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Mid-Holocene to recent sea level changes in Peninsular Malaysia: a tectonic implication

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Abstract: This paper tries to analyse the Peninsular Malaysia mid-Holocene to recent relative sea level index points. 56 reliable sea level indicators are scrutinized and their relative sea levels corrected. Attempt is made to explain the relative sea level difference noted between the Peninsular Malaysia West and East coasts. A relative rate of sea level fall of 0.7 and 0.5 mm/year respectively, are indicated from cumulative analysis of the West and East coasts index points. The significant dissimilarity in the rate of sea level fall suggests differential crustal movement between the two coasts. Explanation of hydro- and tectono-isostasy are put forward to explain the observed discrepancy.

INTRODUCTION

The mechanisms that produce sea level changes are complex. They require the explanation of among other factors earth's rheology, eustasy and isostasy (Peltier, 1987; Pirazzoli, 1991). The variables and contributing causes include glacio-eustasy (eustatic changes related to the accumulation and wasting of land-based ice), geoidal-eustasy (distribution of ocean water under the influence of gravitational forces), tectono-eustasy (earth movements), glacio-isostasy (isostatic changes following shifts in surface loads such as ice), hydro-isostasy (water) and sediment-isostasy (Morner, 1976; Kidson, 1982). In addition, the steric effects (oceanic expansion) produce changes in sea level from changes in water density due to short-term disturbances of the sea surface through variations in air pressure, ocean temperature or salinity (Woodworth, 1985; Devoy, 1987).

Sea level data of Peninsular Malaysia could basically be grouped into the West and East coasts sites. Comparing the relative sea level records between the sites would enable the narrowing down and identifying the contributing mechanisms of sea level change. This would provide better understanding of the relative sea level history between different areas and in a regional context, allow the examination of any differential crustal movement. This paper attempts to analyse the nature of mid-Holocene to recent sea level trend for the West and East coasts of Peninsular Malaysia. Data of reliable sea level indicators were selected and compiled from various sources. Tjia *et al.* (1977), Tjia *et al.* (1983), Tjia (1987) made available data mainly from biological sea level indicators such as oysters and corals. Meanwhile, Geyh *et al.* (1979) and Kamaludin (2002) provide data from depositional sea level indicators mainly from peat overlying brackish deposits. Additional data are also sourced from Yancey (1973), Streif (1979), Yoshikawa (1987) and Bosch (1988). Apart from the selected analysed sea level data, many available data were however found to be rather simple. This particularly concerns the dated sea level indicators and their measured heights, which renders many supposedly sea level data less useful. For any sea level data to be meaningful, the index point needs to satisfy the criteria of age, altitude, geographical location and indicative meaning (Shennan, 1986; Plaasche, 1986). Table 1 shows the compiled reliable sea level data. The errors in the respective relative sea levels are calculated from the indicative meaning and range of the sea level indicators. Table 2 lists the estimated indicative meaning and range values of the various types of sea level indicators.

PENINSULAR MALAYSIA POSTGLACIAL SEA LEVEL CHANGES

In the 1960s the concept of eustatic changes in sea level as discussed by Fairbridge (introduced by Suess, 1906; in Fairbridge, 1961), has influenced the development and perception on sea level studies worldwide. The postglacial sea level history of Peninsular Malaysia has developed in a similar manner. The late Pleistocene-Holocene sea level changes in the Strait of Malacca was investigated by Geyh *et al.* (1979) and Streif (1979), while Holocene to present sea level of Peninsular Malaysia by Tjia *et al.* (1977) and Tjia (1980, 1992, 1996).

Better understanding of the nature of postglacial sea level changes developed upon initiation of the International Geological Correlation Programme (IGCP) Project 61, "Sea level changes during the last deglacial hemicycle (about 15,000 years)". Three main types of new results and ideas discrediting the eustatic assumption were contributed. The geoidal relief and its changes with time as explained by Morner (1976) would cause differences between coastal

Table 1. Compiled data of reliable sea level indicators (SLI), corrected heights and relative sea levels (to about 6,000 years BP) for Peninsular Malaysia.

