

## Allochthonous Terranes of the Southwest Pacific and Indonesia [and Discussion]

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## Allochthonous terranes of the Southwest Pacific and Indonesia

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Rift–drift processes associated with the Mesozoic break-up of Gondwana and subsequent collisional events involving rifted crustal blocks from Gondwana in Tethys led to the formation and emplacement of allochthonous terranes in fold and thrust mountain belts. These terranes include small allochthonous continental blocks (*ca.* 1000 km<sup>2</sup>) and allochthonous exotic blocks that may exceed 200 km<sup>2</sup>. Other processes consequent upon the break-up of Gondwana and subsequent plate convergence between Gondwana and Asia include the emplacement of supra-subduction zone ophiolites as allochthonous terranes superimposed on the continental margin. The accretion of oceanic plateaus to continental and arc terranes in the Western Pacific have resulted from trenches and strike–slip faults being deflected by crustal heterogeneities. Indonesian and Western Pacific regions display allochthonous terranes forming and being emplaced at rates similar to plate movements. Many allochthonous terranes of the SW Pacific and eastern Indonesia have been accreted during the past 3 Ma and, being so young, have not suffered overprinting by later tectonic and thermal events. Furthermore, we can trace some of the very young nappes into their roots and trace some accretionary processes into zones where, at present plate convergence rates, the collision and hence accretion will not occur for about another 1 Ma. These active regions reveal the importance of local events affecting less than about 1000 km of plate boundary over a period of 1–2 Ma.

## INTRODUCTION

In their world-wide review of allochthonous terranes and their role in the evolution of fold and thrust mountain belts Nur & Ben-Avraham (1982) identified oceanic plateaus in all the main oceans, and continental fragments, mainly in and around the Pacific and Indian oceans, as likely candidates for conversion into allochthonous terranes. Coney *et al.* (1980) identified three main crustal types of allochthonous terranes already emplaced in the cordillera of western North America: oceanic, oceanic volcanic arc, and parts of distal continental edges. Some parts of the Wrangellia terrane may have been oceanic plateaus and Cache Creek terrane may include carbonate atolls built on seamounts. Coney *et al.* (1980) pointed out that some existing allochthonous terranes revealed clear indications of having undergone tectonic amalgamation before emplacement and accretion to the North American cordillera. This is also apparent among the SE Asian terranes. However, one notable feature of the terranes accreted to the NE Australian margin is that many of them show strong continental margin affinities in contrast to the dominantly oceanic origin of the Western Cordillera terranes.

The SW Pacific and Indonesian margins of Australia (figure 1) have undergone phases of major continental rifting with both large-scale (10<sup>3</sup> km) and much smaller-scale (10<sup>2</sup> km)

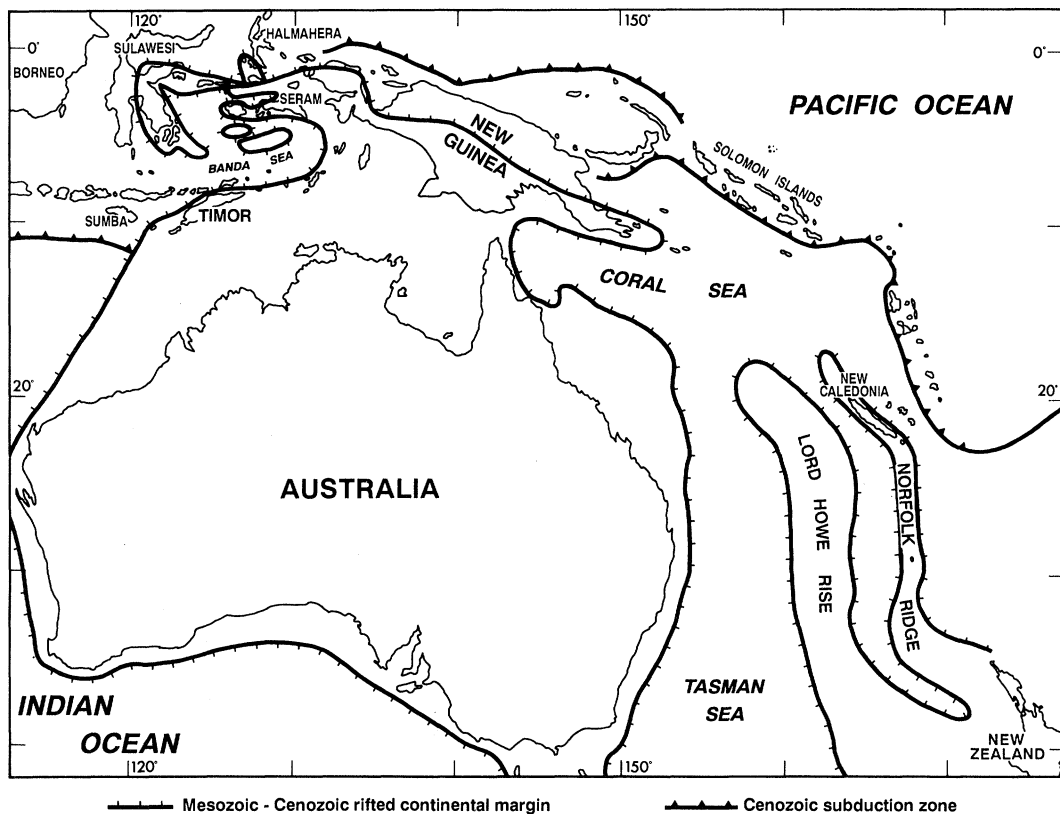


FIGURE 1. Eastern and northern margins of Australia showing the Mesozoic–Cenozoic rifted continental margins of Australian Gondwana. Note the continental blocks removed by Tasman Sea spreading. Note the post-rifting collisions with allochthonous terrane emplacement in eastern Indonesia, New Guinea and New Caledonia shown in figures 2 and 3.

spreading during the late Mesozoic and early Cenozoic (Falvey & Mutter 1981). The SW Pacific region has been characterized during the late Cretaceous and Cenozoic by plate convergence associated with subduction and volcanism. These destructive plate margin processes have influenced the northern Australian margin only since the end of the Palaeogene, related to Australia's 3000 km northward drift. The eastern and northern margins of Australia–New Guinea (figures 2 and 3) provide examples of the active processes of allochthonous terrane formation of all the three main crustal types identified by Coney *et al.* (1980) from the cordillera of western North America. It is possible to recognize all three types for example in the 3 Ma old fold and thrust belt of the Outer Banda Arc and similar allochthonous terranes have been reported from elsewhere along the collisional boundaries of Tethys. There are other types of allochthonous terrane in eastern Indonesia such as the exotic block terranes of Permo–Triassic shallow marine limestones (Maubisse facies) and nappes of volcanic arc accreted to continental crust (Sumba–Palelo arc); both are described below.

