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Impact of India–Asia collision on SE Asia: The record in Borneo

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Abstract

Borneo occupies a central position in the Sundaland promontory of SE Asia. It has a complex Cenozoic geological history of sedimentation and deformation which began at about the same time that India is commonly suggested to have started to collide with Asia. Some tectonic reconstructions of east and SE Asia interpret a large SE Asian block with Borneo at its centre which has been rotated clockwise and displaced southwards along major strike–slip faults during the Cenozoic due to the indentation of Asia by India. However, the geological history of Borneo is not consistent with the island simply forming part of a large block extruded from Asia. The large clockwise rotations and displacements predicted by the indentor model for Borneo are incompatible with palaeomagnetic evidence and there is no evidence that the major strike–slip faults of the Asian mainland reach Borneo. Seismic tomography shows there is a deep high velocity anomaly in the lower mantle beneath SE Asia interpreted as subducted lithosphere but it can be explained just as well by alternative tectonic models as by the indentor model. Very great thicknesses of Cenozoic sediments are present in Borneo and circum-Borneo basins, and large amounts of sediment were transported to the Crocker turbidite fan of north Borneo from the Eocene to the Early Miocene, but all evidence indicates that these sediments were derived from local sources and not from distant sources in Asia elevated by India–Asia collision. The Cenozoic geological history of Borneo records subduction of the proto-South China Sea and Miocene collision after this ocean lithosphere was eliminated, and a variety of effects resulting from long-term subduction beneath SE Asia. There is little to indicate that India–Asia collision has influenced the Cenozoic geological record in Borneo.

Keywords: Sundaland; Borneo geology; Tomography; Strike–slip faults; Sediment provenance

1. Introduction

India–Asia collision is widely considered to have begun in the Eocene, perhaps when the convergence rate dropped sharply (Besse and Courtillot, 1991), although estimates of the age of collision still vary widely from early to latest Eocene (e.g. Tapponnier et al., 1986; Peltzer and Tapponnier, 1988; Rowley, 1996; Aitchison and Davis, 2004; Ali and Aitchison, 2005; Leech et al., 2005; Aitchison et al., 2007). Deformation in Indochina and further south in SE Asia from the Eocene onwards is often interpreted as the result of India–Asia collision. Such interpretations are based on the recognition of major strike–slip faults that cross the Asian continent on which there are important Cenozoic movements (Tapponnier et al., 1982). The strike–slip faults are considered to be the boundaries of crustal blocks that have rotated and moved laterally as India moved northwards into Asia. Several of the major strike–slip faults, such as the Three Pagodas, Mae Ping and Red River Faults, cross Indochina and South China (Fig. 1) and disappear offshore. Some authors project these faults across the shallow marine shelf offshore as far as Borneo, and link them to structures in Borneo (e.g. Tapponnier et al., 1986; Briais et al., 1993; Lee and Lawver, 1995; Leloup et al., 1995; Lacassin et al., 1997). Recent reconstructions (Replumaz and Tapponnier, 2003) of India–Asia collision show a large SE Asian block, with Borneo at its centre, which has been rotated clockwise and moved southwards, with very large displacements on the order of many hundreds to thousands of kilometres; mantle structure interpreted from seismic tomographic studies has been used to support these tectonic reconstructions (Replumaz et al., 2004).

Borneo is the third largest island in the world (Fig. 1) but is not very high. The Central Borneo Mountains separating Malaysian and Indonesian Borneo are mainly below 1000 m,

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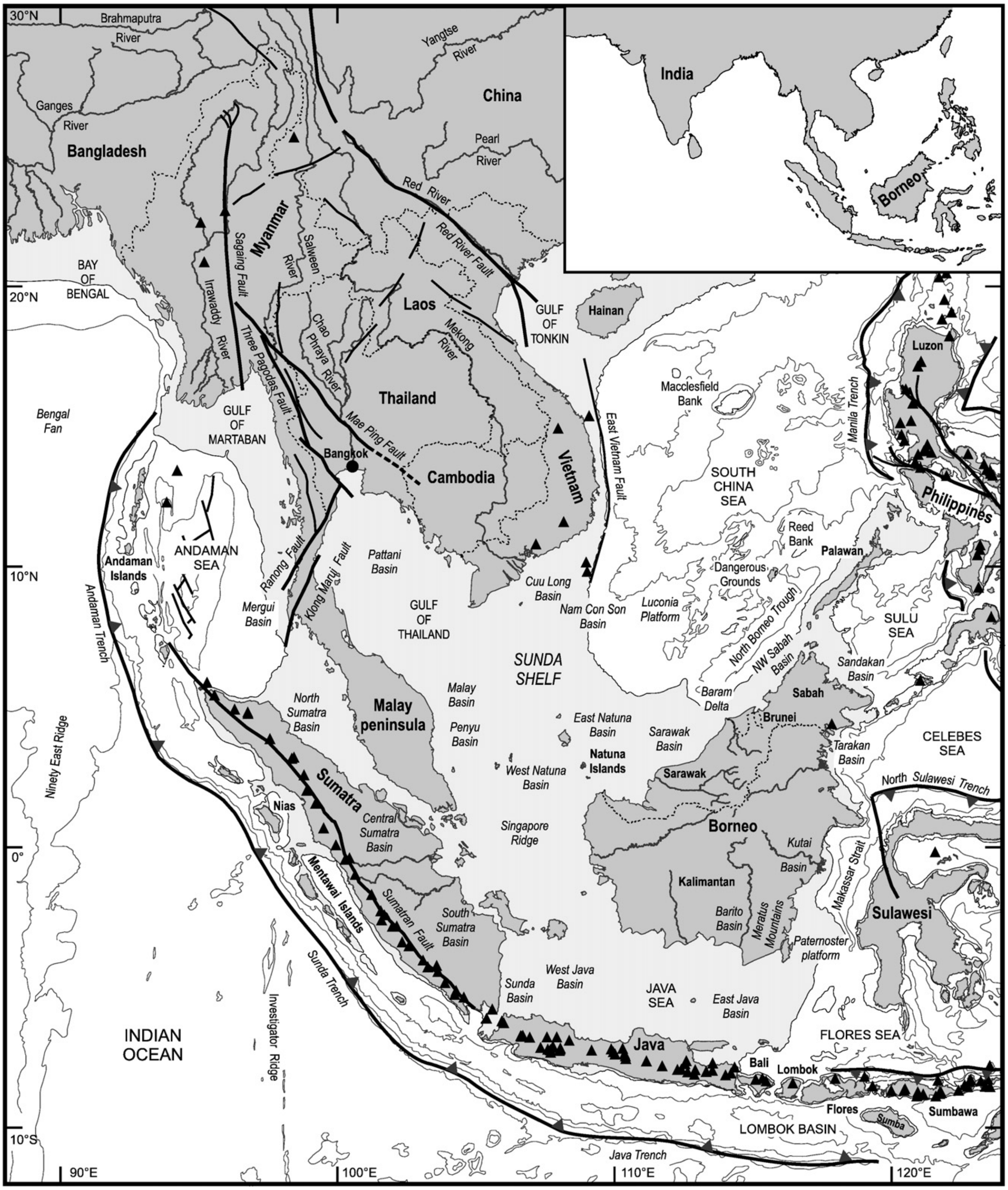

Fig. 1. Principal geographical features of the Borneo region. The Sunda Shelf and contiguous continental shelf of SE Asia is shaded in light grey up to the 200 m bathymetric contour. The other bathymetric contours are at 2000 m, 4000 m and 6000 m. Major strike–slip faults are shown in solid black lines; the uncertain continuation of the Mae Ping Fault is dashed. Quaternary volcanoes are shown as black triangles. Important sedimentary basins of Borneo and surrounding regions are named. Inset map shows the position of Borneo with respect to India.

with a few peaks up to 2500 m, with the exception of the isolated 4100 m peak of Mt Kinabalu in Sabah, at the northern end of the mountain range. Seismicity and GPS measurements show Borneo is currently part of a SE Asian or Sunda block moving slowly relative to Eurasia (Cardwell and Isacks, 1978; McCaffrey, 1996; Rangin et al., 1999; Kreemer et al., 2000;

Bock et al., 2003; Simons et al., 2007). Geologically, Borneo (Fig. 2) is at the centre of a SE Asian promontory of Eurasia that is surrounded by long-lived Cenozoic subduction zones, resulting from convergence of the Indian-Australian, Pacific and Philippine Sea plates (Hamilton, 1979; Hutchison, 1989; Hall, 1996, 2002). The continental core of the region, including peninsular Malaysia, Thailand, SW Borneo, Sumatra and Java, is known as Sundaland and is a composite region of fragments that separated from Gondwana at various times, drifted northward, and accreted to the Eurasian continent in different stages during the Late Palaeozoic and Mesozoic (Metcalfe, 1996). Today Borneo is a relatively stable area with little or no seismicity, and no active volcanoes; there are a small number of Quaternary volcanoes. To the west and south of Borneo is the shallow Sunda Shelf separating Borneo from Indochina, peninsular Malaysia and Thailand, Sumatra and Java. To the north and northeast of Borneo are three deep basins (the South China, Sulu and Celebes Seas) floored by oceanic crust, and to the east is the narrow Makassar Strait. The passive continental margins of all of these areas have relatively narrow shelves before descending to depths of several kilometres.

Despite the low elevation of the island there are large and deep sedimentary basins in and around Borneo which have been provided with sediment since the early Cenozoic. Large rivers crossing Indochina today feed sediment from the India–Asia collision zone and Tibet to the Southeast Asian margins where there are numerous hydrocarbon-rich basins. It has been implied or suggested that much of the sediment in the circum-Borneo basins was supplied from the India–Asia collision zone, and carried south by the large rivers of Asia (e.g. Hutchison, 1996; Métivier et al., 1999; Clift, 2006) distributing sediment in a similar way to the present. Tectonic and sedimentological interpretations portray Borneo as being considerably influenced by India–Asia collision and thus it would be expected that the island should contain a record of the collision. In this paper we consider the impact of India–Asia collision in the Borneo region. We first provide a brief outline of geology of Borneo, and then summarize two tectonic reconstructions which represent different ends of the interpretative spectrum for the region: one (Replumaz and Tapponnier, 2003) considers Borneo geology broadly as the far-field product of India–Asia collision whereas the other (Hall, 2002) interprets it in a SE Asian context as the result of more local events. We then review a number of important lines of evidence that can be used to assess the alternative tectonic reconstructions: the Cenozoic geological history of Borneo, if the Asian strike–slip faults extend into

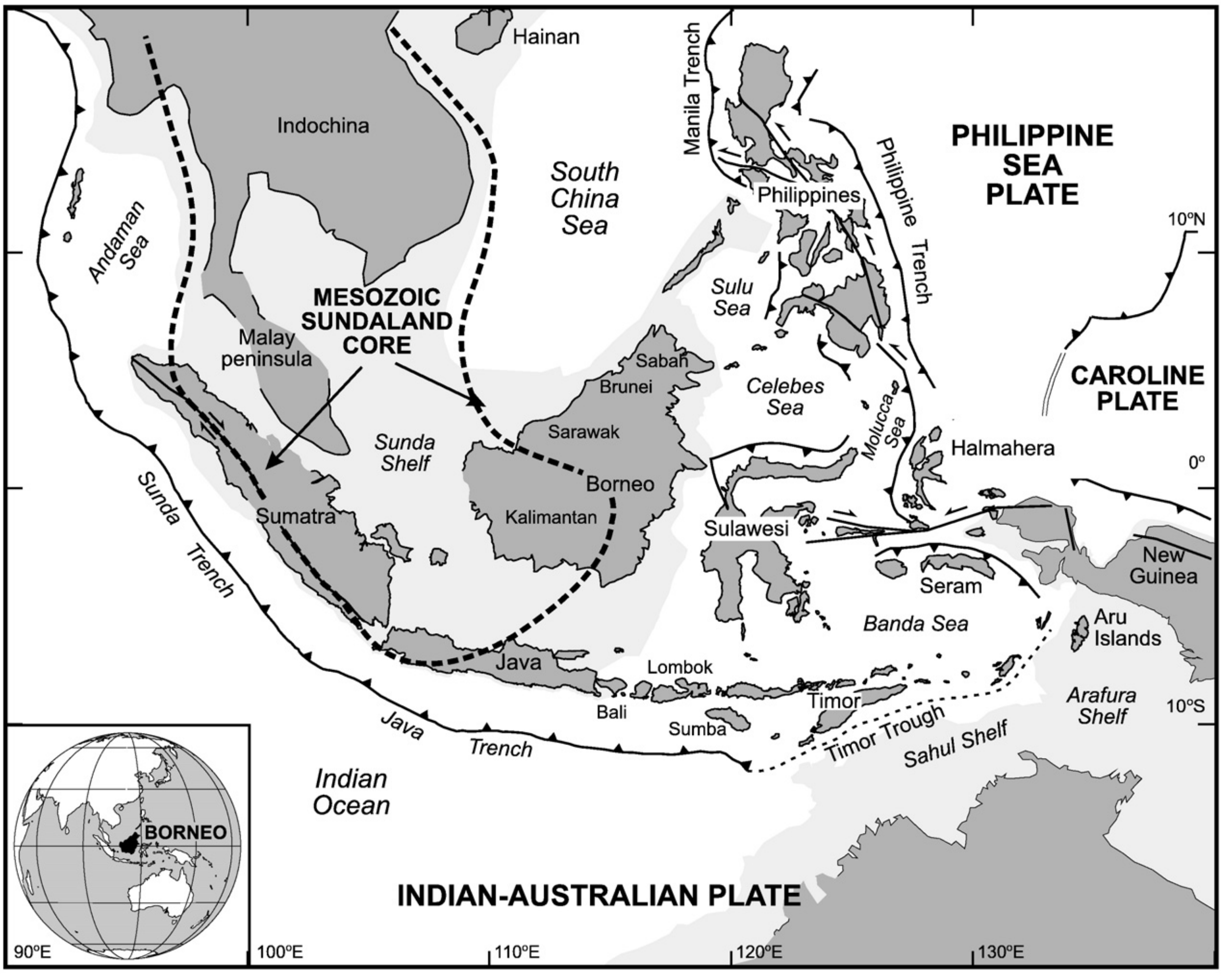

Fig. 2. Plate tectonic setting of Borneo and Sundaland.

Borneo, palaeomagnetic data, seismic tomographic interpretations, and provenance of Borneo sedimentary rocks.

2. Outline of the geology of Borneo

Borneo has a Palaeozoic continental core (Figs. 3 and 4) in west Borneo surrounded by ophiolitic, island arc and microcontinental crust accreted during the Mesozoic (Hamilton, 1979; Hutchison, 1989; Metcalfe, 1996). In SW Borneo the Palaeozoic is represented mainly by metamorphic rocks of Carboniferous to Permian age, although Devonian limestones have been found as river boulders in East Kalimantan. Cretaceous granitoid plutons, associated with volcanic rocks, intrude the metamorphic rocks in the Schwaner Mountains of SW Borneo (Williams et al., 1988). Apatite fission track ages indicate rapid exhumation of the granites in the Late Cretaceous (Sumartadipura, 1976).

North of this block, the NW Kalimantan domain (Williams et al., 1988), or Kuching zone (Hutchison, 2005), includes fossiliferous Carboniferous limestones, Permo-Triassic granites, Triassic marine shales, ammonite-bearing Jurassic sediments and Cretaceous melanges. In Sarawak, Triassic floras suggest Cathaysian affinities and correlations with Indochina. The Kuching zone may mark a subduction margin continuing south from East Asia at which ophiolitic, island arc and microcontinental crustal fragments collided and were deformed during the Mesozoic. In western Sarawak there is a belt of small Cretaceous granitoid intrusions (Tate, 2001). Cretaceous granites are also reported from offshore drilling of the Sunda Shelf (Pupilli, 1973).

West Borneo formed part of Sundaland by the mid Cretaceous and was connected to the Thai–Malay Peninsula which has a Proterozoic continental basement (Liew and Page, 1985). It includes rocks typical of a Palaeozoic continental margin intruded by abundant tin-bearing Permian–Triassic and minor Cretaceous granites. The Permian–Triassic granites are part of the SE Asian Tin Belt (Beckinsale, 1979; Beckinsale et al., 1979; Cobbing et al., 1992; Schwartz et al., 1995), extending from Burma southwards through the Thai–Malay Peninsula into the Indonesian Tin Islands (Fig. 3). Apatite fission track ages indicate episodes of exhumation of the Tin Belt granites in the Cretaceous, and in the Oligocene at about 33–24 Ma (Krähenbuhl, 1991; Kwan et al., 1992).

In north and east Borneo the basement is predominantly ophiolitic. North Borneo has an ophiolitic basement, mainly of Cretaceous age, but with possible older crust indicated by K-Ar dating of igneous and metamorphic crystalline basement (Reinhardt and Wenk, 1951; Dhonau and Hutchison, 1966; Koopmans, 1967) which could be deformed ophiolitic rocks. The ophiolitic basement is intruded by diorites and granites which may represent arc plutonic rocks. There are a few rocks of possible continental origin, such as andalusite-garnet-mica

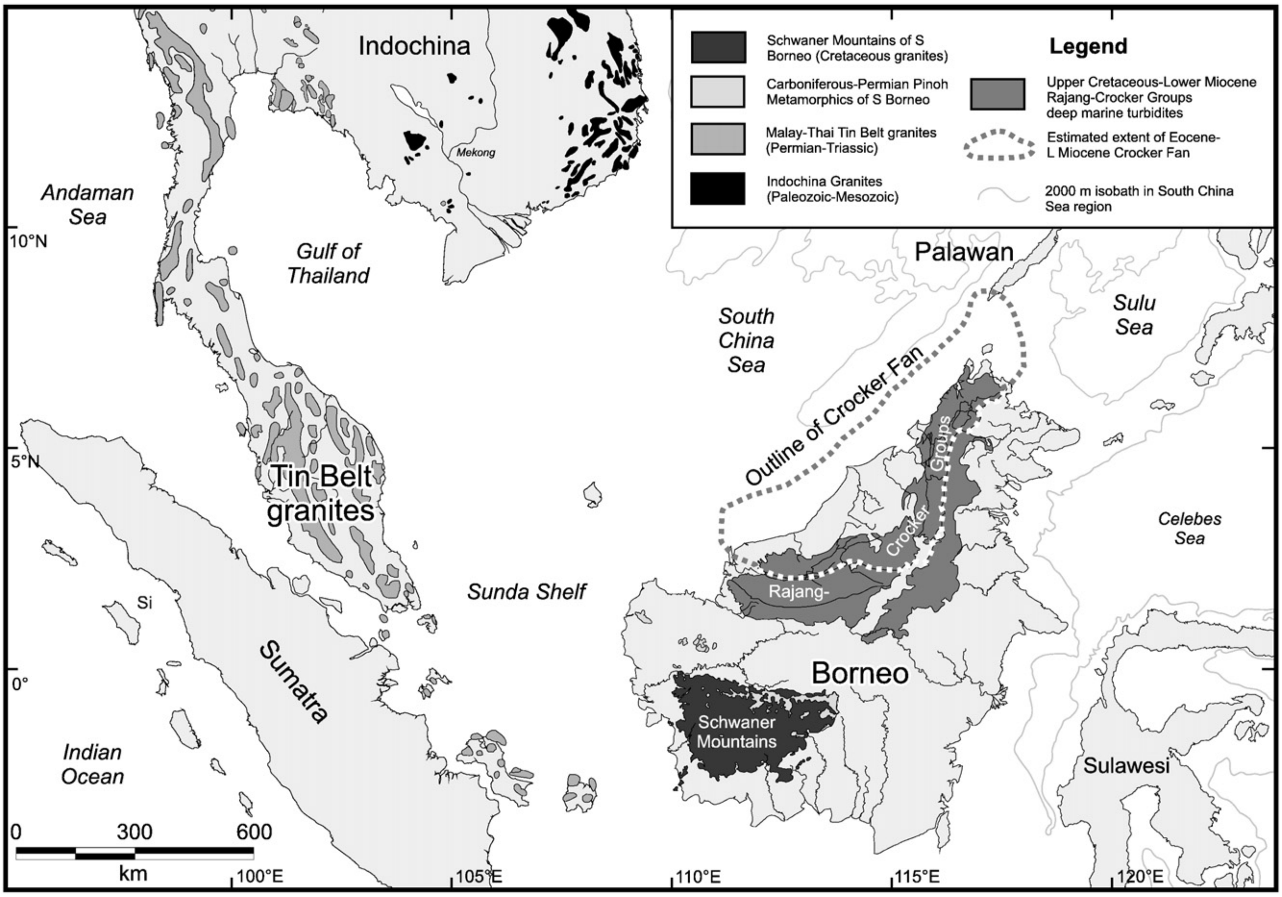

Fig. 3. Simplified regional geological map of Borneo and nearby SE Asia showing the main granite belts and Rajang–Crocker Fan. Land areas are shaded pale grey.

