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The mechanics of progressive deformation in crustal plates— A working model for Southeast Asia

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Abstract: A model explaining the mechanics of Tertiary deformation of the Southeast Asian crustal plates is presented which links Wrench Tectonics and Plate Tectonics. The model realigns the roles of subduction, rifting and shearing in crustal deformation integrating them to form a dynamic and progressive system driven by a single westward directed continuous force.

The Southeast Asian crustal complex overlies the Pacific Plate at the intersection of the Pacific, Eurasian and Austral/Indian crustal plates. Relative plate movements at this intersection have resulted in a high angle of convergence between the Pacific and Eurasian Plates and a low angle of convergence between the Pacific and Austral/Indian Plates.

The Eurasian Plate in acting as a buttress has resisted westward movement of the Southeast Asian and Pacific Plates. Subsequent shortening against this boundary has been accommodated largely by subduction of the oceanic Pacific Plate.

Deformation of the Southeast Asian Plate along the Pacific Plate's southern boundary presents a more complex structural situation. Deformation has occurred in progressive stages, each successive stage overprinting the former. Decoupling has occurred between each stage. The overall results have been:

a. east-west crustal shortening by compressional folding, thrusting, strike-slip faulting and buckling of the Southeast Asian Plates in response to a west directed horizontal principal stress,
b. vertical crustal thickening by basin development and mountain building, and
c. north-south crustal expansion by Island Arc formation.

Initially, east-west shortening and fragmentation of the early Tertiary Southeast Asian crustal plate was accommodated progressively by folding, thrusting and strike-slip faulting. This resulted in the plate being broken by a series of west trending sub-parallel Shear Systems. Continued shortening and endloading of the plate from the east successively buckled the elongate, decoupled, inter-shear fragments away as Island Arcs from adjacent fragments to override the impinging Pacific Plate. Behind these arcs expansion and rotation (primary rotation) was accommodated by rifting and short offset transform faults. The formation of multiple arc complexes by repetitive buckling of crustal fragments not only increased the width of the region of deformation but further rotated (secondary rotation) the older complexes.

The crustal deformation of Southeast Asia, in terms of this new working model, is displayed in a Tectonic Map of the region.

INTRODUCTION

Understanding the complex region of Southeast Asia, where Pacific, Asian, Australian and Indian plates interact, is critical to the acceptance of the concept of

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Global Tectonics. It is to this region that proponents of vertical tectonics point to the bilateral symmetry of mountain belts, crustal thinning, extension and plutonism (Krebs, 1975 McCunn 1973) while proponents of subduction emphasize trench-arc relationships and geometries (Hamilton, 1979a, 1979b, Coleman *et al.*, 1976, Cross *et al.*, 1982). It is in this same region that tremendous strike-slip faults attest to large scale horizontal movements explained by expansionist theories (Carey, 1975a, 1975b), strike-slip theories (Audley-Charles, 1976, Holcombe, 1977) or more recently by the increasingly popular slip-line theory (Tapponier *et al.*, 1976, 1982).

In this paper the author will demonstrate that the tremendously diverse styles of deformation found in this region are interconnected, that they formed through a progressive and orderly sequence and that the predominant driving force was a westward moving Pacific Plate.

The Southeast Asian region lies trapped at the intersection of the Pacific, Eurasian and Austral/Indian crustal plates (Figure 1). In this setting relative plate movements

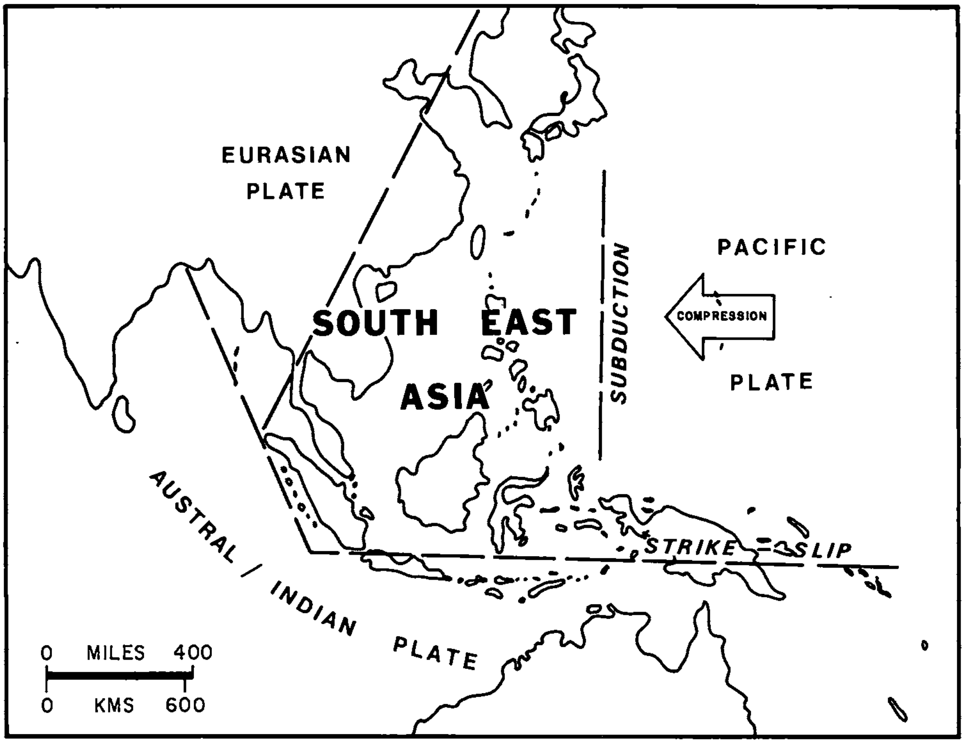


Fig. 1. Southeast Asia, lying trapped against the Eurasian and Austral/Indian Plates, is subjected to compression from the east as the Pacific Plate moves west resulting in subduction along the Pacific Plate's western boundary and strike-slip along its southern boundary.

have resulted in a high convergence angle between the Pacific and Eurasian Plates and a low angle of convergence between the Pacific and Austral/Indian Plates. Sequential deformation along these two convergent plate boundaries combines to develop the overall tectonic patterns in the Southeast Asian region.

HISTORICAL SETTING

As early as the late Nineteenth Century the Southeast Asian region has been mapped by oil explorationists and the continued use of their maps today is a testament to their skill. The compilation by Van Bemmelen, "*The Geology of Indonesia*", first published in 1949, stands as a tribute to the work done by these early explorers and remains one of the most authoritative sources of geologic data for Indonesia available today.

The wide acceptance of Continental Drift Theory by the early 1960's proved to be an exciting time for Southeast Asian geology. Perhaps the complexity of the area, possibly the well documented surface and subsurface information, certainly the necessity to fit this area into the emerging tectonic models, drew and held the attention of world tectonists.

However, it was soon evident that the area was defying a simple solution and Karig, a leader in the field of Tectonics in 1974, concluded, "*The complexities of recent arc patterns in the Melanesian and Indonesian–Philippines regions strongly suggest that unravelling a complex orogenic zone may be possible only in very general terms*". Again in 1977, Tapponier and Molnar, after excellent theoretical considerations relating deformation of a rigid plastic body by a rigid indenter to deformation of Asia along lines of strike-slip faults radiating from the Assam Syntax area unfortunately concluded that, "*Even if the description (of the area) in terms of rigid blocks were accurate, it would be so unwieldy as to be essentially useless*".

Undoubtedly an impasse was imminent and a statement by Meyerhoff in 1976 was proving to be prophetic. The basic subduction model required "*the creation of innumerable ad hoc modifications to fit each arc or arc complex*". Similar difficulties were being encountered with the extension models of Carey and the strike-slip theories of Audley–Charles and Holcombe. It was apparent that the problem was conceptual and that a solution must lie along a new tact.

The co-existence of strike-slip, thrust and tension faulting and block rotation in Southeast Asia has long implied a causal relationship (Moody, 1973, Moody and Hill 1956, Du Bois, 1981). In Southeast Asia strike-slip faults dominate many structural features (Kozhutin *et al.*, 1982). However, major overthrust belts, regional anticlinoriums and major subduction trenches indicate an overall east-west shortening of the region. The source of this compression can be found in the adjacent Pacific plate, a plate whose westward movements against the Southeast Asian region through geologic time are reasonably well recorded (Jurdy, 1979, Schwan, 1980). This continuous westward stress, and the position of Southeast Asia lying boxed against the massive Eurasian Continent to the west and the Austral–Indian Plate to the south (Figure 1) creates the regional setting. A model is derived from theoretical considerations that strain has been accommodated by a progression of folding, thrusting, strike-slip faulting, buckle folding and block rotation.

The model is developed in three stages. First, the stress regimes of folding, thrusting and strike-slip faulting are linked in a predictable progression leading to the development of Shear Systems which fragment large plates into smaller elongate platelets. Second, continued compression is shown to result in buckle-folding of the decoupled and end-loaded platelets and third, the rotation of multiple buckle-folded complexes is demonstrated resulting in the final shape of the Southeast Asian region. Theoretical considerations of each stage of the model are followed by examples from Southeast Asia.

PROGRESSIVE DEFORMATION—THE INITIAL STAGES

CONCEPT—SHEAR SYSTEMS

Confining forces acting perpendicular to each other are defined to be sigma 1 (σ_1), sigma 2 (σ_2) and sigma 3 (σ_3) and are respectively, the maximum, intermediate and minimum forces. In a system under stress, maximum compression will occur parallel to σ_1 while minimum and intermediate compression (i.e. expansion) will occur parallel to σ_3 and σ_2 respectively Folding, thrust faulting and shearing are related to the orientation of these perpendicular forces (Figure 2).

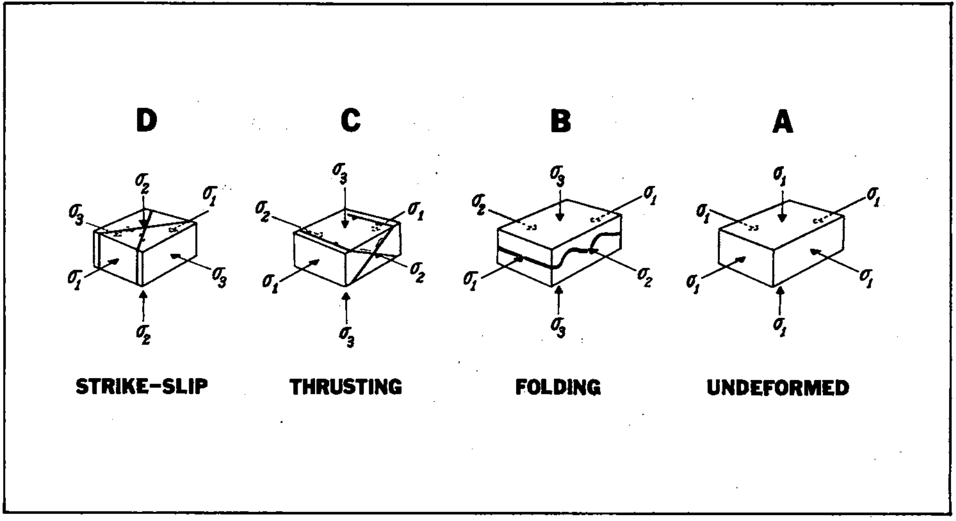


Fig. 2. Stress orientations and deformation under horizontal compression.

Sigma 1 is horizontal, westerly directed and continuous in Southeast Asia. Figure 3 demonstrates the proposed sequence of deformation of a hypothetical crustal block lying within the Southeast Asian region and responding to this continuous horizontal compressive stress. The undeformed block (A), acted on by the left-directed (west) horizontal force (σ_1) will first respond by folding about a horizontal axis parallel to σ_2 (B), folding accommodated by compressional and extensional block faulting. As the amplitude of these compressional down- and up-warps increases, the perpendicular force σ_3 will correspondingly increase and act to collapse the folds away from or towards σ_1 depending on minor deviations of σ_1 away from the horizontal. At some critically shortened length folding will no longer accommodate large amounts of shortening and the now folded block, weakened by radial tension and compressive block faulting, will thrust over itself.

The original block will now be broken, or decoupled into an upper and lower segment (C). Continued thrusting will result in further shortening and vertical thickening of the block. Once again σ_3 will steadily increase and will continue to do so until it approaches the intensity of σ_2. With additional compression a change will occur in the relative positions of σ_3 and σ_2, σ_2 becoming vertical. The new stress orientations will favour strike-slip faulting as the most likely form of deformation (D) and the block will decouple vertically into independent adjacent fragments. This final phase resembles Fitch's (1972) model for decoupling along plate interfaces under conditions of oblique convergence. The original block will now be fragmented into two adjacent smaller blocks separated by a mobile linear belt of folded, thrusted and sheared terrain. This deformed mobile terrain will be referred to as a Shear System. Figure 4 depicts the development of a Shear System in a more realistic form and demonstrates the overprinting of the stages of deformation until the final folded, thrusted and sheared terrain results.

Several features of the Shear System merit expansion. The rate of shortening will not be steady even though σ_1, the driving force, remains constant. During folding or thrusting, as σ_3 increases, the shortening process will become increasingly difficult and steadily slower as the length of critical shortening is approached. At decoupling points instant relief, in a geological time sense, will be noted as an increase in the rate of shortening. This expected pulsating effect is observed in Southeast Asia and correlated with documented Pacific Plate movements.

Another feature is that progressive deformation is independent of scale and looking at Figure 4 again it can be seen that no scale is used. The stress σ_1, is felt along a convex radiating front which will propagate away from the stressed area in three dimensions. Horizontally the resultant strain will initially be a series of expanding arcuate waves or folds (B). As the stress continues and strain reaches its critical limit, the strained area will be thrusted upon itself (C). Finally, shortened again to its critical limit, the area will be fragmented by large vertical strike-slip faults (D). This sequence holds true for the development of a major Alpine belt with its associated frontal foreland basin or "A" type subduction zone. It also holds true for the development of a local basin associated with a single thrust or strike-slip fault.

