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The Eocene unconformity on Southeast and East Sundaland

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Abstract: The Early Palaeogene landmass of Sundaland extended as far southeast as West Sulawesi. The cratonic nature of the Malay Peninsula and China did not extend into or beyond the Borneo region of Sundaland, where the pre-Eocene outcrops were dominated by Cretaceous rocks. Deep water sediments, mélange and ophiolite terrain were characteristic of this non-cratonic southeastern peninsula of Sundaland.

By 45 Ma (magnetic anomaly 19), India was in flush collision with Eurasia, seafloor spreading ceased at the NW Wharton Basin, and a new fracture system was initiated, separating Australia from Antarctica, and extending WNW along the SE India Ocean Ridge towards the Red Sea. This event was felt throughout the whole of Southeast Asia, and is recorded as the major Eocene Unconformity, both onland and offshore Sundaland.

The NNE directed push of cratonic India into the continental margin of Eurasia resulted in a general clockwise rotation of the Sundaland Peninsula, made possible by major right-lateral shear along the pre-existing structural grain (extrusion tectonics). The Sunda arc-trench system was also initiated at 45 Ma. The oroclinal bending resulted in crustal pull-apart in some places and compression in others. Anti-clockwise rotation and left-lateral shear were imparted to eastern Sundaland by the collision of Australia to the east. Rejuvenated rivers carried an increased load from the uplifted areas, active faulting created river capture and lakes, many of which date back to the Eocene in most places, but were locally delayed to the Oligocene. Marine platform carbonates became widespread and characteristic of E and SE Sundaland from Late Oligocene through Miocene, except in the Rajang Group Basin and some rift-related river/delta systems. Late Miocene to Pliocene uplift was important in non-cratonic Sundaland, causing internal subdivision of formerly more extensive Cenozoic basins.

INTRODUCTION

An Eocene unconformity is widespread over the whole region, both throughout the northeast Indian Ocean, and on the extensive early Palaeogene landmass of Southeast Asia, hereafter referred to as Sundaland.

The unconformity is interpreted to be due to the indentation of India into the continental margin of Eurasia. India began colliding %% Ma and became flush with Eurasia by 45 Ma, the time of magnetic anomalies 19 and 20 (Dewey *et al.*, 1989). This was also the time of separation of Australia from Antarctica (Veevers, 1984) and the creation of the new spreading system at the Southeast Indian Ocean Ridge (Packham, 1990). The fossil spreading centre in the northeast Indian Ocean

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indicates that spreading ceased shortly after the formation of magnetic anomaly 20 (Liu *et al.*, 1983) and jumped to the newly created Southeast Indian Ocean Ridge. This major reorganization of the spreading pattern of the Indian Plate may have been a consequence of the collision, but is more likely to represent a fundamental world event, for the Pacific Ocean also reorganized at 45 Ma. The plate reorganization had a major impact on the tectonics and stratigraphy of the whole of Southeast Asia.

In the Bay of Bengal, the Eocene unconformity subdivides the wholly marine sedimentary section into pre-collision continental rise and post-collision Bengal fan (Curray and Munasinghe, 1989; Curray, 1991).

Before collision, northern India should have been topographically depressed as it was dragged down into the Tethyian Trench along its northern margin (similar to Australia at the present-day Timor Trough; Veevers, 1984), resulting in a sedimentary hiatus because India shed little or no detritus as far as the eastern Indian Ocean. The collision led to progressive uplift of Tibet and the Himalaya, erosion of which resulted in the post-unconformity Bengal fan. The unconformity therefore represents the time of the India–Eurasia collision (Curray and Munasinghe, 1989; Curray, 1991).

The Eocene unconformity on Sundaland (Fig. 1) requires a different explanation than that given for the submarine unconformity, but both need to be related to the collision of India. A hypothesis will be offered after the Sundaland landsurface and its Eocene unconformity has been described.

SUNDALAND NORTH OF THE RAJANG BASIN

The Marginal Basin

The South China Sea Basin represents a part of Sundaland that rifted and subsided to the stage of marginal basin seafloor spreading (Fig. 1).

Sea Beam surveys of the South China Sea Basin exhibit two major structural trends: scarps trending 50°, interpreted as normal faults, and scarps trending 140°, interpreted as fracture zones (Briais *et al.*, 1989). Magnetic and gravimetric surveys in the Scarborough Seamounts region show anomalies trending approximately 50°, disrupted by transform faults striking 140°, spaced at less than 20 to 30 km. The E-W trend of the anomalies 11 to 5d (mid-Oligocene to early Miocene), interpreted by Taylor and Hayes (1983), is incompatible with the geomorphology of the South China Sea Basin. The fabric implies a NW-SE direction of spreading, extending about 100 km N and S of the inferred spreading axis at the Scarborough Seamounts. In view of the mistakes that have been made elsewhere in the identification of magnetic anomalies without geological constraints, I would suggest that the spreading ages of mid-Oligocene to early Miocene should be only provisionally accepted until it becomes possible to have direct age determination by drilling.

The northern margins

The sector lying between the northern extent of the marginal basin and the coastlines of China and Vietnam is of rifted attenuated continental crust now lying

