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A Drowning Sunda Shelf Model during Last Glacial Maximum (LGM) and Holocene: A Review

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Abstract - Rising sea levels since the Last Glacial Maximum (LGM), some ~20,000 years ago, has drowned the Sunda Shelf and generated the complex coastal morphology as seen today. The pattern of drowning of the shelf will be utilized to assess likely timing of shoreline displacements and the duration of shelf exposure during the postglacial sea level rise. From existing sea level records around Sunda Shelf region, "sea level curve" was assembled to reconstruct the shelf drowning events. A five stage drowning model is proposed, including 1) maximum exposure of the shelf at approximately 20,500 years Before Present (y.B.P.), when sea level had fallen to about -118 m below present sea level (bpl.), 2) melt water pulse (MWP) 1A at ~14,000 y.B.P. when sea level rose to about -80 m bpl., 3) melt water pulse (MWP) 1B at ~11,500 y.B.P., when sea level was predicted around -50 m bpl., 4) Early-Holocene at ~9,700 y.B.P, when sea level was predicted at about-30 m bpl, and 5) sea level high stand at ~4,000 y.B.P., when sea level jumped to approx. +5 m above present sea level (apl.). This study shows that the sea level fluctuated by more than 120 m at various times during LGM and Holocene. Also confirmed that sea level curve of Sunda Shelf seems to fit well when combined with sea level curve from Barbados, although the comparison remains controversial until now due to the considerable distinction of tectonic and hydro-isostatic settings.

Keywords: Last Glacial Maximum, sea-level changes, transgression, drowning shelf

INTRODUCTION

The Sunda Shelf is located in Southeast Asia and it represents the second largest drowned continental shelf in the world (Molengraaff and Weber, 1921; Dickerson, 1941). It includes parts of Indonesia, Malaysia, Singapore, Thailand, Cambodia, Vietnam coast, and shallow seabed of the South China Sea (Figure 1). During the LGM, when sea levels are estimated -116 m below present sea level (bpl.), the Sunda Shelf was widely exposed, forming a large land so-called "Sunda Land" connecting the Greater Sunda Islands of Kalimantan, Jawa, and Sumatra with continental Asia (Geyh *et al*., 1979; Hesp *et al*., 1998; Hanebuth *et al*., 2000, 2009).

The Sunda Shelf is also considered as a tectonically stable continental shelf during the Quaternary (Tjia and Liew, 1996) and categorized as a "far field" location (far away from former ice sheet region), providing the best example for observing sea level history and paleo-shoreline reconstruction. In such environment, the effects of seafloor compaction, subsidence, and hydro-isostatic (melt water release from the ice sheets) compensation are negligible during the relatively short time interval of thousands of years (Lambeck *et al*., 2002; Wong *et al*., 2003).

This study reviews some published sea level observations then presenting a summary of the Sunda Shelf drowning model. Moreover, it discusses some sea level records from different lo-

