Geol. Soc. Malaysia, Bulletin 47, December 2003; pp. 7-26

New structural framework for SE Asia, and its implications for the tectonic evolution of NW Borneo

KARSTEN M. STORETVEDT[1], LAP SAU LEONG[2] AND MOHAMMAD ADIB[3]

[1]Institute of Geophysics, University of Bergen
Allegt. 70, N-5007 Bergen, Norway

[2]Geophysics Program, School of Physics, Universiti Sains Malaysia
11800 Penang, Malaysia

[3]PRAD-PMU, Petronas Tower 1, Petronas Twin Towers
50450 Kuala Lumpur, Malaysia

"Theory can be tested by experience, but there is no way from experience to the setting up of theory"

Albert Einstein

Abstract: A new theoretical framework, Global Wrench Tectonics, is employed for understanding the structural development of SE Asia, focussing particularly on the NW Borneo continental margin. The new theory, which is strongly aligned to principles of classical physics, shows that this structurally complex region is not one of geological 'self-rule' but a direct product of the global dynamo-tectonic machinery. It can be shown that the Alpine tectonic revolution on Earth is the consequence of a certain westward wrenching of some outer planetary layering, governed by acceleration in spin rate and associated inertia forces. This global system give rise to continental rotations, and strong shear deformation, notably within the thin and fragile oceanic 'lithosphere'. The extensive NNE-SSW oriented foldbelt of the Indian Ocean is a major left-lateral shear zone, having formed in response to a significant northeasterly inertia-driven wrench displacement of a combined Antarctica/Australia block relative to Africa. This northward movement of Australia during the Alpine climax reactivated the old Indonesian Benioff Zone; the present Indonesian region started to attain its arcuate shape, and other structural effects from the Austral-Asia collision began to complicate the picture. A new dynamo-tectonic wave commenced in the early Miocene, and resulting from this global Neogene pulse Australia and environs underwent a 70 degrees of anticlockwise rotation, eventually docking with SE Asia to attain its present azimuthal orientation, in Upper Miocene-Recent time. This geographic juxtaposition of two originally widely separated regions gave rise to the Wallace Line, and a NW-directed stress field imposed significant tectonization in the Celebes Sea, the southern Sulu Sea, and North Borneo (Sabah). Australia's tectonic impingement with SE Asia caused a certain counterclockwise rotation of the eastern half of Borneo, and a marked thrust front and imbricated sedimentary wedge along the western continental margins of Sabah and Palawan evolved. The overall structural situation and basin development of the South China Sea region can apparently be readily accounted for within the framework of the new global theory.

STUDY PERSPECTIVE

The insular region of SE Asia (Fig. 1), for a larger part constituting an intricate network of continental shelves, deep oval-circular shaped sedimentary basins, major seismic and volcanic belts, and some of the world's deepest oceanic trenches, is incontrovertibly one of the most complex tectonic regions on Earth. Along the northwestern boundaries the area coalesces with continental Asia, and through the Sundaland Shelf a coherent sialic crust extends southwards to Sumatra, Borneo and Java (cf. Hutchison, 1996). This southwestern sector constitutes a fairly normal uninterrupted continental crust, limited towards the Indian Ocean by the Indonesian Arc-Trench system. In the region's southeastern extremity the combined continental platform of Australia and New Guinea, the Sahul-Arafura shelfs, merge with the eastern Indonesian Archipelago. Thus, the structurally complex Timor and Seram islands contain a number of tectono-stratigraphic units of inferred Australian continental provenance (cf. Hamilton, 1979; Hutchison, 1996). Seaward of the eastern Indonesian Arc, however, the north Australian shelf is cut by the active Timor-Seram Trench which represents the eastward continuation of the much greater Java-Sunda Trench. The sharp anticlockwise bend of the Timor-Seram Trench is likely to reflect Australia's motion relative to SE

Paper presented at GSM Petroleum Geology Conference 1999

Asia, and the tectonic juxtaposition of the two blocks may also account for one of the world's most significant biogeographical discontinuities: the Wallace Line. In his original works (1858–1880) Wallace drew his dividing line between Lombok and Bali, then northward along the Strait of Makassar (between Sulawesi and Borneo), with further extension south of the Island of Mindanao (southern Philippines). He argued that the insular region west of the line should be considered part of Asia while the eastern islands (Sulawesi, Timor, Moluccas, New Guinea etc.) were remnants of a former Pacific-Australian continent (see also George, 1981). The fact that there has been only modest intermixing between the two biological provinces suggests that they must have been placed side by side in very recent geological time.

The inferred physical juxtaposition between the Pacific-Australian continent and SE Asia has undoubtedly been of paramount importance for the Tertiary tectonic development of southeastern Asia, but the more western sector of this insular region was apparently not strongly affected by this process. Instead, the South China Sea is dominated by a penetrative NE/SW tectonic grain that can be followed along the entire Asian margin. This shear system, along which there are several elongated sedimentary basins (South China Sea Basin, Sulu Sea, Sea of Japan, outer Sea of Okhotsk etc.) cuts across the Japan Trench, continuing into the deep northwestern Pacific Ocean where it lines up with the regional trend of the characteristic marin-magnetic lineations (cf. Storetvedt, 1997). We begin to perceive the idea that the tectonically complex SE Asia is not a 'self-governing' and lonely corner of the Earth, but rather a component part in an interlinking global system.

Within the present climate of opinion, ruled by plate tectonics philosophy, ad hoc proposals have flourished. For example, the many micro-continental fragments between Sundaland and Australia (e.g. the Paternoster Platform of the Makassar Strait, the blocks of Western Sulawesi, NE Sabah, Segama, Mangkalihat Peninsula, and

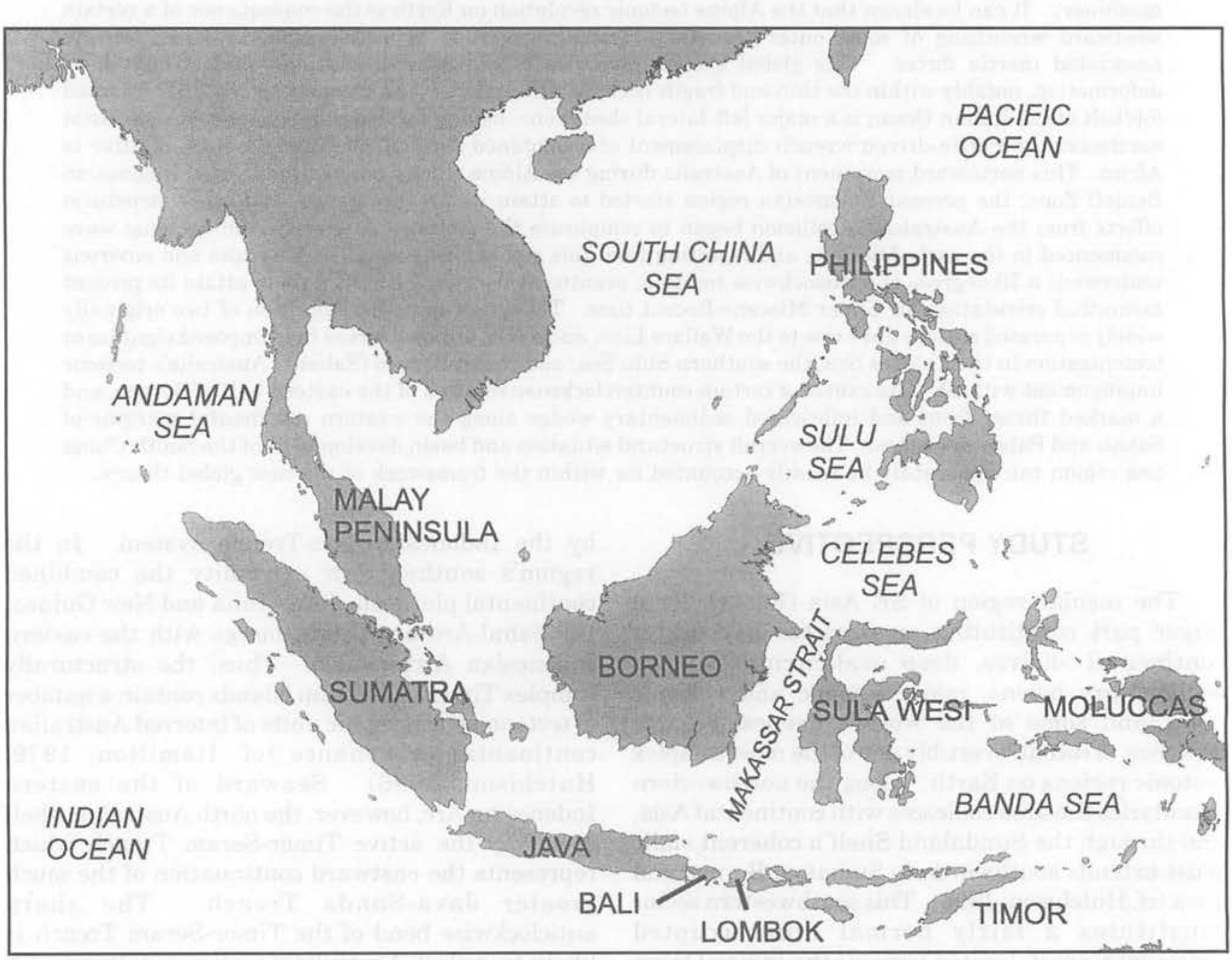

Figure 1. Outline map of SE Asia.

Buton Island, Banggai-Sula Spur, Sumba etc.) have either been ascribed to tectonic isolation called forth by invented cases of rifting and associated 'opening-up' of restricted surrounding seaways, or to more 'exotic' micro-continental fragments allegedly having detached from either Australia or South China. The existing flora of auxiliary smaller-scale interpretations, and the complete absence of an organized unifying link between them, is not building up a trustworthy geological history. The existing jungle of unrelated plate tectonic proposals for SE Asia seems first of all caused by erroneous interpretation of marine-magnetic anomalies, in terms of alleged seafloor spreading. In the conventional belief these anomalies are thought to arise from fossil magnetization with alternating geomagnetic polarity, in combination with seafloor spreading. Contrary to this idea Storetvedt (1997) holds that the lineations are more readily ascribed to variably induced magnetization caused by shear deformation within attenuated continental-oceanic crust. This interpretation is the magnetic-susceptibility-contrast model first proposed by Luyendyk and Melson (1967) and Opdyke and Hekinian (1967), and later emphasized by Agocs *et al.* (1992). In the alternative view fault-controlled alteration of the magnetic mineralogy (primarily iron-titanium oxides), and related changes of magnetic susceptibility, give rise to bands of higher and lower induced magnetization producing the observed 'stripes' of positive and negative field anomalies. Following this explanation the magnetic lineations should be expected to be inversely correlated with crustal thickness, i.e. the thinner the crust the stronger its shear deformation and hence its magnetic anomaly expression. This assumption holds well for SE Asia which to a large extent has continental-transitional types of crust, characteristic magnetic lineations being only confined to smaller-scale depressions underlain by strongly thinned crust (cf. Hayes, 1978). In the alternative interpretation the numbering system invented for these anomalies (since the late 60s they have been directly related to crustal age) has no meaning.

In the present paper we view the Tertiary structural development of SE Asia within a new evolutionary scheme, Global Wrench Tectonics (Storetvedt, 1997). It is intended to show that the Austral-Asia region is not a fortuitous tectonic whirlpool, as in plate tectonic abstraction, but rather an anticipated state of affairs within the operating global system. In other words, the available geological and geophysical observations for SE Asia are found to be consistent with anticipations following from the new theory.

