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Distribution of Heavy Metals in Core Sediments from the Middle Part of Songkhla Lake, Southern Thailand

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Abstract: Songkhla Lake (SKL) in Southern Thailand is regarded to become shallow and excavation of the lake floor is required in the near future. So the middle part of the SKL has been selected for determining depositional rate and heavy metal concentrations and distribution of the SKL sediments if or not they are being dug will effect to the environments. In this study, composite stratigraphy of the lake sediments from 50 drill cores are constructed, sedimentation rate is then determined using stratigraphy and geochronology and heavy metal concentrations of lake sediments are evaluated. Comparison has been made for heavy metal concentrations of the SKL studied sediments with those of the standards. The result on stratigraphic correlation shows the SKL study area consists of 6 sediment layers with the overall thickness of about 6.5 m. The two oldest layers (up to 2 m thick) took place in Pleistocene whereas the overlying layers (up to 4.5 m thick) are of Holocene age. The study SKL sediments have been deposited at the average rate of ca. 0.37 mm year^{-1} and becomes the highest (up to 5 mm year^{-1}) in the youngest layer. This implies that sedimentation become accelerated by anthropogenic activity. The results of heavy metal analyses on sediments reveal that heavy metal contents quantitatively lower than those of the Hong Kong, Dutch and US standards. A few (<0.05%) heavy metals (viz., As and Cu) show the values higher than those of the standards. Therefore, the SKL sediments can be excavated without any environmental problem.

Key words: Heavy metals, lake sedimentation, lake environment, lake sediment, Songkhla lake

INTRODUCTION

The Songkhla lake (called Talay Sab Songkhla by Thai) is the largest natural lake of Thailand, located in the southern part of the country. Covering an area of 1,040 km^2, it borders the provinces of Songkhla and Phattalung. Songkhla Lake is an environmentally sensitive region of rapid population and economic growth with multiple, complex and often competing land-use options (Tokrisna *et al*., 1997). Apart from environmental issues and related problems, one of the major concerns being occurred in the Songkhla Lake is the lake shallowness (Ministry of Natural Resource and Environments, 2005). It was also reported that the lake floor becomes shallower to about 1-2 m within one decade. The rate of sedimentation is believed to be faster than it would be in the past. These environmental problems become a major concern not only for local villagers in the short term but also for the Thai government in the long term for managing the area for transportation network and industrial center. It is also important to know also that if the government decides to excavate lake sediments, it needs to ensure that the sediments being dug will not be harmful to human-beings and natural environments. Therefore, of particular concern in the management of this coastal and estuarine regional area is the impact of lake sediments being dug due to the historically shallow water. Consequently, the Department of Mineral Resources (2006) launched the 3-year research project on the whole SKL region. In the first two years, Chulalongkorn University was granted to conduct the project and therefore a focus is placed on the middle part of the SKL.

At present it is likely that the present anthropogenic inputs of heavy metals into the environment far exceed natural inputs (Jones *et al*., 2003); the former may pose health risks in areas where metals accumulate

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continuously. The impact of heavy metal pollution to coastal and estuarine areas could be substantial because of the variety of inputs to these areas. It is quite likely that potential sources include riverine inputs, local runoff, atmospheric deposition and coastal waters. Local runoff and riverine inputs can carry treated and untreated sewages (Pereira *et al*., 2007) and industrial effluents (Nabizadeh *et al*., 2005) and these inputs have been shown to carry high levels of heavy metals in many areas (Marsalek and Watt, 2003). Coastal waters and atmospheric deposition may also have a major effect on heavy metal concentrations in some estuarine situations (Jones *et al*., 2003). Recent interest in protecting lake areas has stimulated increased monitoring of pollutants in these environments and resulted in sharply decreased inputs of heavy metals to coastal lake and estuarine areas (Lokeshwari and Chandrappa, 2006). For heavy metals deposition in Songkhla Lake, Sompongchaiyakul and Sirinawin (2007) found some significantly metals (Cr and Hg), contained in surface lake sediment, in northern part of Songkhla Lake (Thale Noi) that should be from anthropogenic sources.

In addition to monitoring present additions of pollutants into coastal areas, there is an interest in determining historic additions and accumulation rates in coastal environments. Sediments have been used extensively as indicators of chronological pollution of coastal areas, including both subtidal sediments (Santschi and Honeyman, 1989; Hugget *et al*., 2001) and intertidal wetland sediments (Griffin *et al*., 1988; Sobolewski, 1996). Recent studies in coastal wetlands have successfully developed chronologies of metal additions (Ip *et al*., 2004; Zhang *et al*., 2010; Harikumar *et al*., 2009). One of the consistent findings of many of these studies is the recent continuous increase in heavy metal concentrations in sediments (MacDonald *et al*., 1991; Lee and Cundy, 2001; Mohamed, 2005; Charkhabi *et al*., 2008), especially for Cd, Cu, Pb and Zn (Shi *et al*., 2007; Zakir *et al*., 2008).

Songkhla Lake has been studied in the past few decades. Special emphasis was placed on its sedimentation rate (Chitrakarn *et al*., 1997; Dumrongrittamatt, 2005). Royal Port Department (2003) and Ministry of Natural Resource and Environments (2005) reported sedimentation rate using only bathymetry. These studies are the pioneer work but without any detailed field survey and core sampling.

So, the purpose of this study is to document rates of lake sedimentation and heavy metal concentrations and distribution based upon the results of the core sediment analyses in the middle part of SKL region.

MATERIALS AND METHODS

Site description: Songkhla Lake area (SKL), with the surface areal extent of about 1,040 sq km, is divided into four distinct parts (Fig. 1). The southern part (called Thale Sab) opens by a 380 m wide strait (called Chong Khab) to the Gulf of Thailand at the city of Songkhla. This part contains brackish water of about half the salinity of the ocean. To the north the water changes to fresh water. Further north after a bottleneck of only 6 km width is the large lake (called Thale Luang, 783 km^2) and finally at the northern end in between a mangrove swamp is a small lake (called Thale Noi, 28 km^2).