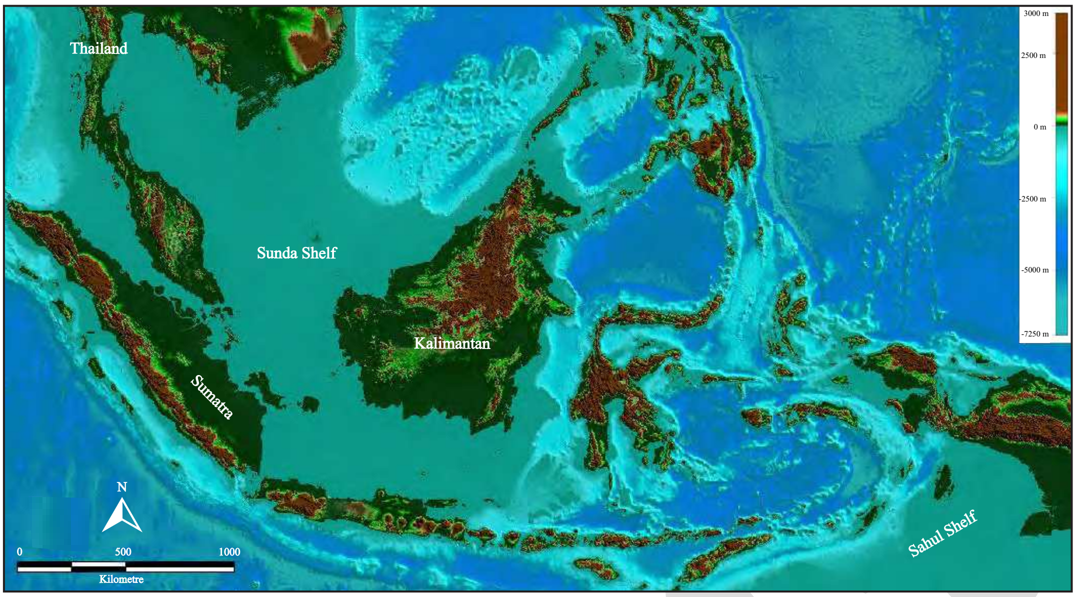

Figure 1. A map shows the Sunda Shelf region derived from 30 arc-seconds resolution bathymetric grid sourced from GEBCO. (after Molengraaff and Weber, 1921; Dickerson, 1941).

calities in time-scale LGM to Holocene (Table 1) and improves detailed colour maps of Holocene sea level transgression on the Sunda Shelf (Voris, 2000; Sathiamurthy and Voris, 2006) in terms of map resolution. The analyses and data presented in this paper provide an up to date overview of the history of sea level and paleo-shoreline changes around Sunda Shelf region since the LGM to Holocene.

RECONSTRUCTING SEA-LEVEL HISTORY

Studies on sea level history around Sunda Shelf have been carried out by Geyh *et al*., (1979), Tjia, (1996), Hesp *et al*., 1998, and Hanebuth *et al*., (2000, 2009) to provide information on paleo-shoreline, paleo-river, and paleo-bathymetry. The most relatively recent studies (Hanebuth *et al*., 2000, 2009) demonstrated an important

Table 1. Sea Level Observations from some Localities presenting LGM - Holocene Sea-level Records

Localities	Proxies	Time scale	Dating	Tectonic setting	References
Barbados	Coral, mostly A. Palmata	LGM - mid-Holocene	^{14}C and U-series	Uplift 0.34 mm/year	Fairbanks (1989), Peltier and Fairbanks (2006)
Tahiti	Fossil coral	MWP-IA - mid-Holocene	^{14}C and U-series where available	Slow tectonic subsidence (0.15 mm/year), far-field location, less affected by hydro-isostatic	Bard *et al*. (1996)
Huon Peninsula, PNG	Coral (Porites, Acropora, Montipora, etc.)	Post glacial - Mid-Holocene	AMS radiocarbon	Rapidly uplifting area (LIg 1.76±0.05 mm/year, Mid-Holocene 2.16± 0.44 mm/ year, far-field location	Chappell and Polach (1991)
Bonaparte Gulf, NW Australia	Sediment core, marine shell, fauna	Pre and post LGM	AMS radiocarbon	Relatively tectonically stable, the effects of hydro-isostatic are small	Yokoyama *et al*. (2001)
Scott Reef, NW Australia	Coral	Holocene	U-series	Tectonic subsidence (0.29 - 0.45 mm/ year), far-field location, less affected by hydro-isostatic	Collins *et al*. (2011)

recent dataset from a number of sediment cores which were dated by AMS radiocarbon, providing records extending from LGM to Holocene that fill some of the late-Glacial gaps from Barbados records. The Sunda Shelf region is believed to have been tectonically stable during the Pleistocene (Tjia and Liew, 1996) and considered as a "far-field" site where tectonic correction and hydro-isostatic compensation are negligible.

