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Maps of Pleistocene sea levels in Southeast Asia: shorelines, river systems and time durations

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Abstract

Aim Glaciation and deglaciation and the accompanying lowering and rising of sea levels during the late Pleistocene are known to have greatly affected land mass configurations in Southeast Asia. The objective of this report is to provide a series of maps that estimate the areas of exposed land in the Indo-Australian region during periods of the Pleistocene when sea levels were below present day levels.

Location The maps presented here cover tropical Southeast Asia and Austral-Asia. The east–west coverage extends 8000 km from Australia to Sri Lanka. The north–south coverage extends 5000 km from Taiwan to Australia.

Methods Present-day bathymetric depth contours were used to estimate past shore lines and the locations of the major drowned river systems of the Sunda and Sahul shelves. The timing of sea level changes associated with glaciation over the past 250,000 years was taken from multiple sources that, in some cases, account for tectonic uplift and subsidence during the period in question.

Results This report provides a series of maps that estimate the areas of exposed land in the Indo-Australian region during periods of 17,000, 150,000 and 250,000 years before present. The ancient shorelines are based on present day depth contours of 10, 20, 30, 40, 50, 75, 100 and 120 m. On the maps depicting shorelines at 75, 100 and 120 m below present levels the major Pleistocene river systems of the Sunda and Sahul shelves are depicted. Estimates of the number of major sea level fluctuation events and the duration of time that sea levels were at or below the illustrated level are provided.

Main conclusions Previous reconstructions of sea-level change during the Pleistocene have emphasized the maximum lows. The perspective provided here emphasizes that sea levels were at their maximum lows for relatively short periods of time but were at or below intermediate levels (e.g. at or below 40 m below present-day levels) for more than half of each of the time periods considered.

Keywords
Sea levels, Pleistocene, Southeast Asia, maps, biogeography, palaeogeography.

INTRODUCTION

The importance of changing sea levels over geological time has long been considered essential to our understanding the distribution of both aquatic and terrestrial organisms (Molengraaff & Weber, 1919; Darlington, 1957; Wallace, 1881). Many of the zoogeographic works that consider the Indo-Chinese and Indo-Australian regions recognize the importance of the Sunda and Sahul shelves in forming land bridges and connecting river systems during the Pleistocene (e.g. Inger & Chin, 1962; Heaney, 1985, 1991; Morley & Flenley, 1987; Rainboth, 1991; Dodson *et al.*, 1995; How & Kitchener, 1997). These studies cite a variety of sources that lead back to Molengraaff & Weber (1919, 1921), Molengraaff (1921), van Bemmelen (1949), Kuenen (1950), Beaufort (1951), Wyrtki (1961), Emery *et al.* (1972), Biswas (1973), Verstappen (1975), Batchelor (1979), Potts (1983) or Gibbons & Clunie (1986). These authors' maps vary but most are limited to estimating the extent of exposed continental shelf at a particular past sea level, usually 100 m below present levels (BPL) and, in some cases, illustrating palaeo river systems on the Sunda and Sahul shelves. Their maps primarily serve to illustrate how the Sunda Shelf connects the major islands of the Indonesian archipelago (Sumatra, Java and Borneo) with Indochina and

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how the Sahul Shelf forms a broad connection between Australia and New Guinea. The documentation for many of these maps was limited and the authors did not relate the map contours to particular time periods or time durations.

Sea-level changes over the past 30 Ma have been well documented in association with tectonic changes (Hall & Holloway, 1998) and glaciation over the past 250,000 years (Ollier, 1985; Matthews, 1990; Dawson, 1992). Papers that focus on sea-level changes during the Pleistocene generally infer sea levels from either geological mapping of retreating shoreline margins e.g. the use of coral reef terraces on tropical coasts (Bloom & Yonekura, 1990) or the marine oxygen isotope record e.g. deviations from the standard of the $^{18}O/^{16}O$ ratios in foraminiferal tests from deep sea cores (Fairbanks, 1989). Typically, these papers present graphical representations of estimated sea levels plotted over time.

The objective of this report is to provide a series of maps that estimate the areas of exposed land in the Indo-Australian region during periods of the Pleistocene when sea levels were below present levels. The major river systems on the Sunda and Sahul shelves are depicted on three of the maps. In addition, estimates of the number of major sea-level fluctuation events and the duration of time that sea levels were at or below the illustrated level are provided for a range of sea levels.

MATERIALS AND METHODS

Depth contours as past shore lines

In this report present day bathymetric depth contours are used as proxies for previous shore lines at particular times in the past 250,000 years before present (yr BP). Sources used to estimate these contours included the General Bathymetric Chart of the Oceans (GEBCO) Series, US Hydrographic and Navigation maps, a National Geographic hydrographic map and WORLDBATH, based on more than seven million soundings taken world-wide. Appendix I provides details on these sources and the specific charts that were consulted.

River systems

The estimated locations of the major river systems of the Sunda and Sahul shelves were based on present day bathymetric depth contours (see Appendix I) as well as the original maps that appear in Molengraaff & Weber (1919), Molengraaff (1921), van Bemmelen (1949), Kuenen (1950), Wyrtki (1961), Emery *et al.* (1972), Ollier (1985) and Rainboth (1991). The largest of these rivers, the North Sunda River, is well defined by '... a wonderful set of long winding valleys, starting off the mouths of many important rivers and joining in the centre to form a huge north-running channel' (Kuenen, 1950). In other areas of low relief in the Pleistocene, such as the Java Sea and the Gulf of Thailand, sedimentation has been extensive (Emery & Nino, 1963; Emery *et al.*, 1972; Tjia, 1980) and the exact location of many of the rivers is largely hypothetical and certainly varied over time due to meandering (Kuenen, 1950; Rainboth, 1991; Bird, 1993). For example, echo sounding profiles south of the Sampit River off the southern coast of Borneo provide visualizations of river valleys 400, 1200 and 5400 m in width (Wyrtki, 1961). The Gulf of Carpenteria River system on the Sahul Shelf is less well documented but the fluctuating salinities of Lake Carpentaria during the Pleistocene suggest a complex estuarine embayment (Torgersen *et al.*, 1985). In addition, the shallow and narrow straits of the Aru Islands support the presence of Pleistocene rivers draining west from New Guinea to the edge of the Sahul Shelf (Umbgrove, 1949).

Table 1 The approximate amount of time during past Pleistocene intervals that sea levels were at or below present levels (BPL) is estimated and the percentage of the period is given. The sources were Fairbanks (1989), Bloom & Yonekura (1990) and Chappell & Shackleton (1986) for 17,000, 150,000 and 250,000 yr BP, respectively.

