquired its curvature as a result of rotation driven by collision. This is often supported by reference to the palaeomagnetic work of Haile (1978a) on Seram. There is a single site of Miocene age showing a large (74 ± 4°) counter-clockwise rotation that Haile warned was "only of a reconnaissance nature" although concluding that this fits with the model of Audley-Charles et al. (1972), which involved a rotation of the entire arc of about 70° since the mid Pliocene. However, there are major tectonic problems in accounting for a rotation of such magnitude of the entire North Banda Arc since the mid Pliocene, although such large local rotations are often produced by strike–slip faulting for which there is evidence on Seram (e.g. Linthout et al., 1991). There have been no further palaeomagnetic studies on Seram and more work is required to establish the age and distribution of rocks with such large declination shifts.

5.8. Palaeobiogeography

Permian limestones of the Maubisse Formation on Timor indicate a low latitude, warm water, environment of formation in the Permian. Audley-Charles (1968) drew attention to the separation by less than 1000 km of Permian glacial deposits in northern Australia and reef limestones of the same age in Timor, which were thought to support the hypothesis of overthrusting of Asian onto Australian sequences. However, Barkham (1993) has since suggested the Maubisse Formation was always part of the Australian margin sequence and records a change from a periglacial to subtropical climate during the Permian.

The parautochthonous Kolbano sequence of Timor includes upper Jurassic to Pliocene deep water deposits containing radiolaria. Clowes (1997) showed that lower Cretaceous strata include radiolarian species, which have been reported only from high southerly latitudes. This is consistent with a north Australian margin origin for this pelagic sequence and a 30° northward movement of Kolbano sequence rocks since the Early Cretaceous.

The Banda Arc also includes much younger biogeographical information of importance for the links between Australia and Asia. For example, fossils of pygmy stegodonts found in Sulawesi, Flores and Timor have been used to argue for Pleistocene land connections (Audley-Charles and Hooijer, 1973) within the Banda Arc, which would imply very rapid and large changes in elevation in the region as a result of collision. If these animals required land connections, migration of stegodonts between islands, which are now separated by very deep waters, indicate Quaternary vertical movements of the order of 3000 m. However, it is now widely accepted that elephants and probably stegodonts could swim and that short marine crossings were made by both animals and early man (e.g. Morwood et al., 1998).

5.9. Deformation associated with collision

Several deformation events are recorded on Timor and other islands of the Banda Arc, which have sometimes been confused with events related to the young arc–continent collision. Some of this confusion may merely be imprecision in explanation, but in some cases collision of the Australian–Banda arc system is said to have begun much earlier than normally interpreted (e.g. Reed et al., 1996; Sopaheluwakan, 1990; Linthout et al., 1997). The age of the first orogenic deformation in the outer Banda arc resulting in nappe emplacement may be dated from the rocks overlying the allochthonous nappes, which are latest Miocene on Seram to post-mid Pliocene on Timor (Audley-Charles, 1986a). The age of the initial arc–continent collision is diachronous along strike as explained by Harris (1991), and deformation is continuing at the present day.

5.10. Conclusions

The Banda orogeny has attracted more argument than any other part of this complex region. Some differences of opinion reflect different interpretations and differences in terminology (e.g. the Banda Suture in the area of Timor could be placed at base of Banda allochthon, at the deformation front in the Timor Trough or in the Wetar Strait) and Harris (1991) has suggested these interpretations may correspond to different stages in the developing collision (Fig. 8). Some of the differences resulted from the application of over-simplified tectonic models during the period of change from geosynclinal to plate tectonic concepts. It is clear from Timor and Seram that very rapid vertical movements have been associated with the collision (Audley-Charles, 1986a,b; de Smet et al., 1990). These have also contributed to different models and caused further confusion, since the vertical movements were accompanied by normal faulting which has complicated the older overthrust structures. The change from south- to north-directed thrusting after the emergence of Timor is noteworthy (Price and Audley-Charles, 1987); subduction reversal may be in progress, accompanied by the disappearance of the Banda allochthon within a very short period. Deep seismic studies have reinforced the suggestion of subduction polarity reversal (Snyder et al., 1996). The Banda Suture deserves to be much better known since it is one of the best examples of an active collision in the world and may offer insights into older orogenic belts (e.g. Snyder and Barber, 1997). Unfortunately, it remains understudied, incompletely understood, and inadequately known to geologists who have not worked in the region.

