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TAIWAN AND TIMOR NEOTECTONICS: A COMPARATIVE REVIEW

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ABSTRACT

Both Taiwan and Timor represent fold-thrust mountain belts built by Pliocene-present convergence between a passive continental margin and a volcanic island arc, the intervening trench and forearc having been eliminated. Although the length, width and elevation of these collision zones is very similar, the rate of uplift has been and continues to be notably greater in Taiwan. Taiwan also has (1) a much thicker and younger deforming sedimentary wedge, (2) a remobilized complex of basement crystalline rocks exposed in the Central Range and (3) an unambiguous suture zone where seismicity is concentrated, none of which find equivalent expression in Timor. The two orogens are thought to represent similar amounts of crustal shortening (~ 200 kms), plate convergence rates (~ 70 km/Ma) and vectors.

The explanation for the notable differences in structural evolution can be sought in the proportion of stratigraphic section involved in the deformation, which may be a function of the different ways in which convergence is being absorbed in the collision zones. The collision zone in Timor is more diffuse than it is in Taiwan where most of the convergence occurs at the arc-continent interface (longitudinal valley). This may account for the greater uplift rates and degree of continental deformation in Taiwan. The different structural expression of arc-continent convergence in these regions may be a function of the location and timing of subduction reversal which could in part be related to the maturity of the oceanic crust adjacent to the evolving orogen.

INTRODUCTION

The islands of Taiwan and Timor represent fold-thrust mountain systems produced in the initial stages of arc-continent collision. Their size, shape, geometry, age and duration of deformation, and present tectonic setting are very similar (Fig. 1 A + B). A comparison of the geodynamic evolution of Taiwan with that of Timor reveals some of the factors that control the processes of arc-continent collision, such as convergence angle, pre-collisional history of passive margin, back-thrusting collapse of forearc, and subduction polarity reversal. Applying these constraints to other arc-continent collisional mountain systems in advanced stages of development (i.e. Appalachians, Brooks Range, Canadian Rockies, Tethys belt and New Guinea) provides important insights into their early evolution and allows the evaluation of similar deformational process in various stages of development (Fig. 2).

GEOTECTONIC SUMMARY

Both Taiwan and Timor are characterised by an imbricate stack of continental margin sediments 100-150 km in width landward of a partly extinguished island arc complex (Fig. 1). The detailed geologic character of both regions is compared in Table 1. These characteristics have been interpreted to represent fold-thrust mountain systems built by

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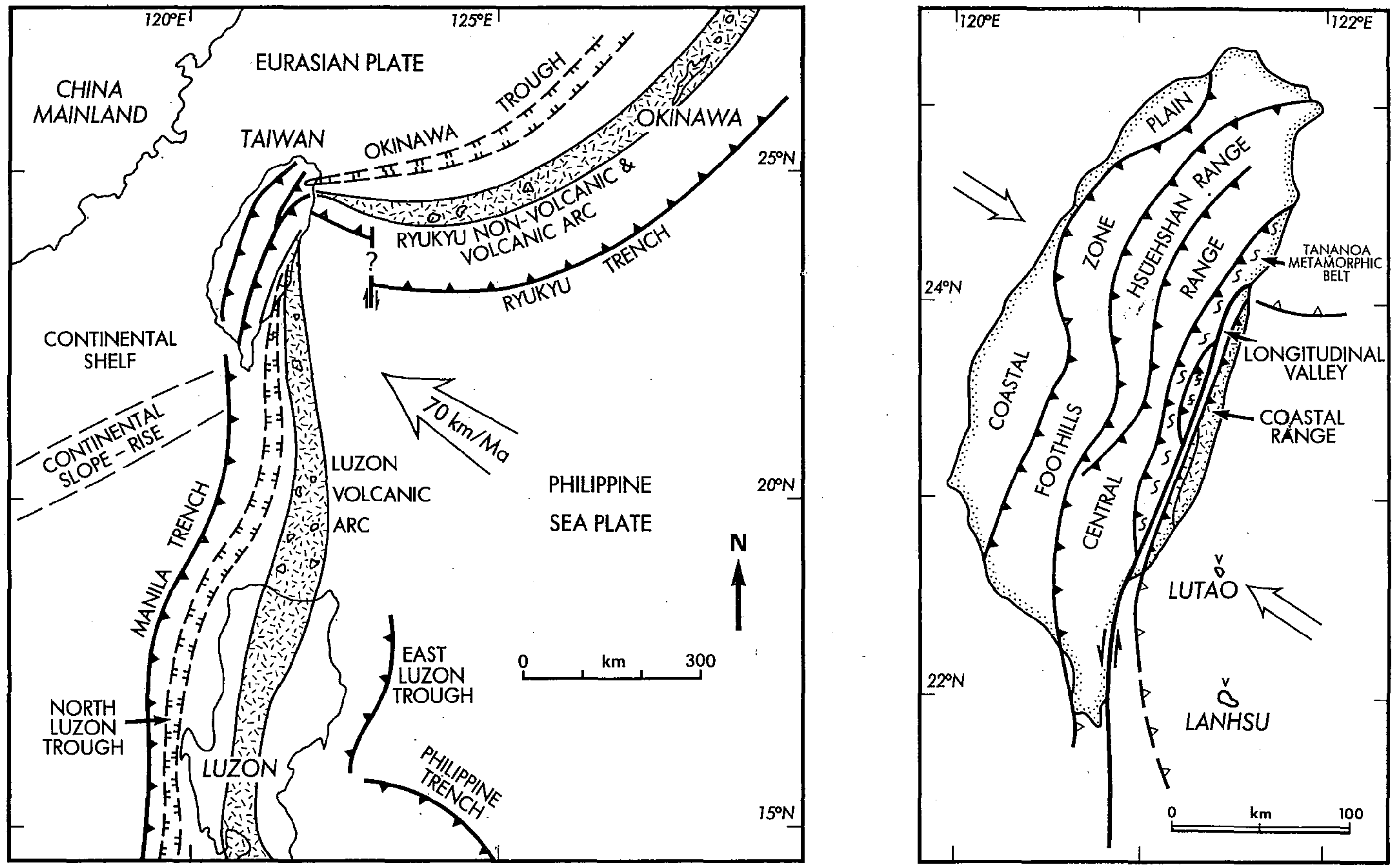
120°E
125°E
EURASIAN PLATE
CHINA MAINLAND
TAIWAN
OKINAWA TROUGH
OKINAWA
RYUKYU NON-VOLCANIC & VOLCANIC ARC
25°N
RYUKYU TRENCH
?
CONTINENTAL SHELF
CONTINENTAL SLOPE - RISE
70 km/Ma
LUZON VOLCANIC ARC
PHILIPPINE SEA PLATE
20°N
MANILA TRENCH
N
0 km 300
EAST LUZON TROUGH
NORTH LUZON TROUGH
LUZON
PHILIPPINE TRENCH
15°N
120°E
122°E
PLAIN
COASTAL
ZONE
FOOTHILLS
HSÜEHSHAN RANGE
CENTRAL
RANGE
TANANOA METAMORPHIC BELT
24°N
LONGITUDINAL VALLEY
COASTAL RANGE
LUTAO
22°N
LANHSU
0 km 100

