The SE Asian gateway: history and tectonics of the Australia–Asia collision

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The SE Asian gateway is the connection from the Pacific to the Indian Ocean and it has diminished from a wide ocean to a complex narrow passage with deep barriers (Gordon *et al.* 2003) as plate movements caused Australia to collide with SE Asia. It is one of several major ocean passages that existed during the Cenozoic but has received much less attention than others that opened, such as the Drake Passage, Tasman Gateway, Arctic Gateway or Bering Straits, or that closed, such as the Panama Gateway or Tethyan Gateway (e.g. von der Heydt & Dijkstra 2006; Lyle *et al.* 2007, 2008). It is not entirely clear why there has been this comparative neglect, but it may reflect the relative limited knowledge of the large and remote areas of Indonesia and the western Pacific, in particular their geological history, and the relatively small number of active researchers in this large region.

Unlike the Panama Gateway and Tethyan Gateway the SE Asian gateway is still partly open and the ocean currents that flow between the Pacific and Indian Oceans have been the subject of much recent work by oceanographers (e.g. Gordon 2005). We now know that the Indonesian Throughflow, the name given to the waters that pass through the only remaining low latitude oceanic passage on the Earth, plays an important role in Indo-Pacific and global thermohaline flow (Gordon 1986; Godfrey 1996), and it is therefore probable that the gateway is important for global climate (Schneider 1998). It is also known that today the region around the SE Asian gateway contains the maximum global diversity for many marine (Tomascik *et al.* 1997) and terrestrial organisms (Whitten *et al.* 1999*a*, *b*). It is not known when and why this diversity originated, if there is a connection between biotic diversity and oceanography, what is the role of the throughflow in the modern climate system, and how the restriction and almost complete closure of the passage between the Pacific and Indian Oceans may be linked to the history of climate change. However, all of these are likely consequences of, or related to, the closure of the wide ocean that separated Australia and SE Asia at the beginning of the Cenozoic.

The gateway closure was caused by the tectonic changes accompanying the northward movement of Australia as it converged with Asia. Collision between Australia and SE Asia began in the earliest Miocene. The gateway was fully open before 25 Ma and significantly restricted by 5 Ma but understanding its history requires detailed reconstruction of an area of great geological complexity (Hall 2002; Kuhnt *et al.* 2004). Biogeographers have given the name Wallacea to the area bounded by the Wallace Line in the west, marking an eastern limit of truly Asian faunas and floras, and Lydekker's Line in the east, which is the western boundary of Australasian faunas and floras, and Wallacea is at the centre of the SE Asian Gateway. Wallacea includes the islands of Sulawesi and the Banda Arc and is marked by high numbers of endemic species, complex distribution patterns, and unusual variations in species richness (Whitmore 1987). The biogeographical complexity reflects the significant changes in distribution of land and sea during the Neogene which in turn reflects the complex geological history of Wallacea, largely driven by subduction, and the rapid changes that have occurred – for example, some of the largest islands in the Banda Arc, such as Seram and Timor, have emerged from the sea only in the last 3 million years (Hall 2001).

The Neogene history of the gateway records a complex history of rapid changes in tectonics, topography and land/sea distributions (Hall 1998). As the deepwater connection closed, mountains rose, there was an increase in land and shelf areas, but new deep basins also formed. There were numerous changes that accompanied the closure. High mountains rose first in Borneo and later elsewhere in Indonesia. Rainfall and erosion rates must have changed. Changes in geologically-controlled passages would have influenced oceanic circulation. There was a change from warm South Pacific to

From: Hall, R., Cottam, M. A. & Wilson, M. E. J. (eds) *The SE Asian Gateway: History and Tectonics of the Australia–Asia Collision*. Geological Society, London, Special Publications, **355**, 1–6.
DOI: 10.1144/SP355.1 0305-8719/11/$15.00

colder North Pacific waters passing through the gateway. There was a change from drier to wetter climate. This tropical gateway is likely just as important as the opening and closure of other oceanic passages and the rise of Tibet for the global climate system. The physical changes influenced biogeography of the SE Asian and West Pacific region. There were major changes in carbonate depositional systems, including increased development of coral reefs (Wilson 2008) and the present-day global centre of biodiversity in some way reflects the interplay of geology, oceanography and climate (Wilson & Rosen 1998; Renema *et al.* 2008).