6. The Borneo Suture

The Borneo Suture is generally overlooked as a collisional suture in the region, although Borneo contains a high mountainous axis that has been shedding vast amounts of sediment to the north, east and south since the early

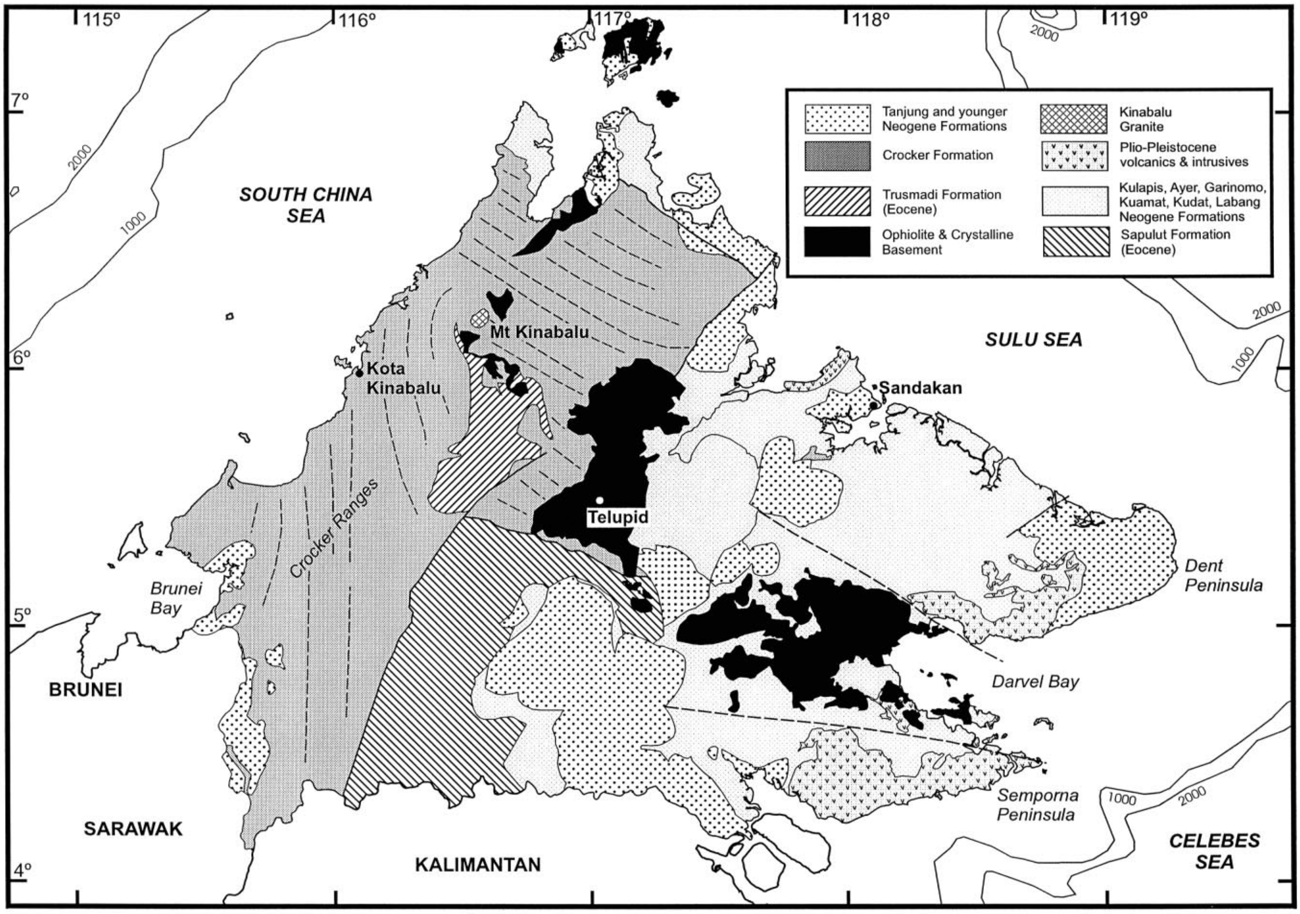

Fig. 9. Simplified geology of Sabah based on Lim and Heng (1985) and Tongkul (1991) but modified from them. Interpretation of the significance and equivalences of different units based on the author's field observations.

