Growing evidence of active deformation in the Malay basin region

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Abstract — Very young crustal movements in the Malay basin region point to the possibility of reactivation of regional faults in the basin proper that may compromise their sealing integrity. In addition, active or reactivated faults that are rooted in the pre-Tertiary basement and reach up close to the base of Quaternary seabed sediments in the basin pose obvious hazards to offshore installations, such as production platforms and pipelines. The Malay basin originated in the Late Cretaceous as a major aulacogen on the Malay Dome and developed structurally through modifications by differential extrusion of Indosinian crustal slabs. Initially the extrusion imparted sinistral transtensional wrenching on the axial basement fault along the basin length. In post Mid-Miocene, wrench slip reversal produced transpression, accompanied by general structural inversion. From the Pliocene onward most of the basin area has been considered tectonically quiet on the basis of horizontal stratification, absence of explosive volcanism, absence of earthquake epicentres, and low topographic/bathymetric relief. However, basement-rooted regional fault zones may intrude into Pliocene-Pleistocene strata and reach as high as 150 metres below the shallow seabed. This suggests reactivation of the faults. Onshore Peninsular Malaysia, small Early Tertiary basins host lacustrine and fluvial-dominated deposits. These basins appear associated with regional fault zones that most probably remained active up to that time. Neogene deposits are apparently missing while the blanket of Quaternary sediments only indicates local disturbances associated with superficial base collapse and gravity sliding. On the other hand, an Early Quaternary pillow-basalt flow near Kuantan on the eastern shore of the Peninsula is traversed by long fractures orientated parallel to faults in the pre-Tertiary basement. The fractures in the basalt are essentially vertical and are evident manifestations of reactivation of the older faults. In Southeast Johor at the edge of the Penyu basin, crustal uplift of 0.5 - 0.8 m during the past 5000 years is suggested by an abrasion platform that is that much higher compared to the eustatic Holocene sea-level curve of the Peninsula which was established from almost a hundred radiometrically determined bio-shoreline indicators. In the northwest on the shores of Langkawi, a 2500-year old abrasion platform is cut by a long fault zone whose associated secondary structures suggest sinistral displacement. The 26 December 2004 mega-thrust Indian Ocean earthquake is shown by GPS measurements to have displaced the entire Peninsula by several centimetres toward west-southwest. One of the findings of ongoing research in the Langkawi islands is of very recent crustal uplift of 40-50 centimetres that manifests as sea-level notches at elevated positions above present mean sea level.

Keywords: Malay basin, active deformation, fault reactivation

INTRODUCTION

From onshore the Peninsula, suspected Quaternary crustal movements were interpreted among others by Raj (1979) and Zaiton Harun *et al*., (2000). The present communication details evidence of very young crustal movements from the Pahang and Johor coasts adjoining the South China Sea, the Johor and Angsa Tertiary basins in the Melaka Strait, and the Langkawi Islands in the northwestern region of the Peninsula.

The Malay Basin region (Figure 1) is located in Sundaland, that according to land-based geologists has been tectonically consolidated by the early Tertiary. Original results indicating this have been compiled by van Bemmelen (1949). Indications of similar conditions in Peninsular Malaysia have also been realised (e.g. Chung & Yin, 1968). During the Tertiary, volcanism was of the basaltic type (Gunung Niut and Pulau Midai in West Kalimantan; Segamat and Kuantan basalts in Peninsular Malaysia), but no explosive volcanic activity that characterises tectonically active regions is known. Bathymetric relief of the Sunda Shelf is low, precluding significant young crustal movements having occurred. Earthquake epicentres are absent. The epicentre of a single magnitude 8.6 event of 16 December 1920 shown on some seismic maps and placed in the centre of northern Sundaland (06.500° N, 105.700° E) resulted from a typing error of the latitude coordinate. Magnitude and date corresponds with an epicentre in China, 30 degrees farther to the north (Irwan Meilano, Institut Teknologi Bandung Indonesia, pers. comm.).