#### LARGE CONTINENTAL ALLOCHTHONOUS TERRANES

By repeated rifting the eastern part of the supercontinent Gondwana broke up into large continental-sized blocks such as India, Australia and Indochina and relatively thin, long and narrow continental slivers such as Sibumasu, which includes parts of South Tibet, Burma,

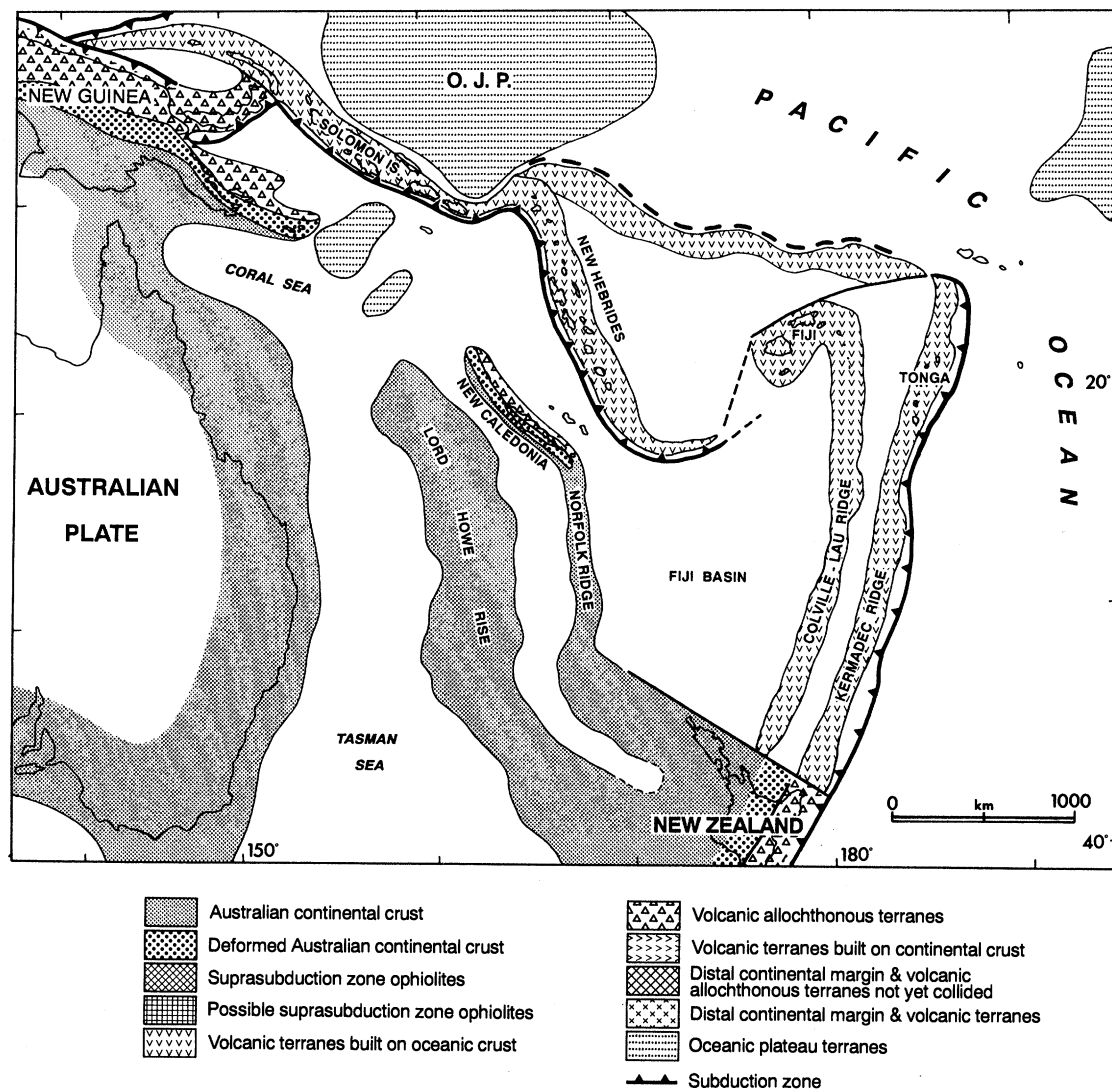


FIGURE 2. Tectonic accretion of allochthonous terranes to rifted continental margins of eastern Australia and New Guinea.

western Thailand, Malay Peninsula and Sumatra (Metcalf 1988), as well as other long, narrow slivers (figure 1) but with thinner continental crust (Shor *et al.* 1971) represented by the Lord Howe Rise, the New Caledonia–Norfolk Ridge (Kronke 1984), both of which are largely submarine. All these rifted continental blocks and slivers have surface dimensions measuring thousands of kilometres long and several hundreds of kilometres wide. These allochthonous terranes are comparable in size with some Canadian and Alaskan ‘cordilleran suspect terranes’ of western North America (Coney *et al.* 1980; Nur & Ben-Avraham, 1982). The processes of formation and subsequent accretion of some of these larger Gondwana continental blocks and slivers into the continental collage of Asia (Metcalf 1988; Audley-Charles *et al.* 1988) provide analogies with the detachment of much smaller continental blocks and slivers having surface dimensions measured in tens of kilometres (figure 4), which were accreted during the late Cenozoic into the evolving fold and thrust belts at colliding continental margins in eastern Indonesia.