INTRODUCTION TO NEW GLOBAL TECTONIC SYSTEM

Any realistic theory of the Earth should readily explain all its major facets (dynamical, tectonic, palaeoclimatic, palaeogeographic etc.) in terms of a coherent system, bound together preferably by simple physical principles. Theory-building always starts with one or more fundamental assumptions which are inventions based partly on observation and partly on intuition. If these innovations rest on sound judgement we will automatically be led on to specific predictions of nature, either to already known phenomena or to discoveries of new ones. If our predictions are in accordance with the observational map, building up a hierarchical and increasingly diversified cause-and-effect system, we can be reasonably sure that we are moving in a prospective direction: towards establishing a substantive theory. However, considering the flora of ever-increasing ad hoc modifications currently invoked, without any ostensible reason but to produce artificial fits to preconceived plate tectonic constructions, it is obvious that our contemporary global geology is without a realistic foundation.

Triggered by the great confusion pertaining to global geology today a completely new system of Earth evolution has recently been launched (Storetvedt, 1997). The basic assumption of the new theory is that the early Archean Earth acquired a relatively thick pan-global sialic incrustation, of either dioritic, anorthositic or granitic composition. At this stage basalt did not feature prominently (if at all) in the surface layers, and it is only with the late Archean Greenstone Belts that a significant amount of basic volcanics are recognized in the Earth's crust (e.g. Windley, 1977). This onset of crustal 'basification' can be viewed as surface manifestations of an internal reorganization of planetary mass, presumably initiating from the outer fluid core or from an undifferensiated part of the deeper mantle. With continued intermittent mantle upwelling, the continental crust has apparently been rendered chemically and gravitationally unstable, having gradually been replaced by the thin basaltic crust beneath the present deep oceans ('oceanization'). The Moho, the present crust-mantle interface, and the upper mantle low velocity horizons (forming an irregular asthenosphere) can be regarded as concomitant products of the internal restoration of matter. In consequence, the suggested vertical redistribution of internal mass would alter the moments of inertia, giving rise to spatial reorientations of the Earth's body (polar wander) and variations in its rotation rate. In fact, these dynamical predictions gain support from palaeomagnetism, palaeoclimate data, and studies of growth rings in fossil shells and corals (see Storetvedt, 1997, for a review). Further, seismic tomography depicts a fairly clear compositional difference between sub-oceanic and sub-continental mantles to depths of several hundred kilometres, the oceanic depressions being probably located above sectors of maximum vertical mass transfer. In regions where upwelling of hot material has had its maximum concentration the original thick sialic crust has apparently undergone complete 'consumption', being largely replaced by the thin basaltic layer beneath the deep oceans. In other sectors of the Earth's interior, where upwelling is thought to have been less predominant, the continental-type crust is still prevalent. The fairly smooth variation in crustal thickness across the globe, from the relatively thick sialic layer beneath cratons to the thin basaltic crust beneath the deepest oceanic depressions, is thus consistent with this view. Also, the long-term draining of the continents as well as the transgression-regression cycles are readily explained by intermittent mass transfer and associated basification and isostatic subsidence of original sialic crust.

Several mechanisms have been proposed to account for gravitational loss of sialic crustal material to the mantle (sub-crustal 'erosion'), but that of eclogitization of lower crustal granulites, amphibolites etc. by fluid migration through shear zones (e.g. Austrheim and Griffin, 1986; Austrheim, 1987) seems presently to be the most promising mechanism. The relatively high pressure required for eclogite production, and the needed supply of water to remove the feldspar(s) in lower crustal material, are probably resulting from hydrostatic pressure increase (provided by changes in Earth dynamics) within the irregularly distributed gas- and fluid-rich (low velocity) asthenopheric layers. The fruitfullness of this model is corroborated first of all by the long prediction-confirmation chain it establishes (Storetvedt, 1997).

According to the new theory, global tectonics is strongly linked to inertia effects due to changes in planetary rotation and, based on classical physical principles of rotating bodies, Earth history becomes a series of interrelated phenomena. For example, it turns out that the major northern hemisphere foldbelts (Caledonian, Hercynian and Alpine) formed along their time-equivalent equators, and geosynclinal precursor stages follow as natural products of mantle upwelling controlled by the centrifugal force of rotation. The logic of this connection is that during events of mantle upwelling there would be a certain concentration of fluid flow in the (palaeo-) equatorial plane along which a great-circle belt of attenuated crust, and an associated sedimentary trough, will develop. Other tectonomagmatic belts formed as rift zones perpendicular to their corresponding palaeo-equators (e.g. Grenville Belt, Oslo Rift, Ural Belt, Rhinegraben etc.) during periods of changes in planetary rotation rate.

At around the K-T boundary, oceanization (basification) of the sialic crust had reached an advanced stage, and the present mosaic of variegated continental blocks and intervening oceanic basins was largely in place. Due to the longstanding progressive changes of crust and topmost mantle the Earth had by now acquired a tectonically much more unstable state than before. Thus, the remaining continental masses had become surrounded by thin and mechanically weak oceanic crust, and the growth of upper mantle low velocity layers had, over larger parts of the Earth, to some extent detached the crust and topmost mantle (i.e. the 'lithosphere') from the deeper layers. Hence, the commencing acceleration in Earth's rate of rotation (eastward) at the end of the Mesozoic (Creer, 1975), providing a westward inertia drag on the global 'lithosphere', triggered the Alpine tectonic revolution, as kinematically demonstrated by Figure 2.

The planetary mobilistic pattern, controlling the major structural cataclysm that swept the Earth in late Cretaceous and Lower Tertiary times (Alpine climax), particularly in low-intermediate palaeo-latitudes, are revealed by palaeomagnetic data from Africa and Eurasia. At that time the palaeo-equator passed along the southern rim of the Mediterranean, with eastward continuation just south of Sumatra/ Java. Resulting from the general westward torsion of the two palaeo-hemispheres, Africa (located south of the relevant palaeo-equator) underwent a c. 25 degrees of *'in situ'* counterclockwise rotation, while Eurasia (situated north of the palaeo- equator) rotated clockwise by a similar amount (Fig. 2). Hence, the combined inertia effect (Coriolis, tidal and Eøtvøs forces) are beginning to show their significance in global geology. Following from the inferred mobilistic pattern, the intervening palaeo-equatorial region was turned into an overall transpressive regime (including the southern rim of SE Asia) that became the Alpine belt proper. The westward torsion of the global lithosphere produced extensive wrench deformation across the globe, first of all within the thin and fragile oceanic crust, but the continental crust too was affected by the global lithospheric torsion. Within this tectonic setting the Indian Ocean lithosphere was subjected to major penetrative shearing, and the crustal segment between the Laccadive-Chagos and Ninety-East ridges evolved into a mega-shear zone: the Central Indian foldbelt. The new global theory presumes that the entire oceanic crust and topmost mantle have been subjected to shear deformation, to a major extent reactivating older (fundamental) fracture systems.

As will be shown below, the mobilistic system depicted in Figure 2 also sets the frame for the tectonic development of SE Asia. With the Lower Tertiary palaeo-equator running just to the south of Indonesia, the whole belt of attenuated continental crust along the eastern margin of Eurasia, bordering the western Pacific, would be disposed to development or reactivation of a 'NE-SW' oriented shear grain (caused by Eurasia's clockwise rotation). Along the deepest of these shear faults eclogitization and associated sub-crustal thinning would then have developed, giving rise to the many elongated sedimentary basins characteristic of that region. However, this simple pattern of shear-oriented basins along the Pacific margins of Asia was not to evolve without tectonic interference, because the extensive inertia-driven shearing in the Indian Ocean (Fig. 2), and the associated torsional translations of Australia (see below), imposed considerable transpressive deformation in southeastern SE Asia. As a result, Austral-Asia is presently featuring as one of the structurally most complex regions in the world, but even so it can be shown that its tectonic entanglements are in line with expectations following from the new global theory.

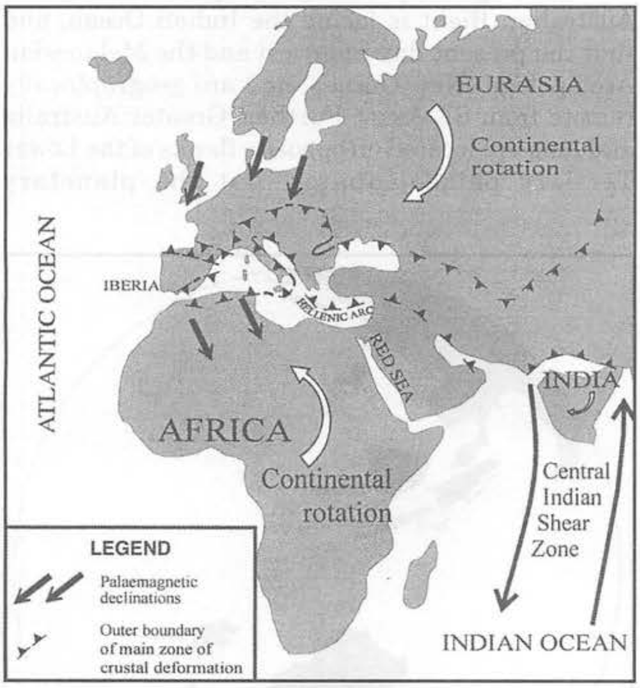

Figure 2. By the end of Cretaceous time 'oceanization' of an original pan-global sialic crust had reached an advanced stage, approaching its present state, and crustal loss to the mantle accelerated Earth's spin velocity (eastward). The inertial response to this rotational increase was a westward torsion of some outer layer ('lithosphere'). Consistent with the classical inertia principles, Africa and Eurasia, located on opposite flanks of the corresponding palaeo-equator, rotated in opposite senses. The intervening palaeo-equatorial region was turned into a major transpressive zone, the Alpine belt. The westward torsion of the two hemispherical 'caps' led to extensive wrench deformation of Earth's crust and topmost mantle, notably within the thin-crusted oceanic regions. The major shear belt of the Central Indian Ocean formed in this way. Simplified after Storetvedt (1997).

THE INDIAN OCEAN FOLDBELT; STRUCTURAL IMPLICATIONS FOR THE SOUTHEASTERN MARGIN OF ASIA

The combined occurrence of major seismic activity, undulations of the order of 200 km in topography and gravity, greatly variable but generally high heat flow, the presence of intense folding of the sedimentary pile, and high-angle reverse faulting demonstrate that the equatorial Indian Ocean is a locus of unusual deformation (e.g. Eittreim and Ewing, 1972; Stein and Okal, 1978; Weissel *et al.*, 1980; McAdoo and Sandwell, 1985; Neprochnov *et al.*, 1988; Currie and Munasinghe, 1989; Bull and Scrutton, 1992; Van Orman *et al.*, 1995 etc.). The broad region of crustal contortion, attenuating seismic waves traversing it (Stark and Forsyth, 1983), has remained a paradox for plate tectonics as the occurrence of a broad tectonic belt in a so-called 'mid-plate' setting violates some of the most basic axioms of that model. The region of the Indian Ocean with the most intensive structural deformation, most likely reaching into the upper mantle, occurs between the Laccadive-Chagos and Ninety-East ridges. The model of wrench tectonics presumes that the entire global oceanic lithosphere is variably affected this way. Within the strongly tectonized belt of the Indian Ocean Neprochnov *et al.* (1988) distinguished between two penetrative fracture sets: 1) an older Alpine meriodional assemblage and 2) a younger Neogene system of wrench faults. The latter set cuts across the older group of fractures, producing *en-echelon* offsets across the Ninety-East and other Indian Ocean ridges. Neprochnov *et al.* (ibid) inferred the existence of sinistral phases of Alpine shearing in the Central Indian Basin. The ruptured nature of the SW Indian Ridge, from which a multiplicity of metamorphic rocks have been recovered, may indeed suggest that the Indian Ocean is cut by a very broad transcurrent fault zone, forming a slightly curved metamorphic-tectonic belt extending from the southern South Atlantic to the Bay of Bengal. Left-lateral shearing along this prominent oceanic foldbelt would naturally reactivate the old Benioff Zone (see below) along the present-day Indonesian Arc, giving rise to underthrusting of the thin 'lithosphere' of the Indian Ocean beneath the much thicker sialic layer to the north.

