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Evidence of Holocene and historical changes of sea level in the Langkawi Islands

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Abstract: About eighty radiometrically dated biogenic and morphological indicators of sea level of the Langkawi Islands prove that since the maximum Mid-Holocene inundation, the paleo-sea surface descended stepwise thrice to reach its current position several hundred years ago. In presumably historical time some parts of the island group were raised between 0.5 and one meter. One of such events was related to the Aceh/Simeulue mega-earthquake of December 2004 which caused live bands of rock-clinging oysters and barnacles to shift 30 to 40 centimeters upward at Teluk Burau. GPS study also yields evidence of 9 to 11 millimeters co-seismic uplift of the northwestern sector of Peninsular Malaysia. The anomalously high sea stands in the early part of the Holocene and latest Pleistocene in northwestern Peninsular Malaysia remain the most outstanding issue in this investigation. Comparison with recently published sea-level curves of the Sunda Shelf strongly suggests that the geoid of the Strait of Malacca was 50 to 40 meters higher in the period of the LGM (Last Glacial Maximum: 21 ka to 19 ka) to the early half of the Holocene at 10 ka to 5 ka. In the early period of the Holocene, sea level was still up to 24 meters higher than over the Sunda Shelf.

Keywords: geoid high, stepwise descent since Mid-Holocene, effect of Aceh mega-earthquake.

INTRODUCTION

Peninsular Malaysia is located on the Sunda subplate, which has the geological characteristics of a Cenozoic semi-cratonic platform devoid of explosive andesitic volcanism, of strong vertical movement, of tectonically folded Tertiary sediments, and of devastating seismicity. The geological outcrops are also predominantly of pre-Tertiary age, implying absence of major subsidence in the Cenozoic. Magnitude of long-term vertical displacement of the crust is in the hundredths to thousandths millimeters per year range and is thus distinctly different from centimeter-rates of crustal uplift and subsidence associated with reef terraces in the tectonically mobile island arcs framing the Sunda subplate. Figure 1 indexes the localities treated in this article.

Recent observations, however, have yielded evidence of moderate but localised co-seismic ground disturbance, morphological anomalies and GPS- determined ground movements in historical time that imply minor differential crustal deformation in the Langkawi Islands. The dated evidence is discussed according to three periods, that is, with reference to latest Pleistocene - Early Holocene sea stands, with respect to the systematically descending sea levels during the Mid-Holocene to the present interval, and those that occurred in historical time. The radiometrically dated evidence for paleo-sea levels of the Peninsular Malaysia region are tabulated in Tjia & Sharifah Mastura (2013). The paleo-sea level data include geographic coordinates, type of dated material, position with respect to current sea level (most commonly the *in situ* determined high-tide), the radiocarbon ages and the associated laboratory or original publication. The age of shoreline indicators consisting of marine material has also been corrected for the 'marine reservoir effect'. At this stage of knowledge, the correction applied was by subtracting 400 years from all previously published age data. No MRE correction is needed for radiometric ages of plant material (mainly mangrove and peat).

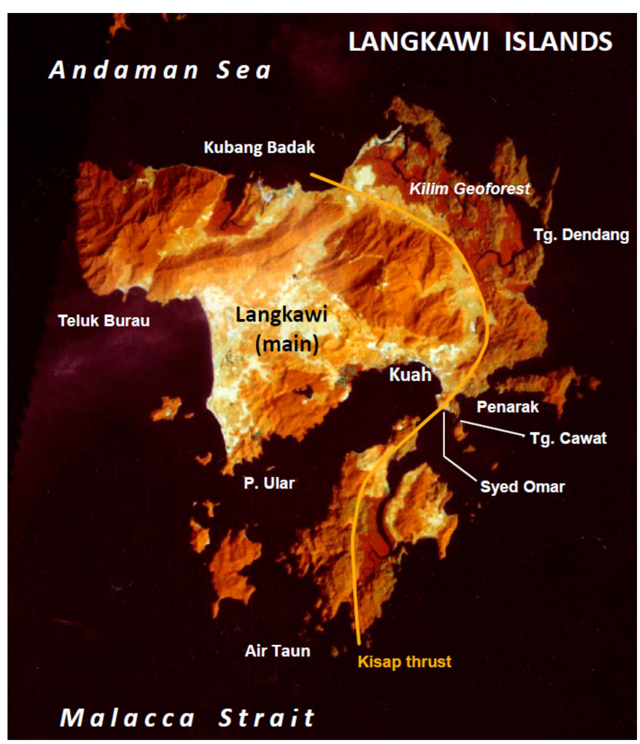

Figure 1: Index of localities mentioned in the article. Width of the main island measures 70 kilometers.