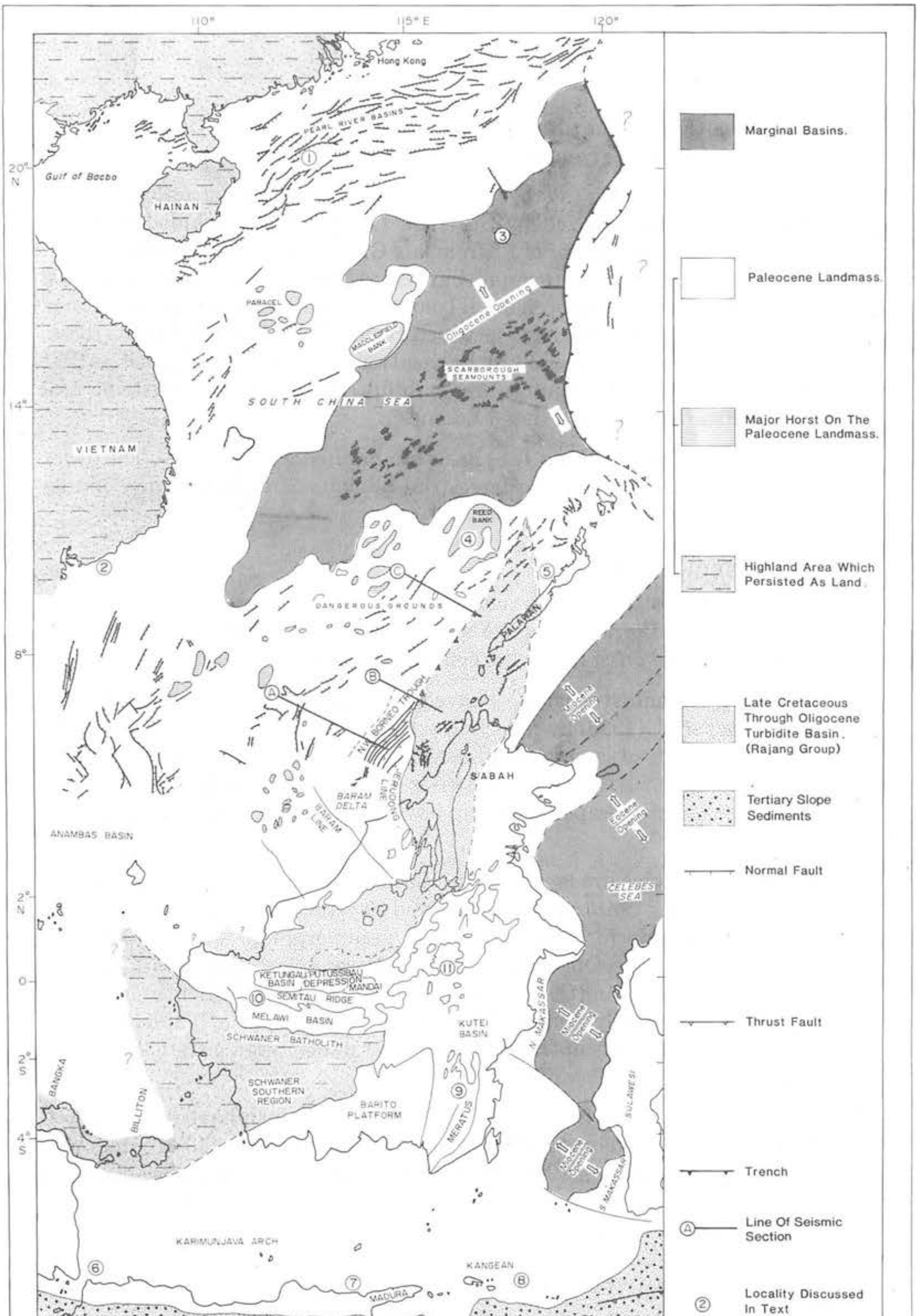

Figure 1: The Palaeocene landmass of Southeastern Sundaland, which has been extensively rifted to form marginal basins and Eocene grabens filled by terrestrial alluvial and lacustrine deposits. Its eastern margins are ill-defined. Numbers 1 to 11 refer to stratigraphic columns of Figures 2 and 4

beneath sea level (Fig. 1). The rifting history is well displayed by the Cenozoic basins which are being increasingly investigated by Petroleum companies.

The basins lying along the coast of China have a common stratigraphy and tectonic evolution, summarized by Su *et al.* (1989), who concluded that the lithosphere stretched by a factor of 1.8 from late Cretaceous to late Oligocene (Fig. 2). Early Eocene red clastics are overlain by early to Middle Eocene dark lacustrine shales, overlain by early Oligocene coal-bearing coastal swamp deposits. These early deposits are preserved in grabens which extend NE-SW parallel to the coast. Spores and pollen are rare especially in the basal redbed alluvial fan deposit, so that the inferred Palaeocene beginnings are doubtful. The overlying lacustrine and swamp deposits are confidently dated Eocene.

The Mekong Trough (Vung Tau) has a similar history (Le, 1986). The lower part of the sequence is of Eocene terrestrial alluvium and lacustrine deposits confined to major grabens (Fig. 2).

The southern margins

The sector lying between the southern extent of the marginal basin and the Palawan–Northwest Borneo Trough (Fig. 1) is similarly interpreted as attenuated and rifted continental crust now lying beneath sea level.

The structure and stratigraphy have been analysed by Hinz and Schluter (1985) and Hinz *et al.* (1989) by reflection seismic analysis (Fig. 3), controlled by critically located dredged samples (Kudrass *et al.*, 1986) and oil company data from the Reed Bank and offshore Palawan (Taylor and Hayes, 1980; Holloway, 1981). Whether the regional extrapolation may have been extended too far is open to discussion.

The oldest samples dredged from the Reed Bank are of late Triassic deltaic sandstones containing *Clathropteris* leaves and claystone containing *Halobia* and *Daonella*. Gneisses and schists have given K:Ar metamorphic dates of late Jurassic/ early Cretaceous. A late Oligocene to early Miocene carbonate platform was extensively developed during the inferred time of spreading of the South China Sea Basin. It has been widely sampled and dated (Kudrass *et al.*, 1986). Young presumably rift-related basalts have yielded K:Ar dates ranging from 2.8 to 0.42 Ma.

The oil company data from the Reed Bank and Palawan have not been well documented, but the sketchy details given by Taylor and Hayes (1980), Holloway (1981) and Hinz and Schluter (1985) indicate important Eocene unconformities and marginal marine sandstones and siltstones underlying the late Oligocene to Recent carbonate platform (Fig. 2).

The Palawan–Northwest Borneo Trough

Many geologists repeat the view of Hamilton (1979) that the Palawan–Northwest Borneo Trough is a NW-facing trench which became extinct in the Middle Miocene. When he published this view, the high quality reflection surveys