Exploration for hydrocarbons that in the 1970s culminated in production from the Malay basin and from the West Natuna basin forces drastic modifications to the concept of stable crustal conditions for Sundaland. The Malay basin contains Early Neogene and older sedimentary rocks that were deformed by Palaeogene synrift sagging, post Mid-Miocene structural inversion, and reversals on the regional wrench faults (documentation in Leong, 1999). Only the AB seismic Group (Upper Miocene and younger) are essentially horizontally bedded sediments representing stable crustal conditions. Even this young sedimentary blanket of the Malay basin is intruded by faults as illustrated in Figures 7.18, 8.4 and 8.11 of the Petronas book (Mazlan Madon *et al*., 1999; Tjia, 1999). Some of the faults reach up from

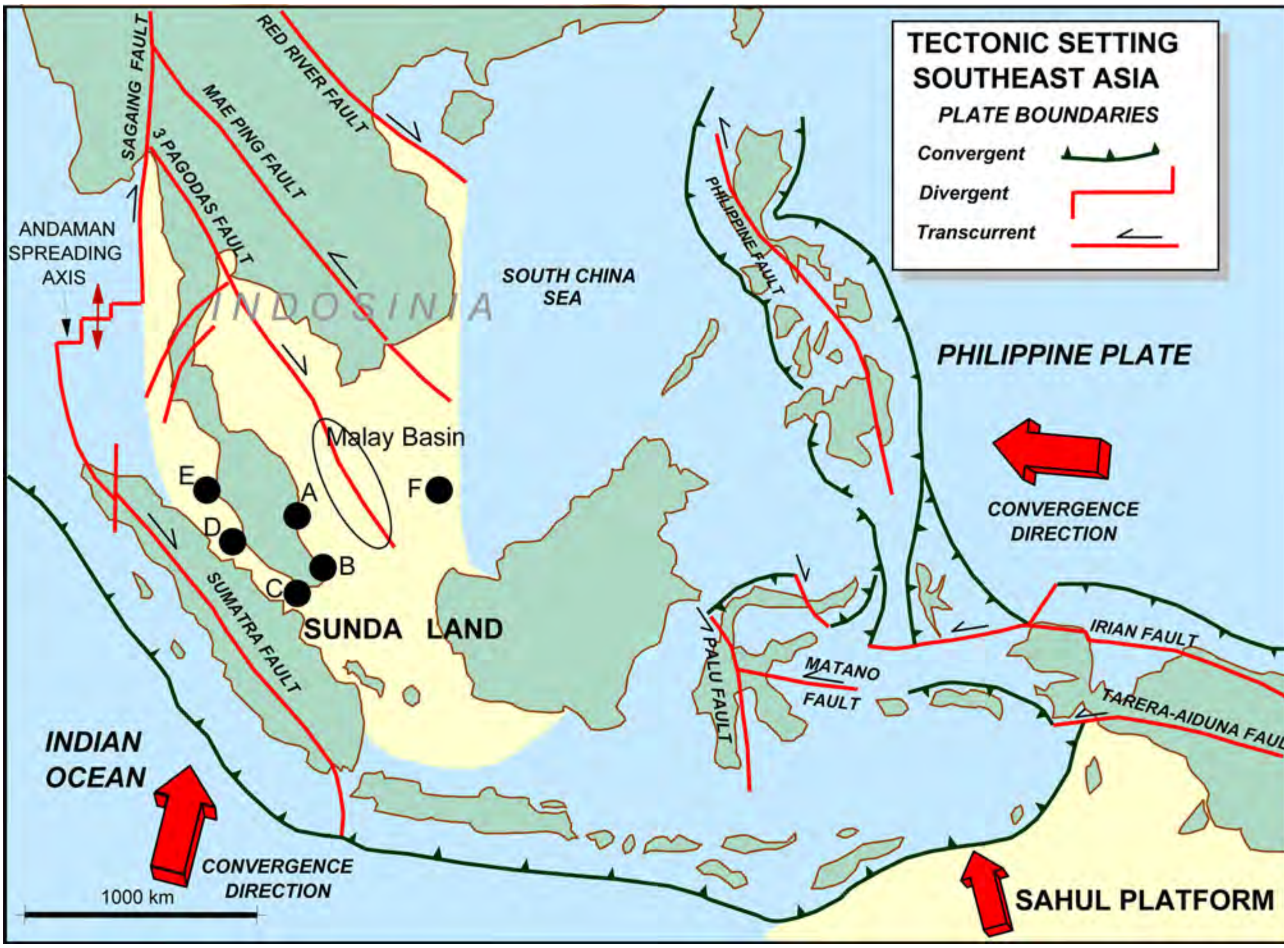

Figure 1: Semicratonic Indosinia and Sundaland of Southeast Asia. The Malay Basin is underlain by a segment of the Three Pagodas fault zone. Only major tectonic elements are shown. Evidence and indications for active crustal deformation are described for the areas: A Pantai Batu Hitam, B Tanjung Lobang, C Johor Graben, D Angsa Graben, E Langkawi Islands, and F Bunguran Besar or Natuna Island.

inside the pre-Oligocene sedimentary interval intruding into the AB Group as high as 150 milliseconds below the floor of the South China Sea. Normal faulting appears to have been active well into the Pliocene. The deep- seated faults further suggest that "basement" of the basin is also involved in the young movements. Extrusion of crustal slabs of Indosinia as proposed by Tapponnier *et al*. (1982) has operated along major northwest faults (Red River, Wang Chao, Three Pagodas) until the present time and has most probably influenced the structural development of the Malay basin (Tjia & Liew, 1996). Current activity of the Wang Chao ,one of the regional faults, can be correlated