Vertically a similar sequence will develop simultaneously. The upward

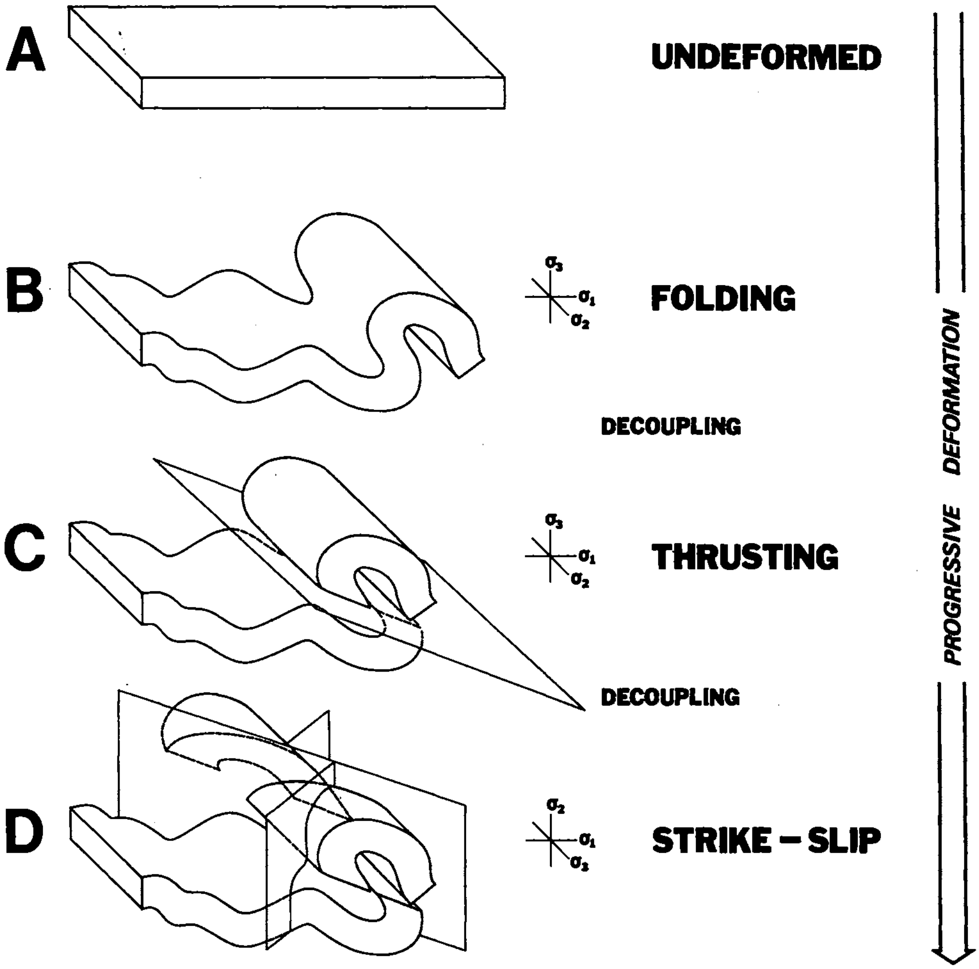


Fig. 3. Progressive horizontal deformation.

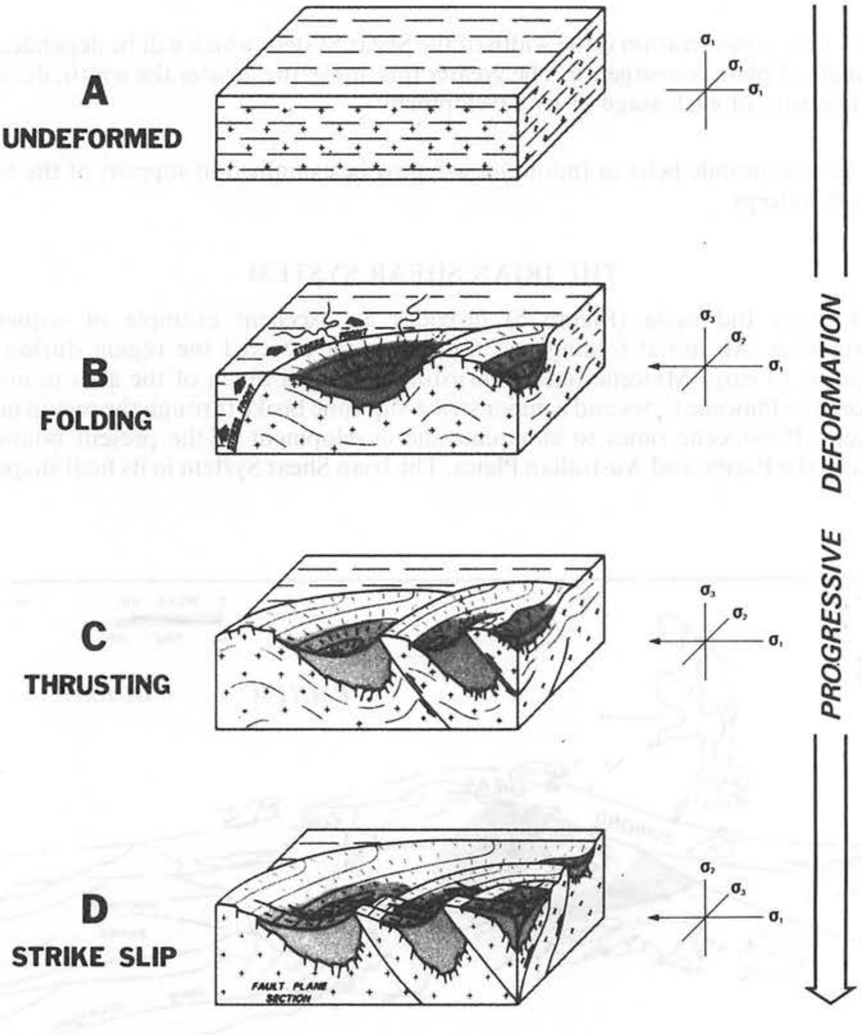


Fig. 4. Block diagram illustrating the three dimensional aspects of progressive deformation resulting from a single continuous horizontal compressive stress.

propagating stress front will raise the surface in an initial doming phase until, under continued stress, the terrain will be thrust upwards and outwards. Uplift will culminate in a central vertical fracture zone breaking through at the surface. This sequence is suggestive of, at a local scale, the familiar "flower" structures of strike-slip systems or, at a regional scale, of the bilateral symmetry of mountain chains.

A final consideration is the width of the Shear System which will be dependent on the angle of plate convergence. The greater this angle, the greater the width, duration and intensity of each stage of its development.

Several mobile belts in Indonesia will now be examined in support of the Shear System concept.

THE IRIAN SHEAR SYSTEM

Eastern Indonesia (Figure 5) provides an excellent example of sequential deformation. An initial folding and faulting event affected the region during late Oligocene to early Miocene times. Thrusting deformed much of the area in middle Miocene to Pliocene times and a major strike-slip zone broke through the region in late Pliocene–Pleistocene times to culminate the development of the present boundary between the Pacific and Australian Plates. The Irian Shear System in its final shape is a

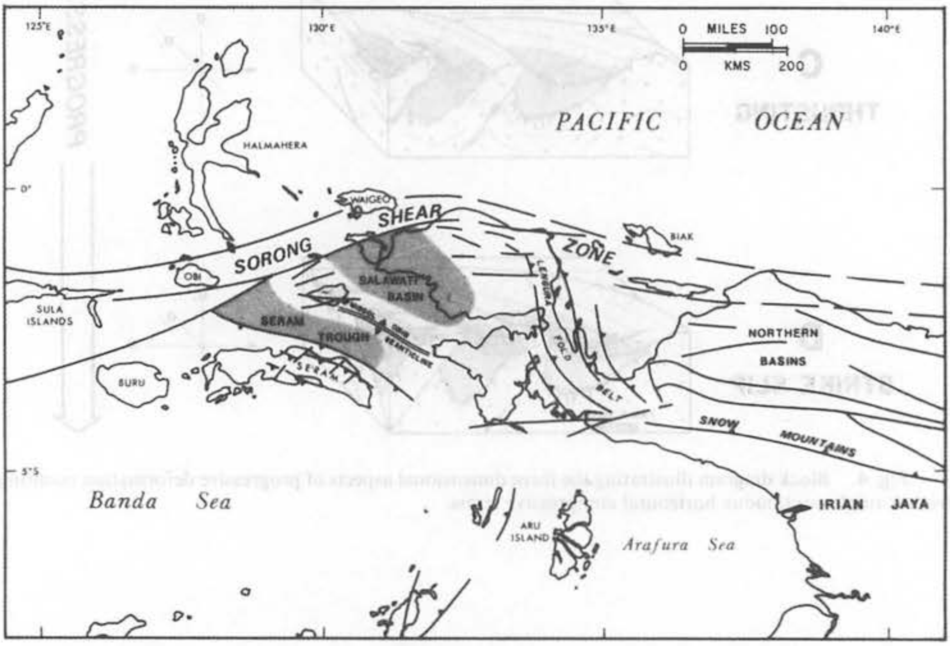


Fig. 5. The Irian Shear System.

series of northwest trending basins and uplifts forming an undulating surface along the length of the east-west striking Sorong Fault.

The Tertiary stratigraphy and structural events of four areas highlight the above sequences: Misool Island lying on the northern limit of the Misool–Onin Geanticline; the Salawati Basin and its southern extension into the Bintuni Basin; the Lengurra Fold Belt; and the extensive east-west Sorong Shear Zone of Northern Irian Jaya and Papua New Guinea.

Misool Island

Misool Island, exposing one of the most complete Mesozoic sections in Southeast Asia, has a noticeably reduced Tertiary section (Pigram *et al.*, 1982). The island lies on the flank of the Misool–Onin Geanticline, an anticlinorium plunging southeastward from Misool Island under the Seram sea before rising again in the south to underlie the Onin Peninsula of Western Irian Jaya (Froidevaux, 1977). The Mesozoic section of eastern Misool Island is overlain by the calcareous quartz sandstones and sandy limestones of the Eocene Daram Sandstone. The Daram Sandstones grade upward into the Zaag Carbonates of Eocene to Oligocene age a section formerly lumped entirely by Visser and Hermes (1962) into an equivalent of the Eocene Faumai Limestone of the Birdshead in Irian Jaya. A late Oligocene to early Miocene unconformity places early Miocene rocks on the Zaag limestones. This early Miocene is conformably overlain in the east by the Miocene Openta Limestone, however to the west over the crestal position of the anticlinorium, the Openta Limestone directly overlies successively older Cretaceous formations indicating uplift of the anticlinorium during the late Oligocene to early Miocene period.

This significant late Oligocene to early Miocene unconformity was recognized by Pigram *et al.*, (1982). They realized that it was not a local event and equated it to the late Oligocene major orogenic folding event in the central mountain belt of Irian Jaya (Van Bemmelen, 1970, Dow, 1977, Jaques and Robinson, 1977).

Lengurra Fold Belt

This folded and thrusted mountain belt extends in a gently eastward sweeping arc south from the Sorong Shear Zone to join the Snow Mountain Ranges, the east-west backbone of Irian Jaya and Papua New Guinea. The ranges consist of Palaeozoic to Palaeogene rocks thrust westward over the Bintuni Basin and south over the Arafura Basins. Van Bemmelen (1970) identified two stages in the development of these mountains, beginning with uplift in the Oligocene followed by younger Neogene and Quaternary south and westward thrusting.

The stratigraphy of the northern Arafura Platform (Nicol, 1970, Visser and Holmes 1962) also suggests this middle Tertiary derivation of the Lengurra Fold Belt. The Mesozoic and early Tertiary sediment provenance was an elevated Australian Plate to the south and west. However, beginning in the late Miocene or early Pliocene time a north and northeast source can be recognized in the sedimentary section (Visser and Hermes, 1962, Oppel, 1970) indicating a rising land mass in the vicinity of the

Central Ranges of Irian Jaya. Sediment influx from the north continued to increase through the Pliocene and into the Pleistocene.

Salawati and Bintuni Basins

The Bintuni and Salawati Basins contain early Tertiary to Recent sedimentary rocks.

The Salawati Basin, a north plunging synclinal trough lying between the Onin-Misool Geanticline and the Lengurra Fold Belt, contains in excess of 20,000 feet of marine Tertiary sediments (Trend, 1973). Basin development began in Palaeocene to Oligocene times. Sediments of this age are not well documented but consist of shelf carbonates with minor shallow marine shales and sandstones. Basin formation increased in intensity early in the Miocene and dark grey basinal limestones and shales were deposited at a time when the adjacent Misool–Onin Geanticline was rising. Development of the basin continued up through the Miocene with more or less continuous deposition of shale in the basin center with intertonguing of fringing carbonates. Renewed uplift in the Pliocene initiated a new regressive phase of sedimentation which deposited sandy glauconitic shales initially and alluvial-deltaic sands, shales and coal beds, as the uplift of the basin margins continued.

The Bintuni Basin, a southern extension of the Salawati Basin, contains the same sequence of rocks. The depocenter of this Basin, however, lies under the leading edge of the Lengurra Thrust Belt, a relationship revealed by the early gravimetric surveys in the area (Visser and Hermes, 1962). This configuration and the fact that these basins overlie Australian continental crust strongly suggests an "A" subduction type boundary as defined by Bally (1983). Structuring of the eastern margin of the Salawati Basin during this same time was restricted to vertical movements (Trend, 1973).

The Sorong Shear Zone

The Sorong Shear Zone is an anastomosing network of near vertical faults bounding the northern edge of the Salawati Basin and extending eastwards more than 1500 km along the northern margin of Irian Jaya and Papua New Guinea and westward some 800 km towards Sulawesi. It is a large left-lateral transcurrent fault zone separating the westward moving Pacific oceanic plate from the Australian continental plate with displacement estimated to be as much as 600 kilometres. The system has been active from middle Pliocene to Pleistocene time (Froidevaux, 1977). The location of recent earthquake epicenters in western Irian Jaya, along the Sorong Shear Zone, in the Seram Island area and along the Arguni Bay Fault Zone south of the Bintuni Basin, suggests that the Salawati area is still under the effect of this east-west left-lateral fault system (Froidevaux, 1977, Pigott *et al.*, 1982).

It is interesting to note that Froidevaux (1977) suggests a 13° counter-clockwise rotation for the island of Salawati. The geometric configuration of the Lengurra Fold Belt and the Misool–Onin Ridge with the intervening downwarp containing the Salawati and Bintuni Basins is also suggestive of counter-clockwise rotation of the area. The area appears to have been swept and squeezed laterally west and south away from the Sorong Fault Zone in a propagating wave-like pattern. Pigott *et al.*, (1982) recognised increasingly oblique subduction along the northern margin of Irian Jaya and Papua New Guinea, an idea also consistent with counter-clockwise rotation of the entire area while the major driving force, the Pacific Plate, remained constant in direction.

SABAH SHEAR SYSTEM

Sabah occupies the northeastern corner of Borneo and is built of sedimentary and extrusive and intrusive igneous rocks of upper Cretaceous, Tertiary, and Quaternary age. Evidence regarding the stratigraphic and structural history of this area has been obtained from a variety of sources but leans heavily on work done by the Geological Survey of Malaysia.

Figure 6 outlines the Sabah Shear System. An apparent northwest directed compressive force has acted on this area at least since lower Tertiary times (Bol and Van Hoorn, 1980, Beddoes, 1976) folding the basement of upper Cretaceous and lower Tertiary rocks into northeast trending, faulted ridges and troughs. Extrusive rocks flooded the area of Central Sabah along north-northwest trending fractures during this same period while folding continuously created provenance and catchment areas for sediments. Deposition began over the upper Mesozoic/lower Tertiary eroded surface in the lower Miocene; was intensified at the end of Miocene time by renewed uplift involving basement thrusting from the southeast; and continued through the Pliocene and Pleistocene. Pliocene volcanics and intrusives in Central Sabah attest to Pliocene structural activity, at a time when shearing movements broke and offset, along strike-slip faults, the northeast trending basins strung along the northeast coast of Sabah. This late stage of deformation imparted the final form to the Sabah Shear System. Differential shear across the width of Central Sabah during this time resulted in the sigmoidal shape of the Central Sabah basement folds. This type of deformation will be dealt with more thoroughly in a later section.

Evidence for the above sequence lies in the geology of Sabah. The oldest rocks comprise chert-spilites, pyroclastics and sedimentary rocks which have yielded microfossils of upper Cretaceous and Cretaceous to Eocene age (Fitch, 1958). This group of rocks forms the backbone of the region in Central Sabah.

