CHAPTER 12

12 GEOPHYSICAL STUDIES & VERTICAL TECTONICS IN BORNEO

12.1 THE USE OF GEOPHYSICS IN BORNEO

12.1.1 The principal use of geophysics in Borneo is to find hydrocarbons. Oil companies rely heavily on seismic surveys to prospect for suitable targets and there is increasing use of 3D seismic surveys. The penetration of such surveys is relatively shallow and with two-way travel times of the order of six seconds with reflections to depths of about 4,000m. However, by adjusting the parameters of the measuring equipment and using larger energy sources, much deeper penetration can be achieved and reflections can be obtained from close to the Moho. Deep seismic surveys are able to reveal the megastructures of the deeper parts of the crust but no such deep seismic data is published for the Borneo region. There is an increasing recognition of the usefulness of gravity surveys following the publication of satellite-sourced gravity maps of the sea areas of the world. Regional structural grain can be recognised on satellite gravity and forms a cheap and easily acquired method of determining underlying structure. Onshore gravity surveys are difficult and often costly to undertake, especially in jungle covered terrain where precise topographical data may not be available. Heat flow data obtained from oil wells and ocean floor measurements are frequently used to predict the underlying geology as well as indicate how sedimentary basins have evolved. The early interpretations of the geology of the South China Sea were based on heat-flow data enabling Karig (1971) to propose the South China Sea basin evolved as a back-arc extensional basin to the Indonesian-Philippines island arc system. Marine magnetic surveys are useful, especially in areas underlain by oceanic crust. Magnetic measurements on orientated samples of suitable rock materials have been used to determine the movement both rotation and azimuth of segments of the crust and studies of paleo-magnetism in Borneo show rotational movement with time but little change of latitude.

12.2 MAGNETIC LINEATIONS

12.2.1 Shipboard measurements of the magnetic features of ocean and marginal basins have been a useful method of determining the evolution and spreading history of oceanic crust since the classic discovery of magnetic lineations in the Pacific Ocean by Vine and Mathews (1960). In the South China Sea area, Turner & Hayes (1980) made measurements in the central part of the South China Sea which showed that the abyssal plain had a series of magnetic signatures (Fig 12.1). The spreading history of the basin has been determined from the interpretation of the magnetic lineations but, in the absence of DSP drill holes, the interpretations are to a large extent unproven. The spreading ages are based solely on matching signature patterns and until borehole samples are obtained, the ages remain subjective.

12.2.2 The abyssal floor of the South China Sea may be subdivided into three areas: a large eastern sector, and narrowing SW sector and a

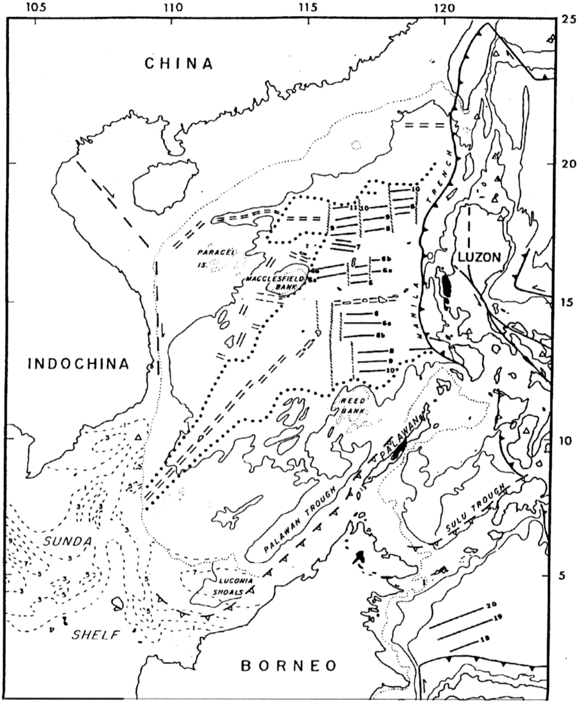

Fig 12.1 Magnetic lineations, South China Sea.
(after Taylor & Hayes, 1980,1983)