The connections between geology and biodiversity were the subject of a Geological Society of London conference held at Royal Holloway University of London in September 2009. The meeting aimed to bring together a range of scientists from a variety of disciplines in Earth and life sciences to better understand the geological history of the gateway, the causes and timing of its closure, and their effects. This Special Publication includes papers by predominantly physical science contributors to the meeting and a second volume will contain papers mainly by life scientists (Gower *et al.* 2011). The papers in this volume (Fig. 1) have been arranged to first explain and discuss the Palaeozoic and Mesozoic geological development of the region, and then its Cenozoic history, which provide the background to understand the present Indonesian Throughflow, oceanographic changes since the Neogene, and finally some aspects of the climate history.

Pre-Cenozoic geological history

One of the important factors that influenced the late Cenozoic history of the SE Asian gateway was the complex structure of the basement acquired since the late Palaeozoic. **Metcalfe** reviews the fragmentation of Gondwana and assembly of Gondwana fragments in SE Asia, accompanied by the closure of Tethyan oceans. He highlights a number of significant recent changes in our understanding

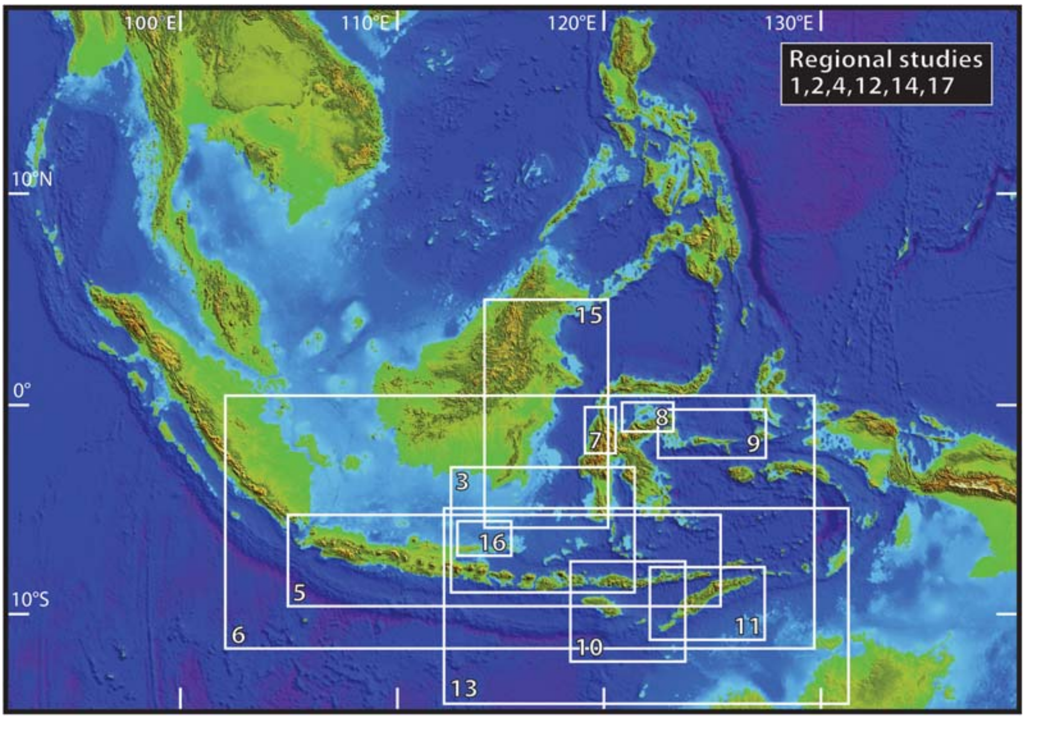

Fig. 1. Numbered boxes show the areas discussed in the papers in this volume. 1, Metcalfe; 2, Clements *et al.*; 3, Granath *et al.*; 4, Hall; 5, Kopp; 6, Widyantoro *et al.*; 7, Watkinson; 8, Cottam *et al.*; 9, Watkinson *et al.*; 10, Rigg & Hall; 11, Audley-Charles; 12, Tillinger; 13, Holbourn *et al.*; 14, van der Heydt & Dijkstra; 15, Morley & Morley; 16, Lelono & Morley; 17, Wilson. The background image is a digital elevation model of SE Asia based on satellite gravity-derived bathymetry combined with SRTM (Shuttle Radar Topographic Mission) topography (Sandwell & Smith 2009).

