



The basins of Sundaland (SE Asia): Evolution and boundary conditions

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ABSTRACT

Most of the basins developed in the continental core of SE Asia (Sundaland) evolved since the Late Cretaceous in a manner that may be correlated to the conditions of the subduction in the Sunda Trench. By the end of Mesozoic times Sundaland was an elevated area composed of granite and metamorphic basement on the rims; which suffered collapse and incipient extension, whereas the central part was stable. This promontory was surrounded by a large subduction zone, except in the north and was a free boundary in the Early Cenozoic. Starting from the Palaeogene and following fractures initiated during the India Eurasia collision, rifting began along large faults (mostly N–S and NNW–SSE strike-slip), which crosscut the whole region. The basins remained in a continental fluvio-lacustrine or shallow marine environment for a long time and some are marked by extremely stretched crust (Phu Khanh, Natuna, N. Makassar) or even reached the ocean floor spreading stage (Celebes, Flores). Western Sundaland was a combination of basin opening and strike-slip transpressional deformation. The configuration suggests a free boundary particularly to the east (trench pull associated with the Proto-South China Sea subduction; Java–Sulawesi trench subduction rollback). In the Early Miocene, Australian blocks reached the Sunda subduction zone and imposed local shortening in the south and southeast, whereas the western part was free from compression after the Indian continent had moved away to the north. This suggests an important coupling of the Sunda Plate with the Indo-Australian Plate both to SE and NW, possibly further west rollback had ceased in the Java–Sumatra subduction zone, and compressional stress was being transferred northwards across the plate boundary. The internal compression is expressed to the south by shortening which is transmitted as far as the Malay basin. In the Late Miocene, most of the Sunda Plate was under compression, except the tectonically isolated Andaman Sea and the Damar basins. In the Pliocene, collision north of Australia propagated toward the north and west causing subduction reversal and compression in the short-lived Damar Basin. Docking of the Philippine Plate confined the eastern side of Sundaland and created local compression and uplift such as in NW Borneo, Palawan and Taiwan. Transpressional deformation created extensive folding, strike-slip faulting and uplift of the Central Basin and Arakan Yoma in Myanmar. Minor inversion affected many Thailand rift basins. All the other basins record subsidence. The uplift is responsible for gravity tectonics where thick sediments were accumulated (Sarawak, NE Luconia, Bangladesh wedge).

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1. Introduction

Our understanding of the basin evolution of Sundaland in Southeast Asia has benefited from numerous studies in the last decades. Basin sedimentary patterns and controlling faults have been defined, often in great detail, thanks to the large amount of industrial drilling and seismic reflection data. Tectonic events

causing basin formation commonly are assigned a local origin due to the complexity of the geodynamic setting since the Cretaceous. On the other hand, the impact of the collision with continental blocks adjacent to Southeast Asia on basin development is emphasized in some models, particularly for the South China Sea (Holloway, 1982; Tapponnier et al., 1986), and reconstructions attempting to visualize the evolution of SE Asia as a whole have flourished (Replumaz and Tapponnier, 2003; Hall, 2002, 2012; Lee and Lawver, 1995; Pubellier et al., 2003a,b).

The Sunda Plate has traditionally been considered part of the Eurasian Plate. GPS analysis in particular has changed this view, and indicates that this region is moving separately from Eurasia, and

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should be treated as a distinct plate, called the Sunda Plate (Michel et al., 2000; Bird, 2003; Simons et al., 2007). The Sunda Plate may only have become a distinct tectonic element in the last 10 My. Our understanding of the plate remains a work in progress, and there is a lack of consensus amongst workers regarding the location of the poorly-defined plate boundaries, particularly the one with Eurasia (Tingay et al., 2010). Because the Sunda Plate only formed after the Middle Miocene and only covers part of the story discussed below, we have opted for the term Sundaland (see review Hall and Morley, 2004) since it represents the geographic entity that covers the continental promontory of SE Asia. In this paper we consider that subduction pull, together with collapse due to crustal thickening are the two key major mechanisms controlling the extension of basins within the Sundaland.

Over the years following the development of basic marginal basins evolutionary models (Karig, 1971) there was a growing interest in the forces related to subduction, rollback, angle and polarities (Uyeda and Kanamori, 1979; Doglioni et al., 2007), and attempts were made to model the processes, including those for the Indo-Australian Plate (Schellart, 2004, 2005). Debate about the evolution of basins in terms of extensional forces is particularly relevant to the basins of SE Asia, because they were all formed in a supra-subduction zone environment to the Tethys Ocean in the Mesozoic and the Indian Ocean during the Cenozoic on the western margin, and the Pacific and Palaeo-Pacific on the eastern margin.