Locality	Description of sea level indicator	^{14}C Age of SLI (years BP)	Height of SLI (m)	Source of data	Height of SLI to MSL (m)	Relative sea level (m)
Tg. Gemuruh, Penang Island, 05°25.3N, 100°11.6'E	Dead oyster attached to granitoid surface	1,500±80 (I-14073)	0 to 0.15 aht	Tjia, 1987; Yoshikawa, 1987	1.17	1.17±1.5
Coast of Strait of Malacca, 01°46'N, 103°01'E	Base of peat on brackish sediments	2,130±155 (Hv-7588)	1.80 to 2.00 MSL	Geyh *et al.*, 1979; Yoshikawa, 1987	1.9	0.4±1.5
Tg. Bongkok, Penang Island, 05°17'N, 100°13.6'E	Dead oyster attached to underside of boulder	2,360±70 (Beta-16814)	0.8 to 0.9 aht	Tjia, 1987; Yoshikawa, 1987	1.95	1.95±1.5
Batu Keramat, Pangkor Island, 4°12.3'N, 100°33.5'E	Dead oyster attached to granitoid	2,430±80 (I-14075)	1.0 to 1.1 aht	Tjia, 1987; Yoshikawa, 1987	2.05	2.05±1.5
Langgun Island, Langkawi, 06°25'N, 99°43'E	Dead oyster in growth position	2,530±100 (GaK-4462)	1.4 aht	Tjia *et al.*, 1977; Yoshikawa, 1987	2.8	2.8±1.5
Dayang Bunting Island, Langkawi, 06°17'N, 99°49'E	Dead oyster in growth position	2,590±100 (GaK-3308)	1.5 to 1.8 aht	Tjia *et al.*, 1977; Yoshikawa, 1987	3.05	3.05±1.5
Teluk Nibung, Langkawi Island, 06°21.7'N, 99°42'E	Dead oyster attached to granitoid	2,600±70 (Beta-15387)	0.9 aht	Tjia, 1987; Yoshikawa, 1987	2.3	2.3±1.5
Gertak Sanggul, Penang Island, 05°16.4'N, 100°11.2'E	Dead oyster attached to granitoid	2,620±80 (I-14068)	0.7 aht	Tjia, 1987; Yoshikawa, 1987	1.8	1.8±1.5
Tg. Gemuruh, Penang Island, 05°25.3N, 100°11.6'E	Dead oyster attached to granitoid cliff	2,720±80 (Beta-16811)	0.9 aht	Tjia, 1987; Yoshikawa, 1987	2.0	2.0±1.5
Batu Keramat, Pangkor Island, 4°12.3'N, 100°33.8'E	Dead oyster attached to granitoid	3,300±100 (I-14074)	0.96 to 1.0 aht	Tjia, 1987; Yoshikawa, 1987	2.08	2.08±1.5
Batu Keramat, Pangkor Island, 4°12.3'N, 100°33.8'E	Dead oyster attached to granitoid	3,450±100 (I-14076)	1.3 to 1.35 aht	Tjia, 1987; Yoshikawa, 1987	2.42	2.42±1.5
Gertak Sanggul, Penang Island, 05°16.4'N, 100°11.2'E	Dead oyster attached to granitoid	3,510±100 (I-14070)	1.4 to 1.5 aht	Tjia, 1987; Yoshikawa, 1987	2.55	2.55±1.5
Tepur Island, Langkawi, 06°16'N, 99°43'E	Raised beachrock	3,660±100 (GaK-4461)	0.7 aht	Tjia *et al.*, 1977; Yoshikawa, 1987	2.1	2.1±1.5
Meru, Kelang, Selangor, 03°9.1N, 101°27.5'E	Base of peat on brackish sediments	4,045±49 (AA37792)	4.193 to 4.203 MSL	Kamaludin, 2001, 2002	4.198	2.898±0.3
Meru, Kelang, Selangor, 03°9.25N, 101°27.8'E	Base of peat on brackish sediments	4,073±86 (AA37793)	4.304 to 4.314 MSL	Kamaludin, 2001, 2002	4.309	2.709±0.2
Coast of Strait of Malacca, 02°01'N, 102°47'E	Peat on brackish deposits	4,135±90 (Hv-7589)	4.95 to 5.00 MSL	Geyh *et al.*, 1979; Yoshikawa, 1987	4.97	3.47±1.5
G. Keriang, Kedah, 06°12'N, 100°19'E	Dead oyster in growth position	4,220±140 (GaK-4665)	1.5 MSL	Tjia *et al.*, 1977; Yoshikawa, 1987	2.9	2.9±1.5