Miocene. Although some authors have referred to collisions between north Borneo and supposed microcontinental fragments of the South China Sea area (Dangerous Grounds, etc.). Neogene tectonic events in this period are often attributed to collisional events in Sulawesi. However, the collisions in Sulawesi were of small fragments, occurred later than uplift in Borneo, and produced little or no uplift in Sulawesi itself; therefore it is difficult to understand why they should have had a much more dramatic effect in Borneo. The island is still relatively inaccessible, rainforested and poorly exposed. Most is known about the hydrocarbon-rich basins around Borneo as a result of hydrocarbon exploration in contrast to its elevated central ranges, which have not been the subject of such intense investigation. Also, Borneo does not fit easily to a simple tectonic model. For these reasons it has been neglected. Sabah is now reasonably well known (Fig. 9), the rocks adjacent to the suture can be seen on land there, and is used here to illustrate the main features of the suture zone.

6.1. Geological background

Northern Borneo has a basement of ophiolitic rocks, probably mainly of Cretaceous age, but with possible older crust indicated by K–Ar ages of igneous and metamorphic rocks (Fig. 9). Metamorphic rocks are described as crystalline basement (Reinhardt and Wenk, 1951; Dhonau and Hutchison, 1966; Koopmans, 1967) and have been suggested to be of continental origin, although most of the protoliths are basic and all could be deformed ophiolitic rocks. They are intruded by dioritic and granitic rocks, which could also represent arc plutonic rocks intruded into an older ophiolitic basement. There are however, a few rocks described that are of possible continental origin, such as andalusite–garnet–mica and sillimanite–garnet schists (Leong, 1974) although none of these rocks are dated. The descriptions by Leong (1974) and earlier workers suggest formation of the crystalline basement in a Mesozoic intra-oceanic arc. Omang and Barber (1996) suggest the crystalline basement rocks are essentially equivalent to the Cretaceous Darvel Bay ophiolite complex. These basement rocks are overlain by a series of poorly fossiliferous Paleogene sedimentary and very low-grade metasedimentary rocks of generally deep water origin. These include turbidites, olistostromes and mélanges. There are some