with dextral wrench faulting as indicated by the focal mechanism of an Mw 5.3 earthquake just offshore the Mekong Delta (7 November 2005; USGS-NEIC). Epicentres located in Peninsular Malaysia have been of weak earthquakes. In the early 1990s initial commissioning of the large Kenyir reservoir in Terengganu was interpreted as the cause. Currently under investigation are a slew of less than M 3 earthquakes occurring since late November 2007 in the Bukit Tinggi area of western Pahang (Jabatan Mineral dan Geosains Malaysia).

EVIDENCE FOR ACTIVE DEFORMATION

Pantai Batu Hitam, Pahang

Quaternary basaltic lava flows occur in the Jabor area north of Kuantan, Pahang, and reaches the shoreline of the South China Sea (Fitch, 1951). At Pantai Batu Hitam, the 1.6 Ma (Bignell & Snelling, 1977) basalt crops out as pillows in the intertidal zone (Figure 2). This suggests that the palaeogeography has not substantially changed since the early Quaternary. The other Tertiary volcanic activity in the Peninsula was at Segamat, Johor, 66 Ma ago (Stauffer, 1972). In the current geological setting, the Jabor basalt is a tectonically anomalous occurrence. Azman Ghani & Nur Iskandar Taib (2007) interpreted from its petrochemistry, especially its rare earths content, that it could represent a mantle-plume origin. At Gebeng, at the north fringe of the Jabor basalt, weathered basalt was found to overlie granite whose quartz displays planar deformation features. An impact origin was suggested by Anizan Isahak (1990). She further proposed that the early Pleistocene basalt volcanism was induced by meteorite impact.

Figure 2: Early Quaternary pillow basalt exposed in the intertidal zone at Pantai Batu Hitam, north of Kuantan, Pahang. The fractures are systematically orientated. Distinct fracture initiation within pillows and parallel with the larger fractures are noticeable, such as in the east centre of the photograph.