LATEST PLEISTOCENE TO EARLY HOLOCENE SEA LEVELS

A score of fossil mangrove and peat material from the bottom of the Strait of Malacca define the Late Pleistocene to Early Holocene sea stands (Geyh *et al*., 1979; Streif, 1979). Figure 2 compiles this information showing a steadily rising sea from a depth of around 68 meters about 34 000 years ago to reach current sea level position by the Mid-Holocene. The average rate of inundation amounts to 2.4 millimeters annually. The available data points suggest that, during the Last Glacial Minimum (LGM) at 21 to 19 k years ago, sea level in the Strait was at least 75-80 meters higher than the -130 m lowstand generally accepted for that period. Shorelines of the Early Holocene are represented by a scatter of data points time-wise and also in elevation sense An extreme elevation of 23 m above high tide was reported for fossil rock-clinging oysters occurring in a notch in the Setul Limestone of Pulau Tanjung Dendang (Zaiton Harun *et al*., 2000). The notch profile is of the fish-hook type and should have been related to stable crustal condition of the sample location. Figure 3 illustrates the two contrasting basic notch profiles that develop on a tectonically stable coast (fish-hook) and tectonically rising coast (lazy-V). The deepest cut of a notch corresponds with mean sea level; the opening height is dependent on tidal range and arriving wave strength. The lower, gently sloping segment of the fish-hook notch merges very gradually into the almost-level wave-base position. In contrast the lower sloping arm of the lazy-V notch joins the wave-base level with a distinct break-in-slope (Figure 3).

During this period between 34k and 5k years, sea stands in the Strait of Malacca (including the Langkawi Islands) were thus significantly higher compared to those interpreted for western Southeast Asia as a whole (e.g. Sathiamurthy & Vorhis, 2006). Hanebuth *et al*. (2000) showed sea-level over the Sunda Shelf during the period 14.6 - 14.3 ka to have risen from -96 m to - 80 m. During the same period the Strait of Malacca was covered by about 40-meter deep sea, again indicating a 40 to 50 m difference from that of the South China Sea (Figure 4). One plausible cause could

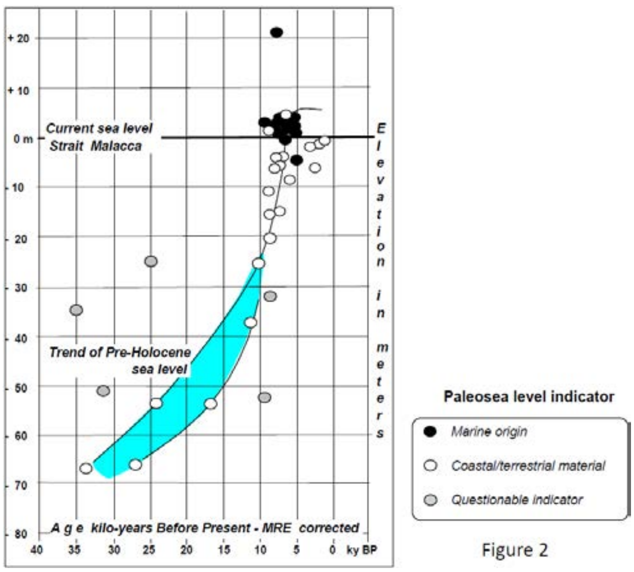

Figure 2: The Late Pleistocene to Early Holocene sea levels indicated by radiocarbon ages of paleo-shoreline indicators in Strait Malacca and Langkawi Islands. The questionable data points concern plant material (including 'wood') without specific reference to sea level.

