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Original Article

Depositional environments of the meandering Pran Buri River, Southwestern Thailand during the last 1000 years

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Abstract

A 370 cm long sedimentary core was investigated using paleoecological proxies to reconstruct environmental changes of the meander bend in Pak Nam Pran area, the Malay-Thai Peninsula during the last millenniums. The sedimentary profile can be divided into four biozones based on their dominant palynomorphs. The *Micrasterias* zone represents a back swamp on the floodplain deposited around 1800 years before present (B.P.) until 1,500 years B.P. After that, the younger *Ilex* zone represents a swampy area with *Ilex* trees until 1,000 years B.P. The younger *Cyclotella striata* zone represents the swampy area near the Pran Buri riverbank up to 150 years B.P. indicating an ongoing marine regression during the last millennium. The youngest Rhizophoraceae zone indicates a mangrove forest occurring from 150 years B.P. with seawater intrusions during daily high tides. Moreover, recent human activities are also recorded within the area indicated by strongly enhanced elements at the top of the core.

Keywords: Pran Buri River, meandering river course, marine incursion, palynology, mangrove

1. Introduction

The Malay-Thai Peninsula lying on the coastline of Gulf of Thailand is one of biodiversity hotspot in Southeast Asia (Polgar & Jaafar, 2017). This Peninsula has been affected by environmental catastrophic events such as coastal erosion, storm surges, flooding and sea level changes over long time scales (Choowong *et al*., 2004; Williams *et al*., 2016). The most detailed Holocene environmental changes on the Malay-Thai Peninsula was focused on sea-level study using various sea level proxies such as abrasion platforms, notches, oyster beds, peat, marine shells and mangrove wood suggesting three potential mid/late Holocene high stands at 6,000, 4,000 and 2,700 years B.P. (Nimnate, Chutakositkanon, Choowong, Pailoplee, & Phantuwongraj, 2015; Scheffers *et al*., 2012; Tija, 1996). The study on biostratigraphy in Sam Roi Yod, Prachuap Khiri Khan indicated after the mid Holocene with a highstand of 3.5 m, a lower sea level occurred until the present day (Choowong *et al*., 2004) and subsequent and coastal progradation. This is consistent with a

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palynological investigation from the mangrove sediments around the Great Songkhla Lakes, Southern Thailand indicating that a rising sea level from 9,700-9,250 years B.P. with a maximum highstand at ~ 4,600 years B.P. and recently falling to the present level (Horton *et al*., 2005). In the northeast of the peninsular in Malaysia, based on geophysical data indicated a rapid sea level rise between 7,000 and 3,000 years B.P., with a highstand up to ~5 m at 5,000 years B.P. (Mallinson *et al*., 2014). Although the significance of Holocene environmental changes to an insight of the relationships between ecosystem, environment (particularly geomorphology, sea level and climate) and human activities of the region, an investigation into Malay-Thai Peninsula environmental history during the Holocene, particularly high resolution of the last 1,000 years has been constrained.

This paper focuses on paleoecological analyses namely sedimentology, geochronology, geochemistry and palynology of sediment in an oxbow lake, Pak Nam Pran subdistrict, the upper Malay-Thai Peninsula where has recently been disturbed by human activities such as aquaculture to describe the history of the changes of depositional environments over the last ca 1000 years. A location selected for a sediment core for this study was under a thicket of natural mangrove forest dominated by dense *Rhizophora* trees. Understanding the original natural vegetation prior to disturbance by human activities using the palynological results and an artificial planted mangrove forest as reforestation can be used for good current and future area planning and managements.

2. Study Area

Pak Nam Pran sub-district is on the sea front about eight kilometers east of Pran Buri district, Prachuap Khiri Khan, South Western Thailand. It is a small sedimentary basin with an area of approximately eight square kilometers, surrounded by mountainous areas to the north, isolated low hills to the west and south and enclosed by the Gulf of Thailand to the east. The easterly flowing Pran Buri River originates the west of Pran Buri district, flows through a water gap in isolated hills, the east of Pran Buri, into the basin, and finally drains into the Gulf of Thailand. Low mountainous areas in the north, generally less than 200 meters high, stretch from Khao Tao to Khao Thung Sai Yai, Khao Benchaphat and Khao Chao Mae. The highest peak is Khao Benchaphat at about 238 meters. Isolated low hills also occur south of the basin (Figure 1). The basin's basement rocks consist of Pran Buri Gneiss (Khao Tao Formation), with bulk compositions of granitic orthogneiss and wollastonite, showing igneous-like characteristics with a regional N-S trending fabric (Pongsapich, Vedchakanchana, & Pongprayoon, 1980).