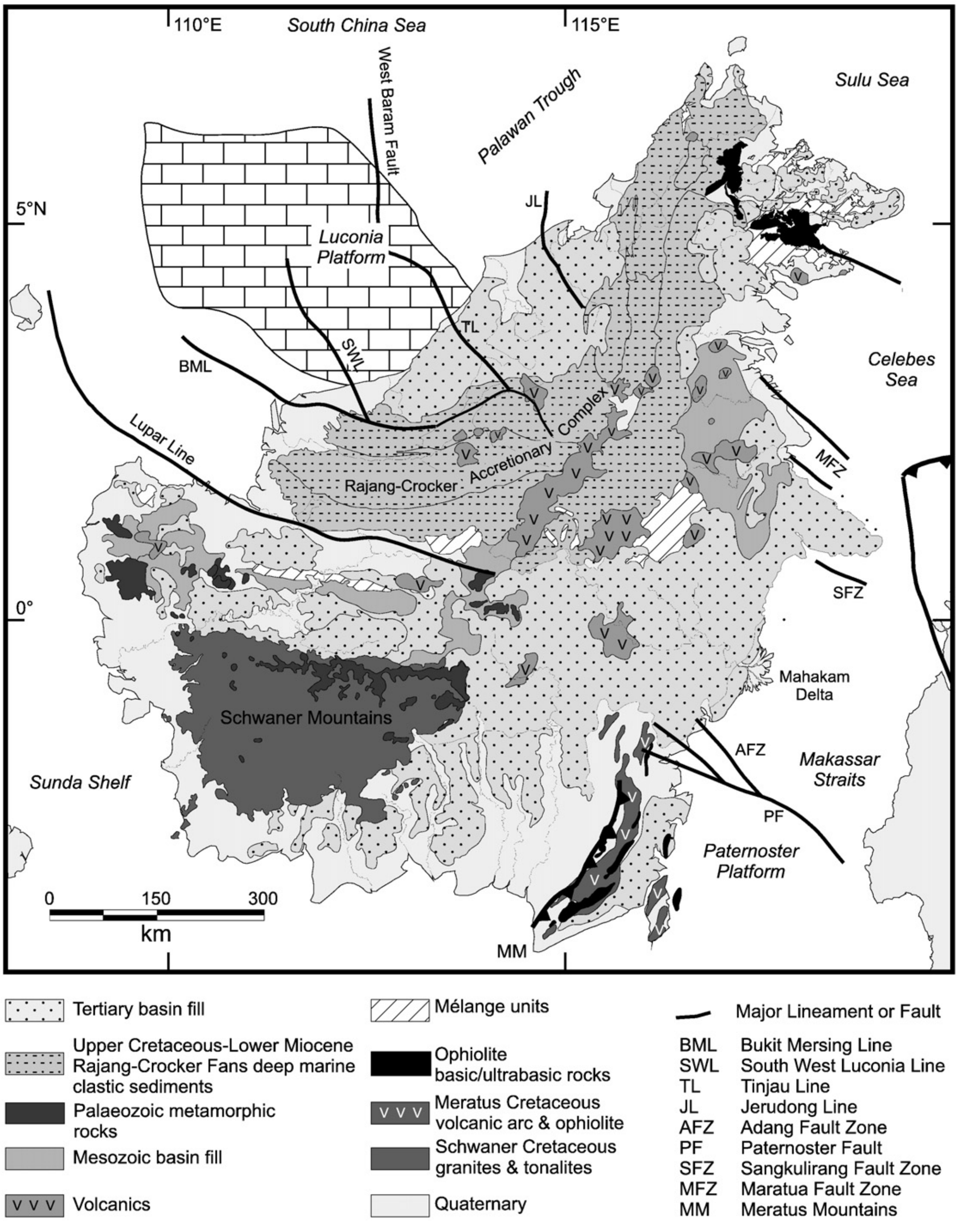

Fig. 4. Simplified geological map of Borneo. Major lineaments that may have been active at times during the Cenozoic are indicated.

and sillimanite-garnet schists (Leong, 1974), but none are dated. The descriptions of Leong (1974) and earlier workers suggest formation of the crystalline basement rocks in a Mesozoic intra-oceanic arc (Hall and Wilson, 2000); Omang and Barber (1996) suggest they are equivalent to the Cretaceous Darvel Bay ophiolite complex. Elsewhere in most of east Borneo the basement is not exposed but in the Meratus Mountains of SE Borneo it includes ophiolitic and arc rocks, also with Cretaceous ages (Sikumbang, 1986, 1990), associated with high pressure–low temperature metamorphic rocks (Parkinson et al., 1998) recording Cretaceous subduction beneath Borneo.

In most of Borneo basement rocks are covered by thick sedimentary sequences, mainly of Cenozoic age. In north Borneo deep marine sediments of the Upper Cretaceous–Eocene Rajang Group form much of the Central Borneo Mountains and Crocker Ranges. The Rajang Group is unconformably overlain by Eocene to Lower Miocene Crocker turbidites and mudstones (Hutchison, 1996; van Hattum, 2005). The Crocker Fan (Crevello, 2001) of north Borneo (Fig. 3) is the largest volume of deep marine Paleogene sediment in a single basin in SE Asia, and was deposited during the early stages of India–Asia collision. In Sabah it includes turbidites and mudstones with a thickness that may locally exceed 10 km (Collenette, 1958; Hutchison, 1996) but is uncertain due to structural repetition of poorly dated strata. Precise dating is difficult due to the common absence of fossils.

Sedimentation of the Crocker Fan terminated in the Early Miocene during an early phase of the Sabah Orogeny (Hutchison, 1996). This resulted in a major unconformity, named here the Top Crocker Unconformity (TCU). Most studies of the offshore region have paid little attention to this important unconformity although younger unconformities are widely discussed (e.g. Levell, 1987; Tan and Lamy, 1990; Hazebroek and Tan, 1993), such as the well-known Middle Miocene Deep Regional Unconformity (DRU) and Late Miocene Shallow Regional Unconformity (SRU). The TCU, which we interpret to mark a collision event (see below), is often correlated with the offshore DRU north of Sarawak, Brunei and Sabah which is commonly shown as the base of the Miocene hydrocarbon-producing strata of NW Borneo. However, Hazebroek and Tan (1993) noted a deeper unconformity offshore, which they did not name, at the top of the Crocker and Temburong Formations, and (Levell, 1987) observed that there was an angular unconformity, older than the DRU, on land at the base of shallow marine deposits of the Meligan Formation, dated by palynology as Early Miocene (Wilson and Wong, 1964). Levell (1987) noted the change in depositional character from deep marine to shallow marine, and the angular discordance, but regarded the DRU as most likely to be related to the end of subduction because it was the most extensive and the latest of the two unconformities. The DRU is commonly said to have an age of about 15 Ma and is shown by Hazebroek and Tan (1993) as 15–17 Ma. On land the DRU has been dated as about 17 Ma (C.K. Morley, pers. comm.., 2007, based on Simmons et al., 1999) but the unconformity at the base of the Meligan Formation is undated and must be older. In south Sabah the oldest unconformities that mark the change from deep water to shallow water deformation are considered to be between 22 and 19 Ma (Balaguru, 2001; Balaguru and Nichols, 2004). Balaguru and Nichols (2004) suggest that these unconformities correlate with the DRU which may be diachronous. However, we suggest that the TCU marks the collision event, and is older than the DRU, and in tectonic terms we suggest this is the more significant unconformity.

Offshore the sequences above the DRU include shelf and delta deposits, turbidites and debris flows (McGilvery and Cook, 2003; Petronas, 1999; Sandal, 1996). In the offshore Sabah margin, Middle Miocene–Recent sequences are generally less than 4 km thick. To the southwest in the Baram Delta province there is up to 12 km of Middle Miocene–Recent section (Sandal, 1996; Morley et al., 2003). The NW Borneo area is characterized by young gravity-style deformation (growth faults, mobile shales, and toe thrusts), tectonic inversion of growth structures (Morley et al., 2003) and by gravitational failure of the shelf resulting in deep water debris flows (McGilvery and Cook, 2003). Onshore, the unconformity marks a change from deep water sediments and melanges to shallow marine and fluvio-deltaic sediments (Noad, 1998; Balaguru, 2001) more than 6 km thick in remnants of a formerly more extensive basin (Balaguru et al., 2003).

There are also thick Cenozoic sedimentary sequences in and around east Borneo. To the east and northeast of Borneo are very deep basins including the Kutai, Tarakan and Sandakan Basins. In the Kutai Basin the thick Miocene–Recent basin sequences filled accommodation space created during Eocene rifting. There is up to 14 km of Eocene–Recent sediment (Moss and Chambers, 1999) and the majority of this was probably deposited since the Early Miocene. It was derived from erosion of the Borneo highlands and inversion of older parts of the basin margins, to the north and west, which began in the Early Miocene (van de Weerd and Armin, 1992; Ferguson and McClay, 1997). Sedimentation continues today in the Mahakam delta and in its deepwater offshore parts in the Makassar Straits. The Tarakan and Sandakan Basins have not been described in any detail. Like the Kutei Basin the offshore thick Miocene–Recent basin sequences of the Sandakan Basin (Graves and Swauger, 1997) have filled pre-existing accommodation space, in this case created during Miocene rifting of the Sulu Sea. In the Tarakan Basin the Plio-Pleistocene sequence alone is about 4 km thick and may be controlled by NW–SE strike–slip faults (Wight et al., 1993) extending into the Makassar Straits. There is young compressional deformation in the Tarakan–South Sabah region with fold axes and thrusts trending WNW–ESE.

3. Tectonic reconstructions

Borneo is situated at the centre of the promontory which extended southeast of Eurasia from Indochina into the Indonesian archipelago during the Cenozoic. The most widely known tectonic interpretation of the east and southeast Asian region is that of the indentor/extrusion model which developed from the work of Tapponnier and co-workers (e.g. Tapponnier et al., 1982). This suggests that large crustal blocks have been extruded laterally from the India–Asia collision zone, with deformation concentrated on a few major strike–slip faults. The model has been the subject of considerable discussion concerned with the importance of the faults, whether the blocks behaved as a rigid fragments with all deformation concentrated on the boundary faults, the amount of displacement on the faults, and the timing of movements (e.g. Briais et al., 1993; Lee and Lawver, 1995; Leloup et al., 1995; Rangin et al., 1995; Hall, 1996; Roques et al., 1997a,b; Wang and Burchfiel, 1997; Hall, 2002; Morley, 2002; Hall and Morley, 2004). The SE Asia region that includes Borneo is at the leading edge of the extruded blocks so may be expected to have deformed in response to India–Asia collision.

Replumaz and Tapponnier (2003) synthesized tectonic data for the India–Asia collision and made a reconstruction of the evolution of the collision zone assuming it can be described in terms of rigid blocks with high strain boundary faults. This reconstruction includes SE Asia and encapsulates the most recent interpretations of India–Asia collision, its indentor/extrusion consequences and its relevance to Borneo. The Replumaz and Tapponnier (2003) data have been used here to produce an animation of their model for the period 0–40 Ma at one million

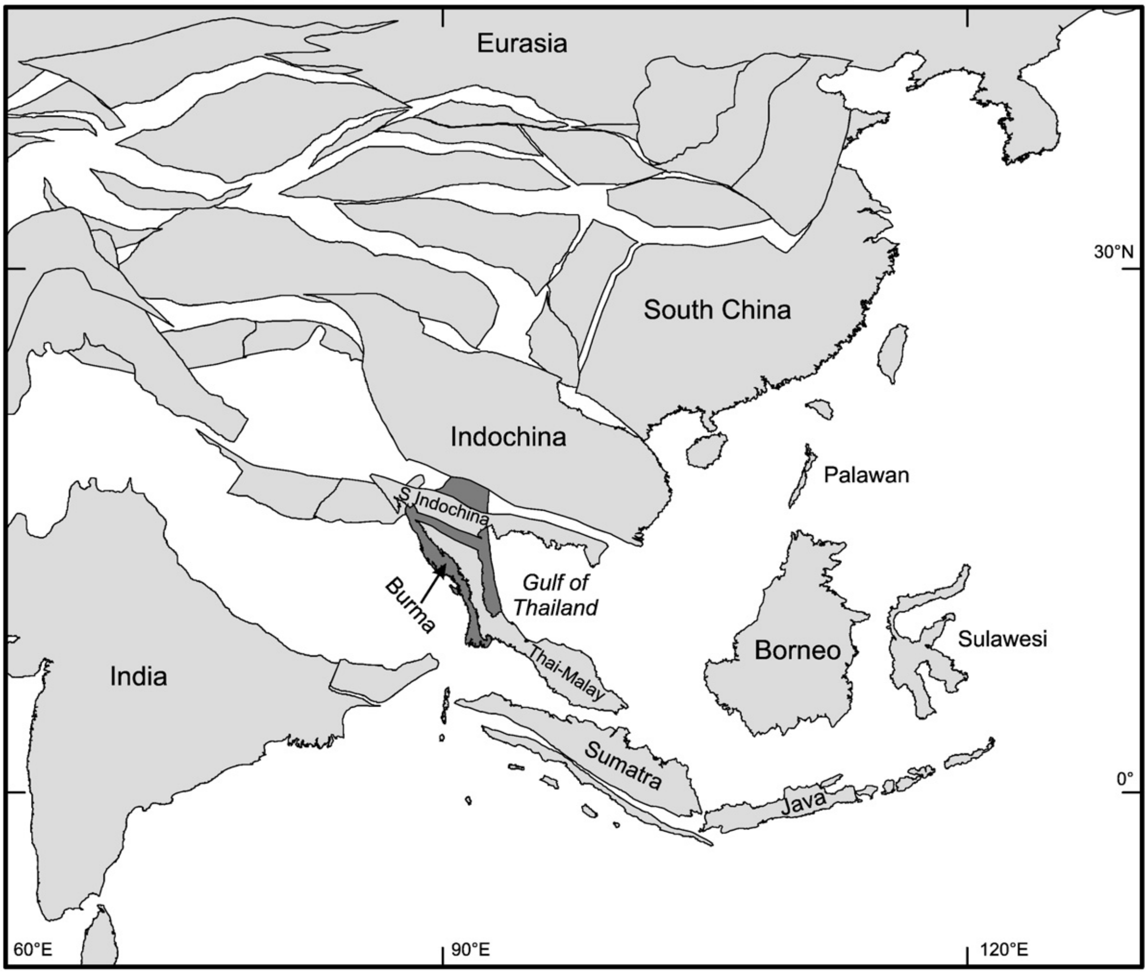

Fig. 5. Reconstruction of SE Asia region at 40 Ma based on Replumaz and Tapponnier (2003). Burma block is shaded dark grey.

year intervals which accompanies this paper[1]. As far as Borneo is concerned the key features of this model are that it is situated at the centre of a large SE Asia block (Fig. 5), as India moved northward into Asia this block was extruded eastwards, and Borneo rotated as part of the block in a clockwise direction by about 20° and moved south by about 10°.

We compare this model to the tectonic reconstruction of Hall (2002). In contrast to the Replumaz and Tapponnier (2003) model this reconstruction can be regarded as a SE Asia-centred model. It is based on palaeomagnetic data from east Indonesia recording Philippine Sea plate motion and interpretation of geological and palaeomagnetic data from SE Asia. Key features of this model for Borneo (Fig. 6) are Paleogene closure of a proto-South China Sea, Neogene counter-clockwise rotation of the island, deformation of a complex mosaic of small blocks within SE Asia, and the relative unimportance of strike–slip displacements extending from Asia into SE Asia. An animation of the model at one million year intervals that can be compared with the Replumaz and Tapponnier (2003) reconstruction for the same 0–40 Ma period also accompanies this paper[1].

4. Choosing between models

Here we briefly consider a number of lines of evidence that can be used to assess the alternative tectonic models. Essentially, the Replumaz and Tapponnier (2003) reconstructions imply a relatively simple history for Borneo in which deformation would be expected to be concentrated either at the end of the strike–slip faults which lead into Borneo, or at the leading edge of the extruded SE Asian block at subduction zones. The Hall (2002) model, based on interpretation of SE Asian geology, shows a more complex history for the Borneo region.

4.1. Cenozoic geological history of Borneo

At the beginning of the Cenozoic Borneo was part of a largely emergent region. Geochronological studies indicate a widespread thermal event at about 90 Ma in the Thai–Malay peninsula, Indochina and Borneo (e.g. Sumartadipura, 1976; Krähenbuhl, 1991; Dunning et al., 1995; Ahrendt et al., 1997; Upton et al., 1997; Carter and Moss, 1999). Cretaceous granites are widespread. They have been interpreted as subduction-related (Tate, 1996) but may also, or alternatively, be the result

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[1] Tectonic reconstructions as Quicktime movie files are available from URL: http://www.gl.rhul.ac.uk/searg/FTP/tectomovies/.