There are 6 major rivers and streams (including the Pa Pha Yom, Na Thom, Tha Chait, Pabon, Pru Por, Rattaphum and U Tapao Rivers) flowing eastward towards the lake (Fig. 1) and the lake has the outlet in the south to the Gulf. Physiographically, the coastal area to the east is characterized by the relatively flat terrain with beach ridge and groove morphology. To the west, the area is well-defined by the adjacent gently-sloping topography and with the highland and mountainous areas farther to the west.

Selection of drilling sites and core log drilling: Four sites from 4 littoral to near – shore areas close to the rivers (Fig. 1) including (a) Ao Ba Teng (area 1 at mouth of the Tha Chiat River), (b) Khlong Khop Khang (area 2), (c) Khlong Ok (area 3) and (d) Ao Bang Teng (area 4 at mouth of the Pak Prayoon River) located in the main inlet of the SKL, were selected for drilling sites (in year 2007) (Fig. 1). Rotary drilling was installed onto the man-made pontoon and rotary drilling using tri-cone bits was operated to the depth of about 4 m from the lake floor. A total of 27 drill holes were performed and 100 lake sediment samples were collected from drilled cores. Core samples were transferred and sealed in the polyethylene vinyl cylinders prior to laboratory analysis.

Lithological and stratigraphic analysis: This step was done in the laboratory to analyze lithologic features of the collected lake sediments from drilled cores. Core log analysis was performed before stratigraphic correlation and construction of stratigraphic model in each specific area. Details of the analyses can be found by Ladachart (2008) and only a summary was described bellows.

Physical properties of sediments, including lithology, colors, grain sizes and shapes, consolidation and sedimentary structures. Sediment samples collected from core samples were then divided for gain size analysis and measurement of water content. In this study, visual

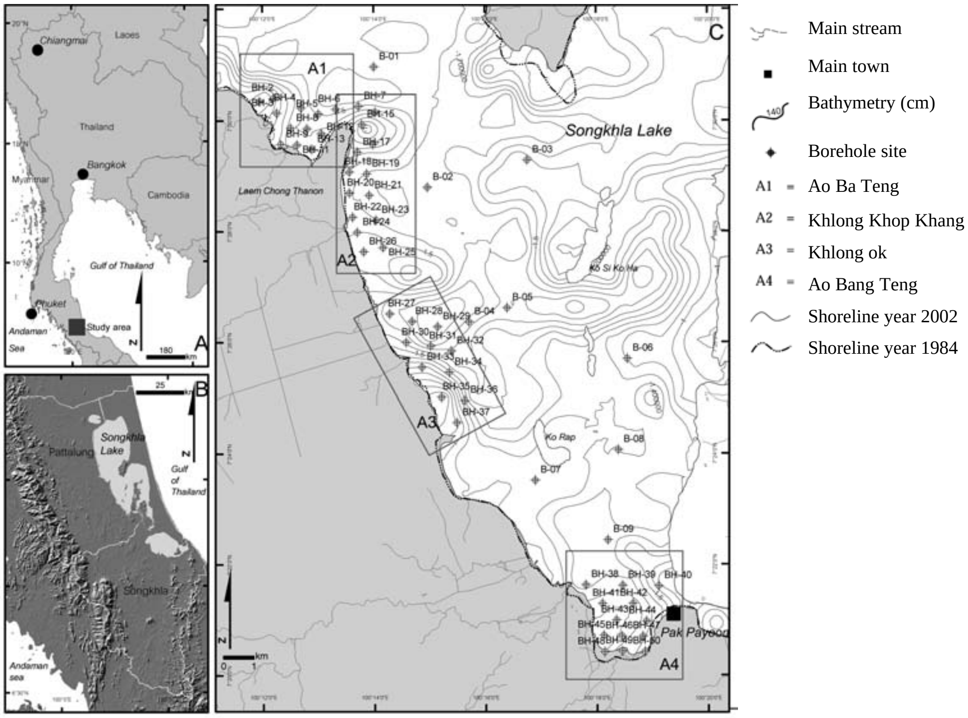

Fig. 1: Index map of Thailand (A) showing Songkhla catchment area (B) and location of borehole sites (C) in the middle part of Songkhla Lake

observation was made for lithological description for the whole column of almost all drill cores. Granulometric analysis was done on the selective samples for grain-size variation on both vertical and horizontal scales. These data were subsequently used for the interpretation of the SKL depositional environments. Stratigraphic correlation analysis was made based on visual description of cored sediments and their properties, such as grain sizes, water contents, dry density and colors. Subsequently, all the data were manipulated and analyzed using Rockware®2004 software to correlate the sedimentary layers and concentrations of heavy metals. Finally, data on stratigraphic collection was transferred to the GIS format for further investigation.

Analysis of depositional rate: This step involves calculation of sedimentation rate based on results of the stratigraphic correlation and the available TL-dating data from Ladachart (2008) and the Cs-137 dating data from Chitrakarn *et al*. (1997). The TL dating technique was done following the method proposed by Berger and Easterbrook (1993). The sedimentation rate was then presented in the map that can be manipulated in the GIS format using spatial analysis tools of ArcGIS 9.2.

Heavy metal distribution analysis: This step was done to review and demonstrate the results of geochemical data. Twenty seven elements of 100 lake sediment samples from 4 areas of concern were analyzed by inductively coupled plasma-optical emission spectroscope (ICP OES) using the extract method described by Gauthreaux *et al*. (1998). They are Al, As, Ba, Be, Ca, Co, Cr, Cu, Fe, K, La, Li, Mg, Mn, Mo, Na, Ni, Pb, Sb, Sc, Sn, Sr, Ti, V, Y, Zn and Zr. Selection was then made for further environmental analysis. The selected heavy metal data are investigated using 3D interpolation by kriging techniques (Fernandez and Bravo, 2007). Subsequently, the results were shown as distribution maps of heavy metals in each specific area. The result of heavy metal analysis was then made in comparison with that of the Hongkong standard for sediment dredging.