Discordantly overlying this folded basement complex in individual downwarps are lower and upper Miocene rocks composed of sandstones and shales with minor carbonates in the lower section. The upper Miocene is generally more argillaceous and often contains carbonaceous material. On the Dent Peninsula a final late Miocene to Pleistocene regressive unit overlies early Miocene clastics around a complex anticlinal nose which forms the eastern tip of the Dent Peninsula. Magmatic activity is evident in two areas. Around Mount Kinabalu the sedimentary cover is intruded by a number of Pliocene hypabyssal stocks while fringing the northeast margin of the Tarakan Basin is an area of Pliocene or younger extrusive volcanics. Evidently the structuring of Sabah since middle Tertiary time has been a combination of folding, thrusting and wrench faulting. Mid Tertiary folding is indicated by the discordancy between Eocene and Miocene sediments in the east-northeast trending downwarps along the northeast coast of Sabah (Figure 6) and the absence of Miocene on the intervening arches.

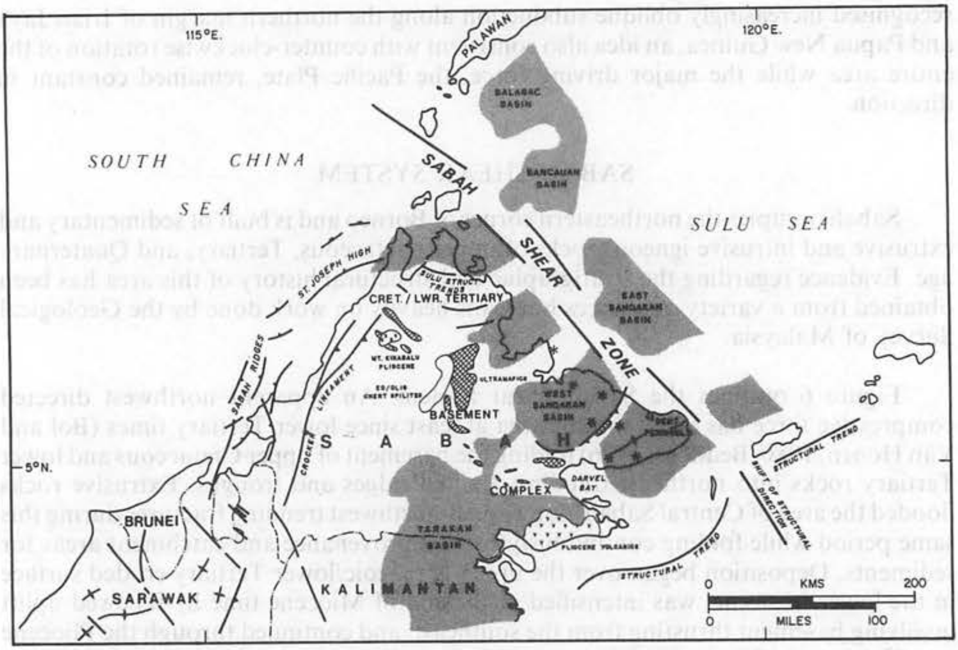


Fig. 6. The Sabah Shear System.

Sedimentation patterns indicate a dominant source from the southwest in Central Sabah, an area tectonically active at intervals since early Tertiary times.

These east-northeast trending basins are not a feature unique to northeast Sabah. Early Tarakan Basin sediments in northeast Kalimantan, Indonesia were deposited in four distinct sub-basins divided by east-west trending pre- to early Tertiary tectonic arches. Eocene and Oligocene sediments filled the east-northeast trending Melawi and Mandai Basins of Central Kalimantan (Van Bemmelen, 1970) and in the offshore area of Sarawak, Malaysia, upper Eocene to lower Miocene clastics flooded northeast filling a northeast plunging trough (Doust, 1977). Apparently the whole Borneo Region has undergone early Tertiary crustal shortening by folding about an east to northeast oriented fold axis.

Thrusting, from local to regional levels, is also common to the Sabah area. A recent study of Landsat data by Lee (1980) in Central and West Sabah has revealed several structural trends. The most prominent lineament of the area, the northeast trending Crocker Lineament, follows an arcuate path, concave to the southeast, and has been defined on the ground as the surface trace of a southeast dipping thrust fault which cuts across older folded strike ridges formed in the Eocene Crocker Formation. This fault can be traced some 144.8 km until it is terminated abruptly, in the vicinity of Mt. Kinabalu, by a zone of north-northwest striking lineaments. Several thrust faults parallel to the Crocker Lineament indicate that it is not unique. Offshore northwest Sabah and offshore northwest Palawan Island, Philippines, similar northeast to east-northeast trending folds and thrusts have been correlated to late Miocene compression (Bol and Van Hoorn, 1980, Hamilton, 1979a).

On a more local level, low angle thrusts have been observed in Sabah in a number of places where they have affected ultrabasic rocks. Along the eastern margin of the ultrabasics, north of Darvel Bay, thrust planes dipping 10°–15° SW and striking N 140° E are recorded (Fitch, 1958). To the southeast the strike of similar surface structures swings east then northeast around the southeast margin of the Miocene West Sandakan Basin. Ultrabasics are exposed in a northeast striking ridge in this region and appear to have been thrust northwest over the Miocene rocks of the Sandakan Basin suggesting at least a late Miocene timing for the thrusting phase of deformation.

Strike-slip faults are well represented in Sabah. Lee (1980) recognized several parallel north to northwest trending lineaments extending from the head of the Tarakan Basin, past Mt. Kinabalu and heading offshore under the South China Sea. These faults dissect the ultrabasic complex and occur at the bend in the Cretaceous–Eocene Basement complex where it changes from a east to southeast direction. This zone of faults and others parallel to it have been recognized by many writers. Tokuyama and Yoshida (1974) suggested a left-lateral fault zone striking across Sabah and Leong (1978) postulated a *"Sabah Blueschist Belt"*, a part shear zone and part melange. Offshore Northeast Sabah a northwest trending shear zone herein called the Sabah Shear zone, with left-lateral offset, has been recognized by surface work (Fitch, 1961) and magnetic surveys (Bosum *et al.*, 1972). Another interesting feature of the Dent Peninsula is a series of mud volcanoes. These line up in parallel rows, trending slightly west of north, and appear to follow a set of fault traces which cut perpendicular across older fold and fault trends. These mud volcanoes appear to occur at the intersections of the northeast trending thrust planes and the north trending strike-slip faults. They are presently active and often lift blocks of lower Miocene sediments to the surface.

TRANS BORNEO SHEAR SYSTEM

Another shear system crosses northwest through the interior of the Island of Borneo from the Makassar Straits to the southern districts of Sarawak, Malaysia (Figure 7). Two major northeast trending Palaeogene basins straddle a wide northwest oriented shear zone. This shear zone is defined in the Makassar Straits by the Paternoster Fault, a fault which separates a carbonate dominated platform to the south from the deep clastic filled Kutei Basin to the north; to the northwest by an offset of the Meratus Mountains and the Samarinda Anticlinorium; in west central Kalimantan by the Semitau Ridge, a northwest oriented uplift; and by the Lupar line lineaments in southern Sarawak, East Malaysia.

To the southwest and northeast of the shear zone a series of northeast trending mountain ranges and basins define an undulating folded and faulted terrain along the

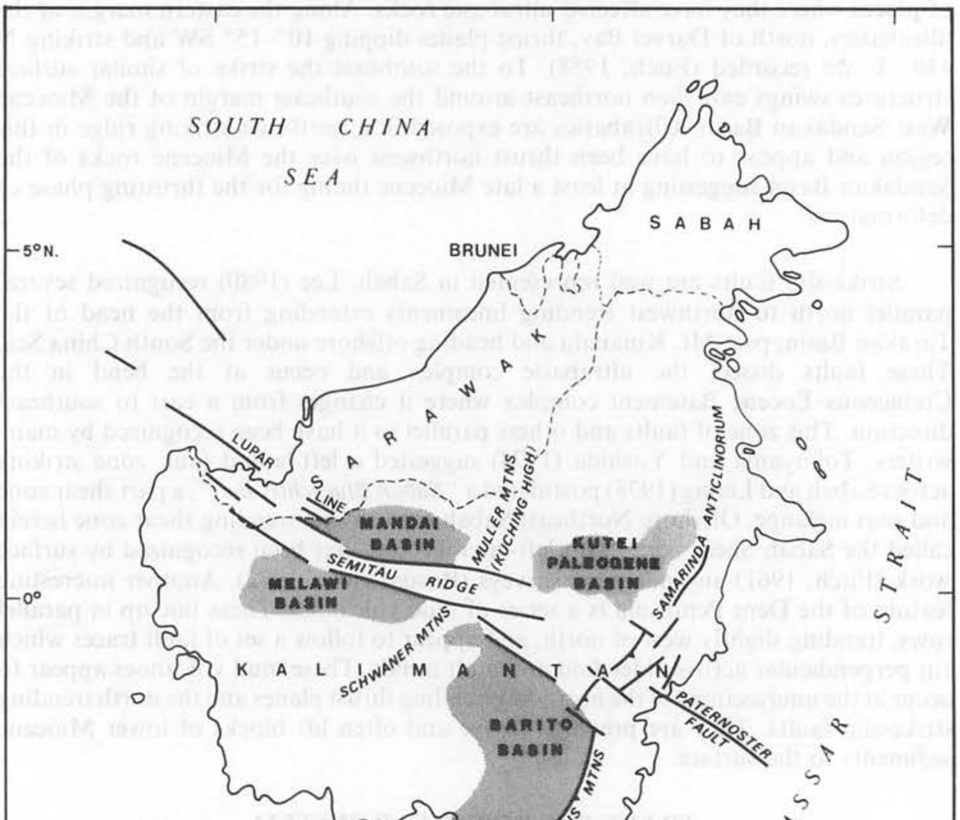


Fig. 7. The Trans Borneo Shear System.

length of the shear zone indicating compression from the southeast and shortening along a southeast-northwest axis. An exceptional example of the sequence involved in this shortening is the southeast margin of the Barito Basin. The Meratus Mountain Range have been thrust northwest over folded basin sediments from the southeast. The Meratus Range is offset in the northern Barito Basin by shears parallel to the Paternoster Fault and the Semitau Ridge to form an arcuate pattern to the mountains, concave to the southeast. A sequence of folding, thrusting and shearing is inferred by these structural relationships.

The early Tertiary stratigraphy of the basins lying adjacent to the shear zone is strikingly similar. In east central Kalimantan, early Tertiary sedimentation was concentrated in a northeast-southwest trending trough covering the present Barito Basin and western Kutei Basin (Samuel *et al.*, 1975). Late Oligocene uplift of the Kuching High resulted in a southeast migration of the basin depocenter and deposition of a thick regressive sequence of bathyal through non-marine clastics in the heart of the basin located under the present intersection of the Northern Barito Basin and the Southern Paloegene Kutei Basin. To the northeast and southwest these sediments interfinger with shallow water shelf limestones, shales and sandstones. An emerging Meratus Range and uplifted Shwaner Massif during the late Miocene, began shedding fanglomerates and these and parallic sediments filled the Barito Basin from the northwest and southeast. The Kutei Basin was dominated by clastic fill from the northwest, burying the Samarinda Anticlinorium and shifting late Miocene to Recent sedimentation to the southeast. The Barito and Palaeogene Kutei Basins areas remained shallow or emergent during the late Tertiary, however, Pleistocene to Recent volcanism produced basic lava flows and cones in the Muller Mountains area (Rose *et al.*, 1978) indicating a late structural reorganization in Central Kalimantan. This may equate to the time of shearing in this area resulting in the left-lateral offset of the northern end of the Meratus Range thrust belt. It should be noted here than Van Bemmelen (1970) places these same volcanics in the upper Palaeogene or lower Neogene. They may, therefore, belong to the late Oligocene uplift of the Kuching High rather than a late Tertiary structural movement.

The Melawi and Mandai Basins of west central Kalimantan are separated by the Semitau Ridge, a northwest striking feature which shows up well on surface geologic maps and landsat data. The Melawi Basin is filled with late Cretaceous and Palaeogene-marine to parallic sediments (Van Bemmelen, 1970, Williams *et al.*, 1984) however their distribution and provenance is presently only poorly defined. The Mandai Basin is less well described but mapping has revealed palaeogene marine sediments (Van Bemmelen, 1970). Neogene sediments are represented only in scattered outliers.

The structural history of these basins is even less well known than the stratigraphy. A pre late Eocene folding event has affected the Melawi Basin sediments and a strong, possibly early Miocene, event has been recorded for the Semitau Ridge (Williams *et al.*, 1984). Van Bemmelen (1970) suggests an initial folding event in the late Cretaceous, a second event at the end of the Palaeogene which affected both basins and a final Neogene event affecting predominantly the Mandai Basin. The uplifted Semitau Ridge has been described as overthrust to the Southwest (Williams *et al.*, 1984) and to the Northeast (Van Bemmelen, 1970) resembling a large scale, bilaterally symmetrical flower structure suggesting an origin in an area of transpression along a major stike-slip fault zone.

The Trans Borneo Shear System fragments the Island of Borneo into two distinct blocks. Similar, albeit less obvious shear faults appear to cross Borneo parallel to the Trans Borneo System and are undoubtedly associated with smaller Shear Systems and further fragmentation of the island.

PACIFIC PLATE MOVEMENTS

A model has been proposed to explain the deformation and decoupling of blocks in Southeast Asia, a model which predicts a pulsating motion during development, which will be felt within all the blocks of the shear system. The Pacific Plate, lying adjacent to the Irian Shear System, provides a good record of this intermittent movement. The timing of activity in adjacent Southeast Asia basins can be related to movements of the Pacific Plate.

Many authors have documented the location, direction and most importantly the duration of spreading of the Western Pacific Marginal Basins (Scott *et al.*, 1980, Jurdy, 1979, De Boer *et al.*, 1980, Taylor and Hayes, 1983, Matsumoto, 1967, Schwan, 1980). The episodic nature of activity within these basins is evident. Activity in the Palaeogene is recorded in magnetic anomalies of the Coral Sea, New Hebrides Basin and West Philippines Basins interrupted only by a short quiet interval from 53–50 Ma (lower Eocene). Activity ceased at about 40 Ma (Eocene-Oligocene boundary) but resumed again in the South Fiji Basin, the Parece Vela Basin, the South China Basin and the Shikoku Basin off Southern Japan at about 33 Ma (mid-Oligocene) and continued through to about 18 Ma (lower Miocene). Activity is again recorded from 7 Ma (Pliocene) to the present. It is more than coincidental that the alternating periods of activity and inactivity from mid Oligocene to the present coincide with the phases of folding, thrusting and strike-slip faulting as recorded in the sediments and structures of Irian Jaya, Indonesia, and other Southeast Asian bordering areas.

SUMMARY

1. An undeformed block, when stressed, deforms in a predictable, sequential manner, first by folding, then by thrusting, until finally it is segmented by strike-slip faulting. The structurally deformed area forms a linear belt, or Shear System, consisting of folded, thrusted and sheared terrain.

2. Along the length of these shear zones lows and highs form an undulating surface, with wave-like regularity.

3. These Shear Systems have bilateral symmetry in cross-section.

4. The Shear Systems separate or decouple blocks which will then be free to deform independently.

5. The intensity and duration of deformation along a shear system will depend on the angle between the strike of the mobile belt and σ_1. The more oblique the stress, the less the deformation which will occur.

6. Movement during the deformation cycle will be episodic, slowing gradually towards the end of each stage. Decoupling will occur rapidly terminating each successive stage.