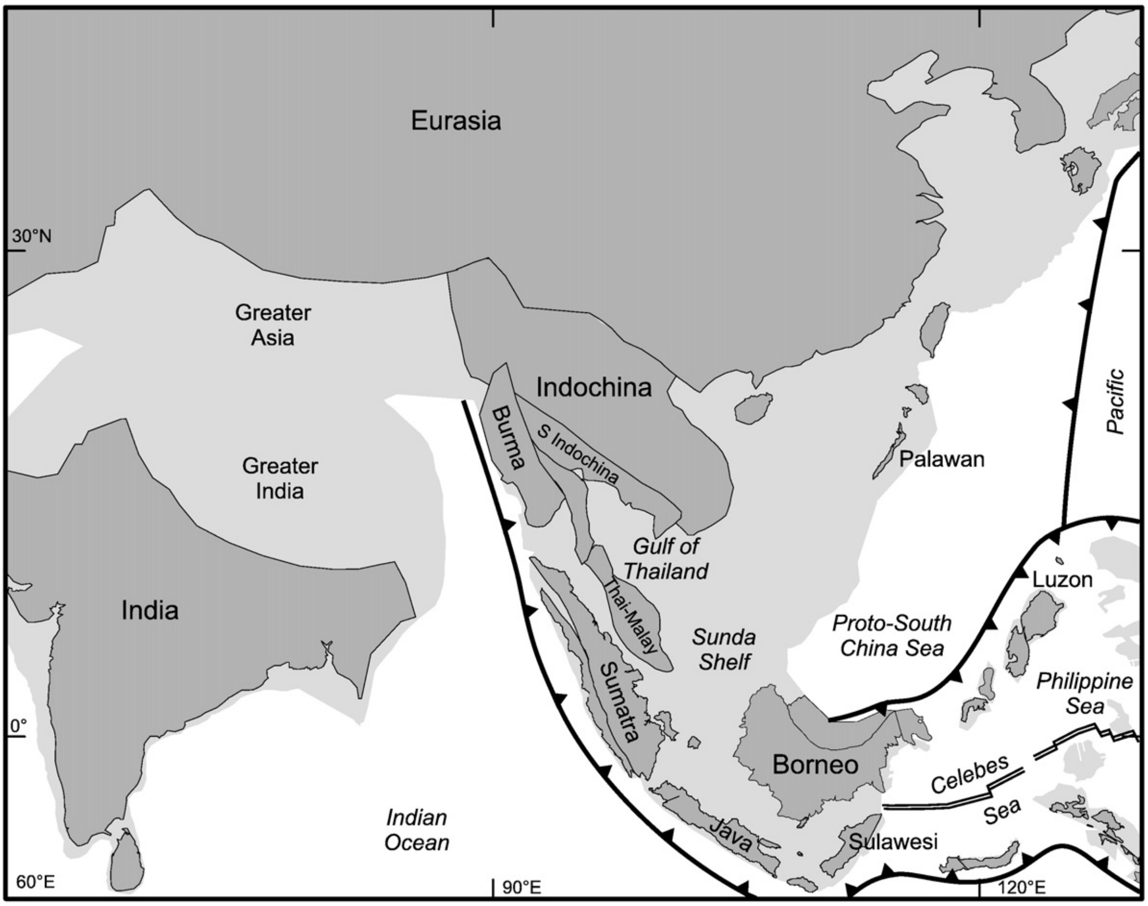

Fig. 6. Reconstruction of SE Asia region at 40 Ma modified from Hall (2002). Light shaded areas are continental shelf areas.

of crustal thickening following Mesozoic collisions at the east margin of Sundaland. Increased exhumation rates in the Late Cretaceous indicated by the few fission track studies suggest exhumation following crustal thickening. Widespread elevation of Sundaland is consistent with the absence of Upper Cretaceous to Paleocene rocks throughout most of the region.

On the south side of the Proto-South China Sea in north Borneo there was deep water in the Late Cretaceous (Haile, 1969) where sedimentary rocks of the Rajang Group have been interpreted as subduction accretionary complexes (e.g. Hamilton, 1979; James, 1984), or submarine fans on a passive margin (Moss, 1998). However, to the south, west and east much of Sundaland was emergent. Parts of Sundaland, such as SW Borneo, probably remained elevated throughout the Cenozoic but early in the Cenozoic subsidence began throughout the region and many new basins formed (Hall and Morley, 2004).

In north Borneo an Eocene tectonic event at about 45 Ma named the Sarawak orogeny by Hutchison (1996) may mark the initiation of south-directed subduction of the Proto-South China Sea. From this time onwards, during the Paleogene, there was subduction beneath Borneo and some volcanic activity (e.g. Wolfenden, 1960; Rangin et al., 1990a; Tan and Lamy, 1990; Hazebroek and Tan, 1993; Moss, 1998; Prouteau et al., 2001; van Hattum et al., 2006). The Eocene–Miocene Crocker Fan was deposited at this active margin.

Elsewhere, basin formation began in the Eocene in an entirely different setting. In eastern Sundaland rifting began in the Middle Eocene (Situmorang, 1982a,b; Hall, 1996; Moss et al., 1997) and formed the Makassar Straits which separate West Sulawesi from East Borneo. Rifting associated with spreading of the Celebes Sea may have propagated into the Makassar Straits (Hall, 1996) and debate continues about whether the crust in the straits is oceanic (e.g. Hamilton, 1979; Cloke et al., 1999; Guntoro, 1999) or attenuated continental (e.g. Burollet and Salle, 1981; Situmorang, 1982a,b). New seismic data suggest that the North Makassar Straits are underlain by thinned continental crust (Nur'aini et al., 2005; Puspita et al., 2005). Extension was widespread throughout Sundaland. South of Borneo basins began to develop in the Middle Eocene (Matthews and Bransden, 1995; Smyth, 2005; Smyth et al., 2007) in the East Java area. This area is structurally complex and was influenced by both rifting that formed the Makassar Straits and by the effects of north-directed subduction south of Java that began in the Middle Eocene (Smyth et al., 2007). To the west and northwest of Borneo basins also began to form in the area between NW Java (Cole and Crittenden, 1997) and the Gulf of Thailand (Petronas, 1999) by rifting (Hall and

Morley, 2004). These basins are typically filled by terrestrial and very shallow marine clastic sediments but many are unusually deep. The record typically begins in the Eocene or Oligocene but because the older parts of most sequences are terrestrial the timing of basin initiation is relatively poorly dated.

To the east, south and west of Borneo subsidence continued throughout the Oligocene within Sundaland while to the north the Crocker Fan was deposited in deep water at the active subduction margin (Tan and Lamy, 1990; Tongkul, 1991; Hazebroek and Tan, 1993; Hutchison et al., 2000). As the Proto-South China Sea was subducted southwards the present South China Sea formed to the north of it between the Oligocene and Middle Miocene (Taylor and Hayes, 1983; Briais et al., 1993). Subduction ceased in the Early Miocene when the thinned passive margin of South China underthrust north Borneo causing deformation, uplift, and crustal thickening. Deep marine sedimentation stopped in north Borneo and the Sabah Orogeny (Hutchison, 1996) deformed and exposed sediments of the Crocker Fan. It was this event that produced the TCU, discussed above, at the end of the Early Miocene. The arc-continent collision (Hutchison et al., 2000) elevated extensive parts of north Borneo and much sediment was carried south and east.

The Early Miocene rise of the Central Borneo Mountains shed sediment first into deltas of the Kutai and Sandakan Basins and later into the Tarakan and Baram Basins. In the Kutai Basin sediment was derived from erosion of the Borneo highlands and inversion of older parts of the basin margins to the north and west (van de Weerd and Armin, 1992; Chambers and Daley, 1997; Ferguson and McClay, 1997; Moss et al., 1998). Inversion migrated from west to east during the Early and Middle Miocene (Ferguson and McClay, 1997; McClay et al., 2000; Moss et al., 1997). In SE Borneo inversion of the Barito Basin and uplift of the adjacent Meratus Mountains occurred episodically from the Late Miocene to Pleistocene (Mason et al., 1993; Satyana et al., 1999).

In north Borneo a new phase of subsidence began in the Early Miocene. This may have been linked to formation of the Sulu Sea which opened as a backarc basin from the Early Miocene (Holloway 1982; Hinz et al. 1991; Rangin and Silver, 1991). However, the tectonic situation in north Borneo was complex. In the Dent and Semporna peninsulas of Sabah there are Middle to Late Miocene–Quaternary volcanic rocks which continue offshore into the Sulu arc (Kirk, 1968) and are probably the product of north-directed subduction of the Celebes Sea (Chiang, 2002). Elsewhere in north Borneo there has been significant Neogene uplift and denudation. The 4100 m granite peak of Mt Kinabalu, the highest mountain in SE Asia, has yielded young K-Ar ages of less than 14 Ma (Jacobson, 1970; Swauger et al., 1995) and fission track data indicate 4 to 8 km of Late Miocene denudation throughout the Crocker Ranges (Swauger et al., 1995; Hutchison et al., 2000), while to the north and south sedimentary basins offshore and in south Sabah were provided with abundant detritus. The cause of exhumation is not known but the rapid uplift on land may be responsible for continuing active deformation offshore.

There is no evidence that Borneo was separated from Sumatra or peninsular Malaysia at any time during the Cenozoic. Information from the offshore basins indicates that Sundaland was broadly a continuous continental region although there was significant local extension and the formation of deep sedimentary basins. However, despite geological continuity there is evidence of widespread and young deformation in and around Borneo. Neogene sediments have been deformed in most of the basins and active deformation is common despite the absence of nearby subduction or collision. Some of the deformation can be explained as the result of gravity tectonics, as observed in large deltas on passive margins, perhaps enhanced by rapid exhumation of areas such as Kinabalu. In some areas, such as south Sabah, there is evidence of Neogene deformation in strike–slip zones (Balaguru et al., 2003). Some authors show major strike–slip faults with NW–SE orientation crossing Borneo linked to faults in Sulawesi and Indochina. There is no doubt that some of these faults have major vertical displacements although this is old (e.g. Eocene or older movement on the Paternoster Fault; Nur′Aini et al., 2005), and some show Neogene strike–slip motion (e.g. Adang Fault and faults close to the Tarakan Basin), but the length of these faults is often exaggerated, and there are no faults demonstrated to cross Borneo, or even to continue east from Borneo across the Makassar Straits.

Overall the geological history of Borneo is much more complex than shown in the Replumaz and Tapponnier (2003) model in which there is passive extrusion of a SE Asian block. A notable absence in their model is subduction of the proto-South China Sea beneath Borneo, a feature largely dismissed or ignored by extrusion modellers (e.g. Leloup et al., 2001), but for which there is considerable geological evidence summarized above. In order to justify the suggestion that deformation in Borneo could be related to extrusion the strike–slip faults must be demonstrated to pass into Borneo, and the timing of the movements on these faults should be consistent with the age of deformation in Borneo. Neither relationship is evident. The continuation of the strike–slip faults towards Borneo is discussed in the next section, but the Replumaz and Tapponnier (2003) model has obvious problems in the region north of Borneo. Their reconstruction shows major shortening in the Gulf of Thailand in the Late Eocene and Early Oligocene between 40 and 30 Ma at a time when extensional basins were forming (Hall and Morley, 2004) in that area. The elevation of Borneo, the beginning of major erosion supplying the Neogene circum-Borneo basins, and the earliest inversion of internal parts of Borneo basins on land, began in the Early Miocene, several million years before spreading ceased in the South China Sea at about 17 Ma. In the South China Sea, or the Gulf of Thailand and Sunda Shelf north of Borneo, the Replumaz and Tapponnier (2003) model either says nothing, or the opposite of what is observed.

An important part of the indentor model is clockwise rotation of blocks as extrusion proceeds, and the reconstructions before 17 Ma reveal other problems, described as “serious incompatibilities” by Replumaz and Tapponnier (2003). Their rotation of SE Asia to its 40 Ma position results in almost complete overlap of Thailand and Burma, a feature completely incompatible with the geology. Their Burma block includes mostly West Burma west of the Sagaing Fault (Fig. 1) which is interpreted by some authors to have been added to the Asia margin in the Cretaceous (Mitchell, 1993; Metcalfe, 1996; Heine et al., 2004) or the Triassic (Barber and Crow, in press) and is generally considered to have rifted from the Gondwana margin, either in the Palaeozoic or Cretaceous. The oldest rocks known at the surface are Triassic sandstones. Hutchison (1989) infers a pre-Cenozoic continental basement for the major part of the block west of the Sagaing Fault. Metcalfe (1996) reports a pre-Mesozoic schist basement overlain by Triassic turbidites and Cretaceous shales in the Indoburman Ranges, and an Upper Mesozoic–Cenozoic arc in the Burmese Central Lowlands. This block overlaps with peninsular Thailand north of the Ranong Fault (Fig. 1), and parts of Thailand now northeast of the Three Pagodas Fault, areas that include Cretaceous granites, Permo-Triassic Tin Belt granites, and interpreted Proterozoic basement, forming part of the Sibumasu block (Metcalfe, 1996). Thus, the overlapping blocks contain rocks that were certainly part of SE Asia by the late Cretaceous, and probably much earlier. This serious incompatibility occurs on all reconstructions older than 17 Ma and by 40 Ma there is complete overlap resulting from the interpreted large clockwise rotations of the SE Asian block. Thus, the geology of these parts of Sundaland is not consistent with the block movements proposed. The large rotations shown in the Replumaz and Tapponnier (2003) model can also be tested using the palaeomagnetic data.

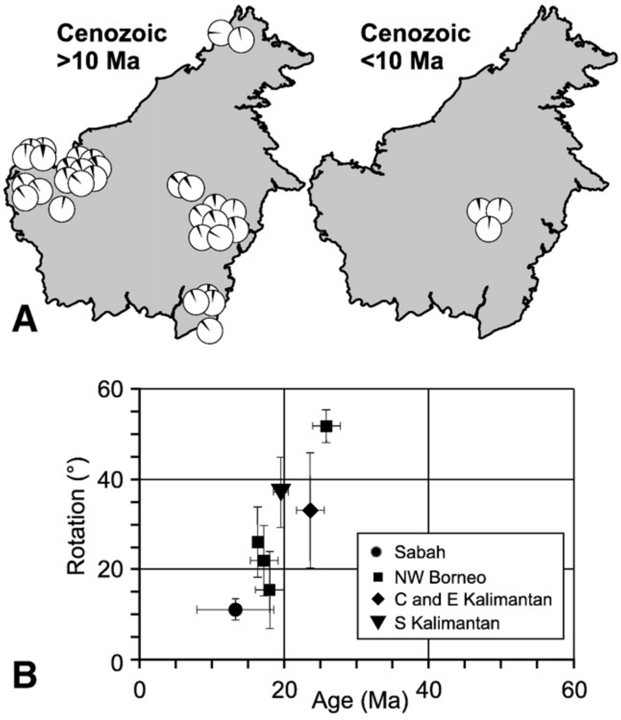

Fig. 7. Summary of palaeomagnetic data from Borneo for Cenozoic rocks, after Fuller et al. (1999). A. Location of all sites and summary of rotations with declinations shown as pie slices with width of slice representing α_{95}. B. Age of rocks and amount of rotation for sites in different parts of Borneo.

4.2. Palaeomagnetism

The Cenozoic rotation history of Borneo has been a subject of controversy (see Hall, 1996, 2002; Fuller et al., 1999) with some authors advocating a large counter-clockwise rotation of the island, whereas others interpret no or even clockwise rotation. There is now quite a large palaeomagnetic dataset from Borneo (Fuller et al., 1999; Haile, 1979; Haile et al., 1977; Lumadyo et al., 1993; Schmidtke et al., 1990; Wahyono and Sunata, 1987). In early reviews Fuller et al. (1991) favoured counter-clockwise rotation of the island, whereas Lee and Lawver (1994) favoured no rotation. Since then newer data (Fig. 7) have been added and the entire palaeomagnetic dataset was reviewed most recently by Fuller et al. (1999). They concluded there is no evidence for a significant change in latitude for Borneo since the Mesozoic. Almost all the palaeomagnetic data indicate counter-clockwise rotation and therefore either require a treatment of Borneo as a single rigid fragment or an explanation in terms of multiple local rotations, but with similar sense. Fuller et al. (1999) concluded that the palaeomagnetic data are consistent with a counter-clockwise rotation of a single block around 45–50° in the period between 25 and 10 Ma and a post-Early Cretaceous counter-clockwise rotation of about 40°. Rotations of this magnitude and direction were incorporated in the Hall (1996, 2002) tectonic reconstructions.

Several authors have rejected the counterclockwise rotation of Borneo (e.g. Rangin et al., 1990b; Lumadyo et al., 1993; Lee and Lawver, 1994) and emphasized problems with the palaeomagnetic data to justify this conclusion. These authors favoured little or no movement of Borneo during the Cenozoic. It is true that there are inconsistencies and problems in the palaeomagnetic data, with obvious shortcomings accepted by Fuller et al. (1999). Some sites show no rotation, many of the sites sampled igneous rocks which are assumed to be undeformed, and for which there is no palaeo-horizontal, and many of the igneous rocks are dated only by the K-Ar method. Given the complexity of Borneo geology, the limitations of our knowledge of the island, and the problems of finding suitable palaeomagnetic targets it is unsurprising that the existing data can be interpreted in different ways: as a single block rotation of the island, or as multiple small rotations without large scale rotation of Borneo. However, no-one has argued, or presented any evidence, for the large clockwise rotation and the large change in latitude shown for Borneo in the reconstructions by Replumaz and Tapponnier (2003) and there are no palaeomagnetic data that support such an interpretation. The large clockwise rotations and movements predicted by the indentor model for Borneo are simply incompatible with the palaeomagnetic evidence.

4.3. Strike–slip faults

In the extrusion model deformation is concentrated on a few major strike–slip faults. It is not our intention to add to the discussion of these faults except for one aspect, which is whether or not they cross the continental shelf into Borneo. The large displacements on the faults require that they terminate in regions of major deformation such as pull-apart basins, thrust zones in orogenic belts, or plate boundaries. There have been no suggestions that the fault terminate on land in China or Indochina, and for this reason the faults are projected offshore across the Sunda Shelf, South China margin, and often as far as Borneo (e.g. Tapponnier et al., 1986; Briais et al., 1993; Lee and Lawver, 1995; Leloup et al., 1995; Lacassin et al., 1997). The suggested importance of the faults and the length of time to which they are supposed to have been active indicate that they should be clearly seen in offshore seismic data sets.