A palaeomagnetic comparison between Africa on the northwestern side of the tectonic belt and Australia and Antarctica on the opposing flank may elucidate the question of the degree of offset. Following the new tectonic scheme (Storetvedt, 1997) smaller (remaining) continental masses like Australia and Antarctica, both being surrounded by thin and fragile oceanic crust, would have been vulnerable to increased mobility when subjected to Alpine phases of global wrench forces. Storetvedt (ibid) has shown that just simple Alpine age rotations of the land masses, around their approximate centroids, may adequately account for their present-day between-continent palaeomagnetic discrepancies. Figure 3 depicts how the mean pole for the Jurassic of Antarctica (AN) and Australia (AU) may match after simple in situ rotation of the two continents. Nevertheless, the combined Jurassic pole for Australia/Antarctica (AN/AU) shows a significant north-northeasterly shift compared to the relative African pole, i.e. consistent with a left-lateral offset of the order of 1,500 km in post-Jurassic time. Hence, the palaeomagnetic data concur with the marine geophysical evidence of Neprochnov *et al.* (1988), giving substance to the idea of major Alpine age transcurrent faulting across the Central Indian Basin. Being the consequence of an event of global lithospheric torsion, formation of this oceanic foldbelt would naturally imply considerable reactivation and underthrusting along the old Indonesian Benioff Zone; a crustal shortening that, provided the Earth's radius is held unchanged, would have to be compensated for by extension and magmatic infilling processes elsewhere in the southern palaeohemisphere.

Figure 4 shows the position of Greater Australia relative to SE Asia in the late Cretaceous, before the Alpine age north-northeasterly wrench translation of Antarctica/Australia (associated with the mega-shearing in the Indian Ocean). Note that in this original palaeo-geographic setting the Australian Bight is facing the Indian Ocean, and that the present-day Sulawesi and the Melanesian Archipelago (New Guinea etc.) are geographically remote from SE Asia. Further, Greater Australia and Asia are located on opposite flanks of the Lower Tertiary palaeo-equator, but the planetary

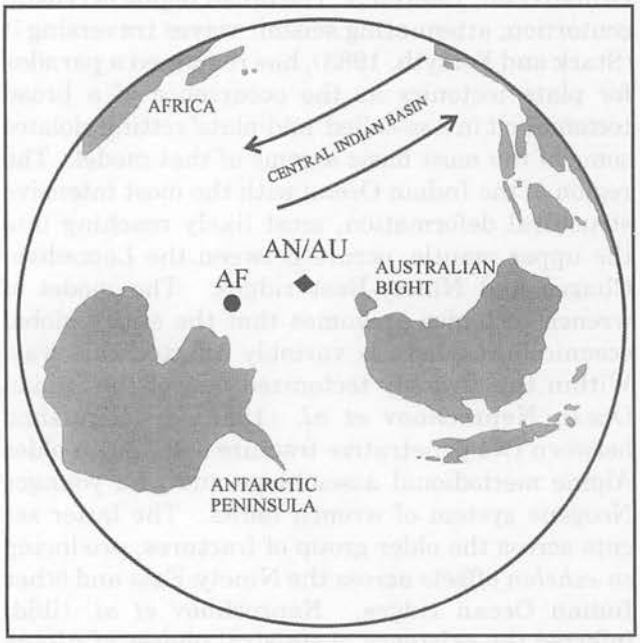

Figure 3. Common position of the Jurassic palaeomagnetic pole for Antarctica and Australia (AN/AU), after appropriate rotations around their approximate centroids, depicts a 15 degrees of NNE shift of these two continents (combined) with respect to the corresponding African pole. This polar offset is consistent with evidence suggesting that the central Indian Ocean Basin represents a major Alpine age left-lateral shear belt. After Storetvedt (1997).

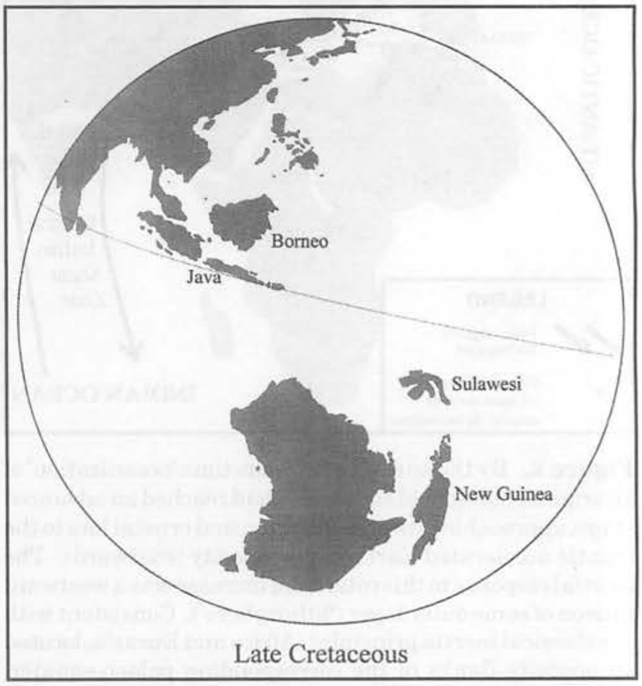

Figure 4. The original position of Greater Australia, before the Alpine age wrench deformation of the southern hemisphere. Note that the Australian Bight is facing the Indian Ocean, and that Sulawesi and New Guinea are remote from SE Asia. Note that the corresponding palaeo-equator is running just to the south of the Indonesian Archipelago.

acceleration at that time generated significant wrenching of the Earth's outer layering and brought Australia and environs into much closer physical contact with SE Asia (see also below). When viewed upon as subduction zones the prominent peri-Pacific and Indonesian Benioff zones have posed an endless number of grave conceptual problems (e.g. Storetvedt, 1997, for a review). For example, the old query of the 180 degree turning of the combined Sunda-Banda Arc (see Fig. 6) has remained an unsolved riddle till this day. However, because the classical Benioff zones show discordantly increasing angles of dip at 'asthenospheric' depth levels (100–300 km) they tend to be better explained as deep contraction dislocations dating from an early stage of planetary cooling (Benioff, 1954; Wilson, 1954; Meyerhoff *et al.*, 1992). On that basis the original Benioff zones are likely to have formed deep great-circle fractures on Earth, and the present-day

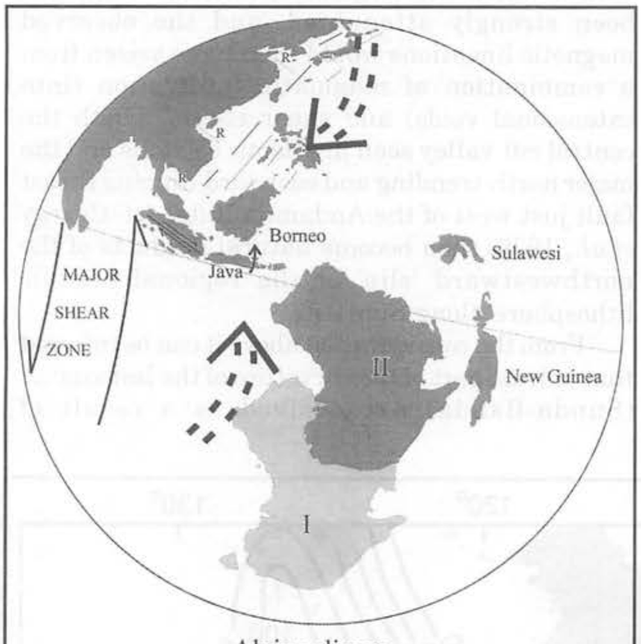

Figure 5. Global wrenching in Alpine time gave rise to the Central Indian foldbelt and an associated northerly translation of Greater Australia, from position I to position II. Tectonic pressure and major underthrusting of thin Indian Ocean crust beneath the Indonesian Benioff Zone produced some counterclockwise bending of the Indonesian region. Due to oblique underthrusting along Sumatra the major right-lateral Sumatran (Barisan) Fault Zone developed. North of the Alpine palaeo-equator the westward inertia drag reactivated an old NE/SW tectonic grain throughout the West Pacific margin, including South China Sea. Crustal attenuation through eclogitization developed, principally along predominating fault zones, and isostatic subsidence formed deep elongated basins and horst-and-graben structures.

curvature of island arcs primarily representing regional bendings brought about by Alpine tectonic stress fields (Storetvedt, 1997). Thus, the hair-pin shaped Sunda-Banda Arc (Fig. 4) can be regarded as a tectonic flexure having formed from an originally closely linear structure.

THE TECTONIC FABRIC AND TERTIARY BASIN DEVELOPMENT IN SE ASIA

The southern margins

During late Cretaceous-early Tertiary time the southern palaeo-lithospherical 'cap' became subjected to inertia-driven tectonic disruption, bringing Greater Australia into closer geographic contact with SE Asia (Fig. 5). The extensive tectonic translation in the eastern Indian Ocean can be related to the more extensive degree of oceanization in the Southern Hemisphere, with more widespread and coherent upper mantle detachment 'surfaces' (the low velocity astheno-layers), than in the Northern Hemisphere. Transpressional deformation along the palaeo-equator (see Figs. 2 and 5) led to formation of the Alpine foldbelt, including major northward thrusting beneath the pre-existing Indonesian Benioff Zone. Late Cretaceous and Lower Tertiary volcanic activity exposed on the major Indonesian islands, traditionally referred to as the 'Old Andesites' (Van Bemmelen, 1970), is consistent with the new tectonic scheme. In the western region the thick continental block of Sundaland may be expected to have been fairly resistant against internal deformation provided by the prevailing transpressional forces, but palaeomagnetic studies have arrived at conflicting conclusions. Thus, McElhinny *et al.* (1974) suggested counter-clockwise rotation of the Malay Peninsula while data by Haile (1979) indicated clockwise rotation of adjacent Sumatra since the Cretaceous. The confusing situation posed by these and other results is most likely a consequence of the inadequate experimental and analytical procedures that have long brought palaeomagnetic conclusions astray, both before and after the tricky problems of remagnetization had been exposed in the 1980s.

The crust of Sumatra, the Malay Peninsula and the rest of Sundaland have apparently not been substantially weakened by sub-crustal thinning, and the absence of seismicity both in the South China Sea and the Strait of Malacca suggests that this lithospheric unit has remained tectonically relatively stable despite of its location within (or close to) the transpressive regime that apparently prevailed along the Lower Tertiay equator. On the other hand, to the east of Sundaland the crust north of the Benioff belt is thinned, faulted and fragmented in a complex manner (see Hutchison, 1996). This is probably a product of an unequal oceanization process having initiated concomitant with the transpressive deformation and underthrusting along the Indonesian Arc. This mechanical weakening of the lithosphere north of Java is the likely cause of the tectonic bending between Sumatra and Java, having started during the late Cretaceous-Lower Tertiary dynamo-tectonic pulse and completed during the Neogene phase. Indeed, the tectonic break-point between Java and Sumatra, the Sunda Strait, has continued to express geological activity into modern times (cf. the Krakatao volcanic explosion of 1883). Also, reconnaissance GPS observations (Wilson *et al.*, 1998) show that the region of Java/Sumatra and adjacent southern Borneo and the Malay Peninsula are presently being subjected to a northeasterly velocity field, i.e. producing a net motion of about 2 cm/year (relative to Eurasia) along the regional NE/SW tectonic grain.