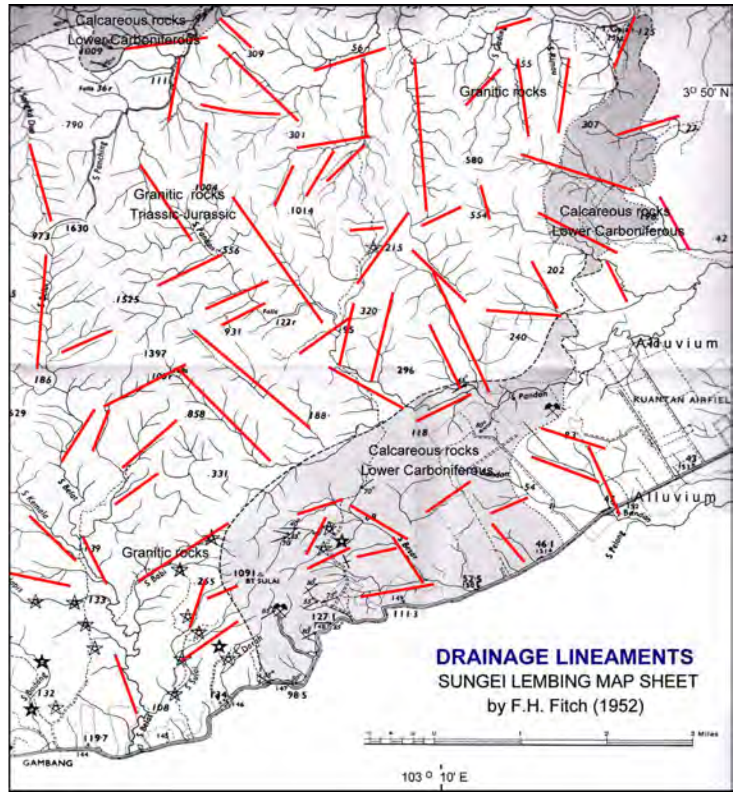

Figure 4: Drainage lineaments displayed on the geological map of the Sungei Lembing map sheet (lineaments in red added to the base map by Fitch, 1951). Except for the north-striking lineaments, the other lineament directions also occur in the pillow basalt of Pantai Batu Hitam.

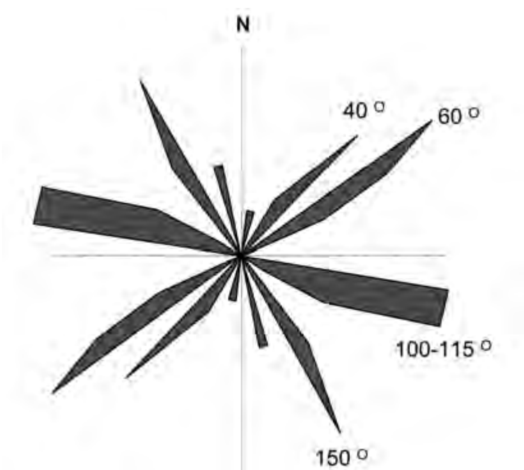

Figure 3: Rose diagram of fractures in the pillow basalt of Pantai Batu Hitam. Three major directions are northwest, east-southeast and southeast.

The pillow basalt of Pantai Batu Hitam is systematically fractured. Joints parallel to the larger fractures are seen within pillow units, continuing in neighbouring pillow units. The major fracture orientations are 060°, 100-115°, and 150°; a less frequent fracture direction is 040° (Figure 3). All fractures are essentially vertical (Figure 2). If the fracturing was produced by cooling of the lava, one would expect fracture orientations to be of either rectangular and/or random patterns. This is not the case. The long and straight fractures are easily traceable over distances in excess of 10 metres. Fractures cutting across pillows are also seen. Lateral displacement was not apparent and vertical offset is not discernible, as the small relief produced by the basalt flow could be due to different pillow sizes.

Drainage lineaments on Triassic-Jurassic (or Permian-Triassic according to Bignell & Snelling, 1977) granite and early Carboniferous sedimentary rocks of the Kuantan area show discrete orientations that are duplicated by fractures in the pillow lava (Figure 4). The single exception is that north-south fractures are not represented in the young basalt. It appears that the Quaternary lava experienced tectonic stress that reactivated pre-Quaternary basement fractures of many orientations.

Batu Lobang, Southeast Johor

Deformed upper Palaeozoic metasedimentary rocks at Batu Lobang were abraded into rock terraces that are now at about 4.5 m and another one slightly over a metre above low tide level (Figure 5). The abrasion terraces represent former low-tide levels. Numerous bio-indicators of Holocene eustatic sea stands in Peninsular Malaysia have been interpreted to indicate a mid-Holocene palaeo-mean sealevel between 4 and 5 metres higher than today (Tjia, 1992). The elevation of the higher terrace corresponds with a sea stand at about 5000 years B.P. Assuming that the palaeo-tidal range was similar with current condition, the corresponding low-tide level would have been 1.5 to

1.8 m below the bevelled rock surfaces .This higher terrace should not have been higher than approximately 3.5 m over present low-tide. A post-mid Holocene uplift of around a metre appears to have occurred.