There is evidence for hundreds of kilometres of Oligo-Miocene displacement on the Red River Fault in Indochina and South China (Tapponnier et al., 1986; Leloup et al., 1995, 2001). What happens to the Red River Fault after it passes offshore is uncertain. The original models (e.g. Tapponnier et al., 1986; Briais et al., 1993) linked the fault to opening of the South China Sea but the locations of faults offshore were not specified. At the southern end of the Red River Fault (Fig. 1) there are deep sedimentary basins which may be pull-apart basins (Rangin et al., 1995; Clift and Sun, 2006) although major strike–slip faults are difficult to identify. However, even if the stratigraphy of these offshore basins is consistent in timing of movement on the Red River Fault (Clift and Sun, 2006) and with analogue models (Sun et al., 2003, 2004) suggesting they are pull-apart basins there remain major problems with the amounts of strike–slip movement and whether the fault system continues south. On the basis of seismic data from the Gulf of Tonkin, Rangin et al. (1995) concluded that offset on the Red River Fault in that area was of the order of tens not hundreds of kilometres. The patterns of faults close to the coast and the small displacements interpreted from seismic data suggest that the Red River Fault terminates in a system of horse-tail splays typical of other strike–slip faults (Morley, 2002, 2007) in the region south of the coast.

Using analogue models Sun et al. (2003) estimated the sinistral displacement required to form the Yinggehai Basin at about 200 km. The pull-apart interpretation of the Yinggehai Basin (Sun et al., 2003, 2004) and analogue models (Sun et al., 2003, 2004) show a sinistral fault continuing south towards the Vietnam margin. If this fault does continue south the geometry indicates its north–south continuation should be a restraining bend that would be expected to show contractional deformation during the Oligo-Miocene. This is inconsistent with extensional movement and the observed large vertical offset on the N–S offshore East Vietnam fault (Roques et al., 1997a,b; Huchon et al., 1998). Taylor and Hayes (1983) also linked Oligo-Miocene movement on the Red River Fault to a N–S fault just offshore of Vietnam which they terminated at a subduction zone north of Borneo but, in contrast to indentor models, they interpreted the whole fault system as dextral. Roques et al. (1997a,b) reported dextral motion before 20 Ma on the N–S faults of the Vietnam margin.

Like Taylor and Hayes (1983), Roques et al. (1997a,b) and Huchon et al. (1998) suggested that subduction at the north Borneo Trench may have driven extension east of Vietnam, including opening of the South China Sea, linked by strike–slip faults. However, the dextral motion required on these faults is incompatible with the sinistral movements reported on land (Leloup et al., 1995) as pointed out by Briais et al. (1993). Furthermore, although the critical area that connects the Borneo margin to the north side of the South China Sea is both politically and commercially sensitive and is not well known, there is no evidence from the published literature that major strike–slip faults can be traced across the South China Sea into Borneo (Blanche and Blanche, 1997; Morley, 2002; Liu et al., 2004; Hutchison, 2004; Liu and Yan, 2004). It seems most likely that the Red River Fault terminates in the Gulf of Tonkin, that it is not related to the East Vietnam fault, and that neither fault continues across the South China Sea into Borneo.

On the southern side of the Indochina block the ductile shear zones of the Mae Ping Fault (Wang Chao Fault of some authors) and Three Pagodas Fault are estimated to account for hundreds of kilometres of motion on land (Lacassin et al., 1997). Offshore basins (Vietnam and the Gulf of Thailand) have been interpreted as pull-apart basins controlled by strike–slip faults (e.g. Molnar and Tapponnier, 1975; Tapponnier et al., 1986; Polachan et al., 1991; Leloup et al., 1995; Lacassin et al., 1997) assuming that these faults continue offshore. However, these suggestions are not supported by offshore seismic lines which generally suggest oblique rifting, perhaps influenced by a basement fabric (Hall and Morley, 2004). As with the Red River Fault, it is very difficult to identify where the Mae Ping and Three Pagodas Faults go offshore. The Mae Ping Fault has been interpreted to terminate in a subduction zone off NW Borneo (Leloup et al., 2001). Reconstructions by Briais et al. (1993) show some of the faults terminating in extensional faults associated with the Cuu Long basin and the Gulf of Thailand. However, on land the continuation of the Mae Ping Fault towards the coast is very uncertain (Fig. 1) and there is little evidence for continuing it east of Bangkok. Morley (2002) traced the fault towards the coast and terminated it in a hypothetical system of horsetail splays linked to NE–SW trending faults in the offshore Cuu Long Basin. The detailed mapping of Morley (2004) suggests that the fault could terminate in a contractional duplex of the Chainat Ridge (Fig. 8) but even if the fault continues east its movement there must have ceased before development of the Late Oligocene–Early Miocene Ayutthaya Basin (Morley et al., 2007) which crosses the fault. Mapping of the Three Pagodas Fault on land (Morley, 2004) suggests it too could terminate in a horsetail system before going offshore (Fig. 8). If these faults do go offshore they should be easily identifiable on offshore seismic lines. Few offshore oil company seismic data are published but in all critical areas there is a lack of evidence (e.g. Morley, 2001, 2002) for the strike–slip faults and for the major displacements suggested on land.

It is therefore very surprising, considering the supposed importance of the strike–slip faults, that in the regions where they should be most easily imaged, in the offshore regions studied by hydrocarbon exploration, they have not been reported. There is no evidence that any of the major faults identified on land in China and Indochina can be traced offshore to Borneo.

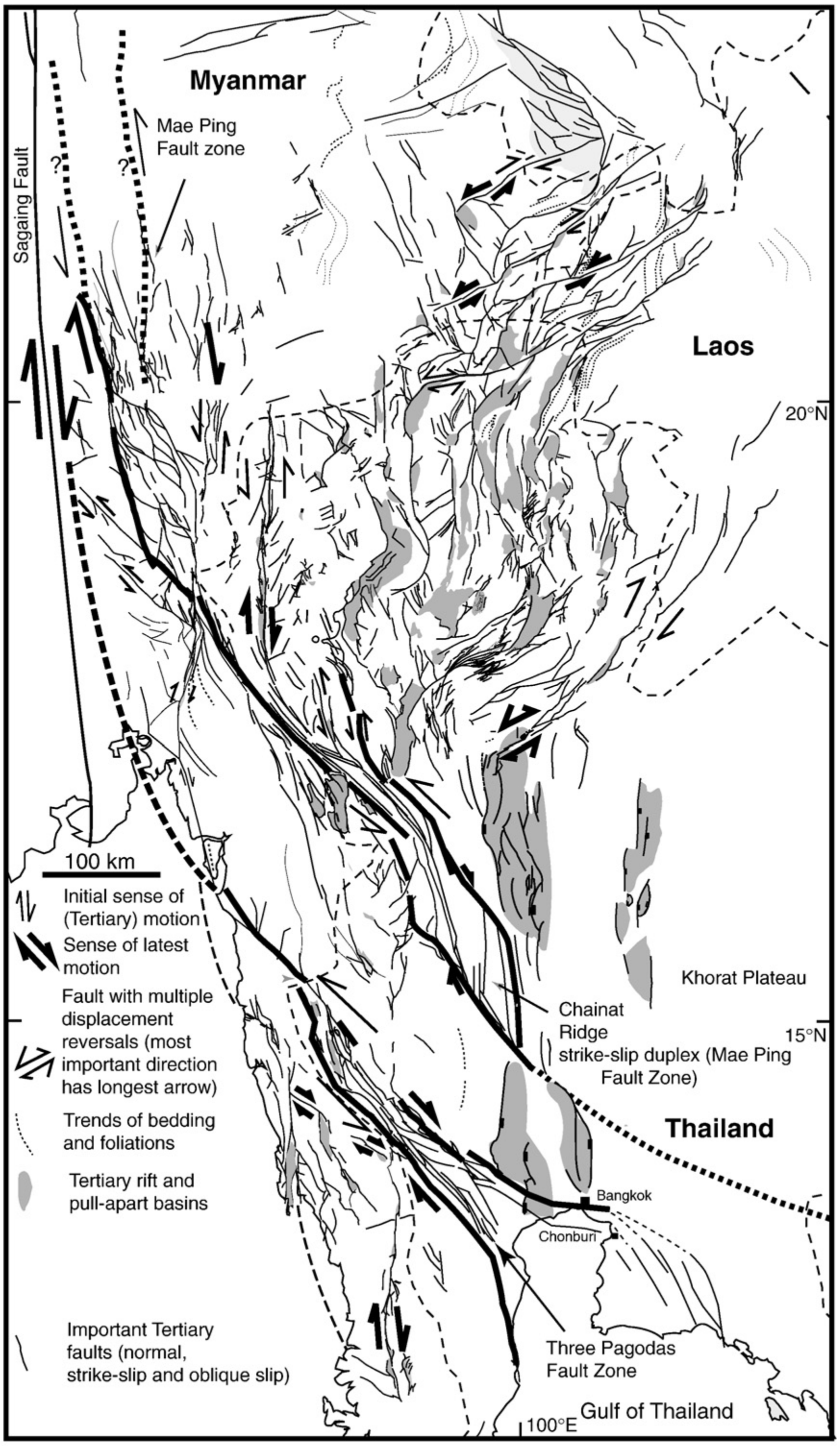

Fig. 8. The many extensional and strike–slip faults and associated basins in Thailand, Laos and Burma mapped from satellite images, surface mapping and seismic reflection data by Morley (2002). The Mae Ping and Three Pagodas Fault Zones display numerous branching, splaying and duplex geometries, suggesting termination close to the coast.

4.4. Tomography

A critical feature of the tectonic history is the position of Cenozoic subduction zones around Borneo and mantle tomography can provide evidence that contributes to assessing different reconstructions. The mantle structure of the region has been imaged in global tomographic models capable of resolving considerable detail (e.g. van der Hilst et al., 1997; Widiyantoro and van der Hilst, 1997; Bijwaard et al., 1998; Hafkenscheid et al., 2001). Replumaz et al. (2004) used tomographic images from the model of Kárason and van der Hilst (2001) to interpret the deep structure beneath the India–Asia collision zone and SE Asia. They discussed the significance of a number of high velocity anomalies in the mantle down to depths of 1600 km and interpreted them using the reconstruction of Replumaz and Tapponnier (2003). Replumaz et al. (2004) identified the position of early Cenozoic subduction zones from the lower mantle high velocity anomalies and used a depth slice at 1100 km to infer the location of 40 Ma subduction boundaries at the northern edge of the Indian–Australian plate.

Fig. 9 shows a tomographic slice from the model of Bijwaard and Spakman (2000) on which the outlines of fragments used in the 40 Ma reconstructions of Replumaz and Tapponnier (2003) and Hall (2002) are marked. The tomographic model of Bijwaard and Spakman (2000) has many similar features to that of Kárason and van der Hilst (2001). It is a P-wave model based on the Engdahl et al. (1998) data set which allows the variation of cell dimensions as a function of the local seismic data density (Spakman and Bijwaard, 2001). The smallest cells used have dimensions of 0.6 degrees laterally and 35 km in depth. As would be expected, the major anomalies can be identified in both models and are in the same positions. The range of the anomalous P-wave velocity relative to the average velocity at depth on Fig. 9 is ±0.5% instead of the ±0.8% in the Replumaz et al. (2004) images which means that the areas of the major anomalies are slightly different. However, for the discussion here we are not concerned with the volume of subducted material and the tomographic models can be considered to show the same features.

There are always problems converting the depths of anomalies in the mantle to the age of subduction and this is particularly important in the lower mantle where subducted slabs are likely to be deformed. An additional point to be considered is the speed of subduction. India moved northwards rapidly until the Eocene when its movement slowed (Besse and Courtillot, 1991). In contrast, although Australia separated from Antarctica in the Cretaceous it began to move northwards at a significant rate only from about 45 Ma. The difference between the rates of subduction north of India and north of Australia means that a single age cannot be assumed for mantle anomalies at a particular depth. This point is further emphasized by the deep mantle structure. At depths below 700 km there is a marked difference between the mantle structure west and east of about 95–100°E. West of this longitude there are a series of linear anomalies trending roughly NW–SE that have been interpreted as subducted remnants of Tethyan oceans (e.g. van der Voo et al., 1999). East of 100°E these anomalies no longer exist, and only the southernmost anomaly can be traced eastwards. However, instead of the clear linear NW–SE anomaly to the west the apparent continuation of the high velocity anomaly beneath SE Asia has a quite different appearance. It has a broad elliptical shape with a long axis oriented approximately NE–SW that terminates at the edge of the west Pacific beneath the Philippines. This raises the question of whether the deep linear anomaly now beneath India, which is convincingly interpreted as a subducted Tethyan ocean (van der Voo et al., 1999) north of India, can be traced east into the much larger anomaly beneath SE Asia.

Replumaz et al. (2004) assume that the 1100 km deep slice corresponds to a 40 Ma reconstruction and argued that the tomographic images support their reconstruction of the collision zone, and in particular the clockwise rotation of SE Asia. As pointed out above, there is no evidence from palaeomagnetism for either the rotation or latitude change suggested by Replumaz and Tapponnier (2003). Furthermore the area of the anomaly extends significantly south of the reconstructed position of the Java trench in the Replumaz and Tapponnier (2003) reconstruction; this is inconsistent with it being due to subduction at a trench in such a position. The reconstruction of Hall (2002) offers an alternative interpretation of the deep anomaly beneath SE Asia. The position of the anomaly fits well with that expected from Indian–Australian lithosphere subducted northward at the Java margin since about 45 Ma, and proto-South China Sea lithosphere subducted southward at the north Borneo trench since 45 Ma, as well as that subducted at several other

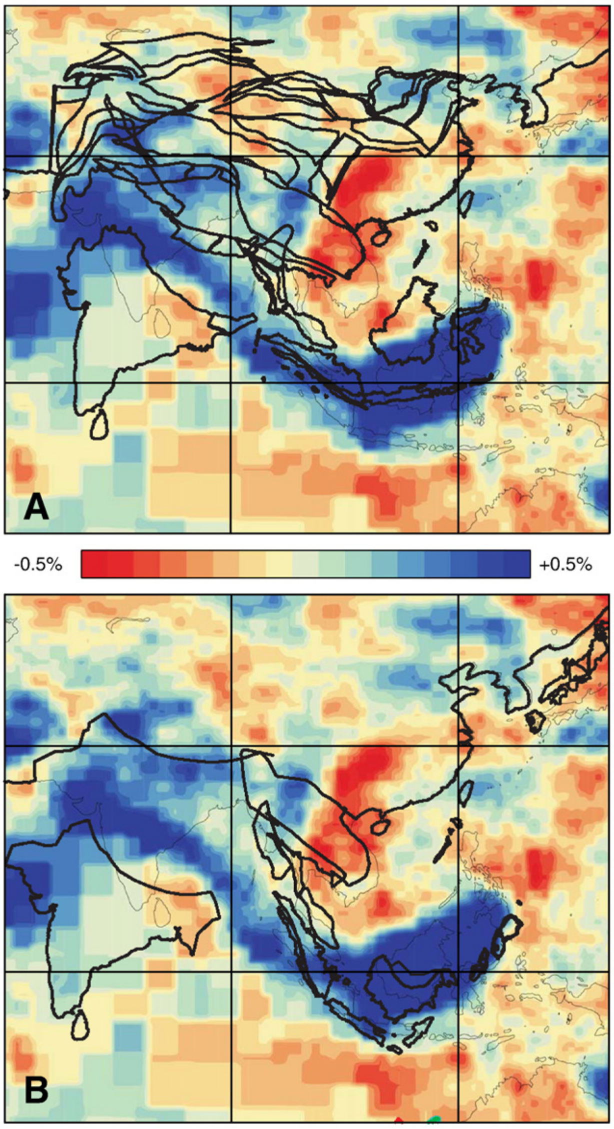

Fig. 9. Depth slice at 1100 km from the tomographic model of Bijwaard and Spakman (2000) on which the outlines of fragments used in the 40 Ma reconstructions of (A) Replumaz and Tapponnier (2003) and (B) Hall (2002) are marked. Compare to Figs. 5 and 6. Heavy black lines show 40 Ma positions of fragments used in reconstructions, and light black lines are present day coastlines.

subduction zones within east Indonesia, such as those associated with the Sulu arc, and the Sangihe arc.

We conclude that the mantle structure beneath SE Asia does not unambiguously support either tectonic model. Since the large clockwise rotation and latitude change are not supported by evidence from Borneo, the tomographic images are insufficient to validate the Replumaz and Tapponnier (2003) reconstruction. The deep anomaly seen on the 1100 km depth slice can be interpreted as subducted lithosphere in both tectonic models, but due to different subduction systems.

4.5. Sediment provenance

Borneo is surrounded by large sedimentary basins (Fig. 10). The Neogene sediments in these basins have evidently come from Borneo as the basins are fed by large rivers draining the island (Hall and Nichols, 2002). However, for the Paleogene the situation is not so clear-cut. As noted above, the large volume Crocker turbidite fan (Fig. 3) was deposited during the early stages of India–Asia collision. This raises a question of the source of sediment: has it been carried into the region after erosion from elevated regions in Asia as implied or suggested by some authors (e.g. Hutchison, 1996; Métivier et al., 1999; Clift, 2006) or was it derived locally? The provenance of Eocene to Miocene sandstones has been recently investigated (van Hattum, 2005; van Hattum et al., 2006) using light minerals (Dickinson et al., 1983), heavy minerals (Mange and Maurer, 1992), and zircon geochronology.