The basin used to hold a fertile, natural mangrove forest along the banks of Pran Buri River affected by both freshwater from the river and marine saltwater during daily high tides. The river in the basin flowed in strong meanders with many meander bends. Khlong Khoi is a natural U-shaped meander loop curving southward nearly forming an oxbow lake as part of the main Pran Buri River. This meander bend is still connected to the Pran Buri River and water between the bend and the main river still flows back and forth during the daily tidal cycles. Between 1981 and 1996, an around one square kilometer area inside this meander loop degraded as a result of many shrimp aquaculture farms developed by some private sectors under royal concessions permitted by the Royal Forest Department. These activities were subsequently withdrawn due to a royal initiated project of mangrove rehabilitation. Since then, reforestation has been carried out by the Royal Forest Department under the patronage of the PTT Public Company Limited as the Sirinart Rajini Ecosystem Learning Center. It is over 20 years to rehabilitate and now it becomes a plentiful lush greenery area again for habitat of fauna.

3. Material and Methods

To achieve the objectives of the research, geological investigations were undertaken in and around the chosen drilling site. A Russian type sediment core sampler was used to obtain sediment samples from an oxbow lake in the Sirinart Rajini Ecosystem Learning Center in the Pak Nam Pran area and around 2 km away from the shoreline.

A 370-cm long sediment core was obtained and 74 sediment samples taken at 5 cm intervals. The lithology of each sediment sample was described using physical properties and their colors were compared with the standard Munsell soil-color charts. As few macro organic materials were found and not enough to conduct acid-base-acid pre-treatment for ^{14}C dating, five bulk sediment samples; two samples (depths of 40-50 and 320-330 cm) at the boundaries of biostratigraphy change and three samples (depths of 120-130, 160-170, 240-250 cm samples) in the middle of the core were sent to Direct-AMS Radiocarbon Dating Service, United States of America, for C^{14} dating by Accelerator Mass Spectrometry. The conventional ages were calibrated with the software OxCal v4.10 (Bronk-Ramsey, 2009) using the northern hemisphere calibration IntCal13 curve (Reimer *et al*., 2013). Each of the 74 sediment samples was tested for sediment pH using a digital pH tester. For these 20 grams of a dry sediment sample was mixed with 100 ml distilled water in a beaker. A stirring rod was used to thoroughly mix the sediment and water before waiting for the sediment to settle down at the bottom of the beaker. Measurements were made by dropping the probe of the pH tester into the upper clear liquid portion and reading five pH values. Twelve sediment samples were 100 °C dried overnight, ground and analyzed for elementary compositions using the XRF at the Suranaree University of Technology. Palynological extraction and pollen identification of the 74 samples was carried out in the Micropaleontology and Microscopy laboratories, Nakhon Ratchasima Rajabhat University. The palynological treatment of each sample was made by digestion with 10% HCl and 49% HF to remove the carbonate and silicate sediment matrix and 7% KOH to remove organic compounds. Heavy liquid separation was applied to some samples. Nylon sieves with 180 µm and 11 µm apertures were used to separate the palynomorphs. Acetolysis, a mixture of 9:1 acetic anhydride and sulfuric acid, was applied to remove lipids and debris from the palynomorphs. The palynomorphs were then stored in a vial with tert-butanol and permanent microscopic slides were prepared by using Eukitt quick-hardening mounting medium.

4. Results

Lithological analysis, age determination, sediment pH value, chemical composition and palynology were used on

Figure 1. Location map of the Pran Buri. (a) Map showing location of the Sirinart Rajini Ecosystem Learning Center study area and part of the Pran Buri River system. (b) The coring site at the Sirinart Rajini Ecosystem Learning Center.

selected sediment samples to determine the changing depositional environments. These five integrated parameters are described as follows.

4.1 Sediment description

Sediment physical features were continuously logged from the ground surface down to 370 cm. The sediment is mostly non-calcareous clay, generally varying in color from greyish to olive green brown between 55 and 155 cm, sandwiched between very dark grey clay layers. The sedimentary profile can be divided into four layers by their color, sediment pH values and palynological composition (Figure 2).