RESULTS AND DISCUSSION

Lithological and stratigraphic analyses: Based on the results of both lithological and granulometric analysis the lake sediments are of 2 size ranges, one being the coarse-grained or sand-dominant sediments and the other being the fine-grained or clay-dominant sediments. Frequency distribution curve and cumulative frequency curve data with the non-systematic kurtosis pattern suggest the low-energy deltaic environment for the SKL sedimentation (Ladachart, 2008). The appearance of the sand layers and lenses (10% of the total volume) suggests the river system of the so-called distributary channels of the lake delta. The clay-dominated sequences (90%) explain the depositional environment being of the low-energy system. However, in some areas, there exist 2 clusters of distribution, suggestive of more than one provenance involved in the generation of the lake sediments.

Based upon bore-hole data along with stratigraphic correlation using fence diagram (Fig. 2), we can group the SKL sediments into six layers. Using standard stratigraphic subdivision (Gibbard *et al*., 2007), sediments of the top four layers were deposited in the Holocene epoch whereas those of the two underlying layers which are more coherent than the younger overlying ones, were accumulated in the Pleistocene epoch. The overall thickness was estimated to be 6.5 m from the lake bottom. The results of stratigraphy are summarized below.

Layer 1, or the black clay unit, is the youngest layer. It consists mainly of black to very dark brown, organic-rich clay with abundant wood fragments. The thickness ranges from 0.25 to 2 m. This unit becomes thinner from the west to east in area 1 and is absent in areas 2.

Layer 2, or the brown clay unit, is the light brown to brown clay layer with the thickness varying from 0.2 to 3.5 m. A small seam of organic clay is intercalated in the upper part. It was found as a very small layer in area 2 and the thickest layer of this unit is found in area 3.

Layer 3, or the green clay unit, is mainly characterized by the greenish grey to grayish green clay with ferricrete

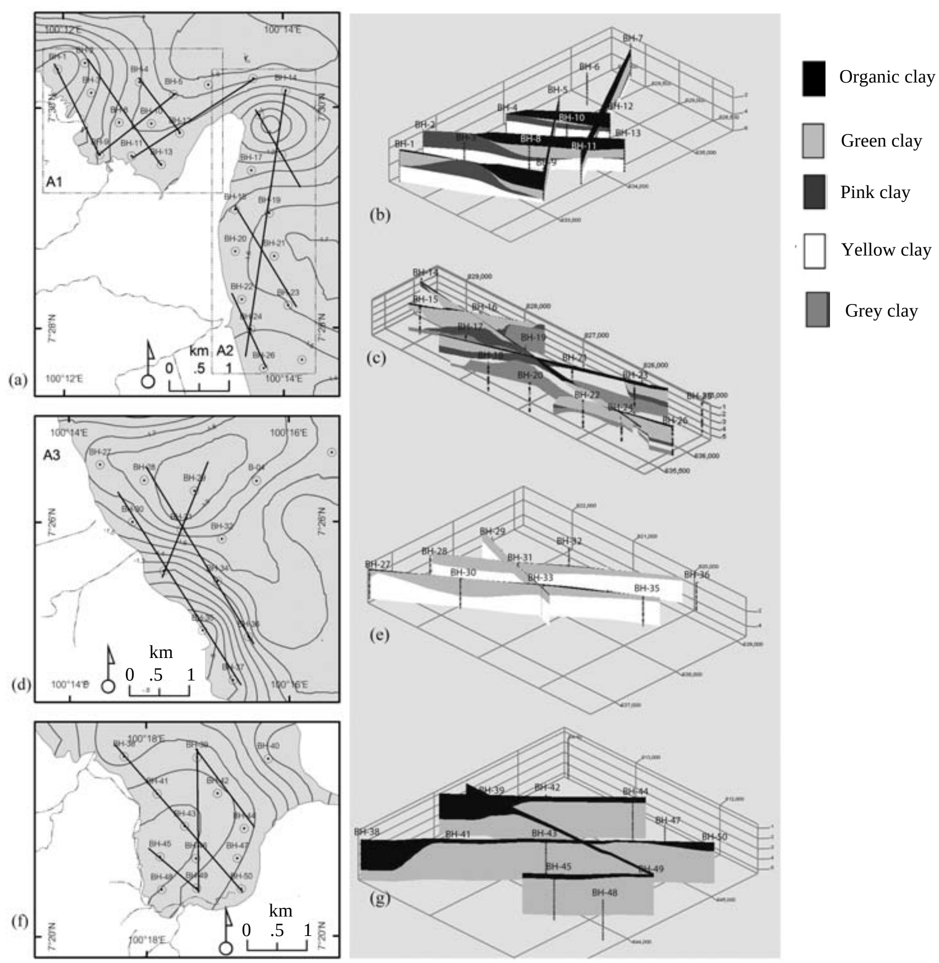

Fig. 2 (a-g): Map showing the distribution of borehole locations in Ao Ba Teng, (a): Khlong Khop Khang, (d): Khlong Ok (f): and Ao Bang Teng with fence diagram interpreting from stratigraphic correlation in (b): A1, (c): A2, (e): A3 and (g): A4 patches (1-2 cm in diameter) and sand lenses (1-2 cm). The occurrence of ferricretes is interpreted to have developed as ferruginous foot slope accumulations within topographic depressions and they display an obvious discordance with the underlying substrate lithologies (Widdowson, 2003). The thickness of this layer varies considerably from 0.5 (east) to 3 m (west). The maximum thickness of Layer 3 is in Area 4.

Layer 4, or the red clay unit, is mainly reddish to pinkish grey to brownish red clay with abundant patches of ferric-oxides and few sand lenses. Iron-stained mottles and patches are very characteristic (>30%) of this layer. The thickness of this layer ranges from 0.25 to 1 m. The original color is considered to be gray.

Layer 5, or the yellow clay unit, is defined by the light brown to yellowish brown clay and silt with scarcity of iron-stained patches. This layer displayed at least 2 cycles of graded-bedding sediments. Variation in thickness from west (thicker) to east (thinner) suggests its provenance from the west. This layer is more compacted than the overlying layers. The thickness of layer 5 varies from 1 to 1.5 m. Due to its semi-consolidation, durability nature and scarcity of ferricrete; we infer that this unit was deposited onto a gentler slope surface than its underlying layer in the late Pleistocene shallow water environment.