The significant changes in orientation of the Sunda Trench towards northwest, from nearly easterly along Java to northerly in the Andaman-Nicobar sector, produces an increasing obliquity of the underthrusting along the Benioff plane. This change in orientation of the thrust plane seems to account for the continuous change in seismo-tectonic pattern from Java to the Andaman Sea (e.g. Hatherton and Dickinson, 1969). Beneath Java the Benioff plane is seismo-tectonically active down to depths of around 600 km, while along Sumatra, where underthrusting is oblique, focal depths beneath Central and North Sumatra are limited to only the uppermost 100–200 km. The Sumatran Benioff Zone clearly terminates abruptly at the Semangko (Sumatran) Fault. Instead of being forced down to deeper levels beneath Sumatra the thin Indian Ocean lithosphere is apparently subjected to a significant westward 'slippage' along regional upper mantle low velocity horizons. Such a trench-parallel relative motion along the Benioff Zone may have provided the needed drag effect for shear reactivation of the old Semangko Fault (see Fig. 5), and the 400 km dextral transcurrence inferred for this complex fault zone (Hutchison, 1996) is indeed consistent with such reasoning.

Continuing to the northwest the Semanko Fault is thought to run along the northerly trending West Andaman Fault (Curray *et al.*, 1979) forming a natural western tectonic boundary to the Andaman Sea. In the new tectonic framework the Andaman Sea becomes a transtensional basin within which the original continental crust has been strongly attenuated, and the observed magnetic lineations would then have arisen from a combination of magmatic infiltration (into extensional voids) and shear effects. Both the central rift valley seen in seismic sections and the major north-trending and eastward-dipping thrust fault just west of the Andaman Ridge (cf. Curray *et al.*, 1979) then become natural products of the northwestward 'slip' of the regional oceanic lithosphere along Sumatra.

From the consideration above it can be inferred that at least part of the curvature of the Indonesian (Sunda-Banda) Arc evolved as a result of

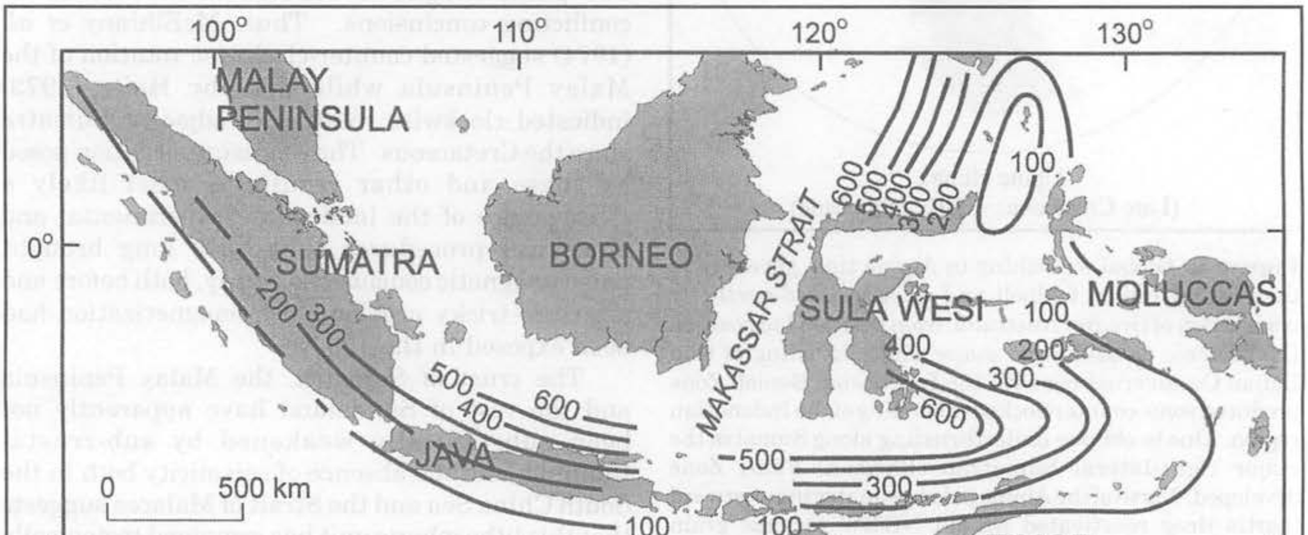

Figure 6. The landward-dipping seismotectonic zone along the Indonesian region. Simplified after Hatherton and Dickinson (1969).

lithospheric wrench deformation during the Alpine climax. Also, the rather significant northward 'push' of Greater Australia initiated Alpine tectonic contortions in SE Asia and the SW Pacific, bringing about considerable bending of the SW Pacific Benioff plane, and the major knee-shaped Tonga-Kermadec-Vitiaz ridge/trench system began to take shape. However, it was not until the Neogene that the present-day structural intricacies along the SW Pacific margins developed. Figure 6 depicts the present-day curved Indonesian Benioff Zone with the hair-pin shape of its eastern branch.

Basin development in SE Asia

The lithospheric torsion of the northern palaeo-hemisphere brought about considerable shearing within the attenuated continental crust of eastern Asia, producing (or more likely, reactivating) the penetrative NE/SW structural grain along the NW Pacific margin (cf. Fig. 5). Due to Earth's dynamical changes fluids trapped in the upper mantle astheno-lenses (the low velocity horizons) were subjected to hydrostatic pressure increase, instigating their upward migration along the prevalent fracture systems. At the lower crust, provided the necessary accessibility of fluids and the required level of pressure, the granulite facies mineral assemblages would undergo a transition into eclogite, in turn giving rise to gravitational instability with loss (subsidence) of the transformed crustal material to levels of the mantle. Hence, fault-controlled crustal attenuation led to its isostatic subsidence and associated basin formation, thus explaining why most of the marginal basins of eastern Asia (Outer Sea of Okhotsk, Sea of Japan, South China Sea, Sulu Sea etc.) have NE-SW elongated shapes. The Celebes Sea, Molucca Sea, Macassar Strait etc. certainly also formed along the same NE-SW oriented tectonic grain, but due to major counterclockwise rotation of Greater Australia during the Neogene (see below) this southwestern corner became structurally much more contorted than the rest of SE Asia. For example, in the relatively deep and thin-crusted Banda Sea Basin, completely surrounded by thick continental crust (see Bowin *et al.*, 1980), linear magnetic anomalies ought to be present (as a result of shearing), but instead a featureless magnetic field prevail over most of the Banda Sea. The subdued magnetic anomalies is most likely a consequence of strong crustal contortion, the magnetic signal having been effectively averaged out by development of a rather 'chaotic' basement structure.

The deepening of the marginal basins of the western Pacific occurred intermittently also beyond the Alpine climax. A 35 degree of spatial reorientation of the globe at around the Eocene-Oligocene boundary, relative to the astronomical rotation axis, shifted the equatorial bulge to near its present position. This dynamical change is bound to have reactivated the NE-SW trending fracture system along which crustal thinning processes and associated basin subsidence became enhanced well into the Oligocene. A new wave of mantle upwelling with resulting crustal attenuation commenced in the Lower-Middle Miocene, further speeding up the deepening process and accumulation rates of these basins. The general thinning of the platform regions of the South China Sea (part of Sundaland) can similarly be related to sub-crustal processes of eclogitization and subsequent gravitational sinking (of tectonically broken sialic material). However, the difference in fracture zone development, and associated uneven rate of eclogitization and subcrustal erosion (between individual fault zones), readily explains the characteristic NE-SW trending horsts and half-grabens forming, for example, the structural style of the NW Sabah Platform. According to Hazebroek and Tan (1993) the half-graben fill most likely represents clastic material of Palaeocene-early Miocene age, a suggestion that is in line with the evolutionary pattern advanced here.

The various events of Alpine lithospheric wrenching (i.e. at around the K-T boundary, in late Eocene-early Oligocene, and finally during the Neogene) gave rise to reactivation and rifting of another set of old fractures, including the Philippines, the Babco-Sabah, the Thai-Burma-Natuna, and the Sumatra fault zones, running near-perpendicular to the characteristic NE-SW oriented shear grain. The NW-SE trending embayments/basins of eastern Asia (Malay Basin, South Mekong Basin, Yellow Sea Basin etc.) can therefore be explained by reactivation (rifting and sub-crustal attenuation) of this second set of fundamental fractures. Such orthogonal fracture networks are not only ubiquitous phenomena on Earth, cutting rocks of all ages and displaying consistency in their orientation over regions of continental size, but they also feature prominently on other planets. These universal fracture patterns were probably implanted into planetary surface layers as extensional features (Storetvedt, 1997) at an early stage of planetary evolution. Once formed, the probably deeply penetrating rupture patterns would be prone to repeated rejuvenation as long as the planet is dynamo-tectonically active, impressing the old fracture system into steadily younger surface strata. For planets in dynamo-tectonic development, such as the Earth, the changing global and regional stress fields have led to significant deformation of the outer layering during which one of the conjugate fracture sets may have developed into fault/shear zones. Many of the predominant fault systems of present-day SE Asia may therefore be regarded as Precambrian in origin, and a related finer scale mineralogic fabric combined with the long history of intermittent global wrenching have certainly intensified these characteristic rupture networks. During repeated planetary torsion, regional segments of the large scale fracture systems may therefore have been twisted out of their original alignment.

Figure 7 depicts the trend of some major fault systems in SE Asia. One notices that the Philippines, Red River-Sabah, Thai-Burma-Natuna-Lupar, and Sumatra (Semangko) shear zones constitute a broad NW/SE oriented system. These mega shears have bearings that correspond to the orientation of pre-Alpine palaeoequators and corresponding northern hemisphere foldbelts (see Storetvedt, 1997), so these fractures have probably a long history of reactivation. The fracture systems characterizing younger sedimentary blankets are therefore most likely inherited from these fundamental sets of basement fractures. However, towards the southeast, beyond an approximate line drawn from the Sunda Strait, across Central Borneo to north of Mindanao in the Philippines, these major structural trends show a squeezing together, in addition to displaying a certain northerly bending around eastern Borneo. This tectonic distortion can be readily accounted for by Australia's inertia-driven motions (see below). From this broad regional view it seems that structural contortion stemming from the Australia/SE Asia tectonic clash fade away northwestward, being apparently minimal in the South China Sea beyond the NW Sabah-Palawan tectonic front.

With the presence of two fundamental tectonic grains, trending NE/SW and NW/SE respectively, and accepting the view that attenuation of sialic crust has evolved along pre-existing dislocations, it should be expected that sedimentary basins would have a tendency to form orthogonal systems. Thus, on a smaller scale the principle of structure-controlled basins has repeatedly been reported from studies in NW Borneo, and Tongkul (1993), for example, suggested that the two main structural trends in Sabah, with NE/SW and NW/SE orientations, have controlled the distribution and development of the Neogene basins. The same pattern can be seen on a larger scale in the southern South China Sea where the thick (up to 12,000 m; CCOP Bulletin 1991) NE/SW trending Sabah Basin