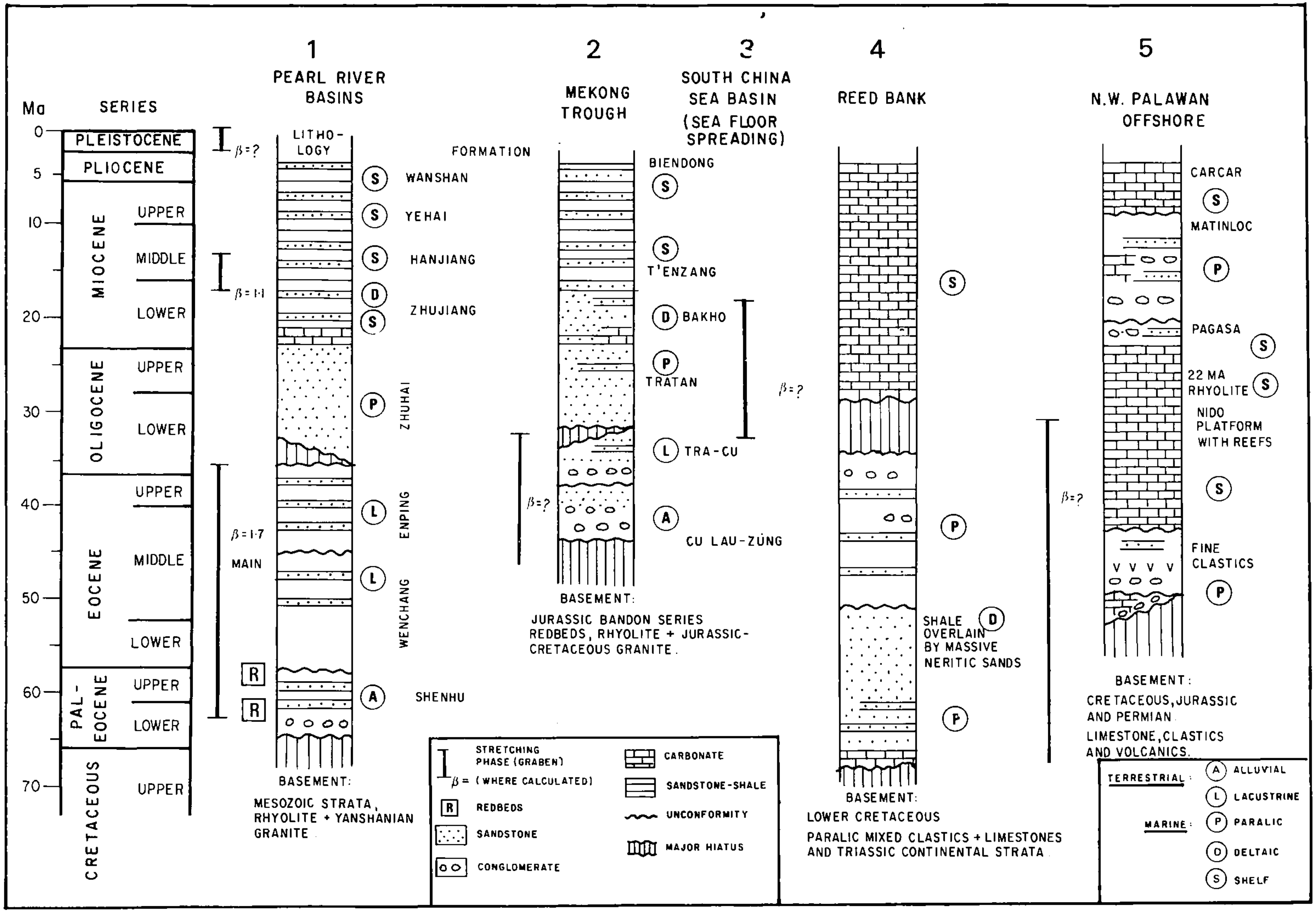

Figure 2: Some typical stratigraphic sections of Cenozoic basins of the South China Sea. 1: after Su *et al.* (1989); 2: after Le (1986); 3: from Taylor and Hayes (1983); 4 and 5: after Taylor and Hayes (1980), Hinz and Schluter (1985) and Holloway (1981). See Figure 1 for localities.

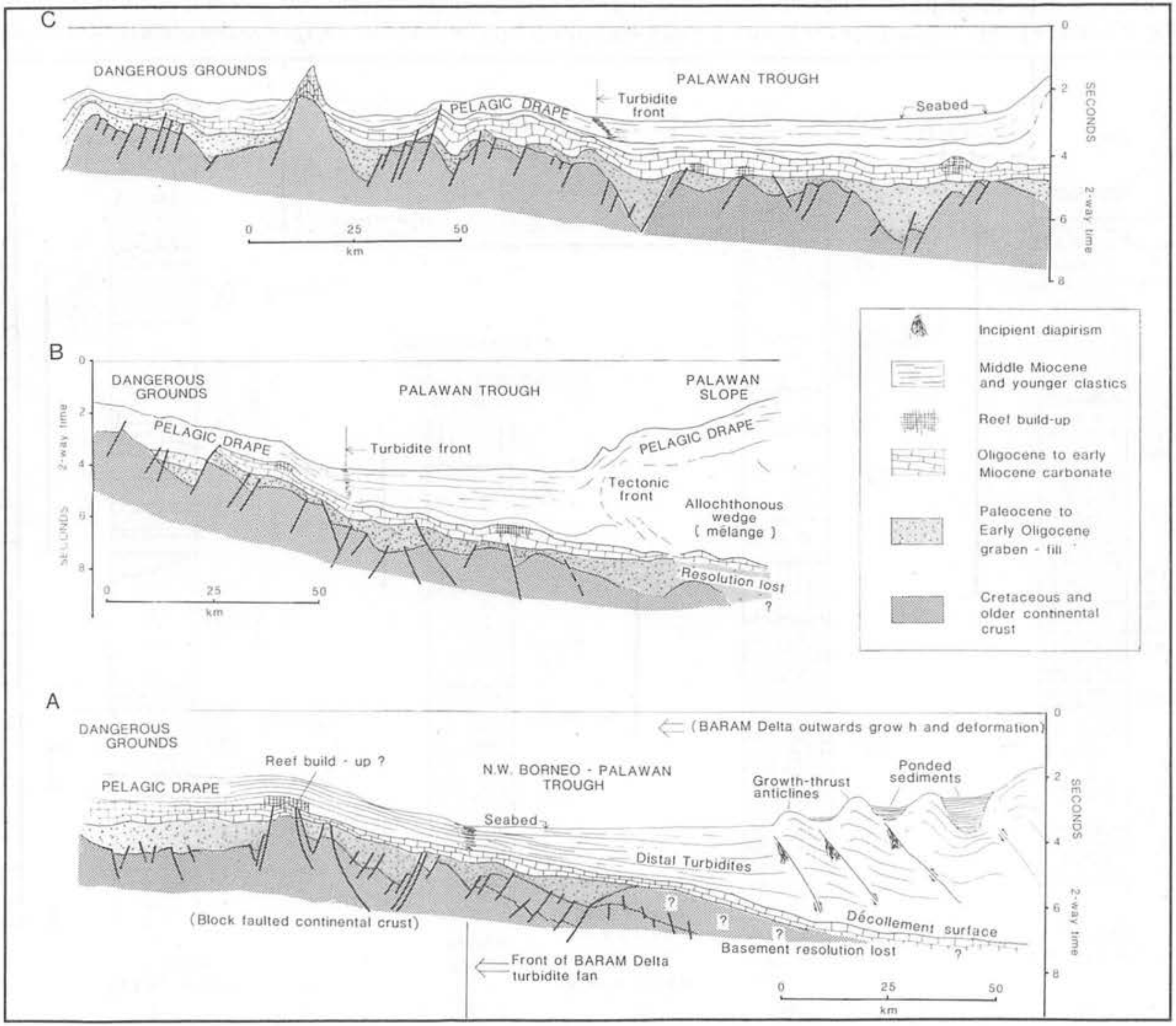

Figure 3: Interpreted reflection seismic profiles of the Dangerous Grounds and Palawan–Northwest Borneo Trough, based on Hinz and Schluter (1985) and Hinz *et al.* (1989).

(Fig. 3) had not yet become available. The seismic sections show that the Trough bears little resemblance to a trench. The trough area is a 60 km broad area of flat undeformed deep water Middle Miocene or younger sediments. The Dangerous Grounds Terrain is stationary and not converging on Borneo, otherwise the sediments of the Trough would be deformed. The sediments reaching the Trough represent the turbidite front of deltas originating from the elevated Rajang Group terrain of Borneo (e.g. the Middle Miocene and younger Baram Delta). These sediments are actively being deformed and redistributed away from the Borneo coastline, by thrusting, growing anticlines, ponding and spilling over of sediments oceanwards. The delta front progressed rapidly oceanwards over under-compacted pro-delta muds. Their subsequent de-watering resulted in active mud diapirism, which on some seismic sections is seen as submarine mud volcanoes near the tectonic front.

The delta sediments continuously transgressed over the Dangerous Grounds continental lithosphere, loading and depressing it, resulting in its landward dip (Fig. 3). It is this landward dip that led to the erroneous interpretation that the Dangerous Grounds terrain is subducting southeastwards at the Palawan–Northwest Borneo Trough. There are no scraped-up sediments and no deformation in the trough.

The Sarawak and Brunei sector of the Baram Delta (section A of Fig. 3) does not include Paleogene Rajang Group. However, farther to the NE (sections B and C of Fig. 3), the equivalent of the Baram Delta has prograded oceanwards over a deformed basement of Rajang Group. The northwestwards and westwards extent of the Rajang Group basement is interpreted to be the tectonic front of sections B and C (Fig. 3) and the Jerudong Line of Brunei (Fig. 1).

