Subsidence and uplift by slab-related mantle dynamics: a driving mechanism for the Late Cretaceous and Cenozoic evolution of continental SE Asia?

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Abstract: Continental SE Asia is the site of an extensive Cretaceous–Paleocene regional unconformity that extends from Indochina to Java, covering an area of c. 5 600 000 km². The unconformity has previously been related to microcontinental collision at the Java margin that halted subduction of Tethyan oceanic lithosphere in the Late Cretaceous. However, given the disparity in size between the accreted continental fragments and area of the unconformity, together with lack of evidence for requisite crustal shortening and thickening, the unconformity is unlikely to have resulted from collisional tectonics alone. Instead, mapping of the spatial extent of the mid–Late Cretaceous subduction zone and the Cretaceous–Paleocene unconformity suggests that the unconformity could be a consequence of subduction-driven mantle processes. Cessation of subduction, descent of a northward dipping slab into the mantle, and consequent uplift and denudation of a sediment-filled Late Jurassic and Early Cretaceous dynamic topographic low help explain the extent and timing of the unconformity. Sediments started to accumulate above the unconformity from the Middle Eocene when subduction recommenced beneath Sundaland.

Throughout continental SE Asia (referred to here as Sundaland; Fig. 1) there are almost no Upper Cretaceous and Paleocene strata, suggesting that much of the region was elevated during this time. Cenozoic rocks rest on older rocks with a profound unconformity. Rocks beneath the unconformity are considered basement and comprise predominantly Cretaceous and older granites, Mesozoic sedimentary rocks, accreted ophiolitic and arc rocks, and pre-Mesozoic metamorphic rocks. Sedimentary rocks above the unconformity are Eocene and younger (Fig. 1) and include siliciclastic, volcanogenic and carbonate lithologies that were deposited across the region in extensional half-graben basins, and at the Sundaland continental margins. These deposits are initially commonly terrestrial and their depositional ages are often poorly constrained.

The unconformity has previously been interpreted as the result of a poorly defined tectonothermal event that occurred throughout Indochina and the Malay Peninsula (e.g. Krähenbuhl 1991; Ahrendt et al. 1993; Dunning et al. 1995; Upton 1999) or as a consequence of continental collision at the Sundaland margin (e.g. Hall & Morley 2004; Smyth et al. 2007; Hall 2009). However, there has been no attempt to estimate the extent of, or describe, the unconformity itself, or to propose a driving mechanism capable of producing uplift over such a large area.

In this paper we demonstrate that the area covered by the unconformity is in excess of 5 600 000 km² (c. 2000 km by c. 2800 km – greater than the area of the Western United States; Fig. 2 or ten times the size of mainland France) and it extends from Indochina to SE Borneo and East Java (Fig. 1), and that micro-continental collisions in the Late Cretaceous were coincidental with the onset of regional uplift. However, from an assessment of the spatial extent of accreted continental crust, the corresponding extent of the unconformity (Fig. 1), and regional exhumation trends, we suggest that uplift of a Late Jurassic to Early–mid Cretaceous dynamic topographic low (DTL) also contributed to the formation of the unconformity. Uplift was triggered by termination of subduction, slab detachment and the resulting dynamic rebound across the region. Furthermore, we support the suggestion (Hall 2009) that the initiation of Cenozoic basin development may have been related to resumption of subduction at c. 45 Ma.
Fig. 1. (a) Our interpreted extent of the unconformity, the core of Sundaland as defined by Hamilton (1979), and the approximate positions of accreted ophiolitic and arc-type rocks and continental fragments added to the margin in the Late Cretaceous. (b) Sedimentary basins and their ‘ages’ in the region that is affected by the unconformity. Highlighted basins are the Malay, Nam Con Son, West Natuna, Central Sumatra, South Sumatra, Kutei, Barito and SE Java basins (Polochan et al. 1991; Gwang et al. 2001; Doust & Noble 2008; Smyth et al. 2008) – simplified lithostratigraphies are shown in Figure 6.
Expected styles of uplift: collisional-v. mantle-driven