4.2 Ages of selected sediments and average sedimentation rate

Five sediment samples from selected depths were dated by radiocarbon. The calibrated ages of the sediments range from the present to as old as 1,000 years B.P. (Table 1). The age of sample 5 is younger than sample 4, possibly caused by reworking of organic debris from root penetration bringing the younger carbon down and/or percolation of humic acids through leaching depositional environments. Therefore, the sample 5 was rejected for the interpretation and the estimated age of the basal depth (370 cm) and 320 cm using a linear interpolation of alibrated dates was around 1810 cal

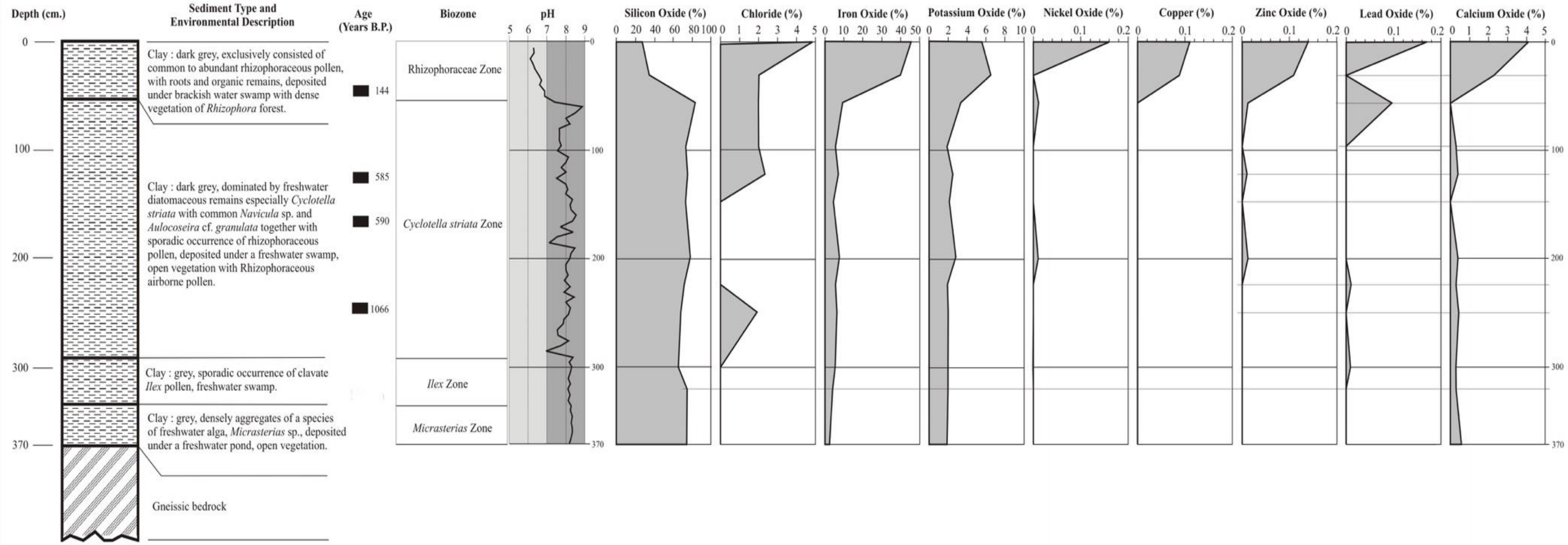

Figure 2. Diagram showing sediment type and environmental descriptions, ages, pH, biozones and some of selected elements of the sedimentary profile.

Table 1. Conventional and calibrated ages of sediment samples from five selected depths.

No.	Depth (cm)	^{14}C Radiocarbon age (Years B.P.)	Range cal. (Years B.P.)	Cal. years B.P.
1	40 - 50	99 ± 27	268 - 21	144 ± 124
2	120 - 130	566 ± 28	644 - 526	585 ± 59
3	160 - 170	577 ± 28	647 - 533	590 ± 57
4	240 - 250	1125 ± 32	1173 - 959	1066 ± 107
5	320 - 330	992 ± 25	961 - 799	880 ± 81

years B.P. and 1510 cal years B.P., respectively. Sedimentation rate at the lower part (370-160 cm) is relatively low at 0.17 cm/year while the rate at 160-120 cm is extremely high at 8 cm/year. The sedimentation rates are low in the upper part (120-40 cm) at 0.18 cm/year and relatively higher to the top of core at 0.31 cm/year.

