Hydrocarbon basins in SE Asia: understanding why they are there

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ABSTRACT: There are numerous hydrocarbon-rich sedimentary basins in Indonesia, Malaysia and southern Thailand. Almost all these basins began to form in the Early Cenozoic, they are filled with Cenozoic sediments, most are rifted basins that are the product of regional extension, and they formed mainly on continental crust. Many different models have been proposed to account for their formation and age. Understanding basin development requires a better knowledge of the Mesozoic and Early Cenozoic history of Sundaland, which mainly lacks rocks of this age. Sundaland is a heterogeneous region, assembled from different continental blocks separated by oceanic sutures, in which there has been significant Mesozoic and Cenozoic deformation. It is not a 'shield' or 'craton'. Beneath Sundaland there is a marked difference between the deep mantle structure west and east of about 100°E, reflecting different Mesozoic and Cenozoic subduction histories. To the west are several linear high velocity seismic anomalies interpreted as subducted Tethyan oceans, whereas to the east is a broad elliptical anomaly beneath SE Asia indicating a completely different history of subduction. Throughout most of the Cretaceous there was subduction north of India, preceding collision with Asia. However, north of Australia the situation was different. Cretaceous collisions contributed to elevation of much of Sundaland. Subduction beneath Sundaland ceased in the Cretaceous after collision of Gondwana continental fragments and, during the Late Mesozoic and Paleocene, there was a passive margin surrounding most of Sundaland. When Australia began to move northwards from about 45 Ma, subduction resumed at the Sunda Trench. Basins began to form as the region went into compression at the time of subduction initiation. There was widespread extension, broadly orthogonal to the maximum compressive stress but modified by pre-existing basement structure. After subduction resumed, the weakness of the Sundaland lithosphere, unusually responsive to changing forces at the plate edges, meant that the basins record a complex tectonic history.

KEYWORDS: sedimentary basins, Sundaland, subduction

INTRODUCTION

There are numerous hydrocarbon-rich sedimentary basins in and around the Sunda Shelf in Indonesia, Malaysia and southern Thailand, in the continental area described as Sundaland (Fig. 1). Almost all of these basins began to form in the Early Cenozoic, many are very deep and they are typically filled with terrestrial and shallow-marine sediments. The basins formed on continental crust, although this crust has a complex character, in terms of fabric and lithologies, and probably differs considerably from older major continents. From a tectonic point of view the basins present two particular problems: exactly when did they begin to form and why? The two questions cannot be separated and it is not possible to identify a mechanism without knowing the timing. The abundance of basins suggests a major driving force should be identifiable. There are several large tectonic causes that have been proposed or are feasible, including effects of India–Asia collision, collisions at the SE Asian margins, regional extension due to subduction-related processes, such as hinge rollback, or plate boundary changes following events elsewhere in the global plate system.

In this paper it is proposed that most of the basins began to form broadly synchronously in the Middle Eocene. It is argued that they formed in response to breaking of the plate of which Sundaland was part when new subduction systems were initiated around Sundaland. The considerable variation in the geometry, character and distribution of the basins, and their subsequent histories, reflect two important features of Sundaland: the composite character of its basement and the weakness of its lithosphere.

BASIN FORMATION MODELS

A great deal has been written on the basins of the Sundaland region and a large number of models have been proposed to account for the formation of some or all of the sedimentary basins. It is not the intention of this paper to discuss the
distribution and details of different basins, or basin models, and
the reader is referred to reviews or special volumes (e.g. Williams et al. 1995; Howes & Noble 1997; Longley 1997; Petronas 1999; Hall & Morley 2004; Doust & Sumner 2007) and papers cited below for this information.

The basins have been classified in different ways and assigned to different categories. Many have been suggested to have originated as pull-apart basins due to strike-slip faulting (e.g. Davies 1984; Tapponnier et al. 1986; Polachan et al. 1991; Huchon et al. 1994; Cole & Crittenden 1997; Shaw 1997; Leloup et al. 2001). A few have been suggested to have a flexural origin (e.g. DeCelles & Giles 1996; Wheeler & White 2002). Most authors have suggested that all or most basins are rifts (e.g. Burri 1989; Williams & Eubank 1995; Longley 1997; Wheeler & White 2002; Hall & Morley 2004; Doust & Sumner 2007).

A variety of mechanisms have been suggested to account for basin formation. Many authors link basin formation to India–Asia collision, either related to extrusion-related strike-slip faulting (e.g. Huchon et al. 1994; Madon & Watts 1998; Leloup et al. 2001; Tapponnier et al. 1986) or by driving extension (e.g. Cole & Crittenden 1997; Longley 1997). Many other authors have explicitly or implicitly linked basin formation to subduction. Some of the basins are described as forearc basins (e.g. Madon 1999), and many have been described as back-arc basins (e.g. Eubank & Makki 1981; Bushy & Ingersoll 1995; Cole & Crittenden 1997; Barber et al. 2005), although it is not always clear if this term is being applied in a purely descriptive sense, referring to their present setting, or a mechanistic sense, to indicate they formed behind an active arc. Morley (2001) suggested extension driven by subduction rollback to account for the formation of some Sundaland basins and Moulds (1989) proposed subduction-driven compression could account for extension of Sumatran and possibly other basins. Many authors have noted the importance of pre-existing basement structures in influencing basin development (e.g. Hamilton 1979; Moulds 1989; Hutchison 1996a; Madon 1999; Hall & Morley 2004; Sapiie & Hadiana 2007).

One of the problems in interpreting the causes of basin formation is identifying the ages of basin initiation. Dating the initiation of basin formation is problematical because the oldest parts of the sequences are terrestrial, typically lack fossils and, in many cases, are observed only on seismic data. The older parts of many basins have not been sampled because they are too deep. It is possible that there is a progressive change in the age of basin formation from the external parts of Sundaland, with basin initiation becoming younger towards the interior, but it appears more likely that subsidence began at approximately the same time across most of Sundaland (Longley 1997; Hall & Morley 2004; Doust & Sumner 2007). More work is certainly needed to try to date basin initiation more accurately, but the problems in doing this will not be overcome easily and ages will remain uncertain, because Upper Cretaceous and Paleocene sedimentary rocks are missing from most of Sundaland, probably reflecting widespread uplift and subsequent erosion after the mid-Cretaceous. It is reasonably certain that rifting began almost everywhere except in Thailand in the Eocene, and the oldest proven rift sequences are Middle Eocene. Therefore, the best estimate for basin initiation is suggested here to be about 45 Ma. The ideas proposed below are not critically dependent on this proposed age or the synchronicity of basin formation.

