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Paleoenvironment of Acid Sulfate Soil Formation in the Lower Central Plain of Thailand

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Abstract: This study aimed to elucidate the environment of sulfidic material accumulation and the development of acid sulfate soil by focusing on the kinds of acid sulfate soil in various soil profiles and the characteristics of sediments in the Lower Central Plain of Thailand. The kinds of acid sulfate soil in all the soil profiles were identified, the soils categorized into profile types A-D and the characteristics of sediments in sedimentary columns were described. The developed acid sulfate soils, profile types A and B, were distributed in the deltaic plain in areas occupied by tidal flat to salt swamp in the period of middle-late Holocene. Sulfidic materials were accumulated in this environment in which mangrove and plant roots were the organic material source for sulfidic formation. Non-acid-sulfate soil, profile type C, was distributed in the tidal plain where shallow marine areas and open bay existed in the middle-late Holocene. The lack of an organic material source and base-rich condition was inappropriate for accumulation of sulfidic material here, whereas in young acid sulfate soil, profile type D, sulfidic material was accumulated recently and the soils have continued developing in the present estuary conditions. Acid sulfate soil in each profile type had different degrees of development due to the influence of oxidation.

Key words: Acid sulfate soil, sulfidic material, Lower Central Plain of Thailand, Holocene transgression, paleoenvironment

INTRODUCTION

Acid sulfate soils have a worldwide distribution estimated at 120,000-140,000 km^2 (Beek *et al*., 1980) and are mostly distributed in Southeast Asia, particularly Indonesia, Vietnam and Thailand (Dawson, 2009; Van Breemen, 1982). The Land Development Department (2006) reported that acid sulfate soil occupies approximately 8,800 km^2 of Thailand. It has been observed over large areas in the Lower Central Plain (Fig. 1) and to a lesser extent in the coastal plains of the Southeast Coast and Peninsular Thailand. Major cultivation areas in the Lower Central Plain are utilized as paddy field and the average yield is low. However, a diversification of land uses for growing various crops and for aquaculture is presently being carried out (Vacharotayan and Attannandana, 1985). Acid sulfate occurring in soil causes this area to have a low potential for agricultural use and its management often requires the application of a remediation technology (Vijarnsorn and Panichapong, 1977).

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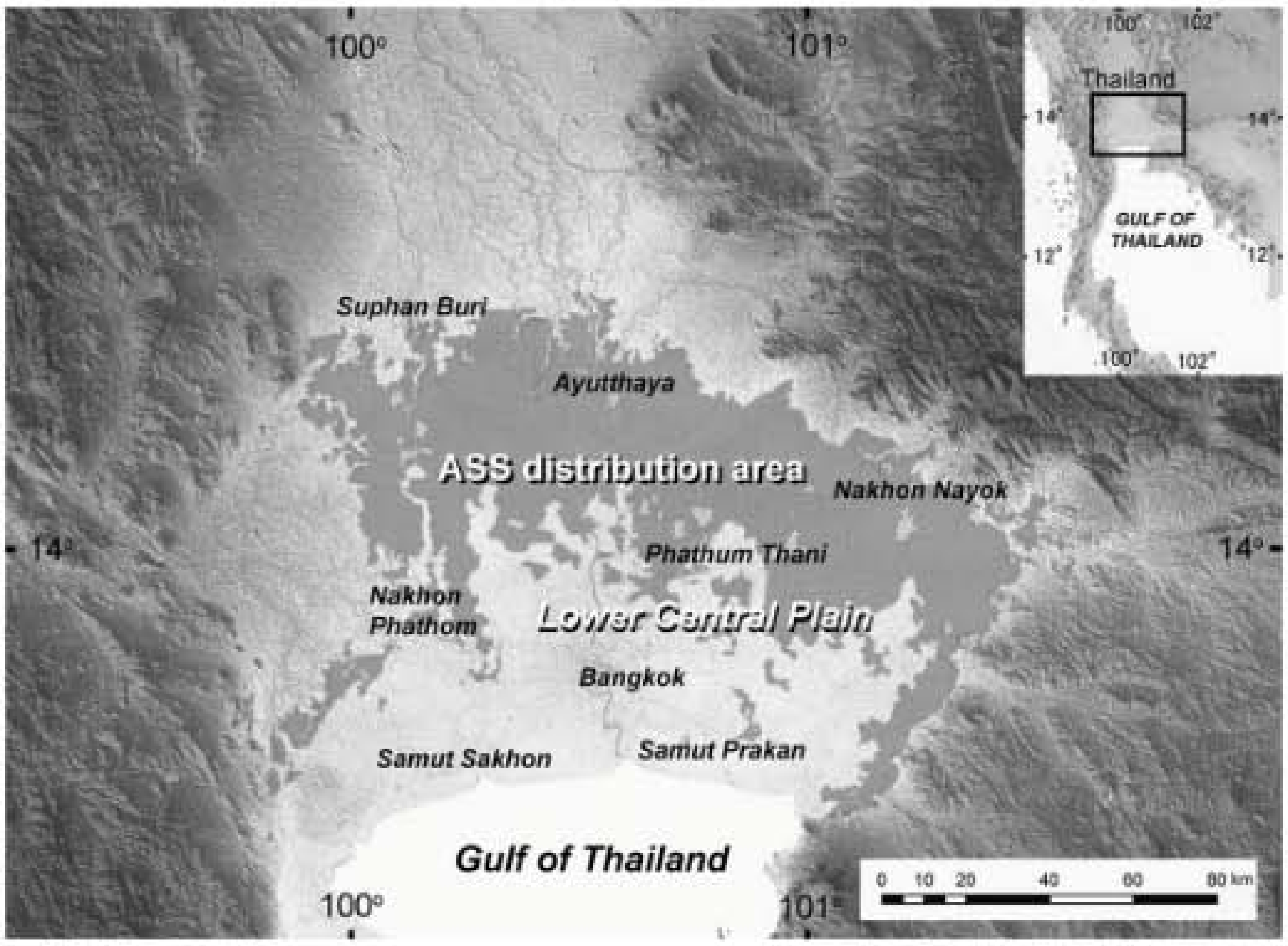

Fig. 1: Distribution of acid sulfate soil in the Lower Central Plain (distribution of acid sulfate soil is based on Land Development Department (2006) report)

The definition of acid sulfate soils given by Pons (1973) is that acid sulfate soils include all soils in which sulfuric acid either will be produced, is being produced or has been produced in amounts that have a lasting effect on major soil characteristics. Subsequently, Fanning (2002) reported that this definition includes potential acid sulfate soils, active acid sulfate soil and post-active acid sulfate soil. Potential acid sulfate soil contains sulfidic materials, mostly pyrite (FeS_2), at significant levels in near-surface horizons/layers. The materials are expected to generate acid upon exposure to oxidizing conditions as the sulfides are oxidized to form sulfuric acid, found mainly as jarosite ($KFe_3(SO_4)_2(OH)_6$). Sufficient sulfuric acid can drive the pH of these horizons/layers to ultralow levels (Van Breemen, 1982; Fanning, 2002; Soil Survey Staff, 2006).