4.3 pH testing

The pH values of the 74 sediment samples (Table 2) provide an understanding of the changing depositional environments during sedimentation. The sedimentary profile can be divided into three layers on the basis of the sediment pH curve pattern (Figure 2). The bottommost layer, between 370 and 292 cm, is alkaline. The middle sediment layer from 292 to 55 cm, has greatly varied pH values but it is still alkaline. The uppermost layer, 55 – 0 cm depth, has dramatically decreased pH values and is acidic.

4.4 Sediment XRF analyses

Twelve sediment samples were quantitatively analyzed by XRF for a range of elements (Table 3). The results show that there are variations in elemental oxides from layer to layer representing changes in depositional environment. Two sediment layers are clearly divided on the basis of percentage variations of some elements with a boundary at ca 55 cm depth.

High SiO_2 content from 370 to 55 cm abruptly decreases in the upper layer from 55 to the surface while Cl, CaO and Fe_2O_3 contents are relatively high in the upper sediment layer.

4.5 Palynological zonation

Palynomorphs, which are including pollen and diatom, are rarely found in the sediment samples. The paucity of palynomorphs is possibly caused by the high alkalinity of the sediments. The uppermost acidic layer at 55 – 0 cm, yielded exclusively abundant rhizophoraceous pollen. The sedimentary profile can be divided into four palynological zones on the basis of the dominant palynological elements of each zone as described in Figure 2 namely *Micrasterias*, *Ilex*, *Cyclotella striata*, and Rhizophoraceae zones.

5. Interpretation and Discussion

A multi-proxy analysis is useful in describing changes in depositional environments. Palynomorphs are the main elements for zoning the sedimentary profile with radiocarbon ages marking the time span of each zone. Chemical composition and pH of the sediments provide additional information about each zone.

Micrasterias Zone: This 370 and 335 cm zone contains sediments and palynomorphs dated at ca 1800-1500 years. The palynomorphs are mainly composed of a dense aggregation of freshwater green algal remains, *Micrasterias* sp. (Neustupa, Šťastny', & Škaloud, 2014) clearly indicating that the depositional environment of the area changed from ca. 1,800 years ago to the present day. The area approximately 1 km south of the Pran Buri River (Figure 3a) began at ca. 1,800 years B.P. with a stagnant freshwater pond, suitable for photosynthesis by freshwater green algae dominated by *Micrasterias*, in an open, lowland forest environment. Water in the pond was derived from rainwater and surface runoff with not much organic debris deposited. River sediments are generally high in silica (Bien, Contois, & Thomas, 1958; Harriss, 1967) as floodplain environments with back swamps filled with sediment derived from river overflows during the flood seasons. Some water in the pond might have been derived from the Pran Buri River during flood seasons and the high SiO_2 content of the sediments therefore was probably from surrounding surface runoff during rainfall and overflows from the River. Low sediment alkalinity is due to the lack of organic debris to transform into humic acid (Swift, Heal, & Anderson, 1979). There was no evidence of marine influences or mangroves at this time. The results of freshwater green algae and high SiO_2 support the evidences of marine regression that was recorded in the Peninsula after the mid Holocene highstand (Choowong *et al*., 2004; Nimnate, Chutakositkanon, Choowong, Pailoplee, & Phantuwongraj, 2015) and subsequent occurrences of coastal progradation and floodplain with meanders across the plain to the coast (Choowong *et al*., 2009).