Extension as a direct consequence of crustal thickening in the Himalayas (England and Molnar, 1997) has been identified from GPS and metamorphic studies (England and Molnar, 2005; Maurin and Rangin, 2009; Searle, 2010). The processes of extension in continental crust, from the early models of pure and simple shear, have taken into account the effects of multiple layers of the lithosphere on deformation style (Kusznir and Park, 1987; Sokoutis et al., 2007; Huismans and Beaumont, 2008). The importance of extensional detachments in passive margin formation has been increasingly recognized worldwide as a result of initial studies from the Atlantic passive margin and outcrops in the Central Alps (e.g. Manatschal and Bernoulli, 1999; Péron-Pinvidic and Manatschal, 2009). Recently, detachment faults were identified on the margin of South China (Pubellier et al., 2008; Chan et al., 2010), offshore northern margin of the South China Sea Margin, and the Vietnam margin (Cullen et al., 2010; Savva et al., 2013). Extension of the crust by detachment faults has been extensively documented in orogenic collapse processes in old orogens (Dewey, 1988; Jolivet et al., 2001), and may form large extensional provinces such as the Basin and Range of Northern America. One of the earliest potential metamorphic core complexes identified in SE Asia is the Doi Inthanon and Doi Suthep areas west of the Chiang Mai Basin in Northern Thailand (MacDonald et al., 1993; Dunning et al., 1995). More recently metamorphic core complexes have been identified in other parts of Thailand (Morley et al., 2011a,b), Vietnam (Jolivet et al., 2001) and in Sulawesi (Watkinson, 2011).

Increasing isotopic dating of igneous and metamorphic rocks in recent years has provided a new understanding of the early setting of Sundaland along its Pacific margin and indicates that by the end of Mesozoic times a large Andean type margin (Yenshanian orogen) had developed. Dating studies have also allowed the timing of deformation near the plate boundaries to be determined, for example in Myanmar (Bertrand et al., 2001; Bertrand and Rangin, 2003; Maurin and Rangin, in press), in Peninsular Thailand (Watkinson, 2011), and along the Red River fault zone (Searle, 2007). Mid-Cretaceous (90–100 Ma) and Paleocene thermal events have been recorded in Peninsular Malaysia and western Thailand (Cottam et al., 2013; Palin et al., 2013). On the northern margin of the South China Sea, zircon fission track data has identified a thermal event from 140 to 90 Ma (Chan et al., 2010). There,

the Cretaceous event was followed by Eocene to Oligocene denudation indicated by AFT data (Chan et al., 2010).

Finally, a better control on the plate motion and age of docking of crustal blocks of Australian origin, and the identification of the dominant shortening direction of the basins since the Early Miocene permits consideration of the effects of boundary forces acting on the Sunda Plate convergent margin (Seton et al., 2012; Pubellier and Meresse, 2013; Zahirovic et al., 2012). The presence of well documented, widely distributed basins over Sundaland, with large controlling faults and long-lasting subduction around most of the plate (Fig. 1), means it is a good example to discuss the geometry, timing of controlling faults, evolution, boundary conditions and state of stress in a supra-subduction zone setting. Stretching of the continental crust affected the core of Sundaland formed during the Indosinian Orogeny by the Early Jurassic and parts that were accreted later during the Cretaceous and Paleocene (Fig. 1).

This paper is proposed as an introductory paper for the Special Publication on the South China Sea and Adjacent basins. We firstly present the issues often debated on the geodynamics of this part of Asia, with emphasis on the thickening followed by extension in Sundaland. Then we review the rifting history of the basins by comparing their evolution on the eastern and western sides of Sundaland, and finally we come up with a model discussing the interactions of the continental masses and the subduction zone, as an important factor to control the opening of the Sundaland basins.

2. Geodynamic setting of Sundaland

In this paper we put side by side the expected forces resulting from the convergence of Sundaland with the Indo-Australian Plate composed of two major continental lithospheres (India and Australia) and one oceanic lithosphere (Indian Ocean). Before the India and Australia collision with Eurasia other smaller blocks, also of Gondwanian origins, had docked against Eurasia (Lhasa Block, Qiantang Block) or against Sundaland (Burma, Argo, S. Java; Metcalfe, 2013). Other less documented effects are of intra oceanic origin (e.g. the Woyla Terrane collision with Sumatra, Cameron et al., 1980; Wajzer et al., 1991; Barber, 2000).

2.1. Influence of India–Eurasia collision on deformation of Eastern Eurasia and Sundaland

India is the largest continental block to have affected Southeast Asia during the Cenozoic and it started to interfere with the region from the Eocene until the present. The way India is connected to basin opening in Southeast Asia has been the focus of passionate debate and has to be considered in any analysis of the tectonics of the region. One end member is the view that extrusion of rigid crustal blocks from the India–Asia collision zone along a number of discrete, high-displacement strike-slip faults has dominated regional tectonics, and basin development in mainland Southeast Asia and their adjacent coastal areas, including opening of the South China Sea spreading center (e.g. Tapponnier and Armijo, 1986; Leloup et al., 2001; Replumaz and Tapponnier, 2003). The other end member is that similar to the lower crust, the upper crust exhibits gradual changes in displacement amount and direction (from GPS data) more akin to flow (actually a continuously deforming solid), rather than abrupt changes across discrete faults (e.g. England and Molnar, 1997, 2005).

Most workers recognize that significant strike-slip faults developed under extrusion. However, many consider that Cenozoic deformation in Southeast Asia falls somewhere between the two end-members and that extrusion is too simplistic a model to explain the geometry, timing and complexity of basin development. Arguments include: 1) some strike-slip faults began

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