The occurrence of sulfuric acid in the soils is not suitable for growing plants due to the low contents of major plant nutrients, particularly phosphorus, the low basicity and high hydrogen sulfide toxicity. Sulfuric acid also dissolves iron and aluminum from the soil, making it readily available in toxic quantities through water in the soil. These conditions interrupt plant growth and cause low productivity in such an area (Kyuma, 2004; Sammut and Lines-Kelly, 2004). Moreover, free sulfuric acid produced by the leaching of acid sulfate soil can cause contamination of ground and surface water with acid and metal. Sulfuric acid also causes damage to aquatic and riparian ecosystems. Widespread acidification of land also causes damage to infrastructure by corrosion of concrete, steel pipes and bridges (Sammut *et al*., 1994; Department of Natural Resources and Water, 2009).

The predominant case of the formation of sulfidic material is observed in saline and brackish lowlands including tidal flats, salt marshes and mangrove swamps (Pons and van Breemen, 1982). Poleman (1973) reported that acid sulfate soil is not only found in recent marine deposits but also in older inland areas occurring far from the coast and remote from the recent influence of sea water. As reported by the Department of Environment and Conservation (2009), sulfidic material often occurs in former seashores which may have existed several kilometers inland from the current shore. Melville *et al*. (1993) reported that sulfidic material was particularly accumulated in the Holocene maximum-transgression period, about 7,000 years ago. At the time of the Holocene transgression the sulfidic material accumulated under mangrove and reed swamp (Dent and Pons, 1995).

Acid sulfate soil in the Lower Central Plain of Thailand has been described by several soil scientists e.g., Brinkman and Pons (1968), Pons and van Der Kevie (1969), Slager *et al*. (1970), Vlek (1971), Van Breemen (1973, 1976), Vijarnsorn and Panichapong (1977) and Dent and Pons (1995). Most of these studies focused on morphological, physical and chemical aspects of acid sulfate soils and discussed the genesis and agricultural potential of acid sulfate soil with particular reference to improvement and reclamation of acid sulfate soil areas. However, only limited attention has been given to the study of the initial phases of sulfidic material sedimentation and the characteristics of acid sulfate soil in relation to the paleoenvironment and land evolution.

This study aimed to elucidate the environment of sulfidic material accumulation and the development of acid sulfate soil. The attention was giving to the kinds of acid sulfate soil in various soil profiles and the characteristics of sediments in the Lower Central Plain of Thailand. The characteristics of several soil profiles were studied and the kinds of acid sulfate soil they contained were identified. The formation of acid sulfate soil could be observed from soil profiles as the characteristics of soil are influenced by soil-forming factors e.g., climate, relief (topography), parent material, living matter and time. Soils are the same wherever all elements of these five factors are the same (Soil Survey Staff, 1993). Features in soil profiles describe where sulfidic material is formed and how acidity is produced in soil bodies. The profiles were grouped into profile types by similarities in their successive kinds of acid sulfate soil, where each profile type had a range of characteristics of similar profiles. These could be used to describe distribution patterns of each profile type and regional differences in geomorphological conditions on the plain. Moreover, the characteristics of sediments and sedimentary sequences were also studied could be used to describe the chronosequences of sedimentary conditions, changes of sedimentary environment and the evolution of the plain. The significance from this study is benefit to understand typical characteristics of soils in particular positions and review condition of acid sulfate soil in the Lower Central Plain of Thailand. The understanding may assist in considering of reclamation of potential acid sulfate soil area, land management, land use planning and also environment issues such as climate change in the future.

MATERIALS AND METHODS

Regional Setting

The central plain of Thailand has been recognized as the rice bowl of Thailand. It is a broad, flat, low-lying area located in the central part of the country; the plain is divided into upper and lower parts. The upper central plain originates from the Ping, Wang, Yom and Nan rivers that flow from the North converging to form the Chao Phraya river in Nakhon Sawan province; around this confluence a number of monadnocks are found scattered over the plain.

The study area is the Lower Central Plain of Thailand. The Lower Central Plain, the name given by Sinsakul (2000), has also been called the Southern central plain by Rau and Nutalaya (1983) and the Chao Phraya Delta by several researchers such as Vijarnsorn and Panichapong (1977) and Tanabe *et al*. (2003). The Lower Central Plain is delimited by the

Chainat province (15°15'N, 100°15'E), where the Chao Phraya river passes the monadnocks and flows southward through the flat, low-lying plain until reaching the Gulf of Thailand at Samut Prakarn province (14°30'N, 100°30'E). The distance from Chainat province to the mouth of the Chao Phraya river is about 200 km and the widest part of the plain, along the East-West axis, is about 180 km, with a total area of approximately 36,000 km^2. The elevation of the plain ranges from 15 m above mean sea level (msl) at Chainat province to 2.5 m MSL at Ayutthaya province and 1.5 m MSL at Bangkok, which is about 25 km North of the Gulf of Thailand. The Southern edge of the plain is marked by a narrow strip of tidal flat, with vegetated mangrove forest, extending for 30 km along the banks of the Chao Phraya River estuary (Sinsakul, 1997, 2000; Somboon, 1990). In the era of King Rama V, in the late 19th century, the hydrological engineering here was regarded as a milestone in the history of Thailand. In this period, the excavation of canals used for both irrigation and transport facilities expanded rapidly, until nearly all of the deltaic areas were covered with high-a density canal network that still exists in the present day (Hara *et al*. 2005).

Landforms of the Lower Central Plain were classified by Somboon (1990) into 13 units: tidal, brackish swamp, delta plain (marine clay), floodplain, delta plain (brackish clay), lower terrace, fan delta, old alluvial fan, middle terrace, high terrace, peneplain, marl terrace and mountain and hill. The study also considered sea-level change; Holocene sea-level transgression covered most of the present Lower Central Plain and this sea incursion reached to the North of Ayutthaya province. Alternately, Umitsu *et al*. (2002) classified the landforms of the plain into four units: alluvial fan in the West, floodplain in the North, the deltaic plain in the central and the tidal lowland in the Southern region of the plain (Fig. 2). They also