SUNDALAND LITHOSPHERE

The interior of SE Asia, particularly the Sunda Shelf (Fig. 1) and surrounding emergent, but topographically relatively low areas of Sumatra, the Thai-Malay peninsula and Borneo are largely free of seismicity and volcanism, in marked contrast to its margins. This tectonically quiet region forms the continental core of Sundaland (Hall & Morley 2004). Sundaland extends north into Indochina, much of it was terrestrial for most of the Cenozoic and it formed an exposed landmass during the Pleistocene. Most of the shelf is flat, extremely shallow, with water depths considerably less than 200 m. Seismicity (Cardwell & Isacks 1978; Engdahl et al. 1998) and GPS measurements (Rangin et al. 1999; Michel et al. 2001; Bock et al. 2003; Simons

Fig. 1. Geography of SE Asia and surrounding regions. Small black filled triangles are volcanoes from the Smithsonian Institution, Global Volcanism Program (Siebert & Simkin 2002), and bathymetry is simplified from the GEBCO (2003) digital atlas. Bathymetric contours are at 200 m, 3000 m and 5000 m.
et al. 2007) indicate that a SE Asian or Sunda microplate is currently moving slowly relative to the Eurasian Plate. The Sunda Shelf is widely regarded as a stable area (e.g. Geyh et al. 1979; Tija 1992; Hanebuth et al. 2000) and sea-level data from the region have been used in construction of global eustatic sea-level curves (e.g. Fleming et al. 1998; Bird et al. 2007), despite evidence of very young faulting and vertical movements (e.g. Bird et al. 2006).

The present stability and the extensive shallow area of the Sunda Shelf has led to a widespread misconception that Sundaland was a stable area during the Cenozoic. It is often described as a shield or craton (e.g. Ben-Avraham & Emery 1997; Gobbert & Hutchison 1973; Tija 1996; Parkinson et al. 1998; Barber et al. 2005), or plate (e.g. Davies 1984; Cole & Critenden 1997; Replumaz & Tapponnier 2003; Replumaz et al. 2004), implying a rigid block with deformation concentrated at the edges during the Cenozoic. Some authors suggest Sundaland rotated clockwise as a block during the last 8–10 million years (e.g. Rangin et al. 1999) or over a longer period (Replumaz et al. 2004).

However, the character of the Sundaland deep crust and mantle is quite different from nearby continental regions and from cratons (Hall & Morley 2004; Hyndman et al. 2005; Currie & Hyndman 2006). Unlike the well-known shields or cratons (e.g. Baltic, Canadian, African, Australian), Sundaland is not underlain by a thick cold lithosphere that was stabilized in the Precambrian. There has been significant deformation during the Cenozoic with formation of the sedimentary basins, as well as localized inversion and widespread elevation of mountains. There are numerous faults that have been active during the Cenozoic (e.g. Pubellier et al. 2005; Doust & Sumner 2007). The Sundaland interior has high surface heat flow values, typically greater than 80 mW m⁻². Doust & Sumner (2007) noted exceptionally elevated heat flow (>150 mW m⁻²) and temperature gradients in the area that extends from the Central Sumatra Basin northward into the southern Gulf of Thailand with an unknown cause. At the Indonesian margins high heat flows reflect subduction-related magmatism but the hot interior of Sundaland mainly reflects upper crustal heat flow from radiogenic granites and their erosional products, the insulation effects of sediments and a large mantle contribution (Hall & Morley 2004). Locally very high heat flows may reflect fluid movements in the upper crust. P- and S-wave seismic tomography (Bijwaard et al. 1998; Ritsema & van Heijst 2000) also show the region is characterized by low velocities in the lithosphere and underlying asthenosphere, in marked contrast to Indian and Australian continental lithosphere to the NW and SE. Such low mantle velocities are commonly interpreted in terms of elevated temperature, and this is consistent with regional high heat flow, but they may also partly reflect the mantle composition or elevated volatile contents.

Sundaland has been very far from stable (Hall & Morley 2004) and it did not behave as a single rigid block during most of the Cenozoic. The considerable evidence for a heterogeneous pattern of subsidence and elevation indicates significant internal deformation (Hall 1996, 2002; Hall et al. 2008). The upper mantle velocities and heat flow observations suggest the region is underlain by a thin and weak lithosphere (Hall & Morley 2004; Hyndman et al. 2005) that extends many hundreds of kilometres from the volcanic margins. Of critical importance is the observation that such extensive regions of thin and hot lithosphere are weak (Hyndman et al. 2005; Currie & Hyndman 2006) and have a total strength of similar magnitude to forces acting at plate boundaries. When dry, plate boundary forces may exceed the total lithospheric strength during compression and, when wet, during both compression and extension. As suggested elsewhere (Hall 2002; Hall & Morley 2004), this means the entire region is likely to be unusually responsive to changing plate boundary forces. This weakness has been of major importance in the initiation of the Sundaland sedimentary basins, and in their later histories.

SUNDALAND HISTORY BEFORE THE EOCENE

The continental core of Sundaland was assembled from fragments (Fig. 2) that rifted from Gondwana during formation of different Tethyan oceans and this history is well described by Metcalfe (e.g. 1996, 1998). An Indochina–East Malaya block separated from Gondwana in the Devonian and, by the Carboniferous, was at tropical low latitudes where a distinctive Cathaysian flora developed. In contrast, Sibumasu was accreted along the Raub–Bentong suture in the Triassic. West Burma and West Sumatra were subsequently moved along the Sundaland margin. The Woyla Arc was interpreted here to be a Cathaysian fragment rifted from Asia and added to Sundaland during the Mesozoic. SW Borneo (Metcalfe 1990) and East Java–West Sulawesi (Smyth et al. 2007) are interpreted to have been rifted from West Australia and added in the Late Cretaceous.