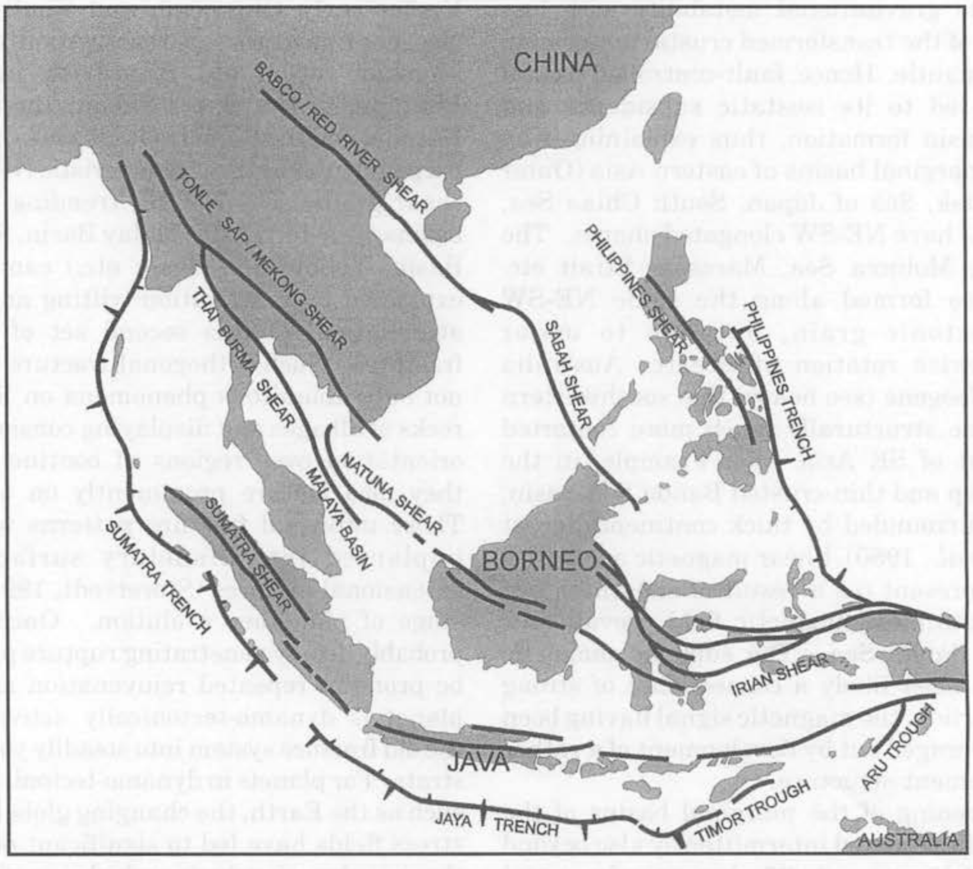

Figure 7. Prominent fault systems in SE Asia. Note their bundle-like concentration to the southeast. Based on Wood (1985).

turns c. 90 degrees through the broader junction of the Sarawak Basin before continuing NW into the outer sector of the South Mekong Basin. Interestingly, the inner branch of the South Mekong Basin is trending NE/SW, i.e. perpendicular to the outer section, giving further substance to the idea that the formation of sedimentary basins are controlled by the fundamental system of orthogonal fractures. Another example of orthogonal basin morphology is seen at the junction of the West Natuna Basin (striking NE/SW) and the Malay Basin (trending NW/SE).

The strong evidence that shape and development of sedimentary basins are controlled by old lineaments, and the fact that the most common tectonic fabric on Earth form two sets of perpendicular fractures, brings us to the question of origin of the arcuate belt of the Rajang Complex, NW Borneo. Again the two principal limbs of the Rajang Basin are nearly perpendicular suggesting that its curved shape is largely primary, having formed through crustal attenuation along orthogonal fault zones. The Rajang Complex consists of Upper Cretaceous-Lower Miocene turbidites, hemipelagics, plus a variety of igneous rocks (e.g. Tan, 1979). From palaeocurrent observations Tan (1979) arrived at a dominantly southwest to northeast transport direction, consistent with earlier views that the Rajang sedimentary complex constitutes a major fan system laid down by turbidity currents from a drainage system in southern Sundaland. The Rajang Basin seems to have been a major deep depositional trough in Upper Cretaceous and Lower Tertiary times, but due to Borneo's position as a major stress junction from Middle Miocene onwards (see below) the depositional history came to a close in late Lower Miocene, being superseded by transpressive deformation with pronounced imbrication, uplift, and erosion.

As inertia forces naturally will be at their maximum in (palaeo) equatorial regions, and because Borneo has had such a geographical location throughout Phanerozoic times, the region of Borneo has undoubtedly had a position that would have been vulnerable to complex tectonic deformation, including intrusions within localized transtensive regimes, shearing, and presumably tectonic rotation. Consistent with such anticipations the Rajang Complex of western Borneo exhibit a multitude of intrusive bodies, and strongly deformed Upper Cretaceous-Eocene flysch sequences occur frequently (e.g. Williams *et al.*, 1988; Tan, 1982). Also, the presence of scattered occurrences of late Cretaceous-Eocene ophiolite bodies along the major Lupar and Mersing faults give evidence of major shearing along the Rajang Belt during the main Alpine age global wrenching. Ophiolites are regarded here as being solid state intrusions of hot upper mantle material brought to the surface by tectonic forces within localized transtensional regimes.

The query of Borneo's tectonic rotation

As will be shown below the prevailing stress situation in Borneo throughout Alpine time would have been prone to cause tectonic rotation, at least of the Sabah sector, but the rotational history based on published palaeomagnetic data is inconsistent. The entire question has therefore remained in the realm of speculation. Existing palaeomagnetic studies have not represented a satisfactory coverage of the island, nor from the arcuate Rajang Complex, the limited data base having first of all been concentrated to rocks from West Sarawak/West Kalimantan. Moss *et al.* (1997) have compiled the available results listing a large spread in rotational estimates from both Mesozoic and Tertiary rocks. Lamadyo *et al.* (1993), from their study of a minor collection of Tertiary material mostly from the Kutai Basin of West Kalimantan, found no evidence of rotation, while a previous study by Schmidtke *et al.* (1990) from western Sarawak reported rotation figures between 40 and 90 degrees in the counterclockwise sense. However, the Schmidtke *et al.* paper does not stand up to present requirements regarding experimental documentation. Examples of remanence behaviour versus progressive damagnetization are not given, and a critical scrutiny of their stereographic presentations of site mean directions may indicate that remagnetization is an unresolved problem in their rock collection. Thus, some fairly marked declination spread-outs suggest that the data base is muddled by unresolved superimposed magnetizations. Their illustrations suggest that many of the directions of magnetization do not represent single-component remanences, but rather vector resultants of normal and reverse magnetizations in various relative combinations, evoking artificial palaeomagnetic declinations and irrelevant rotation estimates. Hence, in the discussion of possible tectonic rotations of Borneo, or parts thereof, the data by Schmidtke and coworkers should be disregared. The relatively undisturbed orientation of the extended Natuna Shear/Lupar Line, following major structural features and elongated basins across Sarawak and Kalimantan, signifies that any tectonic rotation embracing the whole of Borneo is likely to be small. However, the fault lines extending from eastern Borneo to Sulawesi (Fig. 7) indicate a northward bending indicative of a certain counterclockwise rotation or torsion, and the westward bending of the Rajang segment of Sabah give further substance to the idea that some part of eastern Borneo has performed a certain westerly 'swing'. In fact, the conspicuous tectonic front off NW Sabah may attest to the reality of such a postulated rotation. As will be shown below the inferred tectonic bending of North Borneo is of Neogene age being primarily the mechanical response to tectonic forces caused by Australia's impingement with SE Asia.

THE WALLACE LINE AND NEOGENE TECTONISM IN SE ASIA

Origin of the Wallace Line

During times of planetary acceleration, and provided tectonic interaction with other sialic units can be ignored, southern hemisphere land masses would be subjected to northward-pressing counterclockwise rotations. We have already seem how Africa followed this scheme during the main Alpine phase. For the Neogene period we lack a detailed palaeontological record on the variation in Earth's rotation rate, but if we take the existing fossil 'clock' data at their face value (see compilation by Creer, 1975) the Neogene seems to have been a 'period of acceleration' too. After the early Oligocene Australia has indeed moved anticlockwise, of the order of 70 degrees, to attain its present orientation (Storetvedt, 1997), but neither palaeomagnetism nor any other geophysical evidence are able to establish a satisfactory timing for this motion. On the other hand, the structural record of the Banda Sea region and adjoining parts of SE Asia dates the tectonic impingement as primarily between Middle Miocene and Pio-Pleistocene (cf. Huchison, 1996). During this late Tertiary time span Australia gradually changed from its original setting (pos. I, Fig. 8) to its present azimuthal orientation (pos. II, Fig. 8).

Before the Neogene the present-day insular region north of Australia (New Guinea, the Moluccas, Timor, Lombok, etc.) was part of a former SW Pacific continent, geographically remote from regions like Java, Borneo and the Philippines, but the inferred late Tertiary rotation of Australia brought the two regions into their present juxtaposition, producing a marked biogeographic discontinuity. Since Wallace originally drew his Line, some 150 years ago, between Bali and Lombok in the south, continuing north along the Makassar Strait, and then to the south of the Philippines, the more precise location of this biological boundary has from time to time been debated. However, since its very discovery the existence of this sharp biological discontinuity has never been in doubt, and the extremely limited intermixing between the Oriental and Austral biota indicates strongly that the two provinces must have been placed side by side in fairly recent geological time.

Some regional tectonic implications

From the consideration above we infer that the Neogene geodynamic event in Austral-Asia can be related to global inertia-driven torsion within which the lithospherical shells were subjected to relative and equatorward translation. Within this geodynamic system Greater Australia eventually performed its final anticlockwise rotation (note that this is also the theoretically expected sense of rotation in the Southern Hemisphere). On the Asia side of the Wallace Line the transpressive stress must have been directed northwesterly, and according to regional structural information the tectonic effect has its maximum expression in the Celebes Sea-southern Sulu Sea-North Borneo-southern Palawan sector. In the Makassar Strait region the tectonic forces gave rise to transcurrent reactivation of older deep faults, ophiolite emplacements (i.e. solid state intrusions of hot upper mantle material brought to the surface by tectonic forces), and volcanism (cf. Huchison, 1996). However, it is off North Sulawesi that the tectonic forces show their most significant expression. Here, at the margins of the southern Celebes Sea Basin, where water depths drop to around 5 km, that an approximately east-west running trench has developed and marine sediments have been underthrusted to the south (beneath the north arm of the island). This compressive overriding of the Sulawesi block has produced an ill-defined deep 'Benioff Zone'. Though most seismic activity within the frontal zone is confined to crustal levels some focal mechanisms have occurred also at depths of 200–300 km (Cardwell *et al.*, 1980). An implication of the inferred northwesterly tectonic push of Sulawesi would be left-lateral shearing in the Makassar Strait region. In fact, the western boundary fault of the North Sulawesi trench system is the Palu Fault for which earthquake focal studies have indeed indicated left-lateral strike-slip motion (Hamilton, 1979).

Further to the northwest, in the West Sulu Sea basins (off North Borneo) the basement displays a NE-SW striking 'basin-and-ridge' morphology which Wood (1985) attributed to shearing on the Sabah Fault. Wood's interpretation may account for the apparent non-alignment of the NW Sabah and southern Palawan structural fronts (see Fig. 8), probably implying a relative northwesterly shift of the southern Palawan wedge (including the island). In the same context Hinz and Schlueter (1985) argued that the imbricated and chaotic depositional wedge off southern Palawan represents an allochthonous mass overthrust from the southeast onto an Oligocene-early Miocene carbonate platform unconformably overlying autochthonous continental basement with half-graben infills. The ophiolites of the allochthonous terrane of South Palawan may belong to Upper Cretaceous-Lower Tertiary equivalents of the Rajang Complex in North Sabah, having been disconnected from its original alignment and thrusted to the northwest (towards its present location) after the late Lower Miocene. According to the interpretation of Hinz and Schlueter (1985) the Palawan wedge and tectonic front dates from Middle-Upper Miocene, and the modestly expressed South Palawan Trough can be explained by moderate gravity loading provided by the overthrusted tectonic wedge. NW Borneo too was affected by the late Tertiary compression (or transpression), resulting in a significant fold and thrust belt off NW Sabah. In the northwestern tip of Sabah the NW Borneo trend of the Rajang Group makes a sharp turn into the NW-SE Sulu trend, and the tectonics west of this structural knee is more complex than for the rest of the NW Sabah continental margin. It is tempting to conclude therefore that the Neogene tectonic stress field triggered off by Australia's clash with SE Asia had its maximum effect in the southern Sulu Sea and adjacent North Sabah. This westward tectonic 'push' produced the distinct tectonic fronts along the north-western continental margin of Sabah/

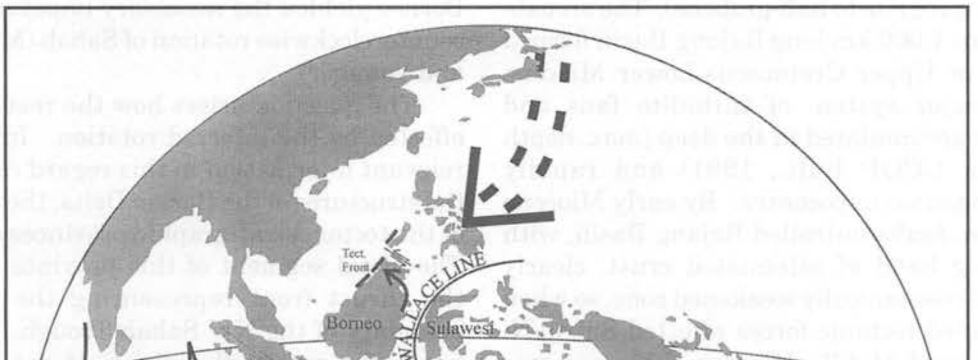

Figure 8. Consistent with its orientation just south of the present relative equator (which dates back to the Eocene-Oligocene boundary), and due to the maximum inertia effect at low latitudes, Greater Australia has undergone 70 degrees of anticlockwise rotation in Neogene times. Owing to this motion the world's most distinct biogeographic boundary, the Wallace Line, has been formed. The Australia/SE Asia collision produced a major northwesterly directed tectonic pressure with significant structural effects in southern SE Asia, including the hairpin shaped sector of the Indonesian Benioff Zone (see also Fig. 6). The tectonic fronts along the western continental margins of NW Sabah and South Palawan were constructed in this process.