Layer 6, or the gray clay unit, is the oldest unit and is greenish gray to grayish green gray and looks apparently similar to the layer 2 (green clay). Layer 6 contains more abundant ferri-crust or ferricrete and become harder, more consolidated and compacted than the layer 2. The layer also contains small sand lenses in the higher percentages than layer 2. The occurrence of graded beds in some areas (i.e., areas 1 and 3) makes the other good criterion for distinguishing this layer to the younger layers. The thickness of this unit varies ranges 0.5 m (east) to 1 m (west), suggesting the direction of transportation is from the west with higher angle of slopes (Widdowson, 2003).

Rate of sediment deposition: Table 1 shows the Thermoluminescence (TL) dating result of the core sediments of the SKL study area which indicates that all the ages are within the Holocene to Late Pleistocene times.

In Area 1 of Ao Ba Teng, six sediment samples from black clay and green clay layers yielded the TL ages ranging from ca. 3,400 to 15,400 years. One sample in Area 2 of Klong Kob Khang gives the TL date of ca. 25,000 years. Ten samples from green clay to yellow clay layers in Area 3 of Klong Ob with the age range of ca. 19,600 to 33,600 years. Ten samples from red clay unit and greenish gray clay layers in Area 4 of Ao Teng yielded the TL ages varying from ca. 20,500 to 56,900 years.

Based on our TL geochronological results, depositional ages of individual layers are summarized below:

- Black clay layer (layer No. 1) was deposited from recent to 3,400 years
- Brown clay layer (layer No. 2) was deposited from recent to 3,400 years
- Gray clay layer (layer No. 3) was deposited during 3.400 to 9,000 years
- Red clay layer (layer No. 4) was deposited during 9,000 to 19,000 years

Table 1: Details of depositional ages and rates of lake sediments deposited in the study area using by TL-dating

Area	Borehole No.	Depth from lake bottom surface (cm)	Layer No.	Sediment layer	Geological time	Age of deposition (thousand year)	Av. depositional rate (mm year^{-1})	Different in age of deposition rate (mm year^{-1})
1	BH12	100	2	Brownish gray soft sandy clay	Holocene	3,400±650	0.29	0.1
	BH12	225	3	Greenish gray sandy clay		9,060±150	0.25	
	B01	156	3	Light grey soft sandy clay		5,190±400	0.30	0.1
	B01	343	3	Grey soft sandy clay		8,830±850	0.39	
2	B02	451	3	Greenish grey sandy clay	Pleistocene	13,350±2,700	0.40	0.1
	B02	580	4	Reddish grey sandy clay		20,650±5,000	0.28	
3	BH34	569	5	Yellowish white sand		19,600±1200	0.29	0.1
	BH34	608	5	Yellowish grey sand		33,650±3,300	0.18	
	BH29	578	5	Yellow clay		19,700±3,900	0.29	0.1
	BH29	618	5	Light grey sand		33,400±1,700	0.19	
	BH27	585	5	Light grey clay		22,450±2,600	0.26	0.2
	BH27	623	5	Light grey sandy clay		30,550±8,800	0.20	
	BH30	601	5	Orange sandy clay		24,100±2,600	0.25	0.2
	BH30	627	6	Greenish grey sandy clay		37,550±1,600	0.17	
4	BH38	630	6	Greenish yellow soft clay		47,800±13,500	0.13	1.5
	BH38	639	6	Yellow soft sand		48,000±12,200	0.13	
	BH40	569	5	Reddish grey sandy clay		35,900±3,200	0.16	0.1
	BH40	650	6	Greenish grey clay		56,900±15,700	0.12	

- Yellow clay layer (layer no. 5) was deposited during 19,000 to 37,500 years
- Green clay layer (layer no. 6) was deposited before 37,500 years

Rate of deposition is estimated from the integrated results of the stratigraphic logs, fence diagrams and TL dating data. Summarized data for rates of sedimentation are shown in Table 1. Two age rages of sediments are encountered, namely Holocene and Pleistocene epochs. The dated Holocene sediments are located in B-01 and BH-12 in area 1. The sedimentation rates have been estimated to be about 0.07 and 0.14 mm year^{-1} in drill hole nos. B-01 and BH-12, respectively.

The sedimentation rate can be calculated from TL-dating data correlation from 2 drill holes. As shown in the composite stratigraphy in Fig. 3, the Holocene sedimentary sequence has the overall thickness of about 35 cm (from the lake bottom surface). This thickness is confirmed by the use of sand-rich lens in the green clay layer from 310 to 332 cm depth (avg. 320 cm) and this sand layer yields the TL age of about ca. 8,830±270 years for the drill hole B01 (Fig. 1). The estimated rate of sediments is about 0.36 mm year^{-1}.

The depositional rate of sediments was supported by the other TL dates of the other sand-rich lens of the green clay layer (located NE of the area 1) at the depth of between 340 and 350 cm (av. 345 cm) from the lake bottom surface. This layer yielded the TL date of about ca. 9,060±150 years from the drill hole no. BH-12 (Fig. 1). So the rate of sedimentation is calculated to be about 0.38 mm year^{-1}.

Therefore, it is quite likely that the overall sedimentation rate during the Holocene epoch is ca. 0.36 to 0.38 mm year^{-1} (or averaging 0.37±0.01 mm year^{-1}). The difference in ages of about 200 years and in thickness from the lake bottom of about 25 cm can give rise to the difference in sedimentation rate of about 0.125 mm per year during Holocene age. We interpret that the sediment influx during early Holocene is relatively higher than the overall average sedimentation rate.

From Table 1, it can be noted that the depositional rate of Late Pleistocene sediments ranges from 0.8 to 1.5 mm year^{-1} and that the mean rate is about 0.33 mm year^{-1}. This means that the rate of sedimentation is inferred herein to have been almost similar since Pleistocene.