B

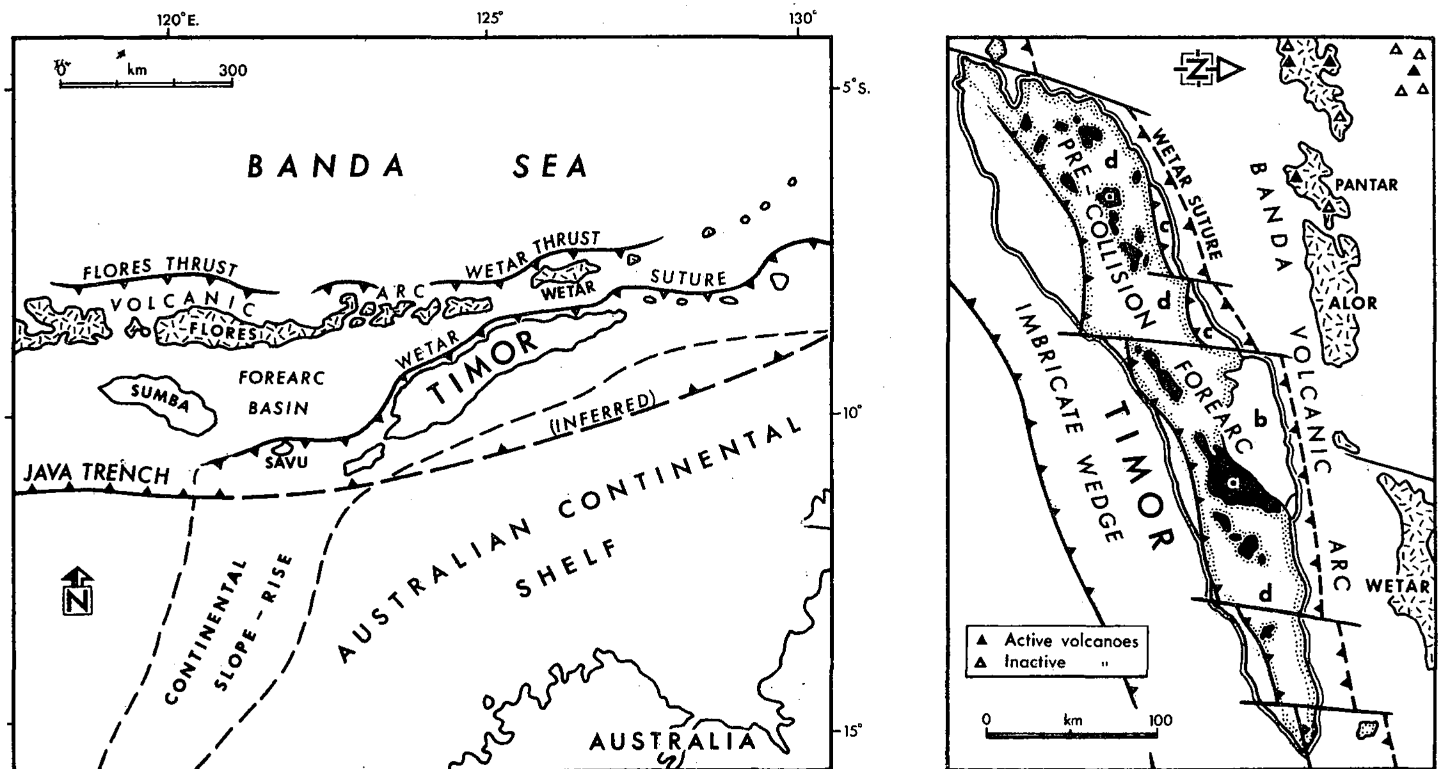

Fig. 1 A + B: Sketch maps to compare the tectonic setting, size and structure of Taiwan (A) and Timor (B). Note that in Fig. 1B (a) = Lolotoi-Mutis metamorphic outcrops; (b) = Aileu Formation; (c) = Atapupu ophiolite and (d) = Bobonaro olistostrome complex.