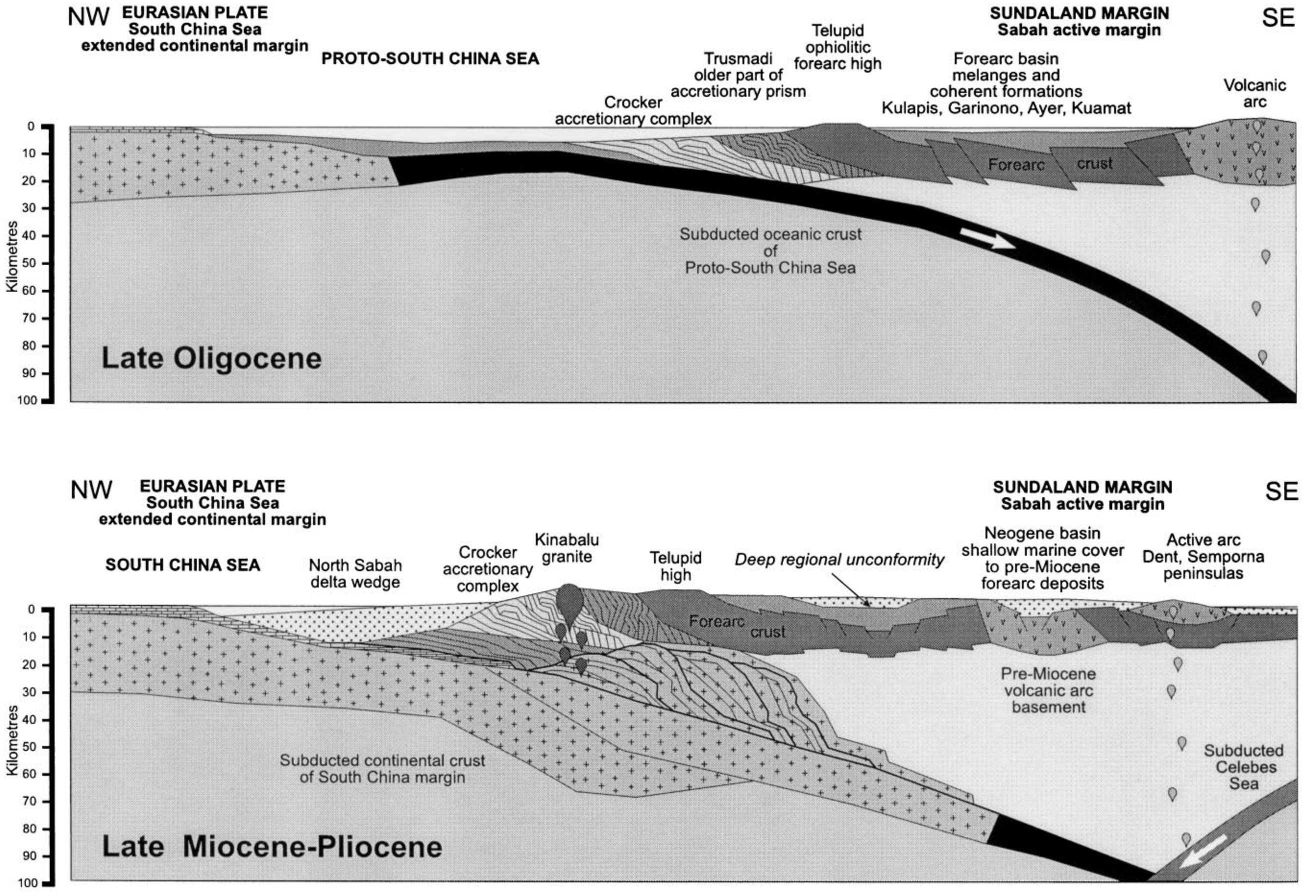

Fig. 10. Schematic cross sections across the Borneo suture at the same vertical and horizontal scales drawn at different stages in the collision. The Paleogene subduction of the proto-South China Sea beneath Sabah was followed by collision with the leading edge of the extended South China continental margin in the early Miocene. Subduction of continental crust continued into the Miocene leading to the interpreted thickening of continental crust beneath the Crocker Ranges. Neogene shallow marine deposits were extended during the Neogene, and subduction of the Celebes Sea from the south from the late Miocene led to formation of the Dent-Semporna-Sulu volcanic arcs. This ceased during the last few thousand years.

volcanic rocks of apparent subduction character. The sedimentary rocks in particular are difficult to subdivide and date and hence map; further, the rainforest cover has exacerbated these problems, leading to a large number of formation names and an uncertainty in stratigraphic and structural interpretation. From the Eocene, the setting appears to be have been an accretionary margin with subduction to the southeast although without a major volcanic arc (Fig. 10). In the early Miocene there was uplift, and shallow water sediments were deposited unconformably upon the older accretionary complex rocks in south Sabah. Further north accretion continued until later in the Miocene, represented by the Crocker sequences as the thinned passive margin of South China underthrust north Borneo (Fig. 10). The resulting mountains of the central Borneo ranges shed sediment, first into deltas of the Kutai and Sandakan basins and later into the Tarakan and Baram basins. The younger delta complexes in part overlie the older accretionary rocks, and the associated volcanic arc and the suture itself is not exposed. The history of the NW Sabah region is discussed in detail by Tan and Lamy (1990), Tongkul (1991) and Hazebroek and Tan (1993). Hutchison et al. (2000) provide a more recent interpretation of the geological evolution of the region.

6.2. Age of the suture

Northern Borneo records a collision between the extended passive continental margin of South China and the active margin of north Borneo, which was the northern part of the Eurasian Sundaland continental margin (Fig. 10). Collision began in the early to middle Miocene and was preceded by Eocene-Oligocene subduction of the proto-South China Sea. Slab-pull forces seem to be the most likely driving force for the continent–continent collision, together with forces transmitted from Australia's impact to the east, which caused the rotation of Borneo. East of Borneo, the suture zone passes into an arc–continent collisional suture between the Neogene Cagayan Arc and the Palawan sector of the South China rifted margin. After this arc–continent collision in the middle Miocene, the polarity of subduction reversed and the site of subduction jumped southwards, and from the late Miocene the Celebes Sea was subducted beneath the Semporna-Dent arc towards the north.