Rate of very recent to present-day sedimentation rate in the middle part of the Songkhla Lake body becomes higher as supported by Chitrakarn *et al*. (1997) and Dumrongrittamatt (2005) using CS-dating method. Both results gave almost the same average sedimentation rate of about 5.0 mm year^{-1}. In the same year, Ministry of Natural Resource and Environments (2005) reported the present-day rate of sedimentation to be approximately 3.33 mm year^{-1} using the echo-sounding bathymetry data of the year 1975 and 2002 provided by Royal Port Department (2003). The maximum shallowness was about 15 mm year^{-1} at the northernmost part of the SKL study

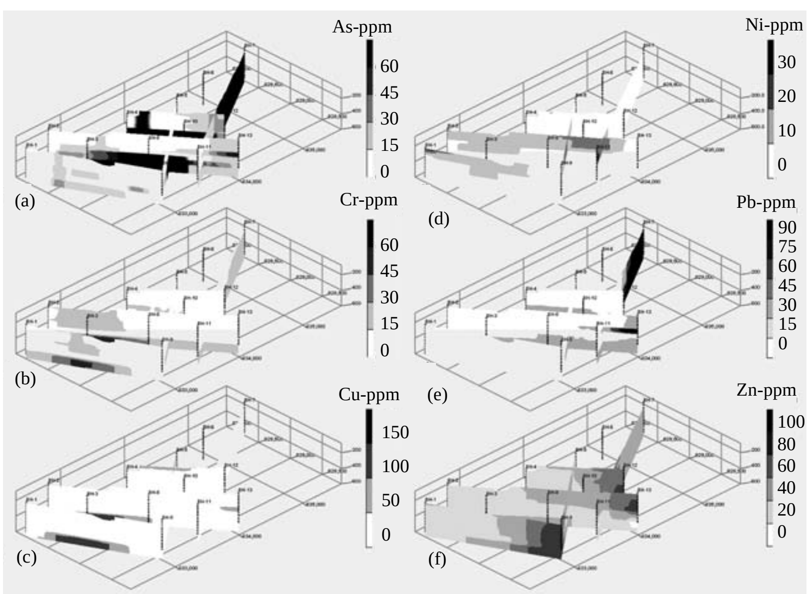

Fig. 3 (a-f): Relationship between composite stratigraphy and TL age and rate of sediment deposition of core sediments, (a): As, (b): Cr, (c): Cu, (d): Ni, (e): Pb and (f): Zn, the SKL study area, Southern Thailand area whereas the southern part of the SKL study area the rate a little is 15.8 mm $year^{-1}$.

Rate of soil erosion and sedimentation: The result reveals that the present-day rate of overall sedimentation for the SKL study area is about 0.37±0.01 mm per year. It is likely that the rate of sedimentation is slightly lower than that of the erosion. It can be interpret that the less in the rate is probably due to the fact that much on land sediment has been transported, after continuous and extensive erosion, on the way along rivers and some are deposited before reaching bay mouths.

Zhang *et al.* (1998) demonstrated in his world map of soil erosion, that the region of Thailand has the average range of erosional rate between 1 and 2 mm $year^{-1}$. Our rate of 1.6 mm $year^{-1}$ falls within the range of his evaluation. For the Southeast Asian region, Wen (1993) argued that the present – day erosional rate is about 3.33 mm $year^{-1}$ which is much higher than our erosional rate.

The higher rate of deposition at the beginning of the Holocene is probably due to either changes of shorelines to become more emergent or the presence of the high-relief terrain, or the changing of world climate, or very low sea-water level at that time. Evidence of stratigraphic correlation and logging reveal that much of the lake sediment derived from its landward provenance from the west. The rate of sedimentation becomes lower in the middle and late Holocene due to slightly higher sea level. However, at present to about 50 years ago, lake shorelines have been governed by more marine action than river action, as reported by Ladachart (2008). Therefore, one may suggest that the erosional shorelines are more prominent than deposition shorelines (Fig. 8). This perhaps has caused the rate of deposition become higher and given rise to the shallowness of lake floors.

However, it is also interpreted from our result that the higher rate of lake deposition at present (within the 50-year period) has been attributed mainly to the higher acceleration by human activities.

Heavy metal distribution: The selected geochemical data are displayed in Table 2 and only some selected elements with high concentrations, including As, Cr, Cu, Ni, Pb and Zn, were used for analyses.

Arsenic (As) in the analyzed core sediments varies in concentration from 3 to 63 ppm and its average value is almost 13 ppm in Area 1. In Area 2 As ranges from 3 to 12 ppm with the average concentration of 6 ppm. In Area 3 it ranges from 3 to 57 ppm with the average concentration of 11 ppm that is the maximum concentration in whole four areas. In Area 4 it ranges from 3 to 16 ppm with the average concentration of 9 ppm. The arsenic shows high concentration in organic (or black) clay layer with the average value of about 17 ppm and the maximum concentration of about 63 ppm at the depth of 1.80 to 2.00 m in area 1.

Table 2: Some statistics of heavy metal concentrations (ppm) of core sediments of the study Songkhla Lake

Area	Statistics	As	Cr	Cu	Ni	Pb	Zn
1	Mean	12.81	14.00	42.71	6.62	32.50	94.54
	Max.	63.00	61.00	365.00	33.00	73.00	1920.00
	Min.	3.00	5.00	1.80	2.00	7.00	2.30
	SD	15.62	10.48	83.47	6.97	19.07	373.42
2	Mean	6.22	13.22	16.51	4.22	22.00	7.86
	Max.	12.00	33.00	68.30	15.00	67.00	19.10
	Min.	3.00	5.00	2.10	1.00	7.00	1.20
	SD	3.49	8.60	22.80	5.85	17.92	7.22
3	Mean	10.64	18.15	51.87	6.68	31.31	19.60
	Max.	57.00	62.00	242.00	30.00	241.00	72.20
	Min.	3.00	3.00	1.10	2.00	4.00	0.60
	SD	13.68	17.04	69.60	8.18	43.90	20.93
4	Mean	7.67	15.42	15.18	11.79	28.08	18.59
	Max.	16.00	27.00	70.40	35.00	94.00	44.20
	Min.	3.00	8.00	2.40	1.00	2.00	1.90
	SD	5.02	5.12	21.92	9.78	18.08	14.40

Max.: Maximum, Min.: Minimum, SD: Standard deviation. Study littoral zone 1: Ao Ba Teng, 2: Klong Khop Khang, 3: Klong Ob, and 4: Ao Teng (Fig. 1)

Chromium (Cr) varies in concentration from 5 to 61 ppm and has the average value of 14 ppm in Area 1. In Area 2, Cr ranges from 5 to 33 ppm and has the average concentration of 13 ppm. In Area 3, it varies from 3 to 62 ppm and has the average concentration of 18 ppm. In Area 4, Cr ranges from 8 to 27 ppm and has the average concentration of 15 ppm. The chromium has high concentrations in yellow clay layer with the maximum concentration of about 62 ppm in red clay layer at the 3.50-3.65 m depth in area 3.