rhombohedral NW sector (Ru & Piggot,1986). Initially, Bowen *et al.*,(1978) recognised magnetic lineations trending N70°E offshore Luzon. Taylor and Hayes subsequently correlated magnetic profiles trending roughly E-W in the eastern part of the abyssal floor with a geo-magnetic reversal time scale and identified magnetic anomalies indicating the sea-floor ranged in age from 32 to 17 Ma. Additional data was examined and Taylor and Hayes (1983) revised the distribution of fracture zones and revising the time scale. No data was available from the narrower SW part of the abyssal floor but Taylor & Hayes (1983) inferred magnetic lineations trending NE-SW and combined with heat flow measurements (Watanabe *et al.*,1977) suggested an early Miocene age for that part of the floor. New data from the SW sector has been interpreted by Lu *et al.*,(1987) who infer discrepant ages between the eastern and SW sectors. There is presently no consensus on the age of the SW sector. Hutchison (1992) remarks that the E-W magnetic lineations interpreted by Taylor & Hayes (1983) in the E sector are incompatible with the geomorphology of the South China Sea Basin. Sea Beam bathymetric data collected in the *M/V CHARCOT* 1985 cruises in a 200 km wide axial region of the abyssal floor reveal NE and NW-striking topographic scarps indicating NE-SW spreading in the region of the Scarborough seamounts.

12.2.3 The overall evolution of the spreading episodes in the South China Sea has been interpreted basically in two different ways yielding two contrasting models (Fig 12.2). Taylor & Hayes (1983) envisage right-lateral faulting along a N-S transform offshore the Vietnam coast with Indochina and

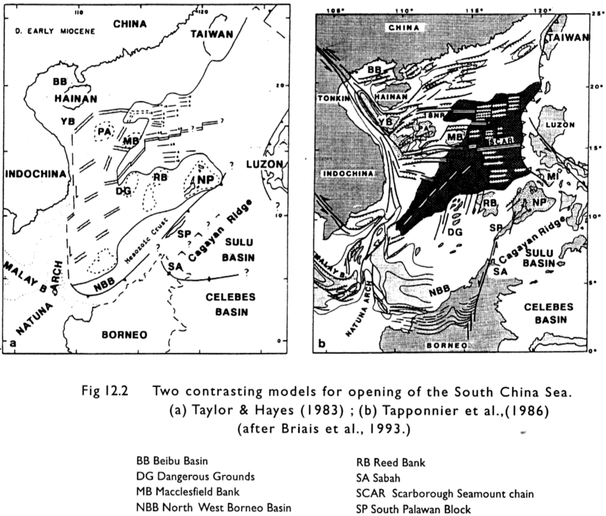

Fig 12.2 Two contrasting models for opening of the South China Sea. (a) Taylor & Hayes (1983) ; (b) Tapponnier et al.,(1986) (after Briais et al., 1993.)

BB Beibu Basin
DG Dangerous Grounds
MB Macclesfield Bank
NBB North West Borneo Basin
NP North Palawan Block
PA Paracel Ls. (Xisha)
RB Reed Bank
SA Sabah
SCAR Scarborough Seamount chain
SP South Palawan Block
YB Yinggehai Basin

Borneo in a fixed position relative to South China. Tapponnier *et al.*,(1986) propose that spreading motion in the South China Sea is taken up by left lateral shear along the Red River between South China and Indochina with Borneo moving in tandem with Indochina.

12.2.4 Reconstruction of sea floor spreading has been re-examined by Briais *et al.*, (1993) who re-analysed both the original data available to Taylor & Hayes as well as later data obtained from French and Chinese sources (Fig 12.3). Rifting is thought to have commenced in the Eocene-mid Oligocene (40-30Ma) with the formation of rift basins in the offshore region of South China (Holloway,1982; Ru & Piggot,1986) although somewhat earlier periods of rifting are interpreted from seismic and well data are assigned to latest Cretaceous-Eocene (Rangin & Silver,1991). Briais *et al.*,(1993) point out that left lateral motion on the Red River fault complex may have caused oceanic crust to form in the late Eocene along the E margin of the Eastern sector. The oceanic crust may be the source of obducted ophiolites in Central Palawan (H. Kreuser *in:* Hinz *et al.*,1985).