Geologists have long recognized that convergence of continental lithospheric blocks or plates is accommodated by crustal thickening and regional uplift (orogenesis). This occurs over relatively short distances (tens to hundreds of km; Murrell 1986) perpendicular to the collision suture but may extend great distances along strike, forming an orogenic belt. During continental collision, deformation starts at the margin of the indenting plate with continued convergence leading to development of a fold-thrust belt that propagates outwards from the collision suture. Rapid exhumation of lower crustal material is common, marking significant rock uplift and related denudation, and the resulting unconformity often cuts deep into basement rocks with dimensions reflecting the pattern of crustal deformation (i.e. narrow across, and elongate along strike). The size of the indentor, rate of convergence and pre-existing structural trends are all important factors that may modify styles of deformation (e.g. Murrell 1986; Ellis 1996; Willingshofer & Sokoutis 2009), uplift and the extent of the resulting unconformity. Even major orogens such as the European Alps and New Zealand’s Southern Alps show topographic profiles that rarely exceed several hundred kilometres in width (Fig. 3) (Koons 1995). Deformation belts in smaller orogens involving less significant collisions are often much narrower. Where contractional deformation is observed away from continental margins these are often sites of older stretching and crustal thinning. Here, intra-plate stresses drive inversion that is initially linked to the reactivation of individual, pre-existing (extensional) faults, with further compression also leading to fold-thrust belt development and orogenesis (e.g. the European Pyrenean orogen; Munoz 1992).

Intra-plate stresses can also be manifest as vertical crustal movements that result from lithospheric folding (e.g. Lambeck et al. 1984; Cloetingh et al. 1999, 2006; Horváth et al. 2006). Typically, theoretical studies suggest that coupled and decoupled behaviour of continental lithospheres generate mono- and biharmonic modes of folding respectively (Gerbault et al. 1999; Faccenda et al. 2009) and the spacing between regularly distributed folds can be expected to be 4–8 times the thickness of the competent layer (brittle crust) (Martinod & Davy 1994). However, examples of irregular lithosphere folding (e.g. Cloetingh et al. 1999), as observed in the Pannonian–Carpathian region, may be up to 25–40 times (350–400 km wavelength) the thickness of the brittle crust (Dombrádi et al. 2010). In such instances of lithospheric folding the associated unconformity could be expected to be broad and with minimal incision,

Fig. 2. Indonesia, Malaysia and Indochina compared to the USA. The SE Asia Regional Unconformity is 5600000 km² (c. 2000 by c. 2800 km) – greater than the area of the Western United States. The box is 60° from west to east and 30° from north to south (Indonesia and Malaysia comparison to USA modified from Hall & Smyth 2008).

Fig. 3. Topographic profiles from (a) Southern Alps, New Zealand and (b) the Western European Alps (modified from Koons 1995) illustrating that even major orogens rarely exceed several hundred kilometres in width.
but not to extend beyond the fold crest. Importantly, physical models (Dombrádi et al. 2010) predict that such fold wavelengths are reduced dramatically when crustal heterogeneities are present, particularly if the lithosphere is hot and weak.

Lithospheric flexure, driven by crustal loading/subduction processes, may also contribute locally to uplift, although the viscoelastic nature of continental lithosphere dictates that such uplift cannot be sustained for (geologically) long periods of time (e.g. $10^4$ to $10^6$ years or more). Such estimates are dependent upon mantle viscosity and the flexural rigidity of the lithosphere.

Processes in the viscous mantle (buoyancy forces/mass anomalies) have also been shown to drive uplift and subsidence of continental and oceanic lithosphere (e.g. Gurnis 1990, 1992, 1993; Lithgow-Bertelloni & Gurnis 1997). Mass anomalies in the mantle transmit stress to the base of the lithosphere via viscous flow and create dynamic topography (e.g. Gurnis 1993; Moucha et al. 2008). For example, viscous mantle flow associated with subduction of a cold, dense slab causes subsidence creating a dynamic topographic low (DTL; Fig. 10b). The DTL can extend thousands of kilometres from the subduction zone and have an amplitude of several hundred metres to more than 1 km depending on the dip and age of the slab (e.g. Burgess & Moresi 1999; Husson 2006; Steinberger 2007). When the slab detaches and sinks into the mantle the viscous forces maintaining the DTL are reduced or removed, and the area is uplifted (Fig. 10d). Any sedimentary rocks deposited in the DTL will tend to be eroded, generating an unconformity, the extent of which is similar to the original DTL (e.g. Gurnis et al. 1996; Burgess et al. 1997). Uplift is further accentuated by denudation and the resultant isostatic rebound, with a damped positive feedback driving further uplift.

