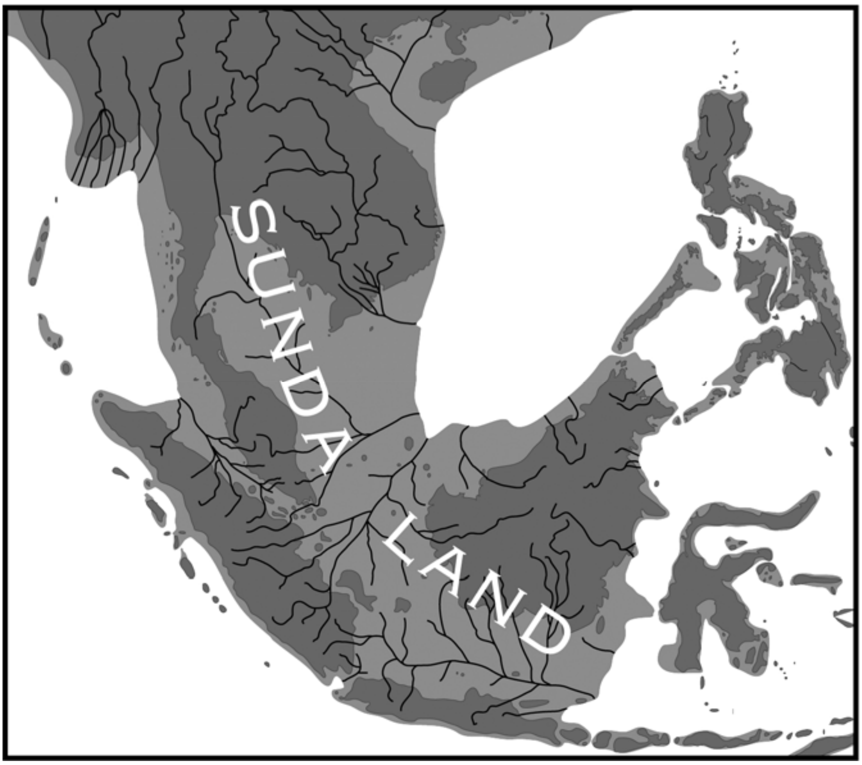
ISSN 1513-9700

The Natural History Journal of Chulalongkorn University

วารสารธรรมชาติวิทยาแห่งจุฬาลงกรณ์มหาวิทยาลัย



Official Publication of

Chulalongkorn University Museum of Natural History

Department of Biology, Faculty of Science, Chulalongkorn University, Bangkok, THAILAND

Supplement 2 **August 2006**

The Natural History Journal of Chulalongkorn University, Supplement 2: 1-43, August 2006

Maps of Holocene Sea Level Transgression and Submerged Lakes on the Sunda Shelf

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ABSTRACT.–Color maps are presented that depict Holocene sea level transgressions and probable submerged lakes on the Sunda Shelf in Southeast Asia. The present-day topography of the Sunda Shelf and the existence of present-day submerged depressions on the Sunda Shelf have been detected through spatial analysis of the Sunda Shelf using the Digital Elevation Model (DEM) developed from the ETOPO2 Global 2' Elevation data. These depressions could be paleo-lakes that existed when the Sunda Shelf was exposed during the Last Glacial Maximum (LGM). These depressions were gradually submerged when the sea level began to rise from –116 m below present-day levels (BPL) during the terminal phase of the LGM, 21 thousand years before present (ka BP) to its maximum, +5m above present-day mean sea level (MSL), during the mid-Holocene (4.2 ka BP). The topography of these depressions is presented on maps and discussed. The results of this study identify several large submerged depressions that may contain sediment dated from the LGM to the mid-Holocene and we recommend that sediment layers be sampled to confirm or disprove the presence of these proposed fresh water paleo-lakes on the Sunda Shelf.

KEY WORDS: Maps, Holocene, Sea levels, Sunda Shelf, Marine transgression, Submerged lakes, Submerged depressions

INTRODUCTION

The Sunda Shelf is located in Southeast Asia where it forms a large submerged extension of the continental shelf of mainland Asia. It includes all the Greater Sunda Islands of Borneo, Java and Sumatra and the bulk of the shelf forms the shallow seabed of the South China Sea, the coastal areas of Cambodia, Peninsular Malaysia, Singapore, Borneo, and parts of the coast of Indonesia, Thailand, and Vietnam. This shelf is characterized by deep sediments and a low gradient (Hanebuth and Stattegger, 2004) and was exposed during the Last Glacial Maximum (LGM) when sea levels are estimated to have been approximately 116 m lower than modern mean sea levels (Geyh et al., 1979; Hanebuth et al., 2000; Hesp et al., 1995). The exposed shelf formed a large land mass (Sunda Land) connecting the islands of Borneo, Java, and Sumatra with continental Asia during the LGM and from time to time in the more distant past. In fact, Morley (2000) suggests that the land area of the Sunda region was at or near its maximum about 70 ma BP.

In the past, sea levels below present-day levels affected regional climatic conditions and vegetation zones dramatically (Morley, 2000;

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Sun et al., 2000). For example, the terminal Eocene global climatic cooling event at about 35 ma BP must have produced a marked reduction in moisture availability in the Sunda region (Morley, 2000) and subsequent changes in vegetation. This relatively dry period was followed by a sudden rise in sea level that flooded much of the Sunda Shelf at about 25 ma BP (Morley, 2000).

The modern climate of the Sunda region is dominated by the East Asian Monsoon System and a seasonal reversal in wind direction affects the annual distribution of rainfall (Sun et al., 2000). Located at the equator and near the "West Pacific Warm Pool", this region is characterized by high temperatures (24–28 ^{o}C) and rainfall in excess of 2000 mm/year in most areas (Kuhnt et al., 2004; Sun et al., 2000). The vegetation on the land masses changes with altitude, with equatorial and tropical rainforest (dipterocarp forest) dominating at elevations below 1000 m (Sun et al., 2000; Morley, 2000). In general, low montane forest is found from 1000 m to 2500 m, while elevations above 2500 m are dominated by upper montane evergreen rainforest (Morley, 2000).

During the LGM the climate of the Sunda Land region was generally cooler than today but much of the exposed shelf was dominated by vegetation similar to that of modern-day lowlands, i.e., lowland rainforest and mangroves (Morley, 2000; Sun et al., 2000). There were periodic expansions of montane rainforest that were perhaps occasioned by a strengthened northern monsoon which would have made more rainfall available to the vegetation. This expansion implies that there were falling temperatures at least on the highlands, and there is also some evidence for a drier and cooler environment in the mountains of Sumatra and the Malay Peninsula possibly creating a corridor of open savanna (Morley, 2000; Sun et al., 2000).

The lower sea levels of the Holocene had the combined effects of climatic change, the formation of land connections (bridges) among the Greater Sunda Islands, major reconfigurations of the Sunda river systems, and greater separation of the Indian Ocean and the South China Sea (Voris, 2000). We assert that these changes in particular and other similar changes in the more distant past are important forces behind the process of allopatric speciation and the generation of the high biodiversity observed today.

This paper expands on Voris (2000) and presents improved, detailed color maps of Holocene sea level transgressions and submerged depressions on the Sunda Shelf. These depressions could have been lakes during the LGM persisting up to the mid-Holocene. The paleo-lakes depicted likely contain sediments that date from the time of their appearance during the LGM. These sediments likely retain signatures or paleo-environmental records of pre-marine conditions on the Sunda Shelf (Biswas, 1973; Lambeck, 2001; Torgersen et al., 1985) and we suggest that appropriate studies be conducted to explore this.

MATERIALS AND METHODS

Sea Level Stages

The stages of rising sea levels, from 21 ka BP to 4.2 ka BP, that have been used in this study are given in Figure 1 and are derived from the literature. Hanebuth et al. (2000) have described the stages of sea level rise on the Sunda Shelf between 21 ka BP and 11 ka BP as follows: The LGM reached its terminal phase by 21 ka BP. After 21 ka BP, the sea level began to rise slowly from -116 m at the rate of 0.10 m per 100 years and reached –114 m by 19 ka BP. Between 19 and 14.6 ka BP, the sea level rose from –114 m to –96 m at the rate of 0.41 m per 100 years. Sea level rise accelerated between 14.6 and 14.3 ka BP, going from –96 m to –80 m at the rate of 5.33 m per 100 years. This acceleration has been associated with polar melt water pulses. Between 14.3 and 13.1 ka BP, the sea level rose from –80 to –64 m at the rate of 1.33 m per 100 years. Between 13.1 and 11 ka BP, the sea level rose about 8 m in 700 years. It is worth noting that these results are largely supported by additional detailed work by Schimanski and Stattegger (2005).

The rise of sea levels during the Holocene between 10 ka BP and modern times, based on the research of Geyh et al. (1979), Hesp et al.

TABLE 1. Estimates of exposed land area at 10 m bathymetric contours from +5 m above present-day mean sea level (MSL) to the estimated level during the terminal phase of the last glacial maxima (LGM), 21 thousand years before present (ka BP). Two sets of area calculations are presented. One set of calculations is based on planimetric area (columns 2-4) and one set is based on total surface area taking into account elevation (columns 5-7). The surface area values are nearly always higher because absolutely flat terrain is not common. The contour of +5 meters above present-day MSL was used as the base contour to allow the +5 m Holocene Highstand to be included in the area estimates.

Bathymetric Contour (m)	Total Area Above Sea Level[1] (sq. km)	Total Area Exposed[2] (sq. km)	Total Additional Area Exposed (sq. km)	Total Surface Area Above Sea Level[3] (sq. km)	Total Surface Area Exposed[4] (sq. km)	Total Additional Surface Exposed (sq. km)
5	2,165,929	-176,897	nr	2,168,904	-179,874	nr
0	2,342,826	0	nr	2,345,803	0	nr
-10	2,701,845	359,019	359,019	2,704,825	362,002	362,002
-20	2,930,044	587,218	228,199	2,933,027	590,207	228,205
-30	3,229,247	886,421	299,203	3,232,235	889,420	299,213
-40	3,547,058	1,204,232	317,811	3,550,049	1,207,237	317,817
-50	3,810,186	1,467,360	263,128	3,813,180	1,470,371	263,134
-60	4,068,545	1,725,719	258,359	4,071,543	1,728,738	258,367
-70	4,291,648	1,948,822	223,103	4,294,649	1,951,847	223,109
-80	4,458,957	2,116,131	167,309	4,461,961	2,119,162	167,315
-90	4,554,831	2,212,005	95,874	4,557,839	2,215,044	95,882
-100	4,623,103	2,280,277	68,272	4,626,114	2,283,322	68,278
-110	4,680,184	2,337,358	57,081	4,683,199	2,340,411	57,089
-116	4,709,397	2,366,571	29,213	4,712,413	2,369,626	29,215

[1] Total planimetric area on the map that is +5 m above the present-day mean sea level (MSL).
[2] Total planimetric area exposed below present-day MSL.
[3] Total surface area (taking into account surface elevations) on the map that is +5 m above the present-day MSL.
[4] Total surface area (taking into account surface elevations) exposed below the present-day MSL.
nr = non relevant

(1998), and Tjia et al. (1983), may be summarized as follows. Between 10 and 6 ka BP, the sea level rose from –51 m to 0 m. Between 6 and 4.2 ka BP, the sea level rose from 0 m to +5 m, the mid-Holocene highstand. After this highstand, the sea level fell gradually and reached the modern level at about 1 ka BP.

Topographic and Bathymetric Data

Present-day topographic and bathymetric data covering the Sunda Shelf were extracted from the ETOPO2 Global 2’ Elevation data (2-Minute Gridded Global Relief Data, U.S. Department of Commerce, National Oceanic and Atmospheric Administration, (ETOPO2), National Geophysical Data Center (NGDC), U.S.A., see web page at: http://www.ngdc.-noaa.gov/ngdc.html). ETOPO2 Global 2’ refers to 2 minute spatial resolution of captured data (i.e., data points about 3.61 km apart). The horizontal resolution is 2 minutes of latitude and longitude (1 minute of latitude = 1.853 km at the equator). The vertical resolution of ETOPO2 is 1 meter. The extracted elevation data (in x, y and z coordinates) were exported into ArcView 3.2 (Environmental Systems Research Institute, Inc., ESRI). These coordinates were converted into points. Using the point data, a Digital Elevation Model (DEM) using Triangulated Irregular Network (TIN) method or TIN DEM was generated. TIN DEM was used for spatial analysis because of its accuracy. However, the maps presented were generated using Grid DEM. For the purpose of a two-dimensional

TABLE 2. Location and descriptive details (e.g., depth, and outlet elevation) are given for 32 submerged depressions on the Sunda Shelf. For each depression or possible paleo-lake the outlet or lowest lake boundary elevation was compared to the sea-level curve (Fig. 1) in order to estimate the time of marine transgression. A depression or paleo-lake was considered to be transgressed (flooded or inundated) when the sea level reached its outlet or boundary level. The duration of the paleo-lake's existence using the 21 ka BP or the LGM as a base period was estimated by subtracting the time of marine transgression from the LGM. The 32 depressions were ordered according to the time of marine transgression: those most recently inundated by the sea listed first.

Depression Site Identifier[1]	Latitude (decimal degrees)	Longitude (decimal degrees)	Time of Marine Transgression (ka BP)	Rank of Marine Transgression	Deepest Point (m)	Boundary Level[2] (m)	Outlet Level[2] (m)	Paleo-lake Depth[3] (m)	Duration of Paleo-lake (span ka BP)
SBH-4	4.90018	118.2996	7.002	32	-156.55	-4	nr	152.55	14.998
JV-3	-7.63456	114.1004	7.08	31	-274.65	nr	-4.34	270.31	14.92
BR-1	5.00052	115.4005	7.454	30	-156.46	nr	-5.96	150.5	14.546
SBH-1	5.66567	115.8663	7.504	29	-179.82	-6.18	nr	173.64	14.496
SBH-3	6.17963	117.9321	7.893	28	-150.89	nr	-7.87	143.02	14.107
JV-1	-7.43514	113.1331	8.511	27	-156.78	nr	-10.57	146.21	13.489
KLM-1	2.13406	118.2001	8.561	26	-445.72	nr	-10.79	434.93	13.439
SBH-2	5.83271	115.9663	9.121	25	-184.55	nr	-13.99	170.56	12.879
SG-3	12.099	102.5014	9.428	24	-88.3	-18.48	nr	69.82	12.572
KLM-4	-2.2334	116.9017	10.065	23	-145	nr	-27.83	117.17	11.935
SG-2	11.76544	102.8663	10.327	22	-173.1	nr	-31.69	141.41	11.673
SBH-10	6.4661	116.1308	11.924	21	-124.6	nr	-50.59	74.01	10.076
BR-2	5.50081	115.1334	12.101	20	-137.19	-52.61	nr	84.58	9.899
KLM-3	-1.00004	117.434	12.13	19	-142.62	-52.94	nr	89.68	9.87
SG-1	11.36647	100.2001	12.665	18	-125	nr	-59.04	65.96	9.335
KLM-2	-0.60117	117.7346	12.824	17	-198	-60.85	nr	137.15	9.176
JV-2	-8.33181	114.4338	12.834	16	-168.66	nr	-60.97	107.69	9.166

TABLE 2. Continued.

Depression Site Identifier[1]	Latitude (decimal degrees)	Longitude (decimal degrees)	Time of Marine Transgression (ka BP)	Rank of Marine Transgression	Deepest Point (m)	Boundary Level[2] (m)	Outlet Level[2] (m)	Paleo-lake Depth[3] (m)	Duration of Paleo-lake (span ka BP)
SRW-2	4.15241	113.468	13.123	15	-151.66	nr	-64.35	87.31	8.877
SRW-1	3.39625	112.7309	13.421	14	-158.84	-68.31	nr	90.53	8.579
SRW-5	4.7006	114.133	13.486	13	-126.28	nr	-69.17	57.11	8.514
SRW-3	4.60193	113.6392	13.526	12	-172.63	nr	-69.71	102.92	8.474
SRW-4	4.66634	113.9339	14.078	11	-154.53	nr	-77.05	77.48	7.922
SCS-2	8.03288	108.0005	14.432	9	-127.92	nr	-87.04	40.88	7.568
SCS-3	6.76733	108.3005	14.507	8	-125.97	-91.04	nr	34.93	7.493
SCS-4	4.74803	112.2343	14.537	7	-177.96	-92.62	nr	85.34	7.463
SCS-1	5.03623	107.9353	15.09	6	-127.93	nr	-97.97	29.96	6.91
SCS-5	4.63302	111.8668	15.876	5	-139.58	nr	-101.19	38.39	6.124
MLC-1	5.86579	98.46096	15.944	4	-125.75	nr	-101.47	24.28	6.056
SBH-9	6.53258	115.8667	16.366	3	-215.15	nr	-103.2	111.95	5.634
SBH-7	6.09722	118.5973	17.195	2	-274.24	-106.6	nr	167.64	4.805
SBH-6	6.36587	118.6001	18.3	1	-147.75	nr	-111.13	36.62	3.7

[1] The locations are plotted on Figure 27. The abbreviations are as follows: SG, Gulf of Thailand; SCS, South China Sea; SRW, Coast of Sarawak, Malaysia; SBH, Coast of Sabah, Malaysia; BR, Coast of Bruni; KLM, Coast of Kalimantan, Indonesia; JV, Coast of Java; MLC, Malacca Strait.
[2] Either boundary level or outlet level is known, nr = not relevant.
[3] Measured from the boundary or outlet elevation to the lowest point in the depression.

layout, a rigid cell Grid DEM was used within the ArcView environment. Mapinfo 6.0 (ESRI) was used for the three dimensional layout.

The progress of marine transgression between 21 ka BP to 4.2 ka BP was mapped by correlating the topography of Sunda Land with the sea level curve shown in Figure 1. Several assumptions were made in the analytical procedures of this paper. First, it is assumed that the current topography and bathymetry of the region approximate the physiography that existed during the span of time from 21 ka BP to present-day. However, because sedimentation and scouring processes have affected the bathymetry of the Sunda Shelf over the last 21,000 years (Schimanski and Stattegger, 2005), we know that this is only an approximation. Thus, it should be emphasized that the depth and geometry of the Sunda Shelf and the existing present-day submerged depressions do not reflect past conditions precisely.

Second, it is assumed that the present-day submerged depressions are likely to have existed during the LGM and have not resulted from seabed scouring by currents, limestone solution, or tectonic movement–possibilities that were pointed out by Umbgrove (1949) as perhaps taking place during early post-Pleistocene transgression. In the case of tectonic movement, Geyh et al. (1979), mentioned that the Malacca Strait was tectonically stable at least during the Holocene. Furthermore, Tjia et al. (1983), state that the Sunda Shelf has been largely tectonically stable since the beginning of the Tertiary. Nevertheless, Tjia et al. (1983) indicated that sea level rise in this region may be attributed to a combination of actual sea level rise and vertical crust movement. Hill (1968) in reference to earlier work done by Umbgrove (1949), suggested the possibility of limestone solution as a mode of depression formation (as in the case of the Lumut pit off the coast of Perak, Malaysia), and gave an alternative explanation, which was of tectonic origin. He also explained that the Singapore "deeps" could be a result of small grabens or cross-faulting.

Analytical Procedure

A color scheme was applied to the DEM in which areas below –116 m (LGM sea level, 21 ka BP) are represented by blue colors so that the LGM coastlines and depression areas may be easily identified.

To appreciate the scale of the landscape that was exposed at different stages of the LGM, area estimates were calculated. Two sets of calculations were made. One set of calculations was based on planimetric area, and one set was based on total surface area taking into account elevation (Table 1). The latter surface area values are nearly always higher than those based on planimetrics because absolutely flat terrain is not common. The contour of +5 meters above present-day mean sea level (MSL) was used as the base contour to allow the +5 m Holocene highstand to be included in the area estimates.