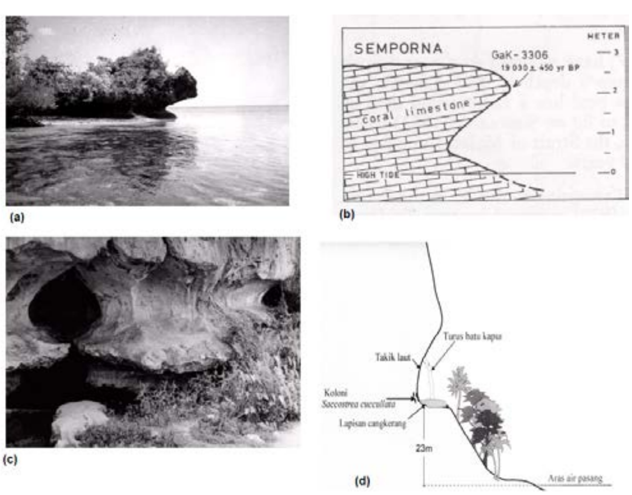

Figure 3: Notches in limestone cliffs. (a) and (b) are of the lazy-V type characteristic for rising coasts in tectonically mobile regions: respectively Selu Island (Tanimbar group, Outer Banda Arc, eastern Indonesia) and Semporna (eastern Sabah). Its MRE corrected radiocarbon age is 18 630 ± 450 y BP. At that time of the LGM, global seas were at their minimum position at least 100 m below current datum. The Semporna reef sample represents tectonic uplift of ≥ 102 m or an average of 5.5 mm each year. Figures 3 (c) and (d) illustrate fish-hook type notches in the limestone cliff of Kodiang (Kedah) and Pulau Tanjung Dendang, Langkawi, respectively. The fish-hook notch profile of (d) implies the current high position of the Mid-Holocene rock-clinging oysters was reached by secular drop of sea level.

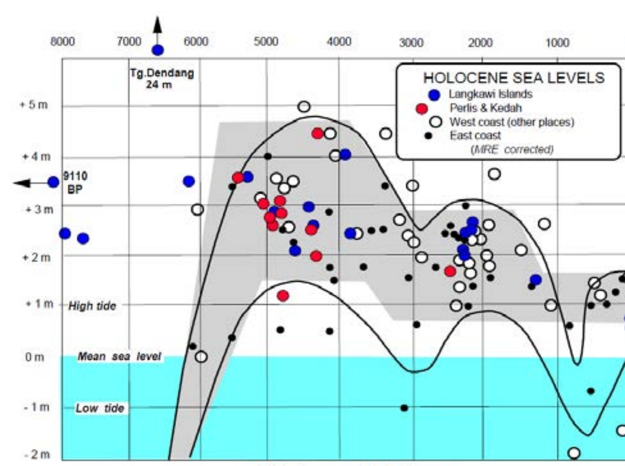

Figure 4: Radiometrically dated paleo-sea level indicators representing Peninsular Malaysia. Five pre-6000 y BP data points from Langkawi presumably relate to a high geoid position. Most of data points fall within the two wavy solid lines as well as within the stepwise descending grey zone. Elevation and occurrence of stacked notches in Langkawi and elsewhere in the Peninsula are in agreement with the stepwise descent of the sea during the Later Holocene (discussion in the text). Each of the paleosea stillstands lasted 1000 to 1200 years.

be that the geoid had a different configuration. At present, the Strait of Malacca roughly coincides with a neutral geoid. zone that demarcates a positively high geoid culminating some 60 meters in the New Guinea region from a negative geoid region that reaches a deep 100 meters depression in the Srilangka region. During a reduction of the angular velocity of the Earth's rotation, geoidal relief will probably "flatten" and its neutral zone shifts westward. This westward shift brings Peninsular Malaysia into the positive geoidal region concomitant with high sea stands.

Radiometrically dated paleo-sea level indicators of Peninsular Malaysia is shown on Figure 4. Seven of the data points represent sea stands in the pre-6000 y BP interval. Five of these data points originate from the Langkawi Islands and possess distinctly anomalous positions with respect to the projected sea level rise in the Malacca Strait (single black line on Figure 2). Sea levels during the Early Holocene (10 k to 6 k years) in Langkawi were 20 to 24 m higher than projected. The most extremely high position is that of 6600 years BP rock-clinging oysters at Pulau Tanjung Dendang situated 24 m above current mean sea level (Zaiton Harun *et al*., 2000). The fossil oysters are hosted in a typical fish-hook notch profile (Figure 2d) which should correspond with a tectonically stable substrate. These five anomalously high paleo-sea level indicators of Langkawi most probably represent a geoid high.

The other two post-6000 y BP data points are from the west coast and from the east coast of the Peninsula, respectively.