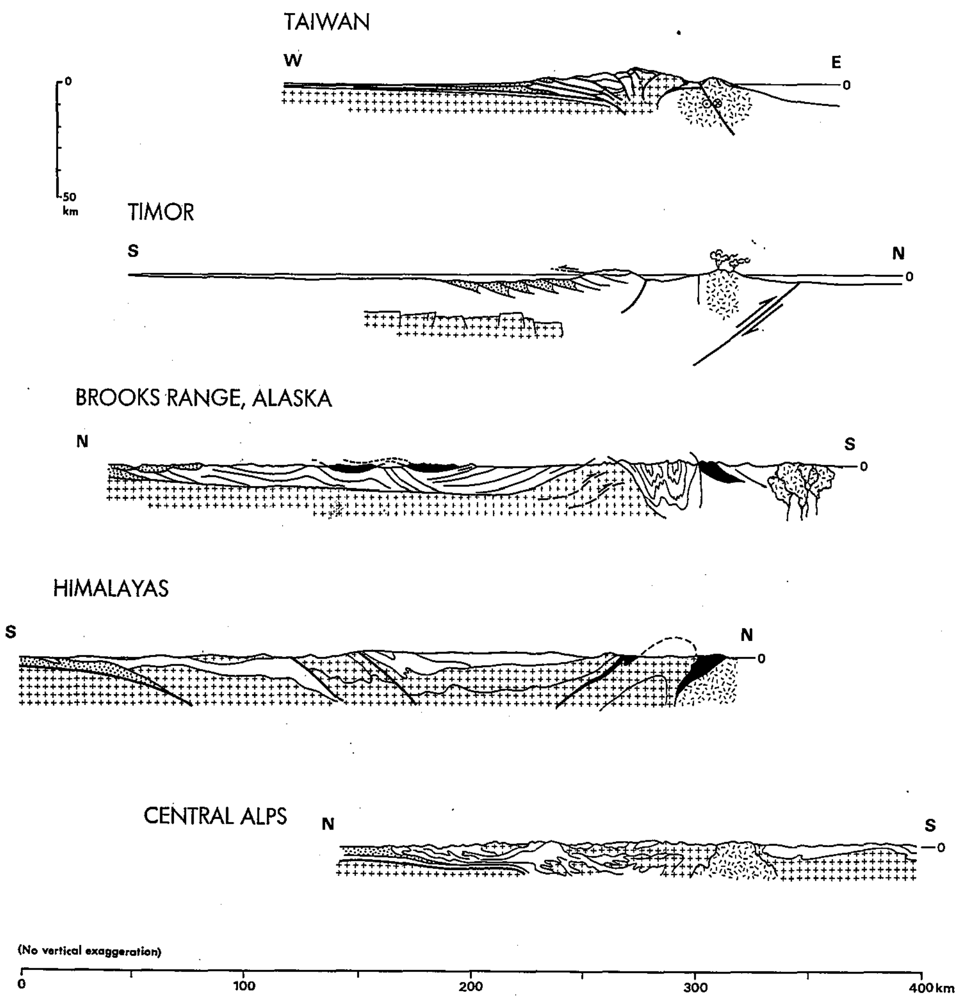

Fig. 2. Comparative cross-sections (all at natural scale, but with some slight vertical exaggeration of Taiwan to reveal detail). + = crystalline basement, black = ophiolite. Dots are molasse basins and positions of major plutons are also ornamented.

Pliocene-present convergence between a passive continental margin and a volcanic island arc, the intervening oceanic basin, forearc, and trench having been mostly eliminated. The arte of convergence in both regions is around 70 km/Ma (Seno, 1977; Minster and Jordan, 1978) and 160-200 km of shortening is documented (Suppe, 1980; Audley-Charles, 1986). Other significant similarities in the geological character of these regions are: surface area, relief, arc-volcanism, metamorphism, sediment thickness, and age and duration of deformation (Table 1). The significant differences between the two regions are: elevation, length of collision zone, seismic expression, uplift rate, convergence angle, age of pre-orogenic sediments, arc-trough distance, crystalline basement involvement, and geometry of subduction reversal. We will now discuss each of these characteristics in more detail.

Table 1. Comparison of geological features in Taiwan and Timor

Geological Feature	Taiwan	Timor
Surface area	400 x 140 km	550 x 100 km
Elevation (max.)	4000 m	3000 m
Relief (trough-trough)	4-5 km	5-6 km
Uplift rate/yr.	5.0 +/– 0.7 mm (1)	1.5-3.0 mm (2)
Convergence rate	70 km/Ma (3)	75 km/Ma (4)
Convergence angle (4)		
1. margin-trough angle	50°	0-5°
2. motion vector-trough angle	64°	45°
Length of collision zone	400-600 km	1500-2000 km
Width of collision zone	100-120 km	150-200 km
Depth to Moho	26-36 km (5)	30-38 km (6), 40 km (7)
Seismicity	shallow, concentrated at arc-continent interface, transpressional (8)	shallow, diffuse, extensional (9)
Volcanism		
1. age	E. Miocene-1.8 Ma (5)	13-3 Ma (10)
2. basement	U. Oligocene-E. Miocene oceanic	E.-L. Cretaceous oceanic or Banda Allochthon
Plutonism	dioritic dikes (5)	dioritic dikes (10)
Metamorphism, Grade (time)	high (L. Mesozoic), medium (L. Miocene ?), low-very low continentward (Plio-Pleistocene) (11)	high (> 70 Ma), high-very low continentward (12-8 Ma) (12)
Continental margin, age (thickness)	Permian-Tertiary (?), Eocene-M. Miocene slate belt (several kms), Neogene (8000-500 m continentward) (5)	L. Permian-M. Jurassic (3-4 km), Jurassic-Paleogene (500-1000 m), Neogene (1-4 km)

REFERENCES: (1) Peng *et al*., 1977; (2) Audley-Charles, 1986; (3) Seno, 1977; (4) Minister and Jordan, 1978; (5) Ho, 1982 (6) Milsom and Audley-Charles, 1986; (7) Bowin *et al.,* 1980; (8) Tsai, 1986; (9) McCaffrey *et al.,* 1985 and 1987; (10) Abbott and Chamalaun, 1978; (11) Liou and Ernst, 1984; (12) Berry and McDougall, 1986; Brown and Earle, 1983.