Johor Graben at the South End of Strait Melaka

A basement-involved normal fault down throwing northwest is shown on Figure 10.5, a geoseismic section of the Johor Graben (Mazlan Madon & Mansor Ahmad, 1999, p. 243 in Leong, 1999). This fault intrudes into the lower part of the Pleistocene-Recent Minas Formation. In the geoseismic section, many of the other faults are shown to end at the base of the Minas, which represents the Pliocene-Pleistocene angular unconformity. The fault transgressing the unconformity and intruding into the Minas sediments indicates Quaternary activity.

Angsa Graben, Northwest off Port Kelang

On Figure 10.5 is also a geoseismic section of the Angsa Graben which shows similar structural conditions to that of the Johor Graben (Mazlan Madon & Mansor Ahmad, 1999). Quaternary crustal movement is indicated by a basement-involved normal fault down-throwing to the southeast. The fault crosses the base-Minas that is an angular unconformity and intrudes the Minas sediments to a level slightly below 200ms.

Langkawi Islands

Pulau Ular is an uninhabited rocky islet off the main Langkawi island in the northwestern part of the Peninsula. The islet is oriented northwest and consists of three low hills connected by a well developed abrasion platform about a metre above present mean sea level (Figure 6). The entire islet is composed of a member of the upper Palaeozoic Singa Formation, consisting of meta-siltstone with metres-wide slump intervals. The platform represents a palaeo-low tide level which can be interpreted to correspond with the eustatic sea stand approximately 2500 years ago. Eustatic sea levels for the later part of the Holocene of Sundaland have been determined using scores of various bio-indicators and compiled in Tjia (1992). A relatively straight fault zone of less than 0.7 m wide runs across this platform and is indicated as "Main fault" in an inset of Figure 5. Differential vertical displacement of the abrasion platform by the fault ranges from 10 cm to 30 cm (another inset in the figure). Straight fracture splays at oblique angles of 40 degrees branch out from the main fault (illustrated in the plan and are visible on the right part of the photograph). The combined deformation pattern suggests the main fault as a sinistral wrench moving actively in post-2500 y time.

The Kilim limestone area that covers the northeast part of main Langkawi Island, and since 2007 declared a UNESCO-approved Geoforest Park, has notches and arcades at levels corresponding with the three Holocene eustatic sea stands. In places the base of limestone cliffs (Setul Formation) have shallow notches, approximately half a metre above current mean sea level (Figure 7). These shallow notches are interpreted as product of a former mean sea level, most probably in the recent past. The situation shown in the figure most probably resulted from crustal uplift.

Tanjung Dendang is a cliffed rocky island in the Kilim Geoforest Part. In place palaeo-intertidal bio-indicators (rock-attached fossil oyster shells and accumulation of mollusc shells) at 23 metres above present sea level have a radiocarbon age of 7000 years (Zaiton Harun *et al*., 2000). Seven thousand years ago the sea of the Langkawi Islands was a few metres below or above present level (Tjia, 1992). The Tanjung Dendang intertidal zone with the fossils is at least 20 metres out of phase. Zaiton Harun (pers. com.) suggested that the geoid of that time was that much higher.

The Mega-thrust Indian Ocean Earthquake of 2004

Research institutions of the European Union and relevant agencies of many Southeast Asian nations initially established 42 GPS base stations throughout the region. Results of two measuring campaigns in 1992 and 1994 show that Sundaland moved as a single block in easterly direction in the ITRF92 framework. Subsequently many more base stations were set up. The effect of the mega-thrust earthquake of 26 December 2004 could thus be determined good accuracy. With respect to the pre-quake baseline, Sundaland was found to have been displaced in west-southwest direction (Figure 8). Lateral displacements were less than 2 cm at the Indosinian base stations and incrementally increased that amounted to 6-7 cm on the

Figure 5: Tanjung Lobang abrasion terraces at 4.5 and about 1 m above current low tide level (shown on this photograph).