of SE Asian basement structure, notably recognition of the importance of the Sukhothai arc and associated terranes that separated Sibumasu and Indochina in the Permian and Triassic, the addition of the West Sumatra and West Burma blocks in the Permo-Triassic, and the identification of Borneo, Java and West Sulawesi as the Argoland blocks rifted from NW Australia in the Late Jurassic. The collision of these Australian fragments was complete by the mid Cretaceous and subduction ceased around Sundaland until the Eocene. **Clements *et al*.** propose that a widespread regional unconformity was a dynamic topographic response to termination of subduction and is the reason for the almost complete absence of Upper Cretaceous and Paleocene rocks throughout most of Sundaland. Sedimentation began again in the Eocene when subduction resumed. Based on new regional deep seismic surveys **Granath *et al*.** show that beneath the unconformity in the Java Sea is an unexpected and thick sedimentary section which is probably Precambrian to Triassic in age and was deposited when this basement block was still part of the Australian margin.

Cenozoic subduction

During the Eocene, subduction beneath Indonesia began as Australia moved north, gradually closing the deep passage linking the Pacific and Indian Oceans. In the Early Miocene the leading edge of the Australian continent began to collide with the SE Asian margin in East Indonesia. **Hall** interprets the development of the Neogene collision to have been strongly influenced by the shape of the Australian continental margin, due to Jurassic rifting, and the presence of an oceanic embayment, leading to subduction rollback into the embayment. However, young deformation is also attributed to a component of lower crustal flow which has enhanced the effects of sediment loading and driven uplift and exhumation of mountains in northern Borneo and Sulawesi. Subduction has been the most important tectonic driving force of change in Indonesia but its consequences are very varied. **Kopp** reviews subduction along the Java margin and shows how the deep structure of the margin varies from west to east. Features of the margin, its seismogenic character and seismic hazards reflect many factors such as sediment supply, relief of the subducting slab, and geometry of the plate interface. The still deeper structure of the subduction zone can be imaged from P wave seismic tomography and **Widiyantoro *et al*.** show how this reveals a complex geometry with a hole in the subducting slab beneath East Java, and a possible tear beneath eastern Indonesia. This provides valuable information which can be related to the surface expression of subduction, such as deformation in the volcanic arc and variation in history and type of volcanic activity.

Sulawesi and Neogene tectonics

Sulawesi is situated close to the centre of Wallacea and includes parts of the pre-Neogene Sundaland margin and Australian crust that was added in the Cretaceous and the Neogene. West Sulawesi is cut by the Palu-Koro Fault which is an active strike-slip fault with spectacular surface expression, important seismicity and clear evidence of young deformation. It represents a potentially major hazard but little is known of its history. **Watkinson** shows that deformed rocks close to the fault reveal a complex structure and ductile deformation which must pre-date Pliocene to present-day movement on it. Just east of the Palu-Koro Fault is the wide Gorontalo Bay, also known as Tomini Bay, which is one of the enigmatic inter-arm bays that give Sulawesi its unusual K-shape. Seismic and multibeam data have recently been acquired from the bay and provide almost the first information about the submarine parts of it, but there are a number of small islands including Una-Una volcano that erupted destructively in 1983, and the Togian group, that reveal some of its history. The Togian Islands have been reported to include igneous rocks that have been interpreted as part of the Cretaceous–Eocene East Arm ophiolite, or as younger volcanic rocks of uncertain tectonic setting. **Cottam *et al*.** report new observations from the Togian Islands that contribute to understanding the origin of Gorontalo Bay, its basement and the volcanic history of the area. They show that there is an old volcanic basement, probably Palaeogene, that the southern part of the bay was close to sea level during the Middle Miocene when shallow marine carbonates were deposited, and there were explosive eruptions from a nearby volcano and marine deposition of reworked volcanic ash in the Pliocene. However, alluvial fan deposits show that there were Pliocene connections to the East Arm from which the islands are now separated by a deep marine basin implying rapid and large subsidence of parts of Gorontalo Bay. The eastern end of the East Arm includes the collisional contact of the ophiolite with one of the microcontinental fragments of eastern Indonesia: the Banggai-Sula block. Banggai-Sula and other microcontinental blocks have long been interpreted as sliced from the Bird's Head of New Guinea and carried east in the left-lateral Sorong Fault Zone. **Watkinson *et al*.** cast doubt on this interpretation based on new offshore multibeam and seismic data by showing that faults that can be traced offshore from the East Arm are dextral, not sinistral, that splays of the Sorong Fault do not exist where they previously have been interpreted, and that through-going thrusts shown on many maps are not connected and have different causes. All of these studies of Sulawesi indicate that previous models for tectonic development of this region require substantial re-evaluation.