Table 2. pH values of sediment samples from each five centimeters interval

Depth (cm)	pH	Depth (cm)	pH	Depth (cm)	pH	Depth (cm)	pH	Depth (cm)	pH
0 - 5	6.26	75 - 80	7.70	150 - 155	8.26	225 - 230	7.94	300 - 305	8.20
5 - 10	6.36	80 - 85	7.58	155 - 160	8.58	230 - 235	8.40	305 - 310	8.08
10 - 15	6.10	85 - 90	7.62	160 - 165	8.30	235 - 240	8.02	310 - 315	8.20
15 - 20	6.20	90 - 95	7.78	165 - 170	7.84	240 - 245	8.20	315 - 320	8.12
20 - 25	6.34	95 - 100	7.62	170 - 175	8.28	245 - 250	8.10	320 - 325	8.24
25 - 30	6.64	100 - 105	8.18	175 - 180	7.60	250 - 255	7.90	325 - 330	8.10
30 - 35	6.70	105 - 110	8.02	180 - 185	7.10	255 - 260	7.84	330 - 335	8.28
35 - 40	6.60	110 - 115	7.74	185 - 190	8.44	260 - 265	7.54	335 - 340	8.22
40 - 45	6.88	115 - 120	7.94	190 - 195	8.24	265 - 270	7.58	340 - 345	8.30
45 - 50	6.88	120 - 125	7.56	195 - 200	8.16	270 - 275	8.16	345 - 350	8.24
50 - 55	7.38	125 - 130	8.04	200 - 205	8.00	275 - 280	7.80	350 - 355	8.30
55 - 60	8.88	130 - 135	8.10	205 - 210	8.02	280 - 285	6.96	355 - 360	8.32
60 - 65	8.52	135 - 140	8.08	210 - 215	8.14	285 - 290	8.28	360 - 365	8.26
65 - 70	8.00	140 - 145	8.30	215 - 220	7.96	290 - 295	8.16	365 - 370	8.18
70 - 75	8.20	145 - 150	8.18	220 - 225	8.16	295 - 300	8.26		

Table 3. XRF quantitative analyses of some chemical variances from sediment samples of twelve selected depths (ND: Not detected)

Variance/ Sample no.	SRN-1 (0-5)	SRN-2 (20-25)	SRN-3 (50-55)	SRN-4 (95-100)	SRN-5 (120-125)	SRN-6 (150-155)	SRN-7 (195-200)	SRN-8 (220-225)	SRN-9 (250-255)	SRN-10 (295-300)	SRN-11 (320-325)	SRN-12 (365-370)
MgO	ND	ND	ND	0.894	ND	0.997	2.281	2.655	3.077	2.731	ND	ND
Al_2O_3	ND	5.34	ND	13.076	4.87	13.105	ND	12.614	13.211	13.556	14.539	14.232
SiO_2	27.681	33.809	83.674	72.516	75.129	72.622	77.705	71.266	68.01	70.551	73.538	73.831
SO_3	7.423	4.084	2.381	5.424	6.98	5.538	7.769	5.224	4.825	4.939	3.941	3.985
Cl	4.9	2.005	ND	ND	2.34	ND	ND	ND	1.887	ND	ND	ND
Ar	ND	2.317	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
K_2O	5.746	6.48	3.276	1.943	2.368	2.096	2.882	1.981	1.993	1.982	2.016	1.883
CaO	4.043	2.353	ND	0.238	0.318	ND	0.407	0.285	0.441	0.278	0.301	0.606
TiO_2	2.943	3.231	1.134	0.64	0.802	0.719	0.988	0.68	0.663	0.642	0.68	0.645
Cr_2O_3	0.237	0.122	0.027	0.025	0.025	ND	0.026	0.017	0.016	0.017	0.015	0.018
MnO_2	0.512	0.294	0.037	0.028	0.07	0.038	0.116	0.075	0.179	0.108	0.075	0.093
Fe_2O_3	45.22	39.774	9.28	5.184	7.063	4.874	7.772	5.195	5.686	5.177	4.893	4.699
NiO	0.161	ND	0.01	ND	ND	ND	0.009	ND	ND	ND	ND	ND
Cu	0.108	0.087	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
ZnO	0.137	0.107	0.013	ND	0.01	ND	0.012	ND	ND	ND	ND	ND
Br_2O	0.396	ND	0.009	ND	0.011	ND	0.013	ND	ND	ND	ND	ND
Rb_2O	ND	ND	0.03	0.011	ND	ND	0.02	ND	0.012	0.009	ND	0.011
SrO	0.115	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
ZrO_2	0.208	ND	ND	0.02	ND	0.012	ND	ND	ND	ND	ND	ND
Ta_2O_3	ND	ND	0.029	ND	0.011	ND	ND	ND	ND	ND	ND	ND
PbO	0.172	ND	0.098	ND	ND	ND	ND	0.011	ND	0.01	ND	ND