Borneo and southwestern Palawan. The NW-directed tectonic pressure inferred from geological evidence is bolstered also by modern space geodesy data. Thus, GPS results from the GEODYSSEA 94-96 project (Wilson *et al.*, 1998) has shown that the Australasia collision zone is associated with NW-directed contemporary velocity fields, representing the largest motions observed (relative to Eurasia) within the SE Asian insular region.

Neogene tectonic rotation of NW Borneo

During the Alpine climax the South China Sea region developed a number of fault-controlled, mostly narrow, NE-SW and NW-SE striking continental basins including a complex system of horsts and tilted basement blocks (that subsequently gave rise to half-grabens). The arcuate and more than 1,000 km long Rajang Basin formed in this way in Upper Cretaceous-Lower Miocene times. A major system of turbidite fans and hemipelagics accumulated in the deep (max. depth c. 10,000 m, CCOP Bull., 1991) and rapidly subsiding elongated depocentre. By early Miocene time the deep, fault-controlled Rajang Basin, with its underlying band of attenuated crust, clearly represented a mechanically weakened zone, so when the NW-directed tectonic forces affected Sabah/N. Borneo at around Middle Miocene the scene was set for reactivation of the Rajang crustal segment and its overlying sedimentary pile. Thus, the westward directed tectonic pressure turned the Rajang succession of turbidites and hemipelagics, along with the adjacent deep marine sediments of the South China Sea, into a structural wedge with a marked tectonic front. A number of geophysical and geological observations suggest that during the Neogene tightening-up and westward thrusting of the Rajang-Crocker Complex, the resulting tectonic wedge overriding a continental Oligocene-early Miocene carbonate platform (cf. Hinz *et al.*, 1989), North Borneo underwent a certain counter-clockwise rotation of imbricational type.

EVIDENCE FOR TECTONIC ROTATION

Structural features off NW Borneo

Hinz *et al.* (1989) found that many imbricated thrust sheets along the NW Borneo margin (their structural unit III) were followed over distances of up to 190 km. The thickness of the individual sheets could vary between 3 and 15 km, but generally decreasing towards northeast where the imbricated wedge becomes increasingly complex, defining a compressed fold belt. In addition, Hinz *et al.* (ibid) distinguished a major thrust sheet unit IV, consisting of two superimposed internally imbricated zones. These two 'exotic' masses were regarded as of pre-Middle Miocene age, including Rajang-Crocker Group material. To the northeast and landward of unit IV a zone of even stronger structural complexity, unit V, representing several successive phases of deformation, was also identified. The belt of maximum structural distortion off NW Sabah, covered by units IV and V, Hinz *et al.* (ibid) extended northeastward for a distance of about 350 km towards Palawan. This 'chaotic' NE Sabah-South Palawan sector apparently represents the peak of deformation along the western thrust zone caused by transpressive forces set up by the Austral-Asia collision. It appears reasonable to suppose therefore that the northwestward stress field affecting northernmost Borneo yielded the necessary impetus for a certain counterclockwise rotation of Sabah (Middle Miocene and younger).

The question arises how the rest of Sabah was effected by the inferred rotation. Interesting and relevant information in this regard can be found in the structures of the Baram Delta, the southernmost of the tectonostratigraphic provinces of NW Sabah. The distal segment of this province forms part of the thrust front representing the southeastern boundary of the NW Sabah Trough. On the other hand, the proximal division of the Baram Delta Province constitutes a number of larger seaward facing growth faults, and to the northeast each of these major curved extension fractures is connected to another set of curved megafaults (see Hazebroek and Tan, 1993; Hutchison, 1996), apparently shear features with an overall NNE-SSW trend. It is tempting to relate these combined observations to the suggested counterclockwise rotation of Sabah. Both the NNE-SSW striking tectonic megastructures and their link-up with curved northwest facing extension or growth-faults to the southeast would be consistent with the proposed counterclockwise rotation of NW Borneo. From the evidence at hand it seems that in North Borneo this tectonic rotation included at least the region of Sabah.

Tectonomagmatic effects in eastern Borneo

If correct, a westward torsion of North Borneo ought to show up by structural deformation and localized extensional features w/magmatism rearwards, i.e. northern and central regions of Kalimantan would be obvious areas to look for such tectonomagmatic evidence. Though there are no basin-boundary faults to the deep Kutai Basin of Central Kalimantan (Moss *et al.*, 1997) it seems reasonable to assume that it represents the eastern extension of the major Ketungau/Mandai and Melawi basins. These latter depocentres, thought to have come into existence in Upper Cretaceous-Lower Tertiary times, are regarded here as products of sub-crustal attenuation along the trans-Borneo fracture zone. Figure 9 gives a schematic presentation of the Kalimantan basins. As we discussed above the SE Asia system of characteristic fractures and fault zones constitute a common orthogonal pattern, in this case with overall strike directions of NE/SW and NW/SE respectively. In Kalimantan, however, there are systematic deviations from this rule. Firstly, the orientation of the trans-Borneo sedimentary belt itself is trending WNW/ESE rather than NW/SE. Secondly, in the Kutai Basin, in the extended area of the Pliocene Samarinda anticlinorium, the thick succession of Middle-Upper Miocene sediments is

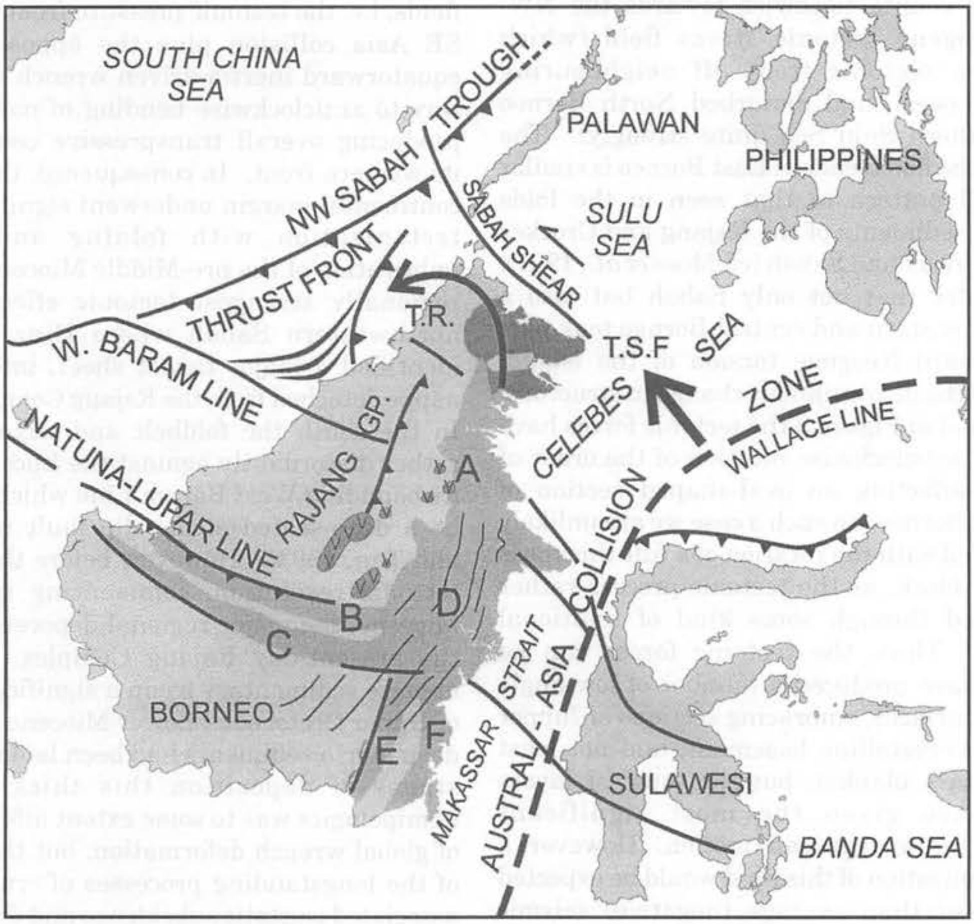

Figure 9. An overall view of the Neogene tectonic setting of Borneo. The Austral-Asia collision effect and resulting tectonic stress field (T.S.F.) have given rise to a significant northwesterly transpressive effect, including a counterclockwise rotational imbrication of Sabah (northern Borneo). Structural implications of this tectonic rotation (T.R.) can be seen over a wider region of East Borneo, demonstrated by: a counterclockwise rotation of the tectonic axes characterizing the region of the Kutai Basin, a northward bending around eastern Borneo of the extended Natuna-Lupar Line and other trans-island shear zones, with their associated narrow sedimentary basins, and a NNE-trending band of acidic to basic volcanism (marked by v-symbol) apparently triggered by transtensive conditions arising rearwards of the rotated Sabah block. The tectonic 'swing' of NE Borneo is also demonstrated by the structural variability along the western front. Thus, off the northwestern tip of Sabah, where the tectonic pressure was at its maximum, the tectonic front includes a major allochtonous mass, a 'Thrust Sheet' defining the northeastern 'termination' of the NW Sabah front. The southern sector of the tectonized wedge (the Baram Delta abutting against the West Baram Line) displays seaward-facing extensional growth-faults suggesting that the tectonic stress field has reversed to a southeasterly direction. In all, it appears that the Neogene rotational imbrication of Borneo only embraced the eastern half of the island. The Tertiary sedimentary basins (medium grey), after Moss *et al.*, 1997, are: A, Tarakan Basin; B, Ketungau/Mandai Basin; C, Malawi Basin; D, Kutai Basin; E, Barito Basin; F, Pasir/Asem-Asem Basin. Sabah Miocene basins are indicated by dark grey colour.

cut by a major system of curved faults and folds, apparently representing a shear grain whose origin within the plate tectonics school of thought has remained enigmatic (Moss *et al.*, 1997). As can be seen from Figure 9 the strike direction in the southern sector is NE/SW, corresponding to one of the regional strike directions. Further to the north, however, the structural trend gradually attains NNE/SSW orientations, i.e. the fold and fault trends clearly curve counterclockwise towards the NW-directed Neogene tectonic stress field (which produced the tectonic front off neighbouring northern Sulawesi, and disturbed North Borneo and the southern Sulu Sea quite strongly). The curvature of the fold trends of East Borneo is similar in its overall pattern to that seen in the folds affecting the sediments of the Rajang and Crocker groups of Sarawak and Sabah (cf. Moss *et al.*, 1997). Hence we infer that not only Sabah but also a major part of eastern and central Borneo took part in the westward Neogene torsion of the island. Judging from the discontinuous change in structural trends depicted in Figure 9 the tectonic forces have produced an anticlockwise rotation of the order of 20 degrees, affecting an oval-shaped section of northeastern Borneo. In such a case we are unlikely to be concerned with the rotation of a full-thickness 'lithospheric' block, as the tectonic process rather have operated through some kind of rotational imbrication. Thus, the tectonic forces can be expected to have produced a number of low-angle detachment surfaces, embracing sections of ?upper mantle, crust/crystalline basement, and not least the sedimentary blanket, but the topmost layers probably have given the most significant contribution to the aggregate motion. However, a 'crustal' tectonization of this kind would be expected to cause lower than average (negative) seismic velocities, and a recent study of tomographic P-wave anomalies for SE Asia (Spakman and Meinesz, 1998) has presented data consistent with such prediction. Thus, versus their chosen reference model and at a depth of 53 km the elongated eastern sector of Borneo (concerned with here) gave a c. 2% lower P-velocity than average at that depth.