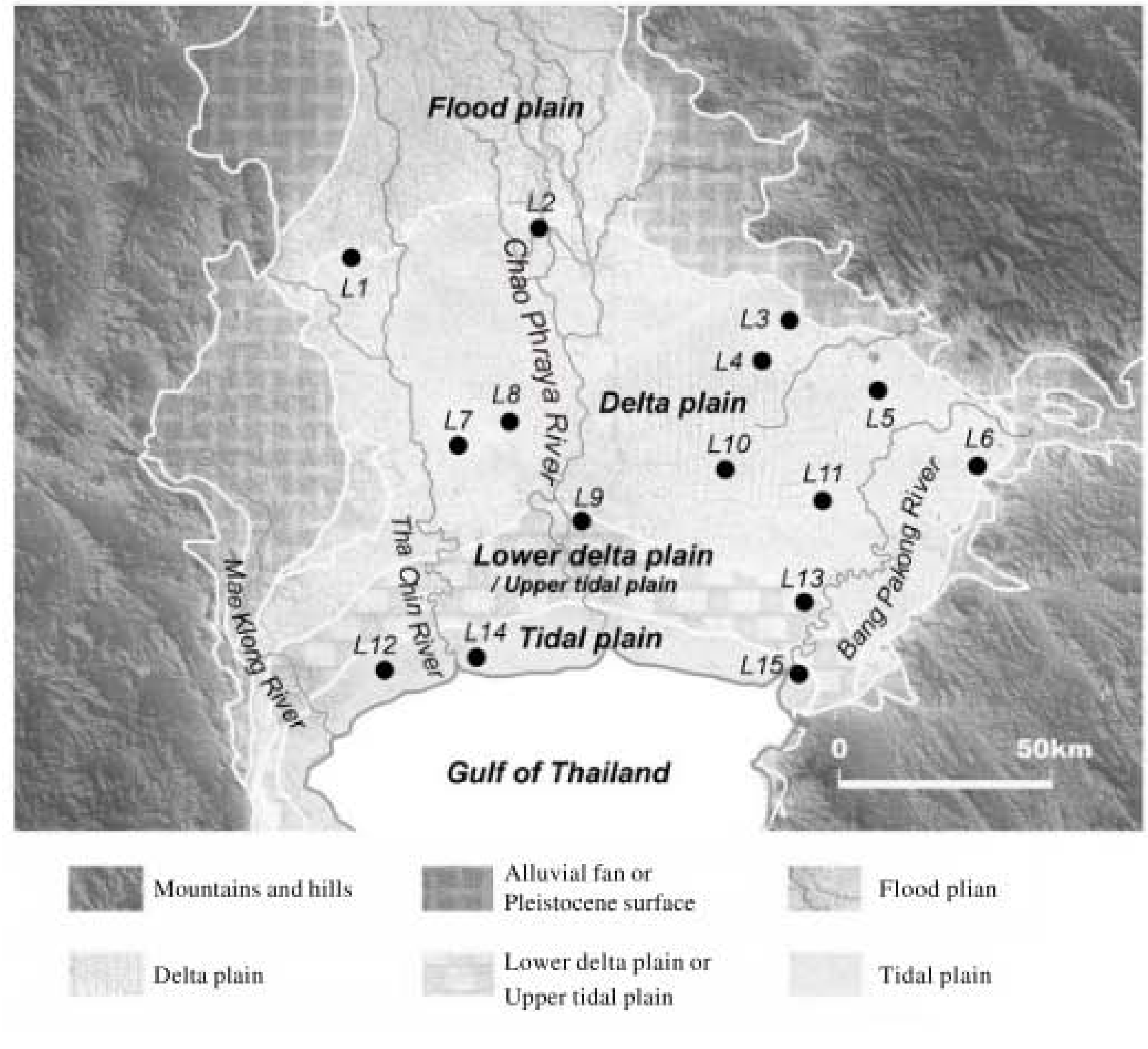

Fig. 2: Landforms of the Lower Central Plain of Thailand and soil-sampling sites

explained that sea level rose rapidly by 7-6 cal kyr BP and the maximum height of the sea level at the time was considered to be more than 2 m above present sea level. The geological features of the plain were studied by Tanabe *et al*. (2003), including prodelta, delta front, river-mouth flat and delta plain. The deltaic plain consists of tidal flats (mud and sand), mangrove, beach ridge, a distribution of marine clay, a distribution of brackish clay, alluvial fan, Pleistocene terrace and pre-Pleistocene bedrock units. They reported a sea-level history and delta evolution in which the sea level approached its highest level of 2-4 m above MSL between 8-7 cal kyr BP, which they defined as the mid-Holocene highstand. Sinsakul (2000) reported that the Holocene sea steadily rose until reaching a maximum point at about 6 cal kyr BP at height of 4 m above MSL.

Quaternary sediments are extensively developed in the Lower Central Plain. Both marine and continental deposits are developed along the coastlines of the Gulf of Thailand (Dheeradilok and Kaewyana, 1986). Sinsakul (1997) reported that the main feature of the Lower Central Plain is the tide-dominated process. Sea-level change in the Holocene was the most important factor in shaping the landform of the Lower Central Plain. The evolution of the Central Plain has been reported by Somboon and Thiramongkol (1992), Umitsu *et al*. (2002) and Tanabe *et al*. (2003) where, the embayment of the Holocene transgression extended towards the area of Ayutthaya province, about 100 km from the present shoreline. The paleo-shoreline during the maximum transgression was around Suphanburi, Nakhon Pathom, Ratchaburi, Ayutthaya, Pathumthani, Nakhon Nayok, Prachinburi and Chachoengsao provinces. Most of the present delta plain was under a shallow sea known as the paleo-Gulf of Ayutthaya at the time of mid-Holocene highstand. The area along the paleo-shoreline was covered with mangrove vegetation at that time (Somboon, 1988).

The paleogeography of the plain was explained by Somboon (1988, 1990) the paleo-shoreline in the time of Holocene transgression was bordered by a brackish swamp or coastal salt marsh with thriving mangrove vegetation. This is in agreement with Umitsu *et al*. (2002), who reported that a peat layer in the Holocene sediments developed significantly in the coastal areas of the middle Holocene embayment and that it contains wood fragments which were considered to be mangrove trunks. From the stratigraphic sequence of the plain, peaty sediments are distributed in area. Sinsakul (2000) found peat in clay soils and basal peat in the intertidal flat deposit in the main part of the plain that was deposited in a shallow sea or intertidal environment that graded into mangrove swamps during the transgression in the Holocene. In a paleogeography map illustrating the evolution of the Lower Central Plain constructed by Tanabe *et al*. (2003), areas of mangrove swamp and flat can be seen along the areas of paleo-shoreline between submerged and deposited zones. However, the shapes and locations of these areas were changed in six periods of land development from 8 kyr BP until the present.

Soil Sampling and Laboratory Analysis

To determine soil characteristics, sedimentary successions and laboratory analysis were performed on 15 soil profiles excavated from the Lower Central Plain from April 2007 to February 2009. Most of profiles were dug to a width of 2 m, a length of 1.5 m and a depth of 2 m (Soil Survey Staff, 1993, 2006) except for profiles L13, L14 and L15 which had lower limits due to the high water table in this area; as we were unable to determine the profile for the entire 2 m depth, only the visible parts of the profiles were obtained. The site selections were made with attention to obtaining acid sulfate soils and associated soils in the plain; the sampling locations are shown in Fig. 2. At the sampling sites the environment and surroundings, soil description and soil genetic horizons were determined. Field pH values were measured by using a pH meter (from 1:1 water:soil suspensions). Surface geology and the characteristics of the sediments were described in detail.