Submerged depressions were initially identified and examined by their depths, outlet elevation, size, location and proximity to each other. Depressions that display significant depth, higher outlet elevations and larger size are more likely to have been paleo-lakes than those that are shallow, small, and have outlets that are low and would have provided good drainage. Depressions that are located very near to a plate boundary (i.e., west coast of Sumatra) are not considered because their elevations may have changed due to tectonic instability. In situations where depressions are clustered, only the most significant one was selected for further analysis. Using these criteria, 32 submerged depressions on the Sunda Shelf were initially selected and coded for further analysis (Table 2).

For each of the 32 depressions the outlet or lowest lake boundary elevation (Table 2) was compared to the sea-level curve (Fig. 1) in order to estimate the time of marine transgression. A depression or paleo-lake was considered to be transgressed (flooded or inundated) when the sea level reached its outlet or boundary level. In addition, the duration of the paleo-lake's existence using the 21 ka BP or the LGM as a base period was estimated by subtracting the time of marine transgression from the LGM (Table 2). The 32 depressions were ordered according to the time of marine transgression: those most recently inundated by the sea listed first (Table 2).

From the 32 depressions, seven of the most significant depressions were selected for study

TABLE 3. Area and perimeter data for both basin and lake are given for seven of the most significant depressions listed in table 2. The selection of the seven depressions was based on a combination of criteria that would likely improve the chances that it would contain past environmental signatures that could confirm its existence as a freshwater lake. The criteria applied are provided in the text.

Depression Site Identifier	Area (sq.km)		Perimeter (km)		Highest Point in Basin Max. Elev. (m)	Boundary/ outlet Level Min. Elev. (m)	Range Max.- Min. (m)	Rank of Marine Transgression
	Basin	Lake	Basin	Lake				
SBH-4	6,807.86	1,740.52	381.24	339.34	1,621	-4.00	1,625.0	32
SBH-3	13,547.66	1,220.11	550.76	164.22	4,101	-7.87	4,108.9	28
JV-1	37,962.53	5,905.11	959.21	392.22	3,876	-10.57	3,886.6	27
KLM-1	26,245.16	2,733.91	841.64	275.73	2,053	-10.79	2,063.8	26
SG-1	617,043.99	15,846.95	4,646.42	641.03	2,576	-59.04	2,635.0	18
SRW-1	28,683.82	5,679.78	733.71	358.22	1,070	-68.31	1,138.3	14
SCS-1	398,571.60	4,283.98	2,852.55	468.35	nr	-97.97	nr	6

(Table 3). Selection of the seven depressions was based on a combination of criteria that would enhance the likelihood that they would contain past environmental signatures that could confirm their existence as freshwater lakes. The criteria that were used and that appear in Table 2 were:

Location:- The location of a depression was considered important because identification of depressions that were widely distributed over Sunda Land would allow inferences about the general condition of Sunda Land.

Depth:- The depth of the depression (measured from the boundary or outlet elevation to the lowest point in the depression, Table 2) was considered important because deeper lakes would decrease the likelihood that scouring would disturb the sediment layers.

Duration:- The estimated duration of existence during the Holocene using the 21 ka BP or the LGM as a base period (Table 2) was considered important because the longer the time span, the more likely that significant freshwater sediment layers would be deposited.

The additional criteria that were used and that appear in Table 3 for the seven selected depressions were:

Area:- The probable maximum surface area of the basin and the lake were considered important because a large basin and lake would accumulate more sediments, plant debris, and pollen. Drainage basin refers to the drainage or catchment area supported by a river system that contained and fed into a palaeo-lake/depression. Topographic divides or ridges were used to delineate drainage basin boundaries (yellow lines in Figures 28-32) and compute basin surface areas. The probable maximum lake surface areas for the selected depressions (Table 3) were calculated from the coverage areas defined either by outlet elevations or boundary elevations. Outlet elevations were used for depressions with a detectable outlet whereas boundary elevations were used for depressions without a clear outlet, e.g. isolated depressions. In Table 3, the lake boundary elevations are considered as minimum elevations of the basins, indicated as “Min. Elev.”, because the whole drainage basin of the lake was considered and not just the lake itself.

Perimeter:- The perimeter of the drainage basin was also considered important because its size and shape could suggest the magnitude of the sediment record that might be present.

The elevation range of a basin (i.e., max.–min., Table 3) was calculated by simply subtracting the boundary/outlet level of the basin from the highest point in the basin.

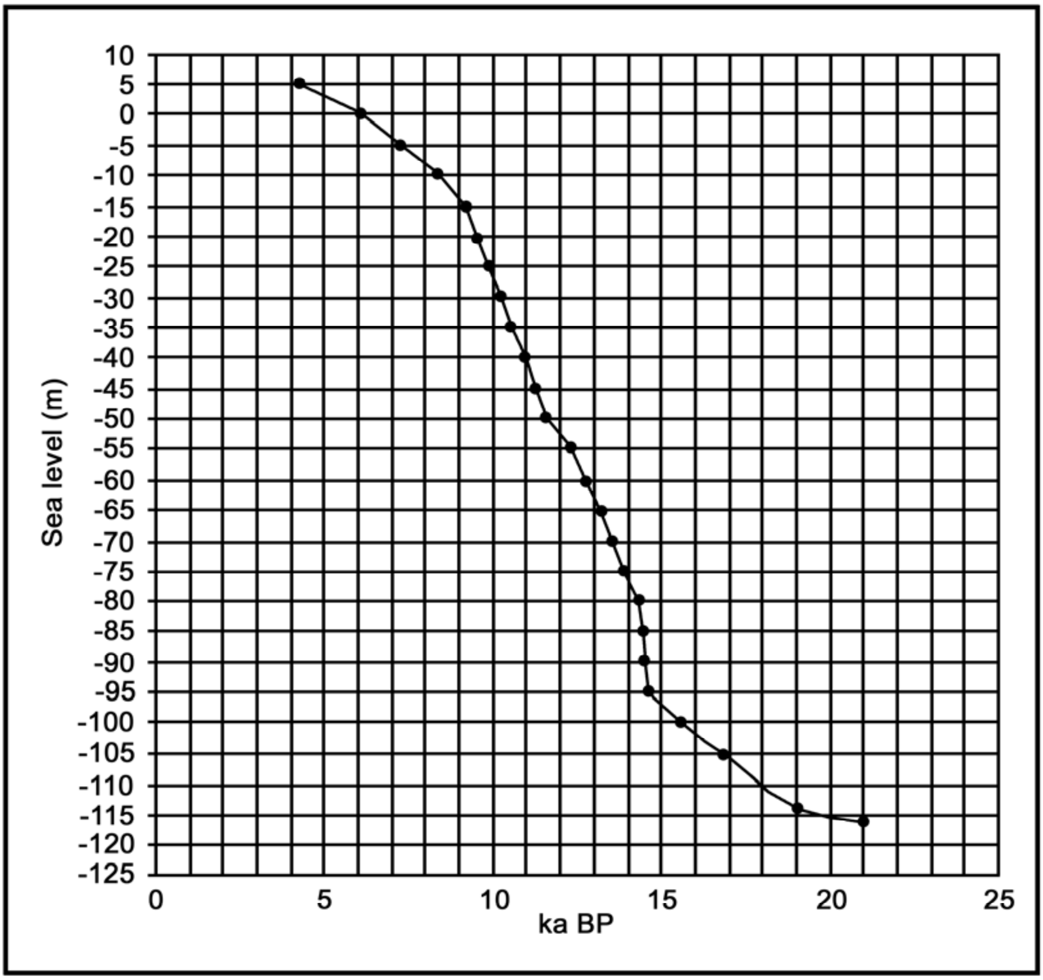

FIGURE 1. The sea level rise curve from 21 ka BP to 4.2 ka BP used in this study was derived from Geyh, et al. (1979), Tjia, et al. (1983) and Hesp, et al. (1995) and Hanebuth, et al. (2000).

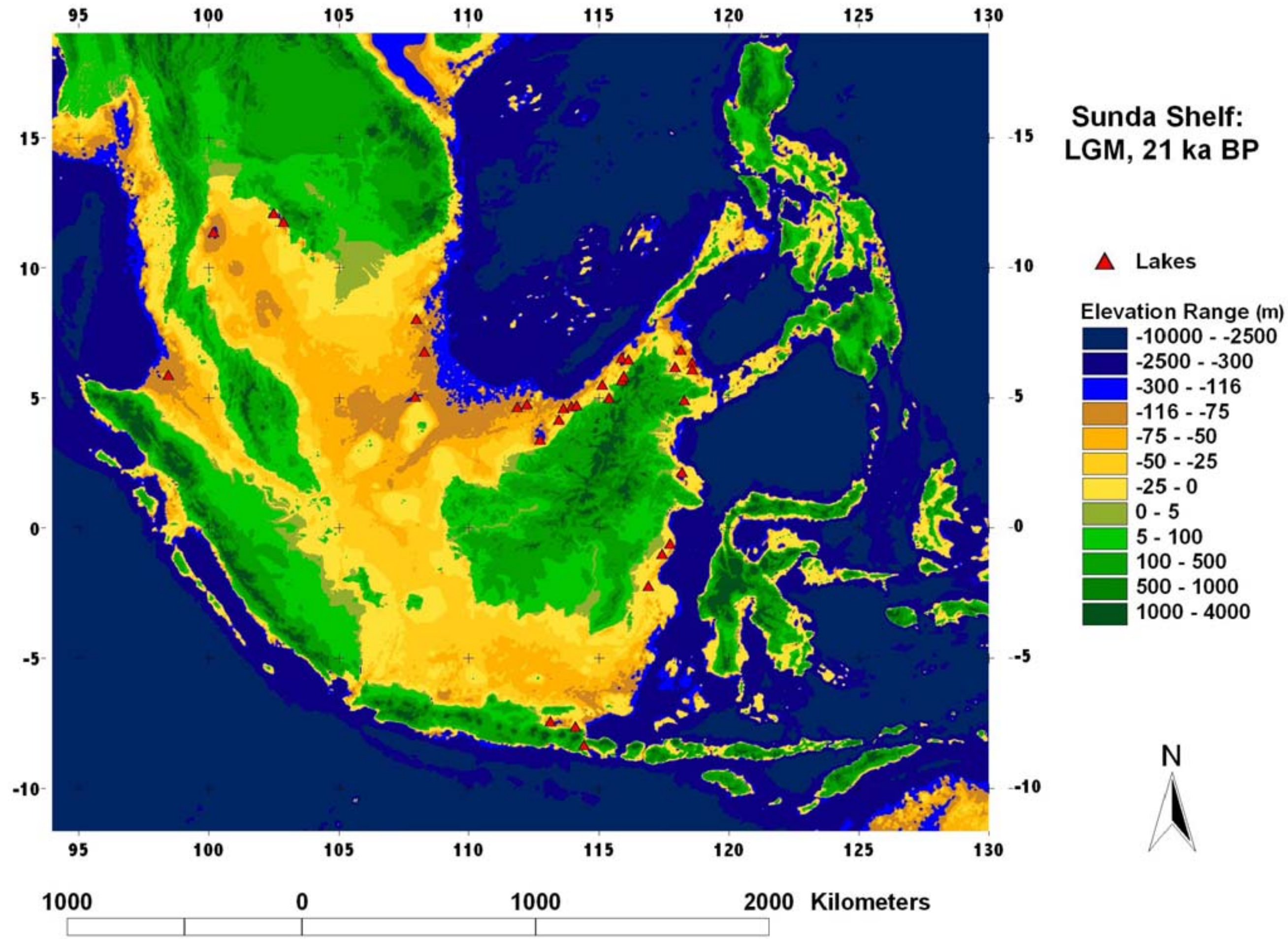

FIGURE 2. Sunda Shelf: LGM, 21 ka BP, -116 m below present-day sea level.

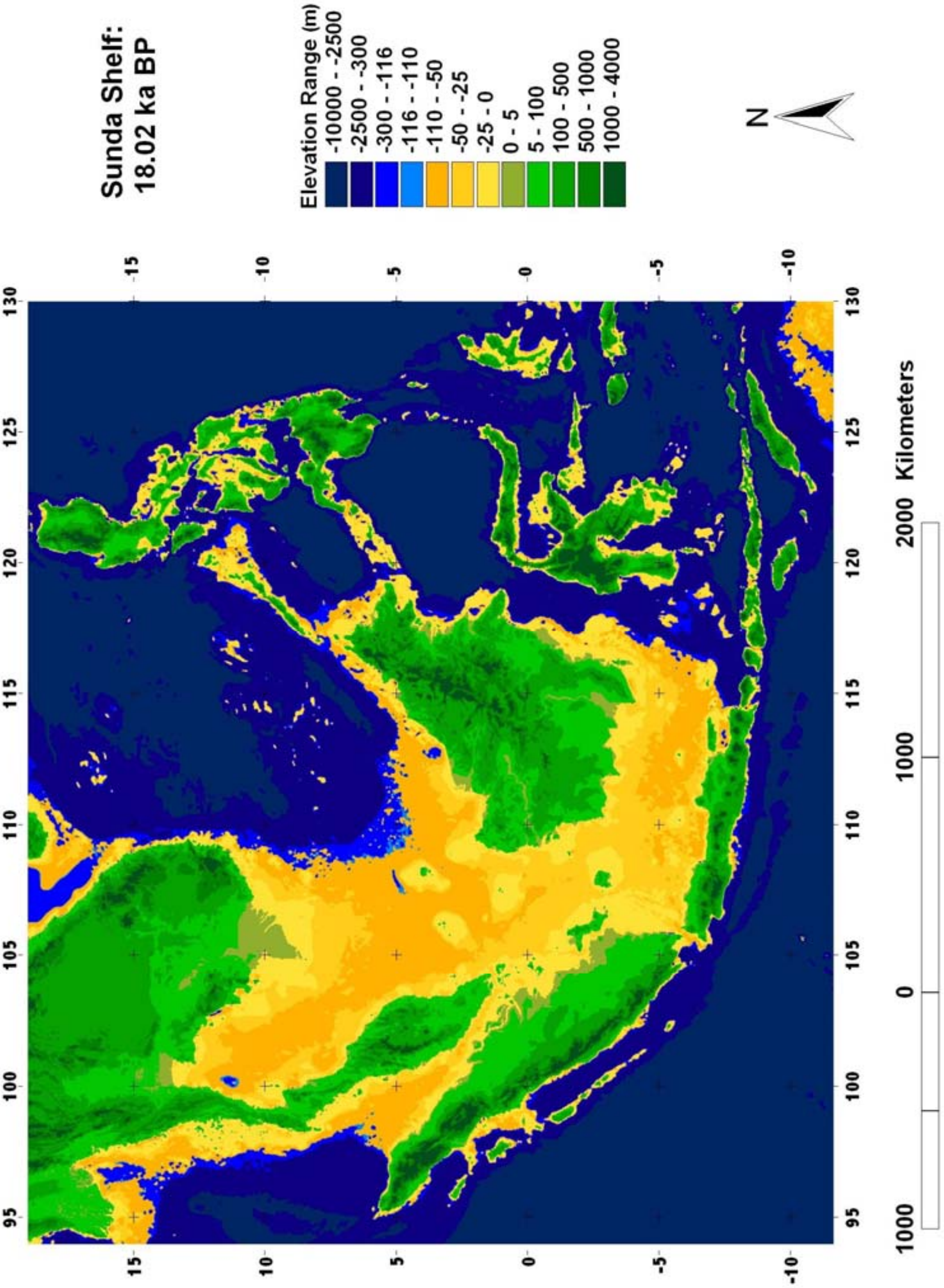

FIGURE 3. Sunda Shelf: 18.02 ka BP, -110 m below present-day sea level.

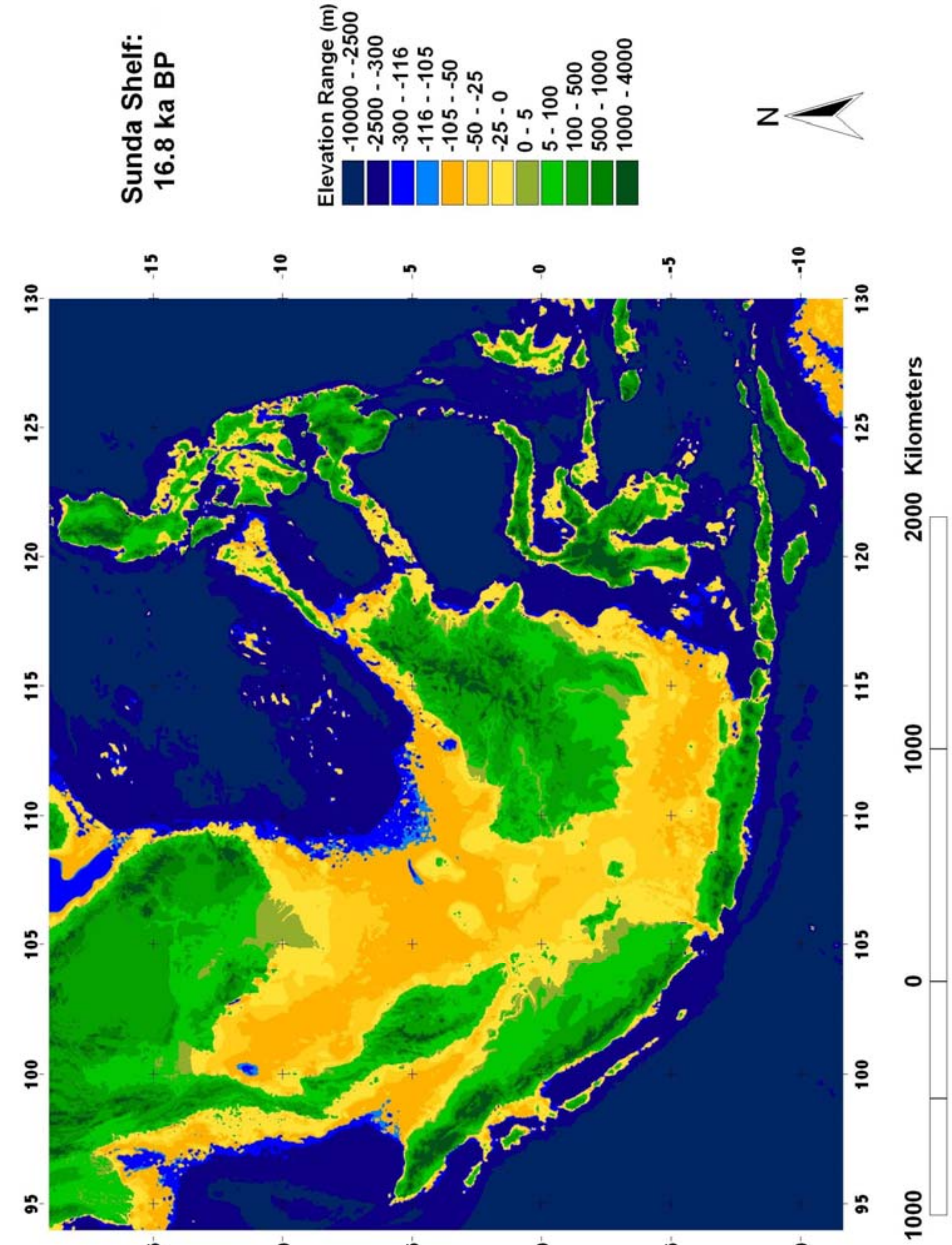

FIGURE 4. Sunda Shelf: 16.8 ka BP, -105 m below present-day sea level.