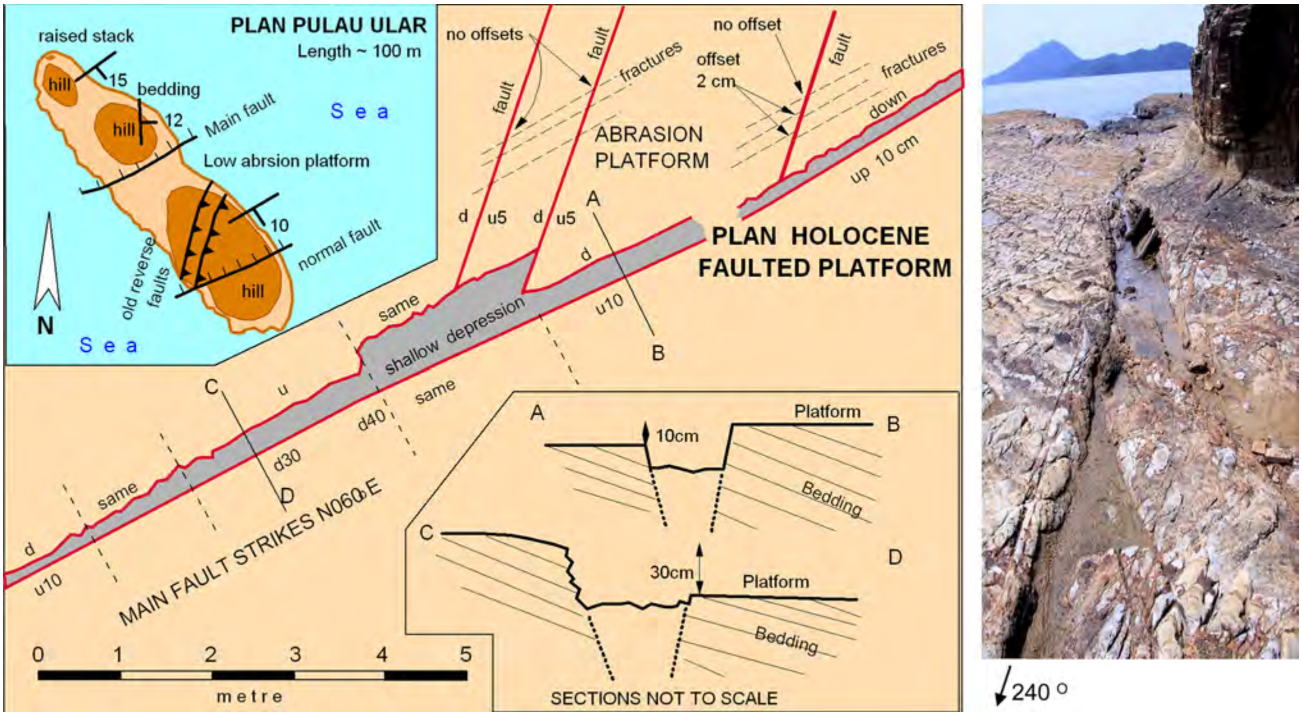

Figure 6: The main abrasion platform of Pulau Ular, Langkawi islands, corresponds with the eustatic sealevel of around 2500 year BP. The main fault deforms this platform and its associated structures are interpreted to indicate sinistral wrenching on the main fault.

east coast to 10-12 cm on the west coast stations of the peninsula, while the maximum was measured at 27 cm near Medan, Sumatera. That particular earthquake originated as a subduction on the Sunda Trench and was of magnitude Mw 9.0, an exceptionally great and rare event. Periodic recurrence of similar large events in the trench to the west of Sumatera had a range of roughly 60 to 170 years (USGS-NEIC records of "significant earthquakes"). It cannot be ruled out that ground movements in Sundaland may have been induced by the relatively small lateral displacements by this single event. Major pipe lines in the South China Sea run east-west, or subparallel to the earthquake displacement. On a geological time scale the incremental amounts of lateral displacement by great earthquakes should be expected to result in ground deformation, including reactivation of faults.