Fig. 2. Sundaland at the end of the Cretaceous, modified after Metcalfe (1996), Barber et al. (2005) and Barber & Crow (2009). West Sumatra, West Burma and Indochina–East Malaya formed part of a Cathaysia block added to Eurasia during the Palaeozoic. Sibumasu was accreted along the Raub–Bentong suture in the Triassic. West Burma and West Sumatra were subsequently moved along the Sundaland margin. The Woyla Arc was accreted in the Cretaceous. The Luconia block is interpreted here to be a Cathaysian fragment rifted from Asia and added to Sundaland during the Mesozoic. SW Borneo (Metcalfe 1990) and East Java–West Sulawesi (Smyth et al. 2007) are interpreted to have been rifted from West Australia and added in the Late Cretaceous.

Several important blocks were added in the Cretaceous. SW Borneo is interpreted here to be a continental block rifted from
the West Australian margin, and added to Sundaland in the Early Cretaceous. The suture is suggested to run south from the Natuna area along the structural lineament named the Billiton Depression (Ben-Avraham 1973; Ben-Avraham & Emery 1973) and originally interpreted by Ben-Avraham & Uyeda (1973) as a transform fault associated with Cretaceous opening of the South China Sea. After collision of the SW Borneo block the Cretaceous active margin ran from Sumatra into West Java and continued northeast through SE Borneo into West Sulawesi. The intra-oceanic Woyla Arc collided with the Sumatran margin in the mid-Cretaceous, adding arc and ophiolitic rocks to the southern margin of Sumatra (Barber et al. 2005). Further east the Early Cretaceous active margin is marked by Cretaceous high pressure–low temperature subduction-related metamorphic rocks in Central Java, the Meratus Mountains of SE Borneo and West Sulawesi (Parkinson et al. 1998). Further fragments were added to Sundaland during the Late Cretaceous (Fig. 3) in East Java and West Sulawesi (Smyth et al. 2007; van Leeuwen et al. 2007).

Until recently, most authors (e.g. Metcalfe 1996) accepted that fragments rifted from the west Australian margin in the Late Jurassic and Early Cretaceous had collided in West Borneo in the Cretaceous, or were uncertain about their present position. However, recent work suggests West Bornea is not a block added in the Cretaceous, but has been part of SE Asia since the Early Mesozoic, possibly linked to West Sumatra (Barber & Crow 2009). The west Australian fragments are now in Borneo, East Java and West Sulawesi. Outboard of the Meratus suture, East Java and West Sulawesi are underlain in part by Archaean continental crust, and geochemistry (Elburg et al. 2003) and zircon dating (Smyth et al. 2007; van Leeuwen et al. 2007) indicate a west Australian origin.

The Cretaceous arrival of continental fragments contributed to crustal thickening, magmatism (see below), emergence and widespread erosion of Sundaland during the Late Cretaceous and Early Cenozoic, thus further diminishing the completeness of the stratigraphic record. Of greater importance for basin development was the considerable variation in basement lithologies and structure, which gave Sundaland at the beginning of the Cenozoic a highly complex basement fabric that varies from area to area, and which includes profound and deep structural features that have been reactivated at different times in different ways. This complex basement structure is the second important influence on the formation and character of the sedimentary basins of Sundaland.

**MANTLE STRUCTURE BENEATH SUNDALAND**

P-wave and S-wave seismic tomography not only indicate the likely strength of the lithosphere but also display the mantle structure beneath Sundaland (Widiyantoro & van der Hilst 1997; Bijwaard et al. 1998; Ritsema & van Heijst 2000) from which important insights into the subduction history of the region can be obtained. Tomographic depth slices of the upper mantle (Fig. 4) reveal very clear, broadly curvilinear high velocity anomalies, mainly parallel to present trenches, interpreted as the principal lithospheric slabs subducted during the Late Cenozoic. However, of greater importance for interpreting the older history are velocity contrasts in the lower mantle. At depth below 700 km there is a marked difference between the mantle structure west and east of about 100°E (Fig. 5). To the west there are a series of linear high velocity anomalies trending roughly NW–SE, interpreted as unbroken remnants of Tethyan oceans by van der Voo et al. (1999). East of 100°E these anomalies no longer exist, and only the southernmost anomaly can be traced eastwards. To the west of 100°E there is a clear linear NW–SE-oriented high velocity anomaly, but to the east the apparent continuation of the 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.

North of India the linear anomalies have been interpreted as a series of subduction zones active during India's northward movement before collision with Asia (van der Voo et al. 1999; Aitchison et al. 2007). The high velocity anomaly in the lower mantle beneath Indonesia represents the accumulation of subducted lithosphere, but indicates a completely different subduction history. Replumaz et al. (2004) have suggested that the lower mantle tomography reflects a large clockwise rotation.
of a single SE Asian block since 40 Ma, as proposed in a reconstruction of the India–Asia collision zone by Replumaz & Tapponnier (2003). However, there is no evidence from palaeomagnetism (Fuller et al. 1999) for the rotation or latitude change suggested by Replumaz & Tapponnier (2003) and the area of the anomaly extends significantly south of their reconstructed position of the Java Trench. The geological history of the region is also much more complex than that expected by rotation of a single rigid SE Asian plate (Hall et al. 2008).

The reconstruction of Hall (2002) offers an alternative interpretation of the deep anomaly beneath SE Asia. Both the upper and lower mantle reveal the importance of long-term subduction at the Indonesian margins. However, most of what is observed in the mantle records the northward movement of Australia during the Cenozoic, which began to move at a significant rate only from about 45 Ma (Royer & Sandwell 1989). There is no evidence for a similar series of Tethyan oceans to those subducted north of India, consistent with the absence of subduction during the Late Cretaceous and Paleocene. The position of the deep lower mantle 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, with contributions from several other subduction zones within east Indonesia, such as those associated with the Sulu Arc, and the Sangihe Arc. The difference in subduction history north of India compared to that north of Australia, with the change occurring at about 100°E, is the third major feature relevant to the formation of the sedimentary basins of Sundaland.