4.5.1. Paleogene sandstones

The sandstones of the Crocker Fan have a mature quartzose composition (Fig. 11) and most of their constituents were

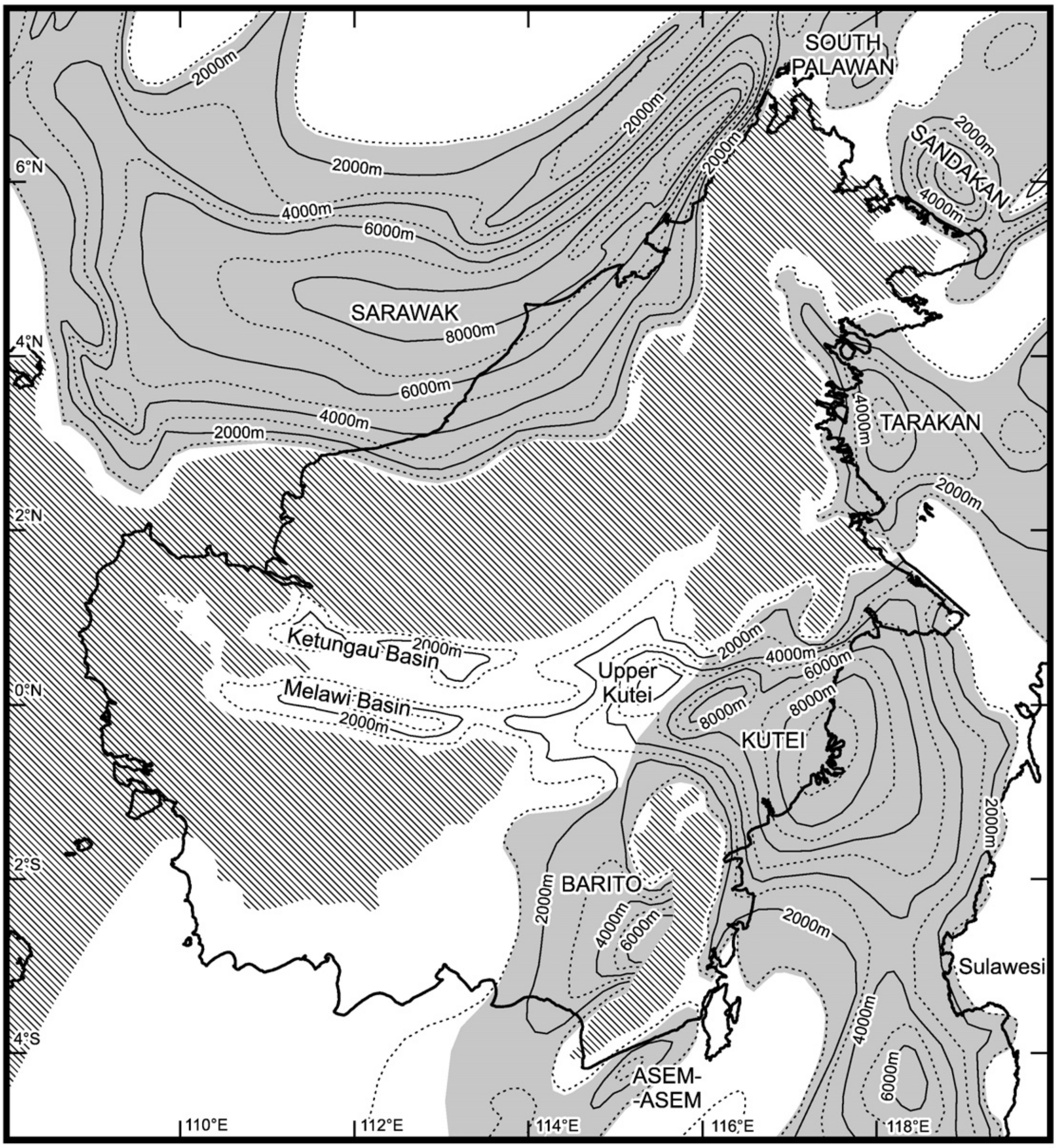

Fig. 10. Isopachs of sediment thicknesses based on Hamilton (1979) modified from Hall and Nichols (2002). Stippled areas are principally areas without Cenozoic sedimentary rocks. The grey shaded areas of the basins are areas which contain more than 1 km of Cenozoic rocks. The Ketungau and Melawi basins contain pre-Neogene rocks.

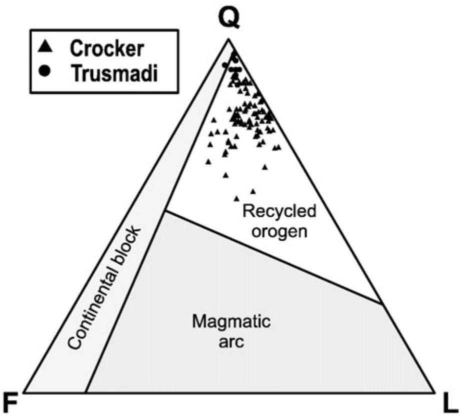

Fig. 11. QFL plot (after Dickinson et al., 1983) of framework detrital modes showing average compositions of Crocker Fan sandstones. Q=Total quartzose, including polycrystalline, grains; F=Feldspar grains; L=Unstable lithic grains of sedimentary, igneous or metamorphic origin.

derived from acid plutonic, with subordinate metamorphic and ophiolitic, rocks (Tongkul, 1987; William et al., 2003; van Hattum, 2005). They contain abundant plutonic quartz with less common metamorphic and volcanic quartz. K-feldspar is the most abundant type of feldspar. Lithic grains include granites, schists, rare acid volcanics and radiolarian cherts. Volcanic clasts are restricted to the oldest samples. Carbonate clasts are rare. Although quartzose in composition, the sandstones are texturally very immature (Crevello, 2001; William et al., 2003; van Hattum, 2005), suggesting first-cycle sandstones. They are poorly sorted, have a muddy matrix and very low porosity. Grains are angular to subangular, and there are few indications of sedimentary recycling.

The heavy minerals (Fig. 12) are dominated by zircon and tourmaline, with common rutile and garnet, and subordinate apatite and chrome spinel. There are minor quantities of pyroxene, amphibole and monazite. Cassiterite is present in a few samples. Authigenic heavy minerals include brookite and anatase. The heavy minerals indicate similar sources to the light minerals. Abundant zircon and tourmaline, less abundant apatite, and rare cassiterite, suggest an acid plutonic source. Rutile and garnet indicate a metamorphic source. The common presence of chrome spinel, showing very little abrasion, and less common clinopyroxenes and amphiboles suggest a local ophiolitic source. Despite the compositional maturity of the heavy mineral assemblages, their grain shapes indicate a low textural maturity, with a high proportion of unabraded, probably first cycle, zircon and tourmaline grains. A small proportion of strongly coloured zircons, mostly purple, are usually well rounded and suggest a polycyclic history. The abundance of garnet is very variable. It is usually subordinate to zircon and tourmaline, but rarely shows signs of chemical destruction, suggesting variation in the source. Chrome spinel is nearly always present, but never exceeds 4% of the total heavy minerals. Apatite is not always present, and many apatite grains that do occur are often pitted or partially dissolved, probably due to acidic tropical weathering (Morton, 1984). Many tourmalines show similar features. Compositional maturity is probably due to acidic weathering during erosion and transport.

The main palaeocurrent direction in the Crocker Fan is to the NNE with a subordinate direction to the NNW (Stauffer, 1967; van Hattum, 2005), suggesting a principal source area in the SSW and some transport from the SSE.

4.5.2. Post-TCU sandstones

Lower Miocene fluvio-deltaic and shallow marine sandstones above the TCU are different in south and north Sabah. In south Sabah they resemble the Paleogene turbidite sandstones. They are quartzose and dominated by monocrystalline plutonic quartz but are more mature in composition and texture (sorting and clast rounding). The heavy mineralogy is dominated by chemically stable zircon and tourmaline and is similar to that of the Crocker Fan sandstones although grains are more rounded. Zircon varieties are also similar. These Lower Miocene sandstones appear to be recycled from the Paleogene turbidites with a short transport path. Relatively large proportions of chrome spinel (up to 8% of total heavy minerals) and the presence of pyroxene in otherwise very mature sandstones indicate input of fresh ophiolitic debris. Palaeocurrent data suggest transport from the SSW.

The Lower Miocene Kudat Formation of north Sabah is exposed on the north coast (Sulu Sea) of Borneo. The basal sandstones are compositionally and texturally the least mature sandstones studied. They contain abundant potassium feldspar and lithic clasts that suggest derivation from a nearby acid plutonic source. The heavy mineral assemblages are the most diverse of the Sabah sandstones (Fig. 12). They are dominated by garnet, with mostly unabraded zircon, tourmaline, unweathered apatite and rutile, appreciable amounts of chrome spinel, epidote, pyroxene, kyanite, and sillimanite, and small amounts of staurolite, corundum, sphene, monazite and olivine. The grains show very few signs of transport, and only limited chemical destruction has

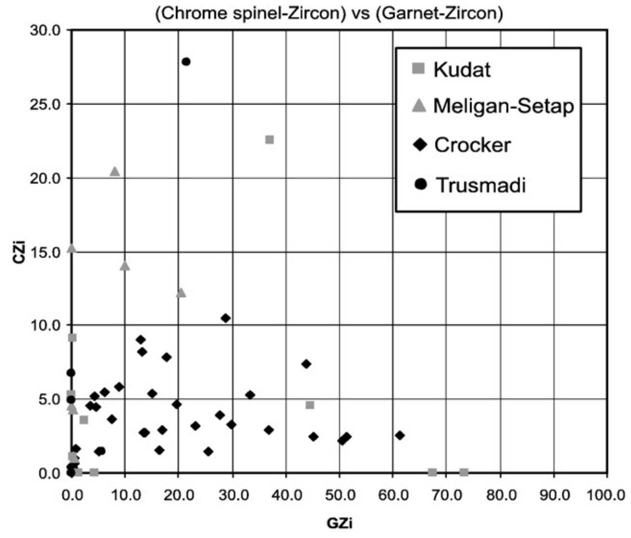

Fig. 12. Chrome spinel-zircon (CZi) vs Garnet-Zircon (GZi) index value diagram for Sabah sandstones. CZi indicates the amount of ophiolitic material relative to acid igneous material, GZi, indicates the amount of metamorphic material relative to acid igneous material. Throughout deposition of the Crocker Formation there was a small but steady input of ophiolitic material, and a variable input of metamorphic material.

occurred. The abundance of almandine garnet, up to almost half of the heavy mineral fraction in some samples, with epidote, kyanite, andalusite, sillimanite, amphibole and staurolite indicates an important metamorphic source. The high proportion of zircon, tourmaline and apatite indicate acid plutonic source rocks. Zircons are typically euhedral and subhedral with very few subrounded and rounded zircons. The heavy minerals suggest a nearby acid plutonic or metamorphic source, rather than sedimentary recycling. Limited palaeocurrent data from the Kudat Formation suggest a source area to the north (van Hattum, 2005).

There are few studies of the provenance of other Borneo clastic rocks and none with heavy mineral and geochronology data. Lower Miocene to Recent sandstones of the Kutei Basin record abundant volcanic activity in the Early Miocene with an increase during the earliest Middle Miocene; younger quartzose recycled sandstones record no volcanic activity (Tanean et al., 1996). In Sarawak, the Lower Miocene Nyalau Formation sandstones are compositionally mature sediments deposited under humid tropical conditions, considered to be recycled and derived mainly from the Rajang Group (Liaw, 1994) and their quartz-rich character has been interpreted as the result of recycling of older sediments. This is plausible but our studies in Borneo (van Hattum et al., 2006) and Java (Smyth et al., 2007) indicate that this conclusion needs to be treated cautiously without heavy mineral and textural data. Tropical weathering and acid volcanic input can both result in quartz-rich sediments that may be wrongly interpreted as mature recycled sandstones with a continental provenance.

4.5.3. Detrital zircon geochronology

Combination of light and heavy mineral studies with dating of detrital zircons can help to identify source areas. Zircons from north Borneo sandstones were dated by the SHRIMP (Sensitive High-Resolution Ion Microprobe) method and results are reported in van Hattum (2005) and van Hattum et al. (2006). There have been no previous dating studies of detrital zircons from Borneo.

Zircons in the Paleogene turbidite sandstones range in age (Fig. 13) from Eocene (49.9 ± 1.9 Ma) to Archaean

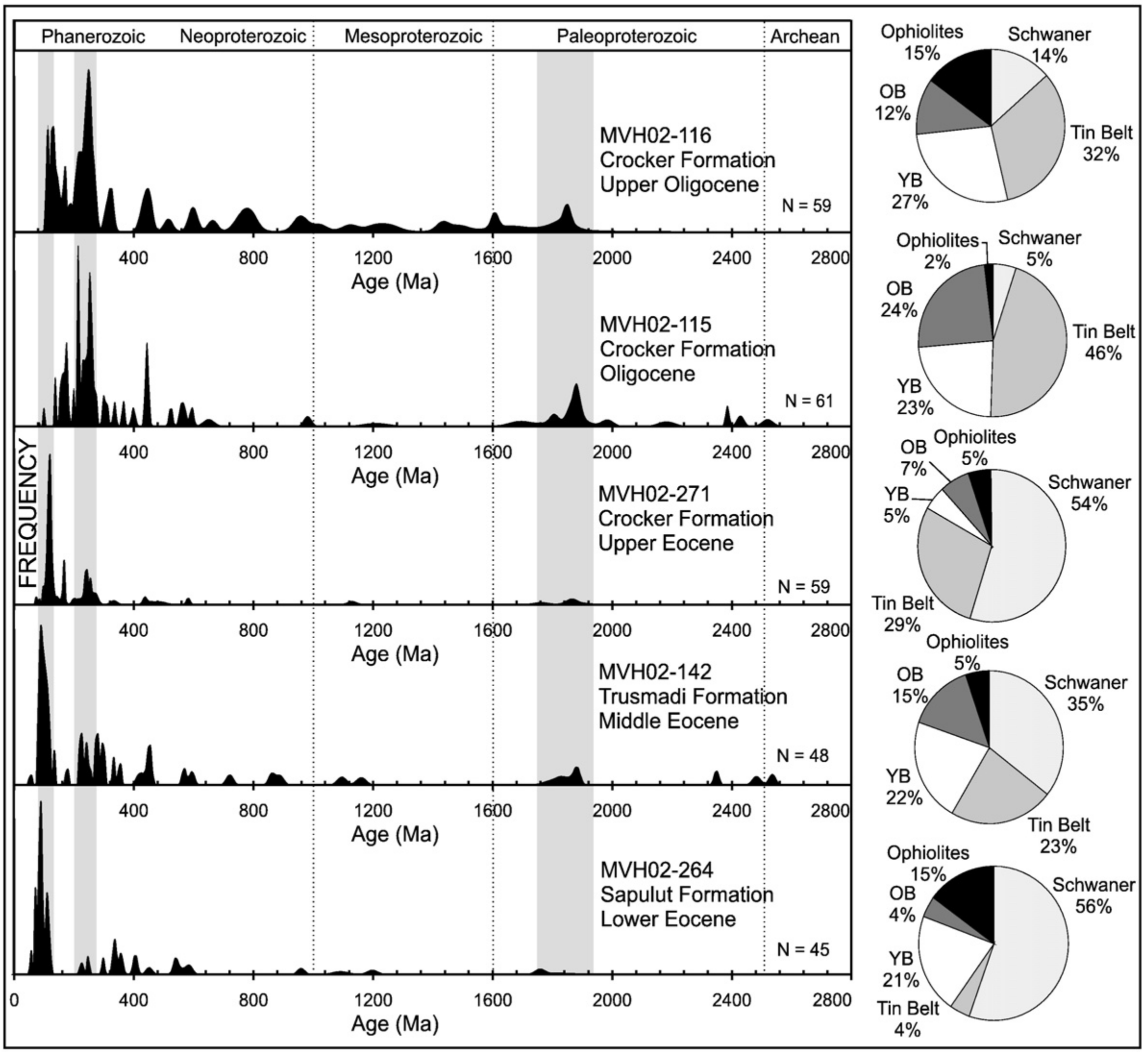

Fig. 13. Detrital zircon age probability plots for Sabah sandstones in stratigraphic order. Pie diagrams show inferred provenance, based on heavy mineral characteristics and principal component analysis of zircon ages. Schwaner = Borneo Cretaceous granites, Tin Belt = Malay-Thai Permian–Triassic granites, YB = Young Basement, OB = Old Basement, Ophiolites = Ophiolitic Basement.

(2531.6±11.2 Ma), the oldest radiometric age reported from Borneo. The most important age populations are Cretaceous (ca. 77–130 Ma), Permian–Triassic (ca. 213–268 Ma), and Paleoproterozoic (ca. 1750–1900 Ma). There are smaller Jurassic and Silurian–Ordovician populations. Eocene sandstones of the Upper Rajang Group contain Upper Cretaceous zircons with subordinate Carboniferous, Devonian and Silurian zircons; Permian–Triassic zircons are very rare. In the Eocene sandstones of the Crocker Fan Cretaceous zircons dominate. These are euhedral grains with no signs of abrasion, which suggests a nearby source area. Permian–Triassic zircons are more common than in the older sandstones. In the Oligocene samples Cretaceous zircons are less abundant and Permian–Triassic ages are common. In all the sandstones there is a relatively large number (10–38%) of Precambrian, especially Paleoproterozoic, zircons. These show a higher degree of rounding than the Cretaceous zircons.

Detrital zircons from the Kudat Formation indicate a different provenance (van Hattum, 2005). They are euhedral, unabraded and colourless with major Early Cretaceous (ca. 121 Ma) and Early Jurassic (ca. 181 Ma) populations. Jurassic zircons are relatively rare in other Sabah sandstones. There are small numbers of coloured and/or rounded zircons, which are mostly Precambrian and the oldest zircon is 2489±16 Ma.

4.5.4. Sources of Borneo sediments

Hutchison et al. (2000) and William et al. (2003) suggested north Borneo Eocene to Miocene Crocker Fan sandstones were recycled from the Rajang Group despite their textural immaturity. The abundance of unabraded zircons and tourmalines and the textural immaturity of the sandstones argues against a recycled source and makes it unlikely that material travelled very far. Obvious sources for the acid igneous and metamorphic material are the Cretaceous granites of the Schwaner Mountains, the Permian–Triassic granites of the Tin Belt, and the rocks into which they are intruded. Hutchison et al. (2000) ruled out the Schwaner Mountains as a possible source region because they argued that the Rajang Group of Sarawak was already uplifted in the Eocene and acting as a watershed. However, U-Pb dating of zircons from two granites in the Schwaner Mountains of SW Borneo has yielded ages between 80 and 87 Ma, very similar to those of zircons in the Eocene sandstones (van Hattum, 2005). Apatite fission track studies of Schwaner granites indicate rapid exhumation in the Late Cretaceous (Sumartadipura, 1976). The presence of cassiterite, which is brittle and easily destroyed during transport, suggests a Tin Belt source. Proterozoic zircons were derived from metasedimentary basement of the Thai–Malay Peninsula, or younger sediments into which they had been recycled. Apatite fission track data show rapid Oligocene (33–24 Ma) exhumation of Malay Peninsula Tin Belt granites (Krähenbuhl, 1991). Common chrome spinel, showing very little abrasion, was probably derived from the Mesozoic ophiolitic basement of north and east Borneo.

The sediment in Cenozoic Borneo basins came almost entirely from Borneo and nearby areas such as the Thai–Malay peninsula. Light and heavy mineral studies, zircon dating and palaeocurrent data show that during the Eocene, Cretaceous granites in the Schwaner Mountains and possibly the nearby Sunda Shelf contributed most sediment to the Crocker Fan (Fig. 14). During the Oligocene Tin Belt granites became increasingly important sources (Fig. 14). Throughout the Paleogene material eroded from nearby ophiolitic basement made a small but persistent contribution. During the Neogene the majority of clastic sediment was derived from local sources (Hall and Nichols, 2002). Most of the basins clearly build out from major rivers on Borneo. After the Early Miocene Sabah orogeny the deformed Paleogene sandstones became a new source of material. Sediment in the fluvio-deltaic and shallow marine sequences was derived mainly from the Central Borneo Mountains elevated by the arc-continent collision that terminated subduction of the Proto-South China Sea. The volcanic constituents of the Neogene sandstones of the Kutei Basin were derived from Borneo (van Leeuwen et al., 1990; van Leeuwen, 1994; Macpherson and Hall, 2002; Yan et al., 2006) or Java where there was major explosive acid volcanic activity in the Early Miocene (Smyth et al., 2007).