Figure 7: Shallow palaeo-mean sea level notches at the base of limestone cliffs in the Kilim Geoforest Park, Langkawi Island. The photograph shows present mean-sea level condition, and the notches are approximately 0.5 metre higher. This situation is interpreted to indicate actual crustal uplift, possibly only in recent years.

CONCLUSION

Based on the known geological development of Peninsular Malaysia and onshore stratigraphy, it can be maintained that it was tectonically stabilised by Early Tertiary. The association of small Tertiary basins with regional faults indicate transtensional wrench conditions to have been periodically active. The presence of many kilometres-thick Oligocene and younger sediments in the Malay, West Natuna and Penyu basins is evident for belt-wide crustal movements. These sediments were deposited during initial synrift that in the Malay Basin was coupled with large-scale wrenching along its Axial Malay Fault Zone. In the Mid-Miocene the plate dynamics of Southeast Asia changed that resulted in wrench-slip reversals and structural inversion. The overall deformation mode was compressional. This condition petered out towards the end of the Neogene and was replaced with relative stability of Sundaland. This is indicated by the widespread occurrence of late Pliocene-Quaternary sediments in horizontal position, the absence of earthquake epicentres and occurrence of only non-explosive volcanism. In other words, tectonic stability for the whole of Sundaland was only achieved at this late stage. However, the examples discussed in this article strongly suggest that (possibly) occasionally crustal movements are still being experienced in parts of Sundaland.

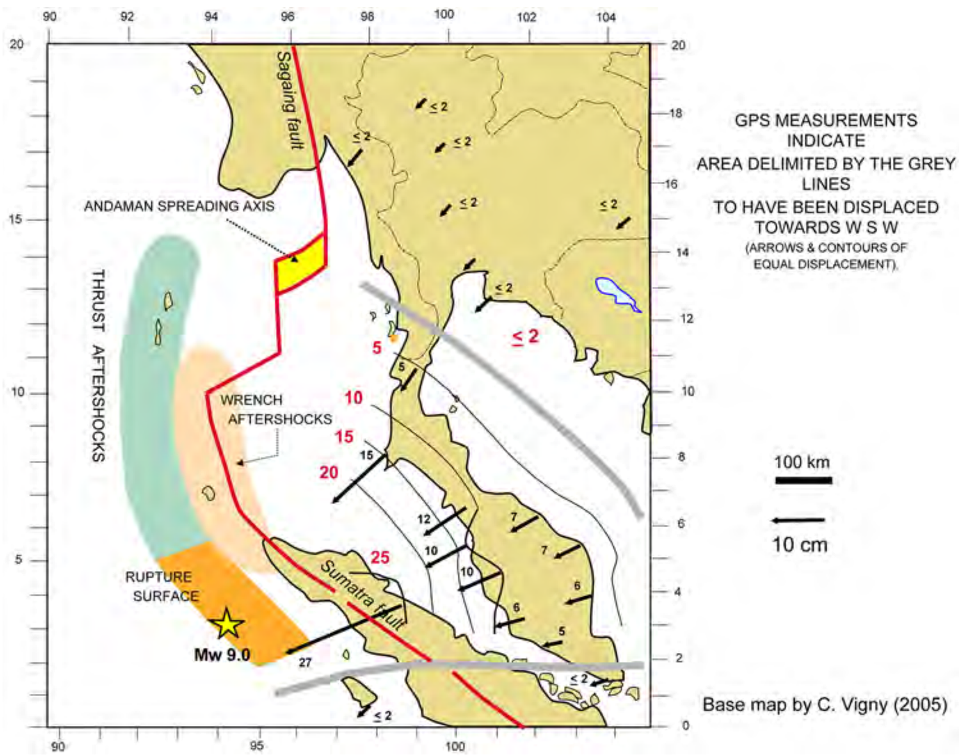

Figure 8: Accurate GPS (global positioning system) measurements that compare post-December 2004 with pre-quake conditions at the various base stations whose locations are at the base of the arrows. These are vectors of secular displacement; the numbers at the arrows are values in centimetres. The base map is by C. Vigny available via internet in 2005.

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