Coast of Strait of Malacca, 01°48'N, 103°15'E	Peat on brackish deposits	4,275±70 (Hv-7587)	4.70 to 4.95 MSL	Geyh *et al.*, 1979; Yoshikawa, 1987	4.82	3.32±1.5
Langgun Island, Langkawi, 06°25'N, 99°43'E	Dead oyster in growth position	4,310±110 (GaK-5290)	1.5 aht	Tjia *et al.*, 1977; Yoshikawa, 1987	2.9	2.9±1.5
Coast of Strait of Malacca, 01°43'N, 103°18'E	Base of peat on brackish deposits	4,335±105 (Hv-7586)	3.75 to 3.80 MSL	Streif, 1979; Bosch, 1988	3.77	2.27±1.5
Anak Tikus Island, Langkawi, 06°25.5'N, 99°54.5'E	Dead oyster in growth position	4,370±110 (GaK-5291)	3.0 aht	Tjia *et al.*, 1977; Yoshikawa, 1987	4.4	4.4±1.5
Bt. Kepah, Seberang Perak, 04°06.8'N, 100°54.7'E	Dead oyster attached to abrasion surface	4,560±200 (Beta-15388)	4.4 aht	Tjia, 1987; Yoshikawa, 1987	5.5	5.5±1.5
Bt. Papan, Perlis, 06°25'N, 100°06'E	Dead oyster in growth position	4,720±110 (GaK-5294)	1 aht	Tjia *et al.*, 1977; Yoshikawa, 1987	2.4	2.4±1.5
Langgun Island, Langkawi, 06°25'N, 99°43'E	Dead oyster in growth position	4,810±90	3 MSL	Yancey, 1973; Tjia *et al.*, 1977; Yoshikawa, 1987	4.4	4.4±1.5
Wang Bintang Perlis, Perlis, 06°28'N, 100°02'E	Dead oyster in growth position	4,830±110 (GaK-5485)	2.5 MSL	Tjia *et al.*, 1977; Yoshikawa, 1987	3.9	3.9±1.5
Coast of Strait of Malacca, 01°29'N, 103°23'E	Base of peat on brackish deposits	4,980±75 (Hv-7580)	3.70 to 3.80 MSL	Geyh *et al.*, 1979; Yoshikawa, 1987	3.75	2.25±1.5
Dayang Bunting Island, Langkawi, 06°17'N, 99°49'E	Dead oyster in growth position	5,060±90	2.0 to 2.1 MSL	Yancey, 1973; Tjia *et al.*, 1977; Yoshikawa, 1987	2.05	2.05±1.5
Coast of Strait of Malacca, 01°60'N, 102°41'E	Base of peat on brackish deposits	5,065±75 (Hv-7590)	3.85 to 4.00 MSL	Streif, 1979; Bosch, 1988	3.92	2.42±1.5
Langgun Island, Langkawi, 06°25'N, 99°43'E	Dead oyster in growth position	5,090±120 (GaK-4663)	2.4 aht	Tjia *et al.*, 1977; Yoshikawa, 1987	3.8	3.8±1.5
Mardi, Kelang, Selangor, 02°59.25N, 101°29.8'E	Base of peat on brackish sediments	5,270±47 (AA37795)	4.675 to 4.69 MSL	Kamaludin, 2001, 2002	4.682	3.08±0.2
Batu Putih, Kuala Perlis, Perlis, 06°15.3'N, 100°15.2'E	Dead oyster attached to cliff	5,310±90 (Beta-15386)	2.6 aht	Tjia, 1987; Yoshikawa, 1987	4.0	4.0±1.5
Tg. Dendang Island, Langkawi, 06°26'N, 99°55'E	Dead oyster in growth position	5,330±120 (GaK-5292)	1.9 aht	Tjia *et al.*, 1977; Yoshikawa, 1987	3.3	3.3±1.5
Mardi, Kelang, Selangor, 02°59.25N, 101°29.65'E	Base of peat on brackish sediments	5,331±46 (AA37794)	4.936 to 4.946 MSL	Kamaludin, 2001, 2002	4.941	3.441±0.1
Mardi, Kelang, Selangor, 02°59.4N, 101°30'E	Base of peat on brackish sediments	5,349±65 (AA37796)	4.787 to 4.797 MSL	Kamaludin, 2001, 2002	4.792	3.092±0.3
Bt. Papan, Perlis, 06°25'N, 100°06'E	Dead oyster in growth position	5,350±90	2.8 MSL	Yancey, 1973; Tjia *et al.*, 1977; Yoshikawa, 1987	4.2	4.2±1.5
Mardi, Kelang, Selangor, 02°59.45N, 101°30.6'E	Base of peat on brackish sediments	5,556±47 (AA37797)	4.738 to 4.748 MSL	Kamaludin, 2001, 2002	4.743	3.343±0.2