Sundaland: continental SE Asia

Much of Sundaland (Fig. 1) is allochthonous and it is a composite region of continental fragments (terranes), volcanic arcs and oceanic accretionary complexes that successively rifted and separated from the margin of eastern Gondwana at various times during the Palaeozoic and Mesozoic (e.g. Metcalfe 1996) and were added to a growing Eurasia. All of these terranes are interpreted to have been derived directly or indirectly from Gondwana (e.g. Sengor 1979; Audley-Charles 1983; Metcalfe 1988) based mainly on comparative studies of the stratigraphy, palaeontology and palaeomagnetism. The continental core of Sundaland comprises the Indochina–East Malaya Block and the Sibumasu Block, both of which separated from Gondwana in the Palaeozoic and amalgamated with the South and North China blocks in the Triassic. Three further blocks were subsequently added to the core of Sundaland; the SW Borneo Block (Hall 2009; Hall et al. 2009) followed by the East Java–West Sulawesi Block (Smyth et al. 2007; Hall 2009) (Fig. 1) were both derived from Gondwana. The Dangerous Grounds Block (Fig. 1) was probably derived from the South China margin (Hall et al. 2009).

Sundaland includes the landmasses of Borneo, Java, Sumatra and the Thai–Malay Peninsula and extends northwards into Indochina (Fig. 1) and is characterized by very little seismicity and volcanism in the interior, away from the active margins. The region has experienced terrestrial to shallow marine conditions for most of the Cenozoic. The area that lies between the major landmasses is referred to as the Sunda Shelf (Fig. 1) and is typically flat and extensively shallow with water depths rarely exceeding 200 m (Hall 2009). These features have led to the common misconception that Sundaland has been a stable area during the Cenozoic (see discussions in Hall 2002, 2009; Hall & Morley 2004) often being referred to as a shield or craton (Ben-Avraham & Emery 1973; Gobbett & Hutchison 1973; Tjia 1992, 1996) or plate (e.g. Davies 1984; Cole & Crittenden 1997; Replumaz & Tapponnier 2003). The apparent stability of the Sunda Shelf (e.g. Geyh et al. 1979; Tjia 1992, 1996; Hanebuth et al. 2000) has resulted in data from the region being used in global eustatic sea level curves (e.g. Haq et al. 1987; Fleming et al. 1998; Bird et al. 2007). Sundaland lithosphere however differs markedly from other regions (e.g. African, Australian, Baltic Canadian shields) of stability (e.g. Hall & Morley 2004; Hyndman et al. 2005; Currie & Hyndman 2006; Hall 2009), and exhibits high heat flow (Doust & Sumner 2007; Hall 2009) and low seismic velocities in the lithosphere and asthenosphere (e.g. Widiyantoro & van der Hilst 1997; Bijwaard et al. 1998; Ritsema & van Heijst 2000). These observations indicate that the lithosphere is thin and weak in the region (Hall & Morley 2004; Hyndman et al. 2005). These characteristics are a consequence of prolonged subduction (Hyndman et al. 2005) and are typical of other back-arc mobile belts such as the North American Cordillera and parts of the NW Pacific (Hyndman et al. 2005).

Evidence for Cretaceous subduction and collision in SE Asia

Plutonic and volcanic rocks

There are abundant plutonic and volcanic rocks of Jurassic and Early–mid Cretaceous age exposed in
Sumatra, SE Borneo, Vietnam, and along the eastern China margin that are generally accepted to be subduction related. These typically occur inboard from the zone of subduction complexes (where present – see below) and, in many places, demonstrate that there was subduction beneath the Sundaland–Eurasian margin prior to collisions in the early Late Cretaceous.