Size and Shape of Islands

The similarities in the surface area and relief of the islands most likely reflect the similar rates and duration of convergence. If we consider Taiwan and Timor from the volcanic arc to the foreland (Fig. 2) both orogens are marked by a depression between the arc and accretionary wedge (longitudinal valley and Luzon Trough in Taiwan, Wetar Strait in Timor), a central mountain range, and a trough at the deformational front (extension of Manila trench in Taiwan and Timor Trough). Although the total amount of relief represented across the islands is similar, the elevation relative to sea level of these tectonic features is about 1-2 km higher in Taiwan. For example, the forearc basin and trough in Taiwan are at sea level but in Timor are 2-3 km below sea level. This difference is most likely related to a greater amount of arc-continent convergence (measured by arc-foreland trough distance, width of collision zone, Table 1) in Taiwan, which is manifest by the almost complete closure of the forearc trough and lack of surface expression of the pre-collisional forearc ridge rocks. In the Banda arc (Timor) much of the forearc element is exposed. If arc-continent convergence were to continue in Timor the arc-foreland trough distance would decrease and mostly likely result in the closure and uplift to sea level of the forearc basin and arc-continent suture, which in Timor is relatively poorly defined along the northern edge of the island.

The mountains in both regions change in elevation and form along strike. The central range of southern Taiwan and the Ramalau Mountains in East Timor decay along strike into foothills divided by a central valley. Suppe (1980) has attributed this occurrence in Taiwan to subduction reversal and the resulting extension (discussed below).

Gravity

The regional gravity signature of both islands is highlighted by very steep positive anomaly gradients (4-5 mgal/km) in the hinterland and maximum negative anomalies underlying the central range in Taiwan (Ho, 1982) and the foreland basin in Timor (Milson and Audley-Charles, 1986). The more symmetrical gravity profile of Taiwan and its thinner crustal estimate suggest that it has reached a steady state and is in isostatic equilibrium compared to Timor. This contrast in crustal structure and response may account for the higher uplift rates documented in Taiwan.

Seismicity

Although both islands are very active seismically, Taiwan displays a concentration of seismic activity at the arc-continent interface, whereas Timor has a very irregular seismic pattern, which suggests a fundamental difference in the distribution of stress in the collision zones. The collisional stress in Timor appears to be diffusely distributed across the width of the arc system (Bowin *et al.*, 1980) instead of along a well defined suture plane as in the Longitudinal Valley of Taiwan (Tsai, 1986).

The explanation for this difference may lie in the length and geometry of the collisional boundary in the two regions. For example, the length of the collision zone in Taiwan is one third that of the Australian margin collision zone. The distribution of collisional energy in Timor is therefore taken up along a much wider and more diffuse area whereas in Taiwan there is an "edge effect" due to oblique convergence causing more stress (force/area).

The oblique convergence in Taiwan (50° angle between trench and continental margin trends) has affected a maximum of 400-500 km of the Asian margin. In Timor, orthogonal convergence (0-5°) has allowed over 2000 km length of the Australian margin to participate in the collisional process almost simultaneously. Although at present the angle between the Sunda Trench and the NW Australian margin is quite oblique, the Pliocene collision involved the presently ENE trending segment of the margin which was subparallel to the Banda Arc.

The expression of earthquakes deeper than 50 kms clearly defines Benioff zones under the volcanic arcs in both regions. However, the downdip length of the Benioff zones is about 800 kms under the Banda Arc (Cardwell and Isacks, 1978) compared to only 200 kms in Taiwan (Tsai, 1986). This contrast is most likely a function of the dramatic differences in age between the downgoing oceanic basins adjacent to the continental margins.

Volcanism

The volcanic arcs adjacent to Taiwan and Timor display age, petrologic, and geochemical variations with time which document the transition from subduction to collision. Both arcs are characterised by (1) 15-20 Ma of island arc volcanism, (2) the occurrence of shoshonitic (Chen, 1983; Neumann van Padang, 1951) and cordierite-bearing (Ichimura, 1929; De Jong, 1942; Heering, 1942) lavas, and (3) an increase in incompatable elements (e.g. K, Sr) around the time of collision (Chen, 1978; Richard *et al.*, 1986; Whitford *et al.*, 1977). The volcanism has been extinguished adjacent to where the forearc troughs have been closed (e.g. Luzon Trough and Savu Basin as in the Wetar Strait). Active volcanism occurs throughout the length of the "uncollided" sections of the arcs. A significant difference between the Luzon and Banda Arcs is that in Taiwan much of the Luzon Arc has accreted to the upper plate through back-thrusting and subduction polarity reversal (Fig. 2) and in the process experienced considerable deformation, whereas in Timor this process, which may have started 3 Ma ago, is less developed along the Wetar thrust north of the arc (Silver *et al.*, 1983).

Metamorphism

Taiwan and Timor both have important occurrences of metamorphic rocks of similar age, lithology, and polarity of metamorphic grade. However, the structural expression of the rocks is very different and represents one of the most fundamental contrasts between the islands.

In Taiwan the metamorphic rocks are interprted as a para-autochthonous basement complex remobilized during the arc-continent collisional process. These rocks, known as the Tananao Basement complex, consist generally of two belts: the inner Tailuko Belt and the outer Yuli Belt (Yen, 1963). The Tailuko Belt is composed of Upper Paleozoic-Lower Mesozoic slope and shelf sediments (limestone, argillite, quartozfeldspathic units and tuffs) and locally allochthonous ophiolites which have all been recrystallised under high T/P metamorphic conditions. The Yuli Belt consists of deep-water argillites and an ophiolitic melange unit metamorphosed under high P/T conditions.