Adding to the purely tectonic evidence for rotation the overall shearing along strike would naturally produce localized transtension paving the way for intrusive/volcanic activity. As seen in Figure 9 Neogene igneous processes have indeed been in operation, defining a NNE/SSW trending belt in the central part of northern Borneo. In all, the tectonomagmatic evidence at hand seems to provide good reasons for believing that a sector of eastern to northeastern Borneo has undergone a certain counterclockwise rotation since Middle Miocene. Such deformation certainly involved shearing along numerous fault zones, and therefore the gradual rotational effect produced would not be easily detectable by reconnaissance type palaeomagnetic studies.

EVOLUTION OF NW BORNEO CONTINENTAL MARGIN

In Neogene times the interacting regional stress fields, i.e. the tectonic pressure from the Australia/SE Asia collision plus the oppositely directed equatorward inertia-driven wrench forces, led the way to anticlockwise bending of northern Borneo producing overall transpressive conditions along its western front. In consequence, the NW Borneo continental margin underwent significant regional tectonization with folding and structural imbrication of the pre-Middle Miocene strata. The regionally strongest tectonic effect is seen off northwestern Sabah where Hinz *et al.* (1989) identified a major thrust sheet, interpreted as a nappe detached from the Rajang Complex landward. In the south the foldbelt and tectonic front end rather discordantly against the Luconia Block and its bounding West Baram Line which is thought to be a deep-seated strike-slip fault (cf. Hazebroek and Tan, 1993). However, before the NW Borneo tectonic revolution, commencing in the Middle Miocene, the major regional depocenter was along the present-day Rajang Complex. Within this arcuate sedimentary basin a significant succession of Upper Cretaceous-Lower Miocene turbiditic and deep marin sediments had been laid down. During stages of deposition this thick sequence of hemipelagics was to some extent affected by events of global wrench deformation, but the culmination of the longstanding processes of crustal thinning, associated isostatic subsidence and deposition came in late Lower Miocene. At that time a new phase of global mantle upwelling initiated crustal uplift along the deeply tectonized crust of the Rajang Belt. The early Neogene does not only represent the onset of the topographic range along northern Borneo but marks also the beginning rise of all modern mountain chains (see Storetvedt, 1997). According to the new theory of Earth evolution the net vertical mass flux in the mantle is the causation of the transgression-regression cycle of the sea, but in the case of NW Borneo tectonic effects interfingered strongly with the eustatic pulse. Uplift of the Rajang Belt exposed the former deep sea deposits to surface denudation, with sediments prograding northwestward from shallow to deep marine (cf. Hazebroek and Tan, 1993). Due to mountain uplift in combination with an overall northwestward thrusting of the pre-Middle Miocene sedimentary pile the depocentres were shifted to the northwest. The Miocene tectonic phases that affected NW Borneo were intimately connected with global geodynamic events, including shear-reactivation of the prevailing NE-SW structural grain across the South China Sea. Also, a certain loading effect from the advancing tectonic wedge (from the southeast) triggered additional fault reactivation and crustal attenuation along deeper frontal fracture zones. Hence, due to the Neogene dynamo-tectonic processes the major depocenter in the region of NW Borneo was shifted from the Rajang Belt to the present-day NW Sabah Trough.

In the new structural interpretation the whole region of NW Sabah is underlain by continental crust having undergone variable but overall increasing attenuation south-eastward, towards the deep Rajang sedimentary belt. Middle Miocene and later tectonic events have led to the progressive development of a broad thrust zone that terminates in a marked structural front, forming the physiographic and tectonic southeastern boundary of the late Neogene Sabah Trough. The major overthrusted wedge contains a mixture of broken fold structures, reverse faults, wrench-related compressive features and thrusting. The basal thrust plane of the entire NW Borneo tectonic wedge is probably the regional pre-Middle Miocene Carbonate Platform. Hinz *et al.* (1989) argued that a widespread pre-Middle Miocene carbonate layer, blanketing a complex system of horsts, tilted blocks and syn-rift grabens, constitutes the top layer of the thinned continental crust upon which the allochtonous tectonic wedge of South Palawan and Sabah has moved. In this interpretation the Sabah Trough becomes a down-faulted NE/SW trending section of the southern South China Sea Platform. Figure 10 depicts the tectonostratigraphic history of the NW Borneo continental margin in conjunction with the time-equivalent regional-global dynamo-tectonic 'pulsation'. The following main stages can be discerned.

i. In the southern South China Sea region the arcuate Rajang Belt, having developed along two characteristic orthogonal fracture systems, appears to have formed the principal sedimentary basin in this region during the Alpine climax (say from Upper Cretaceous to Upper Eocene). However, the reactivation of the basin during a major event of polar wander at around the Eocene-Oligocene boundary apparently extended the subsidence history of the basin throughout the Oligocene. Hence, the rapidly developing Rajang Basin became the site of major influx of clastic (turbiditic) sedimentation and hemipelagic deposits, including the Temburong and Crocker formations. The time span from around Middle Oligocene-early Miocene was characterized by relative geological quiescence world wide, and in the South China Sea region a carbonate platform covered earlier strata and half-grabens. In the Rajang Basin the earlier clastic and deep marine deposits were covered by formations such as the Lower-Middle Miocene Setap Shale and the sand dominated Meligan Formation (cf. Hutchison, 1996), suggesting that by now shallow water/shelf environments prevailed. This shallowing of the deep fault-controlled Rajang Basin is associated with the onset of a new phase of mantle upwelling, and which on a global scale can be associated with sea level rise, to be regarded as a precursor stage of the uplift of the modern mountain chains. The fairly shortlived Lower Miocene sea level low stand (cf. Fig. 10), following the basal Miocene transgression, can be directly related to sub-crustal thinning and associated isostatic subsidence in many regions around the world. According to the stratigraphic section given by Hazebroek and Tan (1993) this eustatic sea-level lowering produced an unconformity in the upper marine section of the Rajang Basin (Fig. 10).
ii. A new and much more persistent event of mantle upwelling began in the late Lower Miocene. By this time a tectonic revolution was under way in southern SE Asia disturbing presumed correlations between unconformities and eustatic low stands. The Middle Miocene can be regarded as the birth of the present-day mountain chains (cf. Storetvedt, 1997), being located along major fracture zones cutting into the uppermost mantle. The Rajang Basin apparently had formed along such deep fault zones, and besides, the late Lower/early Middle Miocene mantle upwelling triggered a new dynamo-tectonic event on Earth. The perhaps most significant global inertia-driven motion brought to light at that time was a counterclockwise rotation of Greater Australia, the approaching continental block docking against SE Asia along a boundary through the Makassar Strait and southern Sula Sea (the Wallace Line). The continental collision produced a northwesterly directed stress field which gave rise to transpressive deformation in the Celebes Sea/North Borneo/southern Sulu Sea sector. The northeastern part of Borneo underwent a 20–30 degrees of counterclockwise imbricational rotation. The tectonic forces produced a major structural front along southwestern Palawan and the northwestern margins of Borneo, and a Deep Regional Unconformity (DRU) developed. Due to the

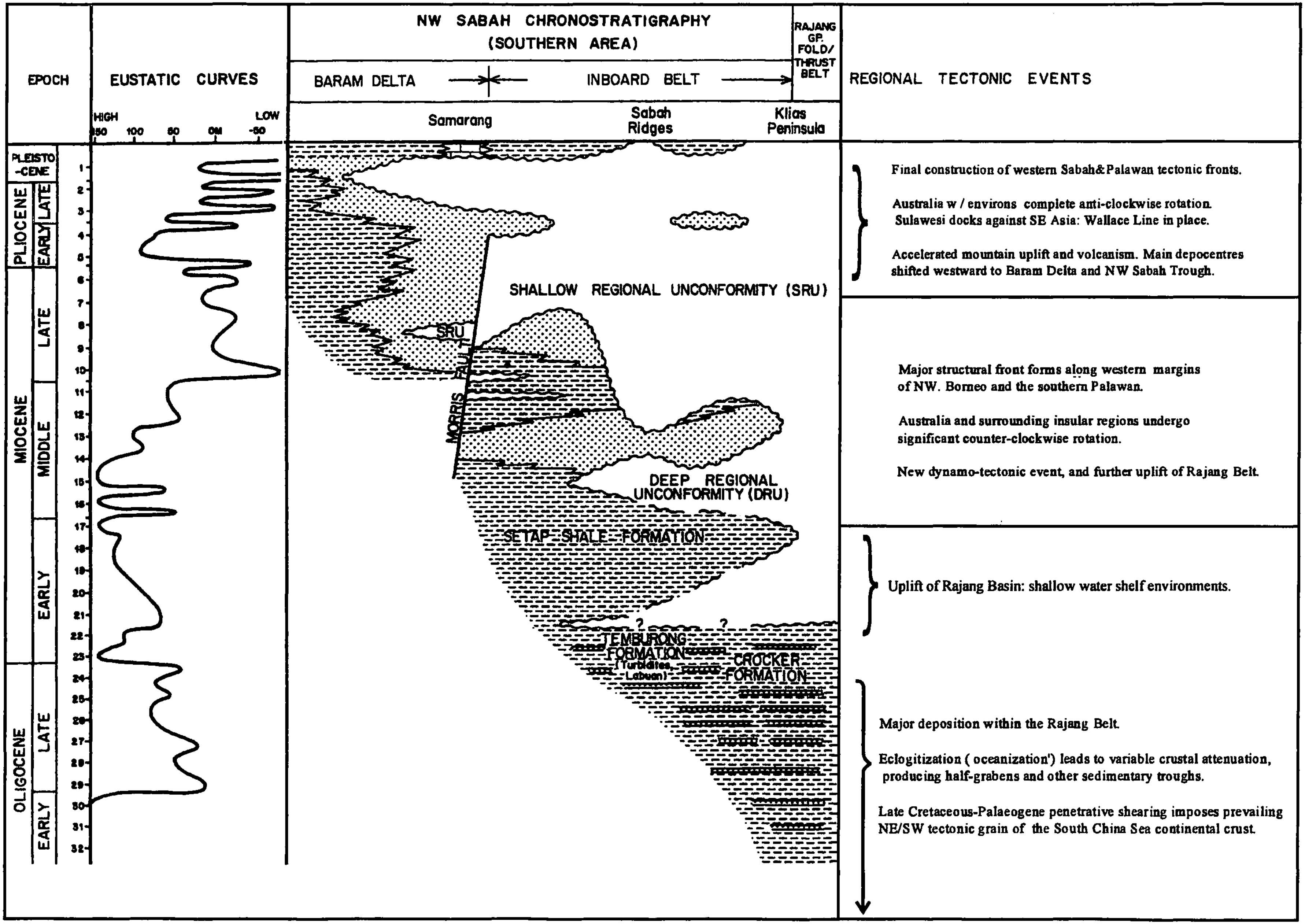

Figure 10. Chronostratigraphic development of NW Sabah (based on Fig. 3 of Hazebroek and Tan, 1993) in conjunction with eustatic sea level variation (Haq *et al.*, 1987) and regional/global tectonic events.

combined uplift and tectonic effects the post-early Middle Miocene sedimentation off NW Borneo, following the DRU, were of clastic shelf/slope character, prograding northwestward over the underlying sedimentary wedge (see Hazebroek and Tan, 1993).

iii. A new phase of mantle upwelling, with associated sea-level fluctuations and tectonic processes began in the late Miocene, continuing into the Pliocene. Mountain uplift accelerated, and associated local transtensional conditions triggered volcanism in places. Australia and surrounding insular regions completed their anticlockwise rotation and a new stage of transpressive deformation, including intricate imbrication, completed the construction of the Sabah and Palawan tectonic fronts. In concert with the relatively rapid sea level fluctuations the syn-depositional chronostratigraphic history of NW Borneo is characterized by a series of tectonic pulses (folding, thrusting and shearing) interspersed with periods of uplift (see also Hazebroek and Tan, 1993). During the late Upper Miocene and Pliocene history of this region the main depocenters shifted westward to the NW Sabah Trough and the Baram Delta. The late Neogene (mainly Pliocene) sedimentary fill of the NW Sabah Trough overlies the down-faulted Lower Tertiary Carbonate Platform of the southern South China Sea.

