Trenches, Troughs and Unconformities; Collision, Contraction and Extension: South China Sea, Borneo–Palawan and Sulu Sea

Robert Hall

SE Asia Research Group, Department of Earth Sciences, Royal Holloway University of London, Egham, TW20 0EX, UK

Northern Borneo is relatively far from the subduction boundaries that surround SE Asia, in a region commonly considered part of the Eurasian Plate. It is a region of relatively little seismicity, no significant volcanic activity, and apparently low but variable rates of present-day crustal movements relative to Eurasia measured by GPS. Yet close to the coast of Sabah in northern Borneo is the highest mountain in SE Asia, the 4100m high Mount Kinabalu, at the northern end of the Crocker Range, which is a Late Miocene granite rapidly exhumed in the Late Miocene and Pliocene, and offshore to the northwest of Sabah is a wide fold and thrust belt between the coast and the deep NW Borneo Trough. The trough is south of the oceanic crust of the South China Sea and its extended southern continental margin of Reed Bank and the Dangerous Grounds. To the east is the Sulu Sea, south of the elongate island of Palawan, and north of the Sulu arc. The cause of the northern Borneo offshore fold and thrust belt, and the elevation of the Crocker Range and Mount Kinabalu on land, and their links to the offshore regions of the South China Sea and Sulu Sea, remain the subject of disagreement and much discussion.

Onshore, mountains of the Crocker Range parallel to the trough expose the Lower Miocene collisional fold belt which has widened gradually since the Middle Miocene. The fold belt changes orientation abruptly through about 90° at the position of Mt Kinabalu, a 7-8 Ma granite pluton, which is in an unusual position at the end of the mountain belt. To the east of the mountain belt are ‘circular basins’ which are remnants of a larger Miocene basin. Further east is the extinct Dent–Semporna–Sulu volcanic arc, active during the Middle and Late Miocene, and the product of northward subduction of the Celebes Sea.

In the offshore region north of Borneo are sedimentary successions with numerous unconformities. They include the Deep Regional Unconformity (DRU) and the Shallow Regional Unconformity (SRU) of offshore Sabah, and Middle Miocene Unconformity (MMU) of offshore Sarawak. Their cause is uncertain. Confusion results from naming unconformities by age, implying they are not diachronous, potential mis-correlation of unconformities of the same age in widely separated areas implying a common cause, and model-driven assumptions about formation mechanisms (e.g. breakup, collision, extrusion).

The offshore Sabah fold and thrust belt, its position close to the NW Borneo Trough, and the elevated Crocker mountain range on land have contributed to interpretations that favour some form of plate convergence. GPS measurements have been interpreted in terms of a North Borneo block moving relative to Sundaland, and separated from the Dangerous Grounds by a trench. The NW

Borneo Trough is often interpreted as a subduction trench attributed to Neogene to Recent convergence. The wide active fold and thrust belt has structures broadly parallel to the trough axis. However, there is no seismicity, dipping slab or volcanic activity. At its SW end the trough terminates at the West Baram Line which is not an active fault.

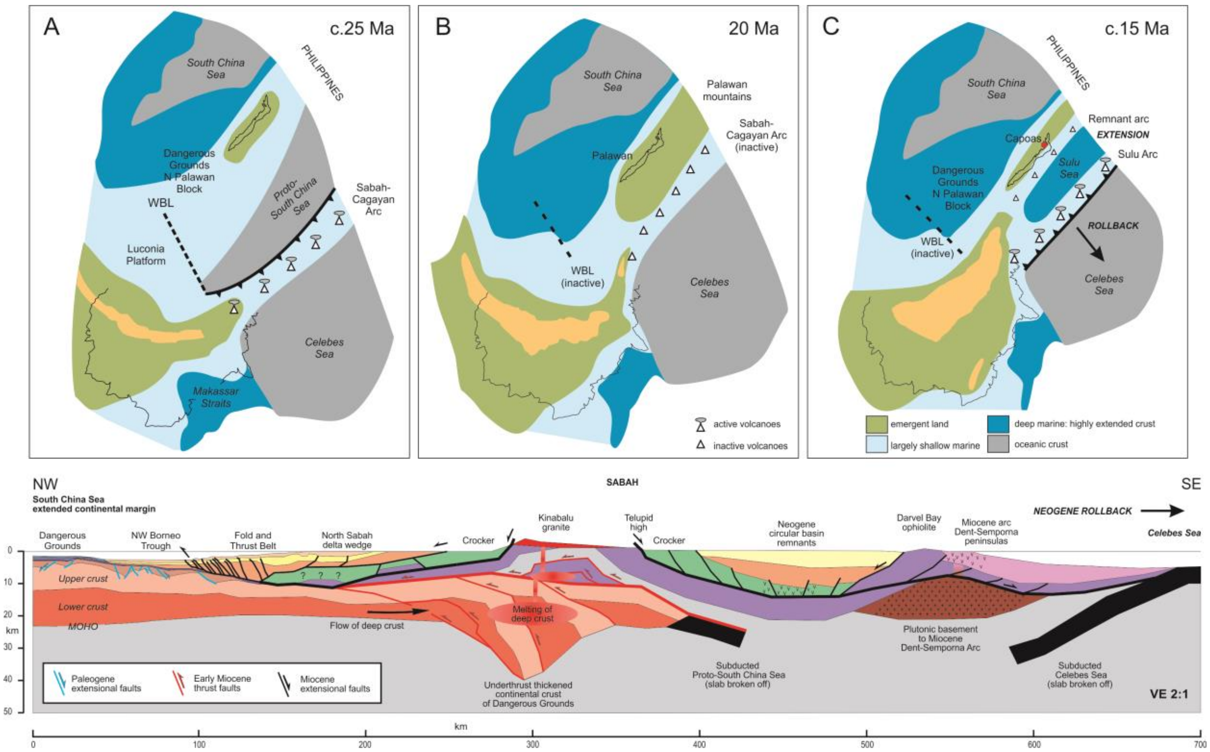
There was subduction beneath Sabah during the Paleogene, and although it appears not to have produced a major volcanic arc, there is a record of subduction in the mantle. However, this subduction ceased in the Early Miocene. The Neogene microplate convergence-subduction interpretation of Sabah-Palawan has numerous difficulties. Based partly on observations in eastern Indonesia I suggest an important role for extension during the Neogene, with a contribution of deep crustal flow, potentially driven by mantle processes. Below I summarise the key features of the interpreted Paleogene and Neogene history recognising that there is still much to learn about the region, a task which would be greatly aided by integration of offshore and onshore data, and new studies on land and offshore.