The stages of rising sea levels on the Sunda Shelf between ~21,000 y. B.P. and ~4,200 y. B.P. were reported by Hanebuth *et al*. (2000). It was initiated by the terminal phase of LGM sea level lowstand (approximately -116 m bpl.) at about 21,000 y. B.P. and followed by transgression, rising sea level to approx. -56 m bpl. at ~11,000 y. B.P. Whilst Geyh *et al*. (1979), Tjia (1996), and Hesp *et al*. (1998) described the sea level highstand and its gradual fall to current levels thereafter in the Mid to Late Holocene. The summary is as follows. In the EarlyHolocene between 10,000 and 6,000 y. B.P., the sea levels rose significantly from -51 m bpl. to 0 m (present level). Following this, it reached a peak in the Mid-Holocene between 6,000 and 4,200 y. B.P., exhibiting sea level highstand from 0 m to +5m apl. After that, the sea level fell gradually until reaching modern sea level at about 1,000 y. B.P. (Figure 2).

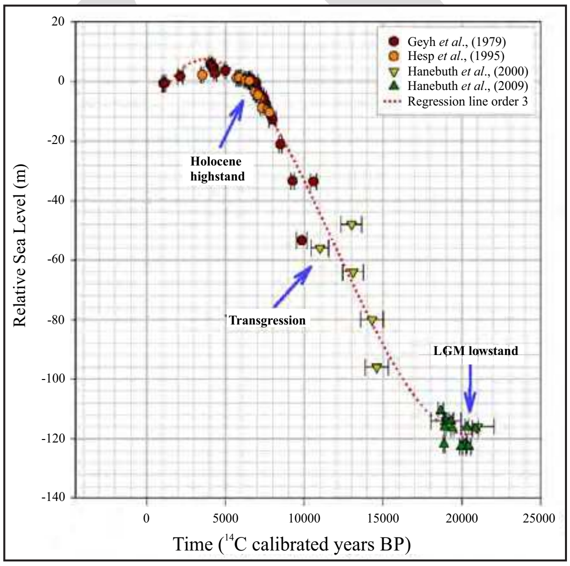

Figure 2. The best-fit sea level curve estimation of Sunda Shelf from 21,000 to 1,000 y. B.P. derived from Geyh *et al*., (1979), Hesp *et al*., (1998), and Hanebuth *et al*., (2000; 2009).

MATERIALS AND METHODS

The ocean topography and land data covering the Sunda Shelf were extracted from the General Bathymetric Chart of the Ocean Grid (Gebco) 0.8 grid with a spatial resolution of 30 arc-seconds of latitude and longitude (1 minute of latitude = 1.853 km at the equator). The bathymetric grid has largely been generated from a database of over 290 million bathymetric soundings with interpolation between soundings guided by satellite-derived gravity data. Land data are largely based on the Shuttle Radar Topography Mission (SRTM30) gridded digital elevation model (see web page at: http://www.gebco.net/data and products/gridded bathymetry data/; accessed July 2013).

The extracted elevation data (in x, y, and z coordinates) were exported into points in ASCII format within GridViewer package programme. These point data were then used to generate a Digital Elevation Model (DEM) using a Triangulated Irregular Network (TIN) method or TIN DEM within the Global Mapper v11.0 toolkit. For the purpose of a two-dimensional layout, a Grid DEM was generated and presented within MapInfo7.0 software. All figures presented on this paper are originally created by the author following the method discussed above.

The sea-level curve estimation in Sunda Shelf as shown in Figure 2 is derived from some previous studies conducted in several localities such as Strait of Malacca (Geyh *et al*., 1979), Singapore (Hesp *et al*., 1998), and former North Sunda River and Mekong Delta (Hanebuth *et al*., 2000, 2009). This sea-level curve was then correlated with the present-day topography and bathymetry of the Sundaland to generate maps and approximate shoreline configuration of the Sundaland during the latest Quaternary. However, several assumptions were made in the workflow of this study as follows: 1) The current topography and bathymetry of the Sunda Shelf are only an approximation and do not reflect past condition precisely. 2) The sea floor compaction, subsidence, and vertical crust displacement due to sedimentation, scouring, and tectonic processes are not taken into account.