Copper (Cu) varies in concentration from 2 to 365 ppm and has the average value of 43 ppm in Area 1. In Area 2 Cu ranges from 2 to 68 ppm and has the average concentration of 17 ppm. In Area 3 it varies from 1 to 242 ppm and has the average concentration of 52 ppm. In Area 4 Cu ranges from 2 to 70 ppm and has the average concentration of 15 ppm. The copper has a high concentration in the red clay layer with the maximum concentration of about 365 ppm at depth of 2.35 to 2.50 m in area 1.

Lead (Pb) varies in concentration from 7 to 73 ppm and has the average value of 32 ppm in Area 1. In Area 2 Pb ranges from 7 to 67 ppm and its average concentration is 32 ppm. In Area 3 it varies from 4 to 241 ppm and has the average concentration of 31 ppm. Pb in Area 4 ranges from 2 to 94 ppm and its average concentration of 28 ppm. The lead shows a high concentration in the green clay layer with the maximum concentration of about 241 ppm from the 2.50 to 2.60 m-depth in area 3.

Zinc (Zn) varies in concentration from 2 to 1,920 ppm and has the average value of 94 ppm in Area 1. It is

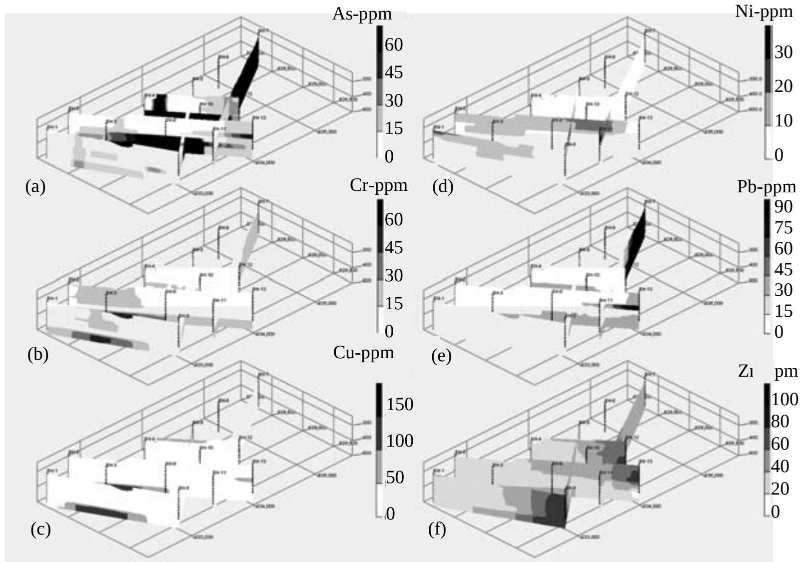

Fig. 4 (a-f): Fence diagram showing heavy metal distribution in Ao Ba Teng (Area 1) of the SKL study area. (a): As, (b): Cr, (c): Cu, (d): Ni, (e): Pb and (f): Zn concentrations (in ppm)

interesting that only one core sample shows unusually high Zn continent, so we believe that it may not be representative. In Area, 2 Zn ranges from 1 to 19 ppm with the average concentration of 8 ppm. In Area 3, it ranges from 1 to 72 ppm with the average concentration of almost 20 ppm. Zn in Area 4 ranges from 2 to 44 ppm and has the average concentration of 19 ppm. The zinc has a high concentration in green clay layer with the average value of about 86 ppm and maximum concentration is about 1,920 ppm in 3.00 to 3.15 m - depth in Area 1.

The variation in heavy metal concentrations through depth of drill holes and stratigraphy are shown in Fig. 4 to 7 for Areas 1 and 2. It is interesting to note that the high arsenic content (3,400 ppm) is in layer 3 where the sediment is about 9,000 year old. The other elements, such as Cu and Zn, also show high concentrations in layers 3 and 2, respectively. It is important to note herein that the sediments with high element concentrations are not derived from the recent Holocene deposition (i.e., within 50 years ago). However, several elements are derived from the depth of about 0.2 to 4.0 m which corresponds to the lower sequence of the Holocene stratigraphy.

It can be recognized that arsenic concentration is high in Area 1, copper and zinc concentrations are high in Area 2 and arsenic, copper, nickel and zinc concentrations are higher in Area 4. As shown in the Fig. 4 there is an increase in some heavy metal concentrations toward the lake floor surface, particularly arsenic and Pb.

As displayed in Table 3, there are two kinds of sample analysis for heavy metal concentrations, one is mainly clay size sediments and the other is sand-size sediment. It is quite clear that apart from the clay with iron oxides, arsenic seems to show no dissimilar contents in clayey and sandy materials. However, copper and zinc elements show remarkable contrast in concentration. Clayey materials are likely to contain Cu and Zn contents less than sandy material. Pb element displays the different scenario, only for the clay with iron oxides contains very high content whereas the sand contains less Cu content than the clay. This may indicate modes of transportation. We consider that Cu and Zn are transported in the form of terrigenous clastic whereas As and Pb are likely to be transported in solution and perhaps precipitate when the environments become much more reduced.