Subsequently, representative samples from each site were collected and carefully transported for laboratory analysis. All samples were air dried in the shade for 8 weeks, after which the samples were crushed and sieved through a 2-mm mesh sieve before analysis. Soil pH (1:1 water suspension) and particle-size classes were measured in each genetic horizon following the procedure described by the USDA-NRCS (1996).

Electrical conductivity (EC) analysis was carried out following Yokoyama and Koizumi (1989) to determine the sedimentary condition. They developed this method by measuring EC values and comparing them with the results of diatom analysis of the same samples. They found that the results of the two measurements had a good correlation and indicated the environment of the sediment. Accordingly, EC values from this method can be used to distinguish marine, brackish water and fresh water sediments. The EC of clay sediment stirred in water (STICS water) was determined as follows: about 20 g of soil was oven-dried at 110°C for 48 h, after which 10 g of dry soil was stirred with a small mixer into 120 mL of water. The EC of this STICS water was measured five days after the mixing time with an electric conductivity meter. The boundaries of freshwater, brackish water and marine conditions were determined by EC values less than 0.499, 0.500-1.299 dS m^{-1} and more than 1.2999 dS m^{-1}, respectively. Several previous studies have been done using this EC-measurement method. For example, in a study by Funabiki *et al*. (2007) they investigated Holocene delta-plain development in the Song Hong (Red River) delta, Vietnam. The EC measurement was used along with lithology, color, sedimentary structures, fossil components, diatom and pollen contents, pH and mud-content results to interpret the environments of the sedimentary units.

For the recognition of different kinds of acid sulfate soil, the terminology and concepts of acid sulfate soil in this paper utilize the definitions of acid sulfate soil of Pons (1973), Fanning (2002) and the Soil Survey Staff (2006). The distinct characteristics were divided into potential acid sulfate soil, active acid sulfate soil, post-active acid sulfate soil, transitional soil and nonacid sulfate soil and their identified features are as follows:

Potential Acid Sulfate Soil

Soil with a pH value greater than 3.5 and that, after being air-dried slowly in the shade, shows a drop in pH of 0.5 or more units to a pH value of 4.0 or less (1:1 water) within 8 weeks; no observation of jarosite and redoximorphic features.

Active Acid Sulfate Soil

Soil with a very low pH of 3.5 or less and commonly containing a concentration of jarosite and/or directly underlying the potential acid sulfate soil.

Post-Active Acid Sulfate Soil

Soil with a field pH greater than 3.5 but having a similar appearance as active acid sulfate soil in containing a concentration of jarosite and/or directly underlying the potential acid sulfate soil.

Transitional Soil

Soil that has intermediate properties between that of sulfidic mud and non-acid sulfate soil; it has high field pH value and shows a dramatic drop to a very low pH, generally to 4.0-5.0, after air drying.

Non-Acid Sulfate Soil

It is the any soil not defined above.

RESULTS

Identification of Kinds of Acid Sulfate Soil and Profile Forms

The formation of soil is observed while studying the soils of an area. A soil is the unique result of soil-forming factors (Soil Survey Staff, 1993). Differences in soil profiles mark differences in soil formation. The characteristics of a soil profile can be interpreted as soil-forming processes, which are linked to the environmental conditions during sedimentation and soil development.

Identification emphasizes the differing appearances of different kinds of acid sulfate soil in a profile; potential acid sulfate soil, active acid sulfate soil, post-active acid sulfate soil and transitional soil. The identification of these kinds of acid sulfate soil was done according to the terminology and concepts defined in the methods section. The most important properties used for identifying types of acid sulfate soil were the field pH and air-dried pH values and the occurrences of jarosite and redoximorphic features. Moreover, the depth of potential acid sulfate soil or transitional soil in a profile which remediation as also considered as the depth affects the possibilities for acidification; the deeper a soil is, the longer is the distance that acid compounds must move upward from the source to the oxidizing zone. The authors assigned a boundary at 100 cm from surface; potential acid sulfate soil appearing above 100 cm was considered shallow potential acid sulfate soil and that appearing below 100 cm considered deep potential acid sulfate soil. During the identification process, soil profiles were found to contain one or more kinds of acid sulfate soil. The succession of acid sulfate soil kinds in the profiles were used to describe processes that had influenced soil-profile development. The results of evaluating field pH, air-dried pH and the appearance of jarosite and redoximorphic features are shown in Table 1 and the distinct characteristics found for the samples were as follows:

The profile of L1 was characterized by low pH both in the field and air-dried conditions and even different pH values in both conditions. At the depth of 110 cm, the soil had a field pH of 4.6-5.1 and air-dried pH of 3.5-3.6. Furthermore, concentrations of jarosite and redoximorphic features were observed at 110-180 cm from surface; these are the characteristics of a post-active acid sulfate soil.

At a depth of 110 to 200 cm in the profile of L2, the soil had a field pH of 5.1-5.3 and an air-dried pH of 3.8-3.9, with the horizon containing jarosite mottles; these are the characteristics of post-active acid sulfate soil. Thus, profile of L2 was similar to L1 as the soils both had post-active acid sulfate soil in their profiles; the pH values were low and showed small differences between field pH and air-dried pH and contained jarosite mottles. The characteristics were also found in the profiles of L3, L4, L5 and L6. The post-active acid sulfate soils began at the depth of 70, 10, 102 and 80 cm in the profiles of L3, L4, L5 and L6, respectively. Profiles of L1-L6 had similar characteristics and were grouped into same category.

The profile of L7 was characterized by post-active acid sulfate soil in the upper part of the profile, similar to the profiles of L1-L6, but potential acid sulfate soil appeared in the lower part of the profile. At the depth 85-190 cm the soil had high field pH values (5.9-6.1) but low air-dried pH values (4.2-5.4). Concentrations of jarosite and redoximorphic features were observed at 85-130 cm. The pH values were low and showed small differences between field pH and air-dried pH and contained jarosite mottles; these are the characteristics of post active acid sulfate soil. In the lower part, at 190-200 cm, the soil had a field pH of 5.9 and an air-dried pH of 3.7; it showed a dramatic decrease in pH value after air drying; there were no investigated redoximorphic features in the horizon. The field pH was high but the air-dried

Table 1: Results field pH, air-dried pH and appearances of jarosite and other color mottles