In the Early Miocene there was a contribution from outside Borneo and the Sunda Shelf, but sediment did not come from mainland Asia. The unusual heavy mineral assemblages, zircon ages and palaeocurrent directions from the Kudat Formation at the northern tip of Borneo suggest sandstones there were probably derived from the north where young granites, high grade metamorphic rocks and ophiolites were elevated by arc-continent collision on Palawan (Encarnacion et al., 1995; Encarnacion and Mukasa, 1997).

During the Cenozoic there is no need to advocate transport of material from the India–Asia collision zone to account for sediment supplied to Borneo and the Sunda Shelf basins (e.g. Clift et al., 2004; Clift, 2006) since areas much closer, such as Borneo and the Thai–Malay peninsula, and briefly Palawan, were elevated and shedding sediment. There is increasing evidence that much of Sundaland was elevated and eroding during the Late Cretaceous and Early Cenozoic, and certainly by the Middle Eocene was a source of sediment deposited in basins in and around Borneo including West Java (Clements and Hall, 2007), offshore East Java (Matthews and Bransden, 1995), SE Borneo (Siregar and Sunaryo, 1980) and East Borneo (Moss and Chambers, 1999). The volume of the Rajang Group sediments (Hutchison, 2005) indicates that SW Borneo was an important source in the Cretaceous, long before the onset of India–Asia collision. Furthermore, even after collision began, there were extensive and long-lived shallow marine carbonate platforms such as the Luconia Platform separating Borneo from Indochina, across which there could have been no significant clastic sediment transport. In other areas the many extensional basins on the Sunda Shelf trapped sediment coming off Indochina (Morley, 2002; Hall and Morley, 2004). Prior to uplift of the Tibetan plateau at 13–9 Ma (Clark et al., 2005), the Mekong and Salween were less important rivers than they are today, and much of the sediment from Tibet now carried south by them was transported to the Gulf of Tonkin by the palaeo-Red River. Any sediment carried south from the collision zone would also have been trapped in the Thailand basins far to the north of Borneo (Hall and Morley, 2004) until the Late Miocene

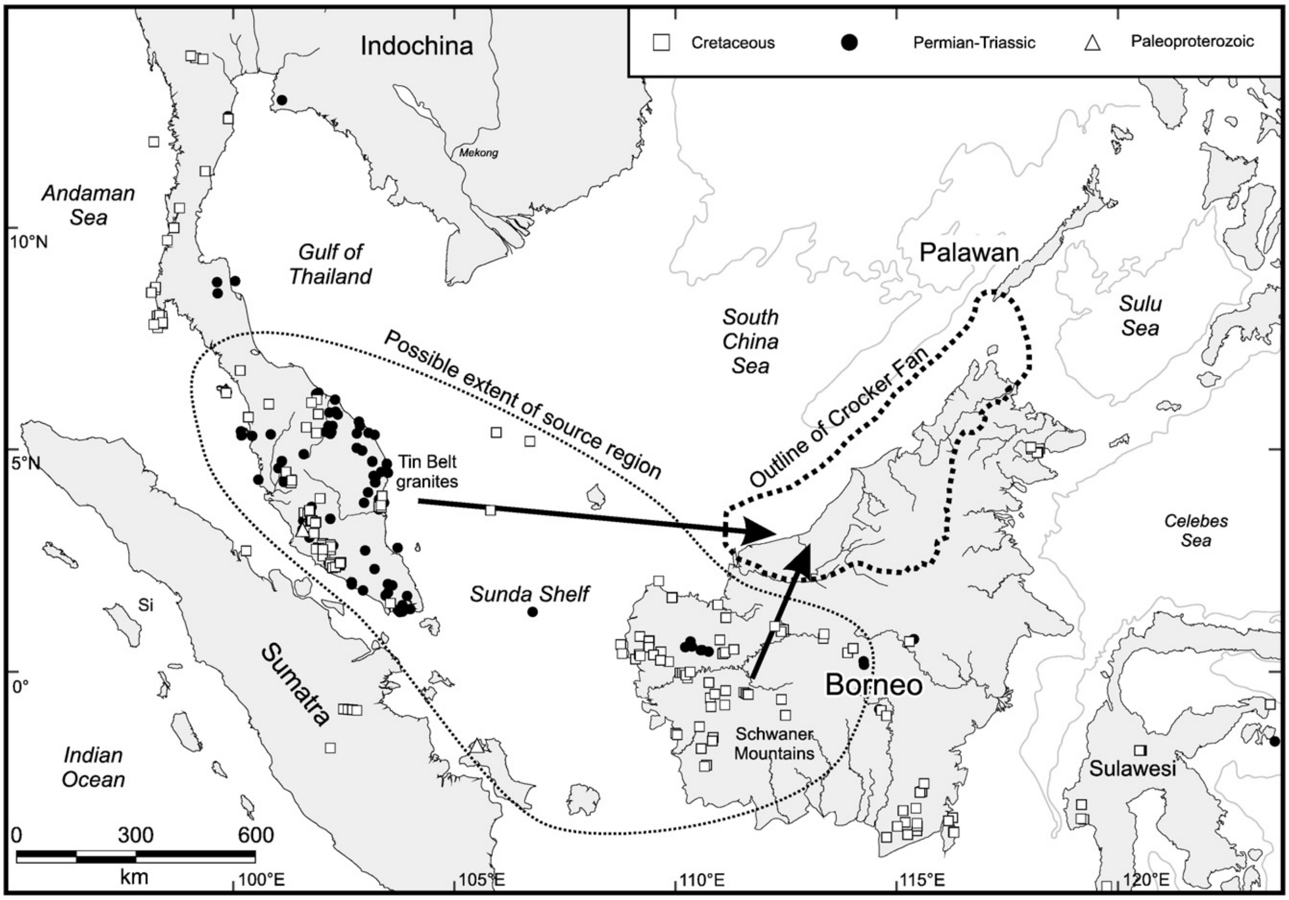

Fig. 14. Provenance of sediment supplied to the Crocker Fan. The Schwaner Mountains was the dominant source area in the Eocene and there was an increasing contribution from the Tin belt granites in the Oligocene. The map shows radiometric ages corresponding to the main detrital zircon SHRIMP U-Pb age groups identified in Crocker Fan sedimentary rocks. Phanerozoic ages (Haile et al., 1977; Suwarna et al., 1989; Williams et al., 1988, 1989; de Keyser and Rustandi, 1993; Wikarno et al., 1993) are based on K-Ar, Rb-Sr, Ar-Ar, U-Pb, Pb-Pb, Sm-Nd and Nd-Sr methods. Precambrian ages are based on Sm-Nd analyses (Liew and McCulloch, 1985).

when drainage changes in Asia produced the major south-flowing rivers (Clark et al., 2004) which now carry material to the Sunda Shelf.

5. Conclusions

Borneo has a complex Cenozoic geological history. Around the island are numerous basins with thick sedimentary sequences which formed in a variety of tectonic settings. There was southward subduction of the Proto-South China Sea during the Paleogene beneath north Borneo and rifting in the east to form the Makassar Straits, while there was complex rifting and extension of the continental Sunda Shelf south, west and northwest of the island. After Early Miocene arc-continent collision in north Borneo there was orogeny and uplift in central Borneo, and inversion of older sedimentary basins which were cannibalized to provide sediment to deep offshore basins in the Makassar Straits, and at the continental margins of the Celebes, Sulu and South China Seas. New subduction beneath the Dent and Semporna peninsulas of NE Borneo probably began in the Middle Miocene and ceased in the Pliocene.

The geological history of Borneo is not consistent with the island simply forming part of a large SE Asia block extruded from Asia following India collision. The large clockwise rotations and movements predicted by the indentor model for Borneo are incompatible with palaeomagnetic evidence. There remains doubt if the large strike–slip faults of Indochina and China continue offshore and there is no evidence that they reach Borneo. The lower mantle high velocity anomaly interpreted as subducted lithosphere can be explained at least as well by alternative tectonic models as by the indentor model. Fig. 15 summarises the tectonic model preferred here at key time periods. Very great thicknesses of Cenozoic sediments are found in the Borneo and circum-Borneo basins but all evidence indicates that these sediments were derived from local sources and not from distant sources in Asia elevated by India–Asia collision. In and around Borneo there are large volumes of clastic sediment eroded and deposited before India–Asia collision. West Borneo was elevated after collision at the southeast Sundaland subduction margins in the Late Cretaceous and Paleogene sediment in the Crocker Fan came from west Borneo and the Thai–Malay peninsula. After Early Miocene

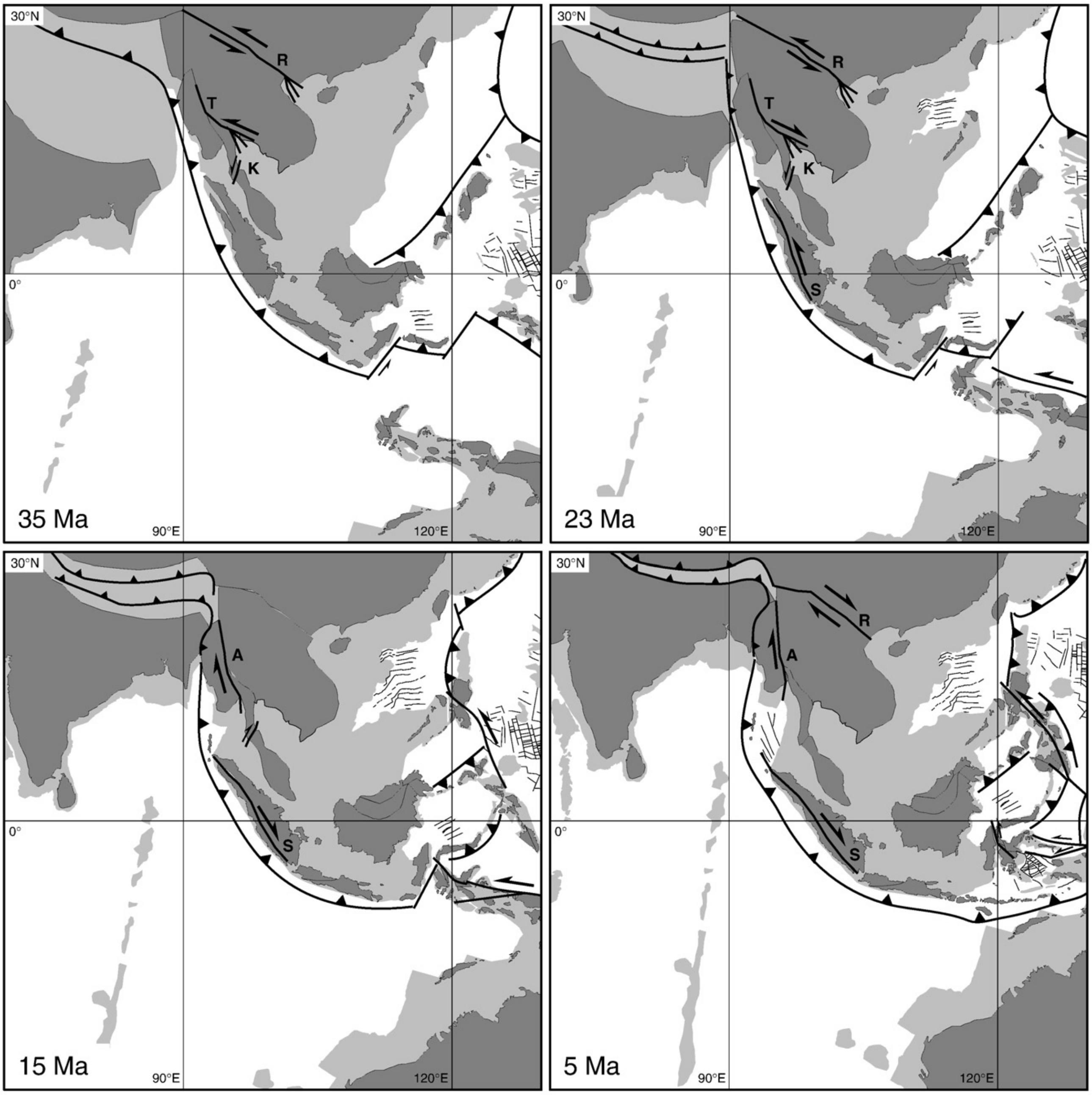

Fig. 15. Reconstructions of the Sundaland region at 35 Ma, 23 Ma, 15 Ma and 5 Ma based on Hall (2002). At 35 Ma India–Asia collision was underway and extrusion of Indochina began by sinistral movement along the Red River (R) Fault and sinistral movement along the Three Pagodas-Mae Ping (T) Faults. Both fault zones are interpreted to terminate in splay systems close to the coast or just offshore. There was sinistral movement on the Ranong–Klong Marui (K) Fault system. At 23 Ma collision with Australia began in east Indonesia and widespread plate reorganization began. The Red River Fault remained sinistral but movement direction changed to dextral on the Three Pagodas-Mae Ping Faults. Dextral movement on the Sumatran Fault (S) began. At 15 Ma movement on the Red River Fault ceased. Dextral movement on the Sumatran and Sagaing Faults was linked via extension in the Andaman Sea. At 5 Ma there was dextral movement on the Red River Fault, the Sumatran and Sagaing Faults and oceanic spreading was underway in the Andaman Sea.

collision in north Borneo Neogene sediment was almost entirely derived from Borneo, with a contribution from explosive volcanic activity in northeast and central Borneo, and possibly Java, and minor input from Palawan.

Sundaland, in which Borneo is situated, is an unusual continental region characterized by high heat flow, a thin elastic thickness for the lithosphere, and very high sediment yields with unusually low velocities at shallow depths in the mantle. Borneo is in part the direct result of subduction and collision, and in part an indirect product of Cenozoic deformation in response to changing forces at the plate edges, driven by long-term subduction, acting on a very weak and probably thin Sundaland lithosphere (Hall and Morley, 2004; Hyndman et al., 2005). There is little to indicate that India–Asia collision has influenced the Cenozoic geological record in Borneo. If the collision age of about 35 Ma suggested by Aitchison et al.

(2007) is correct, tectonic events in the Borneo region are even less likely to be related to India–Asia collision.

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References

Ahrendt, H., Hansen, B.T., Lumjuan, A., Mickein, A., Wemmer, K., 1997. Tectonometamorphic evolution of NW-Thailand deduced from U/Pb, Rb/Sr, Sm/Nd and K/Ar isotope investigations. Proceedings of the International Conference on Stratigraphy and Tectonic Evolution in Southeast Asia and the South Pacific and the Associated meetings of the IGCP 359 and IGCP 383, pp. 314–319. Bangkok, Thailand.

Aitchison, J.C., Davis, A.M., 2004. Evidence for the multiphase nature of the India–Asia collision from the Yarlung Tsangpo suture zone, Tibet. In: Malpas, J.G., Fletcher, C.J.N., Ali, J.R., Aitchison, J.C. (Eds.), Aspects of the Tectonic Evolution of China. Geological Society London Special Publication, vol. 226, pp. 217–234.

Aitchison, J.C., Ali, J.R., Davis, A.M., 2007. When and where did India and Asia collide? Journal of Geophysical Research 112, B05423. doi:10.1029/2006JB004706.

Ali, J.R., Aitchison, J.C., 2005. Greater India. Earth-Science Reviews 72, 169–188.

Balaguru, A., 2001. Tectonic evolution and sedimentation of the southern Sabah Basin, Malaysia. Ph.D. Thesis, University of London, 418 pp.

Balaguru, A., Nichols, G.J., 2004. Tertiary stratigraphy and basin evolution, southern Sabah (Malaysian Borneo). Journal of Asian Earth Sciences 23, 537–5554.

Balaguru, A., Nichols, G.J., Hall, R., 2003. The origin of the circular basins of Sabah, Malaysia. Geological Society of Malaysia Bulletin 46, 335–351.

Barber, A.J., Crow, M.J., in press. The structure of Sumatra and its implications for the tectonic assembly of Southeast Asia and the destruction of PaleoTethys. Island Arc.

Beckinsale, R.D., 1979. Granite magmatism in the tin belt of SE Asia. In: Atherton, M.P., Tarney, J. (Eds.), Origin of Granite Batholiths, Geochemical Evidence. Shiva Publications, Orpington, UK, pp. 33–44.

Beckinsale, R.D., Suensilpong, S., Nakapadungrat, S., Walsh, J.N., 1979. Geochronology and geochemistry of granite magmatism in Thailand in relation to a plate tectonic model. Journal of the Geological Society of London 136, 529–540.

Besse, J., Courtillot, V., 1991. Revised and synthetic polar wander maps of the African, Eurasian, North American and Indian Plates, and true polar wander since 200 Ma. Journal of Geophysical Research 96, 4029–4050.

Bijwaard, H., Spakman, W., 2000. Nonlinear global P-wave tomography by iterated linearized inversion. Geophysical Journal International 141, 71–82.

Bijwaard, H., Spakman, W., Engdahl, E.R., 1998. Closing the gap between regional and global travel time tomography. Journal of Geophysical Research 103, 30055–30078.

Blanche, J.B., Blanche, J.D., 1997. An overview of the hydrocarbon potential of the Spratly Islands archipelago and its implications for regional development. In: Fraser, A.J., Matthews, S.J., Murphy, R.W. (Eds.), Petroleum Geology of SE Asia. Geological Society London Special Publication, vol. 126, pp. 293–310.

Bock, Y., Prawirodirdjo, L., Genrich, J.F., Stevens, C.W., McCaffrey, R., Subarya, C., Puntodewo, S.S.O., Calais, E., 2003. Crustal motion in Indonesia from Global Positioning System measurements. Journal of Geophysical Research 108, 2367. doi:10.1029/2001JB000324.

Briais, A., Patriat, P., Tapponnier, P., 1993. Updated interpretation of magnetic anomalies and sea floor spreading stages in the South China Sea: implications for the Tertiary tectonics of Southeast Asia. Journal of Geophysical Research 98, 6299–6328.

Burollet, P.F., Salle, C., 1981. Seismic reflection profiles in the Makassar Strait. In: Barber, A.J., Wiryosujono, S. (Eds.), The Geology and Tectonics of Eastern Indonesia, Special Publication Geological Research and Development Centre, Bandung, Indonesia, pp. 273–276.

Cardwell, R.K., Isacks, B.L., 1978. Geometry of the subducted lithosphere beneath the Banda Sea in eastern Indonesia from seismicity and fault plane solutions. Journal of Geophysical Research 83, 2825–2838.

Carter, A., Moss, S.J., 1999. Combined detrital-zircon fission-track and U-Pb dating: a new approach to understanding hinterland evolution. Geology 27, 235–238.