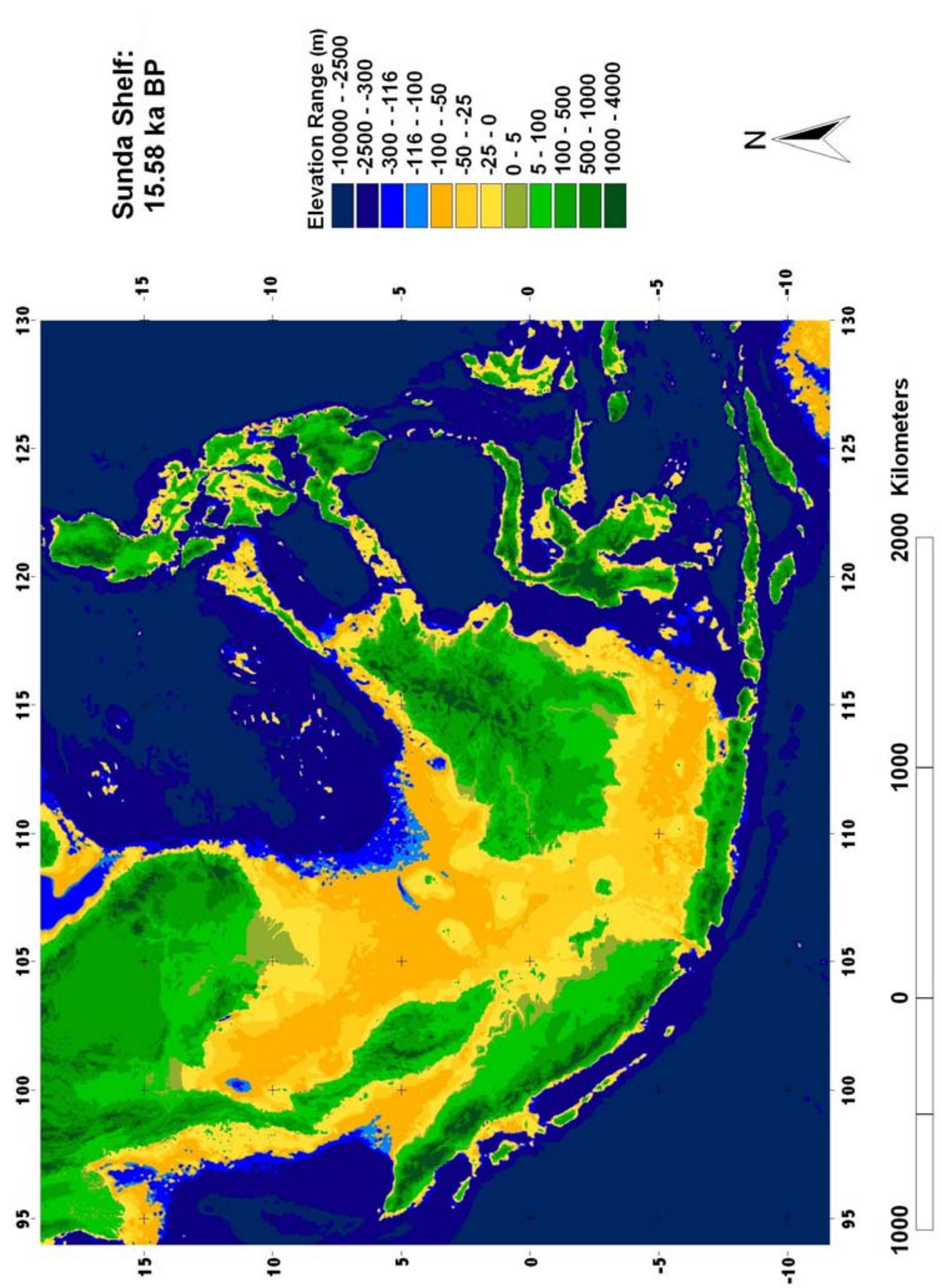

FIGURE 5. Sunda Shelf: 15.58 ka BP, -100 m below present-day sea level.

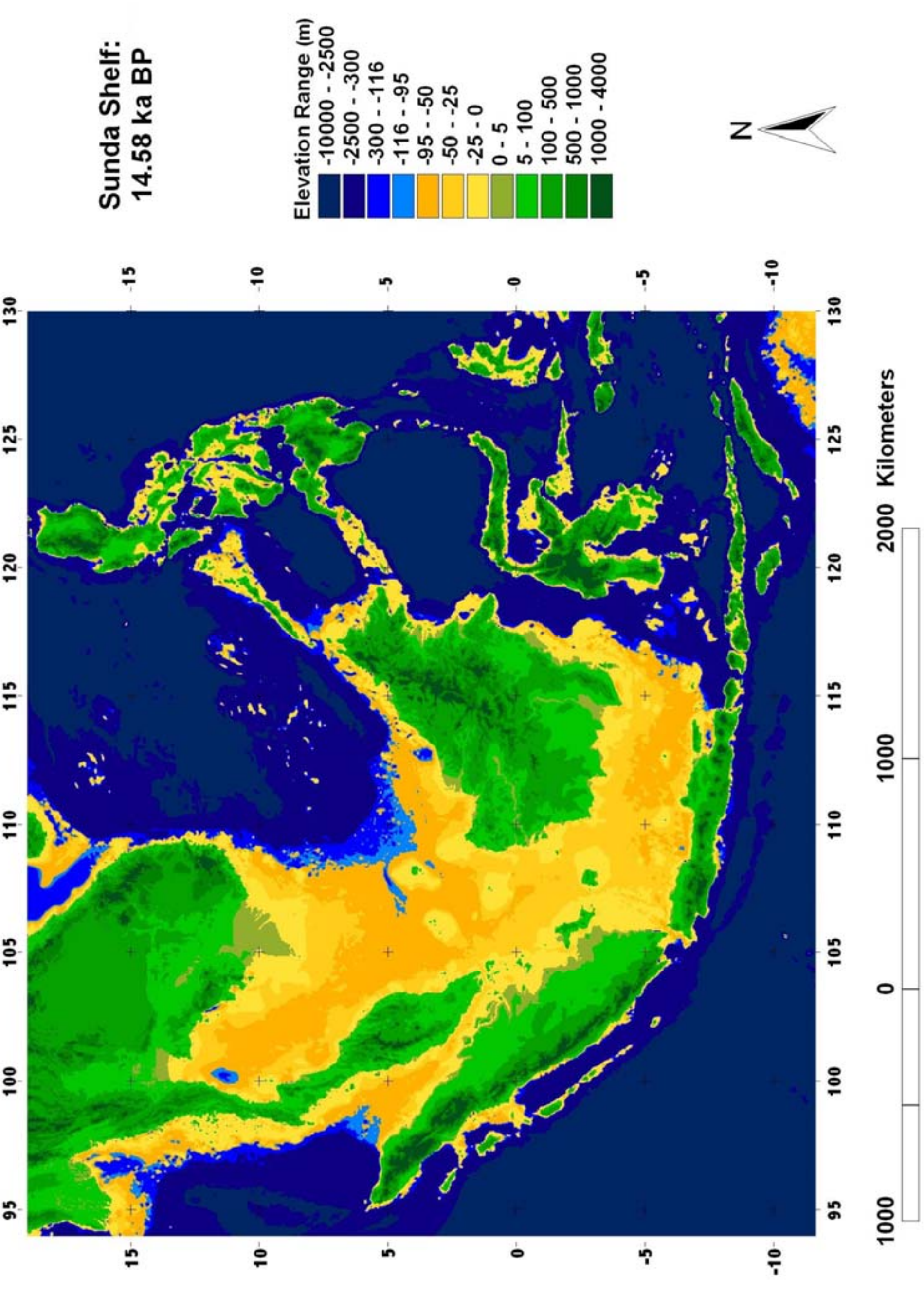

FIGURE 6. Sunda Shelf: 14.58 ka BP, -95 m below present-day sea level.

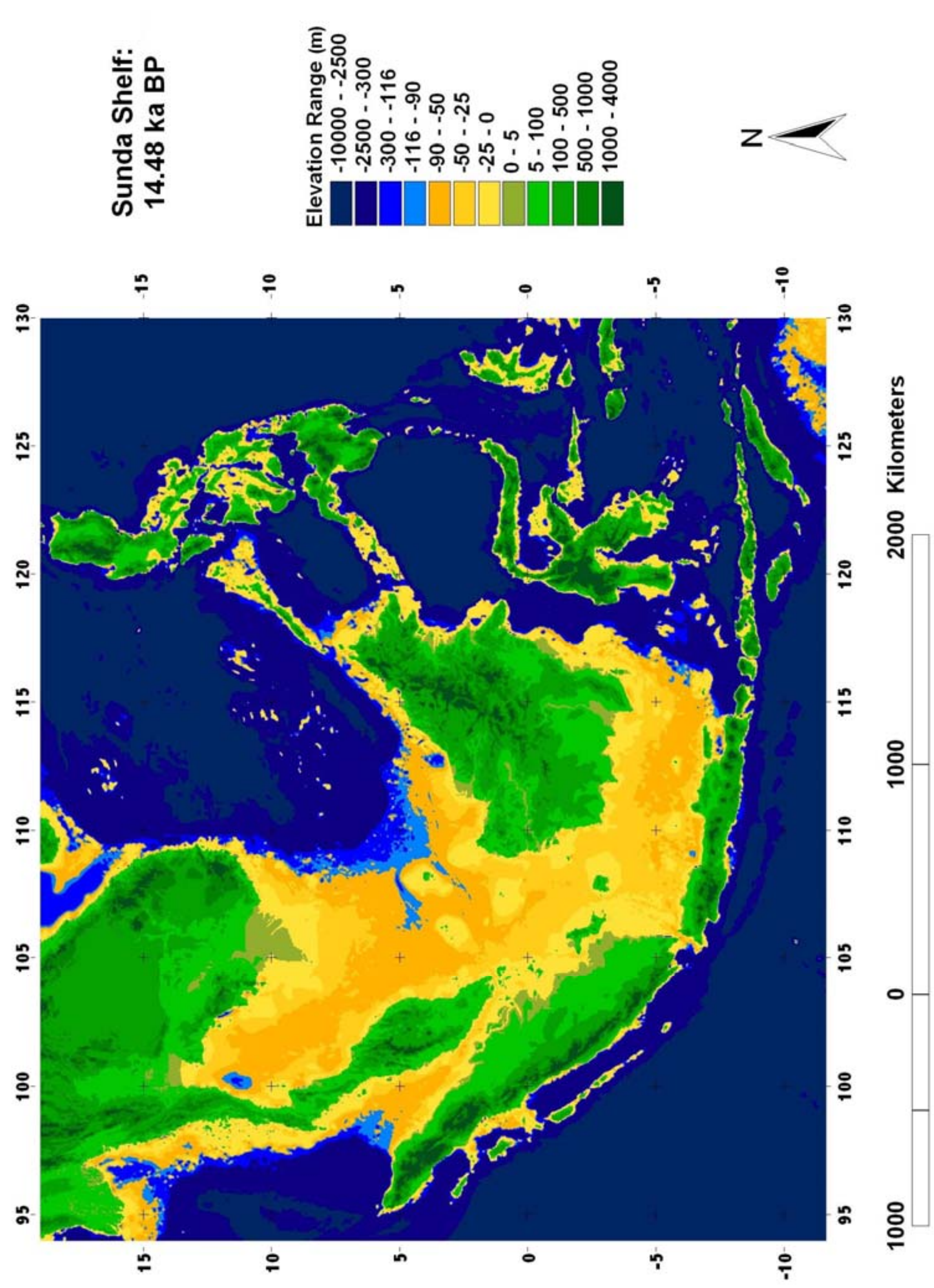

FIGURE 7. Sunda Shelf: 14.48 ka BP, -90 m below present-day sea level.

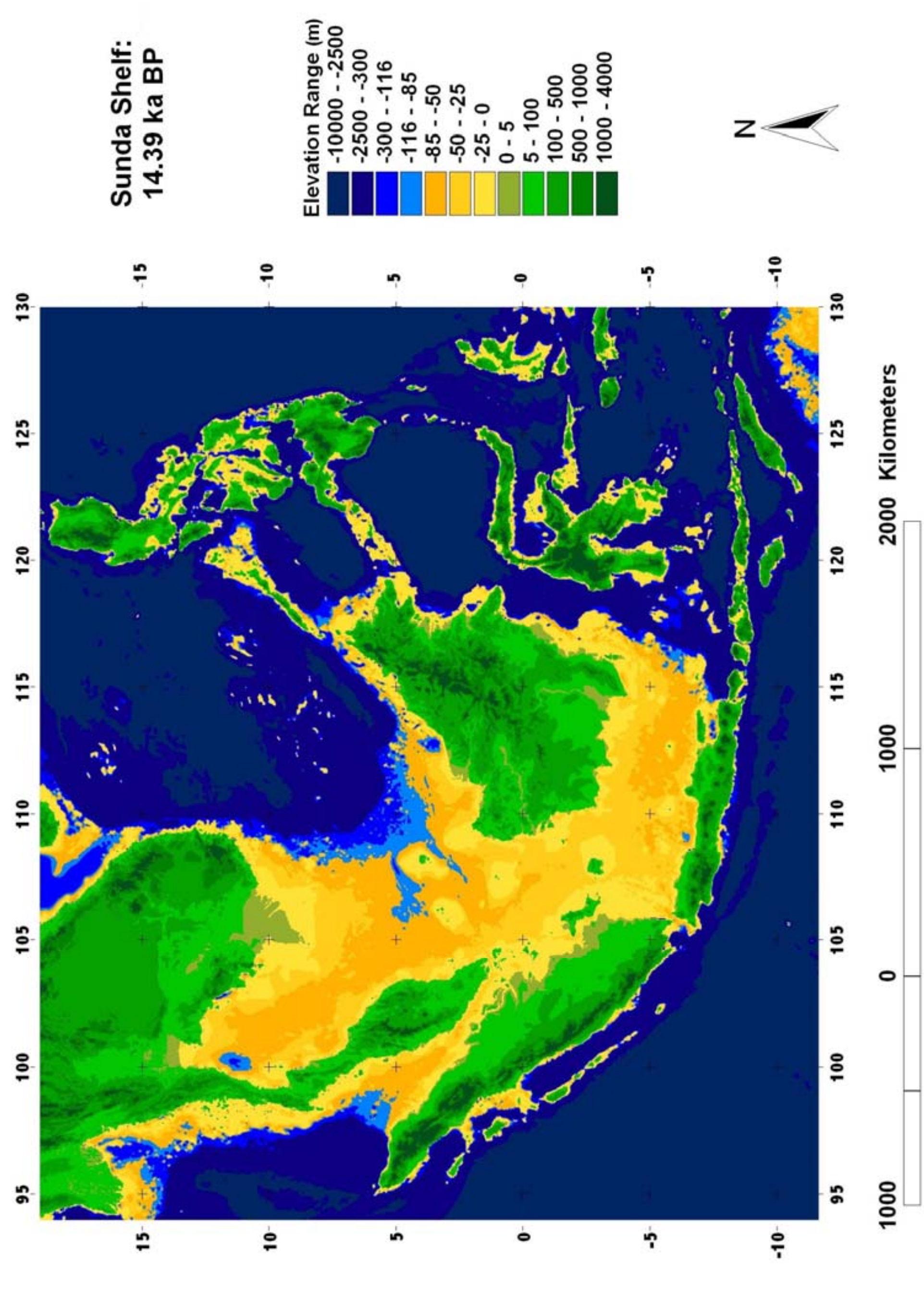

FIGURE 8. Sunda Shelf: 14.39 ka BP, -85 m below present-day sea level.

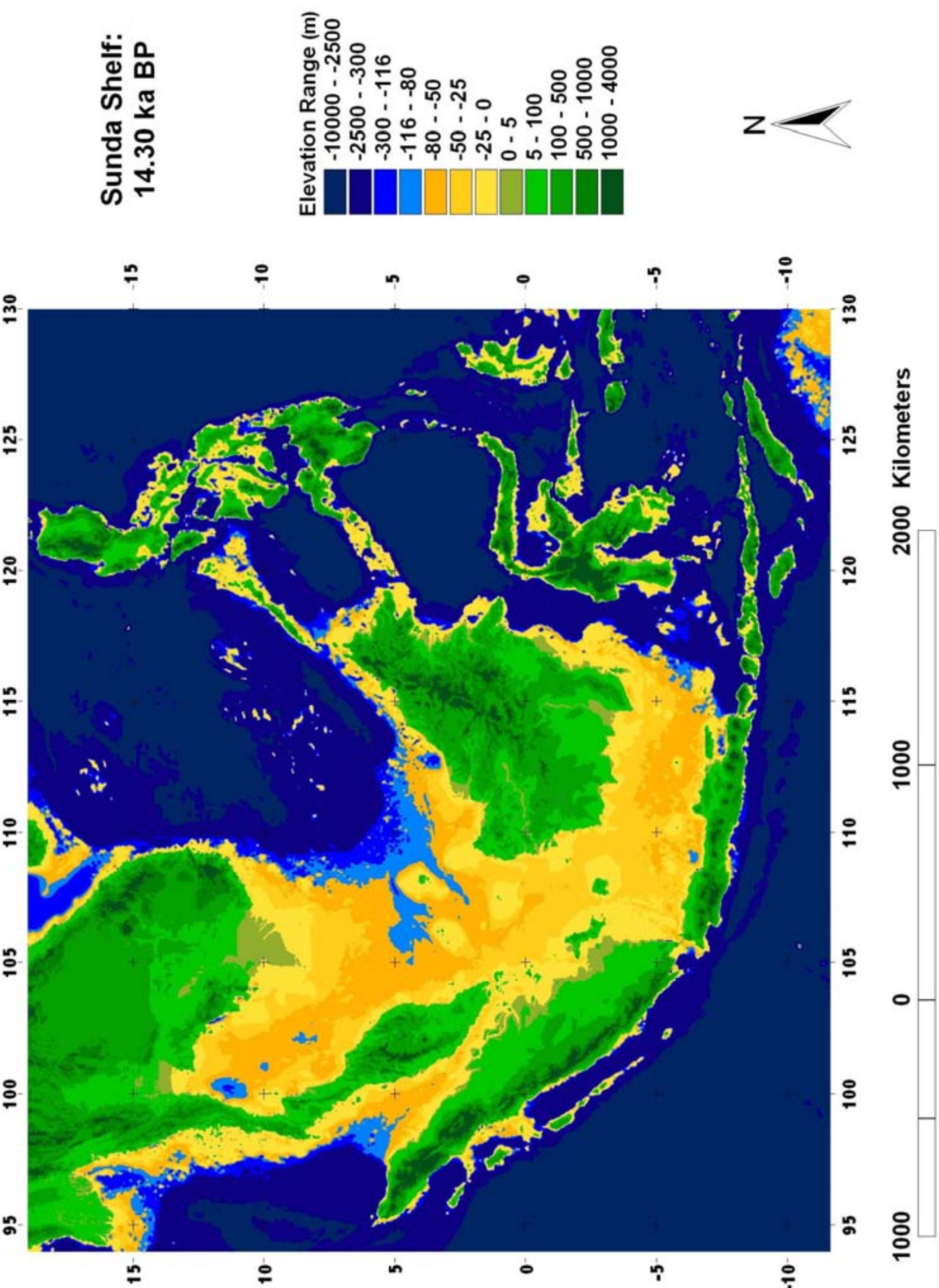

FIGURE 9. Sunda Shelf: 14.30 ka BP, -80 m below present-day sea level.