MID - HOLOCENE TO RECENT SEA STANDS

Approximately 80 data points of paleo-sea level indicators on the coasts of Peninsular Malaysia define secular changes during the later part of the Holocene (Figure 4). More than a third of the data points originates from the Langkawi Islands and nearby shores of Perlis and northern Kedah. The paleo-sea level indicators include fossil rock-clinging oysters, mollusc beach ridges, coral, some calcareous algal crusts, calcareous beachrock, and coastal plant remains, notably mangrove parts. The radiometric ages of the paleo-sea level indicators of marine origin were adjusted for marine reservoir effect, which at this stage was determined to be 400 years younger. The MRE adjustment possibly needs refinement when new reliable standards become available.

The scatter of data points is generally contained within either the progressively descending zone demarcated by the wavy black solid lines, or reside within the step-like grey zone. A third and simpler explanation favoured by other paleo-sea level researchers is for a Mid-Holocene high sea level in Peninsular Malaysia between 5000 and 4000 y BP followed by a general decrease to the present datum level. This opinion is, however, not borne out by field observations or clustering of radiocarbon ages of paleo-sea level indicators as will be shown below. The scatter of data points in terms of elevation may be attributed to various uncertainties in determining the corresponding position of the paleo-sea. Among these are range of paleotides, the original position of the fossil oyster within the paleotidal range, and paleo-wave height influenced by coastal configuration at different elevation of the former seas. The material collected for the laboratory analysis was measured at the site with respect of the reigning high tide level, which is the most practical benchmark recognisable as slope breaks of the beach surface, up-beach limit of loose shells and other flotsam. The high-tide mark may vary in excess of a meter depending on the season. In view of these variables, it has been impractical to apply corrections to the vertical positions of the paleo-sea indicators. Nevertheless, the distinct clustering of data points in Figure 4 has been considered sufficiently representative of the paleo-sea level changes of the younger part of the Holocene.

Initially my close collaborators on paleo-sea levels and I (Tjia *et al*., 1977) preferred the wave-like descent of sea level since the Mid-Holocene for Peninsular Malaysia. Resulting from many follow-up studies, including coastal observations on other islands of the tectonically stable Sunda Shelf, e,g, the Indonesian tin islands of Bangka, Belitung and Kundur, it became clear that stacked Later-Holocene sea level indicators are common occurrences. The compelling evidence consists of sea-level notches and clusters of fossil rock-clinging oysters arranged at three or more levels at various locations in the region. A still stand -however temporary- of sea level is required to develop the notches. Still stands of the descending post-Mid Holocene sea are best explained by the stepwise descent in Figure 4. Figure 5 illustrates the situation at Pulau Ular, a small islet just off the southwest coast of Langkawi main island. Pulau Ular consists of the Permo-Carboniferous Singa Formation that crops out as three low hills protruding several meters from a base of a well-developed abrasion platform approximately 1 to 1.5 m above current high tide. Three notches at 5.5 m, 2.7 m and corresponding with the 1.5 meter above high tide abrasion platform are stacked on the face of the northern hill side. The lowest notch is of a typical fish-hook type. The elevations of the three notches correspond with paleo-sea levels at around 2300 y BP (1.5 m above high tide), 4400 - 3800 y BP (2.7 m aht), and the Mid-Holocene inundation peak between 5000 and 4400 y BP (5.5 m high notch).

An other example suggesting stepwise change of paleo-sea level during post-Mid Holocene are several abrasion terraces cut across granite at Teluk Burau which is located on the west central coast of Langkawi main island (Figure 6, upper). Four levels of abrasion benches, each several meters wide correspond with former low-tides at 0.5 m aht (above high tide, or a corresponding sea level at 1.5 m), 1.75 - 2 m aht (representing 2.75 to 3 paleo-sea level), 3.5 m aht (its associated paleo-sea level was 4.5 m) and 5.5 m aht (of paleo-sea level at 6.5 m). Each of the virtually level bench surfaces indicates approximately the corresponding wave base or paleo-low-tide .

The lower Figure 6 is a synoptic sketch of fossil oyster positions within Gua Kelawar, a short through cave in the

Kilim Geoforest Park, northwest Langkawi. The higher oyster cluster is located 1.2 m to 2.2 m above current high tide; the lower oyster cluster is 0.35 to 0.4 m above high tide. Samples GK-1 and Gk-2 were collected for pending radiocarbon age analysis. The Gua Kelawar fossil oysters suggest that no sun or day light was required for their existence. Note also the so called 'wind-vane' stalactites at one of the exits of Gua Kelawar.