In Sumatra there are abundant I-type plutons (Late Jurassic and Early Cretaceous) that are exposed along the entire active margin (McCourt et al. 1996) and which formed above a northeastward dipping subduction system (beneath Sundaland). Associated with these are volcanic rocks such as Lower Cretaceous andesites exposed in the Omblin Basin (e.g. Koning & Aulia 1985) as well as other examples from within the Sumatra Fault Zone (e.g. Rosidi et al. 1976). In SE Borneo there are andesitic lavas, tuffs and volcanic breccias that are assigned entirely to the Haruyan Formation by Wakita et al. (1998) or placed within the Alino Group by Sikumbang & Heryanto (1994) and Yuwono et al. (1988) that are interpreted to represent a volcanic arc suite. These lithologies are approximately Late Aptian to Cenomanian in age (115–93.5 Ma) (Yuwono et al. 1988; Wakita et al. 1998).

Widespread granitic magmatism in mainland eastern China during the Late Jurassic and Early Cretaceous is generally accepted to be subduction related. Jahn et al. (1976) suggest that a Cretaceous (120–90 Ma) thermal event along the SE China margin was related to westward-directed Pacific subduction. Subduction-related magmatism had ceased in Southern China by 80 Ma (Li & Li 2007). Zhou et al. (2008) used geophysical data to propose that a Jurassic to Early Cretaceous subduction complex can be traced south from Taiwan along the present northern margin of the South China Sea and was displaced to Palawan by opening of the South China Sea. Cretaceous granites are also reported from Vietnam (Nguyen et al. 2004) with youngest ages of 88 Ma. There was probably collision along parts of the eastern margin of Sundaland during the Late Cretaceous. Hall et al. (2009) suggest that the Dangerous Grounds Block became part of the Asia margin at about 90 Ma having rifted from the China margin (Fig. 4). There is little evidence for subduction after 80 Ma along the South China margin.

**Subduction complexes**

Cretaceous subduction complexes including ophiolitic and arc-type rocks are exposed along the west coast of Sumatra, in Java and in SE Borneo, and are products of prolonged subduction beneath Sundaland that continued until the early Late Cretaceous (Fig. 1). In Sumatra, the Woyla Group includes ophiolitic rocks, pelagic and volcanicleastic sedimentary rocks (Fig. 5f), and basaltic-andesitic volcanic rocks, interpreted as a Late Jurassic–Early Cretaceous intra-oceanic arc (Barber & Crow 2005). The timing of collision with Sumatra is estimated at 98–92 Ma (M. J. Crow, pers. comm. 2008) based on overthrust Aptian–Albian fringing reef carbonates (Fig. 5e) and associated metamorphism of rocks of mid Cretaceous age (Barber & Crow 2009). In Java, similar subduction-related lithologies comprise pillow basalts (Fig. 5a), cherts (Fig. 5b), limestones, schists and metasedimentary rocks, interpreted as arc and ophiolitic terranes (e.g. Parkinson et al. 1998; Wakita 2000). Ultra-high pressure metamorphic rocks at Karangsambung, East Java, such as jadeite–quartz–glaucophane-bearing rocks and eclogites (Fig. 5d), are diagnostic of subduction metamorphism (Miyazaki et al. 1998). Radiolarian biostratigraphy (Wakita & Munasri 1994) and K–Ar dates on muscovite from quartz-mica schist (124–110 Ma; Miyazaki et al. 1998; Parkinson et al. 1998) yield Cretaceous
ages for subduction-related rocks. In the Meratus Mountains, SE Borneo, ultramafic rocks (Fig. 5c), basalt, chert, siliceous shale, melange and schist are interpreted to represent accreted arc and oceanic-type crust (Parkinson et al. 1998; Wakita et al. 1998). Radiolarian biostratigraphy yields ages that range from early Middle Jurassic to early Late Cretaceous (Wakita et al. 1998).