SUNDALAND SOUTH OF THE RAJANG BASIN

The Paleocene landmass of Sundaland extended eastwards from the Malay Peninsula and Sumatra at least as far as Kangean, eastern Borneo and West Sulawesi (Van der Weerd and Armin, in press) (Fig. 1). The eastern margins of this landmass are difficult to define, for they have been disrupted by many marginal basins, such as the Eocene Celebes Sea, and younger Makassar Straits and Sulu Seas. The now uplifted Rajang Group of Sarawak and Sabah, in Paleocene time was either a major marginal sea or a gulf of the Pacific Ocean. Its oceanic or marginal sea basement is early Cretaceous (Barremian) chert, which overlay ophiolite, now exposed along the Lupar Line and in NE Sabah (Hutchison, 1991a; Rangin *et al.*, 1990). The sedimentary fill of this marginal sea or gulf is represented by the predominantly turbiditic Belaga Formation of Sarawak and the Crocker Formation and its correlatives of Sabah. This basin probably persisted until early Miocene, when it was compressed and uplifted to form the provenance for the Baram and other deltas which prograded northwards. A possible scenario for the early development of the Rajang Group is given by Ru and Pigott (1986), though they did not recognize the older age of the chert associated with the ophiolite, or by Taylor and Hayes (1983), who more generally referred to the basin as being floored by "Mesozoic Oceanic Crust", representing a gulf of the Pacific Ocean into Sundaland.

The pre-Cenozoic basement of Sumatra and Peninsular Malaysia is of Palaeozoic and Mesozoic rocks. This part of the Paleocene Sundaland landmass may accordingly be considered to have been cratonic. However, the Sundaland peninsula extending eastwards from the southeast coast of Sumatra did not appear to have been cratonic, for the pre-Cenozoic formations are dominantly Cretaceous, many of uplifted ophiolite, mélange and turbidite (Pieters and Supriatna, 1990). It may represent terrain accreted to Sundaland during the late Mesozoic to have become part of the extensive Paleocene landmass.

North Java sector

The N-S elongated grabens, which developed on the pre-Cenozoic landmass of northwest Java, first received the Palaeogene Jatibarang Volcanic Formation (Adnan *et al.*, 1991), which acts locally as an oil reservoir (Fig. 4). The main reservoir lithologies are fractured massive tuff and conglomerate (Reminton and Pranyoto, 1985). The main source rocks are formed by the Oligocene lacustrine Talang Akar Formation (Gordon, 1985), which was deposited in grabens (Fig. 4). The formation represents a progression from continental to deltaic and shallow marine. The basal grits are preserved in graben depocentres, followed by coals and marine shales with thin limestones.

In northeast Java, the Middle Eocene to early Oligocene Ngimbang Formation rests with a pronounced unconformity on the pre-Cenozoic basement. Its base is of coarse grained sandstone, shale with minor coal seams, changing upwards into fine grained limestones, minor marls and sandstone, representing a transition from terrestrial to shallow marine (Soeparyono and Lennox, 1989).

Similar geology extends at least to the Kangean region, NE of Bali (Fig. 1). The basement is of steeply dipping Cretaceous weakly metamorphosed sandstone, siltstone, shale and chert (Kohar, 1985; Phillips *et al.*, 1991). This basement is unconformably overlain in palaeo lows by the pre-Ngimbang Formation. Sparse fossils indicate a Palaeocene to Middle Eocene age. It is composed of sandstone, siltstone and shale with some coal, deposited in a continental to shallow marine environment. The Late Eocene Ngimbang Formation rests unconformably on the pre-Ngimbing. The basal clastic member is of sandstone and conglomerate, grading upwards into a sequence of sandstones, shales and coals, interpreted as terrestrial to marginal marine. Marine transgression is indicated by the late Eocene Ngimbing carbonate (Phillips *et al.*, 1991).

Java Sea

The NE-trending horst and graben structures, which connect Java to Borneo beneath the Java Sea, have been described by Bishop (1980). The pre-Cenozoic basement has been widely drilled and shown to be of a variety of volcanic, plutonic, metamorphic and ophiolitic rocks, many of which are Cretaceous.

Palaeocene to Eocene strata were deposited in grabens developed on an erosional landsurface. These terrestrial (lacustrine and fluvial) sediments include pebbly sandstones and tuffaceous mudstone. As in Borneo and western Sulawesi,

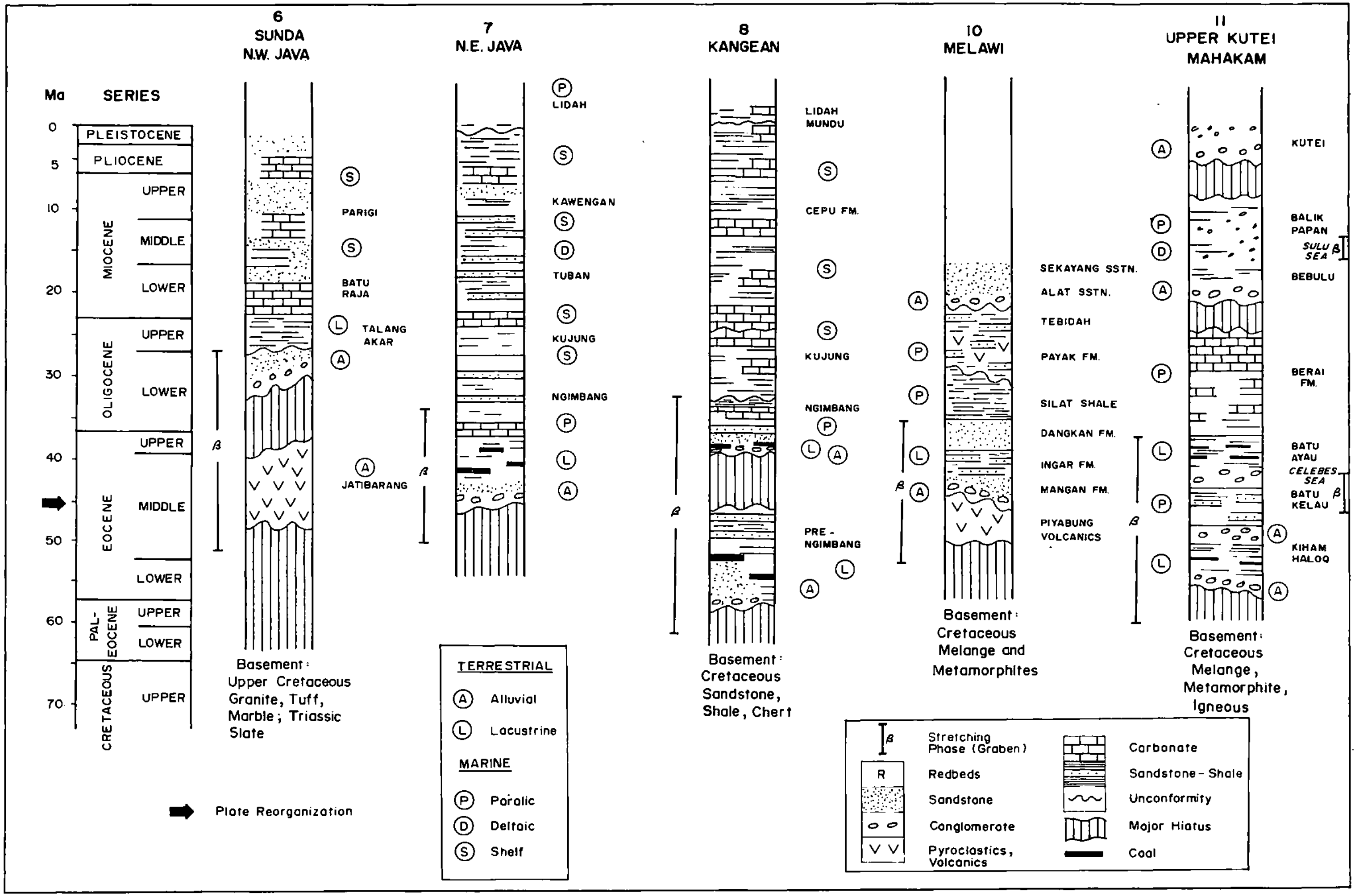

Figure 4: Some typical stratigraphic sections of Cenozoic basins of Sundaland south of the Rajang Group of Borneo. 6: after Gordon (1985) and Reminton and Pranyoto (1985). 7: after Soeparyono and Lennox (1989). 8: after Kohar (1985) and Phillips *et al.* (1991). 9: (given in Figures 5 and 6), after Kusuma and Darin (1989). 10: after Pieters *et al.* (1987). 11: after Wain and Berod (1989) and Van de Weerd and Armin (in press). See Figure 1 for localities.

they are widely transgressed by massive "CD Limestone" of Middle Oligocene to Lower Miocene age, comparable to the Berai Limestone (Bishop, 1980).