General tectonic stability of the main Langkawi Island is also demonstrated by the well-developed fish-hook notch on the cliff of a small peninsula of Setul Limestone located on the southeast of the big island (Figure 7). The crystalline Setul Limestone is laced with crinkly siliceous laminations mistakenly indicated as 'stylolites' in the 'Geology of the Malay Peninsula' (Jones, 1973, p. 35). The smooth, uniformly abraded surface of the lower leg of the notch distinctly contradicts the notion that notches in coastal limestone cliffs are products of bio-erosion (Hodgkin, 1970). Instead mechanical down wear or abrasion has been the cause. Figure 7 further shows the top limit of live rock-clinging oysters equates with the high tide level.

CRUSTAL DEFORMATION IN HISTORICAL TIME

In historical time, crustal deformation of parts of the Langkawi Islands are implied by the following evidence.

Analysis of GPS records of ground movements attributed to the 26 December 2004 mega-earthquake of Simeulue in the Indian Ocean west of Aceh in northern Sumatera, shows vertical displacements in Peninsular Malaysia. Ami Hassan Md Din *et al*. (2012) computed 9 to 11 mm uplift in GPS stations in Perlis and northern Kedah, while recording subsidence of similar values for southwest Johor. The co-seismic ground displacements were lowest in Negeri Sembilan-Selangor region.

Just two years and a few months after the December 2004 disaster, the coastal exposure at Teluk Burau, west-central part of Langkawi, was captured in Figure 8. Live barnacles occupy positions up to 30 centimeters above the top of rock-clinging oyster clusters, a position commonly seen on Malaysian shores. The top limit of growing oysters also marks the maximum reach of high tide. The exposure at Teluk Burau consists of two barnacle- oyster bands. The upper band of 54 centimeters is populated by live specimens. The small size of the live oysters indicate young age. This upper barnacle-oyster association is followed downward by a 35 cm lower barnacle-oyster band that ultimately disappears below loose beach sand (Figure 8), whose surface is approximately a meter above current low tide. The lower barnacle-oyster band has no living individuals and the dead oyster shells have a greenish sheen. The exposure at Teluk Burau appears to indicate: (a) very recent -in historical sense- ground subsidence of at least 35 cm that caused beach sand to smother the lower barnacle-oyster association; (b) followed by uninterrupted development of a younger barnacle-oyster band higher up on the same granite surface; and finally (c) scouring by tidal currents that re-exposed part of the lower dead barnacle-oyster band. The youthful small size of the live oysters could well equate with growth following the tsunami inundation of the western coast of Langkawi which accompanied the Simeulue mega-quake of December 2004.

Figure 5: Three sea-level notches stacked in the cliff of Pulau Ular that consists of clastics of the Late Paleozoic Singa Formation. Development of each notch would require the paleosea to have maintained position for some duration. Figure 4 suggests that the paleoseas associated with the notches existed between 5 ka and 4 ka (forming the 5.5 m aht notch), 4.4 ka and 3.8 ka (2.7 m aht notch), and ~2.3 ka (1.5 m aht notch with corresponding abrasion platform).