12.2.5 Briais *et al.*,(1993) envisage Oligocene seafloor spreading commencing in the north with jumps and southeastward propagation of the spreading centre (Fig 12.3b). Spreading ceased in the NW sector but continued E of Macclesfield Bank. Just after anomaly 7 (26Ma), the spreading system jumped again to the S and began to propagate southwestwards (Fig 12.3d). Spreading continued until approximately lower Middle Miocene (15.5Ma) (Fig 12.3e) when

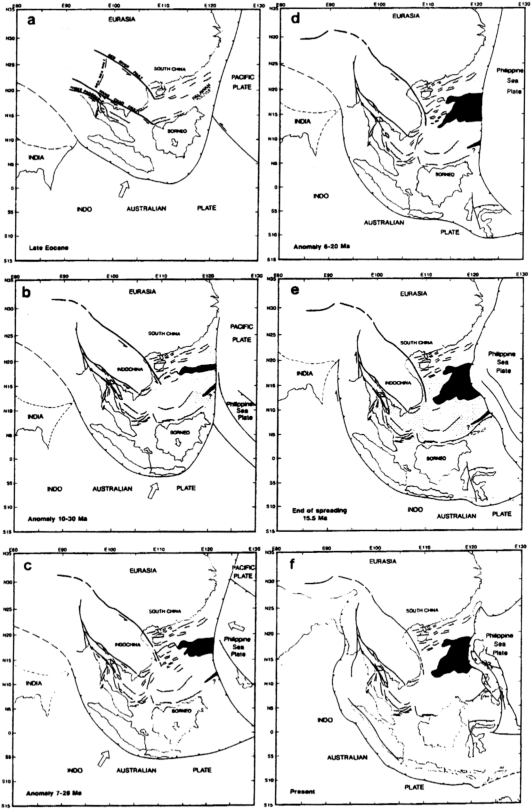

Fig 12.3 Reconstruction of sea floor spreading and opening of the South China Sea (after Briais et al., 1993).

generation of new oceanic crust throughout the spreading axis ceased synchronously.

12.2.6 The generation of new oceanic crust within an apparent "enclosed" marginal basin gives rise to a space problem as old oceanic crust does not appear to be consumed anywhere along the circumference of the marginal basin. There is no evidence of excessive crustal shortening along the NW Borneo margin. The Reed Bank and Dangerous Grounds areas are apparently stationary and have been since the late Miocene (Hinz & Schluter, 1985). The NW Borneo - Palawan trough is not a subduction zone; Oligocene carbonates dip gently beneath Borneo Island (Hinz & Schluter,1985) and appear to be downwarped by loading of the Baram delta and/or NW thrusting of older turbidite successions belonging to the Crocker Formation (Hutchison,1992). Briais *et al.*,(1993) conclude that the left lateral movement on the Red River fault complex of the order of several hundred kilometres in the Oligo-Miocene and documented by Tapponnier *et al.*, (1990) provides the necessary answer to the space problem. A major left lateral shear zone on the E flank of the Yunnan syntaxis is an integral part of the extrusion tectonics hypothesis associated with the Indian-Eurasian plate collision. Any expansion or increase in newly generated oceanic crust within the South China Sea basin would be adequately accommodated by movement and left lateral slip both along NW-SE transcurrent faulting both within the abyssal floor as well as left lateral translation of several hundred kilometers along the Red River fault zone. At the same time, there is rotation of various blocks including Borneo (Peltzer *et al.*,(1982); Tapponnier *et al.*,(1982,1986).