Liou and Ernst (1984) have documented at least three major episodes of metamorphism in Taiwan. In the Tailuko and Yuli Belts respectively these events consist of (1) high T and P metamorphism ("paired" metamorphic belt) around 87 Ma, (2) greenschist and blueschist/greenschist facies metamorphism around 8-14 Ma, and (3) collision-type metamorphism in the Plio-Pleistocene which increases in grade to high-rank greenschist facies toward the hinterland (eastward).

The metamorphic rocks in Timor are all interpreted as allochthonous continental fragments constituting the pre-collisional forearc basement of the Banda Arc (Fig. 1b). They occur as thick (> 2.5 km) flat lying thrust klippe and have been subdivided into three elements. In descending structural order they are (1) the Atapupu ophiolite complex of unknown age composed of serpentinites, amphibolites and meta-mafic and ultramafic rocks (units c, Fig. 1b); (2) the Permian-Upper Jurassic Aileu Formation consisting of a zoned metamorphic sequence of pelitic, psammitic, basic and carbonate-rich rocks which progressively increase in metamorphic grade from low greenschist to upper amphibolite facies arcward (unit b, Fig. 1b); and (3) the Muits and Lolotoi metamorphic basement complexes of West and East Timor respectively, which consist of cordierite-bearing pelitic schists and gneisses structually overlain by dismembered remnants of an ophiolite; the metamorphic grade varies throughout the complex from subgreenschist to upper amphibolite or granulite facies (unit a, Fig. 1b).

The cooling age of the various metamorphic events of the Aileu Formation is around 70 Ma for the prograde phase and about 11-8 Ma for the retrograde phase (Berry and McDougall, 1986). One Rb-Sr whole-rock isochron age of 118 +/− 38 Ma has been reported by Brown and Earle (1983) from the Mutis complex in western Timor, which they suggest represents its protolith age. However, Grady and Berry (1977) report that in eastern Timor limestones associated with the Permian Aileu Formation unconformably overlie the Lolotoi complex. The metamorphic cooling age and history of the Mutis-Lolotoi complex has not been investigated.

The metamorphic complexes in Timor (Banda Allochthon) most likely originated as part of the continental margins of Sundaland (Barber, 1981; Johnson and Bowin, 1981) or Australia (Bowin *et al.*, 1980) and were metamorphosed first during the rifting of Gondawana, and then when the fragment was accreted to the Banda Arc and collided with Australia. We prefer the Australian origin and suggest the continental fragments composing the Banda Allochthon were rifted from the margin of Australia in the Jurassic or Cretaceous and displaced westward later along sinistral transform faults. This transform fault system was probably initiated by the westward shift in Pacific Plate motion around 40 Ma (Engebretson *et al.*, 1984).

A similar process has been suggested by Silver *et al.* (1985) for the origin of the basement outliers of Buton, Buru, Banggai-Sula, eastern Sulawesi, and the Banda ridges. As the postulated source terrain (Bird's Head block of Irian Jaya) for all of these allochthonous continental rocks moved northward, the transform fault system, which accommodated the westward motion of the Pacific plate relative to the Indian plate, continued to slice off continental fragments and moved them westward into the Indian oceanic plate (Wharton Basin). We suggest that the Mutis-Lolotoi and Aileu metamorphic rocks represent some of the earliest, and therefore southernmost, foundered continental fragments. The displacement age of the other fragments young to the north where Banggai-Sula and Birds Head itself are the most recent examples of displacement along this complex transform boundary.

According to this model the Banda Allochthon was incorporated into a newly developed eastern segment of the Sunda forearc around the Middle-Late Miocene. This time is coincident with the East-West Sulawesi collision (Sukamto and Simandjuntak, 1983) which may have caused the demise of the Sulawesi subduction zone. We suggest that the Sulawesi collision was the impetus for the eastward propagation of a new subduction system in order to accommodate continued northward convergence of the Indian Plate. It is also the time when (1) high temperature metamorphism affected the Aileu Formation (Berry and McDougall, 1986), (2) dramatic changes in bathymetry are documented in the sedimentary sequences (e.g. Cablac to Batu Putih Limestone, Audley-Charles, 1986) which unconformably overlie the metamorphic rocks, and (3) the oldest known magmatic pulse occurred in the Banda Arc. The establishment of the new subduction system (Banda Arc) is considered here as analogous to the development of the Aleutian Arc (Marlow *et al.*, 1973; Wallace and Engebretson, 1984).

The continental fragments may have provided a pre-existing crustal anisotropic weakness for the propagation of the new subduction zone. As the old (Late Jurassic-Early Cretaceous) Indian oceanic crust was subducted beneath the Banda Allochthon the eastern Sunda (i.e. south Banda) volcanic arc formed and the Banda Allochthon became the basement of the forearc. Continued subduction resulted in the closure of the oldest part of the Wharton Basin and by the Middle Pliocene the continental basement of the forearc had collided with and partly ramped onto the NW Australian passive continental margin giving rise to the Timor orogen.

Throughout the collision process the transform boundary system between the Pacific and Indian plates continued to operate and is responsible for the translation of Bird's Head of Irian Jaya and the rotation of the NE Banda Arc (Seram) into its present arcuate configuration.

It has also been suggested (Karig, 1973) that the Late-Cretaceous-Early Tertiary deformation in Taiwan (Tananao paired metamorphic belt) is associated with the east-facing arc system which existed in the Luzon Arc of the Philippines. Subduction reversal, perhaps at around 8-14 Ma (the time of metamorphic overprinting), initiated its westward migration and eventual collision with the Asian margin in the Pliocene. According to this scenario, the Tananoa metamorphic complex would represent an accreted forearc basement much like the "Banda allochthon".

This process of arc reversal and incorporation of crystalline rocks into the forearc accretionary wedge is presently occurring in the Ryukyu arc system of NE Taiwan. Exposed basement rocks in the Ryukyu forearc include greenschist, blueschist, siliceous schist, pelitic schist, metagabbro, and Permian marbles (Kizaki, 1986).