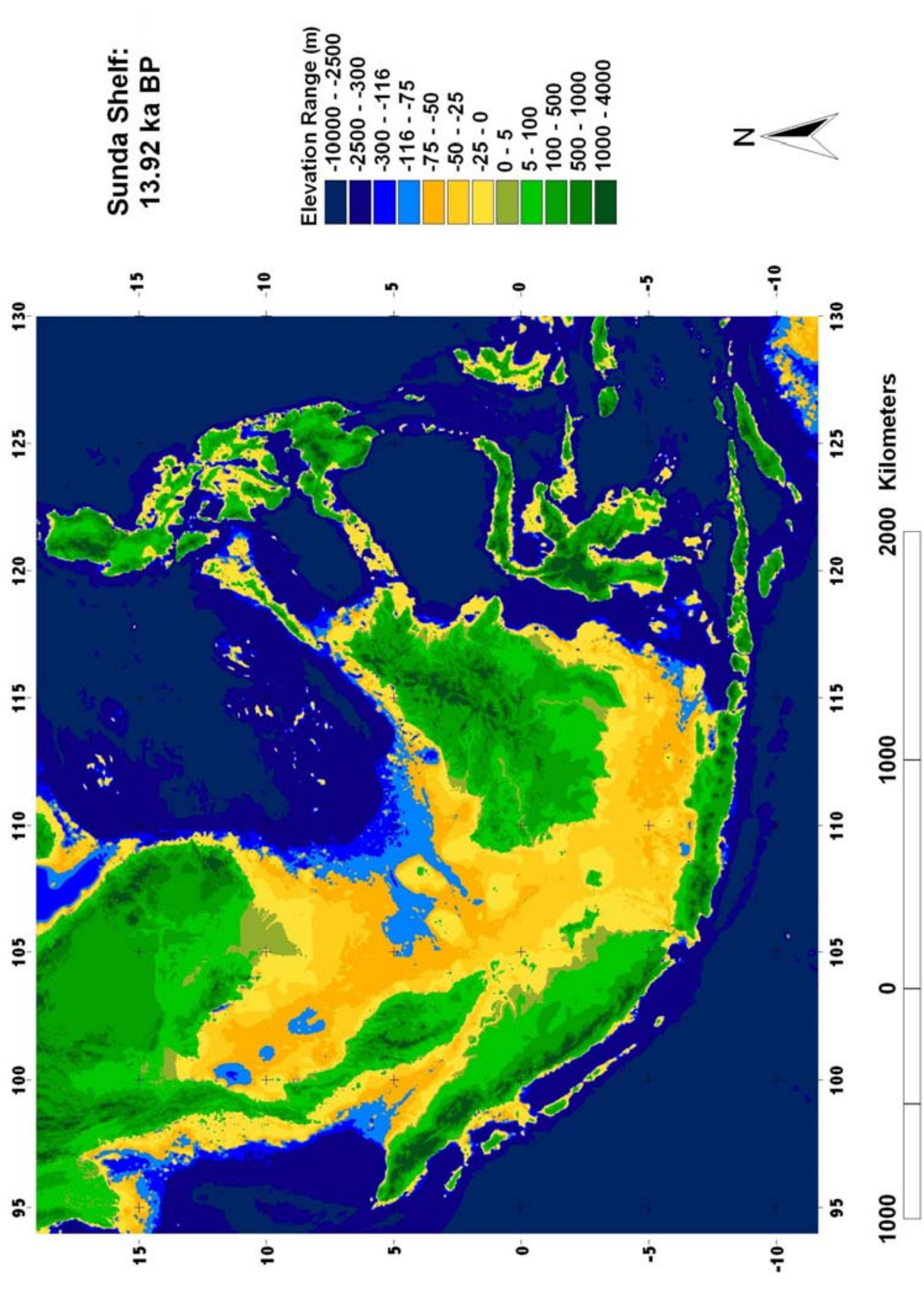

FIGURE 10. Sunda Shelf: 13.92 ka BP, -75 m below present-day sea level.

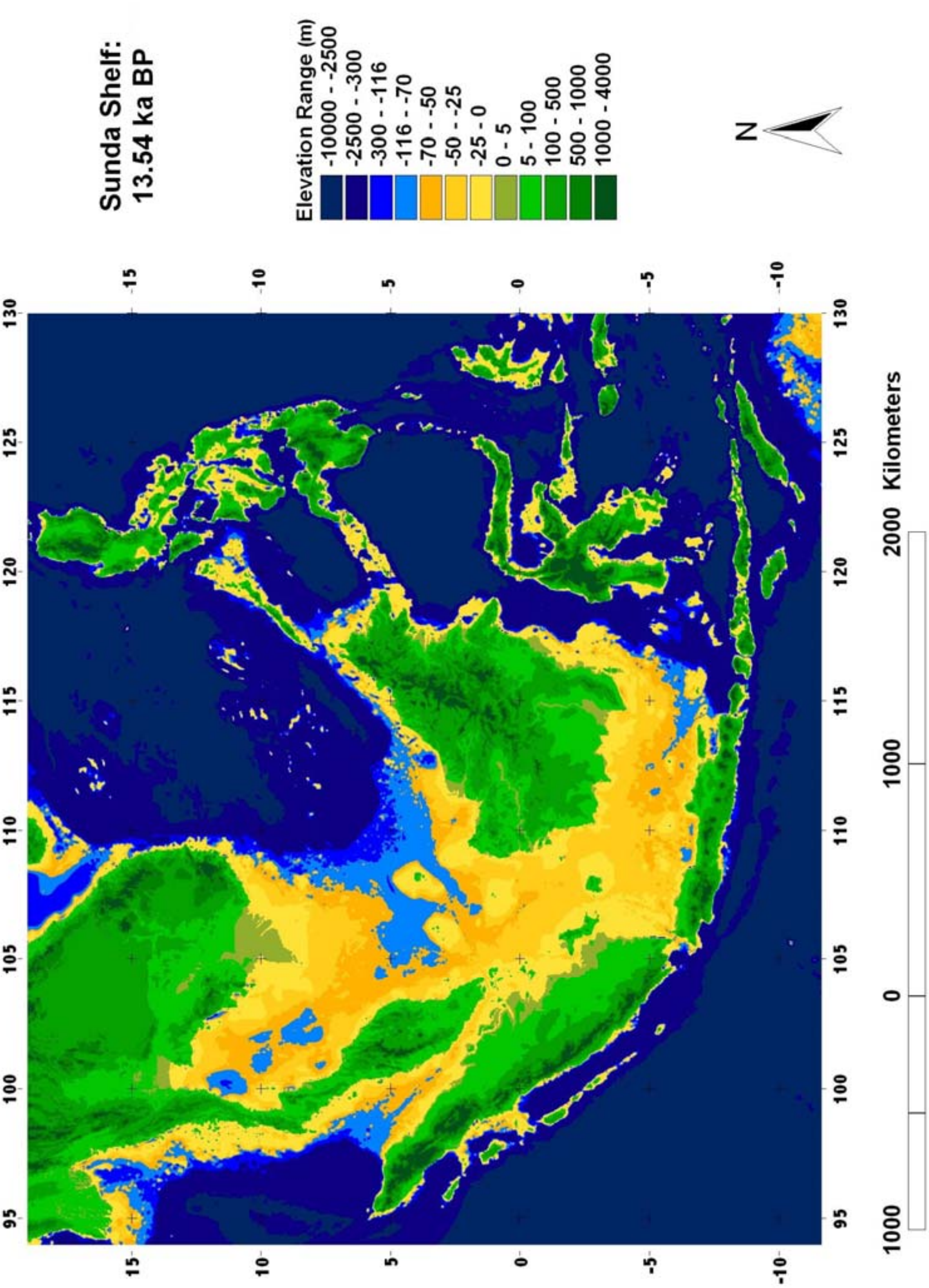

FIGURE 11. Sunda Shelf: 13.54 ka BP, -70 m below present-day sea level.

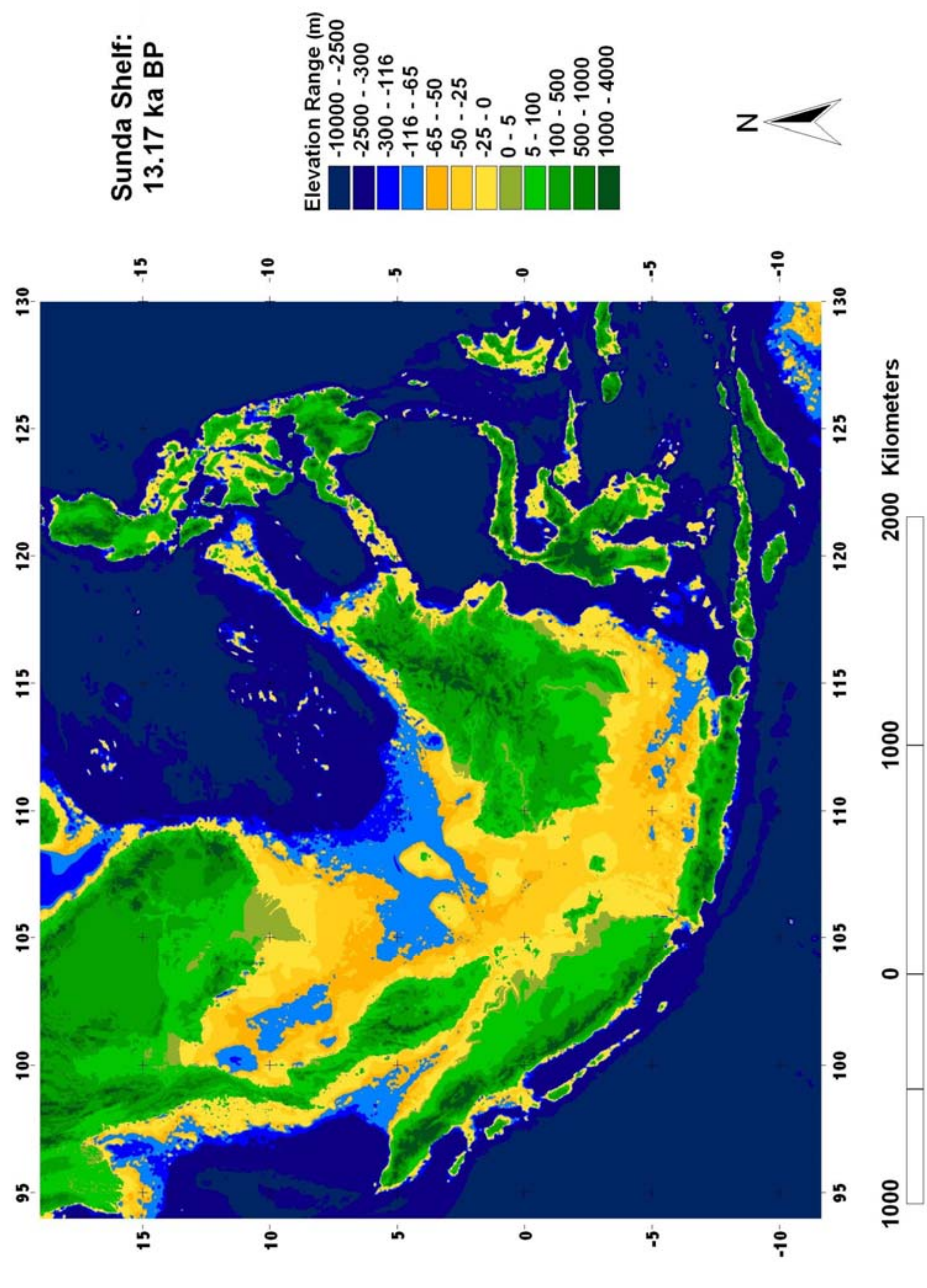

FIGURE 12. Sunda Shelf: 13.17 ka BP, -65 m below present-day sea level.

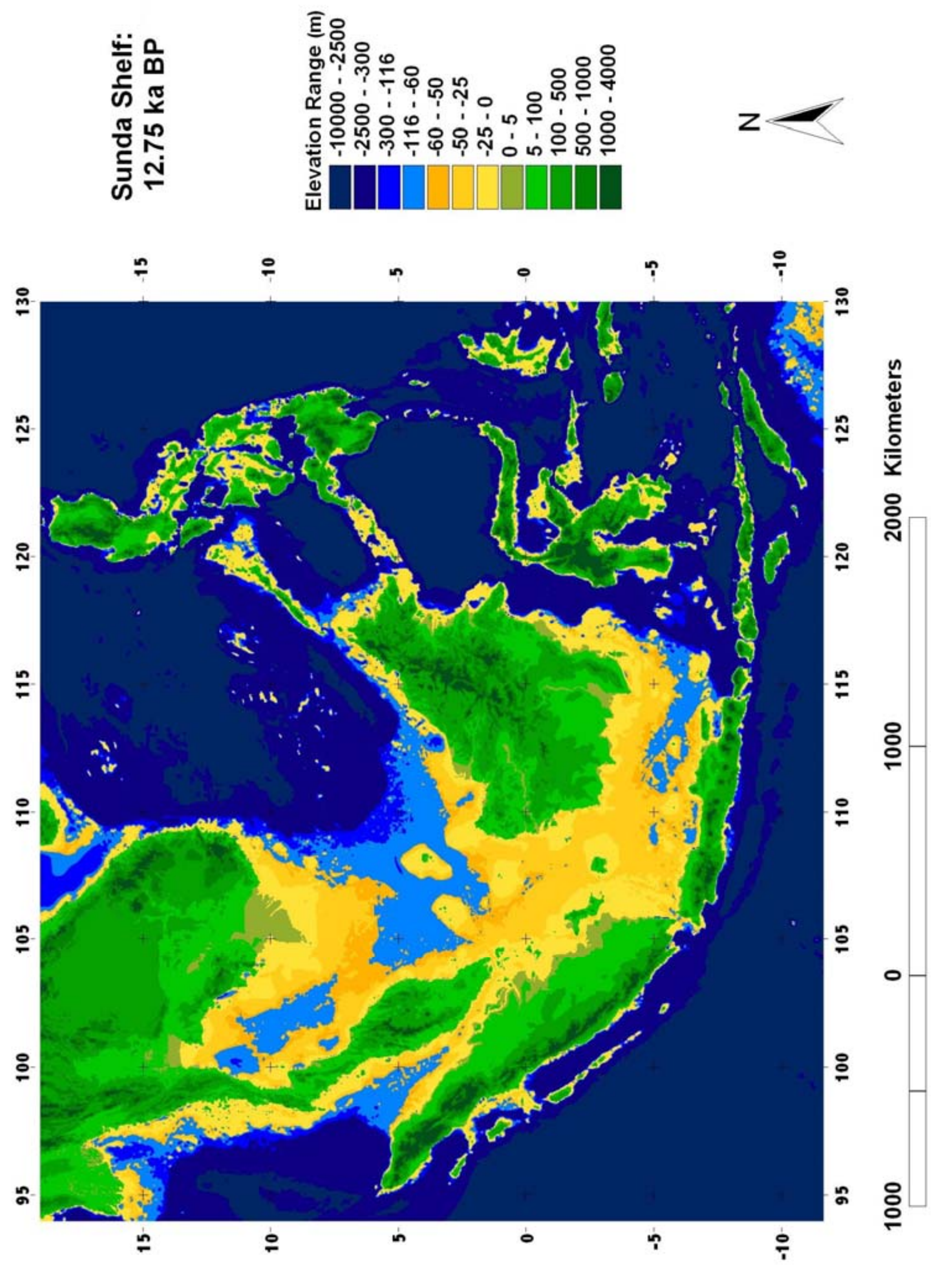

FIGURE 13. Sunda Shelf: 12.75 ka BP, -60 m below present-day sea level.

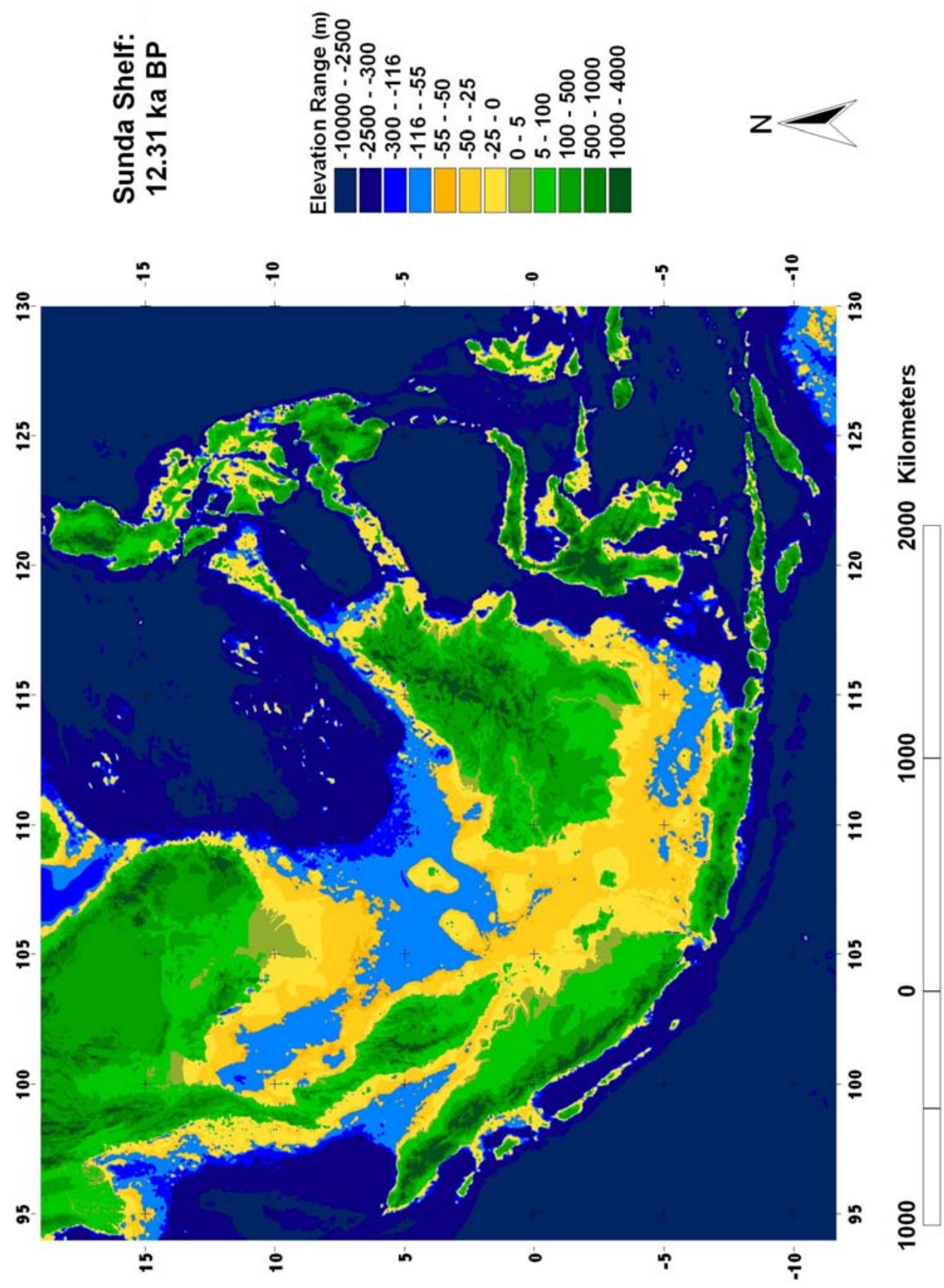

FIGURE 14. Sunda Shelf: 12.31 ka BP, -55 m below present-day sea level.