Banda Arc tectonics

The Banda Arc, and especially Timor, is the source of many ideas about arc–continent collision and is also notable for many controversies, such as the origin of the arc, the nature of the crust within the arc and the age of collision. North and west of Timor is the Savu Basin which has a strange triangular shape, widening west towards Sumba which is situated in an anomalous fore-arc position north of the Java Trench where Indian ocean crust is being subducted, and narrowing to the east, north of Timor where arc–continent collision began in the Pliocene. The Savu Basin is situated immediately north of the position of the change from oceanic subduction to arc–continent collision and new seismic data are discussed by **Rigg & Hall** that help to understand this tectonic transition. The Savu Basin is interpreted to be underlain by Australian continental crust incorporated in the SE Asia margin in the Cretaceous. Seismic sequences offshore can be correlated with stratigraphy onshore and indicate rapid subsidence in the Middle Miocene associated with subduction rollback into the Banda embayment. Subduction of part of the Australian continental margin led to uplift of Sumba and began deformation of former deepwater deposits that are now tilted and slumping northwards into the basin as the former trench became blocked. **Audley-Charles** discusses the effects that followed the Pliocene collision of the volcanic Banda Arc with the Australian margin as the trench was eliminated. Different parts of the Australian margin sequence were detached at major decollements and stacked up beneath the leading edge of the fore-arc represented by the highest nappes of the Banda allochthon. Contraction in this deformed collision complex caused the distance between the former volcanic arc and the Australian crust to be reduced to as little as 25 km.

The Indonesian Throughflow

The Indonesian Throughflow is the last remaining equatorial ocean gateway, allowing heat transfer as water flows from the Pacific into the Indian Ocean. Today, it is regarded as a major component of the modern thermohaline circulation, influencing global climate on short and long timescales (Gordon *et al.* 2003; Kuhnt *et al.* 2004). **Tillinger** describes the causes of the Indonesian Throughflow, the controls on shallow and deep flow, and its variations in different passages. Fluctuations in the West Pacific Warm Pool are related to variability in the Indonesian Throughflow which acts as a control on inter-annual climate variation such as the El Niño-Southern Oscillation (ENSO) and the SE Asian monsoon. Short term modelling of the effects of restricting the throughflow (e.g. Schneider 1998) suggest that it is likely to affect sea surface temperatures, position of ocean warm pools, land temperatures, rainfall, and wind stresses.

The longer term history of the Indonesian Throughflow is of great interest because of the links to global climate but is largely unknown and has been little studied. **Holbourn *et al*.** use $\delta^{18}O$, $\delta^{13}C$ and Mg/Ca analyses of benthic and planktonic foraminifera to estimate variations in sea surface temperature, salinity and water mixing over the last 140 ka. The changes are correlated with glacial and interglacial periods and imply links between the Pacific and Indian Oceans via different passages between the oceans as sea level changed, as well as slowing of global thermohaline circulation during glacial intervals.

The first restriction of the Indonesian Gateway, and termination of deepwater flow, from the Early Miocene appears to have coincided with major perturbations in the global climate system including rapid warming in the Late Oligocene followed by a brief glaciation pulse and associated significant positive carbon isotopic excursion in the earliest Miocene (Zachos *et al.* 2001). Climate and geological records suggest that ENSO variability may have existed on Earth as far back as the Eocene. The long-term development of the Indonesian Throughflow has been controlled by the geological history of the region but up to now there have been only a few studies of it (e.g. Kuhnt *et al.* 2004). However, the effects of other gateways have been modelled and **von der Heydt & Dijkstra** discuss such studies. They also analyse the effect of increased levels of atmospheric greenhouse gases and open tropical gateways on ENSO variability using fully coupled climate model simulations. Their modelling suggests that greenhouse gas variations have only small effects on ENSO variability but changes in oceanic gateways may cause a stronger and less frequent ENSO. A deeper and more open Indonesian Passage would not prevent a Western Pacific Warm Pool from developing, but could cause the warm pool to move into the Indian Ocean.