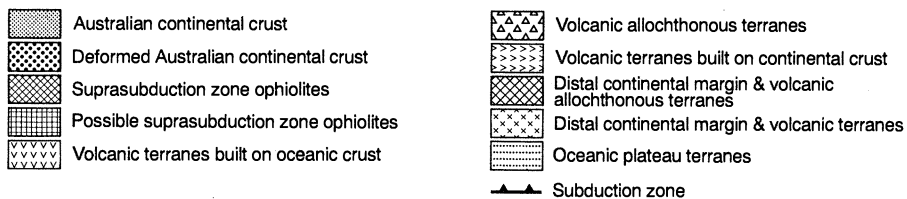
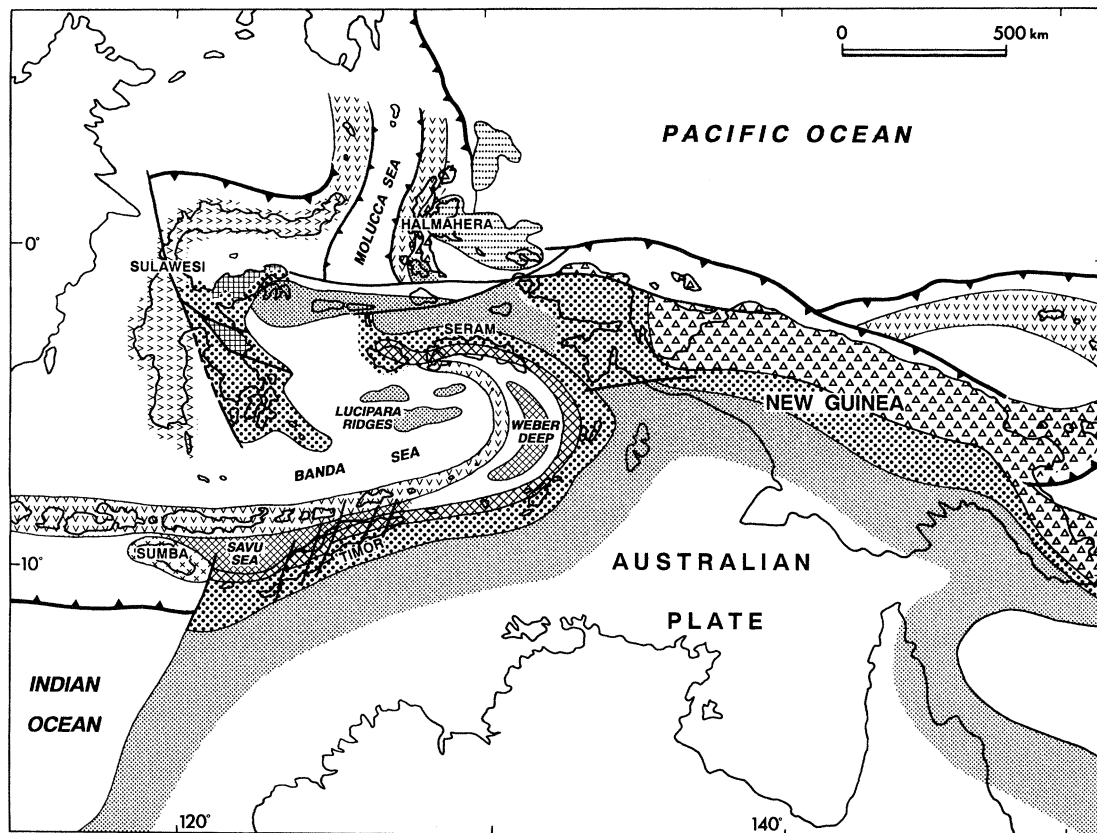


FIGURE 3. Tectonic accretion of allochthonous terranes to rifted continental margins of northeast Australia, and oceanic plateau-arc collisions.

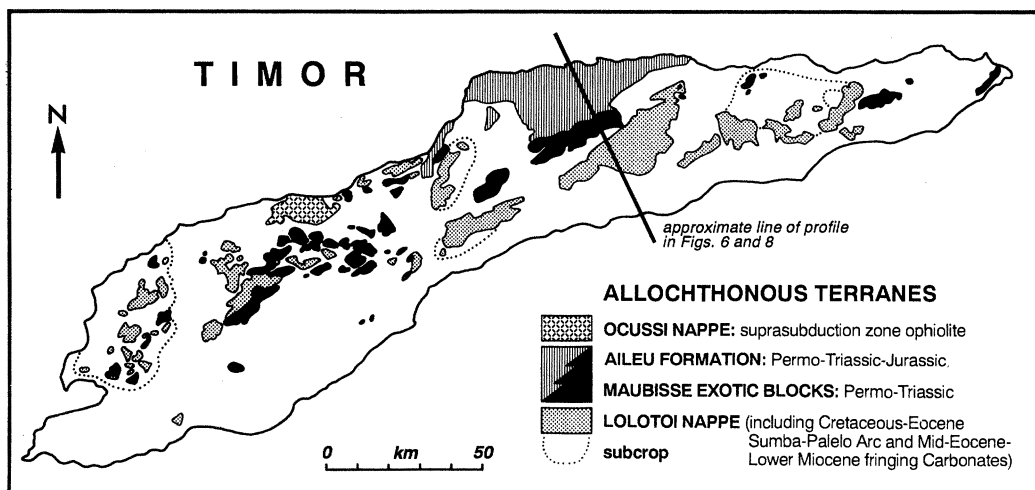


FIGURE 4. Allochthonous terranes in Timor.

## SMALL CONTINENTAL ALLOCHTHONOUS TERRANES

The Outer Banda Arc fold and thrust belt (figure 2) is composed of two main elements: the deformed margin of the Australian continent and an overriding series of allochthonous nappes (Price & Audley-Charles 1987). Within this mountain belt in Timor the lowest nappes (figure 4) have a metamorphic basement about 2 km thick overlain by a Cretaceous–Eocene volcanic and sedimentary cover about 1–2 km thick, overlain unconformably mainly by shallow marine limestones ranging from middle Eocene to early Miocene. Harris (1989) has shown that the sedimentary and volcanoclastic Lower Cretaceous Palelo sequence grades down into the monometamorphic sequence of greenschists to amphibolites forming the upper part of the Lolotoi, below which are the polyphase gneisses (Earle 1981). Locally, serpentinite and tectonized peridotite form the top of the Lolotoi Complex. In Seram, the other large island of the Outer Banda Arc, similar nappes occur having a metamorphic basement of Kaibobo and Kobipoto Complex (Audley-Charles *et al.* 1979).

The allochthonous elements form a forearc basement that is found thrust over the deformed Australian continental margin sequence in Timor (Price & Audley-Charles 1987; Harris, 1989) composed of Permian to early Pliocene cover rocks. These allochthonous volcanic and volcanoclastic rocks may be traced, via a forearc submarine ridge from northwest Timor westwards, into Sumba where these rocks are now exposed as part of the forearc basement of the Banda volcanic arc. New exposures of the overthrust contact in Timor have been revealed in a road cutting through the Lolotoi nappe north of the village of Same. Audley-Charles (1985) demonstrated a close correlation of the Cretaceous to early Miocene deposits of the island of Sumba (figure 4) with the cover rock sequence of the Lolotoi in Timor (and by implication in Seram).

This led Harris (1989) to postulate that the forearc basement of the present Banda volcanic arc was formerly part of a Sumba–Palelo Arc, in which the late Cretaceous–Eocene volcanic forearc deposits accreted to the Lolotoi Complex metamorphic basement (figures 5 and 6). Both Hall (1988) and Harris (1989), noting the mineralogical evidence (Brown & Earle 1983) for rapid uplift of the Lolotoi, which is characterized by (HT/LP) metamorphism, have suggested that the high-temperature metamorphism of the Lolotoi Complex can be most easily explained by the thermal events of the late Jurassic–early Cretaceous rifting and spreading at the Australian continental margin. This is supported by the early Cretaceous isochron age for the polyphase gneiss (data reviewed by Harris (1989)). Thus the Lolotoi allochthonous terrane is viewed as having originated as a narrow sliver from the distal continental margin of Australian Gondwana rifted and separated by Tethyan spreading in the late Jurassic–early Cretaceous (figure 6). The K–Ar cooling ages from the Lolotoi suggested that the Lolotoi was accreted to the Sumba–Palelo volcanic arc in the late Oligocene, followed by the uplift associated with deposition of the unconformably overlying Oligo–Miocene Cablac Limestone.