Sea level BPL (m)	Past 17,000 years			Past 150,000 years			Past 250,000 years		
	Years[1]	% of time[2]	Events[3]	Years	% of time	Events	Years	% of time	Events
120	1,000	6	1	3,000	2	1	15,000	6	2
100	4,000	24	1	7,000	5	1	29,000	12	2
75	5,500	32	1	14,000	9	1	42,000	17	2
50	7,000	41	1	40,000	27	5	99,000	40	5
40	7,500	44	1	65,000	43	7	136,000	54	6
30	8,400	49	1	93,000	62	5	167,000	67	6
20	9,200	54	1	107,000	71	4	201,000	80	6
10	11,000	65	1	134,000	89	3	227,000	91	3

[1] Approximate number of years in each time period (i.e. past 17,000, 150,000 or 250,000 years), that the sea level was at or below the level shown in column 1.
[2] Approximate percentage of years in each time period (i.e. past 17,000, 150,000 or 250,000 years) that the sea level was at or below the level shown in column 1.
[3] The estimated number of times within each time period (i.e. past 17,000, 150,000 or 250,000 years) that the sea level fell below the level shown in column 1.

Time estimates and events of sea level fluctuation

Sea-level changes associated with glaciation over the past 250,000 yr BP have been estimated by several research teams focusing on this entire period or a subset of this period (e.g. Milliman & Emery, 1968; Shackleton, 1987; Pirazzoli, 1991). The time estimates for the duration of particular past sea levels presented here for 17,000, 125,000 and 250,000 yr BP are based on relatively recent works that attempt to take into account multiple sources of data and, in some cases, account for tectonic uplift and subsidence during the period in question (e.g. Bloom & Yonekura, 1990). Estimates of amounts of time at or below a particular sea level were obtained by scrutinizing published graphs. The time estimates for the past 17,000 yr BP presented in Table 1 are based on changes in oxygen isotope deviations presented in figure 2 in Fairbanks (1989). Time estimates for the past 150,000 yr BP (Table 1) are based on figure 6.3 in Bloom & Yonekura (1990) which depicts sea levels grounded on data obtained from coral-reef terraces in Papua New Guinea. The estimates for the past 250,000 yr BP (Table 1) are based on figure 4B in Chappell & Shackleton (1986). The latter figure is based on data obtained from coral-reef terraces in Papua New Guinea and adjusted with oxygen isotope deviation data. Events here refer to the number of times the sea level dropped below a particular level. Events were estimated for each sea level and time period using the same published graphs that were used to determine time durations cited above.

Maps

Figure 1 provides palaeo sea-level reconstructions for tropical Southeast Asia and Austral-Asia based on depth contours of 10, 20, 30, 40, 50, 75, 100 and 120 m. The origin of the base maps presented here is a Geographic projection in ArcView (Environmental Systems Research Institute, Inc.) that is very similar to an Equal Area Cylindrical projection. The Geographic projection has minimal area distortion near the equator.

Availability of maps

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DISCUSSION

It is important to note that the maps, tables and graphs presented here are approximations based on data that have sizable error margins which are usually not fully understood (Bloom & Yonekura, 1990, p. 104). Using present day depth contours as proxies for past sea levels assumes that within the 250,000-year time frame and a 120-m sea-level change, tectonic uplift and subsidence, tidal scouring and the accumulation of sediments were either relatively minor factors affecting present day depth contours or that they are well understood and can be factored into estimates of sea level. The papers that provide estimates of sea levels over the past 17,000 years consider tectonic uplift or subsidence to be a minor factor (Tjia *et al.*, 1984), but estimates spanning the past 150,000–250,000 years recognize that estimated uplift or subsidence rates of as much as 1.5 m per 1000 years greatly complicate the interpretation of oxygen isotope and coral reef data (Bloom & Yonekura, 1990). Thus, the maps presented here are best understood and interpreted as a series of approximations to be refined as new data accumulate.

From the perspective of a zoogeographer each map illustrates one or more general points. At 120 m BPL (Fig. 1a, *c.* 17,000 yr BP), the bulk of the Sunda and Sahul shelves were largely exposed and formed massive lowland connections between present day islands in this region and adjacent continents. Sumatra, Java and Borneo are connected by the exposed Sunda Shelf. If one considers new contiguous shelf exposed south and east of the Isthmus of Kra, an additional 1.53 million sq km of land was annexed to Southeast Asia. This area is three-fourths the present day combined areas of Myanmar, Thailand, Laos, Cambodia, Vietnam, the Malay Peninsula and Singapore (2.07 million sq km) (Webster's, 1980). At 120 m BPL, the total newly connected area of the Sunda Shelf (including Sumatra, Java and Borneo) exceeded 3.2 million sq km, thus increasing the contiguous area of Indo-China by about 1.5 times. In addition, the islands of Hainan and Taiwan were connected to mainland China, and Sri Lanka was connected with India. Natuna Island and the other smaller islands of today's South China Sea (e.g. Anambas Islands and Tambelan Archipelago) were a part of the exposed Sunda Shelf and likely offered some significant topographic relief. Although Borneo and Palawan were not connected by a land bridge at 17,000 yr BP, the Balabac Straits were reduced to a width of only about 12 km. Sulawesi remained separated from Borneo by a narrow but very deep ocean trench. To the east the exposed Sahul Shelf broadly connected Australia and New Guinea and surrounded the Aru Islands.

At 100 m and 75 m BPL (Fig. 1b, c, *c.* 15,000 and 13,000 yr BP), the configuration of the exposed Sunda and Sahul shelves remained very similar to the 120 m BPL arrangement and no major land connections were lost. At 75 m BPL (Fig. 1c), it is likely that one or more freshwater lakes or swamps existed at various times in depressions where the Gulf of Siam is now located (Emery & Nino, 1963) and bottom cores taken off the east coast of the Malay Peninsula contained peat deposits indicating a Pleistocene peat swamp (Biswas, 1973). Furthermore, evidence of old coast lines support the presence of a brackish water lake in the Gulf of Carpentaria at about 60 m BPL (Torgersen *et al.*, 1985).

At 50 m BPL (Fig. 1d, *c.* 11,000 yr BP), extensive land bridges still connected the Malay Peninsula, Sumatra, Java and Borneo. At 50 m BPL (Fig. 1d), Natuna Island, Midai Island and the