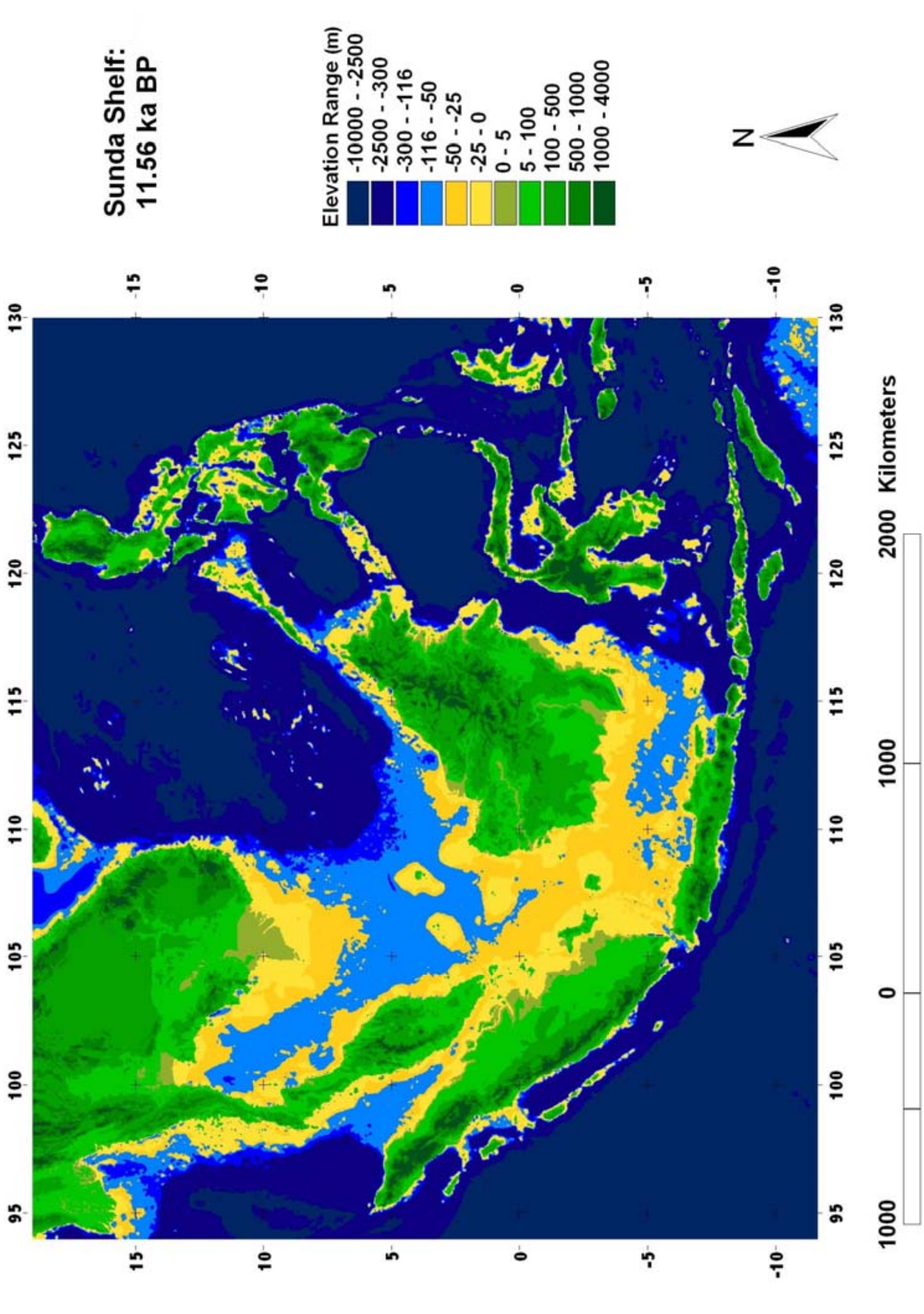

FIGURE 15. Sunda Shelf: 11.56 ka BP, -50 m below present-day sea level.

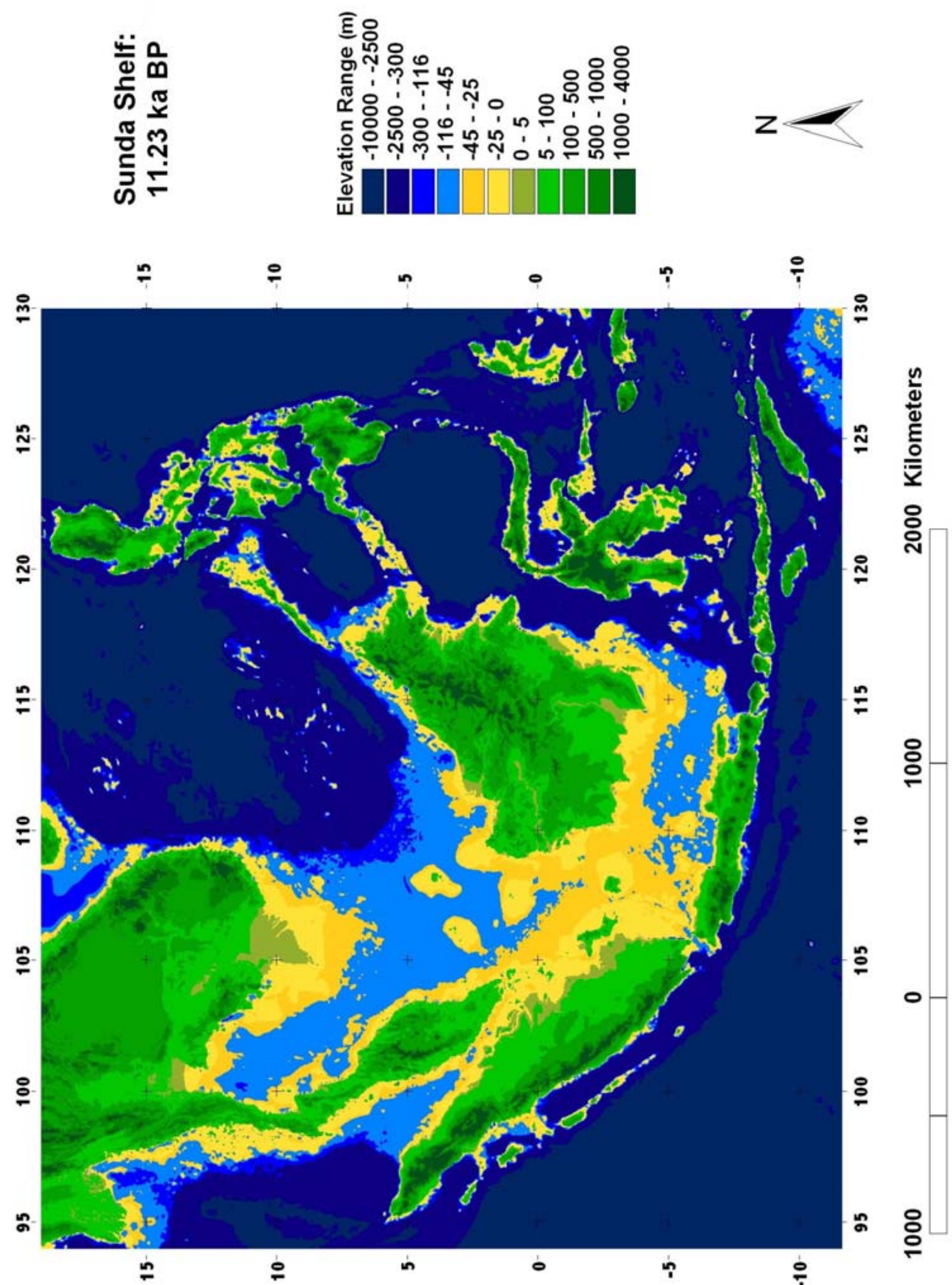

FIGURE 16. Sunda Shelf: 11.23 ka BP, -45 m below present-day sea level.

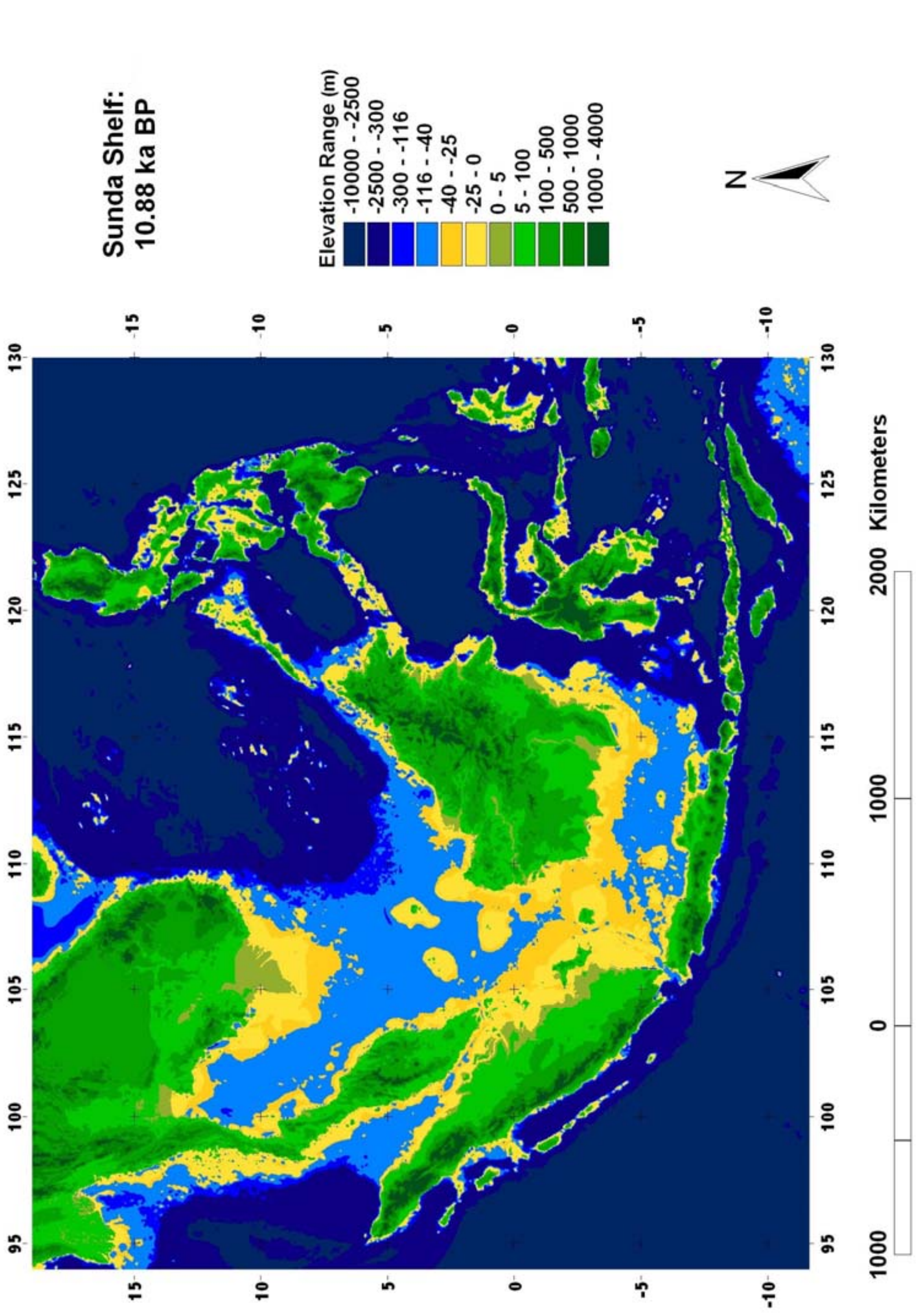

FIGURE 17. Sunda Shelf: 10.88 ka BP, -40 m below present-day sea level.

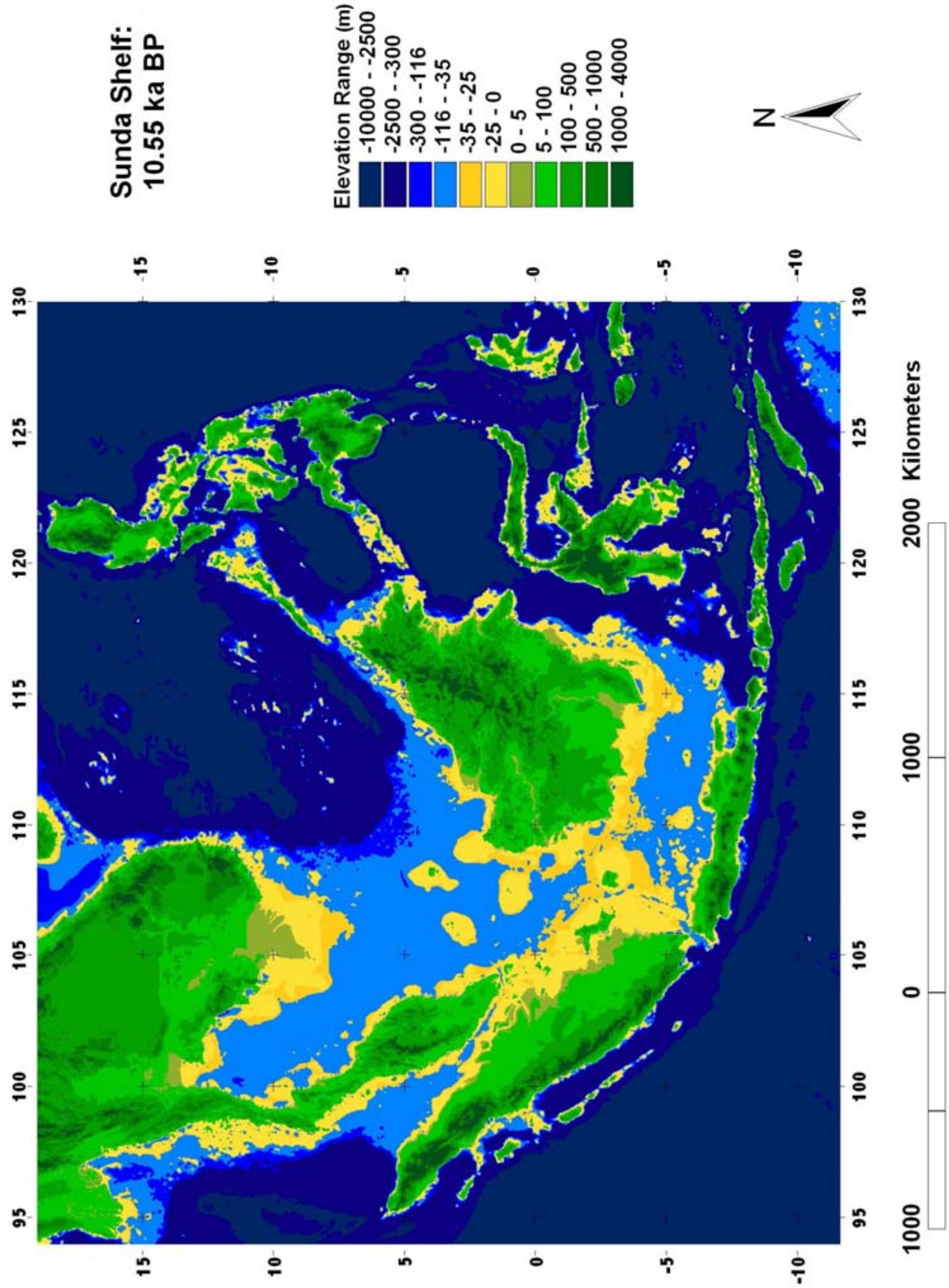

FIGURE 18. Sunda Shelf: 10.55 ka BP, -35 m below present-day sea level.

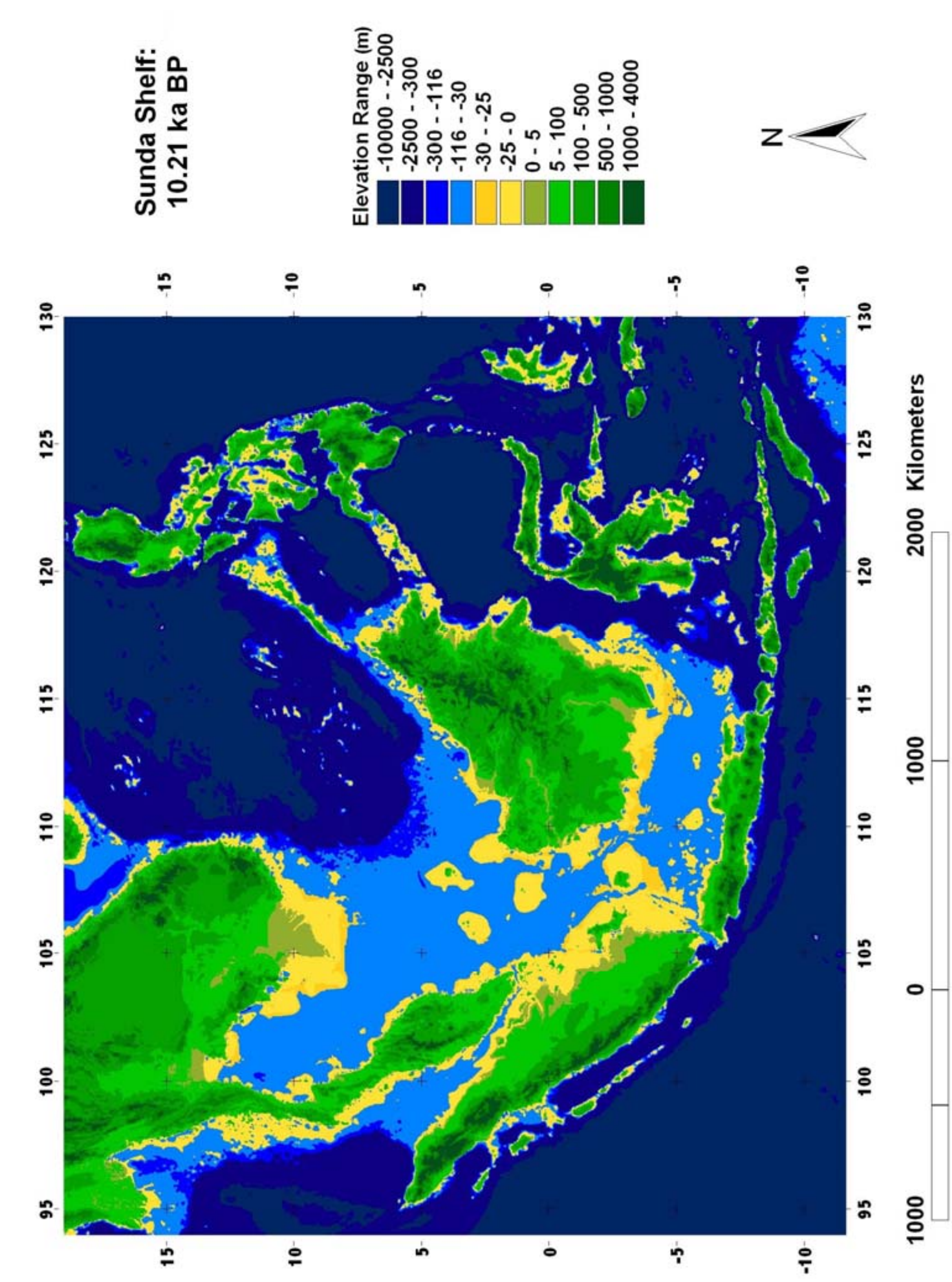

FIGURE 19. Sunda Shelf: 10.21 ka BP, -30 m below present-day sea level.