**IGNEOUS ACTIVITY FROM THE LATE CRETACEOUS TO EOCENE**

Typically, plate tectonic reconstructions have assumed subduction was underway at the Sunda Trench at least by the Early Eocene (e.g. Hall 1996, 2002) or from the Late Cretaceous (e.g. Metcalfe 1996; Sribudiyani et al. 2003; Barber et al. 2003; Whittaker et al. 2007). There is abundant evidence for subduction-related magmatism since about 45 Ma from Sumatra eastwards but, in contrast, there is little volcanic record in the expected position of the volcanic arc during the Late Cretaceous and Paleocene, except in West Sulawesi and Sumba. However, there was widespread granite magmatism across most of southern Sundaland in the Cretaceous, which unlike products of older episodes (e.g. Hutchinson 1989; Krümelbühl 1991; Cobbing et al. 1992; McCourt et al. 1996) is not arranged in linear belts, and suggests crustal melting across a large region during a long period, rather than subduction-related plutonism.

**Volcanic activity**

Throughout most of SE Asia, Upper Cretaceous and Paleocene rocks of all types are almost entirely absent. The evidence for Late Cretaceous and Early Cenozoic volcanic activity (Fig. 6) is almost entirely based upon K–Ar ages, mainly from whole-rock dating, and there are many reasons to be cautious about such ages (McDougall & Harrison 1988; Harland et al. 1990; Macpherson & Hall 2002; Villeneuve 2004), particularly in SE Asia where the effects of tropical weathering are superimposed on tectonically and thermally altered rocks, commonly with low potassium contents. If these ages are accepted, they suggest an interval of significantly diminished volcanic activity, possibly post-collisional and often interpreted as not directly related to subduction, succeeded in many parts of the Sundaland margin by renewed abundant volcanism from the Middle Eocene, which can be confidently linked to subduction.

Crow (2005) reviewed the record of Cenozoic volcanic activity in Sumatra. No Upper Cretaceous rocks are known (Page et al. 1979), but there are a small number of Paleocene ages reported from boreholes, dykes and a few volcanic rocks, mainly basalts, which are mostly in south Sumatra (Bellon et al. 2004). The Paleocene Kikin Volcanics include volcanic breccias, tuffs, and basaltic to andesitic lavas. De Smet & Barber (2005) interpreted a period of erosion in Sumatra between the Late Cretaceous and Early Eocene, with some volcanic activity in the area of the Barisan Mountains, although they noted that the age of the volcanic rocks is poorly constrained. Middle to Upper Eocene volcanic rocks are known from a few parts of West Sumatra (Crow 2005). They include subaerial pyroclastics and lavas interpreted as arc volcanics in Aceh, and volcanioclastic sediments. K–Ar and zircon fission track ages are less than 47 Ma. In Sumatra, prolonged erosion was followed in about the Middle Eocene by a resumption of volcanic activity which became widespread from the Late Eocene. Late Eocene to Early Miocene volcanic activity is indicated by widespread and abundant volcanic rocks throughout Sumatra.

In Java there is an important Eocene unconformity and few exposures of older rocks. Central Java includes the most extensive area of basement rocks, the Lok Ulo Complex (van Bemmelen 1949; Askin et al. 1992). This is regarded as the imbricated product of Cretaceous deformation (e.g. Parkinson et al. 1998; Wakita 2000) at a subduction margin that extended from West Java, through the Lok Ulo Complex, to the Meratus Mountains. The youngest rocks from the Lok Ulo Complex contain Campanian–Maastrichtian radiolarians with ages of about 70–80 Ma (Wakita et al. 1994). The Lok Ulo Complex is overlain by the Eocene–Oligocene Karangasem and Totogan Formations, which include scaly clays with nummulitic limestone blocks, polymict conglomerates and basalt blocks, interpreted as deep-water olistostromes (A.H. Harzolomasko, pers. comm. 2005) or mud diapirs (A.J. Barber, pers. comm. 2008). They lack abundant volcanic material but do contain large amounts of quartzose debris. In West Java the oldest rocks are in the Ciletuh area where there are exposures of ‘pre–Tertiary’ (van Bemmelen 1949) peridotites, serpentinites and gabbros with chloritic schists interpreted as an ophiolitic tectonic melange (e.g. Parkinson et al. 1998; Martodjojo et al. 1992).
1978). K–Ar dating provided few results due to alteration (Schiller et al. 1991). A basalt pebble yielded a Late Cretaceous age, and a gabbro gave Paleocene to Middle Eocene ages. These rocks are probably overlain, although subsequently juxtaposed tectonically (Clements & Hall 2007), by the Middle Eocene Ciletuh Formation, which includes angular volcanoclastic material, ophiolitic and chert debris, rare amphibolites, blocks of nummulitic limestones, and some volcanoclastic sandstones, incorporated when incompletely lithified. They are interpreted as deposits of a deep-marine forearc setting (Schiller et al. 1991; Clements & Hall 2007). In East Java there are a few, very small, exposures of basement greenschists and marbles (Smyth et al. 2007). The contact with overlying sedimentary rocks, including nummulitic limestones, is not exposed but is interpreted to be an unconformity. The oldest sedimentary rocks, in the Nanggulan area, are fluviatile quartzose conglomerates and sandstones lacking volcanic debris. These terrestrial deposits pass rapidly up into Eocene marine deposits, which contain increasing amounts of volcanoclastic debris up-section. The stratigraphy indicates an important change in the Middle Eocene, with initiation of volcanic activity after a prolonged period of emergence and erosion (Smyth et al. 2007).