Western Sulawesi

Cretaceous ophiolite and flysch strata are unconformably overlain by the terrestrial Malawa Formation (Hasan, 1991). It contains abundant quartz sandstones, siltstones and coal beds. As in Borneo, the Early Paleogene clastic strata, locally of redbed facies, are widely transgressed by Oligocene to Miocene Tonasa Formation platform carbonate (Hasan, 1991).

Kalimantan

In Palaeocene time all of Borneo, south and SE of the Rajang Group turbidite basin, was an extensive landmass, contiguous with West Sulawesi and the area now below the Java Sea, and dominated by the Schwaner Mountains High (Fig. 1).

The outcropping rocks of the Palaeocene landsurface were predominantly of Cretaceous age. The highlands of the Schwaner Mountains were dominated, as today, by early Cretaceous I-type granitoids and late Cretaceous volcanic rocks (Williams *et al.*, 1988). Outside of the mountain zone, the outcrops were also predominantly of Cretaceous rocks, composed of abundant ophiolite suite, deep water turbidite strata, volcanic rocks and extensive mélange (Pieters and Supriatna, 1990; Wain and Berod, 1989; Sikumbang, 1986). There was no sign of a Phanerozoic cratonic stratigraphic continuity and the general impression gained from details from the Semitau High (Williams *et al.*, 1988), Meratus Mountains (Sikumbang, 1986) and the Upper Kutei area (Wain and Berod, 1989) suggest that this part of Sundaland was built by Cretaceous accretion onto Sundaland of marginal basin lithosphere and turbidite sedimentary fill, island arcs and numerous mélange terrain.

I am also proposing that Sabah east of the Crocker Range (Rajang Basin) was also an integral part of this non-cratonic Sundaland landmass. There is a large hiatus in the sedimentary record of Sabah. The basement is of marginal sea or oceanic lithosphere overlain by Barremian (early Cretaceous) chert (Hutchison, 1991a) and undated turbidite sandstones of the Chert Spilite Formation. Uplift and erosion of this basement is indicated by serpentinite chert-bearing sandstones and conglomerate in the Bidu-Bidu Hills (Newton-Smith, 1967; Hutchison and Tungah Surat, 1991). The serpentinite sandstones and conglomerates of Sabah occupy a similar tectonic position to the ophiolite-derived coarse clastics of the Pamali Breccia of the Meratus Mountains (Sikumbang, 1986; Bergman *et al.*, 1987). The latter is a Late Cretaceous conglomerate, which contains detrital diamonds, scavenged by the rivers from cratonic Sundaland, and carried to the outer non-cratonic accreted part of the Sundaland land surface.

Eocene extension phase

The early graben phase is best described in the Meratus area (Figs. 4 and 5), which received the Tanjung Formation, consisting of basal conglomerate, sandstones, shales and coals, with local basalt intercalations, regarded as Eocene by de Weerd and Armin (in press) but as old as Palaeocene by Kusuma and Darin (1989). The lacustrine coal-rich deposits provide important source rocks for the Barito Basin.

Similar alluvial and marginal marine strata occur in the Ketungau, Melawi (Fig. 4) and Mandai basins (Pieters *et al.*, 1987). In the Upper Kutei Basinal area (Fig. 4), up to 1500 m of Kiham Haloq Formation ourcrops in the Mahakam rapids. It is of cross-bedded and massive conglomeratic sandstone overlying a basal red-chert conglomerate (Wain and Berod, 1989), interpreted as an alluvial fan deposit. The abundance of chert in the basal conglomerate has been provenanced from early Cretaceous ophiolite and its deep water sedimentary cover, which formed an important part of the pre-Cenozoic landsurface. Whereas Wain and Berod (1989) consider the Kiham Haloq Formation to be as old as Palaeocene, de Weerd and Armin (in press) regard it as Eocene.

In Sabah and contiguous north Kalimantan, the graben development stage was delayed to the late Lower and Middle Miocene, well displayed in the Tarakan Basin (de Weerd and Armin, in press) and the connecting rift system of Sabah, which received the Tanjong and Sandakan formations (Hutchison, 1989). This rift system of North Kalimantan and Sabah is the onland extension of the Sulu Sea marginal basin rifting, recently documented by Hinz *et al.* (1991).

Marine transgression phase

By late Oligocene time, Sundaland south and east of the Rajang Basin was extensively inundated by shallow marine carbonate platform (Fig. 4). It is known as the Berai Limestone in the Barito, Asem-Asem and Pasir basins (Figs. 5 and 6) and in the Upper Kutei–Mahakam area (Wain and Berod, 1989).

The carbonate platform is absent from the more pronounced rifts which became the focus of major river and delta outgrowths. The siliciclastic-dominated areas are mainly the Eocene Kutei Basin, extrapolating WNW to the Melawi and Ketungau basins (de Weerd and Armin, in press) and the Miocene rift system of the Tarakan Basin and contiguous Tanjong Formation basins of Sabah.

Basement uplift phase

The Meratus Mountains did not represent a topographic high from Palaeocene through Middle Miocene. This is well documented by the cross sections constructed across the Meratus Mountains (Fig. 6). The late Oligocene Berai Limestone occurs on both sides of the Meratus (Barito and Pasir basins) as well as on top of the Meratus (Fig. 6). There are no E-W facies and thickness changes and therefore the Meratus was not a palaeo-topographic feature. Throughout the period from Oligocene through Middle Miocene the Barito was continuous with and was one and the same with the Asem-Asem and Pasir basins (Fig. 5). Because these basins were superimposed on the uplifted and peneplained Meratus, they should not be classified in relation to any Cretaceous tectonic interpretation of the underlying Meratus assemblage.