CONCLUDING REMARKS

In this paper we have taken a completely new look at the Tertiary geological evolution of the southern part of SE Asia. By discarding plate tectonic principles and replacing them with a new set of basic rules, defined by the theory of Global Wrench Tectonics, it appears that we have been successful in establishing a logical and coherent dynamo-tectonic system. The evolution of this tectonically extremely complex region now seems to become relatively simple. In any case, the various structural aspects of the NW Borneo continental margin turn out to be anticipated 'end' products of a long chain of interconnected processes.

ACKNOWLEDGEMENTS

We are indebted to the senior management of PMU-PETRONAS and FORTUM PETROLEUM, to our colleagues and friends in PRAD for their kind support, encouragement and help during this study, and to Frank Cleveland for preparing the diagrams. PETRONAS very kindly granted permission to publish this paper.

REFERENCES

AGOCS, W.B., MEYERHOFF, A.A. AND KIS, K., 1992. Reykjanes Ridge: qualitative determinations from magnetic anomalies. *In:* S. Chatterjee and N. Hotton III (Eds.), *New Concepts in Global Tectonics*, 221–238. Texas Tech University Press, Lubbock.

AUSTRHEIM, H., 1987. Eclogitization of lower crustal granulites by fluid migration through shear zones. *Earth Planet. Sci. Lett., 81*, 221–232.

AUSTRHEIM, H. AND GRIFFIN, W.L., 1985. Shear deformation and eclogite formation within granulite-facies anorthosites of the Bergen arcs, Western Norway. *Chem. Geol., 50*, 267–281.

BENIOFF, H., 1954. Orogenesis and Deep Crustal Structures: Additional Evidence from Seismology. *Bull. Geol. Soc. Am., 65*, 385–400.

BOWIN, C., PURDY, G.M. *ET AL.*, 1980. Arc-continent collision in the Banda Sea region. *Am. Assoc. Petrol. Geologists, Bull. 64*, 868–915.

BULL, J.M. AND SCRUTTON, R.A., 1992. Seismic reflection images of intraplate deformation, Central Indian Ocean. *J. Geol. Soc. Lond., 149*, 955–966.

CCOP, 1991. Total Sedimentary Isopach Maps Offshore East Asia. *CCOP Techn. Bull., 23*, Sheets 1–6 and Explanatory Notes, CCOP, Bangkok, Thailand.

CARDWELL, R.K., ISACKS, B.L. AND KARIG, D.E., 1980. The spatial distribution of earthquakes, focal mechanism solutions and subducted lithosphere in the Philippnes and northeastern Indonesian islands. *In: AGU Geophysical Monograph 23*, 1–35.

CREER, K.M., 1975. On a tentative correlation between changes in the geomagnetic polarity bias and reversal frequency and the Earth's rotation through Phanerozoic time. *In:* G.D. Rosenberg and S.K. Runcorn (Eds.), *Growth Rhythms and the History of the Earth's rotation.* John Wiley, London.

CURRAY, J.R., MOORE, D.G. *ET AL.*, 1979. Tectonics of the Andaman Sea and Burma. *Am. Ass. Petrol. Geologists, Memoirs 29*, 189–198.

CURRY, J.R. AND MUNASINGHE, T., 1989. Timing of intraplate deformation, northeastern Indian Ocean. *Earth Planet. Sci. Lett., 94*, 71–77.

EITTREIM, S.L. AND EWING, J., 1972. Mid-plate tectonics in the Indian Ocean. *J. Geophys. Res., 77*, 6413–6421.

GEORGE, W., 1981. Wallace and his line. *In:* T.C. Whitmore (Ed.), *Wallace Line and Plate Tectonics, 3–8.* Clarendon Press, Oxford.

HAMILTON, W, 1979. Tectonics of the Indonesian region. *U.S. Geological Survey Professional Paper 1078.*

HAILE, N.S., 1979. Palaeomagnetic evidence for rotation and northward drift of Sumatra. *J. Geol. Soc. Lond., 136*, 541–545.

HAQ, B.U., HARDENBOL, J. AND VAIL, P.R., 1987. Mesozoic and Cenozoic Chrono-stratigraphy and Cycles of Sea-Level changes — An Integrated Approach. *SEPM Spec. Publ. 42*, 71–108.

HATHERTON, T. AND DICKINSON, W.R., 1969. The relationship between andesitic volcanism and seismicity in Indonesia, the Lesser Antilles, and other island arcs. *J. Geophys. Res., 74*, 5301–5309.

HAYES, D.E. (ED.), 1978. A geophysical atlas of the East and Southeast Asian seas (6 sheets), MC-25. Geol. Soc. Am.

HAZEBROEK, H.P. AND TAN, D.N.K., 1993. Tertiary tectonic evolution of the NW Sabah continental margin. *Bull. Geol. Soc. Malaysia, 33*, 195–210.

HINZ, K. AND SCHLUETER, H.U., 1985. Geology of the Dangerous Grounds, South China Sea, and the continental margin off Southwest Palawan: Results of SONNE cruises SO23 and SO27. *Energy, 10*, 297–315.

HINZ, K., FRITSCH, J., KEMPTER, E.H.K. ET AL., 1989. Thrust tectonics along the north-western continental margin of Sabah/Borneo. *Geologische Rundschau, 78*, 705–730.

HUTCHISON, C.S., 1996. *Geological Evolution of South-East Asia*. Geol. Soc. Malaysia, 368p.

LAMADYO, E., MCCABE, R., HARDER, S. AND LEE, T., 1993. Borneo: a stable portion of the Eurasian margin since the Eocene. *J. SE Asian Earth Sci., 8*, 225–231.

LUYENDYK, B.P. AND MELSON, W.G., 1967. Magnetic Properties and Petrology of Rocks near the Crest of the Mid-Atlantic Ridge. *Nature, 215*, 147–149.

MCADOO, D.C. AND SANDWELL, D.T., 1995. Folding of oceanic lithosphere. *J. Geophys. Res., 90*, 8563–8569.

MC ELHINNY, M.W., HAILE, N.S. AND CRAWFORD, A.S., 1974. Palaeomagnetic evidence shows Malay Peninsula was not part of Gondwanaland. *Nature, 252*, 641–645.

MEYERHOFF, A.A., TANER, I., MORRIS, A.E.L. ET AL., 1992. Surge Tectonics: a new hypothesis of Earth dynamics. *In:* S. Chatterjee and N. Hotton III (Eds.), *New Concepts in Global Tectonics*, 309–409. Texas Tech University Press.

MOSS, S.J., CHAMBERS, J., CLOKE, I. ET AL., 1997. New observations on the sedimentary and tectonic evolution of the Tertiary Kutai Basin, East Kalimantan. *In:* A.J. FRASER *et al.* (Eds.), Petroleum Geology of Southeast Asia. *Geol. Soc. Lond., Special Publ. 126*, 395–416.

NEPROCHNOV, Y.P., LEVCHENKO, O.V., MERKLIN, L.R. AND SEDOV, V.V., 1988. The structure and tectonics of the intraplate deformation area in the Indian Ocean. *Tectonophysics, 156*, 89–106.

OPDYKE, N.D. AND HIKINIAN, R., 1967. Magnetic properties of some igneous rocks from the Mid-Atlantic Ridge. *J. Geophys. Res., 72*, 2257–2260.

SCHMIDTKE, E.A., FULLER, M.D. AND HASTON, R.B., 1990. Paleomagnetic data from Sarawak, Malaysian Borneo, and the late Mesozoic and Cenozoic tectonics of Sundaland. *Tectonics, 9*, 123–140.

SPAKMAN, W. AND MEINESZ, H.B.V., 1998. Mantle Structure and Large Dynamics of South-East Asia. *In:* P. Wilson and G.W. Michel (Eds.), The GEODYnamics of S and SE Asia (GEODYSSEA) Project, Scientific Tech Report STR/14, 313–339. *Geoforschungs Zentrum Potsdam*, Germany.

STARK, M. AND FORSYTH, D.W., 1983. The geoid, small-scale convection, and differential travel time anomalies of shear waves in the central Indian Ocean. *J. Geophys. Res., 88*, 2273–2288.

STEIN, S. AND OKAL, E.A., 1978. Seismicity and tectonics of the Ninety-East Ridge area: evidence for internal deformation of Indian plate. *J. Geophys. Res., 83*, 2233–2245.

STORETVEDT, K.M., 1997. *Our Evolving Planet*. Alma Mater, Bergen, 456 pp.

TAN, D.N.K., 1979. Lupar Valley, west Sarawak, Malaysia. *Geol. Surv. Malaysia, Report 13*.

TAN, D.N.K. (compiler), 1982. Geol. Map of Sarawak, 1:500 000, Geol. Surv. Malaysia.

TONGKUL, F., 1993. Tectonic control on the development of the Neogene basins in Sabah, East Malaysia. *Bull. Geol. Soc. Malaysia, 33*, 95–103.

VAN BEMMELEN, R.W., 1970. *The geology of Indonesia*. Martinus Nijhoff, The Hague.

VAN ORMAN, J., COCHRAN, J.R., WEISSEL, J.K. AND JESTIN, F., 1995. Distribution of shortening between the Indian and Australian plates in the central Indian Ocean. *Earth Planet. Sci. Lett., 133*, 35–46.

WEISSEL, J.K., ANDERSON, R.N. AND GELLER, C.A., 1980. Deformation of the Indo-Australian plate. *Nature, 287*, 284–291.

WILLIAMS, P.R., JOHNSON, C.R., ALMOND, R.A. AND SIMAMORA, W.H., 1988. Late Cretaceous to Early Tertiary structural elements of West Kalimantan. *Tectonophysics, 148*, 279–297.

WILSON, J.T., 1954. The development and structure of the crust. *In:* G.P. Keuper (Ed.), *The Earth as a planet*, 138–214. Chicago Univ. Press, Chicago.

WILSON, P., RAIS, J. ET AL., 1998. *The GEODYSSEA project: an investigation of the geology and geodynamics of South and South-East Asia*. EOS, November 10.

WINDLEY, B.F., 1977. *The Evolving Continents*. John Wiley, London.

WOOD, B.G.M., 1985. The mechanics of progressive deformation in crustal plates — a working model for Southeast Asia. *Bull. Geol. Soc. Malaysia, 18*, 55–99.

Manuscript received 10 May 2000