In SE Borneo there is also a profound unconformity in the Meratus Mountains. The exposed basement includes ophiolites, Cretaceous volcanoclastic rocks (Sikumbang 1986, 1990; Yuwono et al. 1988) and subduction-related high pressure–low temperature metamorphic rocks (Parkinson et al. 1998), which were thrust together during a Late Cenomanian–Early Turonian arc–continent collision (before c. 91 Ma). The Manunggul Group (Sikumbang 1986) or Formation (Yuwono 1987; Yuwono et al. 1988) includes Upper Cretaceous volcanogenic tuffs and greywackes (91 to 65 Ma) which rest unconformably on the older rocks and have a molasse character (Yuwono et al. 1988). These rocks are intruded by basaltic to dacitic dykes and gabbroic to granitic stocks with K–Ar ages from 87 ± 4 Ma to 72 ± 4 Ma, interpreted by Yuwono et al. (1988) to be subduction-related, based on their chemistry. The Manunggul Formation passes transitionally into the Tanjung Formation (Yuwono et al. 1988) which consists predominantly of quartzose clastic sediments and coals. This was originally interpreted to be Middle and Upper Eocene, but Bon et al. (1996) interpreted the deepest part of the Tanjung Formation, dated from three wells, to be Upper Maastrichtian, based on nanoflora previously regarded as reworked. They interpreted the Maastrichtian–Paleocene sediments to be deposits of a passive margin, including minor Paleocene volcanic rocks, formed after the Cretaceous collision. North of the Meratus Mountains, in the Kutai Basin, rifting that led to formation of the Makassar Straits began in the Middle Eocene (Chambers & Moss 1999; Moss & Chambers 1999) and the oldest Cenozoic rocks resemble Upper Eocene quartzose clastic sequence in the Meratus Mountains. Upper Cretaceous volcanic rocks are known from Kelian (Davies et al. 2008) in the Kutai Basin, where an inlier of felsic volcanoclastics is surrounded by Eocene terrestrial and shallow-marine sedimentary rocks. Zircons from a pumice breccia have a U–Pb age of 67.8 ± 0.3 Ma, considered to be the age of eruption (Davies, 2002). Detrital zircon populations from the Kelian and Mahakam Rivers include Cretaceous ages from 126.3 to 67.6 Ma (Setiabudi et al. 2001). Throughout West Sulawesi, Upper Cretaceous formations include material with an igneous provenance and record minor volcanic activity (T.M. van Leeuwen, pers. comm., 2007).
the Lariang and Karama area of West Sulawesi, the oldest Cenozoic sedimentary rocks rest in places on volcanic rocks and volcanoclastic sedimentary rocks that are mainly not well dated and may be Cretaceous or Paleocene (Calvert 2000; Calvert & Hall 2007). In the northern part of West Sulawesi the probable Campanian–Maastrichtian Latimojong Formation is composed dominantly of marine sedimentary rocks with basaltic to dacitic flows (van Leeuwen & Muharjo 2005) and there are volcanoclastic sandstones, tuffs and metabasites in the Latimojong Mountains further south (A.J. Barber, pers. comm., 2007). Volcanoclastic rocks contain Precambrian to Cretaceous zircons and the youngest age population has U–Pb ages of 80–120 Ma (van Leeuwen & Muharjo 2005). In the southern part of West Sulawesi, similar rocks are dated in several places and assigned to a number of different formations. The Balangharu Formation (Hasan 1990, 1991) includes olistostromes and turbidite fan deposits with a maximum age range of Turonian to Maastrichtian age (91–65 Ma). The Marada Formation (van Leeuwen 1981) is Campanian–Maastrichtian and includes distal turbidites which contain quartz, fresh feldspar and andesite fragments as well as volcanic flows or sills.

Unconformably above the Balangharu Formation is the Alla or Bua Formation (Sukamto 1982, 1986; Yuwono 1987), consisting of volcanic and intrusive rocks with K–Ar ages ranging from 65–58 Ma, interpreted as subduction-related (Elburg et al. 2002). This passes upwards into the marginal marine coal-bearing siliciclastic rocks of the ?Lower–Middle Eocene Malawa Formation. Further east are the Middle to Upper Eocene Langi Volcanics (van Leeuwen 1981), which are predominantly andesitic volcanics with a typical arc geochemistry (Elburg et al. 2002); some volcanoclastic rocks in the lower part contain zircons with a fission track age of 62 ± 2 Ma. The Langi Volcanics are intruded by a tonalite/granodiorite with a K–Ar age of 52–50 Ma and pass up into Upper Eocene limestones.

The interpretation of these sequences is not entirely clear. A post-collision passive margin setting has been suggested (Hasan 1990, 1991; Wakita et al. 1996) for the lower part of the Balangharu Formation but igneous debris in the upper part is suggested to be derived from a continental or magmatic arc and may indicate a forearc setting (van Leeuwen 1981). The geochemistry of the Paleocene and Lower Eocene igneous rocks is generally interpreted to indicate a resumption of subduction after Cretaceous collision, and Hasan (1990) interpreted a Late Paleocene–Early Eocene arc, but, if this was the case, the episode of subduction seems to have been short lived. All these rocks are overlain by sedimentary sequences typical of marginal and shallow marine conditions, including platform carbonates (Wilson et al. 2000), suggesting widespread rifting around the present Makassar Straits, which began in the Middle Eocene (Moss & Chambers 1999; Calvert & Hall 2007).

On Sumba there are Upper Cretaceous–Paleocene rocks of the Lasiup Formation resembling the deep-marine turbidites of West Sulawesi in which there are some volcanic rocks (Burrollet & Salle 1981). Abdullah et al. (2000) identified two calcalkaline magmatic episodes by K–Ar dating, one Santonian–Campanian (86–77 Ma) and the other Maastrichtian–Paleocene (71–56 Ma), which they interpreted as the result of subduction at the Sundaland margin producing an Andean magmatic arc. However, the area of volcanic activity is small.

Widespread Cretaceous granite magmatism

In contrast to the paucity of volcanic rocks of Late Cretaceous and Early Cenozoic age, there are abundant Cretaceous and Paleocene granites distributed across a very large area of Sundaland (Fig. 7). The majority of dated granites are Early Cretaceous, and 215 of the 299 ages are older than 80 Ma. For obvious reasons there is little information from offshore, and there are some parts of Indochina for which there is little information, such as Cambodia. None the less, it is difficult to see linear belts that might be expected if they are subduction products, and many granites are far from probable subduction zones.