PROGRESSIVE DEFORMATION—A CONTINUING PROCESS CONCEPT—THE MARGINAL (BACK ARC) BASIN AND PRIMARY ROTATION

If the intuitive logic previously used when describing the initial stages of deformation is again adhered to, then shortening by strike-slip motion or shearing must also have finite limits. There is also no reason to believe that the direction of maximum compression (σ_1) should now change. Indeed it is more reasonable to believe that this direction remains constant and continues to be horizontal and westerly directed.

With these assumptions the following situation would now exist in the area of Southeast Asia. The crust would be fragmented into elongate east-west splinters along sub-parallel shear systems (detachment zones). σ_1 would be horizontal and westerly directed and σ_3, the direction of least confinement, would be horizontal and oriented north-south. Such narrow slices of crust would react much like beams to horizontal stress (Karig *et al.*, 1978). End-loading of these lithospheric *"beams"* from the east would create conditions favourable for buckle folding of the narrow platelets. Three tectonic settings for buckle folding of these lithospheric platelets will be considered. The first will be a setting marginal to a massive continental plate, the second within the interior of a massive continental plate and the third setting will be endloading of a microplate.

Figure 8 illustrates the concept of marginal buckle folding of a large continental plate in a left-lateral system common to Southeast Asia. Compression (σ_1) remains constant and the continental mass at the lower area of the figure is relatively rigid and immovable. As the narrow marginal strip of continental crust is end-loaded in the vicinity of point B, the platelet begins to buckle or arch in the direction of σ_3 pivoting away from the continental mass in an area near point A. The core of the buckle fold will break along tension fractures parallel to σ_1 initiating a zone of spreading. As buckling progresses the detachment zone (Shear System) will propogate to the left (westward). Point A therefore will migrate and the buckling crustal strip, now an Arc complex, will continue to grow and be thrust laterally up and out over the adjacent area while behind the arc a basin will simultaneously open between points A and B. The radius of the arc will decrease continuously, although not symmetrically. As buckling progresses the arc's radius will decrease more dramatically towards point B.

The spreading centers in the back-arc basin will successively rotate counter-clockwise away from the σ_1 direction and progressively becoming inactive. Rotation of

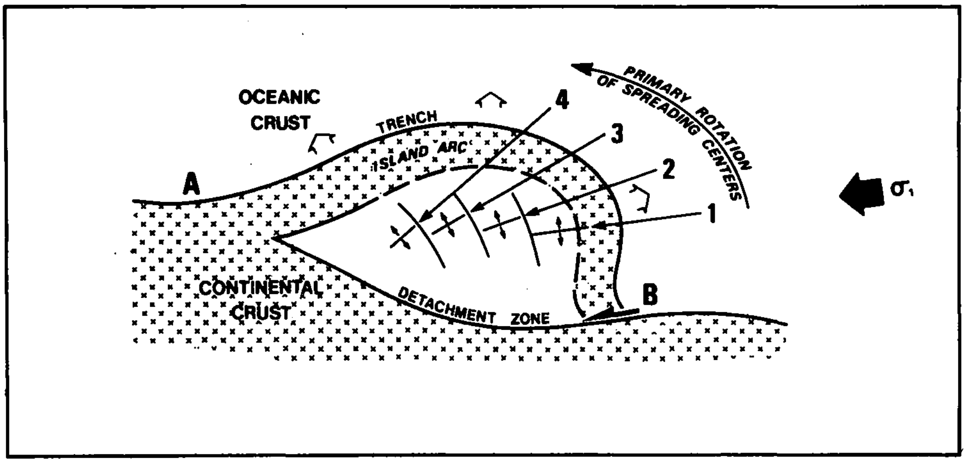


Fig. 8. Buckle folding of a splinter of continental crust at a plate margin. The splinter buckles laterally in the direction of the open arrows creating an Island Arc and Back-Arc Basin. Expansion of the basin occurs at tension fractures created perpendicular to sigma 1 (σ_1). Rotation of these spreading centres occurs simultaneously with the buckling and is accommodated by radial short offset transforms.

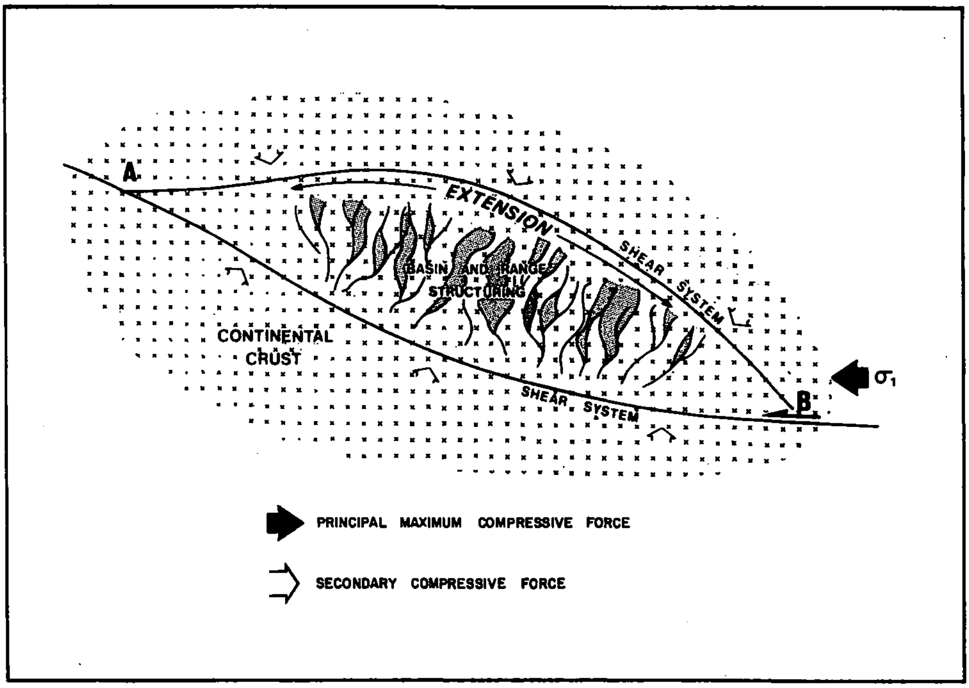


Fig. 9. Deformation of a confined crustal fragment.

the spreading center, herein called Primary Rotation, will be accommodated by arcuate transforms, across which the sense of offset of the spreading ridges will be right-lateral, opposite the sense of offset across the plate margin Shear System.

Figure 9 illustrates the concept of platelet buckle-folding where the platelet is confined within the interior of a massive continental plate. The platelet is shown to lie between two Shear Systems. As it is endloaded in the vicinity of point B, the platelet will begin to buckle or arch laterally. However, a lateral restriction to movement, apparently due to a resistance to vertical movement by equally buoyant confronting plates, will increase the confining stresses acting on the platelet and set up a tremendous secondary cross-plate component of compression. Tension gashes will open parallel to this cross-plate compressional stress resulting in an overall Basin and Range structuring of the platelet.

Figure 10 illustrates end-loading of a small Continental Plate or Micro-Plate. End-loading in the vicinity of point B will, through progressive deformation of the plate, split the plate into two independent fragments along a central Shear System. This Shear System will provide the detachment zone as the two platelets buckle away from each other forming two divergent Island Arcs which will actively override the adjacent plates. Behind the two Island Arcs an elliptical Back Arc Basin will develop with new oceanic crust forming at spreading centers parallel to the maximum stress direction. The primary rotation of these spreading centers with time will be dependent on the orientation of σ_1 relative to the length of the microplate.

This paper has expanded the idea of tectonic buckle folding by adapting established concepts of small scale buckle folding in sedimentary rocks and applying these on a global scale. A more extensive review of buckle folding reveals the following points which have added ramifications for the study of tectonics.

1. The wave length of the buckle will be linked to the width of the folding plate and the rigidity and/or the viscosity contrast of the plate with its surrounding material. Therefore if the buckling plate can be thrust laterally up and over top of the impinging or adjacent plate, like a continental plate overthrusting a simultaneously downgoing oceanic plate, rigidity and viscosity of the surrounding material becomes negligible as thrusting progresses. However if uplift and overriding of an adjacent plate is not possible, as in the case of two similar opposing plates, then resistance to buckling will become intense. This will set up the tremendous cross-plate horizontal compression mentioned earlier, resulting in cross-plate tension fracturing and intense plate margin deformation (Figure 9). This restraint against buckling may be due to an increase in plate size or plate position between two similar confining plates.

2. During buckling a single deforming plate will undergo extension along its outer margin. This may account for the lateral segmentation commonly found in Island Arcs (Ranneft, 1979, Meyerhoff and Meyerhoff, 1976, Murphy 1973). This may however be more a function of later rotation (secondary rotation)—a concept developed later in this paper.

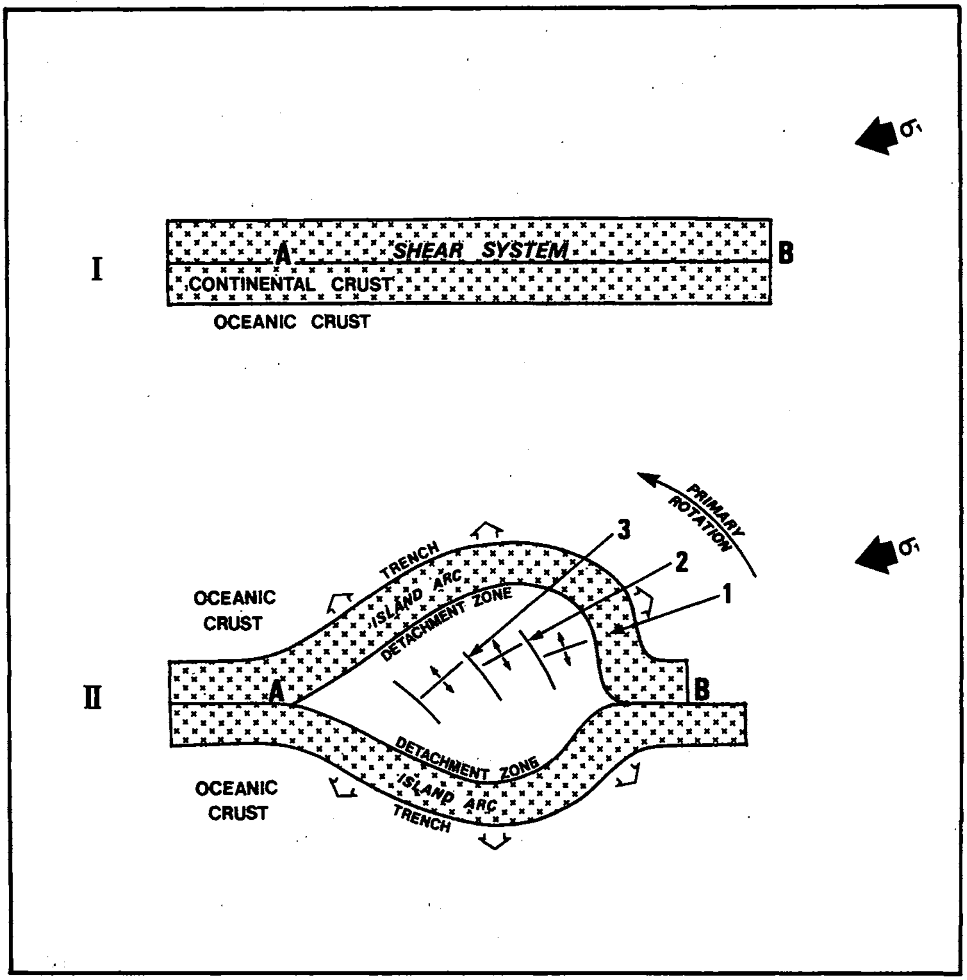


Fig. 10. End loading of a Microplate. Fragmentation of the Microplate along a Shear System and the resulting divergent lateral bulging of the two platelets leaves two opposing Island Arcs and an elliptically shaped Back-Arc Basin. This diagram demonstrates a situation where σ_1 is not perpendicular to the length of the Microplate resulting in a slight asymmetry of the resultant Island Arcs and some primary counterclockwise rotation of the Back-Arc Basin spreading centres.

3. The volume of bordering ductile materials flanking a buckled arc may limit the extent of buckling both in a time and/or areal sense. In buckle folding of sedimentary layers it is suspected that exhaustion of the bordering ductile material can lead to thrust faulting once the fold cannot grow further because of a lack of "core filling" material. The documented fact that marginal basins do have a time limit to their growth (Jurdy, 1979, Scott *et al.*, 1980, Coleman, 1980, Ben-Avraham, 1978) may imply a limit in availability of core (Back Arc Basin) filling material. Perhaps this will shed some light on arguments for or against models such as the partial subduction and emergence system of McManus and Tate (1978) or the induced convection by a downgoing crustal slab idea of Toksoz and Bird (1976).

4. Scattered about the fully developed Back-Arc Basins are fragments of continental crust. Blocks underlie northeast Palawan Island in the Philippines, southwest Halmahera Island and Bangai Island in Indonesia (Hamilton, 1979a). Other fragments are postulated to underlie eastern and western Mindanao, Philippines, and possibly Reed Bank in the South China Sea (Holloway, 1981). The location and scattering of these blocks is a well documented feature of Southeast Asia (Van Bemmelen, 1970; Curray *et al.*, 1979; Audley–Charles, 1976;-Hutchison, 1984), and is a feature cited to back expansionist theories. It is proposed here that the formation of these continental blocks and their dispersal is due to plate end-loading and buckling. The greater the buckling the greater the dispersal of continental fragments accounting for the increase of scattering from the Indochina Plate northeast to the Philippines Plate.

5. Interesting features of many Back-Arc Basins are the aseismic ridges of intermediate crustal material, although often associated with continental fragments, lying perpendicular to the island arcs and sub-parallel to the spreading ridges. The Oki Daito Ridge in the North Philippines Basin, the Palawan Ridge between Sabah, Malaysia, and Mindoro, Philippines, and the Sulu Ridge between Sabah and Mindanao, are prime examples. These ridges are sinuous along their length and where they meet the outer arcs appear to act as rigid rams indenting the outer arcs. These ridges must be elongate fragments of an old plate formed during the cross-plate compressional phase of buckling. These would then be dispersed during further buckling and back-arc extension. Such an origin would account for their rigidity and their resistance to compression. Their sinuous outlines would indicate some shear folding along intraplate shear faults in response to a cross-plate tortional compression, a common phenomenon considered in a later section of this paper.