Fig. 5. (a) Pillow basalts and (b) deformed radiolarian cherts from Karangsambung, Central Java, that were obducted during collision of the East Java–West Sulawesi microplate. (c) Sheared serpentinized peridotites from the Meratus Mountains accretionary belt, SE Borneo. (d) High temperature – very high pressure eclogite from Karangsambung, Central Java. This is of probable Cretaceous age and is related to the Meratus subduction system that existed prior to collision of the East Java–West Sulawesi microplate. (e) Limestone islets of the Woyla Group off the west coast of Sumatra, near Lhoknga, Aceh. These limestones have yielded Late Jurassic to Early Cretaceous fossils (Barber & Crow 2005, p. 41) and probably fringed volcanic cones of the Woyla oceanic arc (A. J. Barber, pers. comm., 2009). (f) Folded volcanioclastic sandstones of the Woyla Group, North Sumatra.
Timing of collision

Collision of the East Java–West Sulawesi block (Hall 2009) was probably responsible for termination of subduction beneath Sundaland (Smyth et al. 2007). The collision must have been later than the youngest radiolarian ages associated with pillow basalts in Java and Borneo (early Late Cretaceous), and the fragment must have been in place before initiation of the present phase of subduction at c. 45 Ma (Hall 2002, 2009). New plate reconstructions (Hall et al. 2009), based on the evidence summarized above and the beginning of a widespread hiatus in magmatism along the margin, indicate that the fragment arrived between 92 and 80 Ma. Clements (2008) and Clements & Hall (2008) suggest an age of c. 80–85 Ma based on U–Pb dating of zircons in Eocene fore-arc sandstones in West Java that record arc volcanism prior to collision and post-collisional magmatism.

![Fig. 6. Regional lithostratigraphic chart. Basins have been chosen as representative of sedimentary fill across the region – basin locations are shown in Figure 1. The earliest sedimentary fill in many of the basins was deposited in a terrestrial setting and depositional ages are poorly constrained. Ascertaining more precise ages for the earliest stages of fill in these basins, particularly in SE Borneo, is the focus of current research. Note that ‘basement’ refers to the pre-Cenozoic section. Modified from Polochan et al. (1991), Gwang et al. (2001), Doust & Noble (2008) and Smyth et al. (2008).]
A Late Cretaceous to Eocene unconformity

We draw attention to the size of the SE Asia Regional Unconformity and the SE Asia region in Figure 2 by comparing both to the United States. The extent of the unconformity is shown in Figure 1. Few sedimentary rocks of latest Cretaceous and Paleocene age (Fig. 6) are preserved within this area, except in NW Kalimantan and Sarawak where there are marginal marine and terrestrial clastic sediments (summarized by Hutchison 2005). Where observed on land – in places such as Sumatra, Java and Borneo – the unconformity is angular and overlies variously deformed rocks that are Cretaceous and older (Fig. 7 shows the unconformity in West Sumatra and Fig. 8a, b illustrates the nature of Eocene terrestrial sequences immediately above the unconformity). The unconformity has also been penetrated throughout the region by exploration drilling offshore (e.g. Hamilton 1979). In the next sections we discuss evidence for regional exhumation from thermochronological studies as well as the nature of rocks that were deposited in the DTL immediately prior to uplift in the early Late Cretaceous.

Regional exhumation data

Thermochronological studies from across the region provide direct constraints on the widespread uplift, erosion and exhumation of basement rocks during the Late Cretaceous and Early Palaeogene. The paucity of such studies in the south (e.g. Java) reflects a lack of exposed pre-Cenozoic rocks, and an abundance of younger (Cenozoic) volcanic rocks that dominate the stratigraphy.