Some granites could be part of an east-facing Andean margin that continued south from South China. Cretaceous granites are known in North China but it is still debated if they were formed at a subduction margin (e.g. Lin & Wang 2006; Li & Li 2007; Yang et al. 2007). Jahn et al. (1976) argued that there was a Cretaceous (120–90 Ma) thermal episode in the SE China margin which may be related to west-directed Pacific subduction. In South China, around Hong Kong, acid magmatism ceased in the Early Cretaceous (Sewell et al. 2000) but mid-Cretaceous granites are reported from Vietnam (Nguyen et al. 2004; Thuy et al. 2004) with youngest ages of 88 Ma. If this was part of an Andean margin it is unclear if and where it continued to the south.

The north–south belt of granites that follows the Thailand–Burma border is plausibly related to NE- or east-directed subduction of the Indian plate (e.g. Mitchell 1993; Barley et al. 2003). Early Cretaceous granites continue south into the Malay peninsula and Sumatra (Fig. 7A) and could be related to this subduction.

Granite magmatism in Borneo might be explained as the product of flat-slab subduction from the west or south, but the positions of the Cretaceous arcs of southern Sundaland are well known in Sumatra, Java and SE Borneo (Hamilton 1979; Parkinson et al. 1998; Barber et al. 2005) and are far outboard of most of the granites. The Cretaceous granites in the Schwaner Mountains (Williams et al. 1988) and western Sarawak (Tate 2001) have been interpreted as the product of Andean-type magmatism associated with subduction dipping beneath Borneo. If SE Sundaland was rotated by 90° from its present position, as suggested by palaeomagnetic studies of Borneo (Fuller et al. 1999), it is possible that the Schwaner granites could be the product of subduction at the East Asian margin. Alternatively, if SW Borneo is an accreted continental fragment that originated in the south, it is possible that granite magmatism was associated with south-directed subduction during its northward movement in the Early Cretaceous.

The granites older than about 80 Ma may thus be explained by subduction of the Indian Plate or Pacific plates. However, the younger granites in the area of Sumatra, Java and Borneo are less abundant and scattered across a wide area. A possible explanation is that they are products of collisional thickening. Further north in Sundaland, younger granites have been interpreted as the product of thickening following continental collision (Barley et al. 2003). It is suggested here that Late Cretaceous and Paleocene, and possibly some of the widespread Early Cretaceous, granites of Borneo and the Sunda Shelf represent post-collisional magmatism following Cretaceous accretion of the SW Borneo continental fragment or the East Java–West Sulawesi continental fragment (see below). This would account for their widespread distribution.

**LATE CRETACEOUS TO MIDDLE EOCENE TECTONIC SETTING**

Many authors have assumed or implied that subduction at the Sundaland active margin was continuous through the Late Mesozoic into the Cenozoic (e.g. Yuwono et al. 1988; Metcalfe
1996; Soeria-Atmadja et al. 1994, 1998; Abdullah et al. 2000; Sribudiyani et al. 2003) with an Andean magmatic arc stretching from Sumatra to West Sulawesi. Most granite magmatism in Indonesia that could be associated with an Andean-margin is older than 80 Ma. Furthermore, as observed above, there is little evidence of volcanic activity in Sumatra, none in Java, very little in SE Borneo and Sumba can a case be made for subduction-related volcanic activity. Volcanic rocks are mainly flows or sills associated with deep-marine turbidites, and some volcaniclastics debris could be reworked from older arc rocks. The arc itself is not seen. Volcanic activity had ceased by the end of the Eocene in SW Sulawesi, although probably continued into the Oligocene further north; its distribution in time and space suggests that it was localized and intermittent, and radiometric age dates and stratigraphic information suggest little or no volcanism between 30 and 19 Ma (T.M. van Leeuwen, pers. comm. 2007). The arguments for subduction-related volcanic activity are based on the subduction-character of the geochemistry, but the subduction signature could simply reflect post-collisional magmatism (Maepherson & Hall 2002). However, even if there was subduction beneath Sumba and West Sulawesi this does not require subduction in other parts of the Indonesian margin.

In contrast, some authors have either explicitly suggested that parts of the Sundaland margin were passive from the Late Cretaceous to the Eocene, or implied a passive margin by identifying Cenozoic resumption of subduction (e.g. Hamilton 1979; Hasan 1990, 1991; Daly et al. 1991; Bon et al. 1996; Carile & Mitchell 1994; Wakita et al. 1996; Parkinson et al. 1996). Parkinson et al. (1998) suggested that subduction ceased in the Cretaceous after collision of a Gondwana continental fragment that is now beneath most of West Sulawesi. Carile & Mitchell (1994) surmised that a collision of the Woyla Arc in Sumatra was connected to collision and ophiolite emplacement in the Meratus Mountains. The age and character of volcanic and sedimentary rocks from SE Borneo and Sulawesi are consistent with a major change in regime at about 90 Ma following collision. Smyth et al. (2005, 2007) have shown that there is a continental crust beneath the Southern Mountains of East Java, and Smyth et al. (2007) proposed that a continental fragment collided in the Cretaceous and terminated subduction. The ages of radiolaria in accreted deep-marine sediments in Central Java show the youngest subduction-related rocks are about 80 Ma. It is therefore suggested here that subduction ceased all around the south Sundaland margin in the Late Cretaceous, at about 90 to 80 Ma (Fig. 8), and was not resumed until the Middle