Chambers, J.L.C., Daley, T.E., 1997. A tectonic model for the onshore Kutai Basin, East Kalimantan. In: Fraser, A.J., Matthews, S.J., Murphy, R.W. (Eds.), Petroleum Geology of Southeast Asia. Special Publication, vol. 126. Geological Society of London, pp. 375–393.

Chiang, K.K., 2002. Geochemistry of the Cenozoic Igneous Rocks of Borneo and Tectonic Implications. Ph.D. Thesis, University of London, 364 pp.

Clark, M.K., Schoenbohm, L.M., Royden, L.H., Whipple, K.X., Burchfiel, B.C., Zhang, X., Tang, W., Wang, E., Chen, L., 2004. Surface uplift, tectonics, and erosion of eastern Tibet from large-scale drainage patterns. Tectonics 23. doi:10.1029/2002TC001402.

Clark, M.K., House, M.A., Royden, L.H., Whipple, K.X., Burchfiel, B.C., Zhang, X., Tang, W., 2005. Late Cenozoic uplift of southeastern Tibet. Geology 33, 525–528.

Clements, B., Hall, R., 2007. Cretaceous to Late Miocene stratigraphic and tectonic evolution of West Java. Proceedings Indonesian Petroleum Association 31st Annual Convention, Jakarta.

Clift, P.D., 2006. Controls on the erosion of Cenozoic Asia and the flux of clastic sediment to the ocean. Earth and Planetary Science Letters 241, 571–580.

Clift, P.D., Sun, Z., 2006. The sedimentary and tectonic evolution of the Yinggehai–Song Hong Basin and the southern Hainan margin, South China Sea; implications for Tibetan uplift and monsoon intensification. Journal of Geophysical Research 111, B06405. doi:10.1029/2005JB004048.

Clift, P.D., Layne, G.D., Blusztajn, J., 2004. Marine sedimentary evidence for monsoon strengthening, Tibetan uplift and drainage evolution in East Asia. In: Clift, P., Wang, P., Kuhnt, W., Hayes, D.E. (Eds.), Continent–Ocean Interactions within the East Asian Marginal Seas. Geophysical Monograph, vol. 149. American Geophysical Union, Washington, D.C., pp. 255–282.

Cloke, I.R., Milsom, J., Blundell, D.J.B., 1999. Implications of gravity data from east Kalimantan and the Makassar Straits: a solution to the origin of the Makassar Straits? Journal of Asian Earth Sciences 17, 61–78.

Cobbing, E.J., Pitfield, P.E.J., Darbyshire, D.P.F., Mallick, D.I.J., 1992. The granites of the South-East Asian tin belt. Overseas Memoir of the British Geological Survey, vol. 10. 369 pp.

Cole, J.M., Crittenden, S., 1997. Early Tertiary basin formation and the development of lacustrine and quasi-lacustrine/marine source rocks on the Sunda Shelf of SE Asia. In: Fraser, A.J., Matthews, S.J., Murphy, R.W. (Eds.), Petroleum Geology of SE Asia. Geological Society London Special Publication, vol. 126, pp. 147–183.

Collenette, P., 1958. The geology and mineral resources of the Jesselton–Kinabalu area, North Borneo. Malaysia Geological Survey Borneo Region, Memoir, vol. 6. 194 pp.

Crevello, P.D., 2001. The great Crocker submarine fan: a world-class foredeep turbidite system. Proceedings Indonesian Petroleum Association 28th Annual Convention, Jakarta, pp. 378–407.

de Keyser, F., Rustandi, E., 1993. Geology of the Ketapang Sheet area, Kalimantan. Geological Research and Development Centre, Bandung, Indonesia.

Dhonau, T.J., Hutchison, C.S., 1966. The Darvel Bay area, east Sabah, Malaysia. Malaysia Geological Survey Borneo Region, Annual Report for 1965, 141–160.

Dickinson, W.R., Beard, L.S., Brakenridge, G.R., Erjavic, J.L., Ferguson, R.C., Inman, K.F., Knepp, R.A., Lindeberg, F.A., Ryberg, P.T., 1983. Provenance of North American Phanerozoic sandstones in relation to tectonic setting. Geological Society of America Bulletin 94, 222–235.

Dunning, G.R., Macdonald, A.S., Barr, S.M., 1995. Zircon and monazite U-Pb dating of the Doi Inthanon core complex, northern Thailand: implications for extension within the Indosinian orogen. Tectonophysics 251, 197–215.

Encarnación, J., Mukasa, S.B., 1997. Age and geochemistry of an "anorogenic" crustal melt and implications for I-type granite petrogenesis. Lithos 42, 1–13.

Encarnación, J.P., Essene, E.J., Mukasa, S.B., Hall, C.H., 1995. High-pressure and -temperature subophiolitic kyanite-garnet amphibolites generated during initiation of Mid-Tertiary subduction, Palawan, Philippines. Journal of Petrology 36, 1481–1503.

Engdahl, E.R., van der Hilst, R., Buland, R., 1998. Global teleseismic earthquake relocation with improved travel times and procedures for depth determination. Seismological Society of America Bulletin 88, 722–743.

Ferguson, A., McClay, K., 1997. Structural modelling within the Sanga Sanga PSC, Kutei Basin, Kalimantan: its implication to paleochannel orientation studies and timing of hydrocarbon entrapment. In: Howes, J.V.C., Noble, R.A. (Eds.), Proceedings of the International Conference on Petroleum Systems of SE Asia and Australia, Indonesian Petroleum Association, pp. 727–743.

Fuller, M., Haston, R., Jin-lu, Lin, Richter, B., Schmidtke, E., Almasco, J., 1991. Tertiary paleomagnetism of regions around the South China Sea. Journal of Southeast Asian Earth Sciences 6, 161–184.

Fuller, M., Ali, J.R., Moss, S.J., Frost, G.M., Richter, B., Mahfi, A., 1999. Paleomagnetism of Borneo. Journal of Asian Earth Sciences 17, 3–24.

Graves, J.E., Swauger, D.A., 1997. Petroleum systems of the Sandakan Basin, Philippines. In: Howes, J.V.C., Noble, R.A. (Eds.), Proceedings of the International Conference on Petroleum Systems of SE Asia and Australia, Indonesian Petroleum Association, pp. 799–813.

Guntoro, A., 1999. The formation of the Makassar Strait and the separation between SE Kalimantan and SW Sulawesi. Journal of Asian Earth Sciences 17, 79–98.

Hafkenscheid, E., Buiter, S.J., Wortel, M.J., Spakman, W., Bijwaard, H., 2001. Modelling the seismic velocity structure beneath Indonesia: a comparison with tomography. Tectonophysics 333, 35–46.

Haile, N.S., 1969. Geosynclinal theory and the organizational pattern of the North-west Borneo geosyncline. Quarterly Journal of the Geological Society of London 124, 171–194.

Haile, N.S., 1979. Rotation of Borneo microplate completed by Miocene: palaeomagnetic evidence. Warta Geologi, Geological Society of Malaysia Newsletter 5, 19–22.

Haile, N.S., McElhinny, M.W., McDougall, I., 1977. Palaeomagnetic data and radiometric ages from the Cretaceous of West Kalimantan (Borneo), and their significance in interpreting regional structure. Journal of the Geological Society of London 133, 133–144.

Hall, R., 1996. Reconstructing Cenozoic SE Asia. In: Hall, R., Blundell, D.J. (Eds.), Tectonic Evolution of SE Asia. Geological Society London Special Publication, vol. 106, pp. 153–184.

Hall, R., 2002. Cenozoic geological and plate tectonic evolution of SE Asia and the SW Pacific: computer-based reconstructions, model and animations. Journal of Asian Earth Sciences 20, 353–434.

Hall, R., Wilson, M.E.J., 2000. Neogene sutures in eastern Indonesia. Journal of Asian Earth Sciences 18, 787–814.

Hall, R., Nichols, G.J., 2002. Cenozoic sedimentation and tectonics in Borneo: climatic influences on orogenesis. In: Jones, S.J., Frostick, L. (Eds.), Sediment Flux to Basins: causes, Controls and Consequences. Geological Society London Special Publication, vol. 191, pp. 5–22.

Hall, R., Morley, C.K., 2004. Sundaland Basins. In: Clift, P., Wang, P., Kuhnt, W., Hayes, D.E. (Eds.), Continent–Ocean Interactions within the East Asian Marginal Seas. Geophysical Monograph, vol. 149. American Geophysical Union, Washington, D.C., pp. 55–85.

Hamilton, W., 1979. Tectonics of the Indonesian region. U.S. Geological Survey Professional Paper 1078. 345 pp.

Hazebroek, H.P., Tan, D.N.K., 1993. Tertiary tectonic evolution of the NW Sabah continental margin. Geological Society of Malaysia Bulletin 33, 195–210.

Heine, C., Müller, R.D., Gaina, C., 2004. Reconstructing the lost Eastern Tethys Ocean Basin: constraints for the convergence history of the SE Asian margin and marine gateways. In: Clift, P., Wang, P., Kuhnt, W., Hayes, D.E. (Eds.), Continent–Ocean Interactions within the East Asian Marginal Seas. Geophysical Monograph, vol. 149. American Geophysical Union, Washington, D.C., pp. 37–54.

Hinz, K., Block, M., Kudrass, H.R., Meyer, H., 1991. Structural elements of the Sulu Sea, Philippines. Geologisches Jahrbuch, Reihe A 127, 483–506.

Holloway, N.H., 1982. The stratigraphic and tectonic evolution of Reed Bank, North Palawan and Mindoro to the Asian mainland and its significance in the evolution of the South China Sea. American Association of Petroleum Geologists Bulletin 66, 1357–1383.

Huchon, P., Nguyen, T.N.H., Chamot-Rooke, N., 1998. Finite extension across the South Vietnam basins from 3D gravimetric modelling: relation to South China Sea kinematics. Marine and Petroleum Geology 15, 619–634.

Hutchison, C.S., 1989. Geological Evolution of South-East Asia, 13. Oxford Monographs on Geology and Geophysics. Clarendon Press. 376 pp.

Hutchison, C.S., 1996. The "Rajang Accretionary Prism" and "Lupar Line" problem of Borneo. In: Hall, R., Blundell, D.J. (Eds.), Tectonic Evolution of SE Asia. Geological Society London Special Publication, vol. 106, pp. 247–261.

Hutchison, C.S., 2004. Marginal basin evolution: the southern South China Sea. Marine and Petroleum Geology 21, 1129–1148.

Hutchison, C.S., 2005. Geology of North-West Borneo. Elsevier. 444 pp.

Hutchison, C.S., Bergman, S.C., Swauger, D.A., Graves, J.E., 2000. A Miocene collisional belt in north Borneo: uplift mechanism and isostatic adjustment quantified by thermochronology. Journal of the Geological Society of London 157, 783–793.

Hyndman, R.D., Currie, C.A., Mazzotti, S., 2005. Subduction zone backarcs, mobile belts, and orogenic heat. GSA Today 15 (2), 4–9.

Jacobson, G., 1970. Geology and mineral resources of the Gunong Kinabalu Area, Sabah, E. Malaysia. Geological Survey of Malaysia Report 8. 111 pp.

James, D.M.D., 1984. Regional geological setting. In: James, D.M.D. (Ed.), The Geology and Hydrocarbon Resources of Negara Brunei Darussalam, Brunei Museum and Brunei Shell Petroleum Company, pp. 34–42.

Kárason, H., van der Hilst, R.D., 2001. Tomographic imaging of the lowermost mantle with differential times of refracted and diffracted core phases (PKP, Pdiff). Journal of Geophysical Research 106, 6569–6588. doi:10.1029/2000JB900380.

Kirk, H.J.C., 1968. The igneous rocks of Sarawak and Sabah. Bulletin, vol. 5. Geological Survey of Malaysia, Borneo Region. 210 pp.

Koopmans, B.N., 1967. Deformation of the metamorphic rocks and the Chert–Spilite Formation in the southern part of the Darvel Bay area, Sabah. Geological Survey of Malaysia, Borneo Region, Bulletin 8, 14–24.

Krähenbuhl, R., 1991. Magmatism, tin mineralization and tectonics of the Main Range, Malaysian Peninsula: consequences for the plate tectonic model of Southeast Asia based on Rb-Sr, K-Ar and fission track data. Geological Society of Malaysia Bulletin 29, 1–100.

Kreemer, C., Holt, W.E., Goes, S., Govers, R., 2000. Active deformation in eastern Indonesia and the Philippines from GPS and seismicity data. Journal of Geophysical Research 105, 663–680.

Kwan, T.S., Krähenbuhl, R., Jager, E., 1992. Rb-Sr, K-Ar and fission-track ages for granites from Penang Island, West Malaysia- an interpretation model for Rb-Sr whole-rock and for actual and experimental mica data. Contributions to Mineralogy and Petrology 111, 527–542.

Lacassin, R., Maluski, H., Leloup, P.H., Tapponnier, P., Hinthong, C., Siribhakdi, K., Chuaviroj, S., Charoenravat, A., 1997. Tertiary diachronic extrusion and deformation of western Indochina: structural and ^{40}Ar/^{39}Ar evidence from NW Thailand. Journal of Geophysical Research 102, 10,013–10,037.

Leech, M.L., Singh, S., Jain, A.K., Klemperer, S.L., Manickavasagam, R.M., 2005. The onset of India–Asia collision: early, steep subduction required by the timing of UHP metamorphism in the western Himalaya. Earth and Planetary Science Letters 234, 83–97.

Lee, T.Y., Lawver, L.A., 1994. Cenozoic plate reconstruction of the South China Sea region. Tectonophysics 235, 149–180.

Lee, T.Y., Lawver, L.A., 1995. Cenozoic plate reconstruction of southeast Asia. Tectonophysics 251, 85–139.

Leloup, P.H., Lacassin, R., Tapponnier, P., Schärer, U., Zhong, D.L., Liu, X.H., Zhang, L.S., Ji, S.C., Trinh, P.T., 1995. The Ailao Shan–Red River shear zone (Yunnan, China), Tertiary transform boundary of Indochina. Tectonophysics 251, 3–84.

Leloup, P.H., Arnaud, N., Lacassin, R., Kienast, J.R., Harrison, T.M., Trong, T.T.P., Replumaz, A., Tapponnier, P., 2001. New constraints on the structure, thermochronology, and timing of the Ailao Shan–Red River shear zone, SE Asia. Journal of Geophysical Research 106, 6683–6732.

Leong, K.M., 1974. The geology and mineral resources of Upper Segama valley and Darvel Bay, Sabah. Malaysia Geological Survey Borneo Region Memoir 4. 354 pp.

Levell, B.K., 1987. The nature and significance of regional unconformities in the hydrocarbon-bearing Neogene sequences offshore west Sabah. Geological Society of Malaysia Bulletin 21, 55–90.

Liaw, K.K., 1994. Stratigraphy, sedimentology, coal geology and depositional environment of the Miocene Nyalau Formation, Merit-Pila Coalfield, Sarawak (Malaysia). Ph.D. Thesis, Universität Fridericana Karlsruhe, 284 pp.

Liew, T.C., McCulloch, M.T., 1985. Genesis of granitoid batholiths of Peninsular Malaysia and implications for models of crustal evolution: evidence from Nd-Sr isotopic and U-Pb zircon study. Geochimica et Cosmochimica Acta 49, 587–600.

Liew, T.C., Page, R.W., 1985. U-Pb zircon dating of granitoid plutons from the West Coast of Peninsular Malaysia. Journal of the Geological Society of London 142, 515–526.

Liu, H., Yan, P., 2004. Tectonic-stratigraphic division and blind fold structures in Nansha Waters, South China Sea. Journal of Asian Earth Sciences 24, 337–348.

Liu, H., Yan, P., Zhang, B., Sun, Y., Zhang, Y., Shu, L., Qiu, X., Guo, L., 2004. Role of the Wan-Na fault system in the western Nansha Islands (Southern South China Sea). Journal of Asian Earth Sciences 23, 221–233.

Lumadyo, E., McCabe, R., Harder, S., Lee, T., 1993. Borneo: a stable portion of the Eurasian margin since the Eocene. Journal of Southeast Asian Earth Sciences 8, 225–231.

Macpherson, C.G., Hall, R., 2002. Timing and tectonic controls in the evolving orogen of SE Asia and the western Pacific and some implications for ore generation. In: Blundell, D.J., Neubauer, F., von Quadt, A. (Eds.), The Timing and Location of Major Ore Deposits in an Evolving Orogen. Geological Society London Special Publication, vol. 204, pp. 49–67.

Mange, M.A., Maurer, H.F.W., 1992. Heavy Minerals in Colour. Chapman & Hall, London. 147 pp.

Mason, A.D.M., Haebig, J.C., McAdoo, R.L., 1993. A fresh look at the Barito Basin, Kalimantan. Proceedings Indonesian Petroleum Association 22nd Annual Convention, Jakarta, pp. 589–606.

Matthews, S.J., Bransden, P.J.E., 1995. Late Cretaceous and Cenozoic tectono-stratigraphic development of the East Java Sea Basin, Indonesia. Marine and Petroleum Geology 12, 499–510.

McCaffrey, R., 1996. Slip partitioning at convergent plate boundaries of SE Asia. In: Hall, R., Blundell, D.J. (Eds.), Tectonic Evolution of SE Asia. Geological Society London Special Publication, vol. 106, pp. 3–18.

McClay, K., Dooley, T., Ferguson, A., Poblet, J., 2000. Tectonic evolution of the Sanga Sanga Block, Mahakam Delta, Kalimantan, Indonesia. American Association of Petroleum Geologists Bulletin 84, 765–786.

McGilvery, T.A., Cook, D.L., 2003. The influence of local gradients on accommodation space and linked depositional elements across a stepped slope profile, offshore Brunei. In: Roberts, H.R., Rosen, N.C., Fillon, R.F., Anderson, J.B. (Eds.), Shelf Margin Deltas and Linked Down Slope Petroleum Systems: global Significance and Future Exploration Potential. GCS SEPM (Gulf Coast Section of the SEPM), pp. 387–419.

Metcalfe, I., 1996. Pre-Cretaceous evolution of SE Asian terranes. In: Hall, R., Blundell, D.J. (Eds.), Tectonic Evolution of SE Asia. Geological Society London Special Publication, vol. 106, pp. 97–122.

Métivier, F., Gaudemer, Y., Tapponnier, P., Klein, M., 1999. Mass accumulation rates in Asia during the Cenozoic. Geophysical Journal International 137, 280–318.

Mitchell, A.H.G., 1993. Cretaceous–Cenozoic tectonic events in the western Myanmar (Burma)–Assam region. Journal of the Geological Society of London 150, 1089–1102.

Molnar, P., Tapponnier, P., 1975. Cenozoic tectonics of Asia: effects of a continental collision. Science 189, 419–426.

Morley, C.K., 2001. Combined escape tectonics and subduction rollback-backarc extension: a model for the Tertiary rift basins in Thailand, Malaysia and Laos. Journal of the Geological Society of London 158, 461–474.