Later this Lolotoi terrane, as part of the Banda allochthon, was thrust over the Australian continental margin of Australia in Timor, Seram and some smaller islands during the latest Miocene (Carter *et al.* 1976) to the present as the collision progressively involves the NW Australian continental margin. The nappe emplacement was a consequence of the collision between the Australian margin and the Banda volcanic arc (figure 7) which, from 20 Ma to the present, has been built on the backarc of the defunct Sumba–Palelo arc (Harris 1989). These Lolotoi terranes (figures 4 and 8) are composed of small fragments (having surface

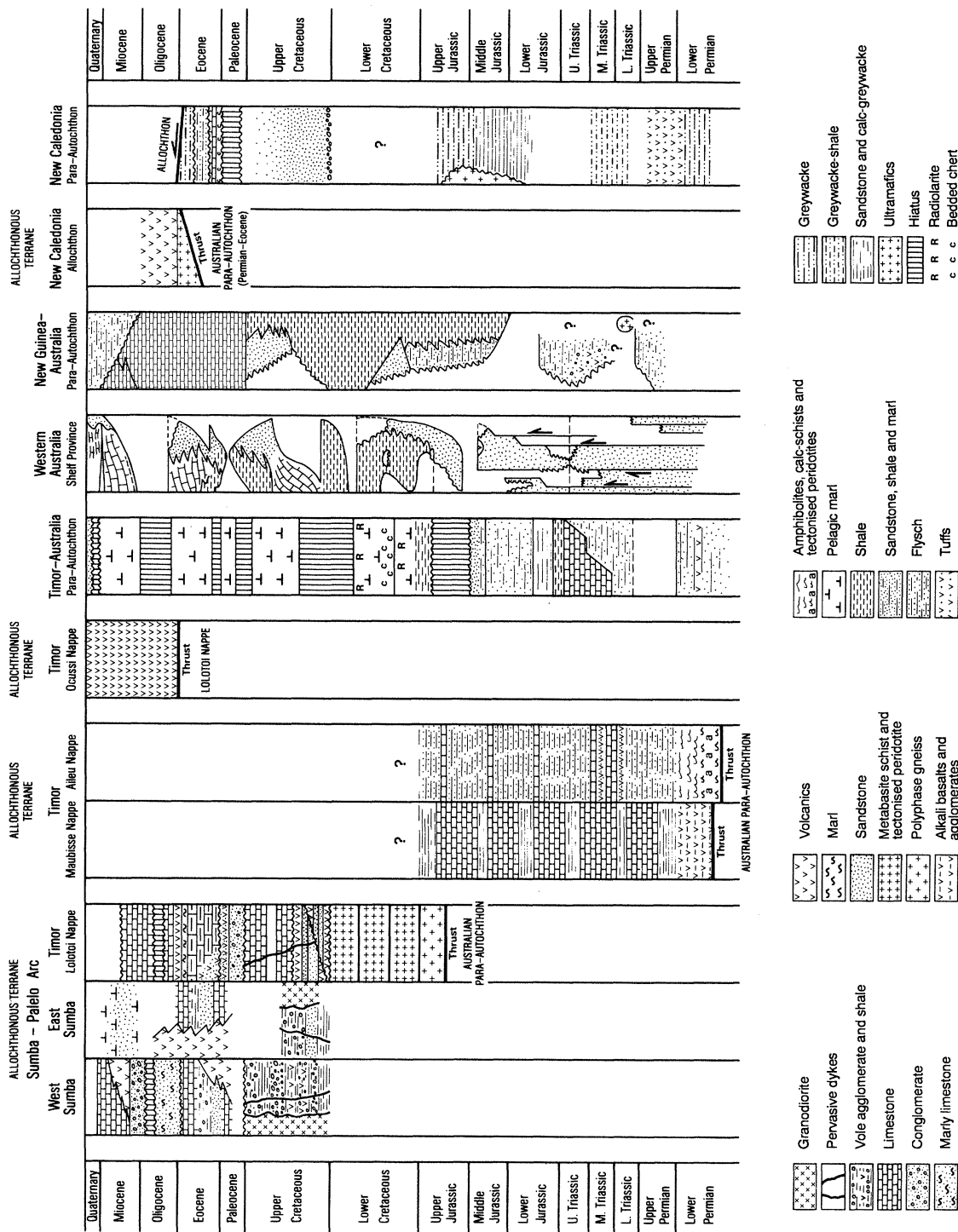


FIGURE 5. Stratigraphic summary of allochthonous terranes in the Timor and New Caledonia, comparison with Sumba and contrasts with the Australian para-autochthon in Timor, Australian Shelf, New Guinea and New Caledonia. Data summarized as follows: Sumba from Audley-Charles (1985); Timor from Audley-Charles (1978, 1985, 1988); Western Australia and New Guinea from Falvey & Mutter (1981), New Caledonia from Guillon (1974).

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577

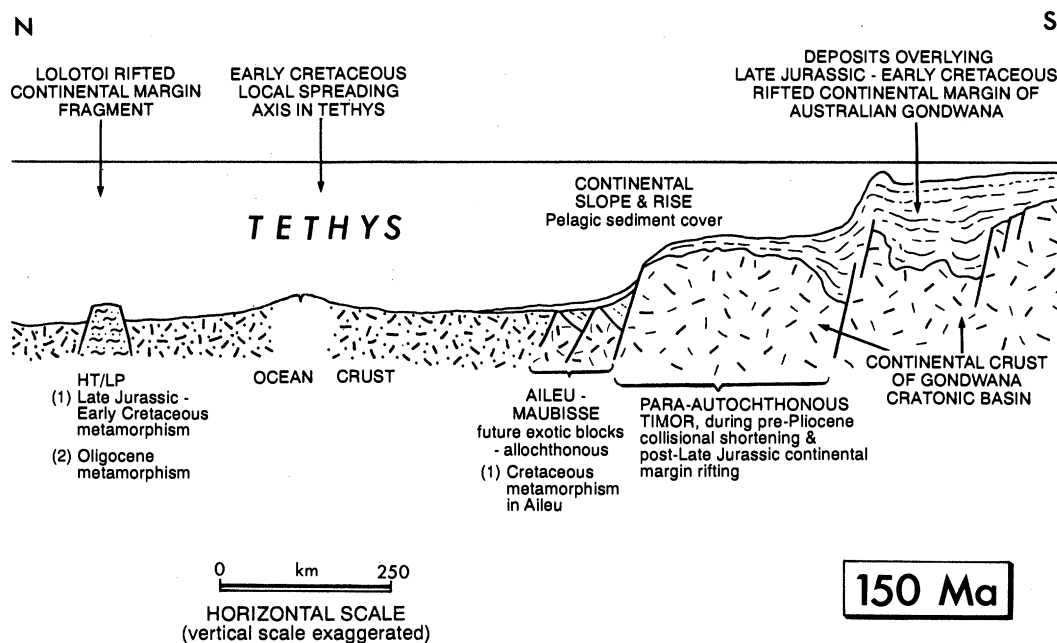


FIGURE 6. Schematic representation of the formation of the Lolotoi and Aileu–Maubisse allochthonous terranes at the Australian continental margin. The Sumba–Palelo volcanic arc was built on the Lolotoi continental fragment during the Cretaceous–Eocene after it had separated from the Gondwana continental margin. See figure 4 for the approximate position of this profile.