12.2.7 Ru and Piggot (1986) in a seminal paper based on careful analysis of regional geologic and geophysical data and heat-flow measurements, concluded that the South China Sea basin experienced at least three stages of rifting and two intervening stages of sea-floor spreading since the early Cretaceous. Evolution of the basin was regarded as episodic with tectonism, thermal cooling and subsidence pulsed by temporally and spatially confined heating events. Rifting episodes deduced from regional geology occurred in the late Cretaceous, the late Eocene and the late early Miocene. The early rift system trends NE-SW whereas the second and third rifting events trend E-W. The two trends coincide with trends in the orientation of magnetic lineations within the abyssal part of the basin. Contrary to Taylor & Hayes (1983) and Briais (1993), Ru and Piggot (1986) suggest, from heat flow measurements and bathymetric data, that the SW sector is considerably older than the NW or E sectors. Subsidence rate curves obtained from regional well data, show that unlike the Atlantic type margins where thermal subsidence rates are conventionally smooth and slow, thermal subsidence in the South China Sea is punctuated by rapid subsidence events chronologically consistent with rifting episodes. Applying McKenzie's (1978) stretching model, Ru & Piggot (1986) derive crustal stretching factors (ß= ratio of new length to original length) for the various subsidence rates analysing well data from four wells in the Pearl River and Beibu Gulf basins and a single well offshore N Palawan after removing the effects of compaction, sediment loading, paleo-bathymetry and changes in sea level. The subsidence/age plots (Ru & Piggot,1986,Fig's 13-17) show curves with both gentle and steep gradients. Ru & Piggot (1986) interpret the gentle gradient as a tectonic record of the thermal decay of the basin floor. The steep gradients are too high to be explained by thermal contraction and must be interpreted as subsidence during rifting. To reconcile differences in subsidence, Ru & PIggot (1986) plotted subsidence *rate* against time. A regional synchroneity is apparent throughout the South China Sea area with two subsidence rate maxima occurring consistently during the early Oligocene and Middle Miocene corresponding to rifting episodes. Lower subsidence rates are interpreted as post-rifting episodes in the Eocene, late Oligocene to early Miocene and late Miocene to Holocene. Ru & Piggot (1986) conclude that the earliest lower subsidence rate in the Eocene coincides with spreading in the SW sector of the abyssal floor and late-Oligocene to early Miocene with spreading in the E and NW sectors. In a series of palinspastic maps, Ru & Piggot (1986) attempt to reconstruct the evolution of the South China Sea by invoking subduction zones which, in the context of new evidence suggesting the absence of Cenozoic subduction notably offshore NW Borneo, are no longer tenable.

12.2.8 The importance of Ru & Piggot's work is that it is the only published research that links thermal activity, particularly igneous activity with basin formation and sedimentation in the South China Sea area. The explanation of basin formation by McKenzie (1978) does not consider the changing rheology of the crust as a basin subsides or as the crust becomes thinner. The thermal aspects of sedimentary basin formation are particularly relevant to the SE Asian region in general and Borneo in particular where igneous activity has occurred throughout every geological era. The geology of the South China Sea will continue to be a matter of conjecture until DSP well sites are drilled in the abyssal plain to check the validity of the age of the magnetic lineations on which most of the hypotheses to date have relied.

12.3 PALEOMAGNETISM

12.3.1 Paleomagnetic studies in Kalimantan are reported in Haile *et al*., (1977), in Sarawak by Haile (1979) and Schmidtke *et al*., (1990) and in Sabah by Schmidtke *et al*.,1986). Paleomagnetic and radiometric measurements on Middle Jurassic to Upper Cretaceous (112-75Ma) mainly granitic rocks indicate that W Kalimantan has rotated about 50° CCW since the middle Cretaceous with no change in latitude. Similar results were obtained by McElhinney *et al*., (1974) from Peninsular Malaysia indicating there has been no differential movement between the areas since the middle Cretaceous. Paleomagnetic measurements on Oligocene- Miocene red beds from Sarawak are indistinguishable from the present magnetic field which Haile (1979) suggests that rotation of the Borneo microplate was completed by the Miocene. Data obtained from Upper Jurassic to Miocene rocks in W Sarawak imply a counter-clockwise rotation of up to 108° with respect to a stable Eurasia during the Cretaceous - mid