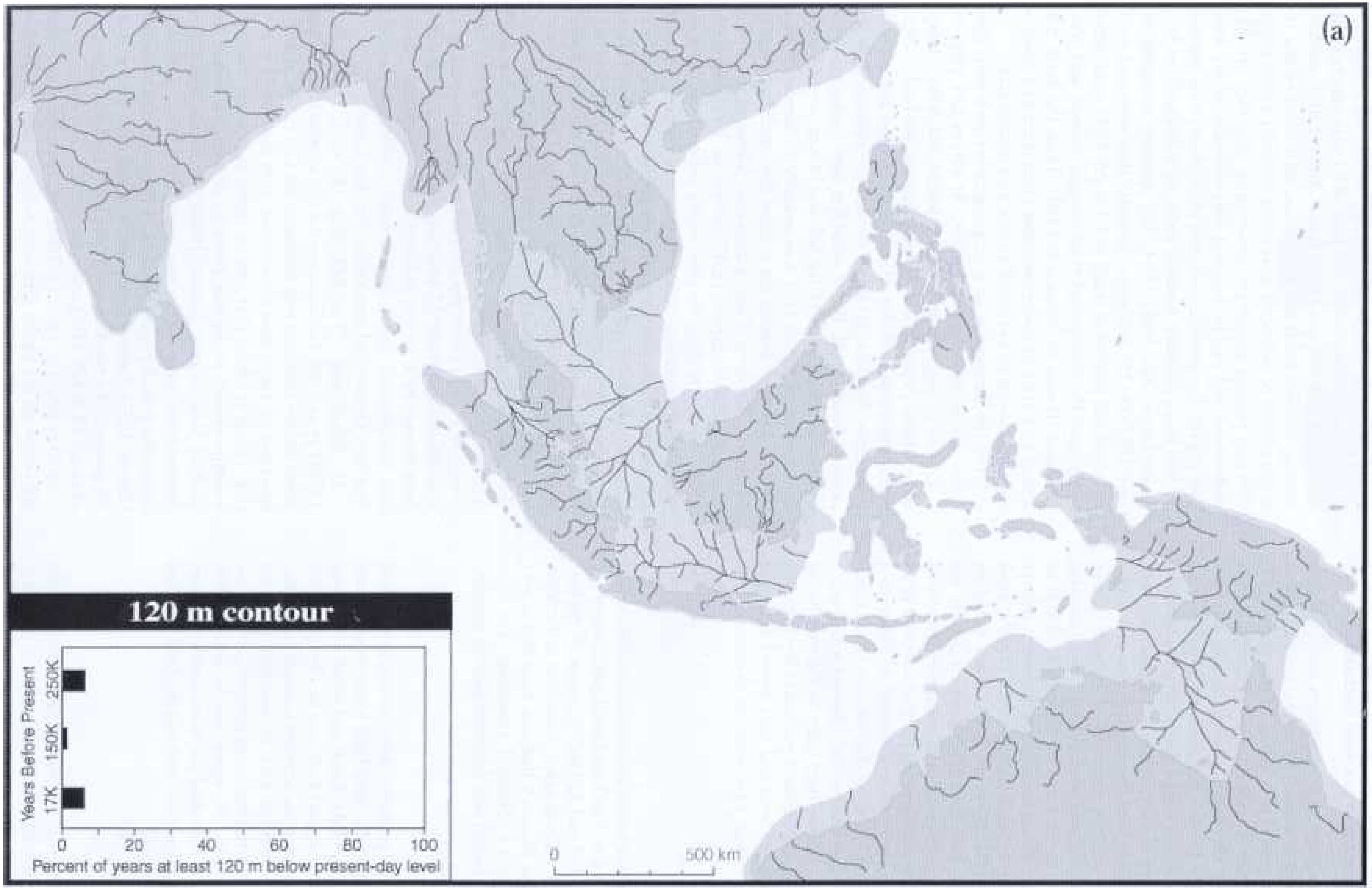
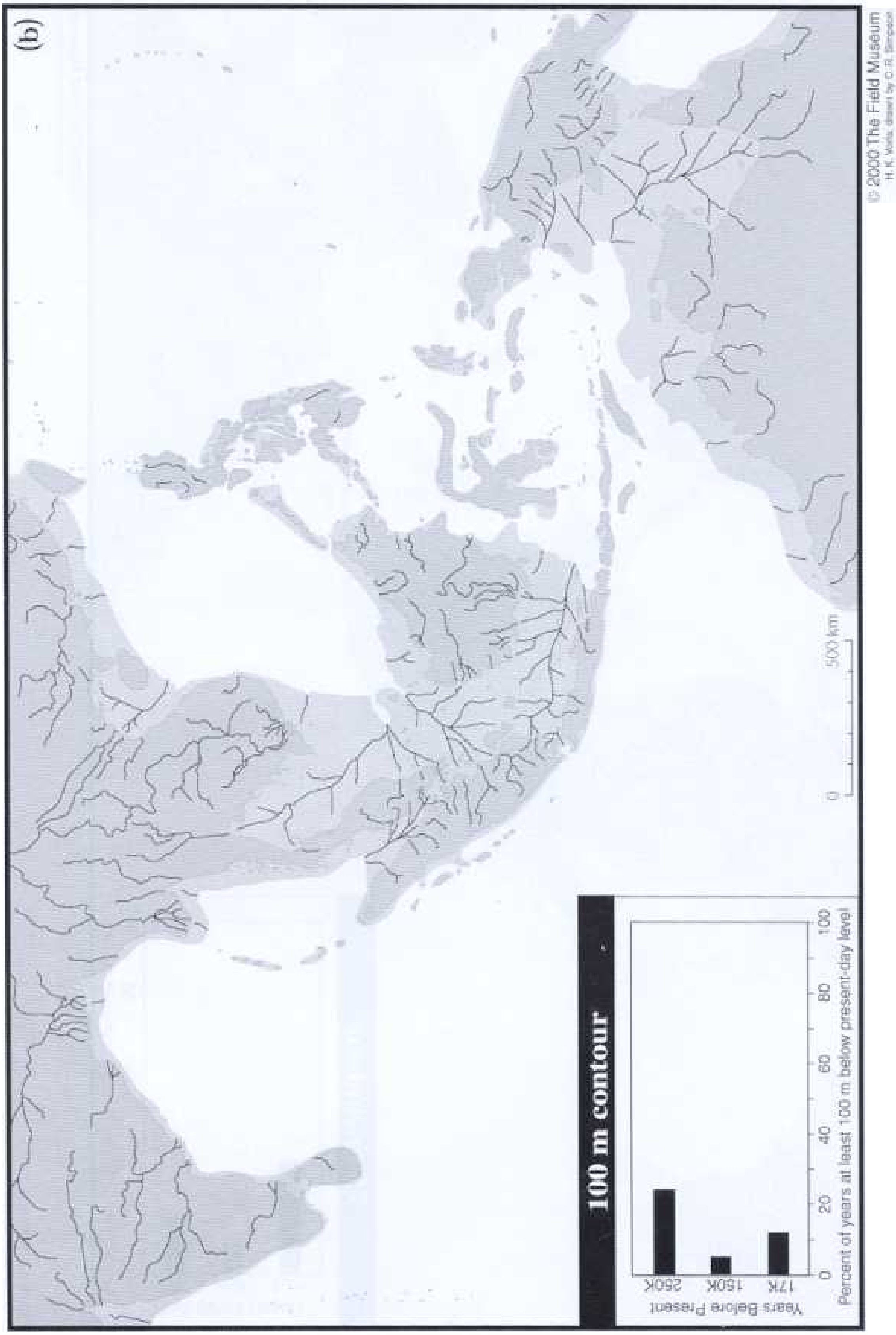


Figure 1 Maps of tropical Southeast Asia and Austral-Asia illustrating depth contours of 10, 20, 30, 40, 50, 75, 100 and 120 m below present level. The origin of the base maps is a Geographic projection in ArcView (Environmental Systems Research Institute, Inc.). Each map has a small horizontal bar graph in the lower left corner that provides estimates of the percentage of time that the sea level was at or below the level illustrated on the map during the past 17,000, 150,000 and 250,000 years. The percentage time estimates for 17,000, 150,000 and 250,000 year intervals are based on Fairbanks (1989), Bloom & Yonekura (1990) and Chappel & Shackelton (1986), respectively.