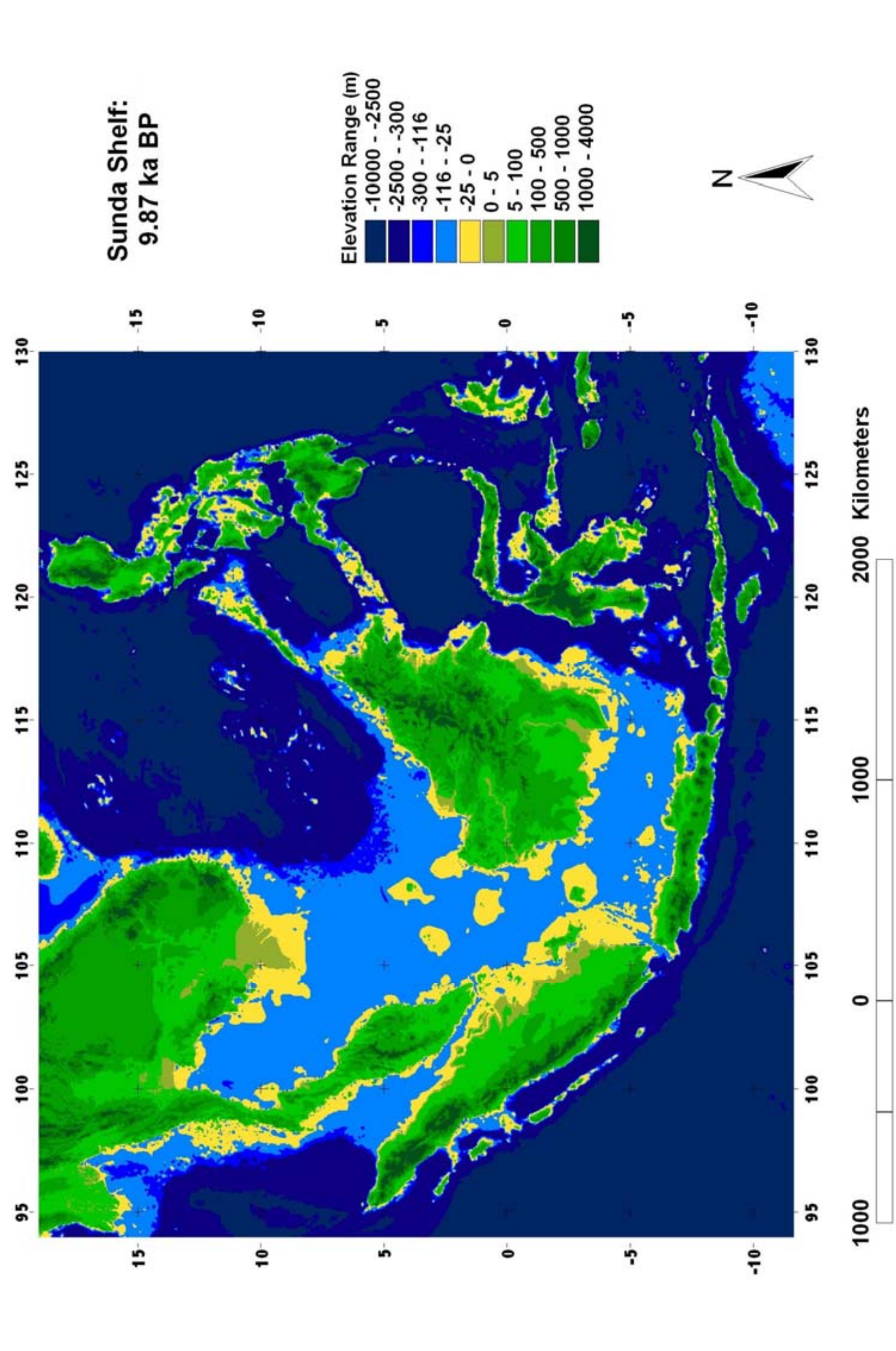

FIGURE 20. Sunda Shelf: 9.87 ka BP, -25 m below present-day sea level.

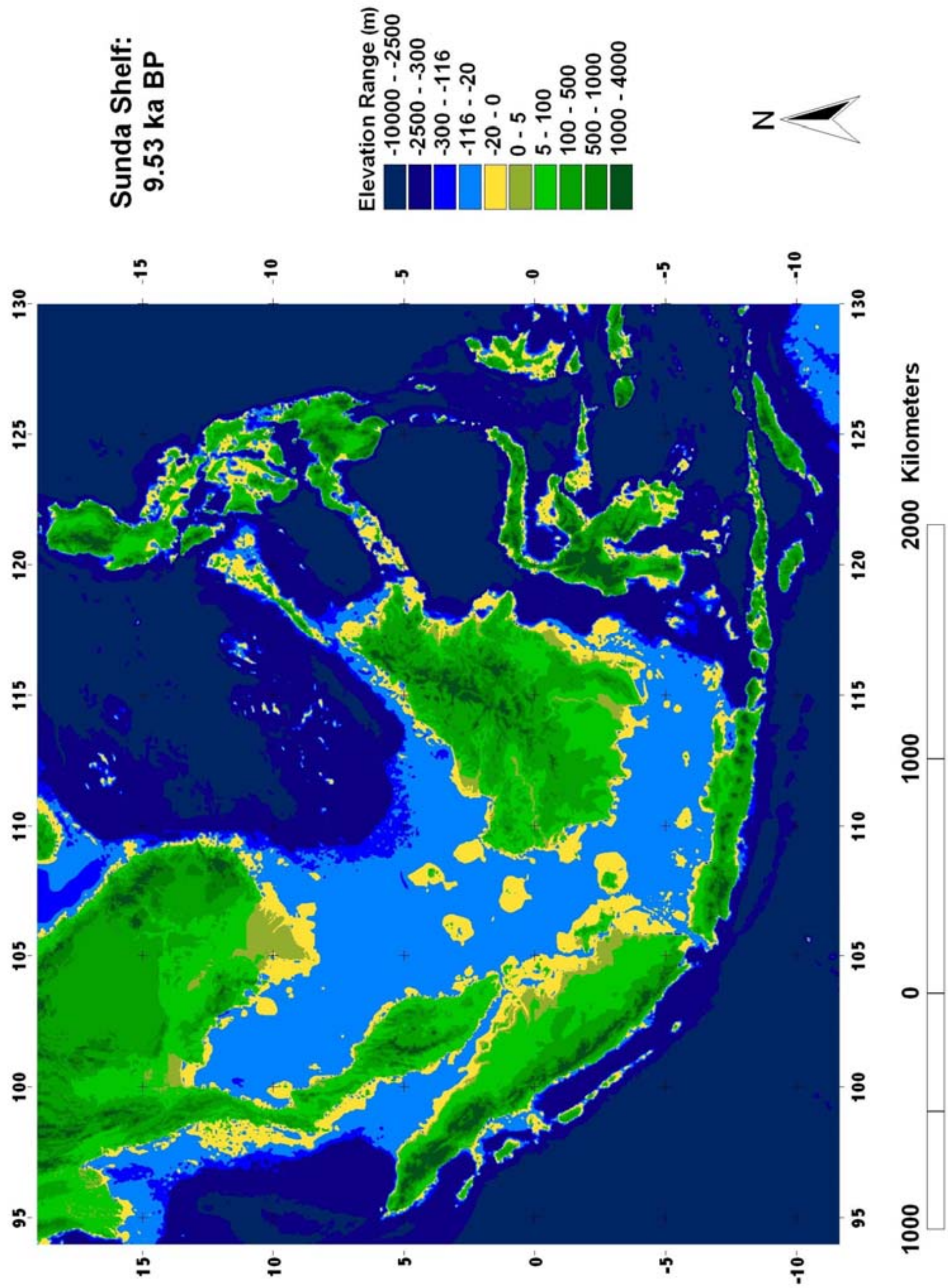

FIGURE 21. Sunda Shelf: 9.53 ka BP, -20 m below present-day sea level.

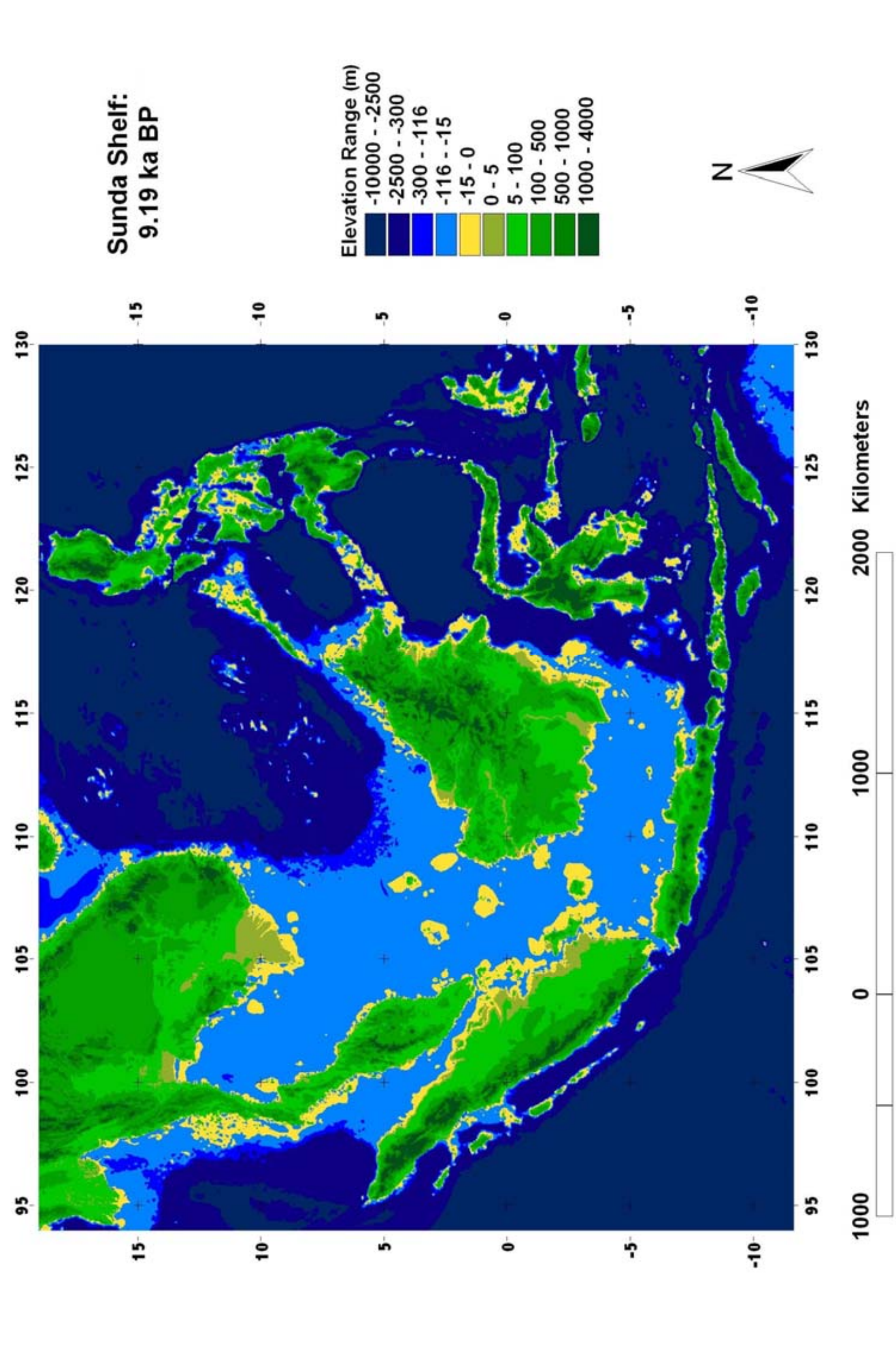

FIGURE 22. Sunda Shelf: 9.19 ka BP, -15 m below present-day sea level.

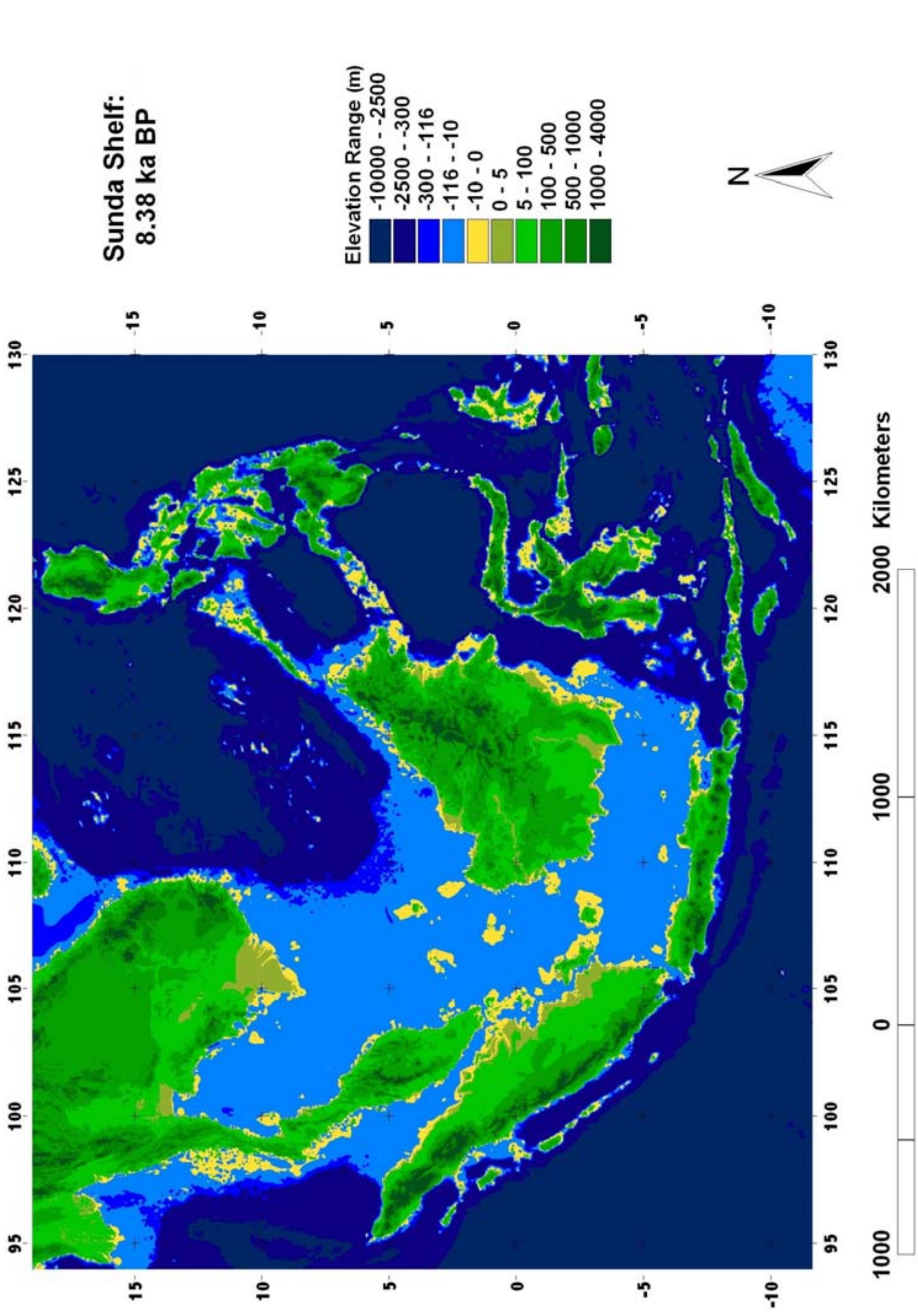

FIGURE 23. Sunda Shelf: 8.38 ka BP, -10 m below present-day sea level.

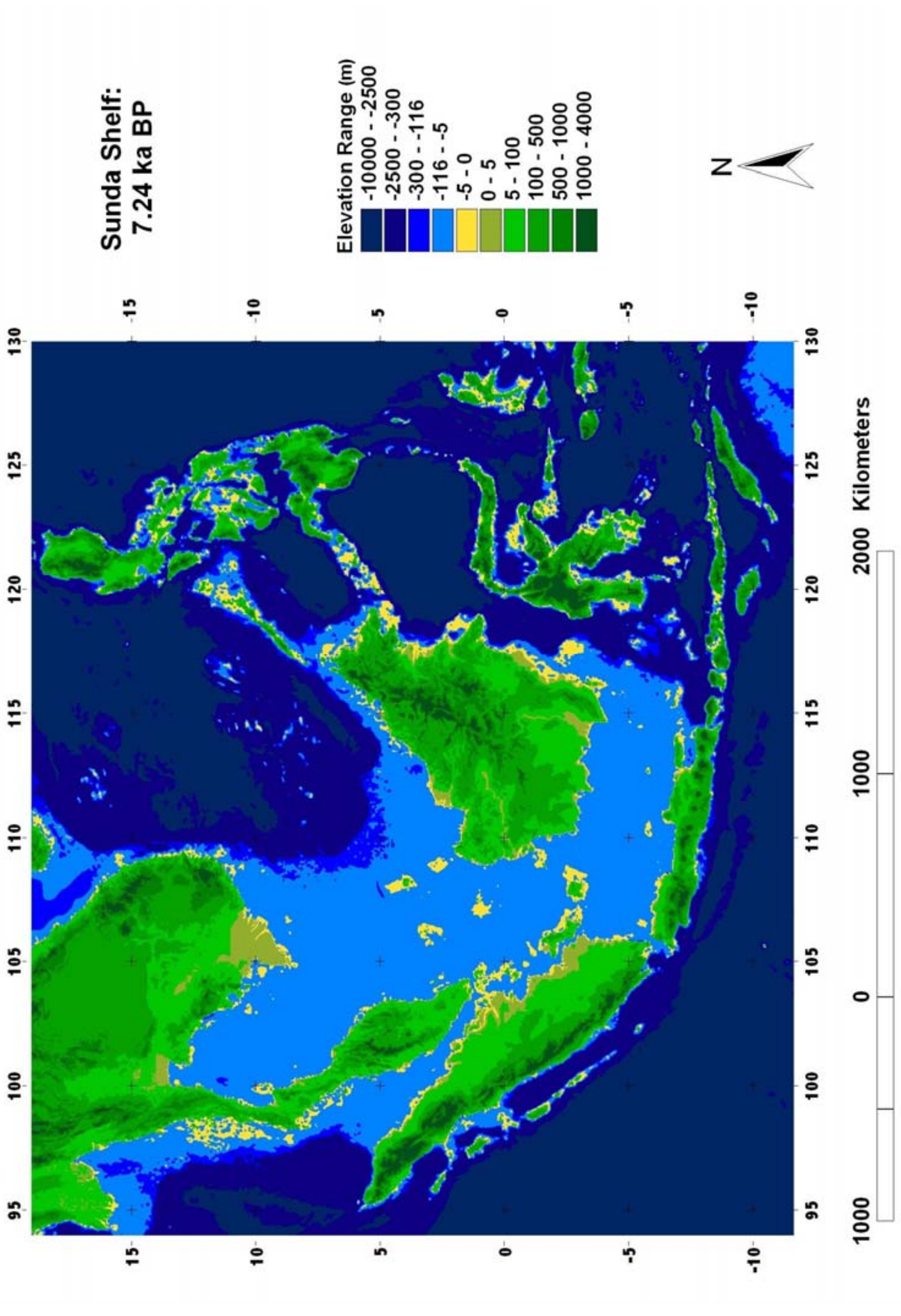

FIGURE 24. Sunda Shelf: 7.24 ka BP, -5 m below present-day sea level.

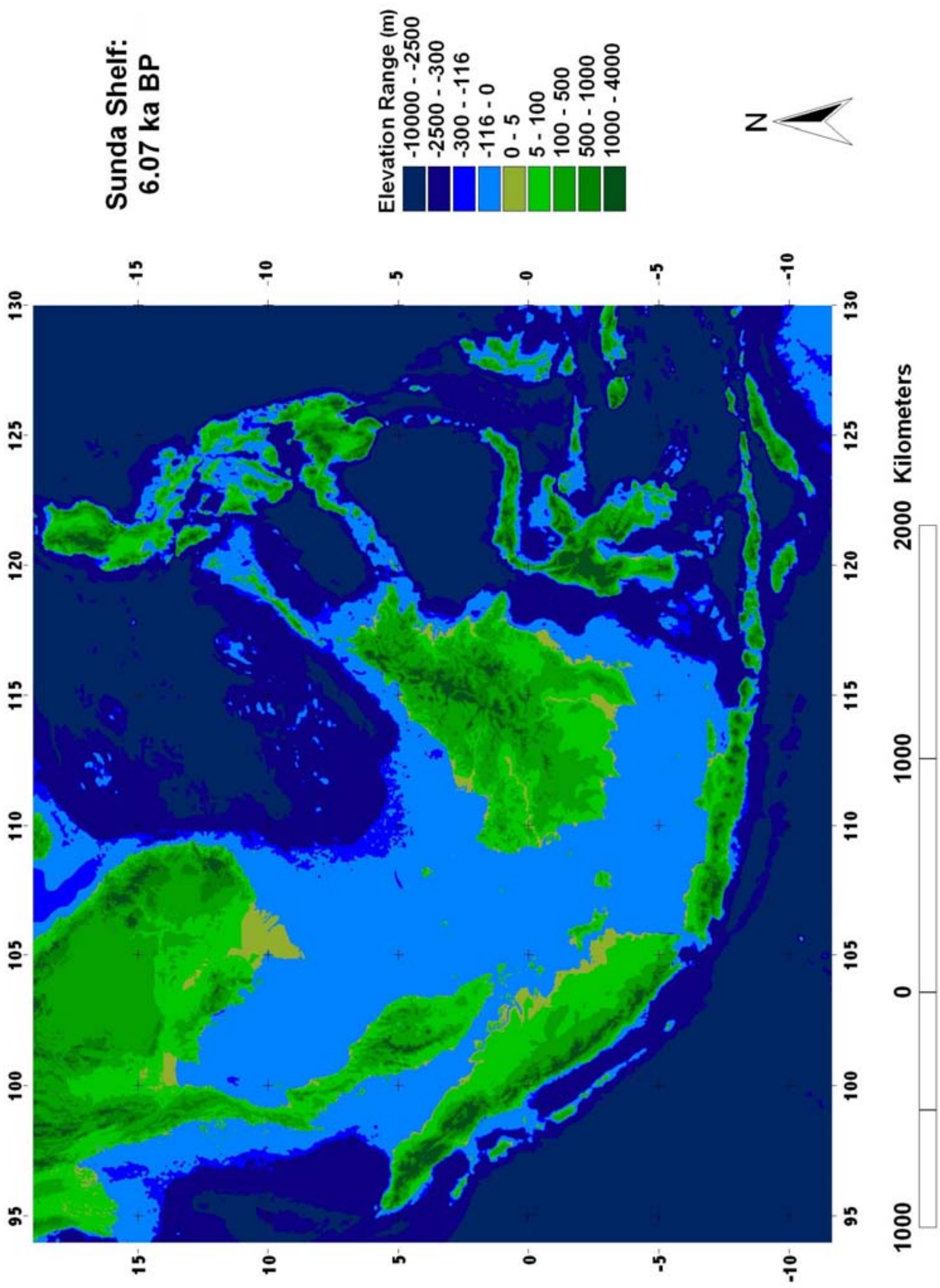

FIGURE 25. Sunda Shelf: 6.07 ka BP, -0 m below present-day sea level.