Uplift of the Meratus took place in the late Miocene–Pliocene, as recorded in the thick non-marine Dahor Formation, which is found only in the Barito Basin, but

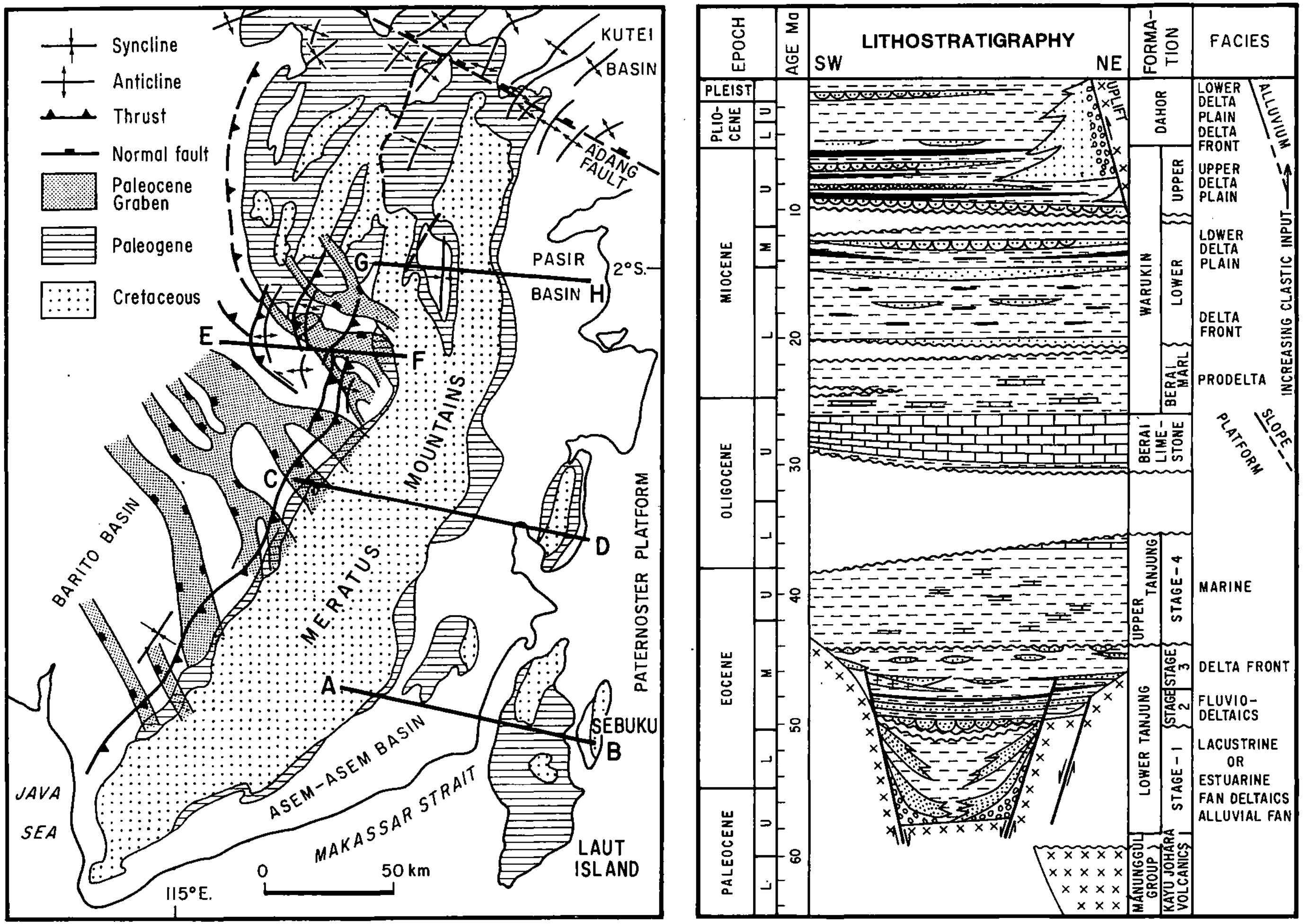

Figure 5: The Palaeogene grabens and lithostratigraphy of the Barito Basin (9 on Fig. 4), SE Kalimantan, based on Kusuma and Darin (1989) and Van de Weerd and Armin (in press). The located cross sections are given in Figure 6.

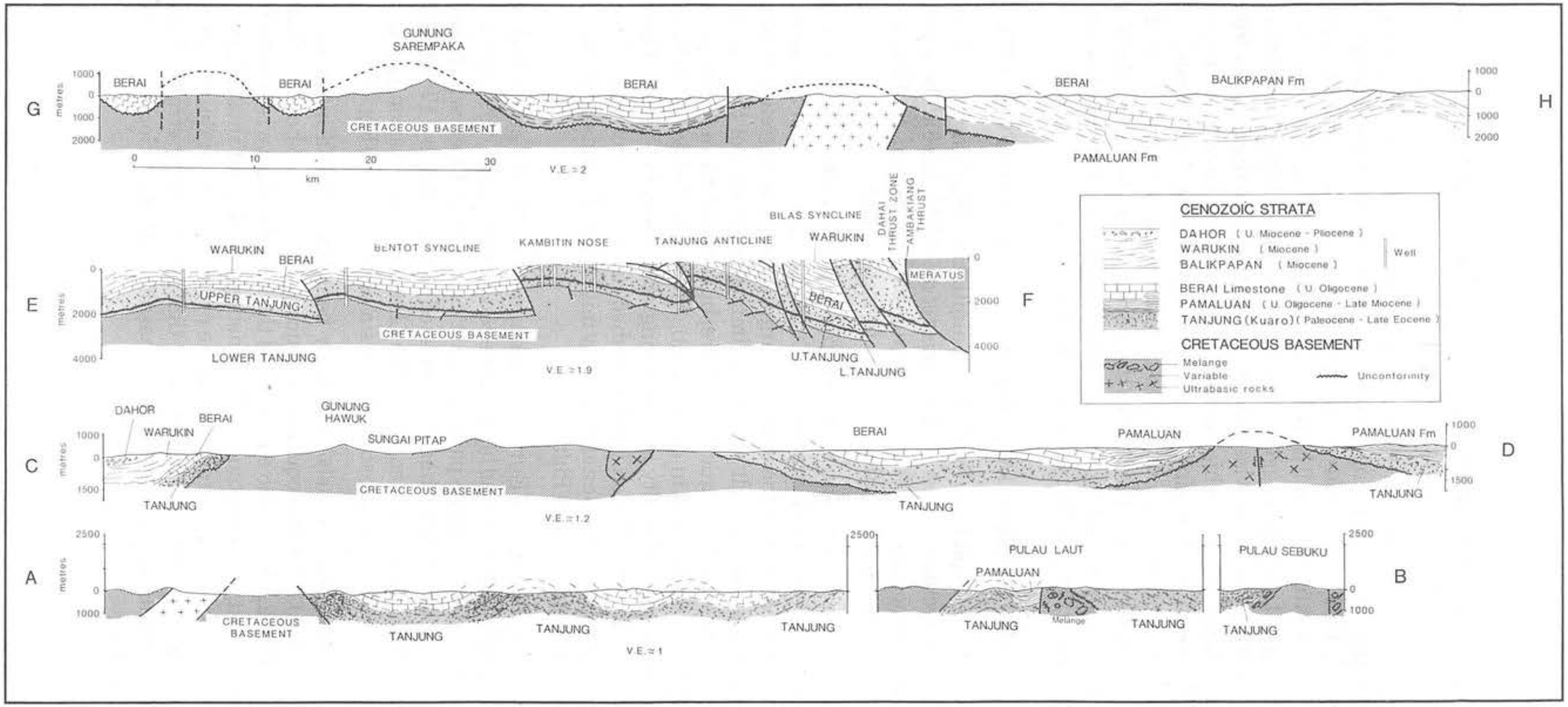

Figure 6: Typical cross sections across the eastern Barito Basin (9 on Fig. 4), the Meratus Mountains uplift, and the Pasir Basin of S.E. Kalimantan. A-B after Rustandi *et al.* (1981); C-D after Supriatna *et al.* (1980); E-F after Kusuma and Darin (1989) and G-H after Umar *et al.* (1982).

not on top of the rising Meratus Mountains (Figs. 5 and 6). Its petrography indicates derivation from erosion of the uplifted Meratus.