The region that extends from the Shan Plateau of Myanmar and northern Thailand through Laos into the Lanping-Simao fold belt was elevated at the beginning of the Cenozoic (Hall & Morley 2004). This elevation is attributed to a ‘diffuse [and] poorly defined orogenic event’ by Upton (1999) and Hall & Morley (2004). Apatite Fission Track (AFT) studies in Thailand and Laos indicate slow cooling between 90 and 45 Ma (Racey et al. 1997; Upton 1999), and in NW Thailand Upton (1999) interprets ‘gentle’ cooling between 70 and 50 Ma, with modelled exhumation rates of 0.048–0.083 km/Ma. Upton (1999) suggests that exhumation in NW Thailand was driven by minor (c. 600 ± 200 m) ‘tectonic’ uplift that ‘started a cycle of erosional denudation driven by isostatic rebound’ sufficient to generate the observed levels of denudation. Along the western margin of the Khorat Plateau in eastern Thailand, 2.3–4.4 km of Jurassic–Cretaceous overburden is estimated to have been removed since c. 65 Ma, and 2–6 km was removed during the Palaeogene in parts of western Thailand (Hall & Morley 2004 and references therein). Carter et al. (2000) interpret a common uninterrupted (slow) (c. 1–1.5 °C/Ma) cooling history in eastern Vietnam between 61 and 48 Ma based on AFT analyses with associated denudation of 1.4–2 km. K–Ar dates and ZFT ages from the Malay Peninsula also indicate a local increase in cooling rate in the Late Cretaceous (e.g. Krähenbuhl 1991).

Rocks beneath the unconformity

Continental red beds of the Upper Jurassic–Lower Cretaceous Khorat Group and lateral equivalents (Racey 2009) are exposed over large areas of eastern Thailand, Laos, Cambodia and parts of Vietnam, southern Thailand, and Peninsular Malaysia (Racey 2009; Fig. 9), and are relatively undeformed (Harbury et al. 1990). These are predominantly fluvial, alluvial and lacustrine facies with lagoonal sandstones, mudstones and limestones also present (Racey & Goodall 2009) (Fig. 8c, d).

Causes of different styles of basin evolution for the Upper Jurassic–Lower Cretaceous red beds in the region are generally poorly understood (Racey 2009). The Khorat Group in NE Thailand is...
Fig. 8. (a) & (b) are Eocene siliciclastic sedimentary rocks that lie immediately above the SE Asia Regional Unconformity (a) Upper Eocene quartz-rich sandstones of the Bayah Formation, West Java – the lower sequence comprises overbank mudstones and crevasse-splay sandstones; the upper sequence is a massive channel sand body. (b) Sequence of conglomerates and conglomeratic sandstones of the basal member, Tanjung Formation, Barito Basin, SE Borneo. A small weathered granitic outcrop (basement) lies immediately to the right, out of shot, of the section. (c) & (d) are Mesozoic alluvial and fluvial red bed sedimentary rocks that lie beneath the unconformity over large parts of the region and were deposited in the DTL. (c) fluvial and alluvial pebbly sandstones from the Khorat Group, NE Thailand and (d) from the Tembling Group, Malay Peninsula. Note the similarity in lithological character between the Mesozoic and Cenozoic sequences.
commonly interpreted to have been deposited in a thermal sag basin (e.g. Cooper et al. 1989) following Late Triassic extension and orogenic collapse of the Early Triassic Indosinian orogen. Others suggest a foreland basin setting (e.g. Lovatt-Smith et al. 1996; Racey 2009) that formed in front of a Jurassic orogenic belt that was situated to the north or NE. Racey (2009) draws attention to the lateral continuity of the Khorat Group stating that the deposits are of ‘broad lateral extent [and of] relatively uniform thickness’. Lovatt-Smith et al. (1996) note that on seismic data there is little evidence for fault-controlled accommodation during deposition and that the Khorat Group formations have a mainly ‘layercake’ appearance. Gentle folding of Mesozoic strata in the Malay Peninsula has been interpreted as evidence for a phase of uplift in the mid–Late Cretaceous (Harbury et al. 1990). Upper Jurassic–Lower Cretaceous red bed sequences typically unconformably overlie older, more intensely deformed metasedimentary rocks (Gobbett & Hutchison 1973; Harbury et al. 1990).