Cenozoic (Schmidtke *et al.*,1990). Samples were collected from Miocene intrusions, Oligocene- Miocene continental sediments from the Silantek Formation, Upper Jurassic-Lower Cretaceous Bau Limestone and Pedawan Formations and Jurassic Kedadom Formation. A pattern of CCW rotation is evident from the results on the intrusions and the result from the Silantek Formation indicates the same CCW rotation. The Bau Limestone Formation yields a variety of directions including remagnetisation in recent fields and a CCW rotation similar to the Silantek; the Kedadom Formation is magnetized in the same direction as the Silantek (Fuller *et al.*,1991). Fold tests on the Bau and Pedawan Formation samples indicate that they show traces of earlier CCW rotation in the Mesozoic (Fuller *et al.*,1991).

12.3.2 The paleomagnetic results from Sabah are only preliminary (Schmidtke *et al.*,1986) ; a small intrusion near G. Kinabalu gave a whole-rock K/Ar age of 13.3 ± 5.3 Ma and showed a slight CCW deflection of declination. The results from the Crocker Formation red shales and Chert-Spilite Formation have yielded poor results. Measurements from samples of Chert-Spilite Formation fail the fold test and magnetisation may have been reset. Fuller *et al.*,(1991) are reluctant to interpret the data in detail.

12.3.3 Fuller *et al.*,(1991) give a resumé of all the paleomagnetic results from Borneo including data from the Eocene Kalasin Formation (Wahyono & Sunata, 1987) and Oligo-Miocene Nanga Raun in W Kalimantan (Sunata, 1987), and they construct apparent polar wandering paths for Sarawak and W

Kalimantan. They conclude the Jurassic poles, which reveal a consistent path moving over Eastern Europe to Africa, cannot be explained by rotation in place because there is a change in paleolatitude, the NW Kalimantan block being S of the equator and strongly CCW rotated by late Cretaceous. The Cretaceous-Cenozoic poles can be explained by rotation in place but whether this is a local or major block rotation is unresolved (Fuller *et al.*,1991).

12.4 GRAVITY

12.4.1 Regional Gravity Studies

12.4.1.1 Early gravity studies were initiated by Vening Meinesz (1954) who obtained measurements in a submarine over the Indonesian deep sea trenches. A free air gravity map of SE Asia compiled by Watts, *et al.*, (1978) shown in Fig 12.4 indicates the distribution of major positive and negative free air gravity anomalies. A band of strongly positive gravity anomalies occurs from the Makassar Straits northwards through the Mahakam delta following the coast of the Mangalihat peninsula and veering NE through Darvel Bay and the Sulu archipelago with a subsidiary spur towards Palawan island. More recent gravity maps of the oceans have been compiled from satellite observations and Xia and Zhou, (1993) have calibrated the satellite data with marine observations in the South China Sea enabling a regional gravity map to be produced (Fig 12.5). Combined with seismic and magnetic profiling, the gravity data enable rough estimates of the thickness of sedimentary basins to be deduced. For example, a