During the Paleogene the Proto-South China Sea (PSCS) was subducted at a trench approximately parallel to the present-day NW Borneo–Palawan Trough. Slab-pull forces due to subduction were the main cause of Paleogene extension of the South China continental margin leading to formation of the South China Sea. There was subduction beneath Sabah NE of the West Baram Line, but not SW of it beneath Sarawak where there was a shallow shelf from the Late Eocene.

Subduction ended in the Early Miocene with collision between the Sabah–Cagayan Arc and extended Dangerous Grounds crust. The Dangerous Grounds had a heterogeneous basement of metamorphic rocks, ophiolites, granites and sedimentary rocks accreted at the Asia-Pacific margin during Mesozoic subduction. Similar rocks form the basement of Palawan and much of Sarawak. Collision formed the Top Crocker Unconformity (TCU) on Sabah at about 20 Ma. Termination of slab-pull ended spreading in the South China Sea at the same time. After collision much of northern Borneo and Palawan became briefly emergent.

Northward subduction of the Celebes Sea began soon after Early Miocene collision, followed by subduction rollback to the SE. This initiated the Sulu volcanic arc, which emerged briefly above sea level and collapsed with Palawan in the Middle Miocene to form the Sulu Sea. The arc was active during Middle and Late Miocene between Sabah and the Philippines. Rollback drove extension in Sabah and Palawan, accompanied by elevation of mountains, crustal melting, and offshore deformation. It is commonly not appreciated how extension can be linked to both subsidence and uplift, to exhumation of the deep crust and even the upper mantle, to melting and magmatism, and how quickly these processes occur. In Sulawesi and the Banda region, where we can date and observe the, relative vertical movements of several kilometres have occurred in a few million years, accompanied by granite magmatism and exhumation of the deep crust which has been exhumed partly by extensional faulting and partly by erosion.

Based on a comparison with eastern Indonesia, I suggest there were at least two important extensional episodes that affected the region in and around North Borneo. The first at about 16 Ma is marked by the DRU, and the second at about 10 Ma produced the SRU and MMU. Both caused exhumation of deep crust, probably on low angle detachments, and were followed by granite magmatism. The NW Borneo Trough is not the site of present or former subduction. It is interpreted as a flexural response to gravity-driven deformation of the offshore sediment wedge, caused by uplift on land that resulted from extension, enhanced by deep crustal flow. It is the uplift of the Crocker Ranges centred on Kinabalu that caused movement of the crust towards the trough and has produced the offshore fold and thrust belt.



Cartoons showing the development of Sabah, Palawan and the Sulu Sea area. A. Before the Early Miocene the Proto-South China Sea was subducted below the Sabah-Cagayan Arc. Parts of Palawan were probably emergent within extended crust of the Dangerous Grounds-North Palawan block south of South China Sea oceanic crust. (WBL – West Baram Line). B. Early Miocene collision terminated subduction and an extensive area of Sabah and the Palawan region became emergent. C. New NW-directed subduction of the Celebes Sea began, which initially formed an arc south of Palawan. The Palawan mountains collapsed and the arc then split as rollback proceeded leading to further extension of the upper plate and formation of the Sulu Sea. The Capoas granite formed shortly after this extensional episode, at 14-13 Ma. The lower figure shows an interpreted cross section across Sabah. The highest parts of the Crocker Range are interpreted to have a continental crustal root of South China continental crust thickened during Early Miocene collision. This became an extensional culmination during Middle Miocene extension, into which the Kinabalu granite was intruded after melting of both deep South China continental crust, and crystalline basement of the former Sabah margin.

This hypothesis is speculative, incomplete and will undoubtedly be challenged. I consider it is required because present microplate models and regional convergence mechanisms are even more unsatisfactory. It can only be tested, and discarded or improved, by including all data that exist, and by new studies. Of particular importance would be linking offshore seismic data to existing and new studies such as dating and provenance work on land. Multidisciplinary research involving passive seismic imaging, geodynamic modelling and structural geology/dating studies could provide greatly improve knowledge of the crust and mantle structure of the region. One recent proposal has suggested use of a high density seismic array in North Borneo to illuminate the underlying crust and upper mantle using a variety of imaging methods (ambient noise tomography, teleseismic tomography, receiver functions, shear wave splitting. Analysis of recorded and historic seismicity and GPS measurements aims to understand the current state of stress in the crust, and ultimately the mechanisms which drive Neogene uplift of North Borneo.