In the case of heavy-metal concentrations in lake sediments, it is likely that not all sediment layers from drill holes contain values within the range of the target values of the Hongkong standard. It appears that only some sediment layers from drill holes nearby lake shores contain elemental concentrations higher than target values. As illustrated in Fig. 8, arsenic contents become higher when lake sediments are close to the near shore side and father away from lake shore the arsenic becomes lower in concentrations. Similar situations occur as well for copper and zinc (Fig. 8). It is interesting that only few sediment samples containing copper contents higher than

Table 3: Heavy metal variation (ppm) of sedimentary layers of the SKL lake sediments in the study area

Sediment layer	As	Cr	Cu	Ni	Pb	Zn
1 and 2 organic and brown clay						
Mean	17.08	12.13	25.29	13.20	34.69	21.83
Max.	63.00	23.00	79.10	35.00	94.00	44.20
Min.	6.00	6.00	3.30	2.00	15.00	5.90
SD	16.40	4.79	28.63	11.67	19.78	13.35
3 green clay						
Mean	7.59	15.94	37.29	5.70	21.85	13.81
Max.	12.00	62.00	242.00	30.00	67.00	72.20
Min.	3.00	3.00	1.10	1.00	4.00	0.60
SD	2.74	15.51	60.43	7.82	12.26	18.25
4 red clay						
Mean	12.65	14.56	24.46	6.52	38.41	86.53
Max.	56.00	27.00	242.00	21.00	241.00	1920.00
Min.	4.00	5.00	2.00	1.00	7.00	1.50
SD	12.11	5.24	54.24	4.96	43.36	366.72
5 yellow clay						
Mean	10.45	19.00	43.81	7.42	27.08	21.75
Max.	24.00	61.00	365.00	33.00	67.00	146.00
Min.	3.00	7.00	2.40	2.00	14.00	2.80
SD	6.39	15.54	103.83	9.20	14.64	40.79
6 green clay						
Mean	13.60	21.57	32.14	4.71	27.43	20.03
Max.	28.00	55.00	90.40	9.00	66.00	40.20
Min.	5.00	11.00	4.80	2.00	13.00	4.60
SD	9.18	15.04	38.46	2.29	17.43	15.26

Max.: Maximum, Min.: Minimum, and SD: standard deviation

Table 4: Comparison between metal concentrations (mg kg^{-1}) of Songkhla Lake sediments and those of the target and intervention values for the dredged sediments of the Hong Kong, Dutch and US standards

Sediments	As	Cr	Cu	Pb	Ni	Zn
Songkhla lake core sediments						
Maximum value	63	62	365	241	35	1,920
Average value	13	18	51	31	11	95
Hong Kong standard						
Target (A) value	8	80	65	75	-	200
Intervention (C) value	42	160	110	110	-	270
Dutch standard	55	380	190	530	210	720
SQE						
TEC	9.8	43	32	36	23	120
MEC	21.4	76.5	91	83	36	290
PEC	33	110	150	130	49	460

Sources: Hong Kong Standard from Lau *et al.* (1993), Dutch Standard from Cairney and Hobson (1996) American Standard (SQE) from Contaminated Sediment Standing Team (2003)

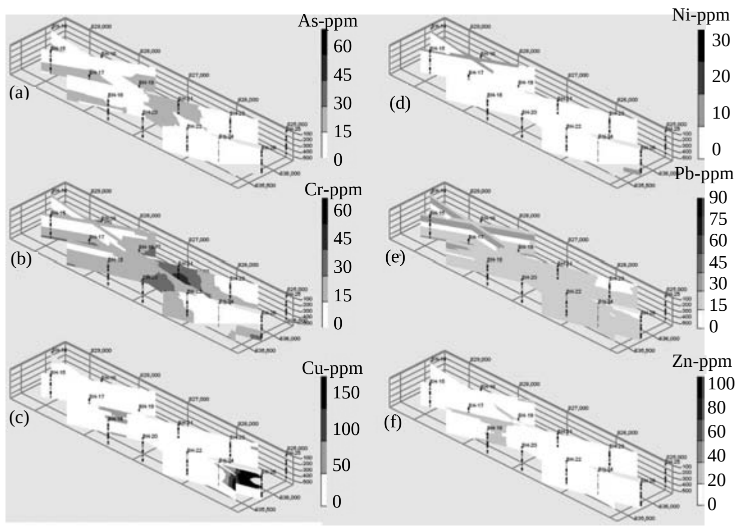

Fig. 5 (a-f): Fence diagram showing heavy metal distribution in Khlong Khop Khang (Area 2) of the SKL study area. (a): As, (b): Cr, (c): Cu, (d): Ni, (e): Pb and (f): Zn concentrations (in ppm)

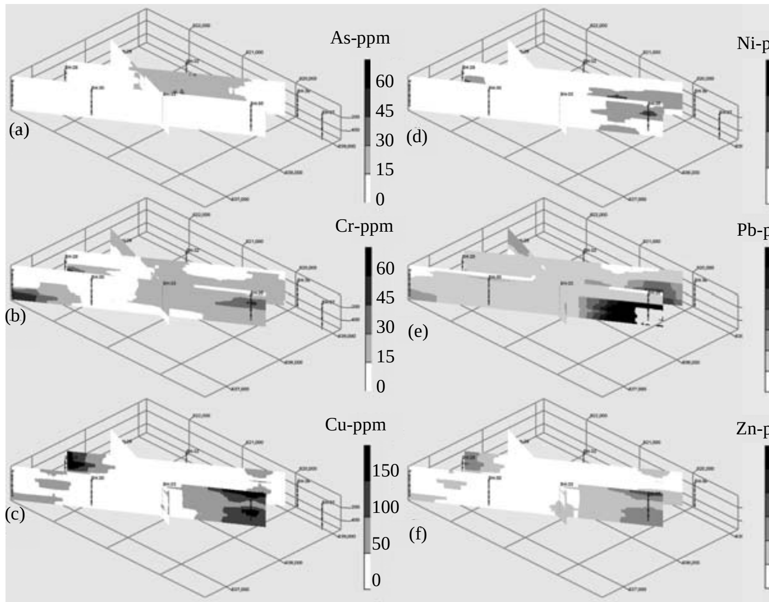

Fig. 6 (a-f): Fence diagram showing heavy metal distribution in Khlong Ok (Area 3) of the SKL study area. (a): As, (b): Cr, (c): Cu, (d): Ni, (e): Pb and (f): Zn concentrations (in ppm)