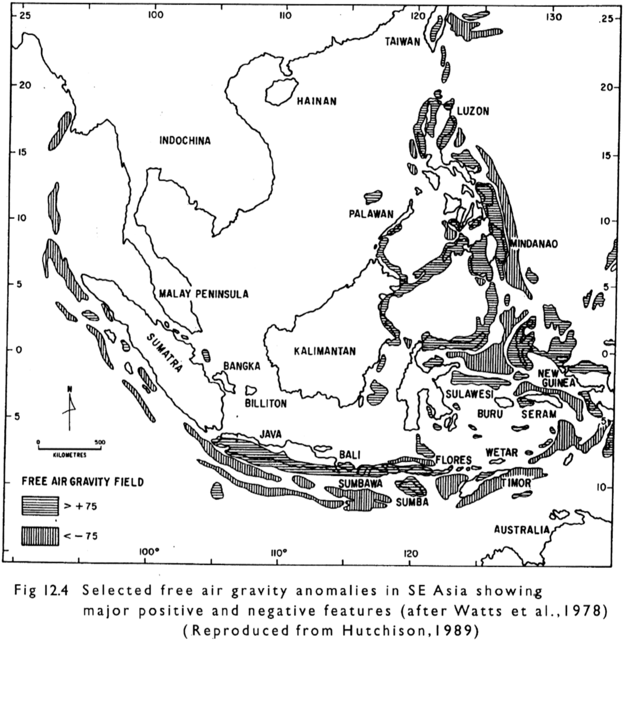

Fig 12.4 Selected free air gravity anomalies in SE Asia showing major positive and negative features (after Watts et al., 1978) (Reproduced from Hutchison, 1989)

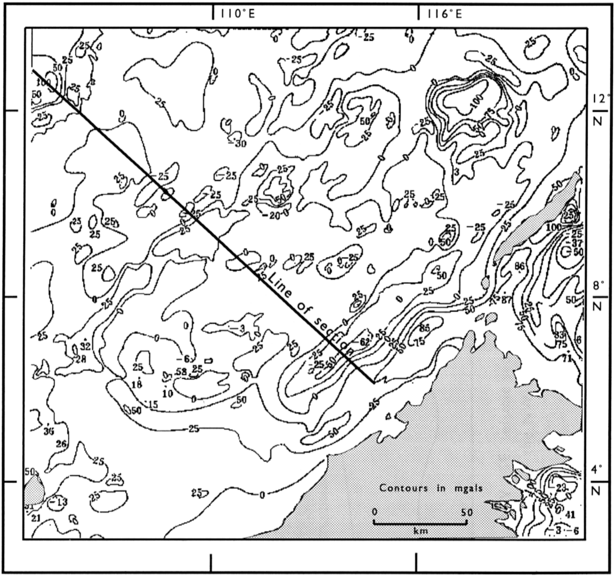

Fig 11.5 Free air gravity anomaly map of the South China Sea offshore NW Borneo
(after Xia & Zhou, 1993)

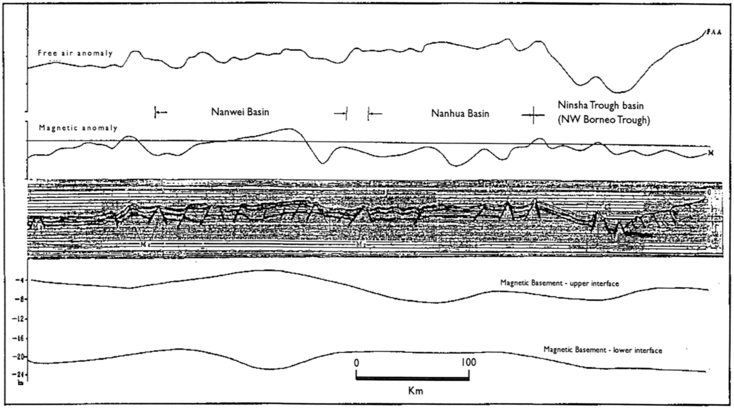

Fig 12.6 NW - SE seismic section , free air anomaly & magnetic curves across the NW Borneo Trough.

(after Xia & Zhou, 1993)

profiling trace across the NW Borneo Trough (Fig 12.6) indicates the maximum depth to magnetic basement is about 8 km (Nanhua basin and Nansha Trough). The gravity values in the NW Borneo Trough (Nansha Trough) are of the order of minus 50mgals. In the Baram delta offshore, the gravity values are plus 50 mgals. Hence the maximum thickness of sediments in the Baram Delta Province is about 16 km, assuming the same average rock density for sediments. The interpretations are only subjective as satellite measurements close to shorelines are subject to error.