Kuala Sura, Terengganu, 04°42'N, 103°27'E	Dead oyster in growth position	235±75 (I-9483)	0.3 aht	Tjia *et al.*, 1977; Yoshikawa, 1987	1.2	1.2±1.5
Teluk Sisik, Kuantan, 03°48'N, 103°13'E	Dead oyster in growth position	530±100 (GaK-5912)	0.3 aht	Tjia *et al.*, 1977; Yoshikawa, 1987	1.2	1.2±1.5
Tg. Sulong, Trengganu, 04°15'N, 103°28'E	Dead oyster in growth position	840±100 (GaK-5907)	0 aht	Tjia *et al.*, 1977; Yoshikawa, 1987	0.9	0.9±1.5
Salang, Tioman Island, 02°52.7'N, 104°09.5'E	Coral colony from reef flat being abraded	940±90 (GaK-9563)	-0.7 MSL	Tjia *et al.*, 1983; Yoshikawa, 1987	-0.7	0.8±1.5
Bt. Teluk Batu, Trengganu, 04°24.5'N, 103°27.5'E	Dead oyster in growth position	1,200±110 (GaK-5915)	-0.4 ht	Tjia *et al.*, 1977; Yoshikawa, 1987	0.5	0.5±1.5
Juara, Tioman Island, 02°46.7'N, 104°13'E	Dead oyster in growth position	2,370±120 (GaK-9566)	2.6 MSL	Tjia *et al.*, 1983; Yoshikawa, 1987	2.6	2.6±1.5
Juara, Tioman Island, 02°46.7'N, 104°13'E	Dead oyster in growth position	2,640±120 (GaK-9567)	1.4 MSL	Tjia *et al.*, 1983; Yoshikawa, 1987	1.4	1.4±1.5
Tg. Penunjuk, Trengganu, 04°20'N, 103°28'E	Dead oyster in growth position	2,730±125 (Hv-6636)	1.4 aht	Tjia *et al.*, 1977; Yoshikawa, 1987	2.3	2.3±1.5
Bt. Keluang, Trengganu, 05°48'N, 102°37'E	Dead oyster in growth position	2,870±70 (GaK-5264)	1.65 aht	Tjia *et al.*, 1977; Yoshikawa, 1987	2.55	2.55±1.5
Juara, Tioman Island, 02°46.7'N, 104°13'E	Dead oyster in growth position	3,160±170 (GaK-9565)	1.9 MSL	Tjia *et al.*, 1983; Yoshikawa, 1987	1.9	1.9±1.5
Tg. Gemuk Trengganu, 04°17'N, 103°29'E	Dead oyster in growth position	3,380±180 (GaK-5914)	0 aht	Tjia *et al.*, 1977; Yoshikawa, 1987	0.9	0.9±1.5
Penor, Kuantan, 03°43.4'N, 103°16.4'E	Peat on brackish deposits	3,967±43 (AA37798)	3.034 to 3.054 MSL	Kamaludin, 2001, 2002	3.044	1.244±0.1
Tg. Gemuk Trengganu, 04°17'N, 103°29'E	Dead oyster in growth position	3,990±105 (Hv-6637)	2.5 aht	Tjia *et al.*, 1977; Yoshikawa, 1987	3.4	3.4±1.5
Tg. Gemuk Trengganu, 04°17'N, 103°29'E	Dead oyster in growth position	4,030±140 (GaK-5910)	1.7 aht	Tjia *et al.*, 1977	2.6	2.6±1.5
Juara, Tioman Island, 02°46.7'N, 104°13'E	Dead oyster in growth position	4,160±150 (GaK-9564)	2.7 MSL	Tjia *et al.*, 1983; Yoshikawa, 1987	2.7	2.7±1.5
Tg. Gemuk Trengganu, 04°17'N, 103°29'E	Dead oyster in growth position	4,700±180 (GaK-5909)	1.0 aht	Tjia *et al.*, 1977; Yoshikawa, 1987	1.9	1.9±1.5
Bt. Teluk Batu, Trengganu, 04°24.5'N, 103°27.5'E	Dead coral in growth position	5,370±180 (GaK-5913)	-0.5ht	Tjia *et al.*, 1977; Yoshikawa, 1987	0.4	1.9±1.5
Bt. Keluang, Trengganu, 05°48'N, 102°37'E	Dead oyster in growth position	5,580±130 (GaK-5263)	3 aht	Tjia *et al.*, 1977; Yoshikawa, 1987	3.9	3.9±1.5
Mukut, Tioman Island, 02°43'N, 104°10.3'E	Dead coral colony from abraded platform	5,940±160 (GaK-9560)	0.3 to 0.5 MSL	Tjia *et al.*, 1983;Yoshikawa, 1987	0.4	1.9±1.5