ANDAMAN BASIN

The first marginal basin to be considered occurs along the western margin of the Southeast Asia region. The Andaman Basin (Figure 11) lies between Sumatra, Indonesia, the west Malaysian Peninsula, the south coast of Burma and the Andaman Islands of India. Although this basin lies within a right-lateral rather than left-lateral it is included as it is an outstanding example of a Back-Arc Basin. The Andaman Basin lies along the southwest facing margin of the Sunda Plate and has been at least since Miocene times (Curray *et al.*, 1979), under the influence of an oblique compressive force

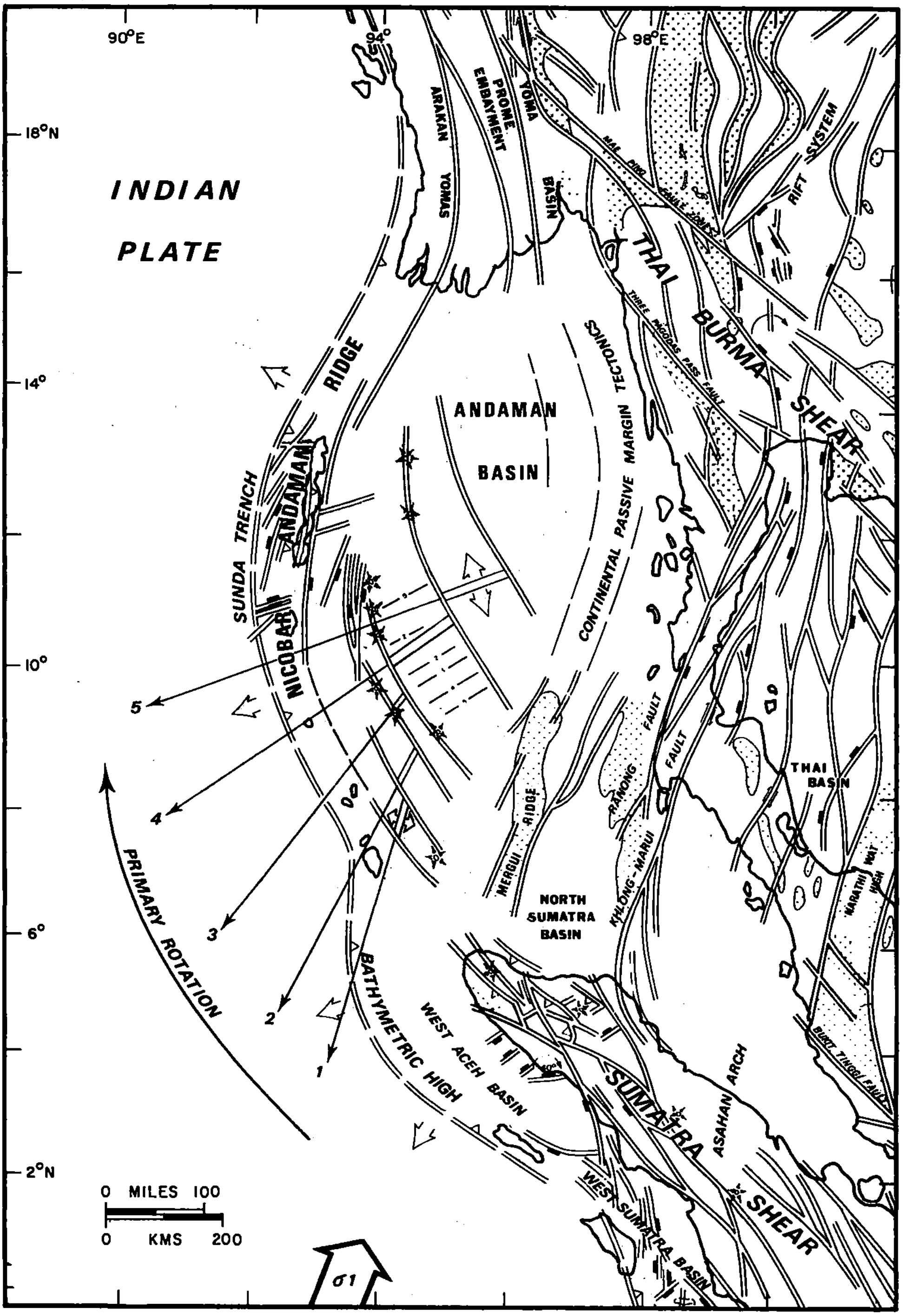


Fig. 11. The Andaman Basin.

(σ_1) directed just east of north (Cameron *et al.*, 1980). The overriding Sunda Plate has responded to this oblique convergence by rupturing along a right-lateral strike-slip fault zone along the length of the Island of Sumatra, the Andaman Nicobar Ridge and western Burma (Beck, 1983, Curray *et al.*, 1979, Aung Khin *et al.*, 1969) breaking loose the micro Burma Plate (Curray *et al.*, 1979) from the margin of the Sunda Plate. Between the northern tip of Sumatra and the southern tip of Burma's Arakan Yoma the Andaman Nicobar Ridge bulges asymmetrically westward overthrusting the Indian Plate at the position of the Sunda Trench. The curvature of this ridge increases southward towards Sumatra. It is important to note that as the ridge curvature increases in a southerly direction the strike of the ridge becomes more oblique to the σ_1 direction and the component of compression increases. This increased compression is indicated by an increase in the width of the Sumatra Semenard Fault in North Sumatra and an increase in the incidents of thrusting in the same area. Behind the arc, extension in the back-arc basin has been active at least since Miocene times as determined by magnetic profiling. Spreading has occurred along the length of a median rift, a rift which is neither straight nor continuous. The southern end of the rift is oriented just east of north almost parallel to the direction of σ_1 for the converging Indian Plate while the northern end of the valley is oriented north of east. Furthermore along its length the rift is repeatedly offset left-laterally by short transform faults. This geometric configuration suggests that the rift has intermittently been rotated clockwise through time.

Before leaving this area the author directs the readers' attention to Figure 12, depicting an area just south of the Andaman Basin along the coast of N.W. Sumatra. Note the West Aceh Basin and the Island Arc containing Simeulue Island which curves first gently then more strongly eastward at its southern end until it is terminated by the Batee Fault. This small area has been deformed by buckle folding in response to northward movement of the Indian Plate in exactly the same way as the larger Andaman Sea area and demonstrates dramatically that the forearc of Sumatra is not a simple rising subduction (Karig *et al.*, 1980) complex as often suggested by two dimensional subduction models but is a complex series of buckle folded platelets. This is not unique to Sumatra. This small scale buckling is in fact common to all major plate boundaries. The Savu Basin north of Timor will be considered in this contex later in this paper.

BISMARCK BASIN

In the area of the Andaman Sea the rigid Sunda Plate remained relatively immobile throughout the period of deformation and basin formation was basically one-sided. The Bismarck Basin represents a back-arc depression formed during the end-loading and lengthwise splitting of a small continental fragment. The divergent lateral bulging of the two resulting platelets has left two opposing Island Arcs and an elliptically shaped back-arc basin. Figure 13 shows the structural setting of the region surrounding the Bismarck Basin. The northern boundary of the basin is formed by a double ridge which forms a convex northward arc of islands including the Admiralty Islands and New Ireland. This Island Arc has been thrust northward over the West Melanesian Trench area. The southern boundary of the basin is formed by the Islands of New Britain and the north coast of Papua New Guinea. This arc of islands and the

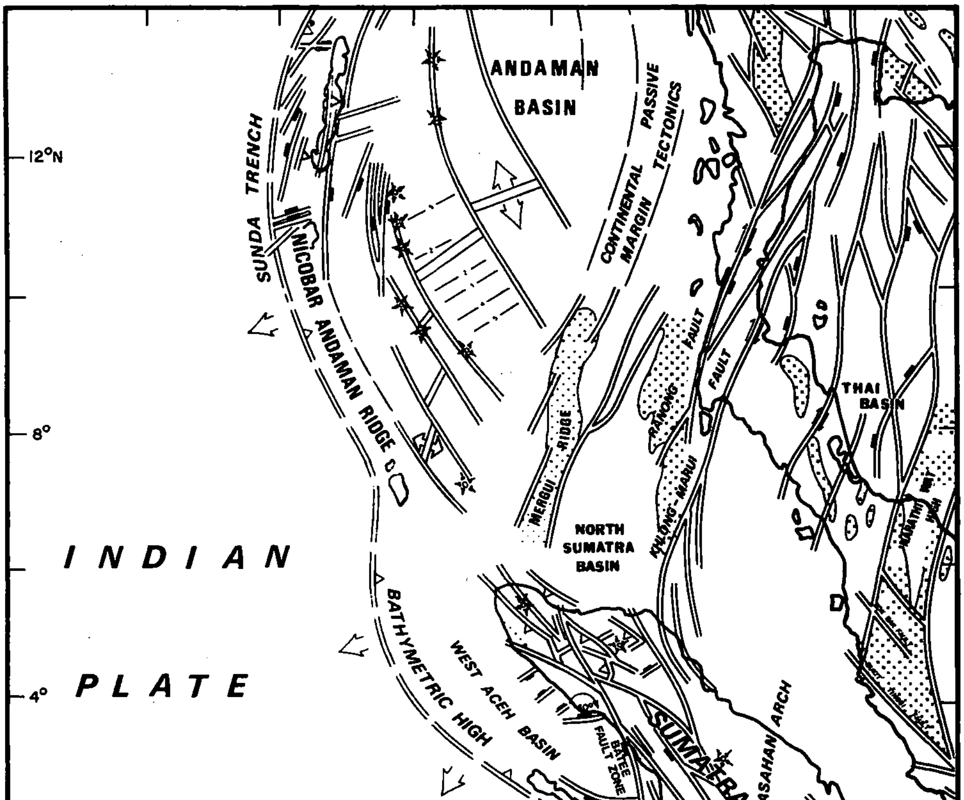


Fig. 12. The North Sumatra Basin.

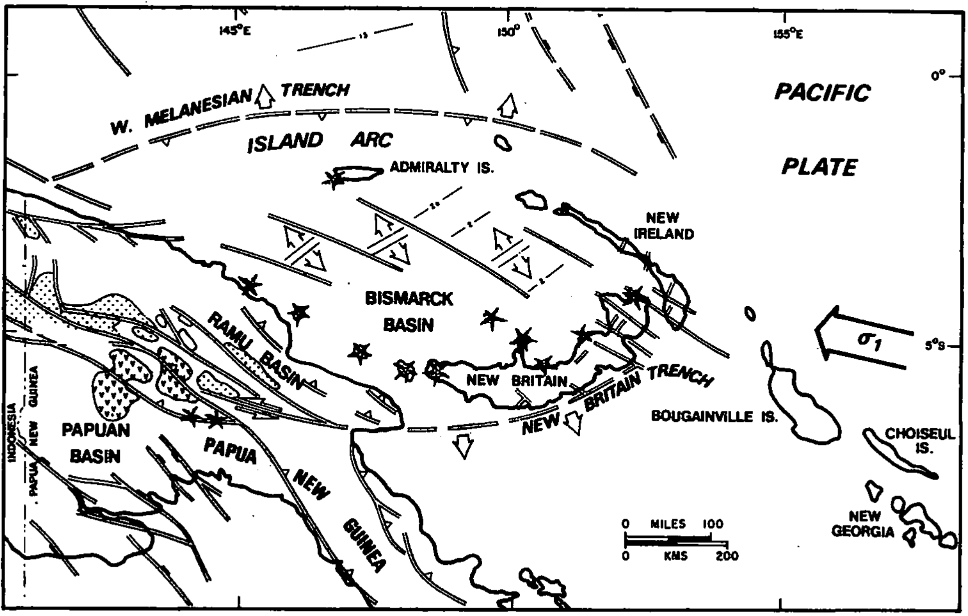


Fig. 13. The Bismarck Basin.

coastal area have been thrust southward over the New Britain Trench and Ramu Basinal area. The Bismarck Basin is floored by oceanic crust which has formed at spreading ridges which are offset in a right-lateral sense. The most westerly spreading ridge is directed more northerly than the more eastern ridges indicating some counter-clockwise rotation through time. The offset of ridges has been accommodated by short transform faults. Magnetic anomalies (circumpacific council map) indicate Pliocene for a minimum age of basin formation.

PARECE VELA BASIN AND MARIANA TROUGH

The Parece Vela Basin and the Mariana trench, arc and basin complex (Figure 14) is a youthful Island Arc area with orientations apparently at odds with other arc systems in the Western Pacific. This uniqueness has stimulated several studies in recent years (Karig *et al.*, 1978, McCabe and Uyeda, 1983, Latraille *et al.*, 1983, Sinton and Hussong, 1983, Hussong and Sinton, 1983) and resulted in multiple scenarios for the origins of the complex.

Poles of rotation are a standard tool often used to prove or disprove associations of plates or fragments of plates in time and space. Karig *et al.*, (1978) found that *"There is no single finite pole of rotation about which the Mariana Trough can be closed without seriously violating observed fracture zone directions and the geology at both ends of the arc".* Furthermore they concluded that *"The present data suggest that the Mariana Trough has opened as if the frontal arc were a horizontal beam pinned at its northern end and deforming laterally so that fracture zones parallel to the spreading direction have*

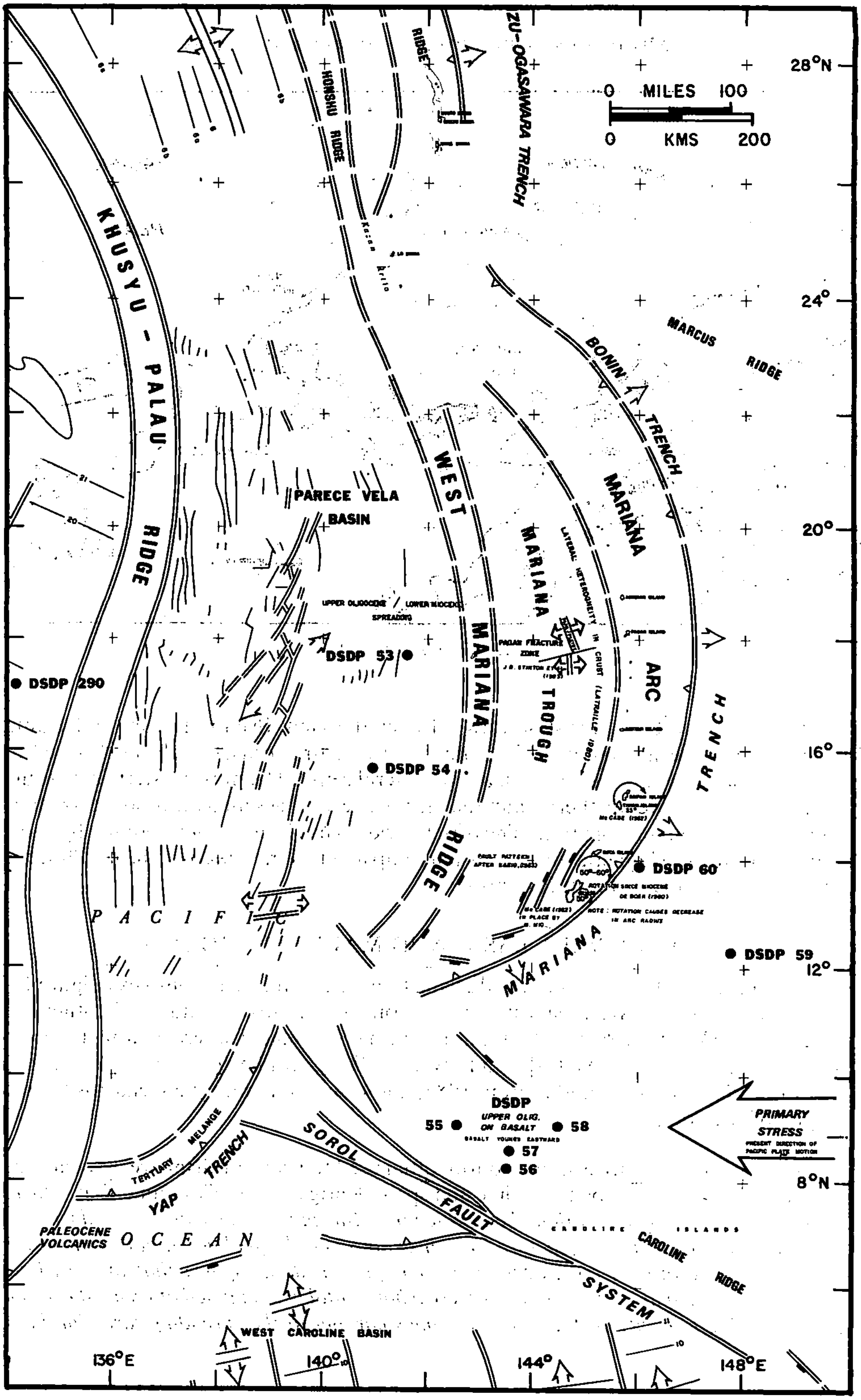


Fig. 14. The Parece Vela Basin and the Mariana trench, arc and basin complex.

themselves undergone minor extension". This idea is equivalent to the buckle folding model introduced here and supportive data are now emerging indicating that the idea is correct. Sinton and Hussong (1983) discuss an east-west oriented short transform fault which offsets the crustal spreading center segment in the central Mariana Trough in a right-lateral sense. McCabe and Uyeda (1983) have demonstrated, using palaeomagnetic data, that the most southern Islands have experienced the greatest clockwise rotation. And, finally, it has been demonstrated that rotation began just prior to the onset of arc formation contrary to the idea that rotation was in response to the opening of the Mariana Trough (Karig *et al.*, 1978, Larson *et al.*, 1975). It is clear that the Caroline Ridge area is the sight of left-lateral strike-slip movement along the Sorol Fault System (Hamilton, 1979a). End-loading of continental strips decoupled from the Philippines Plate in the vicinity of the Caroline Ridge has resulted in northeast lateral buckling of these strips and the opening of, first the Parece Vela Basin in the late Oligocene (Mrozowski and Hayes, 1979, 1980) and then the Mariana Trough in the late Miocene or Pliocene.