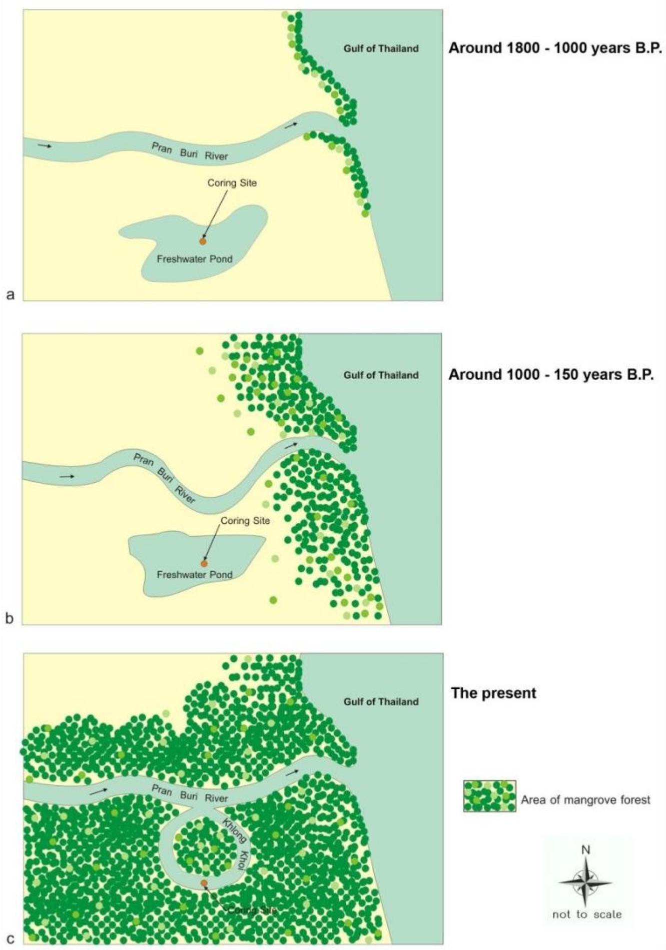

Figure 3. Diagram showing the last 1800 year environmental history of the meandering Pran Buri River and marine induced mangrove invasion)green circles(.

Ilex Zone: This 335 and 292 cm zone contains sediments and palynomorphs dated at ca 1500-1000 years. The depositional environment was similar to that of the *Micrasterias* zone. It was still a stagnant freshwater pond not influenced by seawater without mangrove community present, in a lowland area south of the meandering Pran Buri River which continued to flow south-eastward (Figure 3b). However, there was vegetation around the pond mainly consisted of sporadic herbs and shrubs with scattered small trees indicating by *Ilex* pollen present. *Ilex* grew well here and was probably *Ilex cymosa* which today grows well in the swamps, along the river, or the nearby coast (mangrove). Sediments supplied to the pond were still high in SiO_2 with little organic debris with alkaline. These evidences indicated an ongoing marine regression and floodplain occurring during the last millennium (Choowong *et al*., 2004; Nimnate, Chutakositkanon, Choowong, Pailoplee, & Phantuwongraj, 2015).

Cyclotella striata Zone: This 292-55 cm zone contains sediments, pollen and diatoms dated from slightly younger than 1000 years (ca. 500 years) to ca. 150 years at the top. Sediments are clay, dominated by diatomaceous silica, mainly from *Cyclotella striata*, with minor amounts from *Navicula* sp. and *Aulacoseira* cf. *granulata*. They are probably all freshwater (Edlund & Ramstack, 2009; Jasprica & Hafner, 2005; Roy & Pal, 2015; Vidakovic, Krizmanic, Sovran, Stojanovic, & Dordevic, 2015), although *Navicula* occurs in both freshwater and saltwater. Most marine *Navicula* species do not have convergent striate at their apices (Cloern & Dufford, 2005) as occurs here. The Pran Buri River at this time shifted slightly more south as a meander bend nearly reaching the coring site, particularly prior to ca. 150 years B.P. (Figure 3b). Freshwater diatoms indicate a probable stagnant, freshwater depositional environment or possibly they came from the Pran Buri River during the flood seasons. In addition, the depths of 160-120 cm yielding remarkably high sedimentation rate at 8 cm/year probably coincides with wet conditions prevailing after 500 years B.P. in the northeastern Thailand (Chawchai *et al*., 2015) leading to flooding and high sediment accumulation in this area. Sediments are still high in SiO_2 with low organic debris providing alkalinity. These suggested this area was not inundated by seawater due to ongoing lower sea level (Choowong *et al*., 2004). However, sporadic presence of rhizophoraceous pollen in this zone suggests that mangroves were not part of this swamp and were invading the nearby area with some rhizophoraceous airborne pollen being transported from nearby mangroves. No changes are detectable for PbO as well as other elements commonly indicative of anthropogenic pollution such as CaO, K_2O, NiO, Cu and ZnO.