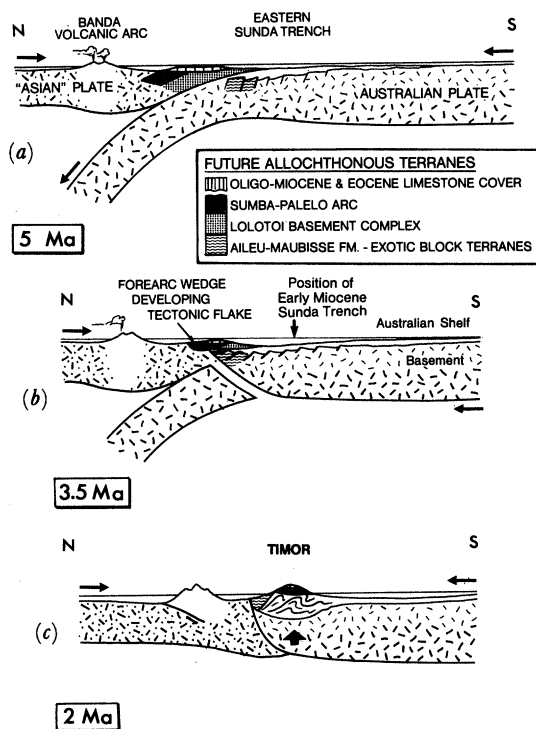


FIGURE 7 *a, b, c*. Schematic representation (after Price & Audley-Charles 1987) of accretion of allochthonous terranes to the Australian margin in the Banda Arc.



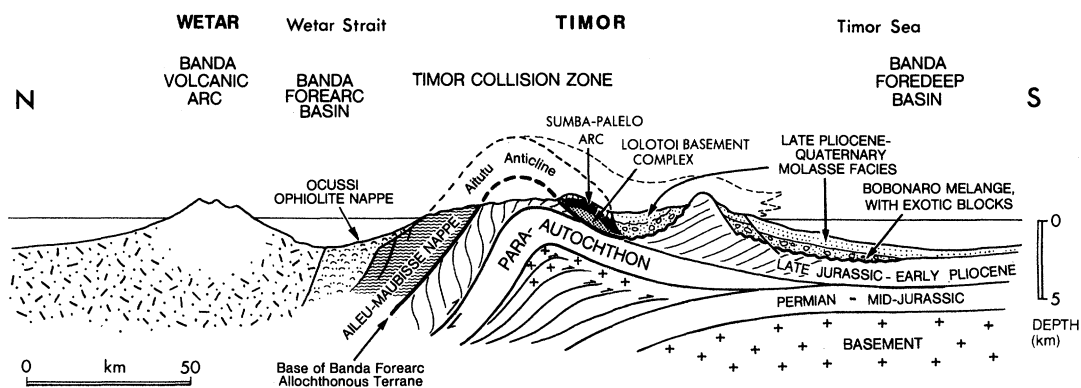


FIGURE 8. Section through Timor and collided Banda volcanic arc to show present position of accreted allochthonous terranes (after Harris 1989). See figure 4 for the position of this profile.

dimensions of a few tens of kilometres by a few hundreds of kilometres of the Gondwana continental margin on which has been preserved part of the Cretaceous–Palaeogene volcanic forearc and later fringing shallow marine limestones. These terranes have been much attenuated by numerous low-angle normal faults (Harris 1989) and also much broken by steep normal faults during the Quaternary.

Similar collisional phenomena have been reported from New Guinea by Pigram & Davies (1988) who have identified more than 10 small continental allochthonous terranes accreted to the Australian margin during the Oligo–Miocene.

#### EXOTIC BLOCKS ALLOCHTHONOUS TERRANES

One of the features of the Tethyan mountain belt is the presence of exotic blocks. One of the most characteristic type of blocks is the highly fossiliferous Permo–Triassic shallow marine limestones associated with pillow lavas, for example in the Himalayas (Marcoux *et al.* 1982; Searle 1983) and Oman (Glenie *et al.* 1974; Searle & Graham, 1982). These blocks are exotic in being allochthonous, in having no known roots and no easily detectable provenance, although Lippard *et al.* (1986) have proposed seamount carbonate cappings for the Oman occurrences. In the Banda Arc these exotic blocks are closely associated with the Bobonaro coloured scaly clay melange in which they appear to be engulfed, and with which they seem to have been emplaced above the Australian continental margin deposits (Audley-Charles 1986). The exotic blocks in Timor (e.g. Mt Lacouse and Mt Legumau) have surface dimensions that in some cases exceed 200 km<sup>2</sup> (figure 4).

In the Tethyan fold belt, and certainly in the Banda Arc these exotic blocks surrounded by coloured scaly clay melange occupy the highest structural position of the allochthonous elements. In the Banda Arc the most common exotic blocks belong to the Maubisse Formation that accumulated in an Australian Gondwana cratonic basin during the Permo–Trias (Bird 1987; Audley-Charles 1988). The mechanism by which they became detached from the Gondwana margin is uncertain, but it must have been a very widespread phenomenon of the Gondwana–Tethyan margin associated with the last episode of continental rifting because the exotic blocks were preserved near the foot of the continental slope. From there they were

carried back by the tectonic collision over the Gondwana margin in a melange along much of its length from the Mediterranean orogens via Oman and Himalayas to Timor and Seram. We suggest they became detached from the Gondwana continental margin, either by large-scale oceanwards slumping by processes analogous to the oceanward displacement of large slump blocks along parts of the Atlantic margins (Dingle 1977), or by the rifting leaving them as the most distal parts of the continental margin.

In the Banda Arc these Permo–Triassic limestone blocks associated with shales and vesicular alkaline basalts (Maubisse facies) appear to have formed the most distal part of the newly rifted continental slope during the late Jurassic–early Cretaceous. Here they were engulfed by deep-sea pelagic sediments of the slope and rise during the late Mesozoic and much of the Cenozoic. Locally, the stratigraphical passage from these shallow marine limestones into a flysch facies (Aileu Formation) of probably Permian to Jurassic age (Brunnschweiler 1978; Barber *et al.* 1977) has been preserved in central Timor. Amphibolites in this Aileu Formation indicate an Ar–Ar metamorphic event more than 70 Ma ago (Berry & McDougall 1986). This would correspond with the continental rifting thermal event comparable with that in the Lolotoi described above. In late Miocene–early Pliocene times the Australian continental margin collided with the Banda volcanic forearc. Parts of these rifted blocks together with part of the engulfing Mesozoic–Cenozoic pelagic sediment (Margolis *et al.* 1978), lying at the foot of the Australian continental rise, were carried over the lowest nappes by the converging Asian volcanic arc forearc ramping up onto the contracting Australian continental slope and rise.