In the south between Java, Sumatra and Borneo, basement has been penetrated by offshore drilling. The most abundant lithologies are granitic rocks and low-grade metasedimentary rocks, with gneiss, quartz diorite, diorite, and mafic and silicic rocks occurring locally (Hamilton 1979). K–Ar ages from this area reported by Hamilton (1979) are predominantly Cretaceous. Lower Cretaceous unmetamorphosed limestones lie beneath the unconformity in one area north of West Java (Hamilton 1979).

Testing the hypothesis: an unconformity due to dynamic topography

As highlighted above, there is no evidence for extensive crustal shortening or orogenesis in the early Late Cretaceous across much of Sundaland. Throughout the region there are older (Palaeozoic?) rocks that are, in places, highly deformed and of medium to high metamorphic grade (e.g. the Malay Peninsula; Harbury et al. 1990). However, these rocks are commonly overlain by relatively undeformed and unmetamorphosed sedimentary rocks of Jurassic and Early Cretaceous age and must therefore represent older regional tectonic events.

There is little evidence for the existence of belts of exhumed (high-grade metamorphic) rocks that might be expected had there been major Late Cretaceous–Paleocene orogenesis and subsequent uplift throughout the region. There is some evidence for crustal shortening at the Sundaland margins during the Late Cretaceous (e.g. the Meratus Mountains, SW Borneo; western Sumatra – discussed above) and this is interpreted as the result of collision, but this deformation did not extend into the Sundaland interior for any considerable distance. Significant deformation (thrusting) at the Sundaland margin is reported by Clements et al. (2009) to affect Neogene rocks in Java, but this deformation also cannot be traced very far northward away from the margin.

We speculate that in the Late Jurassic and Early Cretaceous there was an extensive and broadly low-lying region dominated by fluvial and alluvial sedimentation (e.g. the Khorat Group and lateral equivalents; Racey 2009) with limestones developing at the continental margins (e.g. limestones in part of the NW Java Sea; Hamilton 1979) and perhaps other strata since removed. This setting is consistent with that expected for a DTL maintained.

Fig. 9. The extent of Late Jurassic – Early Cretaceous red beds in Indochina and the Thai–Malay Peninsula. These sequences show remarkable lateral continuity and there is little evidence of major faulting controlling deposition – all consistent with deposition in a DTL.
Regional exhumation data are all consistent with gradual (slow?), long-wavelength uplift between c. 85 and 45 Ma. It is clear that previous studies consider this uplift enigmatic, concluding, for example, that the event was ‘poorly defined’ (Dunning et al. 1995) or ‘diffuse’ (Hall & Morley 2004). The estimated c. 600 ± 200 m of ‘tectonic’ uplift required to positively feedback and drive further uplift and denudation reported by Racey et al. (1997) in western Thailand is comparable to that generated by dynamic topography above a subducting slab (e.g. Burgess & Moresi 1999). Sundaland crust was probably thin, hot and weak as a consequence of prolonged subduction beneath the region during the Late Jurassic and Early Cretaceous (see discussion by Hyndman et al. 2005) precluding major crustal up-warping. The unconformity cannot be a consequence of intra-plate stresses alone given its extent, and the extreme heterogeneous character of the Sundaland continental region (Hall 2011), which would only serve to dramatically reduce the wavelength of irregular lithospheric folding (Dombrádi et al. 2010). Importantly, the thickness of the crust is unlikely to influence dynamic topography, which is driven by mantle processes transmitting stresses to the base of the lithosphere. Of critical importance however is the ability to distinguish subsidence due to stretching from subsidence due to dynamic topography; something that has proven problematical in Cenozoic studies of the region (e.g. Wheeler & White 2000).