6.3. Ocean-floor basalts, deep marine sediments, ophiolites and obduction

No Cenozoic ocean floor basalts or deep marine sediments thought to represent parts of subducted ocean crust are known from the suture zone. Ophiolites are known and are assigned to a Chert–Spilite Formation, which includes cherts and limestones of Cretaceous age. Many of the rocks assigned to the Crystalline Basement also have similarities to deformed ophiolitic rocks. Their age is uncertain. Isotopic ages indicate Mesozoic recrystallisation. The Chert–Spilite Formation and Crystalline Basement seem to form the basement to most of Sabah. It is not clear if the ophiolite was emplaced onto continental crust or was accreted to Sundaland margin along steep faults. Fragments of ophiolitic rocks are found as clasts in Eocene sediments, suggesting that the ophiolite complex had been obducted onto Sabah either in the latest Cretaceous or earliest Paleogene (Omang and Barber, 1996).

6.4. Metamorphism and igneous activity

Blueschists have been reported but they are very rare (Leong, 1978; Hutchison et al., 2000). Pre-collisional volcanic rocks are not abundant. There is evidence of an Oligocene to early Miocene arc. The relative positions of the accretionary wedge and volcanic arc rocks indicate SE-dipping subduction. In the Dent and Semporna peninsulas there are late Miocene-Quaternary volcanic rocks that continue offshore into the Sulu Arc (Kirk, 1968). Subduction ceased in the Dent Peninsula in the last few thousand years. The polarity of subduction is not clear. Hamilton (1979) tentatively suggested a change in the Sulu Arc from NW-dipping subduction of the Celebes Sea to more recent SE-dipping subduction of the Sulu Sea. On land a young SE-dipping subduction would imply a suture or at least significant young deformation NE of the Dent and Semporna peninsulas for which there is no evidence. Recent NW-dipping subduction of the Celebes Sea therefore seems more probable (Fig. 10). Work is in progress on the geochemistry of volcanic rocks from Sabah at London University (K. Chiang, personal communication, 1999).

There are few plutonic rocks with the exception of the Mt Kinabalu granitic body (Vogt and Flower, 1989). This complex is dated by cooling ages of about 10 Ma, and fission track data indicate removal of 4–8 km of crust above the pluton since its intrusion (Swauger et al., 1995; Hutchison et al., 2000). The pluton cuts through the Paleogene accretionary rocks and ophiolitic basement (Jacobsen, 1970).

6.5. Mélanges

The mélanges are mainly subduction-related, and include olistostromes, mud-rich diapirs, and tectonic mélanges. They probably represent different structural positions in the orogenic wedge like those of the Banda Arc, although Hutchison et al. (2000) suggest an origin due to extension associated with Sulu Sea opening. The age of mélange formation is not completely clear. According to Clennell (1991) mélanges are predominantly lower Miocene and older. They are overlain unconformably by uppermost lower Miocene shallow marine and deltaic sediments in some areas, and some of the mélanges can be traced laterally into broken formations and undisturbed equivalents of lower Miocene and greater age (A. Balaguru, personal communication, 2000), suggesting an episode of mélange formation in the earliest Miocene. Younger Neogene tectonism and near-surface movements of partly overpressured sedimentary sequences have probably enhanced the character of older mélanges and produced some Neogene to Recent diapiric mélanges.

6.6. Palaeomagnetic data

Palaeomagnetic evidence has been used to suggest a large scale counter-clockwise rotation of Borneo and is summarised by Fuller et al. (1991, 1999). This has been disputed, and remains controversial because of the difficulty of rotating some parts of Sundaland but not other parts. Counter-clockwise rotation of Borneo is supported by palaeomagnetic data and other regional geological arguments (Hall, 1996), and explains why the long-lived accretionary margin of North Borneo dies out to the west in Sarawak. The rotation is also consistent with the tomographic images of a subducted slab interpreted as the proto-South China Sea by Curtis et al. (1998), which disappears to the west.