#### SSZ OPHIOLITE ALLOCHTHONOUS TERRANES

Another kind of allochthonous terrane process that characterizes the closure of Tethys and which has been active in the SW Pacific and Indonesia during the last 3 Ma is the emplacement of the suprasubduction zone ophiolites. In eastern Indonesia it is possible to trace the Ocussi ophiolite nappe, now being thrust over the passive continental margin in northern Timor, back into its root zone in the Wetar Strait which is the forearc basin of the Banda volcanic arc. This Banda forearc basin is related to the eastern Sunda Trench with which the Australian continental margin collided at 3 Ma. One effect of this collision was the forearc ramping up and over (figure 7*a, b*) the converging continental margin thus closing the trench along the collision suture (Price & Audley-Charles 1987).

Harris (1989) has shown that the clinopyroxene–phyric basalts and andesite-basalts of the Ocussi nappe and the samples dredged from the floor of the Wetar Strait are part of a low-K tholeiite series having trace element affinities with island arc tholeiites. He argued from their geochemical signature and from palaeogeographical considerations that they were most likely formed as new spreading crust in the upper plate adjacent to irregularities in the shape of the lower plate in the collision zone. Transtensional forces associated with the regions sandwiched between the collisional indenters of Seram and east Timor led to the formation of small rhombochasmic basins (Savu and Weber basins), which are now in the process of tectonic emplacement. The Ocussi nappe is the initial manifestation of the emplacement process of the Savu basin as an allochthonous terrane, which is still in contact with its roots in the forearc basin. The formation and predicted emplacement of these basins is most likely a function of continentward trench retreat into embayed regions of the lower plate where young, thin parts

of the forearc ramp up over the passive continental margin (figure 7). Although little is known about the crustal structure and age of these basins the data available (Harris 1989) suggests they are synorogenic and may represent some of the only modern analogues of Tethyan-type ophiolites.

#### ROLE OF STRIKE-SLIP FAULTS IN TERRANE FORMATION

Observations in the SW Pacific and Indonesian region suggests that there are at least two main types of strike-slip generated terrane. Plate boundary strike-slip faulting associated with oblique plate convergence has been suggested (Hamilton 1979) as a mechanism by which slivers of lithosphere become detached and are transported along the obliquely converging plate boundary. The Sorong Fault Zone appears to have removed crustal (or lithospheric) blocks from the northwest margin of New Guinea and to have transported them westwards (Visser & Hermes 1962). The evidence for identifying these terranes has been comparable stratigraphic sequences and characteristic magmatic products. Very little palaeomagnetic data exists against which to test some of these palaeogeographic interpretations (Haile & Briden 1984; Metcalfe 1988). Examples of terranes thought to have been removed from New Guinea in this way include Banggai-Sula (Klompe 1954), eastern Sulawesi and Buton (Audley-Charles *et al.* 1972; Audley-Charles 1988), Obi (Silver & Smith 1983) and Bacan (Hall & Nichols 1990).

Another type of strike-slip fault mechanism influencing terrane distribution has been suggested by Charlton (1988) whereby faults cutting obliquely across the converging active plate margin off-set and so separate the converging allochthons. He applied this model to the southern Banda Arc collision zone, particularly in the Timor region.

#### ACCRETION OF OCEANIC PLATEAUS

One of the discoveries made by the early analyses of allochthonous terranes in the western Cordillera of North America was the relative importance of what appear to be remnants of oceanic plateaus. Studies in the Western Pacific (Hall & Nichols 1990) have revealed the ways in which the thickened crust of these oceanic plateaus can deflect the path of propagating trenches and strike-slip faults and lead to the relatively passive accretion of oceanic plateaus at evolving plate boundaries. Hall & Nichols (1990) have argued that East Mindanao, the Snellius Ridge and the East Halmahera-Waigeo terrane are oceanic plateaus at different stages of amalgamation into the Philippine margin. The complex amalgamation experienced by these terranes before their eventual accretion to the Asian or Gondwana continental margin affords comparison with some of the complex oceanic terranes described from the western Cordillera of North America (Coney *et al.* 1980).

The Ontong Java Plateau is one of the largest oceanic plateaus. It is now impinging on the eastern boundary of the Solomon island arc. It has been suggested (Hughes & Turner 1977) that the difficulty in subducting such a thick slab led to subduction polarity reversal below the Solomon arc in the Tertiary. Following the discoveries of Hall & Nichols (1990) in the Halmahera region (figure 9) continuing plate convergence between Ontong Java and the Solomons seems likely to lead to the development of a new active plate margin on the Pacific side of this huge oceanic plateau with the relatively passive accretion of the Ontong Java Plateau to the Arc. Pigram & Davies (1988) have identified many oceanic allochthonous

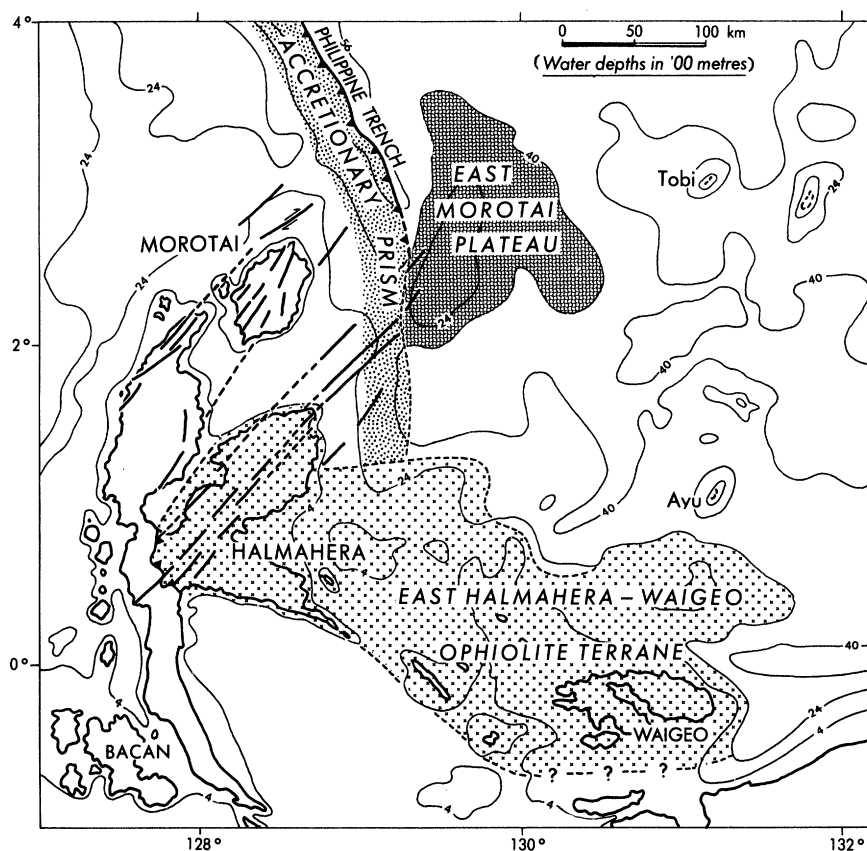


FIGURE 9. Accretion of allochthonous oceanic terranes to arcs in the Halmahera region (from Hall & Nichols 1990).

terranes derived from seamounts and oceanic plateaus that were accreted to New Guinea in the Oligo-Miocene.