PHILIPPINES, SOUTH CHINA AND INDOCHINA PLATES

Figure 15 outlines these three plates. The Philippines Plate has all the attributes of a buckle folded complex. Bound on the east by the Khusyu/Palau, Ridge, on the west by the Philippines Archipelago and on the Northwest by the Nansei-Soyoto Ridge this plate has its Central Fracture Zone, trending just east of southeast, marking the location of the spreading center. This spreading ridge is offset along its length right-laterally by short-offset transforms. Magnetic work has shown that the basin formed about 60 Ma (Palaeocene) with spreading continuing until anomaly 7A or about 26 MA (Oligocene) (Tai-Chang, 1980). During this time the plate drifted northward about 15°–20° and underwent clockwise rotation of 50°–70° since 35–40 Ma (De Boeur *et al.*, 1980). A distinctive bend in the Khusyu–Palau Ridge occurs at about the position of the Palau Trench. To the north the ridge trends roughly north-south but southward the ridge bends sharply to the southwest to Halmahera Island before curving quickly back to the east to emerge with the east-west Sorong Fault Zone.

The Philippines Basin has been formed behind the Khusyu/Palau Ridge as the ridge buckled in response to end-loading near Halmahera Island. The end-loading appears to have been northerly directed. However, as will be discussed later, the Philippines Plate has undergone secondary clockwise rotation since Oliogocene time, after expansion in the Back-Arc Basin ceased. The end-loading stress forming the Philippines Basin was therefore directed more westerly than inferred from the present configuration of the plate.

The South China Plate encompasses the South China Sea area and much of southern mainland China. Its eastern boundary is the arc containing the Philippines Archipelago and Taiwan. This boundary is less well defined where it passes onto mainland China but can be followed as a series of northwesterly to westerly trending strike-slip faults extending from south of Shanghai to Xian separating the northeast trending Ordos and Szechuan Basins. The plate's western boundary is defined by the prominent northwesterly trending shear systems of Sabah, the South China Sea,

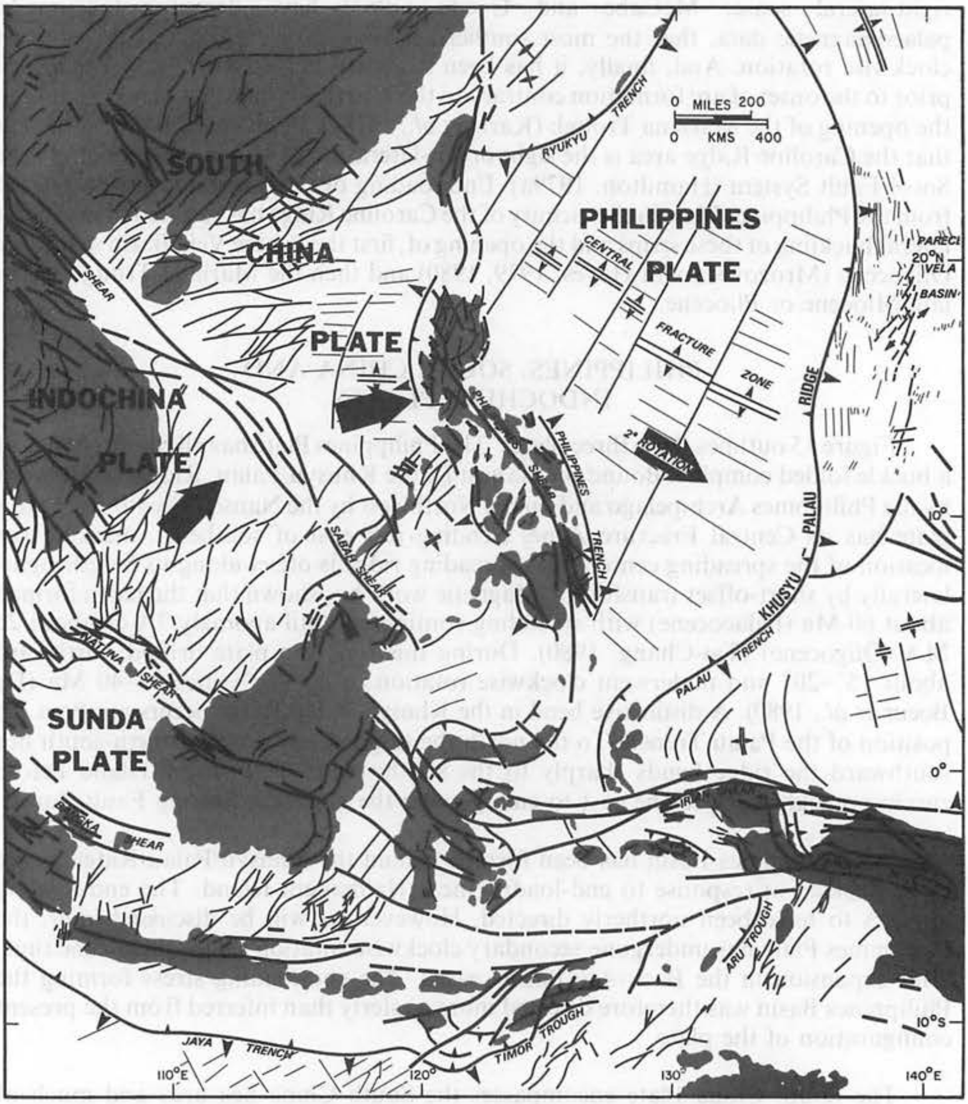


Fig. 15. The Philippines, South China and Indochina Plates.

Northern Vietnam and Laos. The South China Plate where it is underlain by continental crust, features northeasterly to easterly striking basin and range structures, a fault pattern indicating tremendous cross plate compression. In the South China Sea, Sulu Sea and Celebes Sea, the plate is underlain by oceanic crust and magnetic lineations, trending almost easterly, indicate extension at least as old as mid-Oligocene and continuous to at least early Miocene time (Taylor *et al.*, 1983). Right-lateral offset across transforms is also indicated by the magnetic pattern. The basin has actively rotated clockwise during its formation (McManus and Tate, 1978). Once again end-loading of this plate, in the vicinity of Sulawesi, is indicated by the above criteria as well as the abrupt westerly swing of the southern end of the Philippines Archipelago. It is also interesting that the greatest expansion of this plate has occurred where the plate has not been confined by adjacent continental plates, that is, to the southeast and east adjacent to the oceanic Philippines Plate.

The Indochina Plate lies between the South China Plate and the Sunda Plate and is separated from them by two major mobile belts. To the northeast is a belt consisting of the Shear Systems of Sabah, the South China Sea, Vietnam and Laos and to the southwest a belt consisting of the Trans Borneo Shear System and the Thai–Burma System (Ridd, 1971). This plate displays tremendous cross-plate tension faulting oriented approximately northeast to north-northeast indicating a strong cross-plate compression. However, northwest directed compression is also indicated by large northeast striking thrust belts in Sarawak, Sabah, western Thailand and eastern Burma. Finally, a component of torque to the compression is suggested by the sigmoidal shape of the many cross-plate features such as the mountain belt of Vietnam, and the highlands of western Thailand and eastern Burma. This aspect of plate distortion will be expanded in a later section. The IndoChina Plate is under tremendous confining pressures yet has not appeared to buckle significantly possibly due to its position between two dominantly continental plates. However, some expansion due to northeast buckling may have begun in the South China Sea.

OTHER EXAMPLES: S.E. ASIA

Other marginal basins with similar structural histories include, although not so well documented, the Central Basins of Burma and the Savu Basin of Indonesia. They deserve a brief mention.

The Tertiary Burma Basins, Figure 16, were initiated in Eocene times within a rift bounded on the east by the Shan Plateau and the Eastern Highlands and on the west by the Arakan Yomas and Chin Hills. A southerly plunge to the opening rift resulted in a north to south progradation of fluvial and brackish marine clastics from the Eocene to the Pliocene. The initiation of the rift indicates a decoupling of the Arakan Yomas/Chin Hills area from the Eastern Highlands and Shan Plateau areas in Eocene times. End-loading from the south forced the Arakan Yomas/Chin Hills to buckle westward with resultant large-scale continued rifting in the Central Basins area. Lateral westward buckling of the Arakan Yomas/ Chin Hills area was, however, restricted by the proximity of the Indian Continental Plate (Shillong Shield and Mikir Hills) and by mid-Miocene the Burma Region was no longer able to accommodate north-south shortening. The site of shortening shifted south to the Andaman Sea Region where

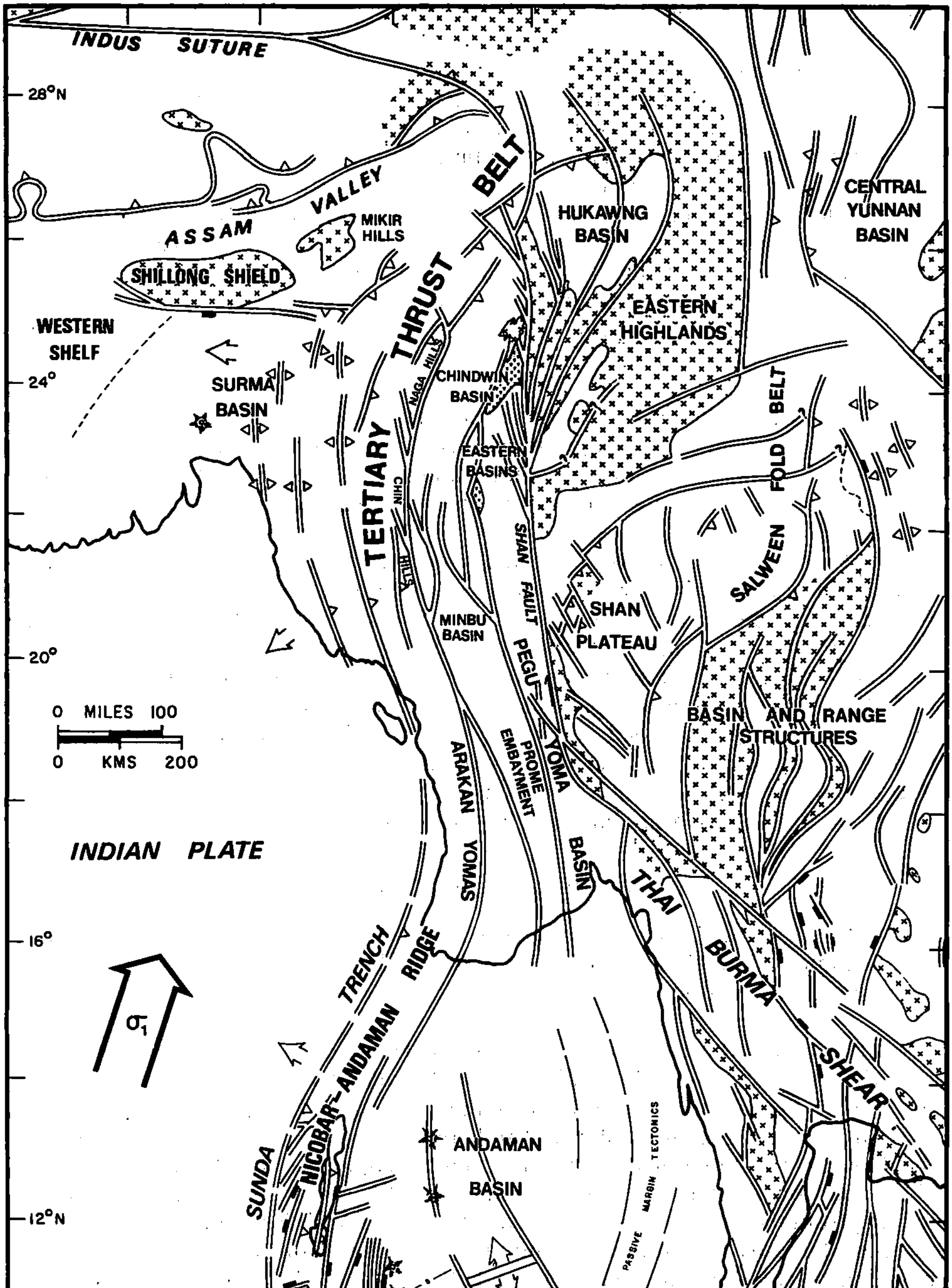


Fig. 16. The Tertiary Burma Basins.

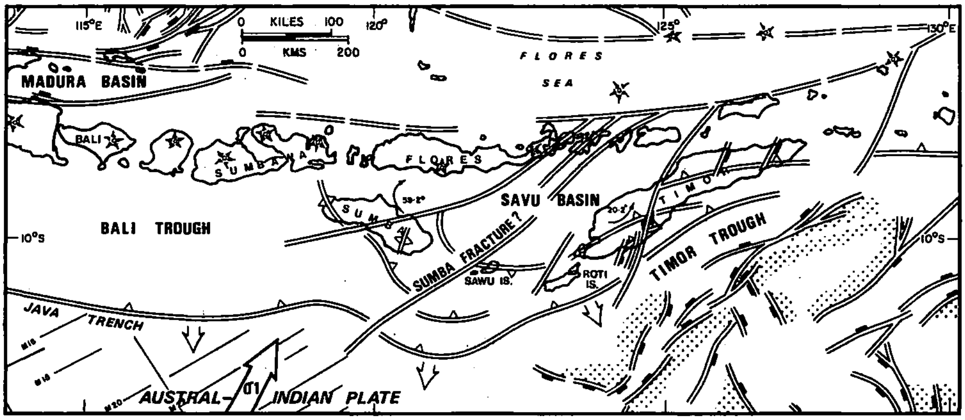


Fig. 17. The Savu Basin of Indonesia.

minimal restriction to westward movements of the Andaman–Nicobar Arch allowed shorteningly by buckle folding to continue to the present time.