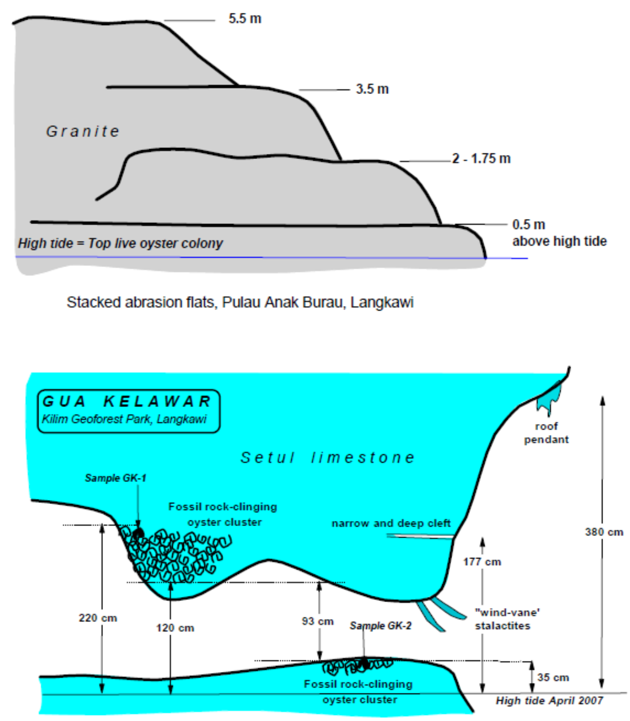

Figure 6: More stacked paleosea-level indicators in Langkawi. Upper: Four abrasion benches at 0.5 m, 1.75 - 2 m, 3.5 m and 5.5 m aht were cut across hard granite . Lower: In the dark through-cave named Gua Kelawar, Setul Limestone of the Kilim Geoforest Park, are two clusters of fossil rock-clinging oysters. The higher cluster extends from 2.2 m to 1.2 m aht; the lower cluster is 0.35 to 0.4 m aht. The higher oyster cluster may be of near Mid-Holocene age; the lower could be in the 2 ka - 3 ka age bracket according to Figure 4. Radiometric dating of samples GK-1 and GK-2 should provide reliabler ages. Note the so called 'wind-vane' stalactites at the cave entrance. Similar forms are common in limestone caves.

Stacked, relatively shallow notches in the Setul Limestone of the Kilim Geoforest Park are exposed along the Kilim river and its branches. Figure 9 illustrates three stacked notches. The photograph was taken at the approximate time of mean sea level that corresponds with the lowest exposed notch position. The top limit of live rock-clinging oyster cluster is ~1.5 m above this lowest notch. Approximately 0.5 m above the live oyster limit is a relatively shallow notch with irregular lateral extent. This notch is oblique to stratification of the limestone which is moderately steep. Although irregular, the notch closely parallels the sea surface. A well-developed notch is ~ 1.2 m above the top limit of live oysters. This notch has a lazy-V profile (marked X) that should represent formation associated with falling sea level caused by land uplift.

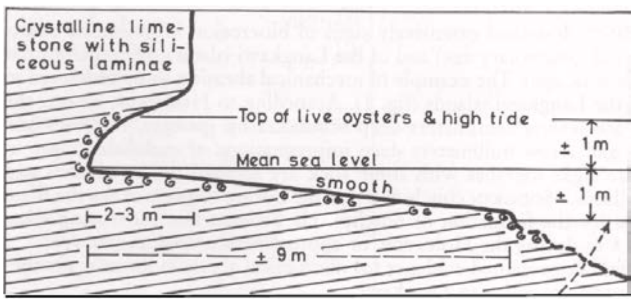

Figure 7: A typical fish-hook notch profile in Setul Limestone of Penarak, small promontory in SE Langkawi. The Setul Limestone is laced with subparallel ~ 1 cm wide siliceous laminae that are harder than the host limestone. The lower leg of the notch profile is smooth, thus proving that mechanical abrasion was the cause. Bio-erosion could not be expected to evenly smoothed out the surface as grazing and other forms of feeding by organisms would have been discrminatory. Further discussion was published earlier (Tjia 1985).

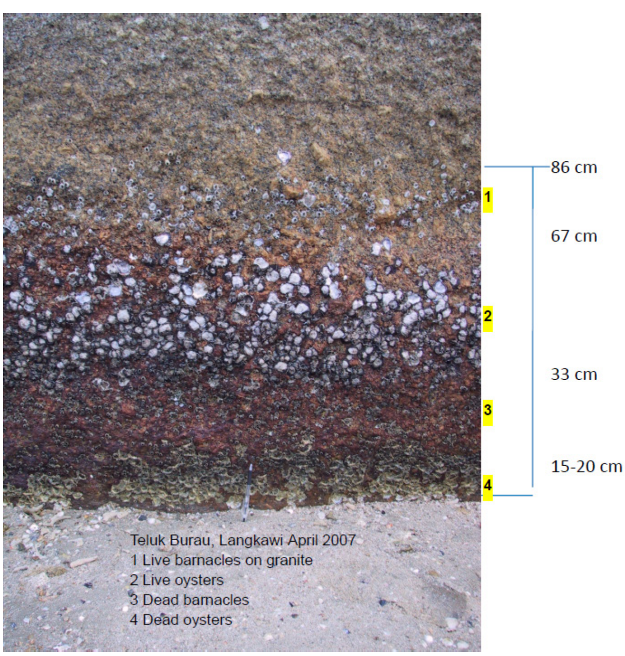

Figure 8: Teluk Burau, two years and five months following the mega-disaster caused by the Simeulue and Indian Ocean-wide tsunami, hosts the exposure in the figure. A dead barnacle-oyster band and a higher positioned growing barnacle-oyster band are attached to the same granite surface of a coastal outcrop. The occurrence suggests that the lower barnacle-oyster band was recently buried and killed by land subsidence of at least 35 cm. A new band of the organisms grew at the higher level. Tidal currents exhumed the lower band just before the photograph was taken.