Site	Depth (cm)	Field pH	Air dried pH	Jarosite mottles	Other mottles
L1	0-20	5.0	4.1	-	X
	20-40	5.3	4.5	-	X
	40-70	5.1	4.5	-	X
	70-90	4.8	3.8	-	X
	90-110	4.8	3.6	-	X
	110-130	4.7	3.5	X	X
	130-155	4.8	3.5	X	X
	155-180	5.1	3.5	X	X
	180-200	4.6	3.6	-	-
L2	0-20	6.2	4.7	-	X
	20-45	6.4	4.2	-	X
	45-85	6.1	3.8	-	X
	85-110	5.2	3.6	-	X
	110-140	5.1	3.8	X	X
	140-180	5.3	3.9	X	X
	180-200	5.2	3.9	X	X
L3	0-15	3.9	3.4	-	X
	15-30/50	3.7	3.4	-	X
	50-70	3.6	3.3	-	X
	70-90	3.7	3.1	X	X
	90-110	3.6	3.0	X	X
	110-140	3.6	3.2	X	X
	140-170	3.8	3.7	-	X
	170-200	3.8	3.5	-	X
L4	0-10	4.4	3.5	-	X
	10-40	4.4	3.6	X	X
	40-60	4.4	3.3	X	X
	60-90	4.2	3.8	X	X
	90-130	4.5	3.4	X	X
	130-170	4.7	4.0	X	X
	170-200	4.4	3.8	-	X
L5	0-30	5.4	3.3	-	X
	30-48/60	4.6	3.2	-	X
	48/60-86	4.5	3.6	-	X
	86-102	4.4	3.5	X	X
	102-130	4.3	3.7	X	X
	130-172	4.5	4.0	X	X
	172-190	4.2	3.8	X	X
	190-210	4.3	3.6	-	-
L6	0-20	4.8	4.3	-	X
	20-40/50	4.2	4.0	-	X
	40/50-80	4.1	4.0	-	X
	80-115	3.9	3.9	X	X
	115-145	4.1	3.9	X	X
	145-170	4.1	4.0	X	X
	170-200	4.2	4.1	X	X
L7	0-20	5.7	5.0	-	X
	20-45/85	5.2	4.5	-	X
	85-95	6.1	4.2	X	X
	95-115/130	6.1	4.5	X	X
	130-145	6.1	4.3	X	X
	145-155/170	5.9	4.9	-	-
	170-190	6.1	5.4	-	-
	190-200	5.9	3.7	-	-
L8	0-20	5.9	3.9	-	X
	20-50	5.1	3.9	-	X
	50-70	4.6	3.4	X	X
	70-100	4.4	3.9	X	X
	100-140	4.3	3.4	X	X
	140-160	4.5	4.0	X	X
	160-175	4.9	4.0	-	X
	175-200	5.3	2.5	-	-

Table 1: Continued

Site	Depth (cm)	Field pH	Air dried pH	Jarosite mottles	Other mottles
L9	0-20	7.1	5.3	-	X
	20-42	7.5	5.8	-	X
	42-60	7.6	6.0	-	X
	60-90	7.6	5.7	-	X
	90-125	7.3	5.8	-	X
	125-155	7.0	5.8	-	X
	155-182	7.4	6.5	-	-
	182-200	7.8	4.6	-	-
L10	0-20/30	6.5	5.8	-	X
	30-58	6.7	4.5	X	X
	58-80	6.5	4.6	X	X
	80-100	6.6	4.5	X	X
	100-130	7.0	6.7	-	-
	130-160	6.7	3.3	-	-
	160-185	7.4	3.6	-	-
	185-200	7.8	3.4	-	-
L11	0-18	5.5	3.5	-	X
	18-46	4.9	3.3	-	X
	46-80	4.9	3.2	X	X
	80-110	5.0	3.0	X	X
	110-128	4.9	2.9	X	X
	128-148	5.0	3.1	-	-
	148-185	5.1	3.1	-	-
	185-200	5.7	3.2	-	-
L12	0-20	7.8	6.4	-	-
	20-40	7.8	6.5	-	-
	40-60	7.9	6.2	-	X
	60-90	7.8	6.0	-	X
	90-120	7.9	6.1	-	X
	120-160	8.0	6.1	-	X
	160-175	7.8	6.0	-	X
	175-200	7.7	6.0	-	-
L13	0-28	7.4	5.8	-	X
	28-42	7.3	5.7	-	X
	42-76	7.3	6.4	-	X
	76-98/115	7.8	6.6	-	X
	98/115-120	7.6	6.5	-	X
	120-150	8.3	6.7	-	-
	150-160	8.5	6.9	-	-
L14	0-18	7.4	6.6	-	X
	18-32	7.4	6.7	-	X
	32-55	7.1	6.4	-	X
	55-72	7.3	6.5	-	X
	72-95	7.8	5.6	-	-
	95-120	8.1	4.5	-	-
L15	0-25	4.8	4.3	X	X
	25-42	4.7	3.0	-	X
	42-70	6.9	3.7	-	-
	70-100	7.1	3.2	-	-

X: Appearance, -: Absence

pH was low and jarosite and redoximorphic features were absent; these are the characteristics of potential acid sulfate soil. In the profile of L8 at a depth of 50-175 cm the soil had a low field pH, at 4.3-4.9 and a low air-dried pH of 3.4-4.0 and contained jarosite mottles from 50-140 cm; it was post-active acid sulfate soil. The lower part, at 175-200 cm, had a field pH of 5.3 which dramatically deceased after air-drying to pH 2.5 and an absence of redoximorphic features; it was potential acid sulfate soil. In the L9 profile, from the surface to 182 cm, the soil had a high field pH (7.0-7.6) and an only slightly lower air-dried pH (5.3-6.5), which is characteristic of non-acid sulfate soil. However, at the depth of 182-200 cm the soil had high field pH of 7.8 but this dropped dramatically to 4.6 after air-drying. The pH value higher than 4.0 and the absence of jarosite characterized it as transitional soil.

Transitional soil has very similar characteristics to acid sulfate soil. A dramatic drop of pH after air-drying shows the soil also contains sulfidic material and can produce acid but the pH value is higher than 4.0. The researchers considered profiles containing transitional soil and potential acid sulfate soil qualified profiles and determined them as identical profiles. Consequently, the profile of L8 and L9 were considered similar profiles to the L7 profile as the soils had deep potential or transitional soil in their profiles; in the horizon from a depth of 100 cm or more, the pH values were high in field conditions but dramatically dropped to very low values after air drying. The characteristics were also found in the profiles of L10 and L11. Similar characteristics to the profiles of L7, L8 and L9 were found in the profiles of L10 and L11. The potential acid sulfate soils appeared at 130 and 128 cm in the profiles of L10 and L11, respectively. The profiles of L7-L11 had similar characteristics and were thus grouped into the same category.

The profile of L12 was characterized by its differences from the profiles of L1-L11 in having both high field pH (7.7-8.0) and high air-dried pH (6.0-6.5) and by absence of any concentration of jarosite throughout the profile; this is characteristic of non-acid sulfate soil. The L13 profile had a field pH of 7.3-8.5 and an air-dried pH of 5.7-6.9 and the absence of jarosite; it was non-acid sulfate soil.