Abbr: aht = above high tide, ht = high tide, MSL = mean sea level

Note: The height of the SLI is expressed to MSL. In many cases, the SLI heights are corrected to the local mean high water (mhw) level, the values of which are referred from tidal observation records published by Department of Survey and Mapping. The mhw level adopted for Langkawi and Perlis coasts is 1.4 m, Penang Island to Lumut/Pangkor as 1.1 m, Trengganu to Kuantan and Tioman coasts as 0.9 m.

Table 2. Estimated indicative meanings of sea level indicator (from Zong, 1992; Kamaludin, 2002).

Type of indicator	Indicative meaning (m)	Indicative range (m)
Oyster in growth position	0	±1.5
Coral in growth position	–1.5	±1.5
Beachrock	0	±1.5
Peat on brackish deposits	1.5	±1.5

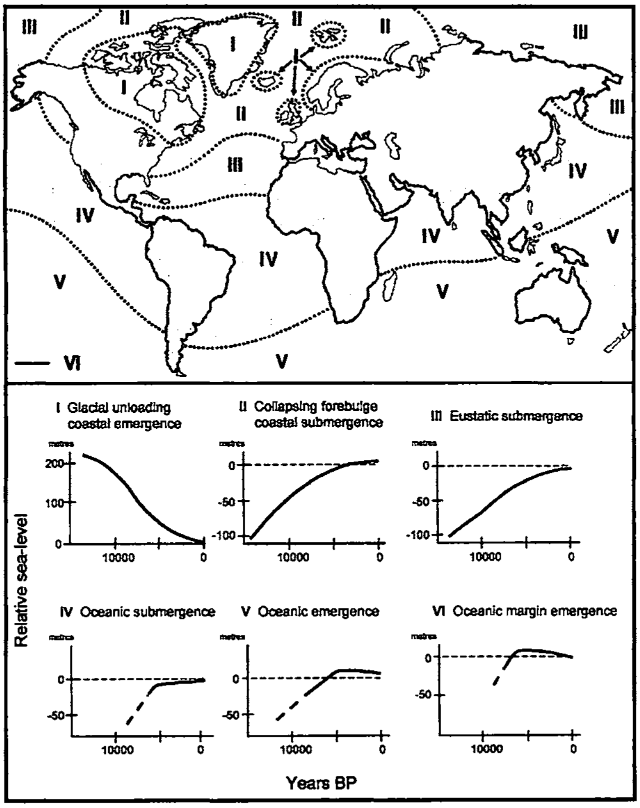

Figure 1. Model of the global changes in postglacial sea level (after Clark *et al.*, 1978).

areas in the relative sea level history. The geoid's concept as shown by the satellite image revealed humps and depressions of the ocean surface topography. The compilation of worldwide postglacial sea level data shows considerable variation between places (Bloom, 1977; Pirazolli, 1977). The geophysical model of Clark *et al.* (1978) predicted the existence of six postglacial sea level zones, each of which has a characteristic form of relative sea level history.