Morley, C.K., 2002. A tectonic model for the Tertiary evolution of strike–slip faults and rift basins in SE Asia. Tectonophysics 347, 189–215.

Morley, C.K., 2004. Nested strike–slip duplexes, and other evidence for Late Cretaceous–Palaeogene transpressional tectonics before and during India–Eurasia collision, in Thailand, Myanmar and Malaysia. Journal of the Geological Society of London 161, 799–812.

Morley, C.K., 2007. Variations in Late Tertiary–Recent strike–slip and oblique-extensional geometries within Indochina: the influence of pre-existing fabrics. Journal of Structural Geology 29, 36–58.

Morley, C.K., Back, S., van Rensbergen, P., Crevello, P., Lambiase, J.J., 2003. Characteristics of repeated, detached, Miocene–Pliocene tectonic inversion events, in a large delta province on an active margin, Brunei Darussalam, Borneo. Journal of Structural Geology 25, 1147–1169.

Morley, C.K., Smith, M., Carter, A., Charusiri, P., Chantraprasert, S., 2007. Evolution of deformation styles at a major restraining bend, constraints from cooling histories, Mae Ping fault zone, western Thailand. In: Cunningham, W.D., Mann, P. (Eds.), Tectonics of Strike-Slip Restraining and Releasing Bends. Geological Society London Special Publication, vol. 290, pp. 325–349.

Morton, A.C., 1984. Stability of detrital heavy minerals in Tertiary sandstones from the North Sea basin. Clay Minerals 19, 287–308.

Moss, S.J., 1998. Embaluh group turbidites in Kalimantan: evolution of a remnant oceanic basin in Borneo during the Late Cretaceous to Palaeogene. Journal of the Geological Society 155, 509–524.

Moss, S.J., Chambers, J.L.C., 1999. Tertiary facies architecture in the Kutai Basin, Kalimantan, Indonesia. Journal of Asian Earth Sciences 17, 157–181.

Moss, S.J., Chambers, J., Cloke, I., Carter, A., Satria, D., Ali, J.R., Baker, S., 1997. New observations on the sedimentary and tectonic evolution of the Tertiary Kutai Basin, East Kalimantan. In: Fraser, A.J., Matthews, S.J., Murphy, R.W. (Eds.), Petroleum Geology of Southeast Asia. Geological Society London Special Publication, vol. 126, pp. 395–416.

Moss, S.J., Carter, A., Baker, S., Hurford, A.J., 1998. A Late Oligocene tectono–volcanic event in East Kalimantan and the implications for tectonics and sedimentation in Borneo. Journal of the Geological Society 155, 177–192.

Noad, J.J., 1998. The sedimentary evolution of the Tertiary of Eastern Sabah, Northern Borneo. Ph.D. Thesis, University of London, 456 pp.

Nur'Aini, S., Hall, R., Elders, C.F., 2005. Basement architecture and sedimentary fills of the North Makassar Straits basin. Proceedings Indonesian Petroleum Association 30th Annual Convention, Jakarta, pp. 483–497.

Omang, S.A.K., Barber, A.J., 1996. Origin and tectonic significance of the metamorphic rocks associated with the Darvel Bay Ophiolite, Sabah, Malaysia. In: Hall, R., Blundell, D.J. (Eds.), Tectonic Evolution of SE Asia. Geological Society London Special Publication, vol. 106, pp. 263–279.

Parkinson, C.D., Miyazaki, K., Wakita, K., Barber, A.J., Carswell, D.A., 1998. An overview and tectonic synthesis of the pre-Tertiary very high-pressure metamorphic and associated rocks of Java, Sulawesi and Kalimantan, Indonesia. Island Arc 7, 184–200.

Peltzer, G., Tapponnier, P., 1988. Formation and evolution of strike–slip faults, rifts, and basins during the India–Asia collision: an experimental approach. Journal of Geophysical Research 93, 15085–15117.

Petronas, 1999. The Petroleum Geology and Resources of Malaysia. Petronas, Kuala Lumpur, Malaysia. 665 pp.

Polachan, S., Pradidtan, S., Tongtaow, C., Janmaha, S., Intarawijitr, K., Sangsuwan, C., 1991. Development of Cenozoic basins in Thailand. Marine and Petroleum Geology 8, 84–97.

Prouteau, G., Maury, R.C., Sajona, F.G., Pubellier, M., Cotten, J., Bellon, H., 2001. Le magmatisme post-collisionnel du Nord-Ouest de Bornéo, produit de la fusion d'un fragment de croûte océanique ancré dans le manteau supérieur. Bulletin de la Société Géologique de France 172, 319–332.

Pupilli, M., 1973. Geological evolution of South China Sea Area; tentative reconstruction from borderland geology and well data. Proceedings

Indonesian Petroleum Association 2nd Annual Convention, Jakarta, pp. 223–242.

Puspita, D., Hall, R., Elders, C.F., 2005. Structural styles of the offshore West Sulawesi fold belt, North Makassar Straits, Indonesia. Proceedings Indonesian Petroleum Association 30th Annual Convention, Jakarta, pp. 519–542.

Rangin, C., Bellon, H., Benard, F., Letouzey, J., Müller, C., Tahir, S., 1990a. Neogene arc-continent collision in Sabah, N. Borneo (Malaysia). Tectonophysics 183, 305–319.

Rangin, C., Jolivet, L., Pubellier, M., 1990b. A simple model for the tectonic evolution of southeast Asia and Indonesia region for the past 43 m.y. Bulletin de la Société géologique de France 8 (VI), 889–905.

Rangin, C., Silver, E.A., 1991. Neogene tectonic evolution of the Celebes Sulu basins; new insights from Leg 124 drilling. Proceedings of the Ocean Drilling Program, Scientific Results, vol. 124, pp. 51–63.

Rangin, C., Klein, M., Roques, D., Le Pichon, X., Trong, L.V., 1995. The Red River fault system in the Tonkin Gulf, Vietnam. Tectonophysics 243, 209–222.

Rangin, C., Le Pichon, X., Mazzotti, S., Pubellier, M., Chamot-Rooke, N., Aurelio, M., Walpersdorf, A., Quebral, R., 1999. Plate convergence measured by GPS across the Sundaland/Philippine Sea plate deformed boundary: the Philippines and eastern Indonesia. Geophysical Journal International 139, 296–316.

Reinhardt, M., Wenk, E., 1951. Geology of the colony of North Borneo. Bulletin of the Geological Survey Department of the British Territories in Borneo 1. 160 pp.

Replumaz, A., Tapponnier, P., 2003. Reconstruction of the deformed collision zone between India and Asia by backward motion of lithospheric blocks. Journal of Geophysical Research 108. doi:10.1029/2001 JB000661.

Replumaz, A., Karason, H., van der Hilst, R.D., Besse, J., Tapponnier, P., 2004. 4-D evolution of SE Asia's mantle from geological reconstructions and seismic tomography. Earth and Planetary Science Letters 221, 103–115.

Roques, D., Matthews, S.J., Rangin, C., 1997a. Constraints on strike–slip motion from seismic and gravity data along the Vietnam margin offshore Da Nang: implications for hydrocarbon prospectivity and opening of the East Vietnam Sea. In: Fraser, A.J., Matthews, S.J., Murphy, R.W. (Eds.), Petroleum Geology of Southeast Asia. Geological Society London Special Publication, vol. 126, pp. 341–353.

Roques, D., Rangin, C., Huchon, P., 1997b. Geometry and sense of motion along the Vietnam margin: onshore/offshore Da Nang area. Bulletin de la Société Géologique de France 168, 413–422.

Rowley, D.B., 1996. Age of initiation of collision between India and Asia: a review of stratigraphic data. Earth and Planetary Science Letters 145, 1–13.

Sandal, S.T., 1996. The Geology and Hydrocarbon Resources of Negara Brunei Darussalam. In: Sandal, S.T. (Ed.), Syabas, Bandar Seri Begawan, Brunei Darussalam. 243 pp.

Satyana, A.H., Nugroho, D., Surantoko, I., 1999. Tectonic controls on the hydrocarbon habitats of the Barito, Kutei, and Tarakan Basins, eastern Kalimantan, Indonesia: major dissimilarities in adjoining basins. Journal of Asian Earth Sciences 17, 99–122.

Schmidtke, E.A., Fuller, M.D., Haston, R., 1990. Paleomagnetic data from Sarawak, Malaysian Borneo, and the late Mesozoic and Cenozoic tectonics of Sundaland. Tectonics 9, 123–140.

Schwartz, M.O., Rajah, S.S., Askury, A.K., Putthapiban, P., Djaswadi, S., 1995. The Southeast Asian Tin Belt. Earth Science Reviews 38, 95–290.

Sikumbang, N., 1986. Geology and tectonics of pre-Tertiary rocks in the Meratus Mountains, South-East Kalimantan, Indonesia. Ph.D. Thesis, University of London, 401 pp.

Sikumbang, N., 1990. The geology and tectonics of the Meratus Mountains, South Kalimantan, Indonesia. Geologi Indonesia. Journal of the Indonesian Association of Geologists 13, 1–31.

Simmons, M.D., Bidgood, M.D., Brenac, P., Crevello, P.D., Lambiase, J.J., Morley, C.K., 1999. Microfossil assemblages as proxies for precise palaeoenvironmental determination— an example from Miocene sediments of northwest Borneo. In: Jones, R.W., Simmons, M.D. (Eds.), Biostratigraphy in Production and Development Geology. Geological Society London Special Publication, vol. 152, pp. 219–241.

Simons, W.J.F., Socquet, A., Vigny, C., Ambrosius, B.A.C., Abu, S.H., Promthong, C., Subarya, Sarsito, D.A., Matheussen, S., Morgan, P., Spakman, W., 2007. A decade of GPS in Southeast Asia: resolving Sundaland motion and boundaries. Journal of Geophysical Research 112, B06420. doi:10.1029/2005JB003868.

Siregar, M.S., Sunaryo, R., 1980. Depositional environment and hydrocarbon prospects, Tanjung Formation, Barito Basin, Kalimantan. Proceedings Indonesian Petroleum Association 9th Annual Convention, Jakarta, pp. 379–400.

Situmorang, B., 1982a. The formation and evolution of the Makassar Basin, Indonesia. Ph.D. Thesis, University of London, 313 pp.

Situmorang, B., 1982b. Formation, Evolution, and Hydrocarbon Prospects of the Makassar Basin, Indonesia. In: Watson, S.T. (Ed.), Transactions of the 3rd Circum Pacific Energy and Mineral Resources Conference, Honolulu, Hawaii, 1982, pp. 227–232.

Smyth, H.R., 2005. Eocene to Miocene basin history and volcanic history in East Java, Indonesia. Ph.D. Thesis, University of London, 476 pp.

Smyth, H.R., Hall, R., Nichols, G.J., 2007. Early Cenozoic volcanic arc history of East Java, Indonesia: the stratigraphic record of eruptions on a continental margin in a tropical setting. In: Draut, A.E., Clift, P.D., Scholl, D.W. (Eds.), Formation and Applications of the Sedimentary Record in Arc Collision Zones. Geological Society America Special Publication, vol. 436. doi: 8 10.1130/2007.2436(10).

Spakman, W., Bijwaard, H., 2001. Optimization of cell parameterizations for tomographic inverse problems. Pure and Applied Geophysics 158, 1401–1423.

Stauffer, P.H., 1967. Studies in the Crocker Formation, Sabah. Geological Survey of Malaysia, Borneo Region, Bulletin 8, 1–13.

Sumartadipura, A.S., 1976. Geologic map of the Tewah quadrangle, central Kalimantan. Geological Research and Development Centre, Bandung, Indonesia.

Sun, Z., Zhou, D., Zhong, Z., Zeng, Z., Wu, S., 2003. Experimental evidence for the dynamics of the formation of the Yinggehai basin, NW South China Sea. Tectonophysics 372, 41–58.

Sun, Z., Zhong, Z., Zhou, D., Qiu, X., 2004. Experimental constraints on Cenozoic development of Ying-Qiong basin in NW South China Sea. In: Clift, P., Wang, P., Kuhnt, W., Hayes, D.E. (Eds.), Continent–Ocean Interactions within the East Asian Marginal Seas. Geophysical Monograph, vol. 149. American Geophysical Union, Washington, D.C., pp. 109–120.

Suwarna, N., Sutrisno, de Keyser, F., Langford, R.P., 1989. Singkawang Sheet area, West Kalimantan. Geological Research and Development Centre, Bandung, Indonesia.

Swauger, D.A., Bergman, S.C., Marillo, A.P., Pagado, E.S., Surat, T., 1995. Tertiary stratigraphy and tectonic framework of Sabah, Malaysia: a field and laboratory study, GEOSEA 95: 8th Regional Conference on Geology, Minerals, and Energy Resources of SE Asia, Manila 1995, pp. 35–36.

Tan, D.N.K., Lamy, J.M., 1990. Tectonic evolution of the NW Sabah continental margin since the late Eocene. Geological Society of Malaysia Bulletin 27, 241–260.

Tanean, H., Paterson, D.W., Endarto, M., 1996. Source provenance interpretation of Kutei Basin sandstones and the implications for the tectono-stratigraphic evolution of Kalimantan. Proceedings Indonesian Petroleum Association 25th Annual Convention, Jakarta, pp. 333–345.

Tapponnier, P., Peltzer, G., Le Dain, A.Y., Armijo, R., Cobbold, P., 1982. Propagating extrusion tectonics in Asia: new insights from simple experiments with plasticine. Geology 10, 611–616.

Tapponnier, P., Peltzer, G., Armijo, R., 1986. On the mechanics of collision between India and Asia. In: Coward, M.P., Ries, A.C. (Eds.), Collision Tectonics. Geological Society London Special Publication, vol. 19, pp. 115–157.

Tate, R.B., 1996. The Geological Evolution of Borneo Island. M.Sc. Thesis, University of Malaya, 393 pp.

Tate, R.B., 2001. The Geology of Borneo Island: map. Geological Society of Malaysia.

Taylor, B., Hayes, D.E., 1983. Origin and history of the South China Sea Basin. In: Hayes, D.E. (Ed.), The Tectonic and Geologic Evolution of Southeast Asian Seas and Islands Part 2. Geophysical Monograph, vol. 27. American Geophysical Union, Washington, D.C., pp. 23–56.

Tongkul, F., 1987. Sedimentology and structure of the Crocker Formation in the Kota Kinabalu Area, Sabah, East Malaysia. Ph.D. Thesis, University of London, 318 pp.

Tongkul, F., 1991. Tectonic evolution of Sabah, Malaysia. Journal of Southeast Asian Earth Sciences 6, 395–406.

Upton, D.R., Bristow, C.S., Hurford, C.S., Carter, A., 1997. Tertiary tectonic denudation in Northwestern Thailand: provisional results from apatite fission-track analysis. Proceedings of the International Conference on Stratigraphy and Tectonic Evolution in Southeast Asia and the South Pacific, Bangkok, Thailand, pp. 421–431.

van de Weerd, A., Armin, R.A., 1992. Origin and evolution of the Tertiary hydrocarbon bearing basins in Kalimantan (Borneo), Indonesia. American Association of Petroleum Geologists Bulletin 76, 1778–1803.

van der Hilst, R.D., Widiyantoro, S., Engdahl, E.R., 1997. Evidence for deep mantle circulation from global tomography. Nature 386, 578–584.

van der Voo, R., Spakman, W., Bijwaard, H., 1999. Tethyan subducted slabs under India. Earth and Planetary Science Letters 171, 7–20.

van Hattum, M.W.A., 2005. Provenance of Cenozoic sedimentary rocks of northern Borneo. Ph.D. Thesis, University of London, 457 pp.

van Hattum, M.W.A., Hall, R., Pickard, A.L., Nichols, G.J., 2006. SE Asian sediments not from Asia: Provenance and geochronology of North Borneo sandstones. Geology 34, 589–592.

van Leeuwen, T.M., 1994. 25 years of mineral exploration and discovery in Indonesia. Journal of Geochemical Exploration 50, 13–90.

van Leeuwen, T.M., Leach, T., Hawek, A.A., Hawke, M.M., 1990. The Kelian disseminated gold deposit, East Kalimantan, Indonesia. Journal of Geochemical Exploration 35, 1–61.

Wahyono, H., Sunata, W., 1987. Palaeomagnetism along transect VII. Joint CCOP/IOC Working Group on SEATAR 1987. Preliminary Report of the Jawa–Kalimantan Transect (Transect VII). Geological Research and Development Centre, Bandung, Indonesia, pp. 1–10.

Wang, E., Burchfiel, B.C., 1997. Interpretation of Cenozoic tectonics in the right-lateral accommodation zone between the Ailao Shan shear zone and the eastern Himalayan syntaxis. International Geology Review 39, 191–219.

Widiyantoro, S., van der Hilst, R.V., 1997. Mantle structure beneath Indonesia inferred from high-resolution tomographic imaging. Geophysical Journal International 130, 167–182.

Wight, A.W.R., Hare, L.H., Reynolds, J.R., 1993. Tarakan Basin, NE Kalimantan, Indonesia: a century of exploration and future hydrocarbon potential. Geological Society of Malaysia Bulletin 33, 263–288.

Wikarno, R., Hardjono, T., Graha, D.S., 1993. istribution of radiometric ages in Indonesia. Geological Research and Development Centre, Bandung, Indonesia.

William, A.G., Lambiase, J.J., Back, S., Jamiran, M.K., 2003. Sedimentology of the Jalan Selaiman and Bukit Melinsung outcrops, western Sabah: is the West Crocker Formation an analogue for Neogene turbidites offshore? Geological Society of Malaysia Bulletin 47, 63–75.

Williams, P.R., Johnston, C.R., Almond, R.A., Simamora, W.H., 1988. Late Cretaceous to Early Tertiary structural elements of West Kalimantan. Tectonophysics 148, 279–298.

Williams, P.R., Supriatna, S., Johnston, C.R., Almond, R.A., Simamora, W.H., 1989. A Late Cretaceous to Early Tertiary accretionary complex in West Kalimantan, vol. 13. Bulletin Geological Research and Development Centre, Bandung, Indonesia, pp. 9–29.

Wilson, R.A.M., Wong, N.P.Y., 1964. The geology and mineral resources of the Labuan and Padas Valley areas, Sabah. Geological Survey of Malaysia, Borneo Region, Memoir, vol. 17. 150 pp.

Wolfenden, E.B., 1960. The geology and mineral resources of the lower Rajang Valley and adjoining areas, Sarawak. British Territories Borneo Region Geological Survey Department, Memoir, vol. 11. 167 pp.

Yan, P., Deng, H., Liu, H., Zhirong, Z., Jiang, Y., 2006. The temporal and spatial distribution of volcanism in the South China Sea region. Journal of Asian Earth Sciences 27, 647–659.