The profile of L12 was similar to the L13 profile, as they are both non-acid sulfate soils, had high pH values both in the field and air-dried conditions and even different pH values in both conditions. The profiles of L12 and L13 had similar characteristics and were thus grouped into the same category.

The profile of L14 was characterized by its content of transitional soil, which was similar to the L9 profile but the transitional soil in the profile of L14 appeared shallower than in L9. In the upper part of the profile, the soil had high field pH values (7.1-7.4) and air-dried pH (6.4-6.7) and an absence of jarosite; these are characteristics of non-acid sulfate soil. At the depth of 72 cm, the soil had a high field pH of 7.8-8.1 but the pH dropped dramatically to a very low value after air drying (4.5-5.6); along with the absence of jarosite, these are the characteristics of transitional soil. From the surface to the depth of 42 cm the profile of L15 had a field pH of 4.7-4.8, which slightly dropped to 3.0-4.3 after drying and a few jarosite mottles were observed in the topsoil; these are the characteristics of post-active acid sulfate soil. However, from 42-100 cm, the soil had a field pH of 6.9-7.1 and an air-dried pH of 3.2-3.7, the characteristic of a potential acid sulfate soil. The characteristic of this profile of post active acid sulfate soil overlying potential acid sulfate soil was similar to the profiles of L7, L8, L10 and L11, but the potential acid sulfate soil of profile of L15 appeared shallower than those of the other profiles.

The L14 profile was similar to the L15 profile as they both contained potential acid sulfate soil or transitional soil above 100 cm; the soils both had high field pH values which dropped dramatically to very low values after air drying; they were thus shallow potential acid sulfate soil or transitional soil. The profiles of L14 and L15 had similar characteristics and were grouped into the same category.

From the information above, the kinds of acid sulfate soil presented a wide range of profile forms as determined by their succession in the soil profiles. However, there were similarities in profile forms and these could be distinguished into 4 types: profile type A, profile type B, profile type C and profile type D. The characteristics of each type are as follows:

Profile type A is a soil that has post-active acid sulfate soil in the profile. The pH values are low and show small differences between field pH and air-dried pH and contain jarosite mottles. Profile type A consists of the L1-L6 profiles.

Profile type B is a soil profile that has deep potential acid sulfate soil or transitional soil. The pH values of transitional soil and potential acid sulfate soil are high in field conditions but dramatically drop to very low values after air drying and they occur at a depth of 100 cm or more. Profile type B consists of the L7-L11 profiles.

Profile type C is a soil that has only non-acid sulfate soil in the profile. The pH values are high both in the field and air-dried conditions. Profile type C consists of the profiles of L12 and L13.

Profile type D is a soil profile having shallow potential acid sulfate soil or transitional soil. The pH values of transitional soil and potential acid sulfate soil are high in field conditions but dramatically drop to very low values after air drying and they occur before a depth of 100 cm. Profile type D consists of the profiles of L14 and L15.

The terms profile type A, profile type B, profile type C and profile type D will be used in the remaining sections of the study including the results, discussion and conclusion.

Characteristics of Sediments

Measurements and observations of sediment colors, textural classes, EC values and accumulated materials were completed to obtain the characteristics of the sediments. The results of the colors, textural class and EC measurements are shown in Table 2 and the sedimentary columns are shown in Fig. 3. The characteristics of the sediments in all the sedimentary columns were as follows:

Sediments in the surfaces of sequences of profile type A were very dark gray to black or dark grayish brown silty clay to clay with yellow, brown and red mottles. Decayed roots could be found in some encrusted tubes. The EC values ranged from 0.27-0.51 dS m^{-1}, which were interpreted as being fresh-water to brackish-water sediments. Sediments in the middle parts were dark gray to gray and brown silty clay loam, silty clay to clay with jarosite, yellow, brown and red mottles. Commonly, the sediments contained decayed roots 0.1-0.5 cm in diameter and what appeared to be small, oxidized iron encrusted tubes 0.1-1 cm in diameter; additionally, gypsum crystals were observed in some sediments. The EC values ranged from 0.28-1.91 dS m^{-1}, which were interpreted as fresh-water to brackish-water and marine sediments. Sediments in the lower parts, which were observed only in the sequences of L1, L3, L4 and L5, were dark grayish brown and brown silty clay to clay, some showing yellowish red mottles. The sediments usually contained abundant wood fragments and decayed roots 0.1-0.5 cm in diameter and iron encrusted tubes 0.5-1 cm in diameter were common. EC values ranged from 0.43-2.07 dS m^{-1}, which were interpreted as fresh-water to marine sediments.

Sediments in the surface and middle parts of the sequences of profile type B were similar to those of profile type A and the EC values were also interpreted similarly, with fresh-water to brackish-water sediments near the surface (0.24-0.59 dS m^{-1}) and fresh-water to brackish-water and marine sediments in the middle parts (0.23-2.07 dS m^{-1}). However, the sediments in the lower parts of the type B profiles were dark greenish gray to greenish or gray, brown and black silt loam to silty clay with yellow and brown mottles. Decayed roots, mostly 0.1-0.5 cm in diameter and iron encrusted tubes 0.3-0.5 cm in diameter were observed. The EC values ranged from 1.41-2.50 dS m^{-1}, interpreted as marine sediments.

Sediments near the surfaces of the sequences of profile type C were very dark gray, dark grayish brown and dark to dark greenish gray silty clay to clay with brown and red mottles. The EC values ranged from 1.0-1.95 dS m^{-1}, interpreted as brackish-water to marine sediment.