Rhizophoraceae Zone: This ca 55 cm thick, uppermost zone represents ca 150 years to present. The Pran Buri River has now shifted southward and the meander bend was breached by a chute channel that connected the two closest parts of the bend. This caused the flow to abandon the meander bend and flow straight downslope to the Gulf of Thailand. The meander bend (Khlong Khoi) turned into an isolated oxbow lake (Figure 3c).

During the last 150 years the Pran Buri River occasionally joined the abandoned meander bend, Khlong Khoi, particularly when seawater intruded through a dense mangrove thicket into the river during the daily high tides. This also suggested a landwards move of mangrove communities to the study site and adjacent areas consistent with a mangrove study on the upper west of Gulf of Thailand indicating a rise in sea level in historical times (Punwong *et al*., 2018). The lake sediments had a much lower silica content than the river sediments (Laguna, 1964) suggesting that the lake received some direct surface runoff and rainfall. This decrease in SiO_2 is another evidence of environmental change from a river with its floodplain to an oxbow lake environment. The brackish water from river overflow during the daily high tides provided less dissolved silica than the upstream water (Peterson, Conomos, Broenkow, & Scrivani, 1975). Over the last 150 years, sedimentation in Khlong Khoi took place under a stagnant water regime with a high accumulation of organic debris derived from mangroves. Sediment in this zone is therefore characteristically low in silica (Harriss, 1967) and slightly acidic caused by humic acid derived from organic debris in the sediments (Sukardjo, 1994; Swift *et al*., 1979). The area was colonized by mangroves with roots that induced formation of iron oxide plaque and increased Fe^{2+} concentration in the sediment pore-water. Fe mobilization is promoted by reduction under conditions of low redox potential and chelation with organic acids such as exudates from plant roots (Inoue, Nohara, Matsumoto, & Anzai, 2011).

In addition, there is also a strongly enhanced element content of CaO, K_2O, NiO, Cu, ZnO, and PbO in the uppermost of the core possibly indicates recent human activities occurring around the catchment including agriculture, industry, and wastewater over the last decades that were reported as high concentrations found at the mouths of Pran Buri river (Cheevaporn & Menasveta, 2003). Shrimp farming rapidly developed along the coast of Thailand including this area during the 1980s could contribute to such change of Cu that is a component of some chemical use by Thai shrimp farmers such as pesticides and disinfectants (Visuthismajarn, Vitayavirasuk, Leeraphante, & Kietpawpan, 2005). CaO can be used as ingredient of cement (Chang & Chen, 2006) for buildings and is probably released in river sediment during constructing and dumping of such concrete material. Coincident with these changes, a higher accumulation of these elements in this oxbow lake deposits reflect the contamination passing through the river.

6. Conclusions

Sedimentology, geochronology, geochemistry and micropaleontology is used to develop four biozones covering the last 1,800 years or so at Khlong Khoi, Pran Buri, Thailand. These biozones, in upward succession, *Micrasterias*, *Ilex*, *Cyclotella striata* and Rhizophoraceae Zones, provide evidence of the changing depositional environments of the area from a back swamp on the floodplain deposited from around 1,800 years B.P. to a mangrove forest at around 150 years B.P. These changes have been caused by a meandering river and marine incursions.

The royal concession areas issued for shrimp farming greatly disturbed the natural mangrove forests and the surface sediments in the Khlong Khoi meander bend. Rare *Rhizophora* pollen was recovered from the *Cyclotella striata* Zone and changed upward to become abundant in the Rhizophoraceae Zone. This sedimentary pollen record and the natural *Rhizophora* trees now in the study area indicate that the original trees were exclusively *Rhizophora* which gradually invaded in conjunction with brackish water intrusions occurring from 150 years B.P. onwards. However, this study was done under a single sediment core as a preliminary study and further studies are recommended.

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