The coincidence in the timing of pre-collisional uplift and metamorphic cooling in both Taiwan and Timor suggests that the geodynamic processes may have been linked, perhaps documenting a kinematic reconstructional event in plate motion affecting both areas. For example, during the Middle Miocene the South China Sea ceased spreading and collisions associated with ophiolite obduction occurred in Mindoro in the Philippines (Stephan *et al.*, 1986), Palawan (Murphy, 1973), and Sulawesi (Sukamto and Simandjuntak, 1983).

Forearc

Estimates of the size and shape of the pre-collisional forearc accretionary complexes are derived from the non-collided segments of the forearc in each region. The Banda forearc is notably larger (Figure 1). However, both islands display only a small fraction of the pre-collisional forearc material, which raises the fundamental question of what happens to the forearc during the collisional process. If the forearc completely over-rides the continental lower plate and then is rapidly eroded, the root zone of the overthrust forearc should still exist. Another possibility is that the forearc has been overridden by the continent. In Taiwan, Suppe and Liou (1979) proposed that the forearc acts as a wedge between the lower plate basement and its cover allowing it to be overridden by hinterland directed backthrusts of once lower plate cover rocks (Fig. 3). In Timor, Audley-Charles (1981) and Price and Audley-Charles (1984) proposed that during the Banda Arc-Australia collision, part of the

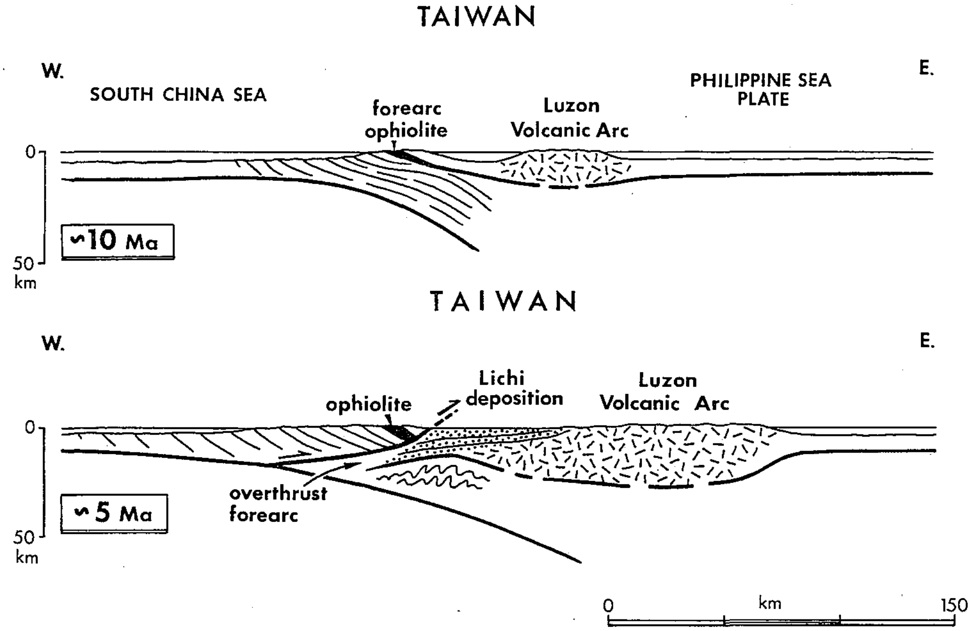

Fig. 3. Cartoon illustrating how collisional orogenesis in Taiwan leads to loss of forearc when this is overridden and hence hidden by overthrusts. (from Suppe and Liou, 1979).

forearc (Banda Allochthon) developed into a roof thrust and the rest was overridden by the continent.

Large-scale backthrusting of lower plate rocks over the forearc basement (Fig. 3) has also been proposed in several other collisional belts (Mitchell, 1983). The development of backthrusts is dominately controlled by traction along the base of the orogenic wedge. The underthrusting of buoyant continental lithosphere uplifts the wedge and increases its basal traction or coupling with the lower plate both of which cause it to move arcward with the lower plate through the development of backthrusts (Platt, 1986).

Continental Margin

At face value, the Australian and Asian continental margins appear very similar (Table 1, Fig. 2). They have nearly the same thickness of pre- and syn-orogenic sediment and are floored by Permian or older basement. However, a major difference exists between the regions in the history of sedimentation and the proportion of stratigraphic section involved in the deformation.

In Taiwan, the crystalline basement of the continental margin (Tananoa metamorphic belt) was remobilized by backthrusting during the collisional phase of orogenesis, whereas in Timor there is no direct evidence for the continental basement being involved in the collisional deformation phase (Fig. 2). This may be more apparent than real. The Taiwan basement rocks may be forearc basement or the basement in Timor may be involved but not exposed. If this different role of the basement is real it implies a fundamental difference in the structural evolution of these collisional events.

One possible controlling factor of basement remobilization may be the difference in the strength of the continental margins at the time of collision, which is evidenced by the difference in the pre-collisional history of the continental margins. The pre-collision sediment cover of the Asian margin, although similar in thickness to that of the Australian margin, is mostly Neogene in age. This rapid accumulation of sediment in addition to the thermal effects of the South China Sea rifting would cause crustal thinning and increase the thermal gradient of the margin and thus weaken it (Murrell, 1986). The thermal activation would be close in time, and may even be responsible for the Late Miocene metamorphic event recorded in continental margin basement. If the basement was thermally unstable and structurally elevated at the time of collision it would be much more likely to be involved in the deformation due to a high degree of coupling between the over-riding and subducting plates.

After Jurassic rifting, the Australian margin and its adjacent ocean basin was quiet and relatively starved of sediment until Neogene collision, by which time the margin was most likely relatively cool and dense. This long, passive history may have prompted a more rigid and competent response to the collision and the decoupling of the basement rocks from its cover.