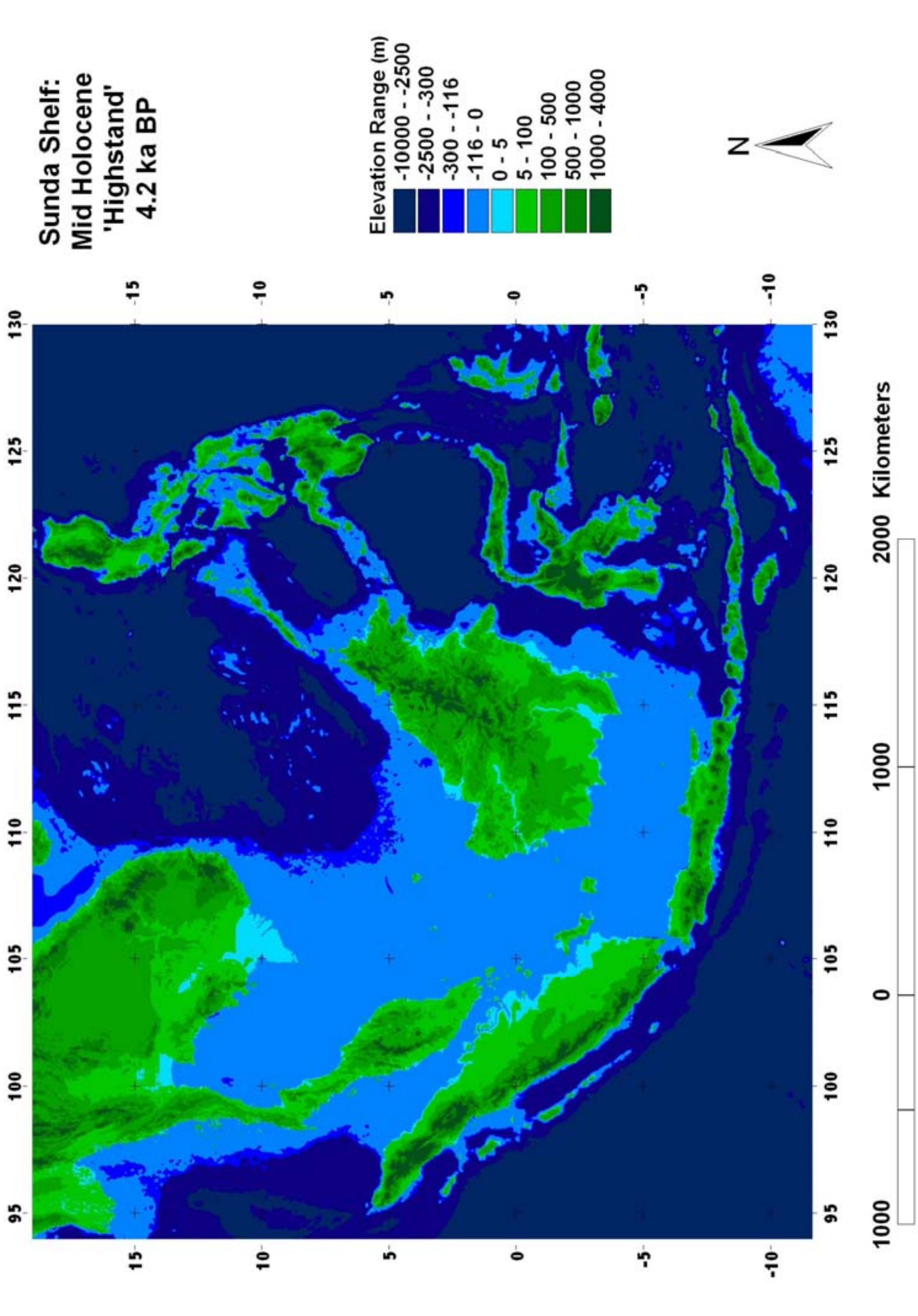

FIGURE 26. Sunda Shelf: Mid Holocene Highstand, 4.20 ka BP, +5 m above present-day sea level.

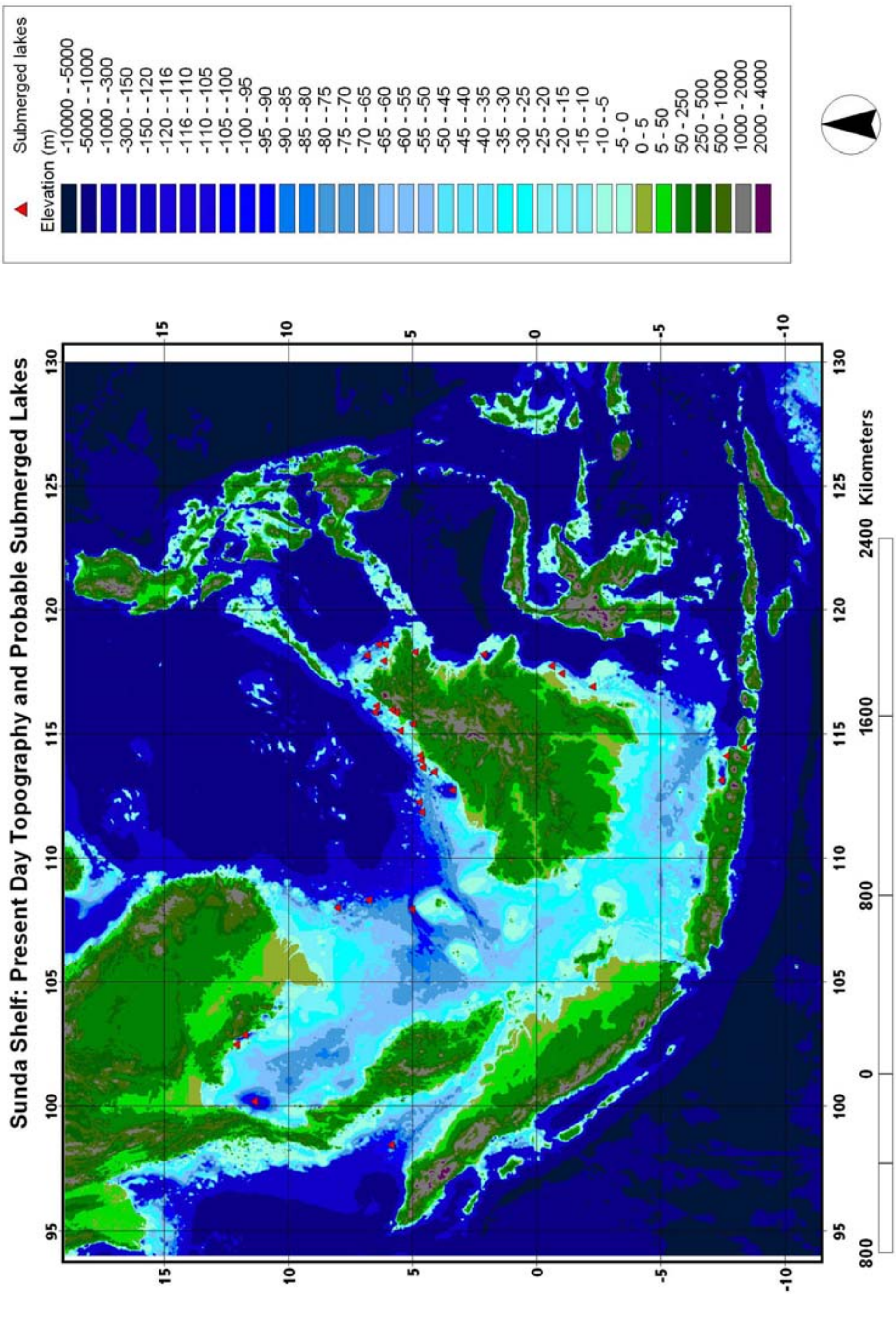

FIGURE 27. Present-day bathymetry of the Sunda Shelf and the locations of the 32 probable submerged lakes detailed in Table 2.

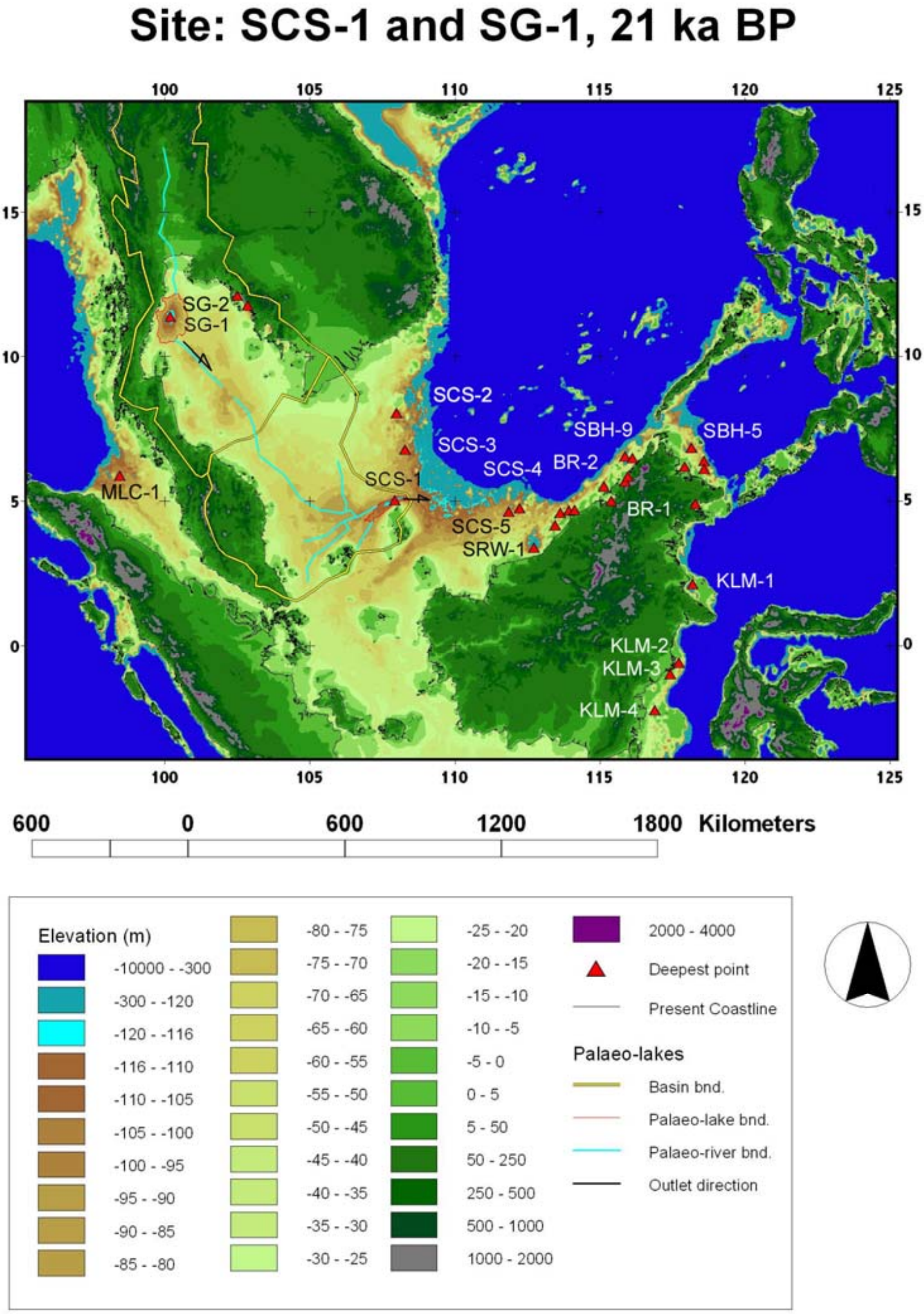

FIGURE 28. Sunda Shelf: Submerged depressions SCS-1 and SG-1 at 21 ka BP.

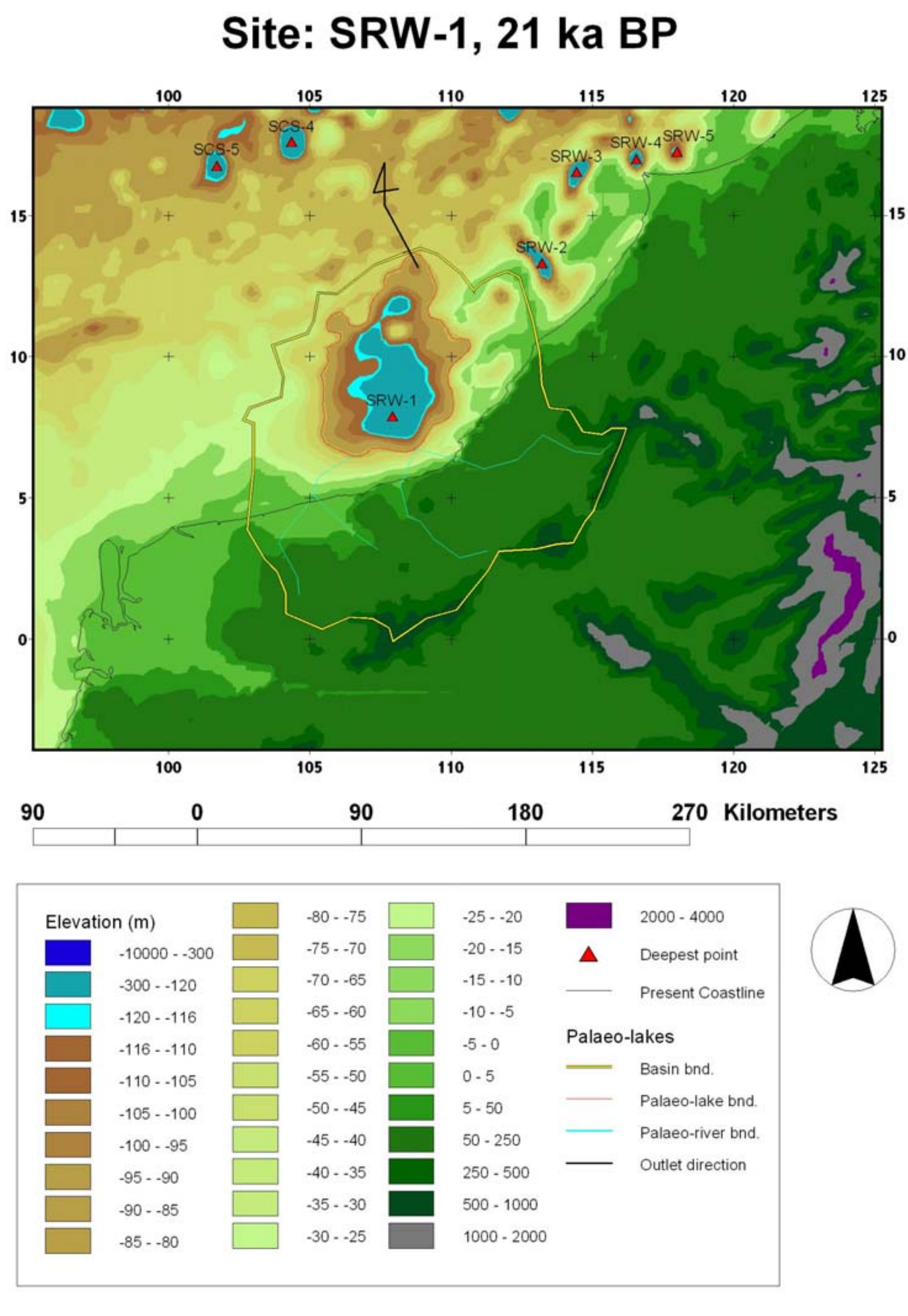

FIGURE 29. Sunda Shelf: Submerged depression SRW-1 at 21 ka BP.

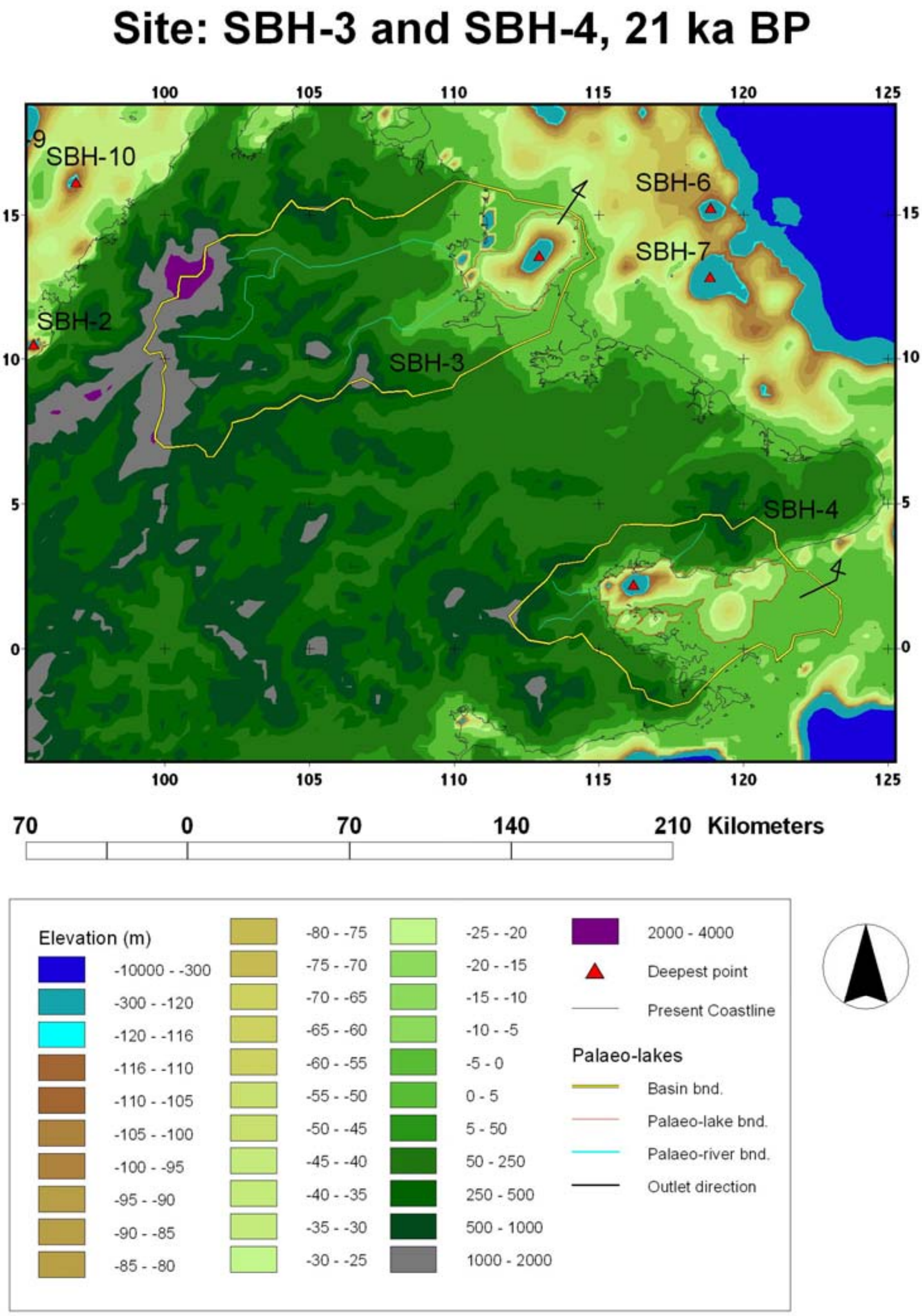

FIGURE 30. Sunda Shelf: Submerged depressions SBH-3 and SBH-4 at 21 ka BP.