Maps

The maps presented in this paper show a summary of the gradual Sunda Shelf drowning model which represents the predicted shorelines and shelf exposures during LGM and Holocene. Starting from -118 m depth contour, the drowning model was gradually established on a vertical elevation of -80 m, -50 m, -30 m, +5m, and present sea-level which every depth contour corresponds to ^{14}C calibrated years Before Present age. For example, the current -118 m depth contour was predicted as a shoreline at approx. 20,500 y. B.P., while the current -50 m depth contour was attributed to 11,500 y. B.P., etc. Topographic and bathymetric contours are indicated by the change in colour scheme as shown in the legend; however, the grey colour is also applied to the DEM representing the exposed shelf. In addition, the flowage of paleo-river of Sunda Shelf during LGM is also presented with refers to the map of paleo-river (Voris, 2000; Sathiamurthy and Voris, 2006).

RESULTS

The Drowning Sunda Shelf History

The history of the drowning Sunda Shelf was initiated at approximately 20,500 y. B.P. when sea level had fallen to around -118 mbpl. By this time, the Sunda Shelf was largely exposed, forming a massive lowland which connects present-day mainlands in this region (Kalimantan, Jawa, Sumatra, and Malaya Peninsula) (Figure 3a). During melt water pulse (MWP)-1A, some ~14,000 y. B.P. (Fairbank, 1989), sea level rose rapidly to approx. -80 m bpl., inundating Sunda Shelf around the present-day Natuna Island. However, the mainlands were still connected to each other and the configuration of the exposed Sunda Shelf remained very similar to the -118 m bpl. formation (Figure 3b).

Following that, the sea-level still experienced a rapid rise and jumped to around -50 m bpl. at about 11,500 y. B.P. (MWP-1B of Fairbank, 1989), exhibiting initial isolation of Natuna and the Anambas Islands from the mainland. Thus, the connections between Kalimantan and Malaya Peninsula via South China Sea were initially separated. Adding that, the present-day Jawa Sea, which connects Kalimantan and Jawa, was largely inundated, separating partly the two mainlands (Figure 3c). However, the Greater Sundaland (*i.e.* Kalimantan, Jawa, and Sumatra) were still connected to the Malaya Peninsula.

At approx. 9,700 y. B.P., when sea level was predicted around-30 m bpl., the Jawa Sea became a significant sea. The present-day Sunda , Karimata , and Malacca Straits, the land bridges that connect the Greater Sundaland, were initially inundated, forming a narrow channel among the islands (Figure 3d). The marine transgression reached a peak in the Mid-Holocene at approx. 4,000 y. B.P., rising sea level to about +5 m apl. and drowning some lowland areas in the mainland (Figure 3e). Finally, the sea level fell gradually returning to present-day level at approx. 1,000 y. B.P. (Figure 3f).

Paleo-rivers on the Sunda Shelf

There were four large river systems on the Sunda Shelf that drained the Sundaland during the LGM; the Siam River, the North Sunda River, East Sunda River, and the Malacca Strait River systems (Voris, 2000) (Figure 4). The Siam River system which today is called Chao Phraya included the river system of east coast of Malaya Peninsula (Sungai Endau, Sungai Pahang, Sungai Terengganu, and Sungai Kelantan) and part of the Southwest Vietnam coast. Sathiamurthy and Voris (2006) demonstrated that Sumatra's Sungai Kampar also joined the Siam River system through the Singapore Strait and then ran north to the Gulf of Thailand where the major Siam River system situated and drained to the large expanse of Sunda Shelf.

The North Sunda River system was considered as the major Sunda Shelf River system (Molengraaff Rivers of Dickerson, 1941; Kuenen, 1950; Tjia, 1980) which drained north to the sea northeast of Natuna Island. This system included some tributaries of Central and South Sumatra coast (Sungai Indragiri, Sungai Batanghari, and Sungai Musi) and the large Kapuas River system from Kalimantan.