The along-strike sediment thickness variations in Taiwan from 3 km in the north to 8 km in the south (Covey, 1986) suggest that overall sediment thickness may have very little effect on variations in the collision process. The difference in pre-collisional thermal equilibrium of the continental margins of Taiwan and Timor, and the age and rate of sediment accumulation, which only varied between the islands before collision occurred, are most likely important controlling factors of variations in the structural evolution of the collisional event.

The post-collisional development of foreland basins on the continental margins is very similar in both regions except for the elevation and sediment thickness of the trough. The foreland trough in Timor contains significantly greater depth of water, is filled with less sediment, and is located further continentward than the sediment-filled trough in Taiwan (Table 1, Fig. 2b). This contrast may also reflect the difference between the rigidity of the continental lithosphere causing variations in the wavelength of continental buckling.

Deformation

Shortening estimates for Taiwan and Timor are around 200 km, but the structural style of Quaternary deformation is different. Thrust tectonics still dominates in the Quaternary of southern Taiwan, whereas extensional tectonism prevails in northern Taiwan and most of Timor.

Suppe (1984) has related transition from convergent to extensional deformation in Taiwan to the development of subduction polarity reversal. Because the convergence angle in Taiwan is oblique, he argues that the polarity flip of subduction moves progressively at a critical distance behind the collisional front. He argues that reversal occurred about 3-4 Ma after collision. In Timor subduction polarity reversal may have occurred much sooner (0.5 Ma) after the initiation of collision (Price and Audley-Charles, 1987).

The timing of reversal may explain why the collision processes in Timor appear to be progressing slower than in Taiwan, even though the rate of convergence is the same. If backarc thrusting was initiated in the Banda arc shortly after collision with the Australian margin, then in Timor the maximum principal stress would change from horizontal to vertical, which would "freeze" the compressional deformation in a very early stage and begin to alter it by extension. Where subduction polarity reversal has been documented in Taiwan and Timor this transition from convergence to extension has occurred (Fig. 1). The fact that subduction polarity reversal is documented in both areas suggests it is a common process of arc-continent collisions and may be the end result of backthrusting.

ORIGIN AND EMPLACEMENT OF OPHIOLITES

The dynamics of orogenic wedges has been modelled in several different ways using various rheological assumptions (Elliott, 1976; Chappell, 1978; Davis *et al.*, 1983; Platt, 1986). In all of these models it is suggested that the wedge deforms as a mechanical continuum and that individual features cannot be considered in isolation, but only as part of the system as a whole. This continuity underscores the importance of determining the structural relations between the various anatomical parts of entire mountain systems.

One of the most important characteristics of most fold-thrust mountain systems is the structural arrangement of stacked thrust sheets. The stack is commonly arranged so that successively higher sheets are usually derived from paleogeographic positions further from the interior of the platform. The occurrence of large klippen of ophiolite (distinctive assemblages of mafic and ultramafic rocks) at the top of the stack is common. These panels of ophiolite were usually emplaced onto passive continental margins within 20 Ma of their formation at the beginning of major orogenic pulses, and are often underlain by thin, high T/P, metamorphic soles and melange. Some of these klippen occur up to 150 km from their root zone (Brooks Range, Fig. 2).

Some of the best examples of ophiolites emplaced onto passive margins, in tectonic settings considered analogous to that of Taiwan and Timor, are the Bay of Islands (Newfoundland), Trinity (California), Brooks Range (Alaska), Semail (Oman), Troodos (Cyprus), Vourinos (Greece), Papau (New Guinea), and Sulawesi (Indonesia) complexes. Determining the paleogeographic relations between these ophiolites and the imbricate platform rocks they structurally overlie remains an important unresolved aspect of understanding the evolution of orogenic wedges.

One of the most common models for the origin and emplacement of these ophiolite belts onto passive margins is arc-continent collision (Gealy, 1979). However, in most of these regions the mountain building processes were active for 20-60 Ma, which has in most cases destroyed the original tectonic setting of the ophiolites and increased the structural complexity of the whole mountain system.

Taiwan and Timor offer a unique opportunity to test the simple arc-continent collisional model for the origin of ophiolites and their emplacement onto passive continental margins because the collisional process is in its initial stage of development and the tectonic setting well preserved. Although most of the geologic features in Taiwan and Timor are emblematic of the older mountain systems (Fig. 2), large klippen of ophiolite are missing. This inconsistency with the simple arc-continent collision emplacement model is notable because the initial stages of mountain building in most other fold-thrust belts is marked by the emplacement of thick ophiolite sheets.

In Taiwan there is sedimentary documentation for a major ophiolite obduction phase in the Middle Miocene, some 5-7 Ma before the collisional orogenic pulse (Pelletier and Stephan, 1986). Although the source for the ophiolitic debris has disappeared, the deformational and metamorphic effects of the obduction event are well documented. The most likely origin for the ophiolite is the young (< 20 Ma) marginal basin (South China Sea) situated in the zone of convergence between the Luzon Arc and Asian margin. The process of emplacement is poorly understood, but the relative timing and tectonic setting is consistent with the relationships displayed by most other large ophiolite belts (Tethyan-Type).

The Timor ophiolites occur in a narrow band along the north coast and are interpreted as the highest allochthon of the orogenic wedge (Barber *et al.*, 1977). However, these mafic and ultramafic rocks are dismembered and display a penetrative mylonite fabric and depleted lherozolitic composition which is atypical of most ophiolites emplaced on passive continental margins.

The differences between ophiolite occurrences, or lack thereof, in Taiwan and Timor that are directly related to arc-continent collision and other mountain systems must be accounted for in models for the origin and emplacement of ophiolites onto passive continental margins (Hall, 1984). This contrast suggests either that Taiwan and Timor are atypical or that the ophiolite obduction mechanism in the other mountain belts is not directly related to the collision of arcs and continents.