Geophysical modeling of postglacial sea level changes

The Holocene postglacial sea level rise modeled by Clark *et al.* (1978), classifies Peninsular Malaysia within the 'Zone IV-oceanic submergence' form of relative sea level curve (Fig. 1). The hypothesis is based on the calculation of the earth model response to melting of postglacial ice sheets of the Northern Hemisphere and the Antarctic. Emerged beaches are predicted in four zones, which may form even at considerable distance from the ice sheets, while in the remaining zones submergence is dominant with no expected emerged beaches. Large geographical areas including the Southeast Asian region are classified in the Zone IV, where no emerged beaches but dominant submergence are predicted. However, Peninsular Malaysia has well developed Holocene coastal plains, higher than present sea level, straddling its West and East coasts. This alone contradicts the no emerged beaches postulated by Clark *et al.* (1978). The fact that the Peninsula shows higher than present sea levels around the mid-Holocene (Kamaludin, 2002), suggests that apart from hydroisostasy other factors may also have affected the Holocene postglacial relative sea level history of the region. The high mid-Holocene records from south India (Banerjee, 2000), south Sri Lanka (Katupotha and Fujiwara, 1988), Thailand (Sinsakul *et al.*, 1985; Sinsakul, 1992), Singapore (Hesp *et al.*, 1998) to Hong Kong (Davis *et al.*, 2000), all within Clark *et al.*'s zone IV, may well point to the inaccuracy of the latter's model. The relative sea level curve in the region disqualifies Clark *et al.*'s prediction but matches their zone V of oceanic emergence.

Peltier (1998) explained the glacial isostatic adjustment (GIA) process as the reason why relative sea level continued to change even after many millennia since the last glacial ice sheet had completely disappeared. This is due to the extremely high value of the effective viscosity of the earth's mantle, the viscosity governing the rate at which mantle material flows in the process of restoring the deformed shape of the earth to one of gravitational equilibrium. The two individual elements that contribute to the observed relative variation of level are the local radius of the solid earth or the absolute level of the surface of the sea (the geoid) relative to the centre of mass of the planet (the geocentre). The equatorial Pacific Ocean and its western margin (the 'far-field' region or part of zone IV of Clark *et al.* (1978)) are acknowledged to achieve a high stand at 4-6 kyr ago. The predicted sea level history based upon the ICE-4G (VM2) model of the GIA process well predicts the amplitude and timing of the high stand in the region. The nearest site to Peninsular Malaysia modeled by Peltier (1998) is the Sumba island of Indonesia, which is about 2,000 km southeast. The sea level model based on ICE-4G (VM2) shows a quite good fit prediction with that of the raw and tectonic uplift corrected coral-based sea level record of Bard *et al.* (1996). Peltier (1998) stated that correction for the rate of tectonic uplift has become a standard in interpreting the postglacial relative sea level variability within the region. However, no model has yet been made available for Peninsular Malaysia or its close vicinity.

PENINSULAR MALAYSIA MID-HOLOCENE TO RECENT SEA LEVEL ANALYSIS

The sea level index points from Peninsular Malaysia West and East coasts form the basis of the analysis. A total of 55 sea level indicators, 36 from the West coasts and 19 from the East are analysed (Table 1). Figure 2 shows the sea level plot for the Peninsular West and East coasts. In the scatter plot, the West coasts data show a concentration of relatively higher sea level heights as compared the East coasts. Assuming that the sea level fall was a constant progression from the mid-Holocene to the present day, significant difference is noted from the linear rate estimates between the two coasts. A corresponding calculated linear rate of respective 0.7 mm/year and 0.5 mm/year of sea level falls for the West and East coasts are indicated (Fig. 3). The dissimilarity in the rate of sea level falls suggests differential crustal movement between the two Peninsular Malaysia coasts. The possible contributing factors from hydroisostasy and tectono-eustasy are envisaged.

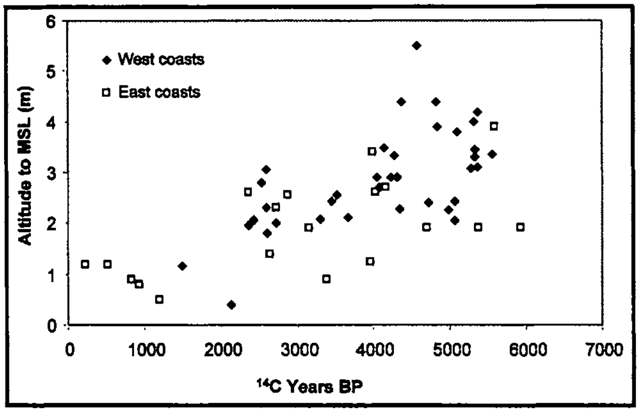

Figure 2. Plot of West and East coasts of Peninsular Malaysia sea level index points, to about 6,000 years BP (indicative range not plotted).