The East Sunda River system drained to the east across what is the present-day Jawa Sea before flowing east to the sea near Bali. This system

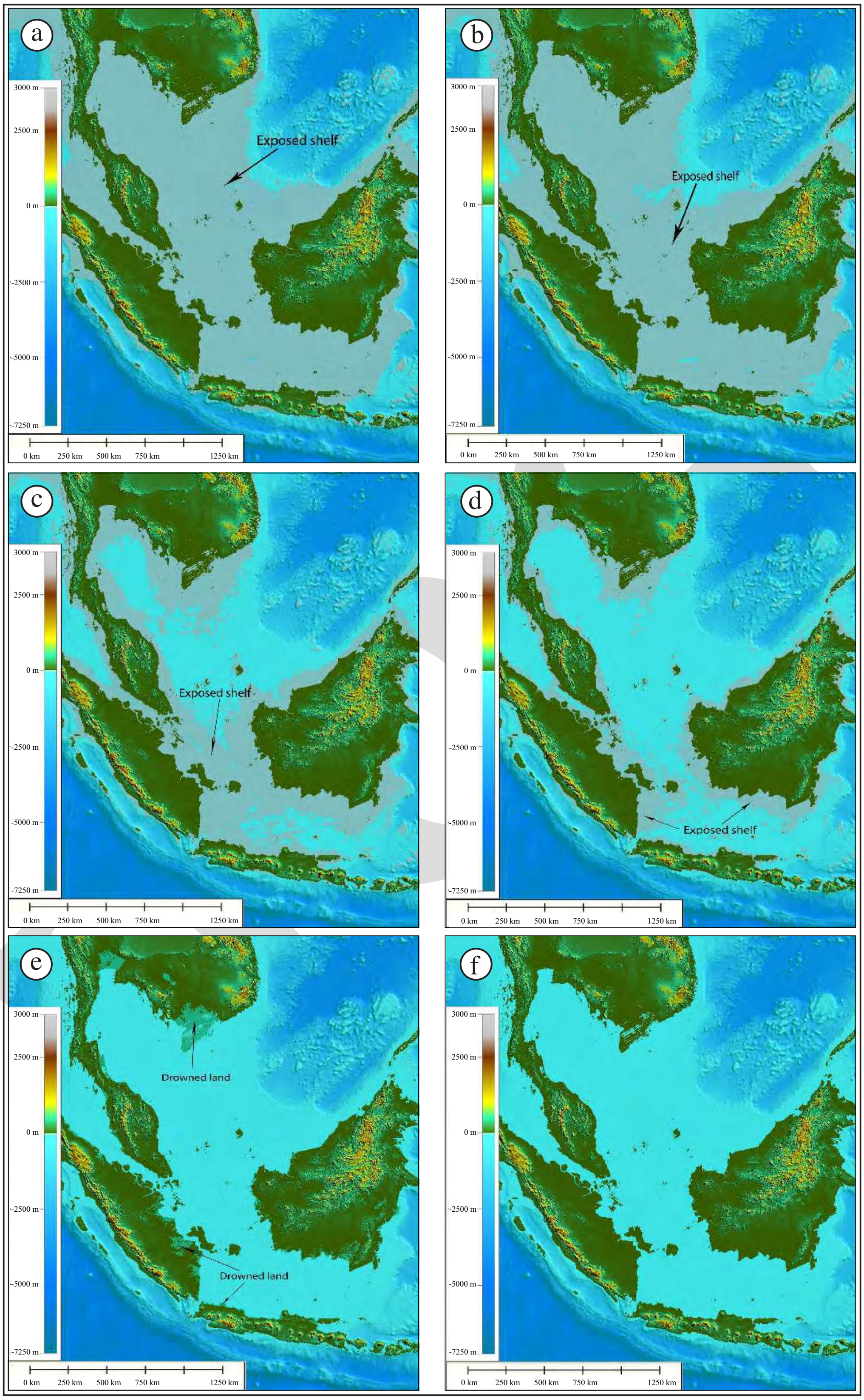

Figure 3. Shelf and sea level exposures at various ages. a). 20,500 y BP, sea level of - 118 m bpl. b). 14,000 y BP (MWP 1A), sea level of - 80 m bpl. c). 11,500 y BP (MWP 1B), sea level - 50 m bpl. d). 9,700 y BP, sea level of - 30 m bpl-predicted. e). 4,000 y BP, sea level +5 m apl. f). Present day sea level. Map derived from 30 arc-seconds resolution bathymetric grid sourced from GEBCO.