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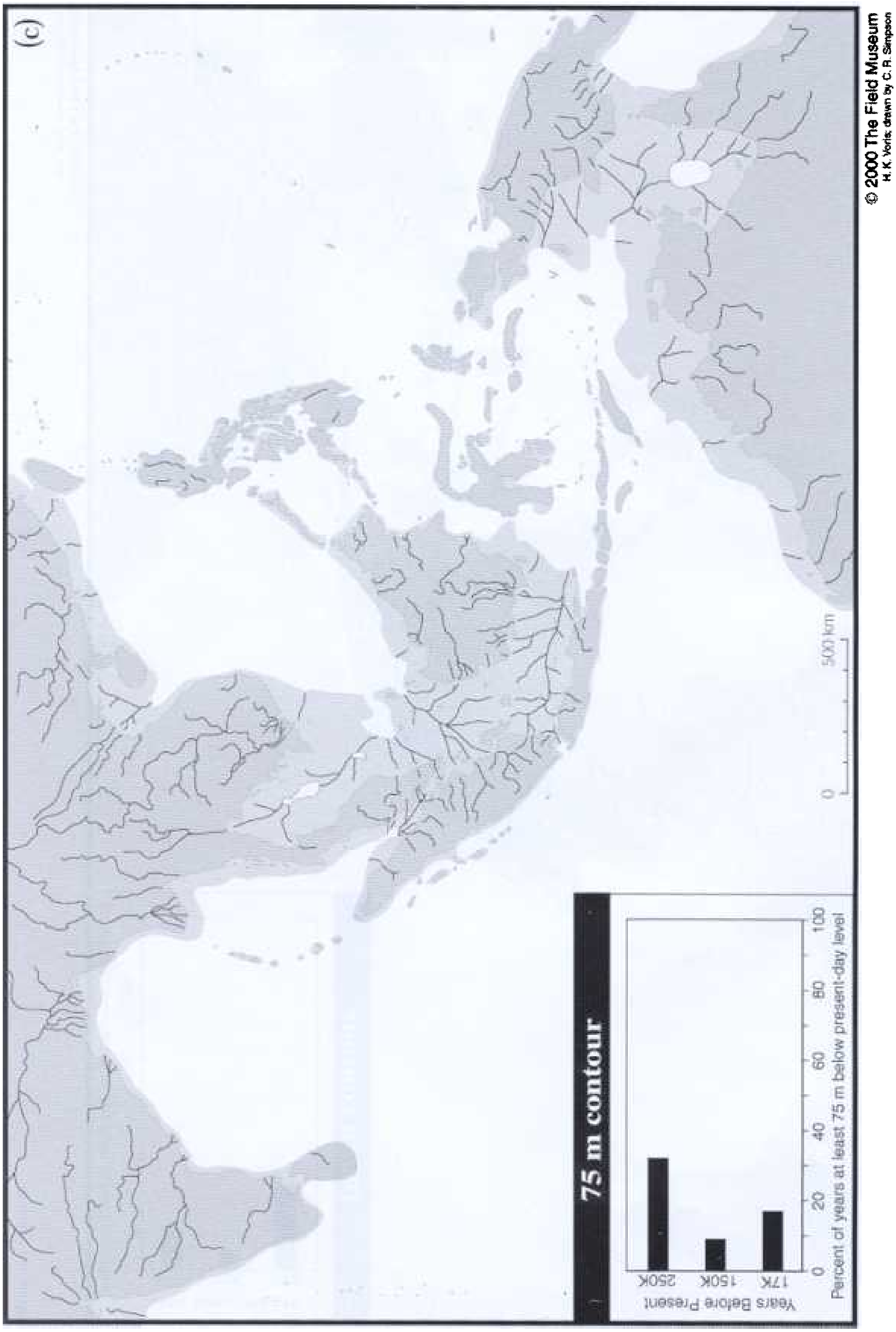

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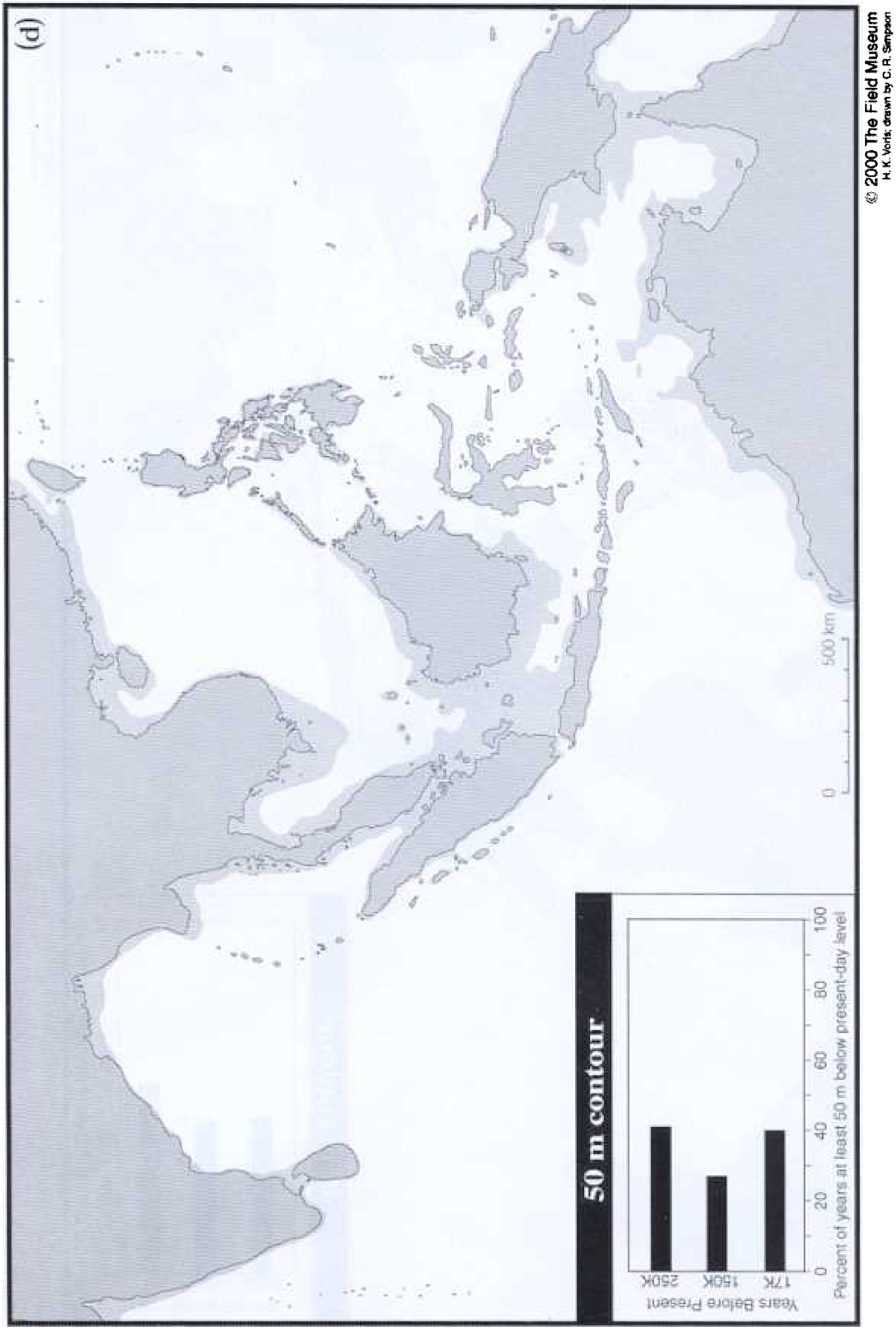