Fig. 7. Distribution of Cretaceous granites in southern Sundaland. There may be more Cretaceous granites offshore beneath the Sunda Shelf, based on personal communications from oil company geologists. (A) Granites older than 110 Ma, suggested to be the age of docking of the SW Borneo block. (B) Granites with ages between 110 and 80 Ma, suggested to be the age of docking of the East Java-West Sulawesi block. (C) Cretaceous to Paleocene granites. The shaded area is the position of the Early Cretaceous arc. Unfilled squares on (A) are Cretaceous but with no precise age (ESCAP 1994; Koning 2003). All other samples are radiometrically dated (Kirk 1968; Gabbett & Hutchison 1973; Pupilli 1973; Patusukismo & Yahya 1974; Garson et al. 1975; Bignell & Snelling 1977; Haile et al. 1977; Beckinsale et al. 1979; Ishihara et al. 1980; Puthapiban & Gray 1983; Puthapiban 1984, 1992; van de Weerd et al. 1987; Darbyshire & Swainbank 1988; Williams et al. 1988, 1989; Yuwono et al. 1988; Seong 1990; Nakapadungrat & Puttapiban 1992; Amiruddin & Trail 1993; Charusiri et al. 1993; de Keyser & Rustandi 1993; Nakapadungrat & Manena 1993; Pieters & Sanyoto 1993; Pieters et al. 1993; Supratna et al. 1993; Wikarama et al. 1995; Dunning et al. 1995; Dirk 1997; Hartono 1997; Utoyo 1997; Nguyen et al. 2004; Cobb, 2005).
indicate very slow separation of Australia and Antarctica until Cretaceous and Early Cenozoic, and hence subduction to the of India for its rapid northward movement in the Late 2000). Lamy 1990; Hazebroek & Tan 1993; Hall 1996; Hutchison was active from the Eocene until the Early Miocene (e.g. Tan & Borneo, at the former passive margin, rather than a collision. subduction of the proto-South China Sea beneath northern Sarawak ‘orogeny’ marks the Middle Eocene initiation of tion of the Late Cretaceous to Eocene setting is that the presented evidence that the Rajang Group sediments were Schwaner Mountains continents. In contrast, Moss (1998) have been widely interpreted as deposits of an active margin in the Late Jurassic at about 155 Ma are shown by the numbered codes (SWB155, WS155 and EJ155). A transform or very leaky transform spreading centre is inferred to have separated the Indian and Australian Plates between 80 and 45 Ma as India moved rapidly northwards.

EOCENE RESUMPTION OF SUBDUCTION AND ITS CONSEQUENCES

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volcanism (Abdullah et al. 2000). The Sunda Arc continued east into the Pacific (Hall 2002).

Subduction also resumed on the north side of the Sundaland promontory at about 45 Ma, and an active margin ran from Sarawak east towards the Philippines (Hall 1996, 2002). In north Borneo, in the Eocene to Early Miocene, there was southeast-directed subduction (Hall & Wilson 2000; Hutchinson et al. 2000) and the Crocker Fan (van Hattum et al. 2006) formed above the subduction zone at the active margin. There was relatively little Eocene to Early Miocene subduction-related magmatism (Kirk 1968; Hutchinson et al. 2000; Prouteau et al. 2001) in Borneo, probably because the proto-South China Sea flowed westwards (Hall 1996, 2002).

However, the most important effect was the initiation of widespread rifting throughout Sundaland leading to subsidence and accumulation of vast amounts of sediment in sedimentary basins. It is suggested here that this rifting was a response to the regional stresses imposed on Sundaland during the breaking of the plate which was required in order to begin subduction.

**SUBDUCTION INITIATION**

Starting subduction is widely considered to be a very difficult process (McKenzie 1977; Mueller & Phillips 1991) for which the dynamics remain poorly understood (Cloetingh et al. 1982; Toth & Gurnis 1998), and has been described as a fundamental, yet poorly understood, process (Hall et al. 2003) or as one of the unresolved problems of plate tectonics (Regenaur-Lieb et al. 2001). None the less, the process must occur regularly and continuously, since long-lived subduction zones disappear and new ones form in other places (Toth & Gurnis 1998). Since McKenzie’s (1977) demonstration that creating trenches is difficult, the problem has been investigated theoretically using numerical and analogue modelling, and most studies have concentrated on breaking a plate in two types of tectonic setting: within an oceanic plate and at a passive continental margin.

There is still considerable uncertainty. It is generally agreed that the stresses required to initiate subduction are very large (McKenzie 1977; Cloetingh et al. 1982; Mueller & Phillips 1991) and, therefore, there have been many suggestions that oceanic lithosphere may break at pre-existing zones of weakness, such as transform faults and fracture zones (Toth & Gurnis 1998; Hall et al. 2003), especially those that are serpentinized (Hilairet et al. 2007). Lateral buoyancy contrasts may also be important, such as might be found at the edges of large oceanic plateaux (Niu et al. 2003). In numerical modelling the assumption of rheology is important; a non-Newtonian viscosity may make subduction initiation easier (Billen & Hirth 2005) and convergence rate is also a significant factor (Hall et al. 2003; Billen & Hirth 2005).

All modelling confirms that old passive margins are difficult to turn into subduction zones. Increasing the age of passive margin does not make it easier to initiate subduction (Cloetingh et al. 1982) and the negative buoyancy of old oceanic lithosphere is insufficient in itself to lead to trench formation. Again, pre-existing weaknesses may be important (Cohen 1982) and faults may be reactivated if convergence is oblique (Erickson 1993). Sediment loading of young lithosphere may play a part (Cloetingh et al. 1982), and sediment loading over long periods (100 Ma) may trigger subduction (Regenaur-Lieb et al. 2001). Water may play an important role in weakening young lithosphere beneath a sediment load (Regenaur-Lieb et al. 2001).

Faccenna et al. (1999) described three scenarios based on analogue modelling. The first produces only folding of oceanic lithosphere and no subduction is initiated at the passive margin; this resembles the situation south of India at the present day (Martinod & Molnar 1995). In this case, it is easier to deform continental Asia than break the plate (Stern 2004). In the two other cases, either an Atlantic-type passive margin evolves over a long period to form a trench or, in the other, the continent collapses towards the ocean, producing back-arc extension and subduction, resembling the Mediterranean. The result depends on the brittle and ductile strength of the passive margin, the negative buoyancy of the oceanic lithosphere, and the horizontal body forces between continent and ocean. Mart et al. (2005) also experimented with analogue models, but in a centrifuge, and suggested that lateral density differences at continental margins may influence the initiation of subduction.