In the limestone cliffs along Pantai Beringin, a stretch of only a few hundred meters long between Pantai Syed Omar and Tanjung Cawat, southeast Langkawi, both lazy-V together with fish-hook notch profiles occur side by side close above present sea level. The occurrence is interpreted as result of recent differential 'tectonic' behaviour, that is presumably attributable to compartmentalisation of the coastal stretch. The Kisap Thrust zone runs nearby (see Jones 1978, pages 158-170; and also Figure 1). Apparently ground disturbance -in historical time as the closeness to current sea level suggests- only affected the coast with lazy-V notch profile.

CONCLUSIONS

During the period of ~ 36 ka to ~5 ka (latest Pleistocene to Mid-Holocene) sea level in the Langkawi-Malacca Strait zone was between 40 m to 24 m higher compared to sea level on the Sunda Shelf of the South China Sea. This condition can be attributed to a geoid configuration that differed from the current situation. Currently the roughly North-South trending zero geoid zone occupies Strait Malacca. A prominent geoid high (+80 m) is located in the West Papua region 42 degrees longitude to the East of the Strait, while a current geoid depression (-100 m) lies off Srilangka some 20 degrees to the West. If the Earth's rotation decreases, one could expect the geoid relief to flatten and to shift westward. The opposite will probably happen if the angular velocity accelerates.

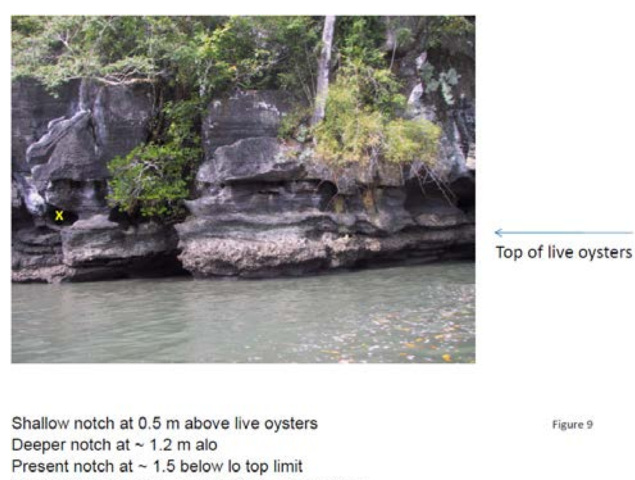

Figure 9: Three notches in the Setul Limetone lining Sungai Kilim. The lowermost notch corresponds with current mean sea level position. A shallow notch that extends laterally in irregular fashion is 0.5 m above current high tide, which corresponds with the top limit of the cluster of rock-clinging oysters. A higher, shallow but well-developed notch is located 1.2 m above current high tide. Its lazy-V profile is at X.

From the Mid-Holocene maximum inundation of the region at 4400 yr BP onward, regional sea level progressively dropped stepwise three times. Periods of sea level stillstands, each of about 1100 to 1200 years duration, allow abrasion to develop level benches on hard rock (granite at Teluk Burau) and notches on limestone cliffs. Figure 4 shows the elevation of the stepwise descent.

Effects of mega-earthquakes, estimated to occur in periods of 400 to 1000 years apart, appear to have extended into the Langkawi areas. Local crustal deformation of the Simeulue event of December 2004 probably caused the 35-cm ground subsidence at Teluk Burau burying and killing a band of barnacle-oyster while permitting a new barnacle-oyster band to evolve at a higher elevation (Figure 8).

The majority of notches in Langkawi are of the fish-hook type indicating development during ground stability. At Pantai Beringin and nearby Tanjung Cawat notches of the fish-hook as well as of the lazy-V types are located side by side and occur close to current mean sea level.Their position with respect to the current sea surface implies recent ages. Compartmentalisation by the Kisap Thrust zone may account for differential ground instability along this short coastal reach.

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