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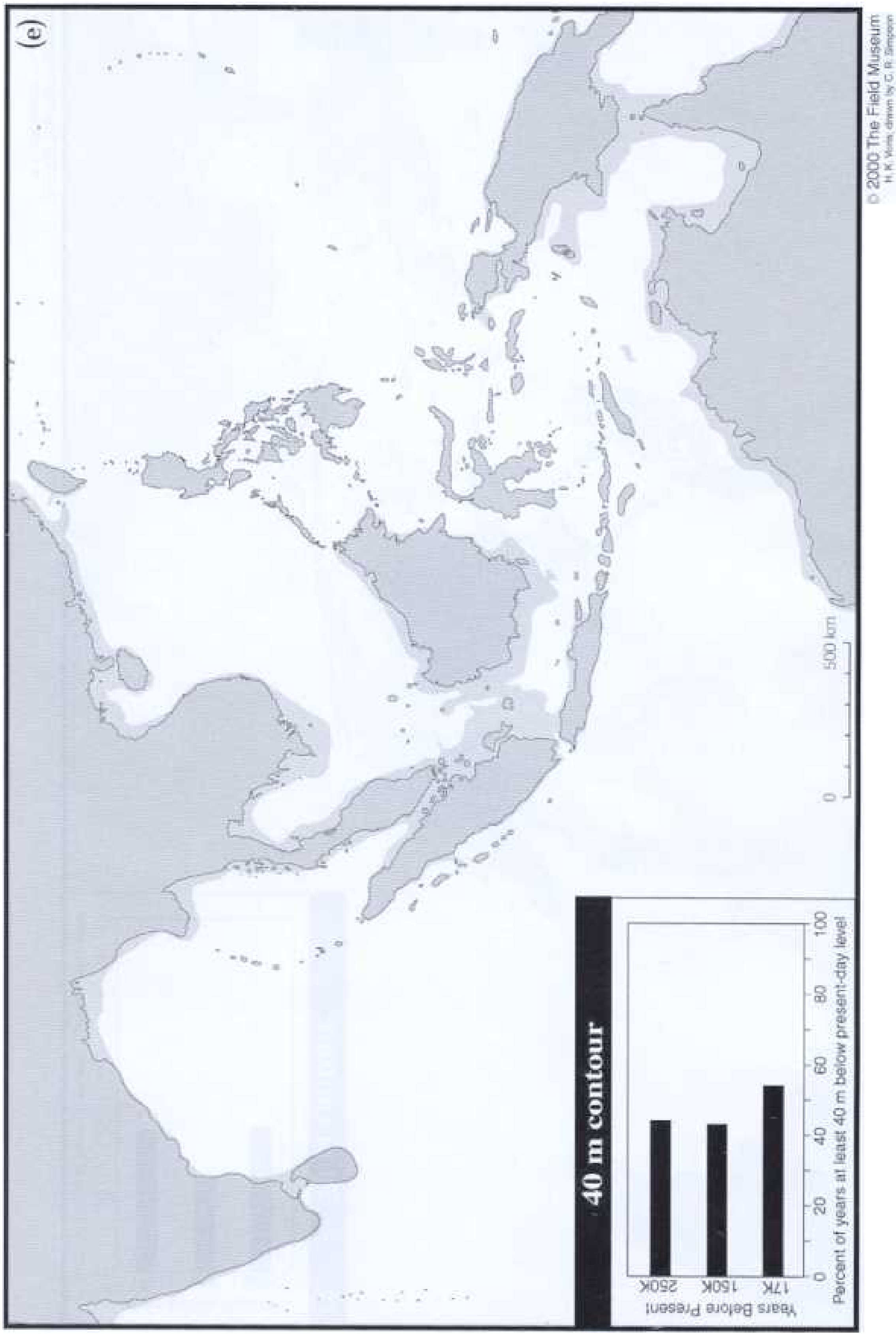

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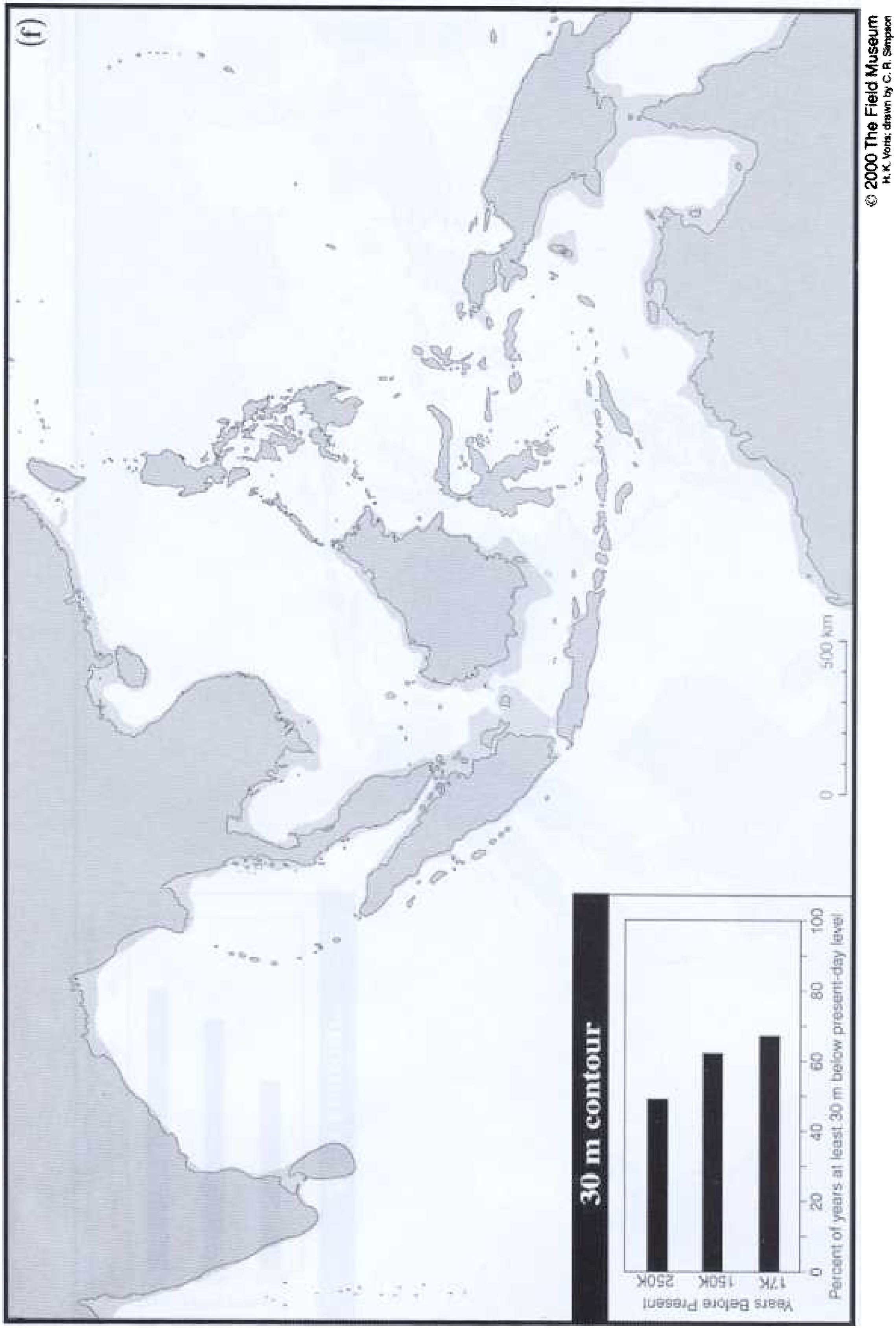