The rapid late Miocene to Pliocene uplift of the Meratus could be held responsible for the steeply dipping westwards overthrusts in the Tanjung Field (Fig. 6, section E-F). However the cause of uplift remains obscure. The mélange formation of the Meratus may well have been developed during this Neogene uplift phase. By analogy, it may be suggested that the Semitau Ridge, predominantly composed of mélange, may likewise have risen up to divide the Melawi from the Ketungau and Mandai basins, which in the Paleogene may have been one and the same basin. To classify such basins as fore-arc is misleading. The Boyan Mélange even contains clasts of granite, unlikely to be found in an accretionary wedge, as interpreted by Williams *et al.* (1988). Like the Barito, Asem-Asem and Pasir, these basins were formed by rifting of a continental landsurface composed of uplifted Cretaceous ophiolite, deep water sediments and mélange.

ORIGIN OF THE SUNDALAND EOCENE UNCONFORMITY

The most elegant hypothesis for the Eocene initiation of faulting and subsidence is that of extrusion tectonics given by Tapponier *et al.* (1982, 1986). These authors emphasized the propogation of faults radiating eastwards and southeastwards from Yunnan. A somewhat modified model is presented here.

From Eocene to the present, India rotated counter-clockwise (Dewey *et al.*, 1989) and made its greatest indentation into Eurasia at the Yunnan Syntaxis (Fig. 7). The northwards passage of the eastern margin of India was greatly facilitated by the prominent transform fault which lies immediately east of the Ninetyeast Ridge. East of it was wholly oceanic lithosphere, but since it has a fossil spreading axis as young as anomaly 19 (Liu *et al.*, 1983), the hot and elevated lithosphere would have experienced difficulty in subducting at the Sunda Trench. Therefore there was also a kind of collision (or diminished subduction activity) along the Sumatra Trench, resulting in the northeasterly migration of Sundaland away from the NNE-moving Indian Ocean Plate.

The continental margin of Eurasia at the time of flush collision is deduced to have been oriented WNW-ESE and lay near the equator (Metcalfe, 1991; Hutchison, 1989). This is consistent with the palaeomagnetic data from Tibet, which indicate that the terrain around Lhasa has been pushed northwards by 17° of latitude (Achache *et al.*, 1983). Before indentation, the Lhasa terrain was contiguous with western Thailand, western Peninsular Malaysia and Sumatra (Fig. 7).

Sundaland was progressively oroclinally bent since 45 Ma into its present configuration (Fig. 7). The consequences of such bending have been outlined by Tapponier *et al.* (1982, 1986), who emphasized the need for clockwise rotation and faulting (escape or extrusion tectonics). Continental Sundaland should have been dominated by right-lateral shear parallel to the progressively bending continental plate. Ongoing palaeomagnetic studies show that the Tertiary strata of several onland basins of Thailand and Late Tertiary basalts indicate a clockwise rotation (Fuller *et al.*, 1991).

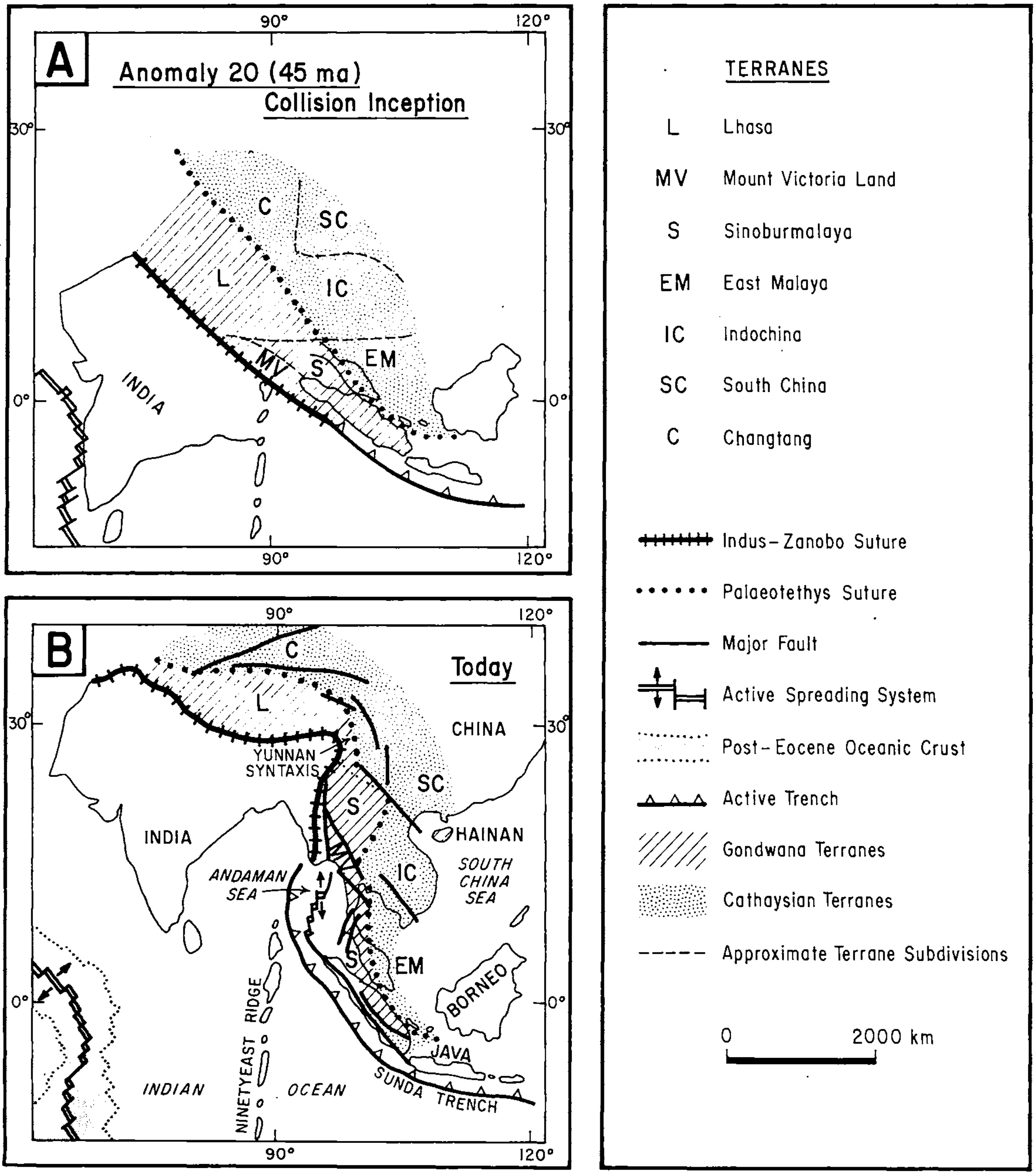

Figure 7: Indentation of India into Southeast Asia. A: Inferred palaeogeography at 45 Ma (anomaly 20) at the time of flush collision. B: Present day geography showing maximum indentation in the Yunnan syntaxis and spreading from the SE Indian Ocean Ridge.