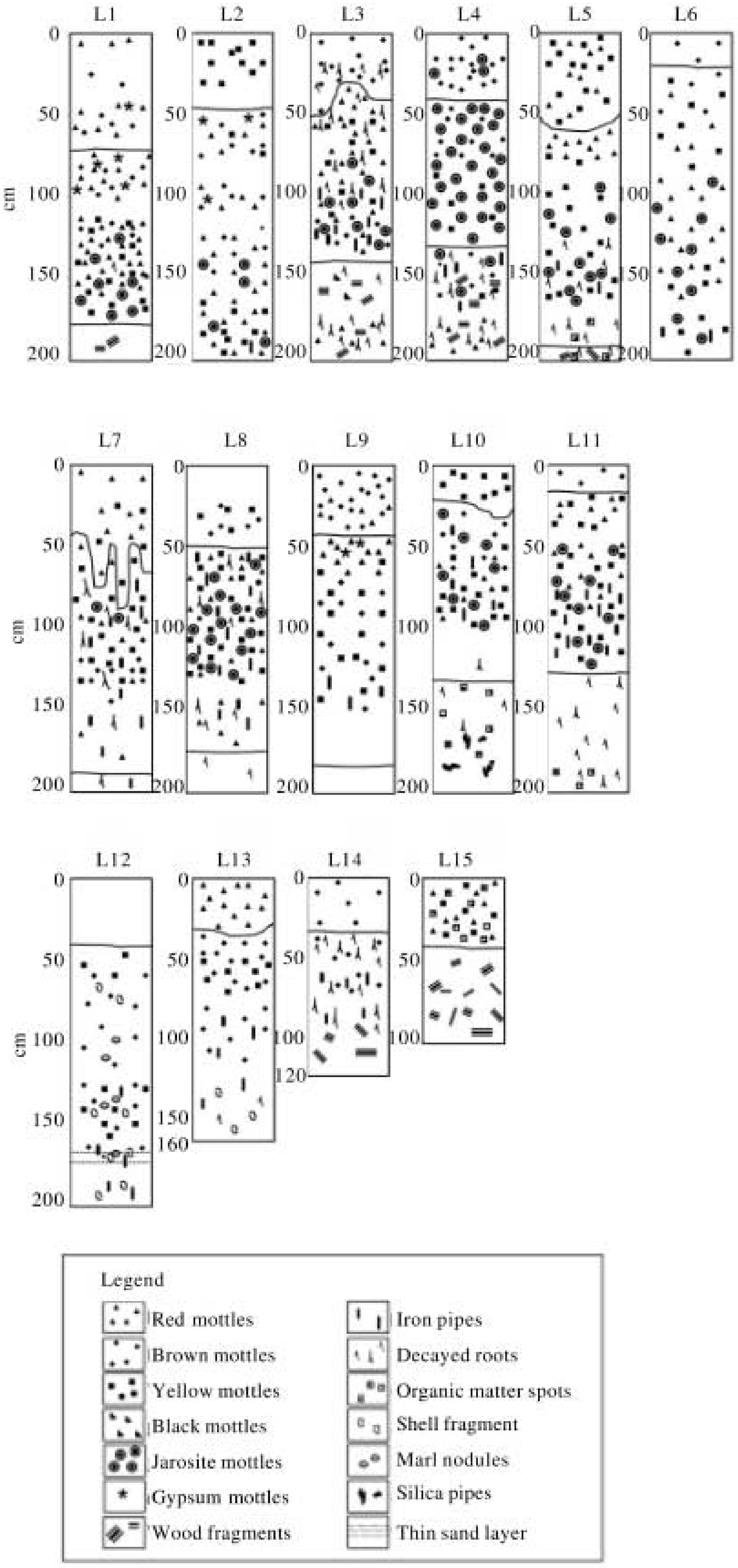

Fig. 3: Graphic models presenting significant features in soil profiles

Table 2: Characteristics of sedimentary sequences

Site	Depth (cm)	Matrix color	Mottles color	Texture	EC (dS m^{-1})
L1	0-70	Very dark gray, dark gray	Red, yellowish red, strong brown, light red, dark yellowish brown	SiC to C	0.27-0.51
	70-180	Dark gray, black, light brownish gray, greyish brown	Jarosite, red, strong brown, yellowish brown, brownish yellow	SiCL to SiC	0.44-1.89
	180-200	Dark greyish brown	-	C	0.43
L2	0-45	Very dark gray, dark gray	Brownish yellow, reddish yellow	C	0.27-0.44
	45-200	Gray to greyish brown, greyish brown, light brownish gray	Jarosite, dark yellowish brown, brownish yellow, red, yellowish red, strong brown	SiC to C	0.30-1.91
L3	0-50	Black, gray	Yellowish brown, dark yellowish brown,	SiC to C	0.42-0.43
	50-140	Greyish brown	dark red brown Jarosite, brownish yellow, red, yellowish brown	SiC to C	0.39-0.45
	140-200	Greyish brown, brown, dark gray	Black, yellowish red	SiC	0.47-1.10
L4	0-40	Very dark gray, dark gray, greyish brown	Jarosite, yellowish brown, dark yellowish brown, strong brown	SiC to C	0.42
	40-130	Greyish brown, very dark gray, dark greyish brown	Jarosite, yellowish brown, dark yellowish brown, strong brown	C	0.42-0.54
	130-200	Very dark gray, dark greyish brown, greyish brown	Jarosite, dark yellowish brown, yellowish red	C	1.01-2.07
L5	0-48/60	Dark gray, very dark gray, dark greenish gray	Reddish yellow, yellowish red, brownish yellow, red	SiC to C	0.33-0.34
	60-190	Greyish brown, dark gray	Jarosite, brownish yellow, red, reddish yellow	SiC to C	0.34-0.38
	190-200	Dark gray, greyish brown	-	SiC	1.34-2.01
L6	0-20	Very dark gray	Yellowish red and strong brown	C	0.45
	20-200	Greyish brown, dark gray, light brownish gray, gray	Jarosite, yellow, reddish yellow, yellowish brown, red	SiC to C	0.28-0.46
L7	0-45/85	Very dark gray, dark gray	Red, brownish yellow	SiC to C	0.55-0.59
	85-190	Light brownish gray, gray, greyish brown	Jarosite, brownish yellow, yellowish red, strong brown, red, yellow, dark red	SiC	0.44-0.54
	190-200	Greenish gray	-	SiC	1.57
L8	0-50	Dark greyish brown, gray	Dark reddish brown, brownish	C	0.27-0.33
	50-175	Gray, very dark gray, greyish brown	yellow Jarosite, brownish yellow, red	C	0.23-0.30
	175-200	Greenish gray and greyish green	-	SiL	2.12
L9	0-42	Very dark brown, black to very dark gray	Reddish brown, red, weak red	SiC	0.31-0.35
	42-182	Gray	Brownish yellow, reddish brown, greenish gray, strong brown, yellowish red, red	SiC to SiCL	0.35-0.74
	182-200	Greenish gray	very dark greenish gray	SiC	1.41
L10	0-20/30	Very dark gray and dark gray	Reddish yellow	C	0.24
	30-130	Greyish brown and gray	Jarosite, brownish yellow, yellowish brown, red, dark greenish gray	C	0.26-0.35
	130-200	Dark greenish gray and gray	Dark greenish gray	SiC to SiCL	1.57-2.50
L11	0-18	Dark gray	Dark yellowish brown and strong brown	SiC	0.33
	18-128	Light brownish gray, gray	Jarosite, yellow, brownish yellow and red	SiC	0.28-0.33
	128-200	Gray, greyish brown, greenish gray, greenish brown, greenish black	-	SiC	0.33-1.48
L12	0-40	Very dark gray, very dark greenish gray, dark greenish gray, very dark gray	-	C	1.00-1.23
	40-200	Greyish brown, greenish gray, gray, brown, brown, dark greenish gray greenish	Brownish yellow, strong brown, brown, yellowish brown, light olive brown and greyish brown	SiC to C	1.80-2.18
L13	0-28	Dark greyish brown	Dark red and red	SiC	1.95