12.4.2 Gravity Studies in Central & W Kalimantan

12.4.2.1 Gravity measurements obtained during the IAGMP programme in Central and W Kalimantan with interpretations by C.A. Foss are included in the various Geological Data Records. The first area studied in Singkawang showed a regional NNW-SSE trend in gravity field ranging from 0 mgal in the NE of the quadrangle to 50 mgal at the coast. Foss (*in* : Suwarna *et al.*,1989) concludes it may mark a deep feature with a transition to a thicker or less dense crust to the E. The NNW regional trend extends between longitude 110° and 114° in a series of three parallel zones of relatively high anomalies, referred to as the Lubok Antu-Kapuas and Boyan gravity ridges and the Schwaner Mountains gravity province, separated by intervening gravity lows corresponding to the Melawi-Silat, Ketungau-Mandai Cenozoic basins and the Embaluh-Rajang accretionary prism.(Williams *et al.*,1988, Fig 3). The gravity distribution in NW Kalimantan shows no well-defined trend although gravity highs show NW axes.

The contrast between eastern and NW gravity provinces coincides with a presumed transcurrent fault which Williams *et al.*,(1988) infers to separate the NW Kalimantan Domain from the Boyan Zone domain. The highest Bouguer values lie in the Kapuas Lakes (Surono and Noya.,1989) where there is a maximum of about 70 mgals. The geology in the Lakes area includes serpentinites and other ultrabasic rocks and suggests that the gravity high is caused by an ultrabasic mass lies beneath the Lakes area (Putussibau depression). A similar gravity high lies in the vicinity of the Lakes area to the W of the Mahakam delta and likewise is due probably to ultrabasic rocks at depth.

12.4.3 Gravity studies in Sarawak

12.4.3.1 Little is published on the gravity of Sarawak. A narrow band of Bouguer gravity data is included on Transect VII (CCOP-IOC,1990). The gravity distribution in the Tatau area shows a significant gravity high in the region of the Tatau horst with a maximum of about 40 mgals (see Chapter 6, Fig 6.8). The high is terminated by one or possibly two major faults, the Balingian Line marking the SW boundary of the Balingian basin and a WNW fault bounding a half graben offshore (Tate, *in press*). The presence of basic rocks in the same area (Mersing pillow basalts) suggests that basic rocks may underlie the Tatau horst area. Another 40 mgal high lies in the area of Sg. Nyalau and may extend inland towards the Tinjar fault.

12.4.4 Gravity Studies in Sabah

A gravity survey was made in Darvel Bay by Ryall and Beattie (1990) and the results indicated a broad gravity high of at least 60 mgals which strikes NW with a maximum on the southern coast of P. Sakar. The anomaly narrows and decreases where it comes ashore towards G. Beeston. Preliminary conclusions regarding recent gravity studies in Sabah by Milsom (1995) indicate that the ultrabasic rocks representing oceanic crust in the Darvel Bay area appear to be confined solely to Darvel Bay. The highest gravity anomalies occur in the neighbourhood of the islands on the S side of the Bay and the high gravity values decrease onshore. Measurements around G. Beeston are relatively low and indicate that the Beeston ultrabasic mass does not have a dense root zone but possibly lies on a klippen. The Danum valley ultrabasic rocks and metasomatised equivalents ("Crystalline Basement") would therefore appear not to be deep-rooted.

12.4.5 In the Telupid area,an E-W traverse across the ultrabasic and basalts show the highest values over the basalts, suggesting that the sequence is layered with dips towards the W. Gravity values diminish rapidly S of Telupid suggesting that the ultrabasics in the Telupid area are separated from the Darvel Bay and Danum valley masses and do not continue at depth beneath the Cenozoic circular basins of Tangkulap and Kuamut.