Climate history

Cane & Molnar (2001) suggested that Pliocene plate tectonic changes, including the northward movement of New Guinea, caused a change from warm saline South Pacific Water to colder North

Pacific water passing through the SE Asian Gateway. They proposed that cooler surface water in the Indian Ocean resulted in increased aridity over eastern Africa. Decreased heat transport out of the tropics may have also stimulated global cooling, resulting in the formation of ice sheets. The climatic changes related to oceanographic and atmospheric changes in the gateway can be assessed using fossils. **Morley & Morley** provide such an assessment based on palynological studies of cores from petroleum exploration wells in the Makassar Straits, which is now the main passage for the Indonesian Throughflow. Their results provide a record of the vegetation and climate change for the last 30 ka and indicate there were rain forests in Borneo in contrast to extensive grasslands, suggesting a distinctly seasonal climate, in south Sulawesi and the Java Sea during the last glacial maximum. They argue that the equatorial climate has been everwet since the Middle Miocene, but at subequatorial latitudes seasonal climates were established from the Late Pliocene.

Lelono & Morley use palynomorph assemblages from marine cores to determine Oligocene climate change in the East Java Sea area. They propose that the Early Oligocene had an everwet climate that favoured rain forest, there was a more seasonal climate in the early part of the Late Oligocene marking reduction in rain forest and increase in grasslands, and a return to rain forest with a superwet climate in the latest Late Oligocene. Some taxa suggest dispersal into Sundaland via the Ninetyeast Ridge in the Oligocene, earlier than previously thought, rather than from Australia during the SE Asia–Australia collision.

SE Asia contains the most diverse shallow marine biota on Earth, and a large proportion of this diversity is associated with coral reefs and associated habitats. Carbonates are also a particularly valuable source of environmental and climatic information for the Cenozoic but studies of carbonates of this type have barely begun (Fulthorpe & Schlanger 1989; Wilson 2008). **Wilson** reviews the information that carbonates are beginning to provide in SE Asia, from annual to million year timescales. Terrestrial runoff, nutrient upwelling, tectonics, volcanism and human activity are major influences on the modern carbonate systems. Quaternary and Pleistocene deposits reveal significant localized tectonic uplift and coeval subsidence, and allow quantification of factors such as interglacial to glacial temperature changes (up to 3–6 °C), ENSO fluctuations (± 2 °C extending back at least 130 ka), meltwater pulses associated with ice sheet breakup, and movement of the Intertropical Convergence Zone (ITCZ), where winds of the northern and southern hemispheres meet. During the Cenozoic major changes in oceanography, plate tectonics, climate change and perhaps fluctuating atmospheric CO_2 influenced significant changes in carbonate producers and the types of platforms that were constructed. Marine biodiversity reaches a global maximum in the region. Fossils and molecular data suggest that this diversity dates from at least the Early Miocene (Wilson & Rosen 1998; Meyer 2003; Duda & Kohn 2005; Read *et al.* 2006; Renema *et al.* 2008) suggesting a possible link to restriction of the SE Asian gateway. These biotic and oceanographic shifts may reflect environmental and tectonically-driven changes in the distribution and nature of shallow seas.

Summary

The collection of papers in this volume written by a variety of Earth and physical scientists reveal significant new data on the processes and timing of large-scale plate tectonic changes in SE Asia, re-evaluate the geological development of specific areas and show the need for significant revisions to previous models. They show the importance of the Indonesian Throughflow and its impact on inter-annual and longer-term regional and global climate and make a start on unravelling the history of environmental and climatic change of the region from the biota and the rocks. These studies have implications for past distributions of land and sea, terrestrial and marine environments, as well as oceanography and climatology. We hope these contributions to understanding the region's geological, oceanographic and climatic history will aid the cross-fertilization of ideas with life scientists investigating the enigmatic biology and biodiversity of SE Asia because a symbiotic relationship of life and Earth scientists is essential for a real understanding of this fascinating region.

The SAGE meeting was organised jointly by the SE Asia Research Group at Royal Holloway University of London, and the Natural History Museum, London. It was sponsored by the Geological Society of London Tectonic Studies Group and Petroleum Group, the Linnean Society, Malacological Society and Systematics Association. We are grateful to the consortium of oil companies who support the SE Asia Research Group: ENI, ExxonMobil, INPEX, Marathon and Murphy; and SEAPEX (SE Asia Petroleum Exploration Society and the Indonesian Petroleum Association for their help and contributions. We thank Niko Indonesia for their generous support for the meeting and publication.

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