The Savu Basin of Indonesia (Figure 17) has been an enigma for years. It is bounded on the south by an arc of islands containing Sumba to the southwest and Timor to the southeast. It has been recognized that this arc of islands is underlain by Australian Continental Crust (Audley–Charles and Carter 1971, Audley–Charles, 1976). The geology of the Islands themselves, however, has a stronger affinity for the Sunda Plate to the north (Audley–Charles, 1976, Von der Borch *et al.*, 1983). It is now proposed that the Islands have been decoupled from the Sunda Plate and displaced by buckle folding southward over the Austral/Indian Plate.

Sumba is composed of Cretaceous to Recent sedimentary and igneous rocks. Its structural grain is created by north-northwest trending undulating folds and faults which are offset, in a left-lateral sense, along an east-northeast trending break across the center of the island. The whole island is tilted north and comprises an exposed part of the Indonesian Forearc (Von der Borch *et al.*, 1983).

To the southeast the islands of Sawu and several adjacent small islands line up in a northeast direction. Thrust structures on Sawu, however, trend almost east-west suggesting that another major offset lies just north of the island. This offset would approximate the site of Audley–Charles' (1975) Sumba Fracture marking the east termination of the Java Trench. The island chain continues to swing east and then northeast to the Island of Timor. Here, east to northeast structural lineaments, offset by north to northeast shear faults, trace the leading edges of south to southeast facing thrust sheets.

Timor is composed of Permian to Recent, igneous, metamorphic and sedimentary rocks recording the following sequence of events. The pre-Tertiary and lower Tertiary are strongly interfolded and thrusted. Eocene sediments, lying directly and discordantly on top (Van Bemmelen, 1970; Audley–Charles and Carter, 1971), indicate a pre-Eocene orogenic event involving southward thrusting on Timor. Following these lower Tertiary events, *"Young Tertiary intensive volcanic activity occurred in the inner zones, north of Timor"*, (Van Bemmelen, 1970) and towards the end of the Neogene the Timor area arched upward while the area to the south bowed downward forming the present Foreland Timor Trough.

Recent palaeomagnetic evidence (Otofuji *et al.*, 1981) from Sumba Island indicate that Sumba was subjected to a clockwise rotation through 79.4° relative to Timor since the Jurassic. This and the physical evidence found on the island chain surrounding the Savu Basin support the idea of a late Mesozoic and lower Tertiary folding and thrusting stage accompanied by development of a south facing Island Arc. The arc formation is compatible with the model of a north to northeast moving Austral/Indian Plate end-loading, from the southwest, a then straight platelet containing the strip from Sumba to Timor and buckling this strip of continental plate into a convex southward Island Arc overriding the Australian Plate margin.

SUMMARY

1. Distinct, Back-Arc Basins of varying dimensions form along the margins of major continental plates where there is a large component of strike-slip movement due to oblique convergence of adjacent plates. Elongate splinters of sheared crust decouple from the main plate mass and are end-loaded as strike-slip motion continues. The leading portion of each splinter remains fixed to the main plate mass while the trailing edge, pushed from behind, slides forward on glide planes provided by the shear zones. Shortening along the length of the shear zone results in buckling of the splinter away from the plate margin and the creation of an Island Arc and extensional Back-Arc Basin.

2. The buckling arc changes its radius of curvature as buckling continues. This change of radius is not constant along the arc but is greatest towards the trailing edge.

3. Initial extension behind the arc appears to be parallel to the arc front and sigma 1. Normal faulting is common, most of which is listric, forming full and half graben structures.

4. Continued extension within the Back-Arc Basin continues to be parallel or near parallel to the end-loading stress inferring that this extension initiates along tension fractures. Upwelling along this spreading rift allows the emplacement of oceanic crust.

5. During arc development, the Back-Arc Basin is rotated. This "primary rotation" is accommodated by short offset arcuate transforms which display a sense of offset opposite the offset of the bounding shear zone.

6. Rotation places a component of compression on the originally purely tensional spreading centers. As rotation continues extension on the early spreading centers

begins to die and spreading in the Back-Arc basin is transferred successively towards the direction of the stress to new spreading ridges.

7. The amount of shortening and therefore the size and life of the Back-Arc Basin is limited by the length and width of the buckling arc.

8. Large intraplate fragments of crust are restricted from buckling by their size and/or confinement by adjacent fragments of equivalent composition. Tremendous cross-plate compression is developed resulting in a cross-plate pattern of tension faults and a Basin and Range structuring of the fragments.

9. End-loading of microplates will fragment these small continental masses lengthwise. Divergent lateral bulging of the two resulting platelets will leave two opposing Island Arcs and an elliptically shaped Back-Arc Basin.

10. The development of Island Arcs and Back-Arc Basins is a process of microtization of continental plates. This is a destructive phase.

PROGRESSIVE DEFORMATION—A FINAL PHASE CONCEPT—SECONDARY PLATE ROTATION AND PLATE DISTORTION

To this point only single shear zones have been considered together with deformation of platelets associated with and adjacent to them, forming Shear Systems, buckled arcs and back-arc marginal basins. In Southeast Asia, cross-cut by multiple left-lateral Shear Systems, three major systems stand out. The Philippines Shear, the Sorong fault through to the Red River Shear via the Palu and Sabah fault zones and the Burma–Thai Shear, are the strike-slip faults associated with these systems. They separate Southeast Asia and southeastern continental China into four well defined plates. The relationship of these plates and their internal deformation is the subject of this section.

Movement of blocks or plates relative to each other is governed by the mobility of the inter-block glide planes, that, is, the shear zones discussed in the foregoing sections. Deformation within individual blocks, on the other hand, is controlled by intra-plate shears. These two movements control (1) secondary plate rotation and (2) plate distortion.

It is well understood, though frequently neglected, that a fault is rarely a single plane but rather a set of subparallel breaks. It is also known that strain along a fault system involves a transfer of small strains from fault plane to fault plane, more often that not, in a fairly regular pattern. The best documentation of strain transfer is contained in literature dealing with thrust faulting and Figure 18 is a simple demonstration of the steps involved in shortening of a thrusted faulted block, shortening occurring over three faults. Sigma 1 is horizontal and sigma 3 is vertical. The oldest fault, No. 1, dies out by rising to the surface seeking a less confined space in the direction of Sigma 3. As it rises it bifurcates as well as folds and lifts the rocks

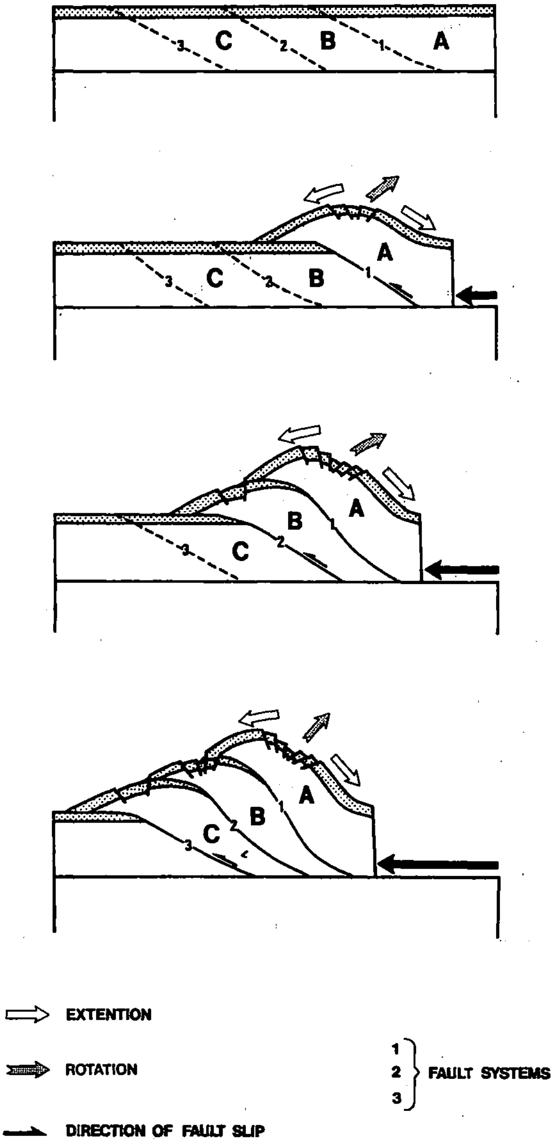


Fig. 18. Fault wedge rotation.

near its leading edge. As the fault plane rises the angle between Sigma 1 and the fault plane increases, compression across the glide plane increases and the fault locks.

There is no reason to believe the existing stress will be relieved and continued stress on the block will result in the new long angled No. 2 fault undercutting the previous fault and the sequence repeating itself. However, as fault Block A is passively carried on the back of Block B, it is raised and rotated back on itself towards the direction of sigma 1. Extension of Block A occurs over the top of the rising anticlinorium accommodated by extensional faulting, normal to the curvature of the anticline. Repeating the sequence will repeatedly uplift and further rotate the earlier detached blocks.

A similar sequence of events is conceived to occur in multiple strike-slip systems (Figure 19). Sigma 1 is still horizontal but sigma 3 is now also horizontal rather than Sigma 2. Initially, overall shortening will occur along a shear system near the margin of the continent plate (Figure 19-1). Continued shortening will result in buckle folding and the formation of a marginal Island Arc and Back-Arc Basin and an overall lateral expansion of the region (Figure 19-2). There is again, however, a limit to the amount of shortening which can be accommodated and upon reaching this limit a new shear system will form, cutting deeper into the continental mass, creating a locus for additional shortening (Figure 19-2). As each new shear system undercuts the previous, the newly formed inter-shear fragments will buckle and be driven laterally as back-arc basins open. However, the older arc and back-arc complexes will be passively carried in the direction of the shortening, driven laterally as buckling expands the newly formed fragment perpendicular to the shortening axis, and rotated as in the thrust fault situation, except now movement and rotation will occur in the horizontal plane. The laterally sweeping and rotating blocks will expand along the sweep front, accommodated by extension normal to the arc front. This sweeping movement will be referred as Secondary Rotation, a rotation very distinct from the Primary Rotation of Back-Arc Basins during their formation.

To this point the intershear fragments or plates have been treated as fairly rigid blocks moving independently in response to a single westerly directed force affected only by extensional or compressional forces. However, as the plates are compressed and rotated, tortional stresses are also active resisting the rotational movement and causing a distortion of the original shape of the block. It is proposed that this distortion is accomplished by a mechanism comparable to shear folding (Figure 20). A shear fold typically takes the form of an "s" bend in the rock and the folds in detail are formed by differential slip along a myriad of parallel slip planes. This mechanism is well accepted in discussions of small scale deformation, particularly in metamorphic rocks however, the question here is, *"can this mechanism work at a continental scale?"*. The work of Holcombe (1977) indicates that the rigid Sunda Plate in the area of Banya Island has been deformed in just such a manner by minor slippage along multiple planes forming the Bangka Shear Zone. An overview of Southeast Asia indicates that regional shear folds form large "S" shaped mountain chains between major shear systems. The mountains of Vietnam and Laos form an "S" between the Hanoi (Red River) Shear to the northeast and the Thai-Burma Shear to the southwest. The mountains of Sarawak, Malaysia, are broadly curved into a northeast oriented "S" and the Lengurra fold belt

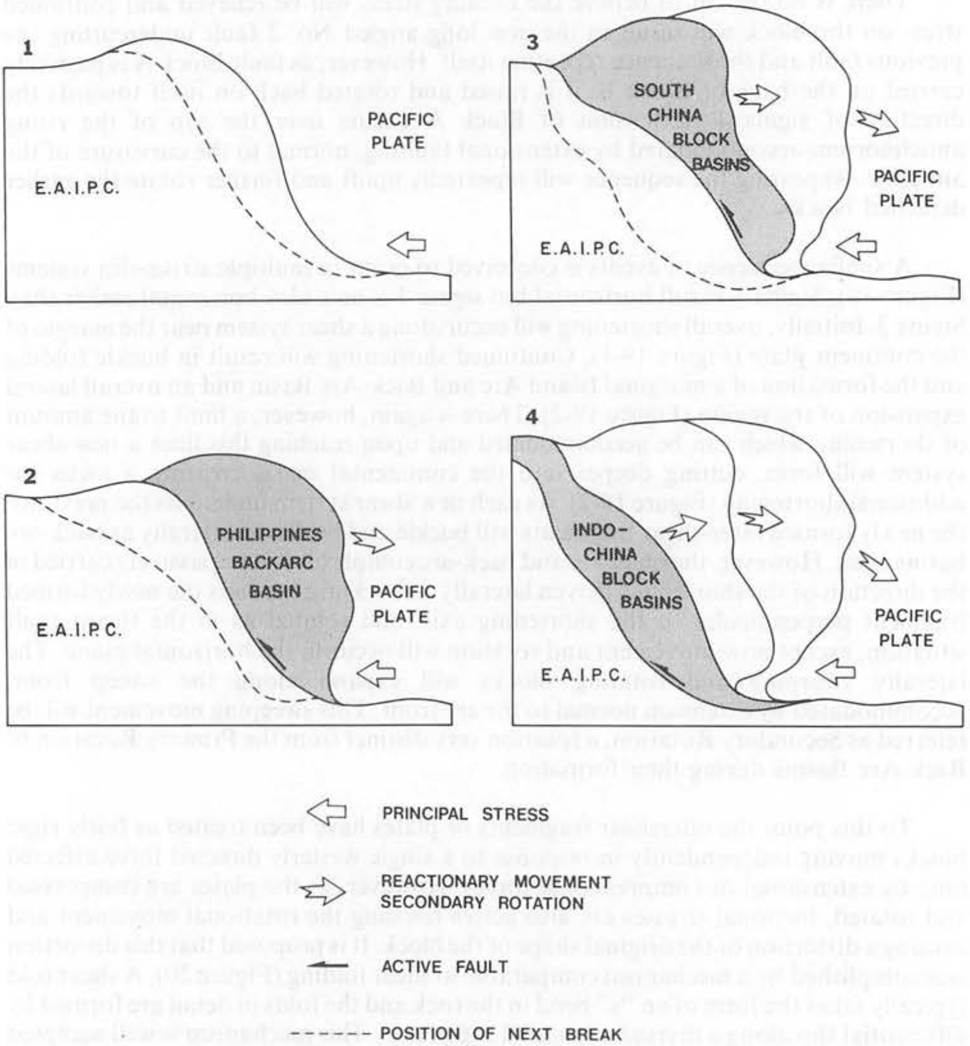
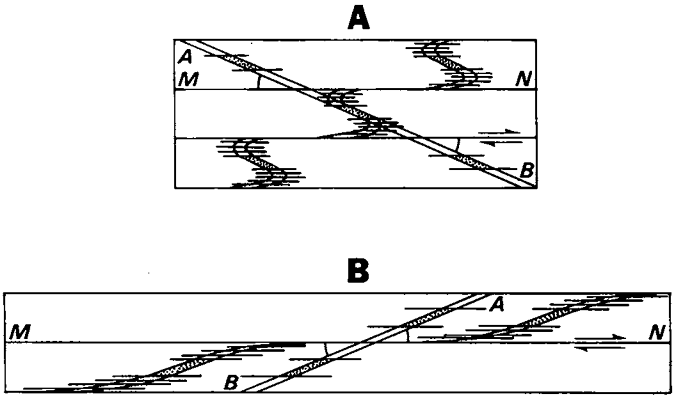


Fig. 19. The Eurasian and Austral/Indian Plate Complex (E.A.I.P.C.) has acted as a buttress, resisting westward movement of the Pacific Plate. Fragmentation of the Plate Complex Margin and end-loading of decoupled fragments have caused deformation by buckling and the formation of Island Arcs and Back-Arc Basins. Successive fragmentation and buckling have rotated previously buckled plates in the horizontal plane, sweeping the plates out over the impinging Pacific Plate. The plate deforming by buckling is stipled.