12.5 VERTICAL TECTONICS IN BORNEO

12.5.1 SE Borneo - Meratus Mountains

12.5.1.1 The Pamali breccia described by Bergman *et al.*, (1987) is a scree slope deposit was laid down directly on uplifted ophiolte and is probably Paleocene. Assuming the ophiolite is a minimum age close to the Jurassic-Cretaceous boundary (135my), the rate of uplift is of the order of 0.09 mm/yr. assuming the ocean floor is about 6km below the present sea level and the ophiolites are now about 1km a.s.l.

12.5.2 Eastern Sabah

12.5.2.1 Similar evidence of uplift occurs at the Rumidi Estate (Bidu-Bidu Hills) where Layers 1 & 2 of an ophiolite complex (upper oceanic crust) were uplifted and erodeded to produce the sedimentary conglomerates associated with plant-bearing sandstones of unknown but probably Oligocene age (Hutchison & Tungah Surat, 1991, Hutchison,1992).

12.5.2.2 Of the many occurrences of glaucophane listed by Leong (1978) the only authenticated in situ outcrop is in the Labuk valley along the NW-SE Lumau Fault in the Sg. Livadai, 12 km NW of Telupid (Johnstone & Walls,1974). Hutchison (1992) reports that thin sections are not blueschist but are composed of muscovite metaquartzite and metabasite containing euhedral porphyroblasts of glaucophane, epidote and piedmontite. The metabasite is interpreted as being representative of the basaltic layer of an ophiolite complex and the metaquartzite the overlying quartz-rich turbidite sandstones, either of the Chert-

Spilite or nearby Crocker Formation. The rocks have been subjected to high pressure but not shear suggesting that they have been dramatically uplifted since the Cretaceous. The presence of the Kinabalu Fault (?shear zone) may have provided a zone of weakness for uplift.

12.5.3 NW Borneo

12.5.3.1 Evidence of vertical tectonics includes the Late Miocene basin inversion of the Oligocene West Crocker- Temburong basin. Tate (*in press, 1996*) presents evidence that the Temburong Formation was loaded with a considerable thickness of sediment which has since been eroded. Hutchison (1996) introduces the term Sabah orogeny for the inversion and comments that Late Miocene G. Kinabalu pluton is a spectacular product of this orogeny with whole rock dates as old as 10my (Jacobson, 1970). G. Kinabalu is rising at a rate of 5mm/yr (Jacobson, 1970).

12.5.3.2 Unconformities identified on marine seismic profiles conducted offshore NW Sabah show episodic uplift. Offshore Cenozoic basins have subsided since the Pliocene whereas onshore basins form spectacular geomorphology in the interior of Borneo with concordant peaks in the region of 7000 ft asl (2.5 km). Similar vertical movements of inversion have taken place in the Cenozoic basins of central Kalimantan.

12.5.3.3 As indicated in Chapter 11, marine terraces, accordant ridges and summits, and mature topography near watersheds testify to the tilt and uplift of relict erosion surfaces which were formerly close to sea level.

The coastal Quaternary terrace traced across the Jerudong anticline in Brunei rises from about 10m a.s.l. to over 30m indicating an exceptional localised rise above the generally emergent Borneo Island (Wilford,1960). The cause at Jerudong is probably due to upwardly mobile shale tectonics in the core of the Jerudong anticline. In the interior of East Brunei, a mature land surface showing dendritic drainage and covered with white sand and clay similar to present day coastal terraces occurs at an elevaltion in excess of 1000m (Wilford,1960). Although no age determinations are available, that part of Brunei has risen at a rate of about 1mm/yr.

12.5.4 Conclusion

The evidence in Meratus and Sabah suggests that there was a period of major vertical uplift in the Upper Cretaceous or at the end of the Cretaceous when the accreted margin of SE Sundaland was exposed as a widespread land surface (Hutchison, 1992b). The causes are unknown; amongst the possible explanations are:

- Upwelling of the asthenosphere
- elastic rebound of the depressed crust immediately following a period of prolonged subduction
- final closure of the Danau Sea and the collision of rifted blocks of con-

tinental China with the Cretaceous subduction zone in the Late Cretaceous or Paleocene.