Eustatic sea level fall from the early Late Cretaceous through Palaeogene could also have contributed to unconformity development. However, pre-Neogene eustatic history is essentially unknown, and eustatic models predicting Cretaceous to Palaeogene eustatic change differ significantly, even regarding long-term changes. For example, Miller et al. (2005) show a eustatic curve derived from backstripping of strata on the New Jersey coastal plain. Their curve features an approximately constant eustatic sea level from Cenomanian through Maastrichtian time, followed by a c. 30 m rise into the Early Eocene, and then a fall of about 60 m into the Oligocene. This differs substantially from the Haq et al. (1987) curve which shows a long term fall of c. 50 m from the Cenomanian to Maastrichtian, possibly because the Haq curve is based in part on stratigraphic studies of SE Asia, although the method and data used in derivation of the Haq curve has always been rather obscure. Further work is required to evaluate and understand the impact of these possible eustatic histories in SE Asia although clearly the impact of subduction-driven subsidence and uplift means that such regions are not as stable as has previously been assumed and their suitability for inclusion in studies that assess eustatic sea level may be problematical at best.

At c. 85 Ma collisions terminated subduction beneath Sundaland at the Sumatra–Java–Borneo margin and possibly in northern Borneo at c. 80 Ma. The termination of subduction in a zone surrounding much of continental SE Asia had a profound effect on the region. The detachment of Tethyan oceanic lithosphere followed by its slow descent into the mantle drove regional uplift and reversed a Late Jurassic–Early Cretaceous DTL (Fig. 10). This process of slow mantle-driven uplift was accentuated by denudation and associated isostatic rebound further driving regional uplift.

![Fig. 10. Schematic diagram illustrating how dynamic topography forms above subducting slabs due to stresses generated at the base of the lithosphere by the slabs negative mass anomaly in the mantle.](image-url)

(a) Predicted dynamic topography (Modified from Burgess & Moresi 1999) (note that the vertical scale from this profile is different to that of parts b, c and d). (b) Dynamic topography above a subducting slab at the Sundaland margin and, (c) above facing subduction systems for example, southern Sundaland at c. 100 Ma (as in Fig. 4). (d) Collision and detachment of oceanic lithosphere would drive regional uplift creating an unconformity similar to the Late Cretaceous–Palaeocene SE Asia Regional Unconformity. Note that in places there may still be a DTL stratigraphic sequence preserved as is the case in SE Asia, particularly in the northern parts of Sundaland.
We suggest that renewed deposition above the unconformity was in part related to the onset of subduction at c. 45 Ma (Hall 2009). Although the style of sedimentation during the Eocene and Oligocene (clearly localized in fault-controlled basins) was markedly different to that during the Jurassic and Early Cretaceous (laterally continuous and not fault controlled), the onset of sedimentary basin formation coincided with the renewal of subduction. The resumption of subduction at this time clearly impacted the Sundaland region but it also imposed some other tectonic mechanism on the area that may already have been hot and weak (Hall & Morley 2004; Hyndman et al. 2005). The apparent younging of Cenozoic basins northward (Fig. 1), although poorly constrained, seems to broadly coincide with the mapped extent of sedimentary rocks (Upper Jurassic and Lower Cretaceous Khorat Group and lateral equivalents) deposited in the DTL (Figs 1 & 9). These observations could be explained by a subduction-driven model, such as that presented here, in so far as the areas expected to be affected most by subduction-related dynamic subsidence and uplift are those in the south of the region, where opposing subduction systems were closest. Furthermore, is there a relationship between the extent of DTL sediments (or where all DTL sediments have been removed) and the location of Cenozoic basins in the region? Such questions are beyond the scope of this paper but may be the focus of future research concerning the impact of subduction on the region as well as better understanding the distribution of Cenozoic basins.

Conclusions

The SE Asia Regional Unconformity is observed across Sundaland with an area of c. 5 600 000 km² (greater than the area of the Western United States) and represents c. 40 Ma of missing time. Uplift was unlikely to have been driven solely by collision tectonics. Vertical displacement of Sundaland continental lithosphere by reversal of a slab-related dynamic topographic low explains the spatial extent of the unconformity, the regional geology both above and below the unconformity, regional exhumation data and the duration of apparent uplift. Furthermore, we suggest that the onset of subduction at c. 45 Ma resulted in renewed subsidence and the development of the numerous petrolierous sedimentary basins that are now present throughout the region. This is the first attempt at assessing the extent of the SE Asia Regional Unconformity as well as providing a plausible explanation for its development; more detailed modelling may test these suggestions.

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References


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