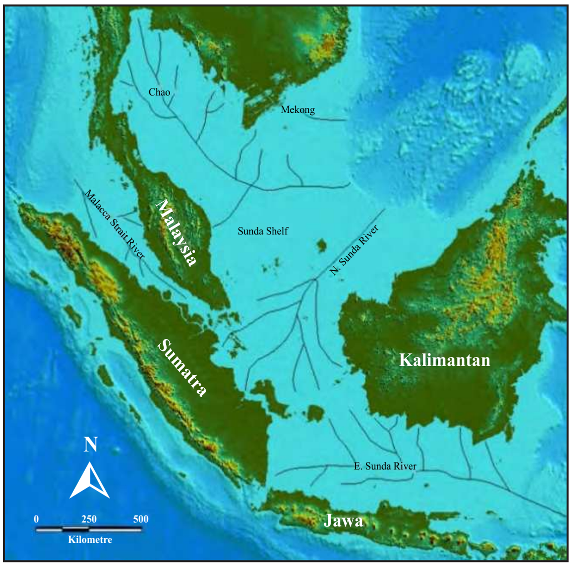

Figure 4. A map shows paleo-rivers on the Sunda Shelf during LGM (After Voris, 2000; Sathiamurthy and Voris, 2006).

included present-day rivers of north coast of Jawa, the south coast of Kalimantan and the northern portion of the east coast of Sumatra. Some smaller rivers in SE Sumatra and the Seribu Islands area of Jawa Sea ran south via the Sunda Strait to enter the Indian Ocean (Umbgrove, 1949; van Bemmelen, 1949).

The Straits of Malacca River system had two drainages separated by a topographic height between the Bernam and Kelang Rivers. One drained NW to the Andaman Sea, including some tributaries of this river system *i.e.* Sungai Simpang Kanan, Sungai Panai, Sungai Rokan, and Sungai Siak of east coast of Sumatra and some rivers from the west coast of Malaya Peninsula *i.e.* Sungai Perak, Sungai Bernam, Sungai Muar, and Sungai Lenek. Whilst the other drained SW and eventually joined the North Sunda River.

DISCUSSION

Comparison with Data from other Studies

Some studies have been carried out from different localities to obtain sea-level stands during LGM and Holocene. The observations resulted in varied conclusions depending mainly on covering time periods, proxies, dating methods, isostatic effects, and vertical tectonic land movement. Hence, it is necessary to consider those mentioned factors when combining the data into a single dataset and generating sea level curve on these data. Also, when comparing these sea-level records to Sunda Shelf data, those factors should be taken into account to avoid bias in analysis and interpretation.

Fairbanks (1989) and Peltier and Fairbanks (2006) reported an important source of information for relative sea-level changes in Barbados during the late stages of the LGM and the late-Glacial period. Using coral cores as a proxy and AMS radiocarbon calibrated by Thermal Ionisation Mass Spectrometry (TIMS) dating methods, the local relative sea level in Barbados stood between -125 m bpl. at 21,000 y. B.P. and -15 m bpl. at 7,000 y. B.P. (Figure 5). The uplift rate was 0.34 mm/year due to local tectonic setting.

Meanwhile, the relative sea-level change data in Tahiti is from Bard *et al*., (1996) with supporting information on coral species given by Montaggioni and Gerrard (1997). Using coral as a proxy, radiocarbon dating yielded time scale between MWP-1A and Mid-Holocene (Figure 5). Tahiti experienced slow tectonic subsidence (0.15 mm/year) and was also characterized as a "far-field" location.