GLEITBRETTER MECHANISM (SHEAR FOLDING)

Fig. 20. The spacing of shear planes affecting bed AB in the direction of shear MN varies. Dotted sectors of beds remain parallel to their original position. The shape of folds depends on the relative attitude of bed in relation to shear direction (Hills, 1963).

of Irian Jaya, Indonesia, takes a similar shape. It is also interesting to note that the general structural pattern of Thailand and Cambodia show a northeast trending sigmoidal pattern in an area bounded by the Hanoi (Red River) Shear and the Thai–Burma Shear.

These large scale features can be explained as a result of differential movements along intra-plate shear faults and regional compression directed perpendicular to the shear zones. This cross plate compression has been discussed earlier and in the context of laterally sweeping continental plates would be secondary to the primary stress, directed just north of west in Southeast Asia which derives the entire system.

PHILIPPINES, SOUTH CHINA AND INDOCHINA PLATES

These plates have already been described in the context of their formation. However, their relative positions is now of interest.

Figure 21 indicates the ages and structural orientations of the Indochina, South China and Philippines Plates. Magnetic work by Haile *et al.*, (1977) and Haile (1978, 1979), McElhinny *et al.*, (1974), Weissel (1980) and others have defined areas of oceanic crust, spreading centers and the period of activity of each basin. Figure 21 demonstrates the rotations of these basins relative to each other.

The axis of the Philippines Basin has been rotated in total as much as 60° clockwise (DeBoer *et al.*, 1980) and as much as 25° relative to the axis of spreading of the South China Basin. Also, active extension in the Philippines Basin preceeded the opening of the South China Basin.

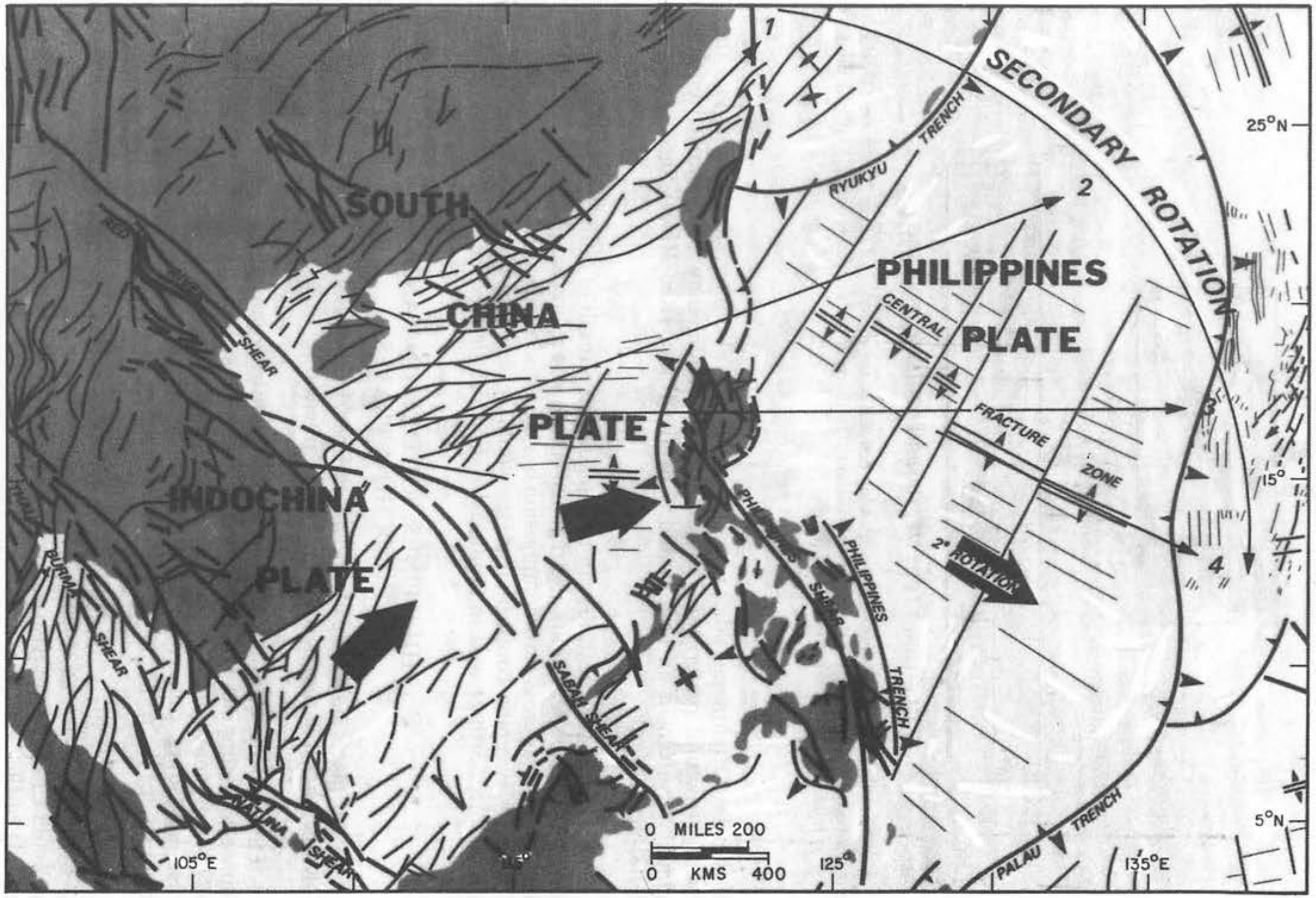


Fig. 21. The structural orientations of the Indochina, South China and Philippines Plates.

The Central Fracture Zone in the Philippines Basin was active from about 60 Ma (Palaeocene) until about 26 MA (Oligocene) (Tai Chang, 1980). Extension of the South China Plate is at least as old as mid-Oligocene and continued to at least early Miocene time (Taylor *et al.*, 1983).

The South China Plate has also been rotated as much as 25° clockwise, this time relative to the Indochina plate, a plate active from Oligocene to Pliocene times. Overall as much as 80° of clockwise rotation is indicated between the Philippines Plate and the Indochina Plates. Restoring these plates counter-clockwise through time, it becomes clear that plate deformation by buckling was due to a westerly directed force and as these plates rotated clockwise away from the stress direction they became inactive. This clockwise rotation has been referred to as secondary rotation.

SUMMARY

Secondary rotation and shear folding of newly formed crustal plates is the third and final phase in the progressive deformation of Southeast Asia. A single westward directed stress has formed, laterally dispersed and rotated crustal blocks leaving a recognizable pattern of Island Arcs and Back-Arc Basins. The following points are noteworthy.

1. Interaction of crustal blocks is controlled by the mobility of interblock Shear Systems. Shear Systems oriented east-west tend to be more mobile than those oriented north-south. As a system is rotated away from its initial eastwest orientation it loses its mobility and locks. New east to northeast trending systems undercut the older systems and take over as sites of mobility.

2. The mechanism of secondary block rotation is viewed as similar to block rotation in thrust faulted terrains except with a reorientation of sigma 2 and 3.

3. Crustal blocks are compressed eastwest and if not buckled, compressed north-south. Compression shatters these blocks and the fragments may then be scattered by later buckling and/or Secondary Rotation.

4. Secondary Rotation occurs as successively adjacent blocks buckle and expand. This action results in crustal blocks sweeping and rotating laterally out over the adjacent area.

5. As blocks are rotated and swept laterally they are subjected to tortional compression and their shape is distorted by shear folding.

6. Blocks have been rotated as much as 60° to 90° or more and now often lie almost perpendicular to the active regional shear systems and the west directed stress.

7. As the plates are rotated clockwise and swept out over the impinging Pacific Plate, the source of the westward compression, they interact and override adjacent plates creating the well known trenches. The overall Southeast Asian structural picture is a result of westward subduction and eastward overriding of plates.

TECTONIC MAP OF SOUTHEAST ASIA

The Tectonic Map of Southeast Asia (Figure 22) has been compiled from published data but incorporates the ideas developed in this paper. The faults have been coded. The interplate and intraplate shear zones are shown as heavy solid lines, the cross-plate tension faults as fine lines and the major thrust systems as lines of intermediate thickness. Secondary Rotation is shown by the solid arrows, while the Pacific and Austral Indian Plate motions are described by the open arrows. The map clearly displays primary and secondary rotation, fragmentation, northeast and southwest expansion, northwest by southeast compression and Island Arc and Back Arc development of Southeast Asia.

Three major Shear Systems, the Philippines, the Red River, and the Thai–Burma–Natuna, separate Southeast Asia into four major plates, the Philippines Plate, the South China Plate, the Indochina Plate and the Sunda Plate. The Khusyu–Palau Ridge may constitute a fifth major Shear System separating the Philippines Plate from the Parece-Vela Plate, however, structural data is sparce over this ridge and confirmation must await further work. Other Shear Systems include the Bangka Shear and the system extending the length of Java, Indonesia, which further segment the southern margin of the Sunda Plate.

Intraplate structural deformation is dominated by anastomosing networks of cross-plate tension faults trending near perpendicular to the marginal Shear Systems. These faults are generally high angle normal faults, often with a component of right-lateral shear due to plate tortional deformation, forming deep half and full graben rift-like basins. Intra-plate shears, paralleling the marginal shear systems, are common and have accommodated plate distortion during rotation by shear folding intra-plate structures resulting in the familiar sigmoidal form of cross-plate structures.

Secondary rotation of the Southeast Asian Plate is visibly demonstrated by the clockwise change in orientation of the cross-plate structures. These structures trend from roughly north-northeast across the Sunda Plate through more than 80° to southeast across the Philippines Plate.

Southeast Asian Island Arcs are among the most frequently cited examples of active Pacific type plate margins, with the Sumatra–Java trench and its associated features adjacent to Sumatra and Java in Indonesia often cited as a simple subduction system. Viewed in two dimensions perpendicular to the subduction system this appears true. However, adding a third dimension reveals a complex interplate Mobile Belt which has accommodated continuous lateral and rotational movement between the Sunda and Indian Plates.

The Sumatra Fault has been formed by a number of shear faults soling out within the Sunda Plate and coalescing into a single master fault system within the plate margin resulting in the decoupling of a number of segments along the length of the margin. The Sumatra subduction system is a series of arcs and back-arc basins formed by the buckle folding of these small continental fragments in response to the north directed movement of the Indian Plate.

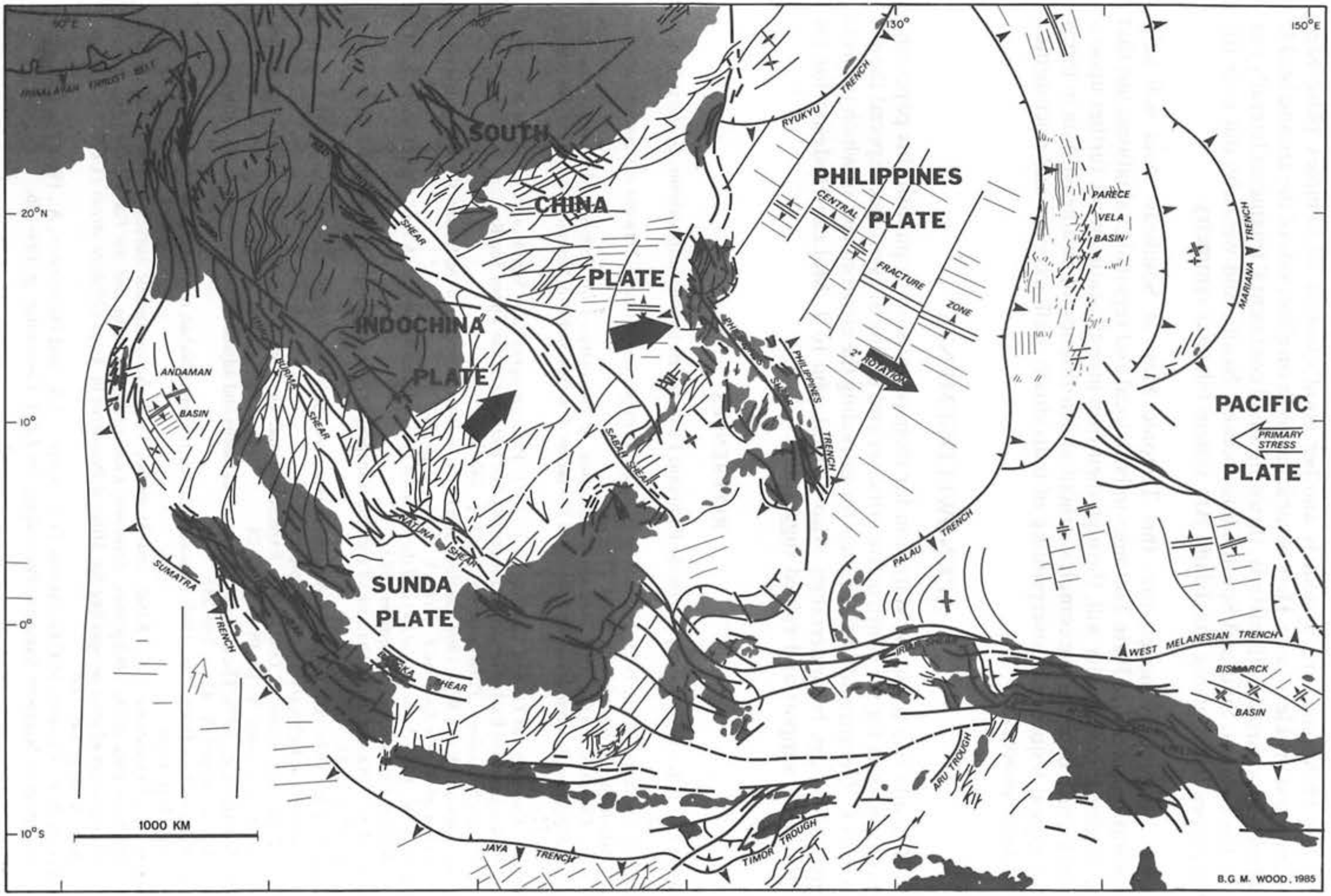


Fig. 22. Tectonic Map of Southeast Asia.

The Philippine Arc System is another good example of complex plate edge shearing and buckle folding. Here oceanic basins lie on either side of the arc and buckle folding has occurred both easterly, thrusting small continental fragments laterally out over the Celebes, Sulu and South China oceanic basins, and westerly, out over the Philippines Basin giving this Island Arc system bilateral symmetry.

It is not only hoped that this Tectonic Map of Southeast Asia will help explorationists utilize Plate Tectonics in both local and regional evaluations, but that the academic community will, through their own investigations, work further upon a model which explains the complex structural deformation of Southeast Asia in terms of a logical sequence of overprinting of individually well accepted and documented structural processes.

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