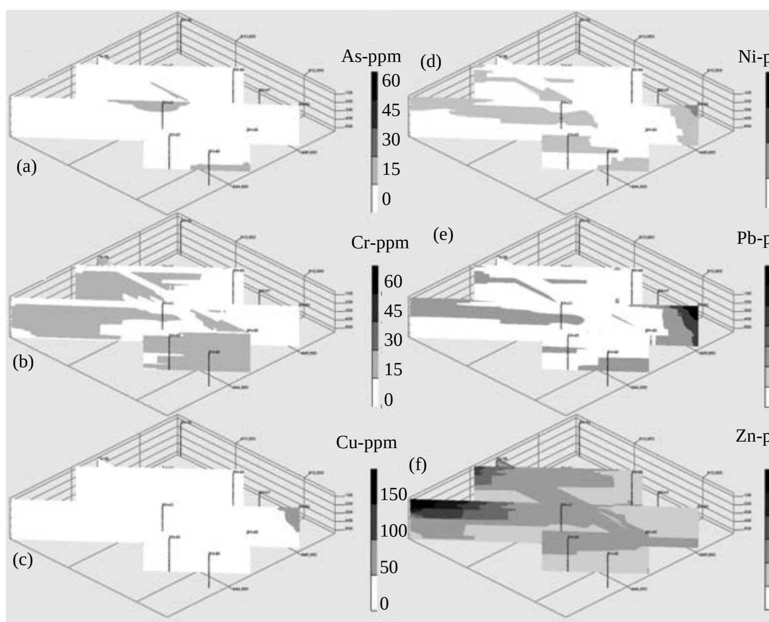

Fig. 7 (a-f): Fence diagram showing heavy metal distribution in Ao Bang Teng (Area 4) of the SKL study area. (a): As, (b): Cr, (c): Cu, (d): Ni, (e): Pb and (f): Zn concentrations (in ppm)

target and interception values are only at near-shore environment. For Pb contamination, only two samples of lake sediments contain Pb contents equivalent to target and intervention values. No lake sediments containing heavy-metal concentrations in any individual layers are as high as the target values. It is also quite interesting that the lake sediments in the uppermost layer from individual drill holes have heavy-metal concentrations higher than or within the standard ranges of the target values.

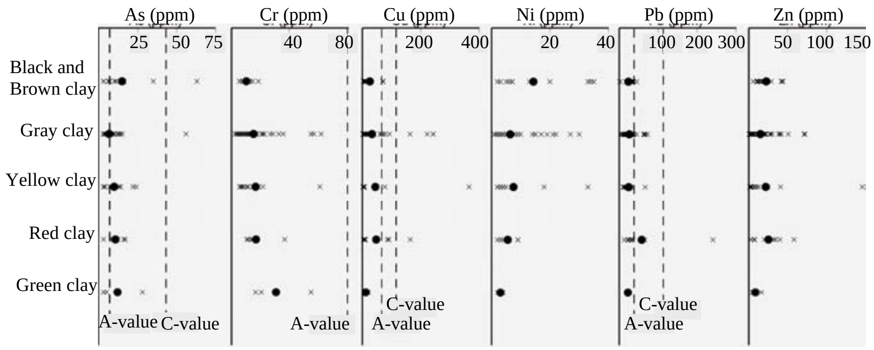

Fig. 8: Comparison between heavy metal concentrations (in ppm) of each stratigraphic layer and target and intervention values of the Hong Kong standard (Lau *et al*., 1993). X is heavy metal concentration and ● is average concentration in the layer

Table 5: Number of heavy metals from core sediments of the Songkhla Lake study area in comparison with standards

Sediments	As	Cr	Ni	Cu	Pb	Zn
Hong Kong-Target (A) value	39	0	-	19	2	2
Intervention (C) value	3	0	-	8	1	2
Dutch standard	3	0	0	6	0	2
SEQ TEC	32	6	6	26	16	3
MEC	7	0	0	9	2	2
PEC	4	0	0	8	1	2

It is apparent that sources of heavy metal concentrations are mostly from land. As shown in Table 4 for the Hong Kong standard values of heavy metal contents in soils in comparison with those values from SKL sediments (Table 5). There are some samples which have high metal concentrations equivalent to target and intervention values. No lake sediments in the SKL study area contain high heavy metal contents so as to justify as harmful or dangerous sediments.

CONCLUSIONS

Results on drilling logs, stratigraphic correlation and geochronological data indicate that sediments in the Songkhla Lake study area, southern Thailand, have been deposited since Quaternary Period to Recent. They are mainly clay and silt layers with intercalation of small sand lenses and with the maximum thickness of 6.5 m. Two oldest layers (totally 2m thick) were deposited in early to late Pleistocene (>37,500 years ago). Then the loosely packed yellow clay layer which was deposited during late Pleistocene (ca. 37,500 to 19,000 years ago). The unconsolidated clay layer occurred in the Holocene (ca. 19,000 years ago to recent).

The average rate of the Holocene sedimentation in this area are estimated from TL-dating data is about 0.37±0.01 mm year^{-1}. However, deposition rate of the Songkhla Lake seems to be less than erosional rate due to strong lake-shore erosion. Depositional rate becomes higher (up to 5 mm year^{-1}) within the present day to 50-year time span. Such high rate is regarded as a result of anthropogenic or human activity.

For the heavy metal distribution in the SKL study area, the Ao Ba Teng (area 1) littoral area in the northern part shows high concentrations of arsenic, lead and zinc metals but the contents are less than those of the Hong Kong standard. The Khlong Ok littoral zone yields the high concentrations of chromium and copper and the Ao Bang Teng littoral zone has high concentration of nickel. However, it is found that they have lower metal values than the Hong Kong standard.

The black clay layer has high arsenic and nickel concentrations whereas the green clay has higher lead and zinc concentrations. Red clay and yellow clay layers contain higher copper and chromium concentrations. However, their metal values are less than those of the Hong Kong standard.

It can be concluded, based on the overall results, that the sediments in the lake show no serious contamination and most heavy metal contents are lower than those of the standard values for lake excavation. Only few samples from organic/ black clay layer yield arsenic and copper contents slightly higher than the standards which can be negligible. Therefore our result suggests that excavation can be performed without any harmfulness to the lake environment within the study area.

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