The local relative sea-level changes were also investigated from a rapidly uplifting area such as Huon Peninsula, Papua New Guinea. The records were obtained from a raised Holocene reef drill core collected by Chappell and Pollach (1991). AMS radiocarbon dating was applied to the samples and uranium series (U-series) ages were subsequently obtained from the same samples by Edward *et al*. (1993), providing sea-level indicators from post-Glacial to Mid-Holocene (Figure 5). The uplift rate was reported 1.76 ± 0.05 mm/year in the last-Interglacial (LIG) and 2.16 ± 0.44 mm/year in the Mid-Holocene. This region was also considered as a "far-field" location.

Moreover, Yokoyama *et al*. (2001) discussed the relative sea-level estimation from the NW Australia Shelf. The information was obtained from the sediment cores of Bonaparte Gulf which were dated by AMS radiocarbon dating, providing sea-level indicators corresponding to a late stage of LGM (Figure 5). The region of NW Australia was assumed to be relatively tectonically stable

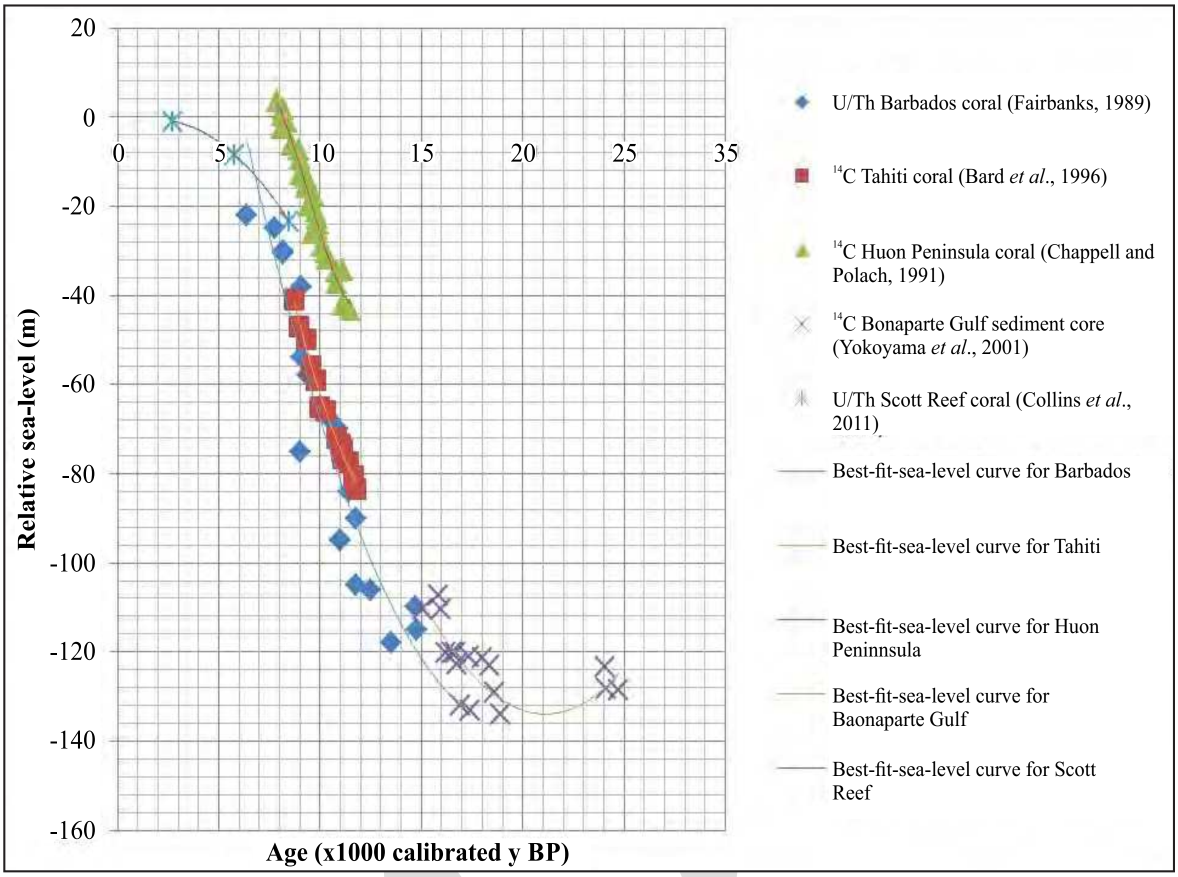

Figure 5. Sea-level curve estimations from some localities presenting LGM - Holocene records.

and was considered as a "far-field" site where the effects of hydro-isostatic are small.