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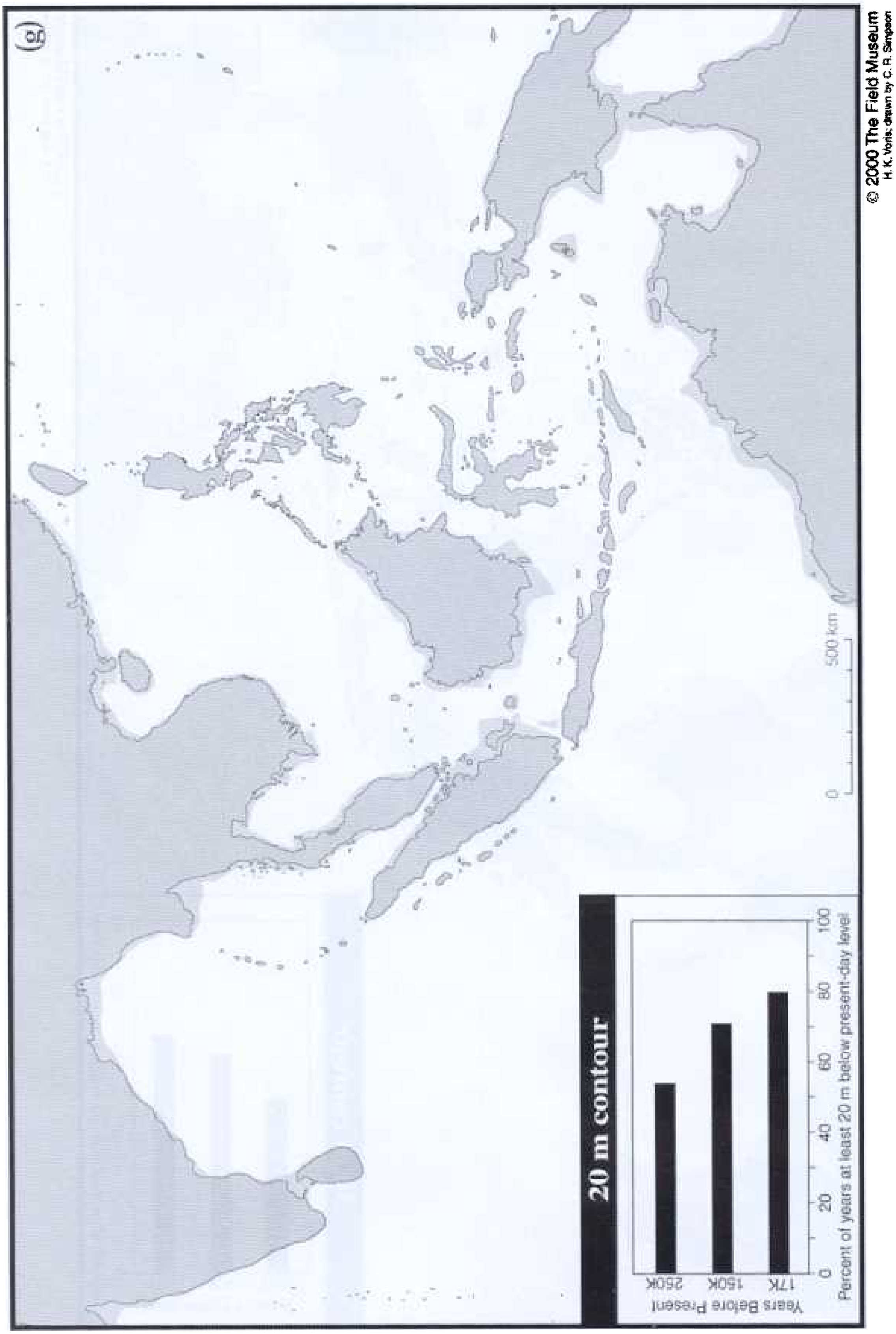