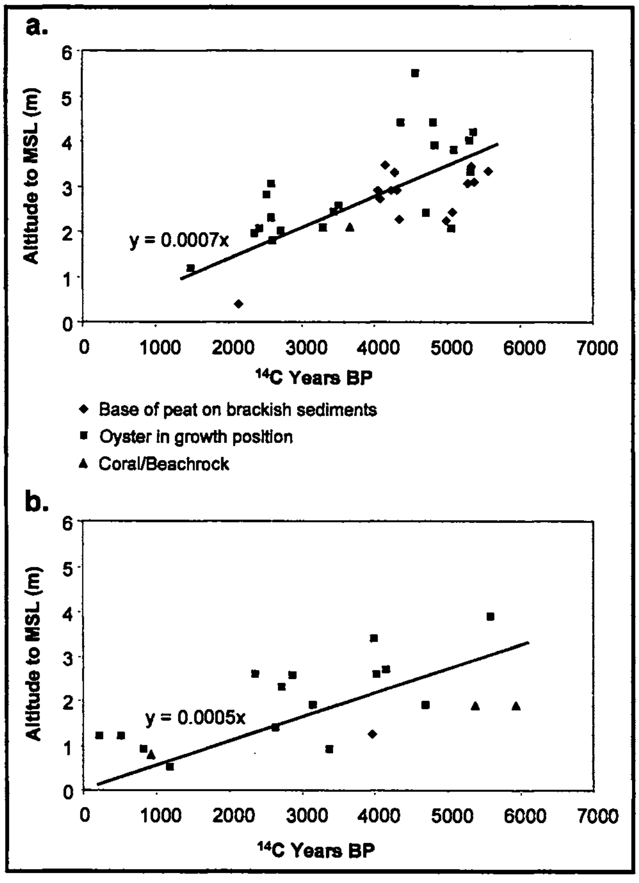

Figure 3. Linear rate estimates of relative sea level fall in Peninsular Malaysia: (a) West coasts and (b) East coasts.

Relative sea level difference is further expressed from the Kelang and Kuantan index points which show quite close ^{14}C ages of 4,045±49 and 3,967±43 respectively, but having relative sea levels height of 2.898±0.3 and 1.244±0.1 (Kamaludin, 2002). It has to be noted that the index points have been sampled and processed at almost the same time, derived using similar method, technique, and dated at the same radiocarbon laboratory (East Kilbride, Scotland). The height difference of approximately 1.5 m between the respective index points but showing quite close ages imply differential crustal movement between the West and East coasts of the Peninsula. Similarly, in few other sea level data, relative sea level difference but at smaller value, between the two coasts are also indicated (Table 1). The relative height difference could probably be resulted from isostatic, eustatic and tectonic factors, which may probably reflect the combined effects of hydroisostasy, geoidal- and/ or tectono- eustasy.

DISCUSSION

The significant discrepancies in relative sea level fall as shown from the cumulative analysis of the Peninsular West and East coasts and the obvious relative height difference noted from the Kelang and Kuantan index points, are explained most probably caused by the combination of hydro-isostatic and tectonic effects. Though factors like sediment compaction, consolidation, paleotidal changes and the indicative meanings of different sea level index points affect relative sea level change, their discussions are but much confined and restricted. Also, numerical quantification of the latter's contribution is beyond the limit of this discussion.