McKenzie (1977), Mueller & Phillips (1991) and Toth & Gurnis (1998) all included inclined pre-existing faults in their models, but Mueller & Phillips (1991) differed in their estimate of resisting stresses on the faults and consequently found subduction initiation to be very unlikely. McKenzie (1977) and Toth & Gurnis (1998) agreed on the magnitude of the stresses required, but McKenzie (1977) concluded that ridge-push forces were insufficient to cause subduction initiation, whereas Toth & Gurnis (1998) argued that they were sufficient, and that combined with additional forces from adjacent subduction zones, subduction initiation is not difficult and expected to be common in the Western Pacific. Observations around SE Asia where there are numerous young subduction zones that have initiated in the last 15 Ma, including the Manila, Negros, Cotabato, North Sulawesi and Philippine Trenches (e.g. Cardwell et al. 1980; Karig 1982; Hall 1996, 2002), support this conclusion. All have developed at the boundaries between ocean crust and thickened arc crust, typically at the edges of small basins, where there is both a topographic and buoyancy contrast.

**SETTING OF BASIN FORMATION**

Features that have been identified in different models as important or critical were present during the Eocene at the Sundaland margins, including pre-existing dipping faults, bathymetric and buoyancy contrasts, weak serpentinized zones, and probable considerable sediment loads. Early Cretaceous Sundaland had been surrounded by active margins and Karig (1982) identified former subduction zone margins which he called ‘deactivated continental or arc margins’ to be likely sites of subduction initiation. At about 45 Ma, Australia began to separate rapidly from Antarctica, hence increasing ridge-push stresses on the Sundaland margin. SE Asia today, and during the Cenozoic, has been the site of exceptionally high rates of sediment supply (e.g. Milliman et al. 1999; Hall & Nichols 2002; Suggate & Hall 2003; Hall & Morley 2004), and it is likely that much of Sundaland was elevated following Cretaceous collisions. Thus, a considerable sediment load at the Sundaland margins is probable.

It is not easy to identify the consequences of subduction initiation on the region from the present limited understanding of the process and, therefore, the following scenario is somewhat speculative. I suggest that in the Middle Eocene, the Sundaland region went into regional compression as Australia attempted to move north (Fig. 9). This would have meant approximate N–S compression and, in consequence, approximately E–W extension, causing basins to form. The local extension direction varied considerably, initially because of variations in basement fabric and, later, because once subduction began, these were augmented by other forces around Sundaland due to the different types and orientations of plate
boundaries. There has been little work on topographic effects as subduction begins, although Toth & Gurnis (1998) showed that in their models a long wavelength depression developed on the overriding plate with a wavelength of \( \sim 400 \text{ km} \). All the models, numerical and analogues, have used simple and typical strengths for different types of lithosphere but, as summarized above, Sundaland is not typical (Hall & Morley 2004) and there is a very large region of weak lithosphere extending more than 900 km to the north of the Sunda Trench (Hyndman et al. 2005; Currie & Hyndman 2006) where plate boundary forces are greater than the strength of the plate in compression.

Thus, once subduction had started it is likely that stresses in different parts of Sundaland varied considerably, leading to reactivation of different structures in the various basins at different times, and resulting in changing orientations of faults, multiple episodes of extension, and inversion. For example, the extension direction observed in the Nam Con Son and Cuu Long basins is likely to reflect an interaction of the regional stresses imposed by subduction initiation, basement structures in the Vietnam margin, slab-pull forces due to southeast-directed subduction of the proto-South China Sea, and far-field effects of India–Asia convergence. The tectonic development of SE Asia in the last 45 Ma (Hall 2002), involving subduction, hinge movements, arc and microcontinent collisions, and new ocean basin formation, led to a complex and frequently changing distribution of forces at the Sundaland margin; Hall &

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**Fig. 9.** The situation just before and just after subduction began beneath Sundaland at about 45 Ma. The initiation of subduction required the plate to be broken at the Sundaland continental margin and it is suggested that compression induced broadly E–W extensional stresses, which were locally re-orientated by basement structures. After subduction was initiated, plate edge forces became increasingly important.
Morley (2004) illustrated these changing forces in a schematic way for different intervals during the Cenozoic and Figure 9 shows the possible forces that influenced basin formation and orientation of local extensional stresses just before and just after subduction began. The subsequent development of the basins, including such features as relative age and sedimentary fill, importance of continental rift inheritance for source and reservoir distribution, and heat flow histories, is described and discussed elsewhere (e.g. Williams et al. 1995; Howes & Noble 1997; Longley 1997; Petronas 1999; Hall & Morley 2004; Doust & Sumner 2007).

CONCLUSIONS

Although it is now widely accepted that the Sundaland basins are dominantly extensional, the origin of the extensional forces remains uncertain. McKenzie-type models are widely applied, but the setting of SE Asian basins is very different from intra-continental rifts like the North Sea, or passive margins like those of the Atlantic, where such models were developed and work well. India–Asia collision was not the cause of basin formation. Even if the indenter model is accepted, the timing of basin initiation is earlier than major movements on the strike-slip faults and there are many other counter arguments discussed elsewhere (e.g. Morley 2002; Hall & Morley 2004; Hall et al. 2008). The collision is often identified as a cause in rather a mystical manner with no clear indication of what was happening, or where India was in relation to SE Asia. Furthermore, there is now doubt about the timing of India–Asia collision which may be significantly younger than previously accepted. Basin formation was well underway before the end Eocene age for continent–continent collision proposed by Aitchison et al. (2007).

Most of the models proposed for basin formation could be right in the sense that all could apply somewhere in the Sundaland region. The regional compression proposed here would cause extension by pure or simple shear, but a variety of different local stress systems may result from other influences, such as local basement structure, reactivated faults, shape of the continental margin, type of crust on each side of the new plate boundary, and locally weak or strong layers within the lithosphere. The composite character of the Sundaland lithosphere means that all of these could apply and local principal stresses could vary considerably around the region.

It is most likely that the plate broke by a tear propagating through the region from an existing plate boundary. This suggests a west to east propagation of the tear from North Sumatra eastwards. However, this is speculative, and the character and orientation of plate boundaries at the Pacific end of the system are not known. The weakness of the lithosphere in the region means that many basins did not subsequently have simple histories. Many are characterized by changing stresses, reflected, for example, in multiple episodes of extension and different directions of extension. This is due to changing balance of forces at plate edges and their interaction with basement fabric, all driven by multiple subduction-related processes. Subduction has been the most important influence on SE Asia for all of its history, and still is.

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Hydrocarbon basins in SE Asia