#### RATES OF ALLOCHTHONOUS TERRANE EMPLACEMENT

Many Mesozoic-Palaeozoic fold and thrust mountain belts display indications of orogenesis involving the emplacement and movement of allochthonous terranes associated with collision and strike-slip deformation of the continental margin extending over several  $10^7$  years. Studies of these processes in the SW Pacific and Indonesia reveal that collisional orogens involving the evolution of allochthonous nappes moving *ca.* 50 km over deforming passive continental margins at *ca.* 8 cm  $a^{-1}$  can be created in less than 3 Ma. Furthermore, active plate margin reversal can occur within 2 Ma (Price & Audley-Charles 1987).

#### IMPORTANCE OF LOCAL TECTONIC EVENTS

One of the processes of active arc-trench systems of the Western Pacific and Indonesia is the relative importance of the local collisional event affecting less than 1000 km of plate boundary over a period of 1–2 Ma. Selected examples include New Caledonia, D'Entrecasteau and Louisville ridges, and the Timor, Seram and East Sulawesi sectors of the Banda Arc. This suggests that the regional scale of collision may be less extensive in some Mesozoic-Palaeozoic

ogens than is generally supposed. There are indications from the western Pacific, Philippines and Indonesia that one or several associated magmatic arcs generated in the Philippine Sea region may have been dispersed by intra-arc spreading and rotation (Haston *et al.* 1988; Lewis *et al.* 1982). Reconstruction of such palaeogeographical details after dispersed arcs have collided separately at different margins may be beyond resolution in ancient orogenic belts.

#### CONCLUSIONS

Allochthonous terranes can be observed in the SW Pacific, Philippine and eastern Indonesian regions in the process of formation. These active terranes closely resemble the main types described from the cordillera of western North America. However, an outstanding feature of the SW Pacific and Indonesian region is the high proportion of continental allochthonous terranes. This may be a consequence of the weakening of the continental lithosphere by repeated rifting of blocks and slivers from Gondwana. Study of these active regions suggests that the construction of a major accretionary cordilleran fold and thrust mountain system proceeds by many small local collisions (less than *ca.* 1000 km strike length). These active regions also indicate that the collision processes involving subduction zone reversal, or change in position of trench or major strike-slip fault related to terrane accretion can occur within 2 Ma. The apparent synchronicity and interpreted regional correlation of mountain building processes in ancient orogens is partly an artefact of the dating imprecision and partly the result of difficulties in resolving palaeogeographies from overprinted tectonic events in an eroded complex accretionary cordillera.

Janet Baker and Colin Stuart produced all the art work.

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#### Discussion

P. D. CLIFT (*Grant Institute, University of Edinburgh, U.K.*). The proposed model for the generation of ophiolites with a suprasubduction zone chemistry (ssz), in a back arc basin and

being emplaced on to the continental margin as the Australian plate comes in to collision with the Banda Arc contrasts markedly with many well-known ophiolites from the Tethyan and Caledonide realms. The Bay of Islands, Semail, Turkish and Greek ophiolites, although partly comprising mafic extrusives whose trace element geochemistry is of ssz type, are not apparently associated with well-developed arcs. Any arcs involved have either been destroyed by subduction (although density contrasts appear to prohibit this) or were never formed in the first place. These ophiolites appear to have been generated and soled shortly after the start of intra-oceanic subduction and were then subsequently emplaced (figure 10). It is important to note that in almost no instance does ophiolite emplacement accompany continental or arc collision events, often predating these by more than 100 Ma.

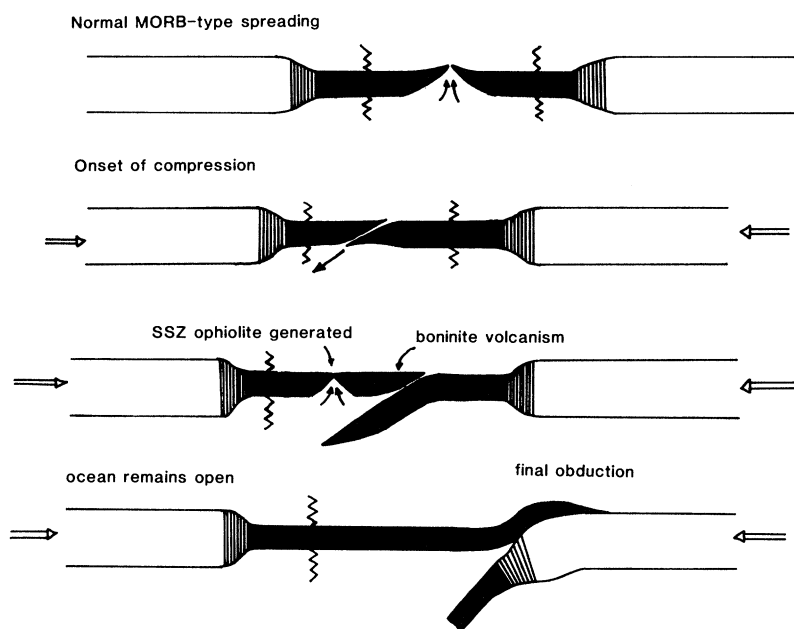


FIGURE 10

M. G. AUDLEY-CHARLES. Dr Clift's question raises two separate issues: (a) the specific matter of the origin and emplacement of the ssz ophiolites in northern Timor, and (b) the more general case of the origin and emplacement of Tethyan-type ophiolites

(a) *Origin and emplacement of Timor Tethyan-type ophiolites having ssz geochemistry*

The top of what we suspect is a large ophiolite appears in northern Timor as the Ocussi nappe (Carter *et al.* 1976). These clinopyroxene–phyric basalt and basaltic–andesite pillows, sheet flows and breccias are part of a low-K tholeiite series having trace element affinities with island arc tholeiites (Harris 1989). Ar–Ar dating suggests these rocks are Oligo–Miocene in age and their stratigraphic cover indicates they must be no younger than upper Miocene. These rocks appear to floor the Banda forearc basin of the Wetar Strait from where samples have been dredged, and they must extend offshore northern Timor to floor part of the Savu Sea Banda forearc basin. Harris (1989) has interpreted the Ocussi nappe as the initial manifestation of emplacement of the Savu forearc basin. This basin is thought to have formed by the retreat of

a subduction trench into embayments of an irregular shaped continental margin during collision. The uplift of the subducted continental margin emplaces what we interpret as the ssz ophiolite of the hanging wall forearc as a roof thrust (Price & Audley-Charles, 1983).