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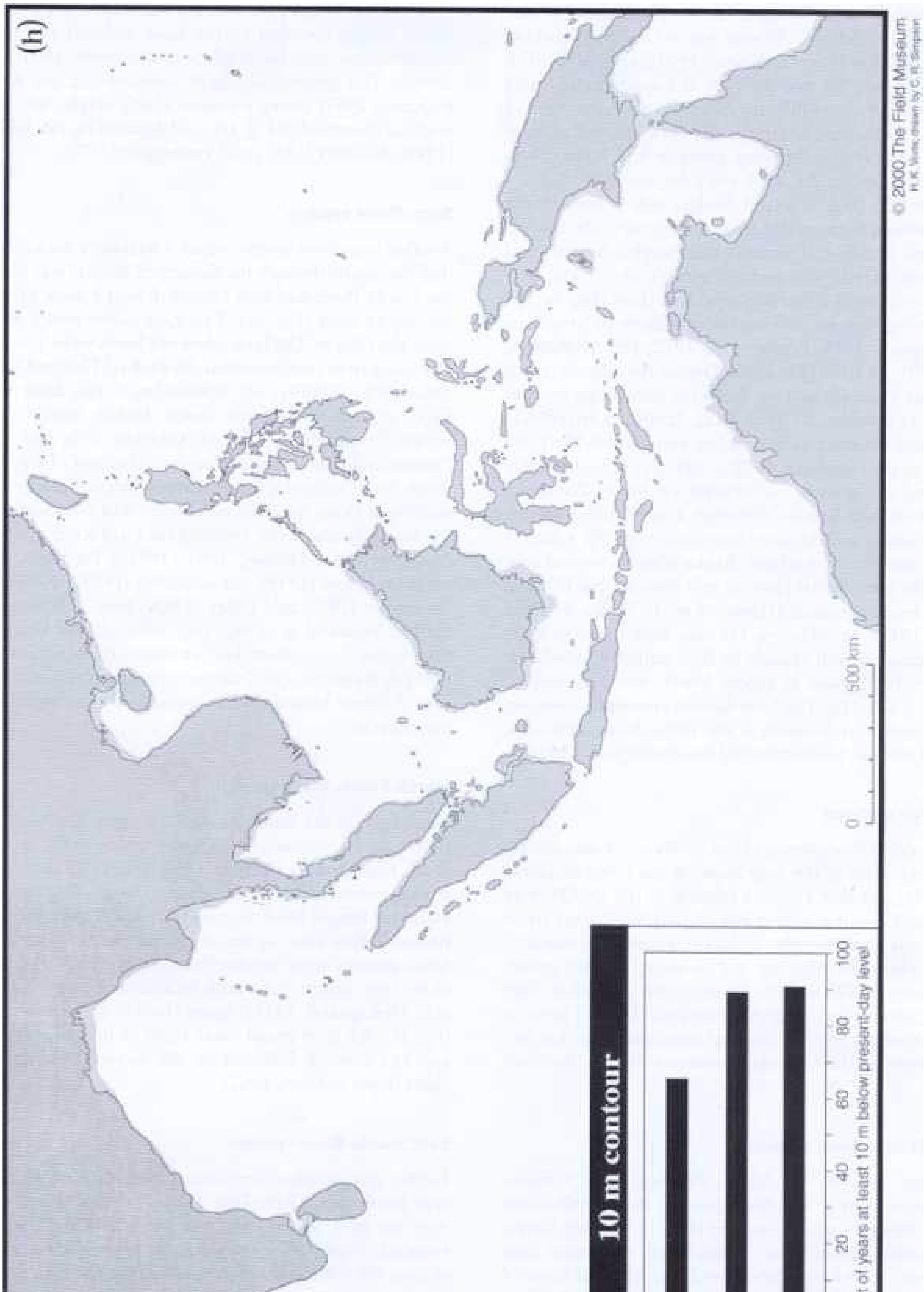

Figure 1 *continued*

Anambas Islands were isolated from the mainland (Parke *et al.*, 1971). In addition, Taiwan was no longer connected to mainland China (Nino & Emery, 1961), and the Gulf of Thailand, the Java Sea and the Gulf of Carpentaria became significant seas. At 50 m BPL, the North Sunda River that had at lower sea levels provided freshwater corridors and perhaps gallery forest corridors between Sumatra and Borneo was largely eliminated (see Fig. 1a, b and c for rivers).

At 40 m BPL (Fig. 1e), land bridges still connected the Malay Peninsula, Sumatra and Java. At 40 m BPL, the connection between Borneo and Sumatra (via Bangka, Belitung and the Karimata Islands) was perhaps as wide as 150 km, or a long narrow channel may have separated them (Fig. 1e). At 30 m BPL (Fig. 1f), the connection was likely to have been lost (Umbgrove, 1949; Emery *et al.*, 1972; Ben-Avraham & Emery, 1973). At 40 m BPL, Pulau Tioman remains connected to the Malay Peninsula and the Tambelan archipelago remains connected to Borneo. At 30 m BPL, Tambelan Island was separate from the coast of Borneo but Tioman was likely still connected to the mainland. At 20 m BPL (Fig. 1g), it is likely that no land bridges existed between the Malay Peninsula, Sumatra, Java and Borneo, although it is possible that the Malay Peninsula and Sumatra were connected by a largely freshwater estuary. At this level, Banka Island remained connected to the low alluvial plane of east Sumatra but Belitung Island had become separated (Emery *et al.*, 1972; Ben-Avraham & Emery, 1973). In addition, Hainan, Bali and Aru were not connected by land bridges to their adjacent mainlands (Umbgrove, 1949; Nino & Emery, 1961). With sea levels as little as 10 m BPL (Fig. 1h), New Guinea apparently remained largely connected to Australia at the Torres Straits (Jennings, 1972), and Melville Island remained contiguous with Australia.

Palaeo river systems

The Pleistocene river systems of the Sunda and Sahul shelves are most extensive in the map showing sea levels at 120 m BPL (Fig. 1a) and they are most relevant to the 17,000 yr BP time frame. First, it is worth noting that the largest rivers of today's mainland Southeast Asia (Ganges, Brahmaputra, Irrawaddy, Salween, Mekong and Yangtze) are not greatly extended even at 120 m BPL. However, on the Sunda Shelf there were several very large river systems. To get a sense of the size of these ancient flowages and the connections that they formed, consider the following summary of only the chief elements.

Malacca Straits River system

The flowage between the Malay Peninsula and Sumatra running north-west to the Andaman Sea had as tributaries several of today's major Sumatran rivers (including Sungai Simpang Kanan, Sungai Panai, Sungai Rokan and Sungai Siak) and no fewer than four large rivers along the west coast of Peninsular Malaysia (including Sungai Perak, Sungai Bernam, Sungai Muar and Sungai Lenek). Some authors have not included this drainage on their maps (e.g. Molengraaff & Weber, 1919; Molengraaff, 1921; Umbgrove, 1949; Emery *et al.*, 1972; Tjia, 1980; Ollier, 1985; Heaney, 1991), while others for no apparent reason have included two separate parallel rivers running north (e.g. Rainboth, 1991; 1996a; 1996b). The present day depth contours (e.g. see Keller & Richards, 1967) strongly suggest that a single river drained north as illustrated in Fig. 1(a) and depicted by van Bemmelen (1949), Beaufort (1951) and Verstappen (1975).

Siam River system

Another large river system included Sumatra's Sungai Kampar that ran north through the Singapore Straits, was joined by the Johore River and then ran north over a large expanse of the Sunda Shelf (Fig. 1a). This river likely joined branches from the Gulf of Thailand when sea levels were 120 m BPL. The main river bed located in the Gulf of Thailand has been obscured by extensive silt deposits but it must have included major contributions from Sungai Endau, Sungai Pahang, Sungai Terengganu and Sungai Kelantan of the east coast of Peninsular Malaysia and, of course, Thailand's Chao Phraya River. Some authors show Sumatra's Sungai Kampar flowing south-east along the coast of Sumatra and then north to join the North Sunda River, avoiding the Siam River system (e.g. Beaufort, 1951; Heaney, 1991; 1996b; Rainboth, 1996a) while Umbgrove (1949), van Bemmelen (1949), Wyrtki (1961), Verstappen (1975) and Ollier (1985) show it flowing to the Gulf of Thailand as in Fig. 1(a). Although the latter depiction seems to conform best to observed bathymetry (see Keller & Richards, 1967) the two opposing arrangements have very different biogeographic implications and merit further investigation.