6.7. Deformation associated with collision

The unconformity in south Sabah indicates accretionary deformation until the early Miocene and terminal uplift of the accretionary complex at that time. Further north, accretion of the Crocker sequence continued into the middle Miocene. Throughout northern Sabah vergence is generally to the NW (Tongkul, 1991). On land the suture zone is overlain by Neogene deltaic and shallow marine sediments of the Baram and Sandakan basins, and in south Sabah these sediments are probably of latest early Miocene age (A. Balaguru, personal communication, 2000). Just south of Sabah possible eastward thrusting in Makassar Strait is seen on seismic lines in the Tarakan region, suggesting late Neogene thrusting some of which may be strike–slip related. There has been some dispute concerning interpretation of thrust structures associated with the NW Borneo Trough, which is interpreted by Hinz et al. (1989) as indicating regional compression and thrusting continuing up to the present day. In contrast, Hazebroek and Tan (1993) draw attention to the similarities of structures in their ‘Outboard Belt’ with thrusts at the toe of the Niger Delta, and argue that the young thrust sheet identified by Hinz et al. (1989) is the result of gravity sliding associated with uplift of the Crocker fold and thrust belt. The early Miocene suture must be landward of the NW Borneo Trough and underlie the Mio-Pliocene sediments of the Baram Delta and its along-strike equivalents.

Strike–slip faulting may have been important in modifying the form of collision-related structures and has contributed to the enigmatic circular ‘basins’ of Sabah. These circular forms have been described as basins, but seem more likely to be remnants of a more extensive thick overpressured sedimentary sequences deposited in a single basin during the early Neogene and deformed in the late Neogene (A. Balaguru, personal communication, 1999).

6.8. Conclusions

The Borneo Suture is still poorly known, although destruction of extensive areas of rainforest for oil palm plantations, active logging, and road building has improved accessibility and geological knowledge. Our understanding of the geological history of the region is handicapped by the monotonous character of many of the sedimentary rocks and difficulties in dating them. Volcanic rocks are not abundant, and the age and chemistry of the rocks that are known have not yet been studied. These problems are being gradually overcome. Despite some obvious similarities to other accretionary complexes such as the Franciscan, the lack of an obvious Paleogene volcanic arc, and the focus of most research on the younger hydrocarbon-rich basins have diverted attention from the active margin history of north Borneo. The insignificance of the Paleogene volcanic arc may be related to the obliquity and the slow rate of subduction near the termination of the subduction zone to the (present) SW. This probably resulted from the geometry of the closing proto-South China Sea implied by the counter-clockwise rotation of Borneo about a pole close to west Borneo (Hall, 1996). The late Miocene-Quaternary Semporna-Dent volcanics seem likely to have resulted from a subduction reversal, with Celebes Sea lithosphere being subducted to the NW. This subduction system must also have died out to the SW, probably in a zone of strike–slip faulting in the Tarakan region.

7. Discussion

Eastern Indonesia includes the junction between the Eurasian, Australian and Philippine Sea plates with a complex of smaller plates moving within a wide active margin. The sutures of eastern Indonesia illustrate the complexities that can develop during the early stages of collision. In each suture the earliest signs of collision are within the last 25 Ma, yet none fit easily into a simple and conventional model. They are insufficiently deeply eroded to reveal some of the features commonly associated with sutures (plutons, blueschists, etc.). Attempting to describe sutures in a systematic way shows that each is different and that models for sutures are too simple when detailed time resolution is possible and when sutures are young.

In each case, plate boundaries are difficult to locate precisely. The most easily located is the Australian–Philippine Sea plate boundary at the Sorong Suture: a suture along which there is predominantly strike–slip movement. There is a clear boundary between continental rocks and arc/ophiolitic rocks. However, future deformation, during continued convergence with the Eurasian margin, could give this suture zone an appearance of a relatively simple arc–continent collision suture, which it is not. The long history of strike–slip movements also means that the age of the suture will be far from clear.