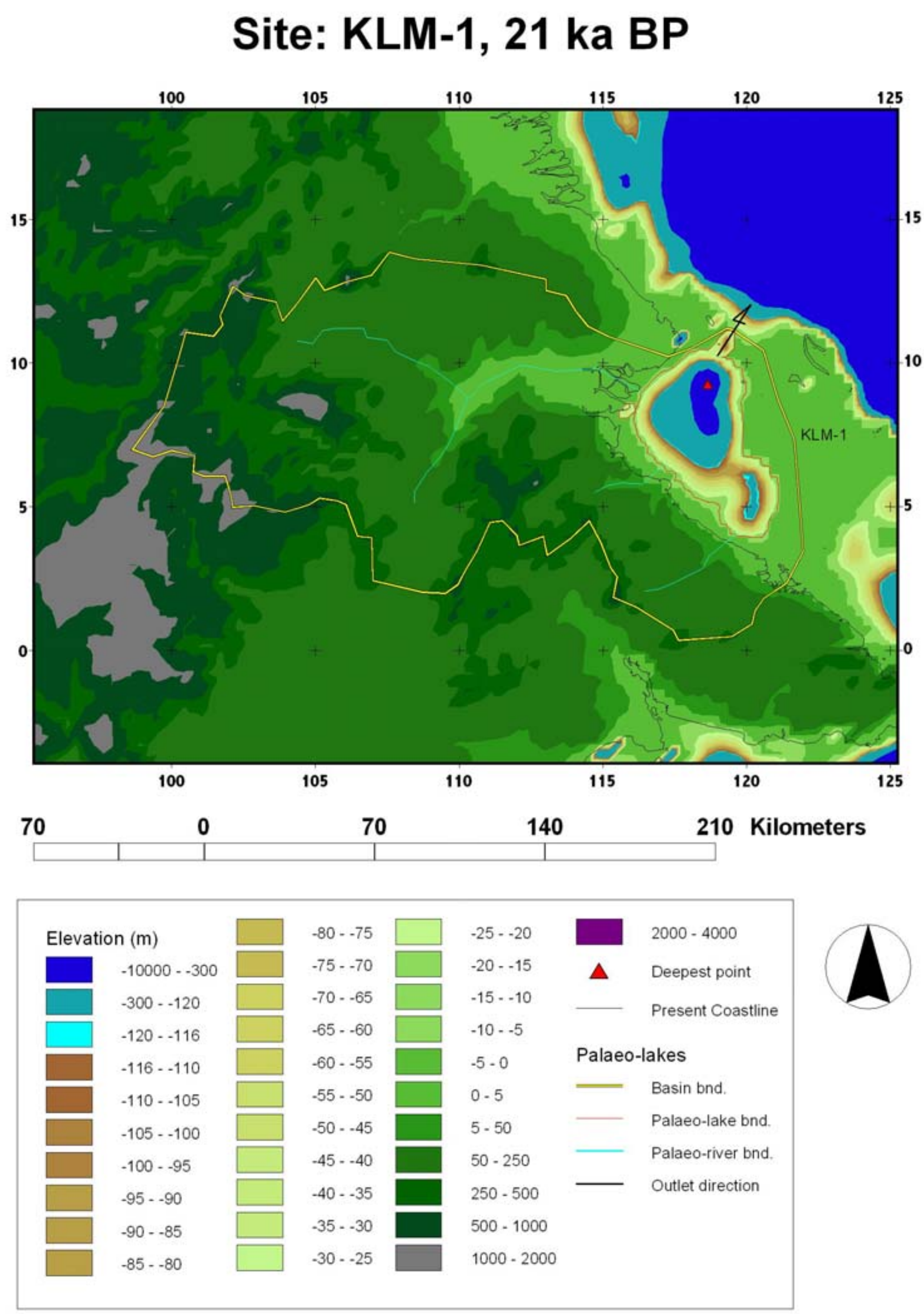

FIGURE 31. Sunda Shelf: Submerged depression KLM-1 at 21 ka BP.

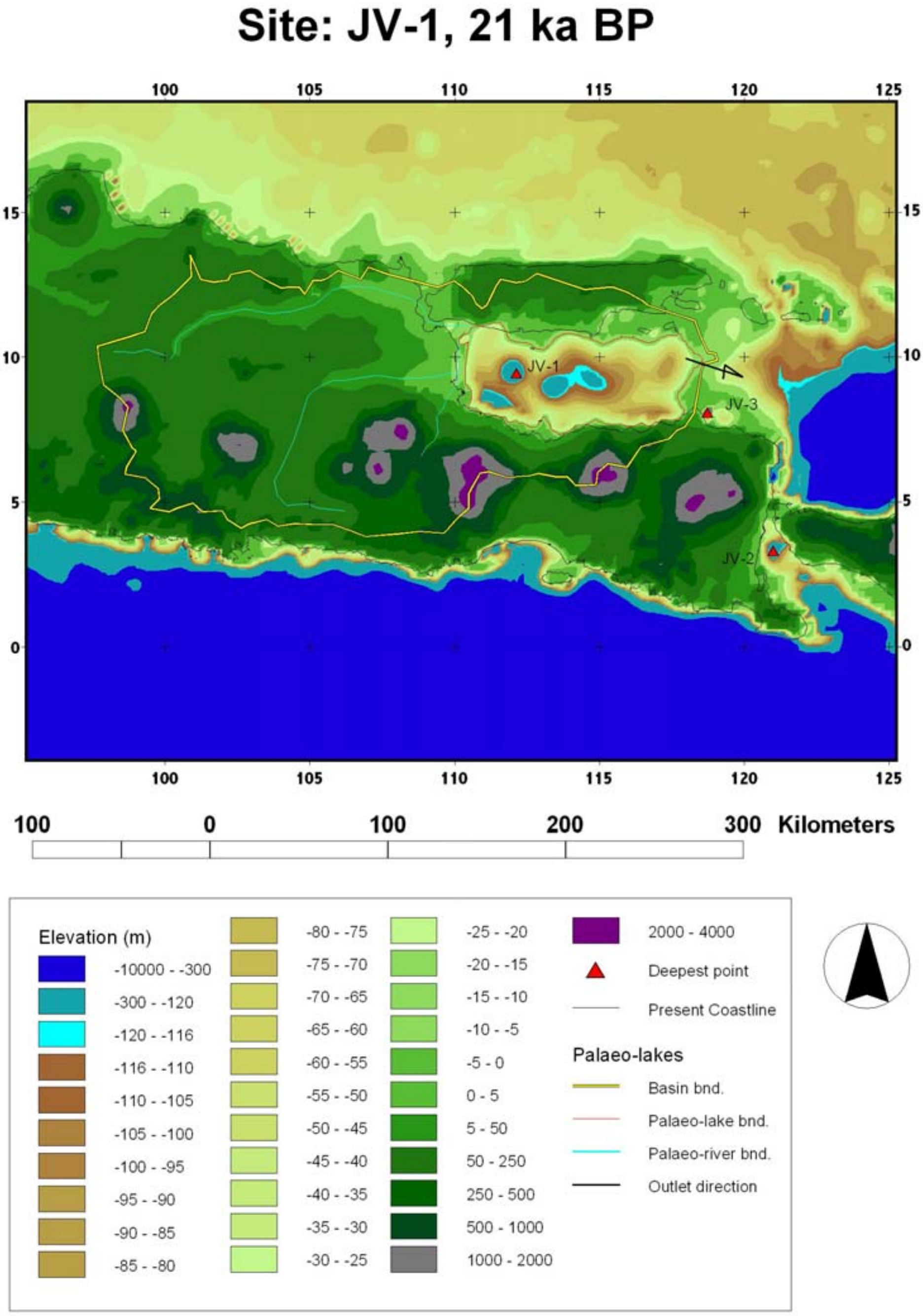

FIGURE 32. Sunda Shelf: Submerged depression JV-1 at 21 ka BP.

RESULTS

Maps showing the progress of marine transgression at 5 m intervals and their time of occurrence between 21 ka BP and 4.2 ka BP are presented in Figures 2 through 26. Figure 27 illustrates present-day topography and the location of the 31 probable submerged lakes detailed in Table 2. The seven most significant depressions that are most likely to have been paleo-lakes having sediments that contain signatures of past environments, are shown in Figures 28-32 and are detailed in Table 3. The general locations of depressions SCS-1, SG-1, SRW-1, SBH-3, SBH-4, and KLM-1 are shown in Figure 28. The location of depression JV-1 is shown in the western part of the Java Sea in Figure 32.

Table 1 provides estimates of the total exposed area on the Sunda Shelf at -116 m and the amount of "new" area exposed at each 10 meter contour. These estimates suggest that when sea levels were -50 m below present-day levels there was about 1.5 million sq km of the Sunda Shelf exposed or roughly an area equal to the area of Mongolia. At -116 m below present-day levels about 2.37 million sq km of the Sunda Shelf were exposed equaling an area nearly five times the area of Thailand.

DISCUSSION

Marine Transgression, Paleo-rivers, and Paleo-lakes

The recognition of marine transgression on the Sunda Shelf in the Holocene is not new (Molengraaff and Weber, 1919; Van Bemmelen, 1949; Umbgrove, 1949; Geyh, et al., 1979; Tjia, et al., 1983; Hesp, et al., 1998; Voris, 2000). The biogeographic importance of this LGM transgression and earlier similar events has also been cited by many authors (e.g., Heaney, 1985; Inger and Chin, 1962; Rainboth, 1991; Voris, 2000). The purpose of the maps presented here is to refine our understanding of the topography, paleo-river systems and paleo-lakes of the Sunda Shelf and thus allow biogeographers to refine their hypotheses.

At 22 ka BP, prior to the terminal stage of the LGM, which started at 21 ka BP, sea level was at -116 m below present-day MSL and depressions on the exposed shelf that existed during the LGM probably formed lakes, which were mainly fed by paleo-rivers that drained Sunda Land. There were four large river basins on the Sunda Shelf, the Siam River system, the North Sunda River system, the East Sunda River system and the Malacca Straits River system (see Voris, 2000). At this time these great river systems connected the fresh water riverine faunas of many of today's rivers that are restricted to Indo-China, the Malay Peninsula or one of the greater Sunda Islands (Voris, 2000). The great rivers on the exposed Sunda Shelf served as bridges between the greater Sunda Islands from well before 21 ka BP up to about 13 ka BP (Fig. 12).

For several thousand years both before and after 21 ka BP the exposed Sunda Shelf served as a vast land bridge between Indo-China and the Greater Sunda Islands (Fig. 2). The land connection linking the Malay Peninsula and all three of the Greater Sunda Islands was likely in place until about 11 ka BP (Fig. 16). Between about 11 ka BP and 9 ka BP (Fig. 21) these land links were drowned.

Duration is an important and sometimes neglected consideration of land bridges, land and sea barriers, and proposed physiographic features such as lakes and river systems. The amount of time that features existed contributes a critical factor in any estimation of the likelihood of particular dispersal events. For example, in the context of this study, by 12 ka BP (Fig. 14), many of the depressions were submerged (see Table 1). The process of sea level rise was at times very rapid and it has been suggested that meltwater pulse caused sea level to rise as much as 16 m within 300 years between 14.6 and 14.3 ka BP (Hanebuth, et al, 2000). By 6.07 ka BP (Fig. 25), all the depressions on Sunda Land identified in this study had been submerged as sea level rose to a level equal to today's level.

The fluctuating and rapid nature of sea level change is further illustrated by the fact that sea level continued to rise after 6.07 ka BP and reached the Holocene highstand by 4.2 ka BP

(Fig. 26), submerging low coastal plains and deltas (e.g., the Chao Phraya delta in Thailand and Mekong delta in Vietnam) and then after 4.2 ka BP, sea level fell gradually to return to present-day level about 1000 years ago (Hanebuth, et al., 2000).

Based on regional topography and bathymetry, all of the selected depressions were part of traceable paleo-river systems with upstream tributaries draining into them and with an identifiable outlet point. These features are shown on the maps (Figs 28-32). We believe that the depressions are deep enough for lake formation and for upstream sediments to have settled in them. Several of these paleo-drainages also appear on maps previously published (e.g., Hanebuth and Stattegger, 2004; Kuenen, 1950; Van Bemmelen, 1949; Voris, 2000)

Depressions SCS-1 and SG-1 (Fig. 28) had the largest drainage areas of the seven detailed in Table 3. Together their catchments covered about 22 % of Sunda Land. The drainage basin of depression SCS-1 was a part of the far downstream section of the Siam River system (today's Chao Phraya) that was immediately below the drainage basin of depression SG-1, and the river systems of East Peninsular Malaysia and part of the south west coast of Vietnam. The SCS-1 depression may have lasted as a lake for about 7,000 years before it was transgressed at 15.09 ka BP (Table 3). It was a shallow depression (15 m deep) compared to the other six depressions. This gives rise to the question of whether SCS-1 was a paleo-lake or formed later by seabed scouring. Thus, cores are now needed from depression SCS-1 to determine if it contains sediments transported by the tributaries of Siam River system and if it contained freshwater vegetation.

Depression SG-1 (Fig. 28) is located in the northern part of the present-day Gulf of Thailand. It had the largest drainage area of the seven depressions. It has a maximum depth of 65 m and is located in the mid section of Siam River system. With a depth of 65 m and very low surrounding topography, depression SG-1 could have functioned as a sedimentation area for the upstream section of the Siam River system (i.e. the Chao Phraya river flowing from the north and rivers from the Isthmus of Kra, and the southwestern coast of Cambodia). Depression SG-1 lasted for about 9,400 years before it was transgressed at 12.7 ka BP.

Depression SRW-1 (Fig. 29) off the coast of Sarawak is the third largest depression (5,700 sq km). It has a depth of 90.5 m and it lasted for about 8,500 years before it was transgressed at 13.4 ka BP. It is one of the three most significant depressions located in the South China Sea area and it is very likely to have been a submerged lake. We assert this because it has steep slopes and a distinct inlet and outlet. Sediment layers from depression SRW-1 could provide environmental records of central Sunda Land and evidence for a paleo-lake.

Depression SBH-4 (Fig. 30) off the coast of Sabah may have the longest sediment record prior to marine transgression. This depression lasted as a paleo-lake for 15,000 years before it was transgressed at 7.0 ka BP. It is likely to have been a submerged lake since it has a depth of 153 m with an outlet area that is just 4 m below the present-day sea level. However, it should be noted that the SBH-4 basin covered a rather small area and is on the outer edge of Sunda Land.

Depression SBH-3 (Fig. 30) also off the coast of Sabah probably has the second longest sediment record prior to marine transgression. It likely lasted as a paleo-lake for about 14,100 years before it was transgressed at 7.9 ka BP. It has a depth of 143 m and like depression SBH-4, its outlet level is near to today's sea level. The most interesting feature of the catchment area of SBH-3 is that it has the highest elevation range (4,109 m) of the seven identified depressions. Its highest point is 4,101 m (Mt. Kinabalu), which is also the highest point in South East Asia. Thus, the pre-marine sediment layers might contain records of paleo-vegetation change at high altitudes not found elsewhere on Sunda Land. Because the drainage basin is facing northeast it might contain environmental signatures of the influence of the winter monsoon during the LGM up to the early Holocene.

Depression KLM-1 (Fig. 31) off the east coast of Kalimantan is the deepest depression or submerged lake on the Sunda Shelf. It has a maximum depth of 435 m and it has a well defined boundary and outlet (10.7 m below present sea level). This probable paleo-lake lasted for about 13,440 years before it was transgressed at 8.6 ka BP. Based on its geometry and depth, it is unlikely that depression KLM-1 was a flooded river valley or the result of seabed scouring. It may have been formed tectonically or by a large-scale limestone solution. Its sediment layers may contain environmental records of east Kalimantan that was partially isolated from the main pathways of the winter and summer monsoons.

Depression JV-1 (Fig. 32) at the east end of the Java Sea is likely to have been a submerged lake that lasted for about 13,500 years before it was transgressed at 8.5 ka BP. It has a depth of 146 m with a very well defined shallow outlet and some nearby high terrain. This paleo-lake had a probable size of 5,900 sq km (the second largest after depression SG-1). It also has the second highest elevation range after depression SBH-3 (3887 m). With its high drainage elevation and its location southeast of Sunda Land, it may contain records of the influence of the summer monsoon originating from central Australia (Sahul Shelf) on regional palaeo-climate and vegetation.

CONCLUSIONS AND SUMMARY

The ETOPO2 2’Elevation data set provides a good general overview of the topography and bathymetry of South East Asia land mass and the Sunda Shelf. This has allowed existing submerged depressions to be detected and measured. Nevertheless, a more detailed hydrographic survey including advanced side scanning sonar is required in order to ascertain the exact locations of paleo feeder tributaries and outlets. Clearly the DEM constructed here is only as accurate as the data on which it is based. The assumptions made in our analysis have been discussed and our results are, of course, subject to the errors that may come with those assumptions.

Color maps showing the progress of marine transgression at 5 m intervals and their time of occurrence between 21 ka BP and 4.2 ka BP are presented in Figures 2 through 26. The present-day topography of Sunda Land and the locations of 32 probable submerged lakes are shown in Figure 27 and detailed in Table 2. The 32 depressions were extracted from the DEM and studied. From the 32 depressions, the seven most significant depressions that could have been paleo-lakes were further analyzed. The results indicate that these seven submerged lakes may contain environmental records of Sunda Land ranging from the LGM to the mid Holocene. Initial assessment indicates that depressions SG-1, SRW-1, SBH-3, and JV-1 may contain sediment profiles that will prove to be representative of the spatial and temporal characteristics of the paleo-environment of Sunda Land.

Availability of Maps and Copyrights

An important goal of this publication is to make these maps widely available to interested colleagues. The maps may be downloaded from the World Wide Web at **http://fmnh.org/research_collections/zoology/zoo_sites/seamaps/** or requested from the corresponding author at **hvoris@fieldmuseum.org**.

ACKNOWLEDGEMENTS

The first author would like to thank Associate Professor Michael Ian Bird for his supervision of this project. We also thank the National Institute of Education at Nanyang Technological University (Singapore), the Field Museum of Natural History (Chicago, Illinois, USA), and Chulalongkorn University (Bangkok, Thailand) for providing their support of this project. In addition, we are very grateful to the National Geophysical Data Centre (USA) for providing the ETOPO2 Global 2’Elevations data that made this work possible. In addition, we wish to thank Robert Inger, Daryl Karns, Fred Naggs, and Helen Voris for helpful comments and editorial suggestions.

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Received: 19 April 2006
Accepted: 20 June 2006