North Sunda River system

The largest of the major Sunda Shelf rivers (the Molengraaff Rivers of Dickerson (1941)) was undoubtedly the North Sunda River flowage (Kuenen, 1950; Tjia, 1980) that ran north from the north-east coast of Sumatra (Sungai Indragiri, Sungai Hari and Sungai Musi) to join the large Kapuas River from Borneo before entering the sea north-east of Natuna Island. Most authors agree on this river system (Fig. 1a) and some of its river valleys have been located and mapped in detail (e.g. Molengraaff, 1921). At sea levels at or below 75 m BPL (Fig. 1c), this river joined many rivers of Borneo and Sumatra and had a major influence on the dispersal of fresh water fishes (Inger & Chin, 1962).

East Sunda River system

Further east, another huge river system, the East Sunda River (van Bemmelen, 1949; Tjia, 1980), ran east across what is now the Java Sea to enter the sea near Bali. This system included virtually all the modern day rivers of the north coast of Java, the south coast of Borneo and the northern portion of the east coast of Sumatra. A much smaller river with tributaries in south-east Sumatra and the Thousand Islands (Seribu Islands) area of the Java Sea flowed south through the Sunda Straits to enter the Indian Ocean (Umbgrove, 1949;

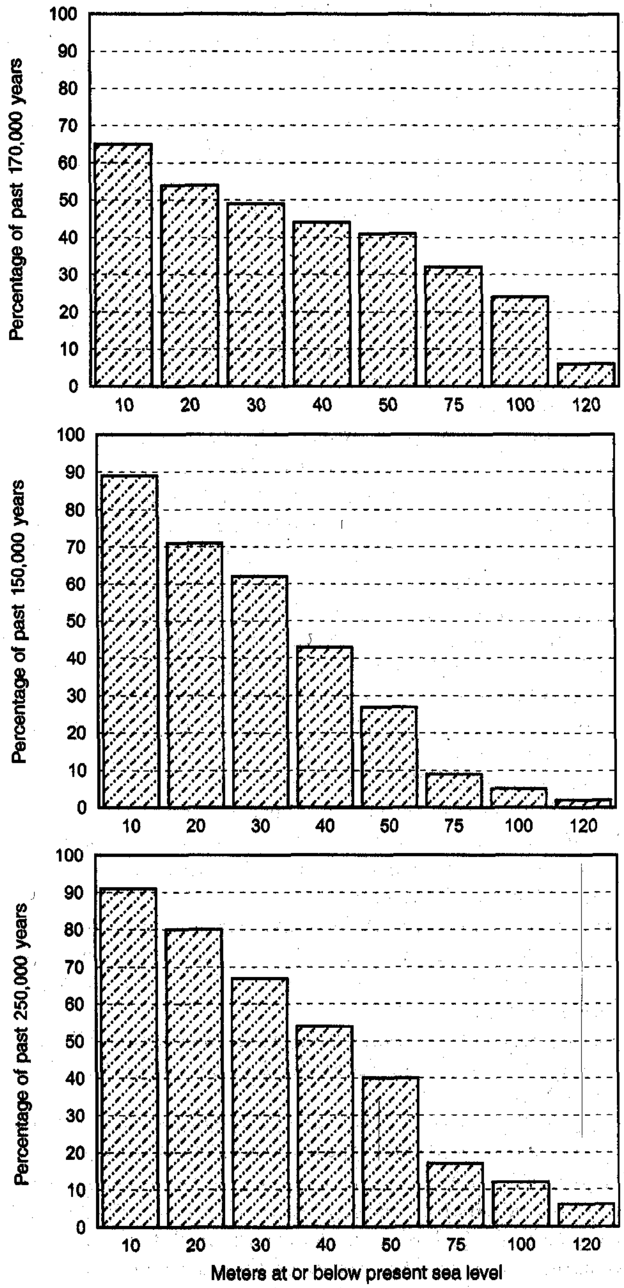

Figure 2 Bar graphs illustrating estimates of the percentage of time that the sea level was at or below 10, 20, 30, 40, 50, 75, 100 and 120 m below its present level during the past 17,000, 150,000 and 250,000 years. The time estimates for 17,000, 150,000 and 250,000 years intervals are based on Fairbanks (1989), Bloom & Yonekura (1990) and Chappel & Shackelton (1986), respectively.

van Bemmelen, 1949). Modern-day bottom contours and bottom sediments (Ben-Avraham & Emery, 1973; Tjia, 1980) strongly indicate that the East Sunda River had a single main channel (Molengraaff & Weber, 1919; Beaufort, 1951; Wyrtki, 1961; Emery *et al.*, 1972; Tjia, 1980; Heaney, 1991) as shown in Fig. 1(a). However, some authors, without providing an explanation, show two parallel rivers running east through the Java basin (e.g. Verstappen, 1975; Ollier, 1985; Rainboth, 1991; 1996a, b).

Other considerations

At the time of the last glacial maxima (17,000 yr BP, sea level 120 m BPL; Fairbanks, 1989) climates in Southeast Asia were drier and more seasonal than today's climates (Whitmore, 1981; Morley & Flenley, 1987; Heaney, 1991; Dawson, 1992; Shackleton, 1994) and thus river discharge probably varied from today's volumes. However, it is noteworthy that at the glacial maximum (e.g. 17,000 yr BP) the Siam River system was approximately equal in length to the present day Mekong River drainage. Recognition of the size and interconnectedness of these major systems has and will continue to provide a powerful tool for understanding the distributions and relationships of present day freshwater faunas (Rainboth, 1991; Dodson *et al.*, 1995; 1996b).

Each map has a small inset graph indicating the estimated amount of time during the past 17,000, 150,000 and 250,000 yr BP that the sea level was at or below the level depicted on the map. Figure 2 summarizes these data and illustrates two points: (1) sea levels were at their maximum lows for relatively short periods of time; and (2) sea levels were at or below 30 and 40 m BPL for more than half of each of the time periods considered. Previous reconstructions of sea-level changes have emphasized the maximum lows only. Figure 2 and Table 1 reinforce the notion that maximum sea-level regression is only one factor in understanding the historical biogeography of the region. The length of time at or below particular sea levels and the number of times sea levels fell below particular levels were very likely to be equally important factors in the dispersal of plants and animals.

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BIOSKETCH

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Appendix 1 The charts, maps and web sites consulted to determine the present-day depth contours used to characterize Pleistocene shore lines when sea levels were below present-day levels.

Topography from WORLDBATH [http://ingrid.ldgo.columbia.edu/SOURCES/ WORLDBATH/bath/]. This is the ETOPO5 5 × 5 minutes Navy database, giving bathymetry/topography on a 5 minute by 5 minute grid. WORLDBATH data are taken from the National Geophysical Data Center (NGDC), under the National Oceanic and Atmospheric Administration (NOAA).
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