The Banda Arc illustrates the necessity of defining a suture with respect to time. The location of the plate boundary appears to have shifted several times in less than 5 Ma, not just in its surface trace, but at lithospheric scale. It is interesting to note that in the regions of the most rapid relative plate motions, the plate boundaries are not clear, are often disconnected segments and deformation is distributed over wide regions. This in part reflects the rapid changes in their positions. In the Molucca Sea the suture is within the melange wedge north of Halmahera, and perhaps at the Halmahera Trough further south. In Sulawesi, the location of the major suture is very uncertain although sutures between minor fragments can be located with less difficulty. In Sabah the suture is not seen.

One reason for the difficulty in defining plate boundaries is that the tectonic situation is changing, and has changed, very rapidly. In the Banda and Borneo sutures subduction reversal followed quickly after initial collision between continents, and it seems probable that the same happened in Sulawesi in the Miocene. In the Molucca Suture one arc is currently being over-ridden by the other and will be completely eliminated within a few million years from now. Ultimately the Halmahera Arc is doomed to disappear. In less than five million years from today the evidence for the collision of two Molucca Sea arcs will be very difficult to find, and the geology of the region will most likely be interpreted in terms of a single arc. This is a very important conclusion for tectonic models and reconstructions. It is likely that other arcs have disappeared in a similar way during arc–arc and arc–continent collisions and most evidence for their previous existence disappears with them. The Neogene Halmahera Arc is no older than 15 Ma, therefore an arc will have been created and entirely eliminated within 20 Ma, an interval of time that might be very difficult to resolve in a Palaeozoic or older orogenic belt.

The rapid change in polarity of the collision system indicates the probable difficulty of determining polarity in older orogenic belts. The absence of the Halmahera Arc in a few million years would mean that at least one internal ocean and subduction zone would probably be overlooked in the reconstruction of this collision belt. The same is true in Sabah, where the subduction polarity in the Sulu-Dent-Semporna arc is very uncertain despite volcanism continuing until the last few thousand years.

One of the most interesting aspects of most of the sutures, and certainly the Australia–Eurasia collision zone as a whole, is the fact that within an overall contractional setting there was also significant extension. In the Banda region this led to formation of the Banda Sea, in Sulawesi, possibly to the formation of Bone Gulf and to high-K magmatism, and in Borneo to the Sulu Sea opening and rapid subsidence of the region behind the rising Crocker fold and thrust belt. The possibility of extension in a long-lived convergent setting is often overlooked, and may account for some of the problems with attempts to explain events in eastern Indonesia using conventional models. For example, the 'sub-ophiolite' metamorphic rocks, 'obduction' ages, and cordierite-bearing magmatic rocks may be better interpreted as the products of rapid extension rather than contraction (cf. Sopaheluwakan 1990; Linthout et al., 1996, 1997; Honthaas et al., 1999).

Within the overall contractional setting, transmission of stresses through rigid lithosphere (e.g. Makassar Strait, Banda Sea) with deformation localised at the edges is required. This emphasises the great differences in behaviour between oceanic and arc/continental regions. In the former deformation is localised and in the latter it is distributed. These differences cause obvious difficulties for attempts to describe the region in terms of rigid plates. Plate tectonic models are a useful first-order approximation and an essential discipline in making regional reconstructions, but can never fully describe the deformation of the region.

The rapid changes in sites of active deformation and ultimately plate boundaries emphasises the need to identify the ages of structures, especially faults, on tectonic maps. Generally mapping of faults does not show clearly which are active at which stages. The difficulty of doing this in young active orogenic regions suggests it is likely to be impossible in older orogens. One of the advantages of studying older orogenic belts is that it is clearer when the orogenic event finished; it is far from clear what is meant by 'syn' and 'post' in situations where deformation continues.

Interestingly, the zone of Australia–Eurasia collision corresponds quite closely to the region of Wallacea, which is a biogeographic region of transition situated between areas with entirely Asiatic and Australian floras and faunas and characterised by unusual biotas with both Asiatic and Australian elements but with high degrees of endemism. On this basis, palaeontologists many million years in the future will undoubtedly recognise the Australia–Eurasia suture as one of global significance. Most other geologists will also probably recognise the suture but probably not recognise the many parts of the sequence of events, multiple minor sutures, missing volcanic arcs and subduction polarity reversals within the few tens of million years between initiation and termination of continent–continent collision.

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