The hydro-isostatic effect contributed from the imbalance water masses between Kelang and Kuantan, respectively fronting the Strait of Malacca and the South China Sea, presumably causes the uplift of the former while sinks in the latter. The narrow passage (width from about 70 km in the SE to 300 km in the NW) and shallowness (depth from about <50 m in the SE to ≤100 m in the NW) of the Strait of Malacca means a smaller volume of water and thus of the weight induced, as compared the South China Sea, contributes to the explanation of lower sea level altitude in Kuantan than Kelang. In addition, the shallowness of the Strait of Malacca (Voris, 2000), implying dry land until about the beginning of Holocene, was thus 'water-free' and disconnected from the South China Sea during most of the glacial period. This is deduced from the recorded almost uninterrupted sea level rise, from about 120 m below the present, from the Last Glacial Maximum to around the mid Holocene (Chappell and Polach, 1991; Ota and Chappell, 1999; Woodroffe, 2000), the event of which has been correlated with the deep-sea oxygen isotope record (Chappell and Shackleton, 1986; Chappell *et al.*, 1996). The incursion and flooding of the narrow Strait of Malacca waterway during the postglacial sea level rise would obviously induce crustal deformation from the water loading processes. However, the nature and magnitude of hydroisostasy is yet to be quantified.

Next, tectonic factors are postulated to also contribute to the discrepancy between the West and East coasts relative sea levels. The relative sea level difference could probably be affected by plate tectonics of the region. Southeast Asia forms the southern-most part of the Eurasian plate. It is surrounded to the west and southwest by the India-Australia plate and in the east by complex configuration of the Philippine and Pacific plates. The India-Australia plate is subducting below the Eurasian plate at a rate of about 67 mm/year (Demets *et al.*, 1990). The subducting India-Australia plate beneath the Eurasian plate, along the plate boundary west of Sumatra (trending almost parallel with the peninsula west coast about 350 km away), probably contributes to the higher uplift of the West coasts of the Peninsular as compared the East coasts. In contrast, the Philippine and Pacific plates in the east are very much further away. This probable tectonic involvement could be roughly estimated by calculating the rate of sea level fall to the present. The cumulative analysis of the Peninsular West and East coasts index points indicate respective rates of 0.7 and 0.5 mm/year of assumed continuous sea level fall. The Kelang and Kuantan index points show a larger difference (about twice) of presumed falling rate, the former approximately 0.7 mm/year while the latter about 0.3 mm/year (Fig. 4). These estimated rates of sea level fall would

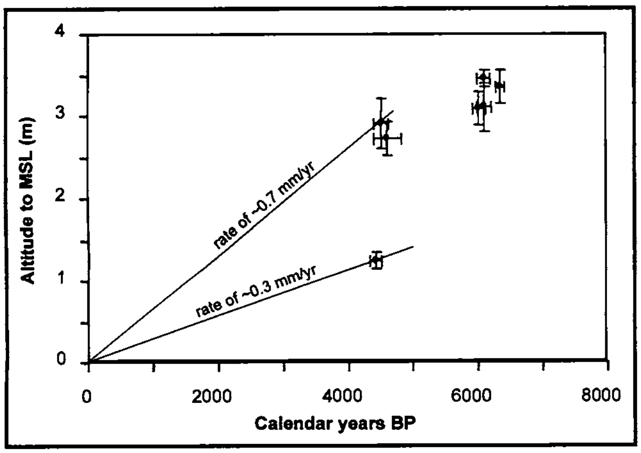

Figure 4. Rate of postulated sea level fall from the Kelang and Kuantan sea level index points (from Kamaludin, 2001).

probably represent the order of magnitude of the long-term tectonic movement in the West and East coasts of the Peninsula. Vertical crustal movement probably varies from 0.3 to 0.5 mm/year in the East and 0.7 mm/year in the West coasts. The finding contradicts the general assumption of Tjia (1996) that the Malay-Thai Peninsula is 'a geological region of relative crustal stability'. Nevertheless, Tjia (1996) also stated that 'the geologically stable regions (Peninsular Malaysia, southern Thailand, etc.) have experienced only very slow vertical crustal movements at rates of 2 to 3 orders lower than those from the mobile regions (up to 10 mm/year)', which could be translated to mean that the vertical crustal movement for the supposed region is about 2 to 3 mm/year! To enable more conclusive evidence on the nature of mid-Holocene to the present sea level change and related tectonic implication, it is recommended that further systematic sea level investigations be carried out in the Peninsular West and East coasts. Also, to assess the effects of plate boundaries and vertical crustal movement it is suggests that studies be extended to other parts of the Peninsula and the region, especially around west and east Sumatra, Sarawak, west Kalimantan and Vietnam.

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