The tectonic response to oroclinal bending can be seen in a scaled-up model of stratal bending of an outcrop-scale fold. The outer western zone of the convex-westwards orocline should have undergone considerable stretching and pull-apart (Fig. 8). The N-S opening of the Andaman Sea is a direct consequence of the bending resulting from maximum indentation at the Yunnan Syntaxis. Further south, the Sumatran Cenozoic basins have resulted from the same bending. The Bengkalis Graben of Sumatra, whose sedimentation began with Eocene Pematang Formation continental redbeds and lacustrine deposits, is interpreted to have resulted from right-lateral shear and pull-apart tectonics. The eastern inner zone of the orocline (East Malaya – Bangka – Billiton – Schwaner Mountains) was compressive during oroclinal bending and did not develop Cenozoic basins. The compressive structures of the Palaeozoic Mersing Beds of the east coast of Johore have been described by Chakraborty and Metcalfe (1984).

The oroclinal bending should have resulted in new topographic relief over Sundaland. The areas under compression were uplifted resulting in rivers with increased sediment load. The active right-lateral shear faulting resulted in river capture and diversion, the most spectacular example being the Mekong, and this is a common feature of most Southeast Asian rivers (Hutchison, 1989, p.68). Pull-apart tectonics resulted in topographic depressions which attracted the rivers, resulting in lakes. The sediments which accumulated in these topographic depressions can be shown everywhere throughout Sundaland to date back only as far as the Eocene Unconformity. Naturally, not all strata above the unconformity yield Eocene dates, some are as young as Oligocene, because the oroclinal bending was an ongoing tectonic process, initiated 45 Ma ago, but not all topographic depressions were created simultaneously, and the river network was constantly changing in response to the right-lateral shear.

Nevertheless, it is remarkable that most of the basal continental sediments overlying the Sundaland unconformity are of Middle to late Eocene age, as determined by regional palynological studies (Morley, 1991, and pers. comm. 1992). The considerably older age (Uppermost Cretaceous) for the basal Kayan Sandstone of Sarawak (Tan, 1986), which represents the western extremity of the Ketungau Basin of Kalimantan, is an outstanding anomaly which requires palynological re-investigation before acceptance.

The non-cratonic southeast peninsula of Sundaland, lying south of the Rajang Basin and east of Sumatra, reacted to the oroclinal bending in a less predictable manner. It is also fundamentally important to bear in mind that a larger cratonic mass – Australia – is in collision with the Banda Volcanic Arc at the Timor Trough and extends much further north to Irian Jaya and the Sula–Buru–Seram region (Hutchison, 1989). This eastern collisional indentation has had a major impact on the eastern extremity of Sundaland, causing its fragmentation and imposing an anticlockwise rotation and left-lateral shear, notably along the Sorong Fault System. The well documented progressive anticlockwise rotation of Sarawak and Kalimantan (Schmidtke *et al.*, 1990; Hutchison, 1991b) may be understood in terms of the indentation of Australia into eastern Sundaland.

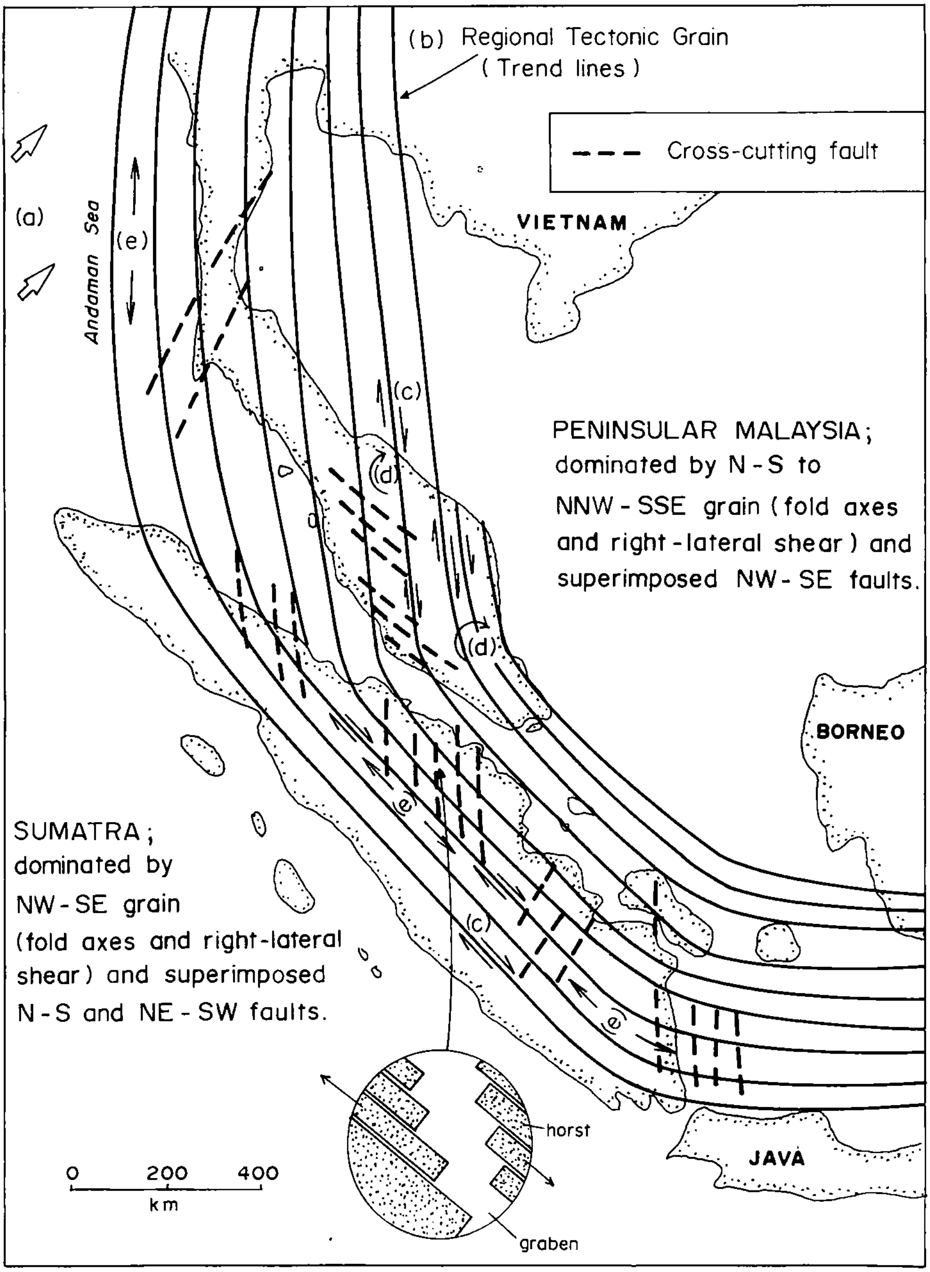

Figure 8: Schematic plan of collision and oroclinal bending. (a): Indian indentation vector, (b): Oroclinal bending of the regional trend lines, (c): Right-lateral shear parallel to the orocline, (d): post-Eocene clockwise rotation of rigid blocks, (e): zone of maximum pull-apart giving Andaman Sea and the Sumatra Cenozoic basins along the outer curvature of the orocline. The inner curvature (Peninsular Malaysia to Bangka and Billiton) is compressional and devoid of Cenozoic basins. Inset: According to Moulds (1989) the N-S trending Bengkalis Graben has followed from pull-apart simultaneously utilizing NW-SE and NE-SW faults, resulting in a N-S trending graben.

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