If a continental margin is old, as is usually the case with Tethyan-type ophiolites the attached oceanic slab, which has already been subducted, will define a steep Benioff zone as in the Banda Arc. Initial collision occurred between the Banda volcanic arc and promontories of the continental margin. The lower plate continues to subduct (roll back) in uncollided regions while the upper plate remains locked to the lower plate at the initial points of collision. This ssz spreading produces oceanic crust above the dehydrating lower plate. Water from the lower plate imparts an arc signature on the new lithosphere (Pearce 1982). The development by transpression and transtension of small rhombochasmic basins in the forearc collision zone is a similar mechanism which account for many of the features of Tethyan-type ophiolites.

(b) *General case of origin and emplacement of Tethyan-type ssz ophiolites*

This is a large issue that obviously cannot be comprehensively covered in a reply to discussion but Dr Clift has focused his question on the apparent lack of associated well-developed arcs with many such ophiolites. The key words here, we believe, are 'apparent lack' and 'well developed'; and later Dr Clift uses the expression 'in almost no instance', weasel words perhaps, how many examples are needed to demonstrate a mechanism can occur? The example of the Banda Arc reveals that even in very young (3 Ma) collision zones any allochthonous volcanic arc terranes may be much broken up by low-angle normal extension faults and steep-angle normal faults, maybe highly dissected and deeply eroded, so much so that all that remains exposed on Timor of the allochthonous Cretaceous–Eocene Sumba–Palelo Arc are several scattered plutons and slices of forearc.

However, some parts of the forearc of the associated volcanic arc in the collision zone have not been overthrust, but on the contrary have been overridden by the converging Australian continental margin. We can see in the region north of the southern part of the Banda Arc between Savu and Tanimbar islands, especially where the exposed Australian margin (Timor island) comes to within 20 km of the exposed Banda volcanic Arc (Atauru island), that part of the forearc having surface dimensions 750 km long by about 150 km wide has 'disappeared'. If the forearc can be overridden, why not the arc? There are only two explanations for the disappearance of this large slice of Banda forearc lithosphere during the last 3 Ma, either it has been overridden by the Australian continental margin as Price & Audley-Charles (1983, 1987) suggested, or it must have slipped laterally along the forearc by major strike-slip faults parallel to the arc. Partly because it has not been found anywhere at the surface Price & Audley-Charles (1983, 1987) proposed it had been underthrust southwards below northern Timor.

The problem with missing arcs associated with orogenic zones is a long-standing argument. Volcanic arc detritus is a common component of most synorogenic deposits in orogenic belts such as the Alps, Cordillera, Oman, and Brooks Range. Sedimentologists find the detritus and trust in heaven for the source. Palaeogeographers see evidence of trenches but very few arc terranes. The evidence suggests that arcs rarely come out of orogens the same way they went in, but their existence cannot be denied. Mitchell (1983) provided a thorough discussion of the problem of missing arcs, suggesting large-scale backthrusting as a mechanism. However, this mechanism alone is inadequate in that these overthrust or buried arc terranes should turn up somewhere in older, more deeply eroded terranes. In some old mountain belts remnants are



found, but if, in addition to overthrusting, the arcs are tectonically eroded by continued subduction or especially subduction polarity reversal, then it would be highly unlikely to find a trace of even 'well-developed' arc systems.

The best example of a vanished or 'Houdini' arc system is the northern Luzon volcanic arc in collision with Taiwan. In southern Taiwan, where arc-continent collision is beginning, the volcanic arc is separated from the fold-thrust belt by a narrow remnant forearc basin, comparable with the Wetar Strait of the Banda Arc. The forearc basin and Luzon volcanic arc remnants progressively narrow to the north where the oblique collision becomes progressively older. North of Haulien, where the collision is around 4–6 Ma (ancient) the polarity of subduction has reversed and no surface expression of the arc remains. The bathymetry of this region suggests most of the arc has been devoured by subduction jaws.

These same jaws are in the process of opening along the Wetar thrust, which represents one of the few places in the world where the critical dynamic relations associated with subduction initiation can be observed. The thrust most likely initiated in arc crust and therefore some of the Banda volcanic Arc has already disappeared (Price & Audley-Charles 1987). If this new subduction system develops, as did the Ryukyu trench in Taiwan, perhaps no trace of the Banda volcanic Arc will remain by the time SE Sulawesi and Timor collide. This throws doubt on Dr Clift's theoretical arguments about density contrasts prohibiting the subduction of arc crust.

Dr Clift suggests that ophiolites are generated and 'soled' after the initiation of intraoceanic subduction. Boudier & Coleman (1981) and more recently Boudier & Nicolas (1988) have championed the intra-oceanic subduction model, suggesting the thermal instabilities at a ridge are an ideal site for subduction initiation. The entire mid-Atlantic ridge and East Pacific rise argue against this suggestion. However, the most compelling evidence against the idea, and probably the reason why Coleman has subsequently abandoned it, is the composition of the ophiolite sole. The argument against this mechanism is simple; if an ophiolite was detached at a ridge or some other intra-oceanic setting its composition would be similar to that of its metamorphic sole (the rocks first accreted to the base of the hot slab). The fact is that metamorphic soles differ significantly from the ophiolite that underlie them. Some of the most compelling compositional differences involve the early incorporation of continental-type sediments into the sole with cooling ages that overlap with ages from the ophiolite and synorogenic sedimentation. The mafic igneous rocks at the base of most ophiolites differ petrologically and geochemically from the ophiolitic igneous sequences.

Most of Dr Clift's question deals with concepts addressed at length for years by geoscientists from various perspectives. The final sentence of his question conflicts with the results of the comparative study of ophiolite emplacements (Harris 1989), and those of several others as far back as Hess (1955), who inferred the close ties in time and space between ophiolite development and continental margin shortening. Searle & Stevens (1984), and others who have studied emplacement of ophiolites, such as Moores (1984) and Edelman (1988), all agree with Hess's inferences based on the mountain of radiometric geochemical and stratigraphical data now available from several detailed studies of Tethyan-type ophiolites. The relationships are clear in suggesting these ophiolites are synorogenic and kinematically linked to progressive contraction of old continental margins.

Dr Clift's figure of 100 Ma between ophiolite emplacement and a major collision event is almost two orders of magnitude greater than all the time elapsed so far during the Banda

Arc–Australian margin collision. During those 3 Ma nappes have moved 50 km over the Australian margin, the collision zone has been uplifted at least 5 km (more likely 6 km), and subduction direction in the Timor region appears to have reversed. We accept that during Dr Cliff's 100 Ma tectonic activity might have been intermittent. Nevertheless, experience of the 3 Ma old Banda Arc–continent collision zone teaches us that 1 Ma is a long time in collision tectonics and 3 Ma is such a long time that many large-scale events can be completed.

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