The most relatively recent studies (Collins *et al*., 2011) demonstrated an important recent dataset from a number of coral cores in Scott Reef, Northwest Australia, which were dated by high resolution U-series dating. The data provided Holocene sea-level records that characterized by moderate rates of sea-level rise of 10 mm/year and confirmed tectonic subsidence of 0.29 - 0.45 mm/year (Figure 5). The region was also less affected by hydro-isostatic due to "far-field" location.

Despite the fact that Sunda Shelf and NW Australia region are proximal and considered to be tectonically stable at least during Holocene and less affected by glacio-isostatic adjustment due to their 'far-field' locations, the sea level curve of Sunda Shelf during LGM and Holocene seems to fit well when combined with sea level curves from Barbados. This is also in accordance with Peltier and Fairbanks (2006) who reported that the combination between Bonaparte Gulf, NW Australia, and Sunda Shelf records did not match together well and suggested that Sunda Shelf records fit much better with the Barbados dataset. However, the tectonic and hydro-isostatic settings of Sunda Shelf and Barbados differ considerably and that comparison remains controversial until now.

Sea-level High Stand during Mid-Holocene and There after

Another issue that arises in the discussion of the Sunda Shelf sea-level history is the controversy of the precise details of the Mid-Holocene highstand. The dispute is likely because of the variation on timing, glacio-isostatic adjustment, and localised tectonics. For example, one appraisal of evidence from Malay-Thai Peninsula (Tjia, 1996) revealed that the sea level highstand peaked at +4 m at 6,000 y. B.P. and +5 m at 5,000 y. B.P. Whilst, an earlier survey in the Strait of Malacca, between Port Dickson and Singapore (Geyh *et al*., 1979) evidenced the highest dated level at +2.5 m to about +5.8 m for the time interval between 5,000 and 4,000 y. B.P. Furthermore, review from two areas in Singapore, Sungai Nipah, and Pulau Semakau (Hesp *et al*., 1998) concluded that the peak of the sea level at about +3 m rather than +5 m between 6,000 y. B.P. and 3,500 y. B.P.

Despite such discrepancies, there is a general consensus (Geyh *et al*., 1979; Tjia, 1996; Hesp *et al*., 1998) that the sea level highstand was attained by ~6,000 y. B.P. or slightly earlier. By that time, the sea level was around +3 m to +5 m above present sea-level then receded to its current datum for the past ~1,000 years. The noticeable impact of sea level rise through the transgression is that shoreline position changed markedly and was higher and landward of present level during the high stand (~6,000 - 4,000 y. B.P.). As sea levels fell post-highstand, the shoreline prograded seaward, forming numerous beach ridges in the sequence.

CONCLUSIONS

The Sunda Shelf provides suitable environments for sea level studies and has provided one of the best examples of sea-level at the time of the LGM. In particular, the continent is relatively tectonically stable and lies far away from the former ice sheets, thus the effects of hydro-isostatic adjustment are less and eustatic changes should be well reflected in the data. The model reveals that the drowning Sunda Shelf was initiated at ~20,500 y. B.P., when sea level had fallen to about -118 m bpl. During sea-level transgression, the Sunda Shelf experienced rapid sea-level rise, inundating the shelf exposures until reaching sea-level highstand at ~6,000 - 4,000 y. B.P., before finally returning to the present sea level at approx. 1,000 y. B.P. LGM and Holocene sea level changes are principally forced by the climate change; with sea level fluctuating by more than 120 m at various times. The trigger for these climate and sea level variations is believed to relate to cyclic changes in the earth's orbit and solar radiation (the Milankovitch cycles) and the insolation of the world's atmosphere and oceans.

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