Atypical behaviour can be supported in Timor by the large thrust sheet of what is interpreted as precollisional forearc basement that was emplaced atop the imbricate wedge and occurs as large isolated klippen above an ophiolite-poor olistostrome and imbricate slope-rise deposits (Fig. 1). It can be argued that if the forearc basement was composed mostly of trapped ocean-like crust then a major ophiolite obduction phase may have accompanied the arc-continent collision.

There is much evidence to support the alternative argument, that ophiolite emplacement onto passive continental margins is not directly related to arc-continent collision but occurs more as a consequence of compressive stress between young, thermally immature ocean-like lithosphere and continental margins which in many cases experiences subsequent collisional deformation (basin inversion). Age relations, lack of arc volcanism in some areas (Oman and Cyprus), composition of subophiolite metamorphic rocks, and consistency with modern analogues (Taiwan and Timor) all support this argument.

We suggest here that the age of the oceanic lithosphere adjacent to the passive continental margin at the time of convergence is critical and may be one of the most important controlling factors of the emplacement of the ophiolites onto the margin. In Taiwan the adjacent South China Sea had recently formed and was no older than 10-15 Ma at the time when the extensional regime of the region changed to convergence (Stephan *et al.*, 1986). The emplacement of ophiolites around the perimeter of the marginal basin at this time was a consequence of the thermal evolution of the basin not the collision of an arc. This contrasts greatly with Timor where the oceanic basin adjacent to the Australian margin formed in the Jurassic.

CONCLUSIONS

Taiwan and Timor both represent Pliocene-present arc-continent collisional orogens with similar tectonic settings, convergence rates, total shortening and topographic relief. However, there are important differences in the structural evolution of the orogens. For example, Taiwan has a remobilized basement complex, evidence of a precollisional ophiolite obduction phase, higher uplift rates, greater amount of arc-continent convergence and less arc-foreland trough distance. These differences may be a result of the different thermal states of the continental margin, age of adjacent ocean basin, pre-collisional sedimentation rates, convergence angles, length of collisional zones and timing of subduction polarity reversal. The most important aspect of this comparative review is to determine which of these differences produce first order effects and control most the variations in structural evolution of these and other arc-continent collisional orogens.

We suggest that the rifting in Taiwan associated with the opening of the South China Sea (within 10-15 Ma of the arc collision) is the most important difference between Taiwan and Timor and can account for most of the variations in the structural evolution of these fold-thrust mountain systems. The thermal instability of the Taiwan margin and adjacent young ocean basin (South China Sea) led to pre-collisional ophiolite obduction and basement remobilization, which most likely is responsible for the greater amount of uplift and arc-contient convergence than Timor.

The old (c. 160 Ma) passive Australian margin and its adjacent Mesozoic ocean basin responded in a much more rigid manner to arc collision than the younger, hotter Taiwan margin. This rigid response of the Australian margin allowed the early development of subduction polarity reversal, which broadened the collision zone, reduced arc-continent convergence and uplift rates, and may have led to the rupture of the lower plate as suggested by Price and Audley-Charles (1984).

Comparison of the geometrical, structural and stratigraphical features of these two Neogene arc-continent collisional orogens has led to three main conclusions of wide application to orogenic belts.

(1) Subduction direction is related to the amount of arc-continent convergence and to the age of the ocean crust adjacent to the volcanic arc. If, after all the ocean crust in the arc-continent convergent zone has been subducted (Taiwan and Timor) the ocean crust adjacent to the volcanic arc is old, it will tend to subduct (e.g. Mesozoic South Banda Sea and Philippine Sea Plate moving below north Taiwan and Ryukyu). This initiates reversal of subduction polarity.

(2) Another conclusion is that crustal shortening in the forearc region (arc-continent convergence) ceases or is rapidly diminished by the development of subduction reversal. When this transfer of the site of convergence occurs the maximum principal stress direction at the arc-continent interface changes from horizontal to vertical as evidenced by the extensional deformation in North Taiwan and most of Timor.

(3) Emplacement of ophiolites onto passive continental margins appears to be influenced critically by the youthfulness of the adjacent ocean crust. Where this is greater than 20 Ma at the time of convergence it is more likely to be subducted than obducted onto the continent as an ophiolite.

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臺灣與帝汶的新構造

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節　　要

臺灣與帝汶同爲在自上新世迄今這一時期內在大陸邊緣與火山弧之間造成的褶皺逆衝帶，原居陸弧之間的洋槽及外弧均已在造山過程中因改組而消失。此二碰撞帶在長度、寬度、及高度上均甚接近，但過去及目前的上升速度在臺灣顯然較在帝汶爲大。臺灣與帝汶在另兩項數據上亦均近似：地殼收縮都在二百公里左右；板塊爲會合而前進的速度均爲每年七公分。然而臺灣有一些爲帝汶所無的特色，如㈠厚度大得多、年代也新得多的通體呈楔狀的沈積岩系、㈡露布於中央山脈的因改造而復活的基盤岩體、及㈢位置因地震集中而更加明確的縫合帶。這些使兩地不盡相同之處可從被構造活動波及的岩層的多寡加以解釋。此因在板塊構造中，會合之後必繼以由碰撞帶去吸收，而變形的岩層的多寡可能因吸收方式不同而不同。帝汶碰撞帶分布散漫，不若臺灣碰撞帶緊湊，後者全程盡在陸弧界限分明的臺東縱谷。此可說明何以臺灣上升較速、何以臺灣構造與大陸式構造較爲接近。總之，臺灣與帝汶之所以在構造上有不同的表現可能取決於隱沒作用於何時何地改取逆向，而改取逆向則又涉及在造山帶鄰近的大洋地殼已成熟至何程度。