Table 2: Continued

Site	Depth (Cm)	Matrix color	Mottles color	Texture	EC (dS m^{-1})
	28-160	Gray and light brownish gray, dark gray and greyish brown, dark greenish gray, greenish gray	Yellowish brown, dark reddish brown, brownish yellow, strong brown and greenish gray	SiC	0.54-2.77
L14	0-32	Very dark gray, greyish brown	Strong brown and greenish gray	SiC	0.80-1.01
	32-120	Very dark greenish to greenish gray, dark gray	Brown, dark brown and strong brown	SiC	0.98-1.54
L15	0-42	Dark greyish brown and dark greenish gray	Jarosite, strong brown and red	C	1.72-1.77
	42-100	Dark greenish gray to greenish gray	-	SiC to C	1.19-1.81

Texture: C: Clay, SiC: Silty clay, SiCL: Silty clay loam, Interpretation EC value: <0.499 dS m^{-1} = Fresh water sediment, 0.500-1.299 dS m^{-1} = Brackish water sediment, >1.2999 dS m^{-1} = Marine sediment

Sediments in the subsurface of these sequences were gray, brown and dark greenish gray to greenish gray silty clay to clay with yellow and brown mottles. Shell fragments and iron encrusted tubes 0.1-0.5 cm in diameter were commonly observed. The EC values ranged from 0.54-2.77 dS m^{-1}, interpreted as brackish-water to marine sediments.

Sediments near the surfaces of sequences of profile type D were similar to those of profile type C. However, a few jarosite mottles and decayed roots and iron encrusted tubes could be observed in the sediments and EC values ranged from 0.8-1.77 dS m^{-1}, interpreted as brackish-water to marine sediments. Sediments in the subsurfaces of these sequences were dark gray and very dark greenish gray to greenish gray silty clay to clay without mottles. The sediments contained an abundance of wood fragments, with decayed roots 0.1-0.5 cm in diameter and iron encrusted tubes 0.2-0.5 cm in diameter commonly observed in the L14 sequence. The EC values ranged from 0.8-1.81 dS m^{-1}, interpreted as brackish water to marine sediments. The decayed roots in sediments appeared in tubular shapes.

DISCUSSION

Characteristics of Soils and Sediments

According to organic materials were found only in the lower parts of profile type A, B and D which were acid sulfate soils. This indicated that organic material had relation and influence to sulfidic material formation. It was supported by a study of Berner (1984) organic matter is the major controlling factor in the formation of sulfidic material in normal (non-euxinic) terrigenous marine sediments where dissolved sulfate and iron minerals are abundant. This also resembled to a previous research of Pons and van Der Kevie (1969) that acid sulfate soil in the Lower Central Plain of Thailand was formed from peaty sulfidic clay originating from dense mangrove vegetation under saline to brackish conditions. The process of sulfidic material accumulation could occur in the presence of sufficient amount of organic matter and fragments of mangrove were organic source. Dissimilar to this study, we found that sulfidic material should be accumulated in greater range of environment. Due to not only wood fragments were accumulated in the sulfidic material horizon of representative soils, but also decayed roots and iron encrusted tubes. This reveals that more than one plant may have acted as an organic matter source for sulfidic material formation in the plain. Wood fragments in the sediments were the remains of mangrove. The decayed roots were assumed to be the remains of salt grass and reed roots due to their accumulation in sediments having high EC values (1.41-2.50 dS m^{-1}) interpreted as marine sediment. Moreover, certain characteristics of decayed roots i.e., their tubular shapes and diameters of 0.1-0.5 cm served to distinguish them from shrub- or tree-like plants. Because the iron encrusted tubes and decayed roots had similar shapes and sizes, the iron encrusted tubes were assumed to be formed by an iron oxide coating over grass and reed roots as an encrustation which occurred during oxidation processes. Mangrove fragments and plant roots were assumed to be deposited in sediments and associated with the formation of sulfidic material. The horizons containing these materials were considered to be the source of sulfidic compounds in the profiles.

Potential acid sulfate soil and transitional soil are soils presenting sulfidic sources in the profiles. These soils were observed in the lower parts of profiles types B and D, which were derived from brackish-water to marine sediments and the horizons should continue to underlying levels. The horizons of profiles type B commonly contained decayed roots and iron tubes, whereas profile type D distinctly contained wood fragments. This indicates that sulfidic materials were accumulated under brackish-water and marine conditions in two different environments. Sulfidic compounds in profile type B were related to formation in a tidal flat close to a swamp with grasses or reeds, whereas sulfidic compounds in type D profiles were formed in a tidal flat with mangrove vegetation.

Nevertheless, the lower parts of profile type A, which had no potential acid sulfate soil, contained wood fragments similar to those in the horizon containing sulfidic materials of type D. These horizons were assumed to be the upper part of the sulfidic material accumulation in the profile; very low pH values and the remains of jarosite are indicators that the horizons formerly contained sulfidic compounds and had already passed through acidification. Upon oxidation, the sulfidic compounds were transformed to sulfuric acid and the acid was leached out afterwards. The above information indicates that sulfidic compounds of type A were formed in a tidal flat with mangrove vegetation.

Profiles of type C, containing shell fragments and calcareous concretions, were distinctly accumulated in marine sediment, having few iron encrusted tubes and an absence of wood fragments. This indicates that non-acid sulfate soil was formed under different sedimentary conditions than acid sulfate soils, such as in marine conditions that plants could not survive. An area that was continuously submerged and experienced less tidal effects the shallow marine and open bay areas may be more appropriate for the accumulation of shell fragments and calcareous concretions but inappropriate for plant growth. Under these restricted conditions, a concentration of sulfidic material did not form due to a lack of organic material required for its formation and the base-rich condition may have obstructed acidification.

Sedimentation and Soil Formation

The variation of sedimentary sequences and distributions in each profile type form a very valuable record of regional environmental changes in the Lower Central Plain. Sediments in lower should deposited prior sediment in upper of sequence. So different characteristics of sediments in each sequence could be explained sequential occurring of phenomenon in the area. It was agreed with a research of Diemont *et al*. (1993) that the diversity of the characteristics of sediments is due to differences in environmental conditions during sedimentation. Sedimentation and soil formation occur simultaneously and a sequence of horizons grow upwards from the bottom of profile. Interpretations of the sedimentary environment of each sedimentary unit are shown in Table 3 and are described as follows:

Most of sediments of the lower part of profile type A were deposited in a tidal-flat with mangrove-vegetation environment, then the environment of the area changed to a fresh-water condition and more recently, alluvium was deposited over the layer. Sediments of the lower part of profile type B were deposited in environment of tidal flat to swamp with

Table 3: Interpretation of the sedimentary environment

Part in profile	Parent material	Sedimentary environment
Surface of profile type A and B	Fresh water sediment which contains low sulfidic material	Recent alluvial condition
Middle part of profile type A and B	Fresh water to brackish water and marine sediment which contain low sulfidic material	Recent alluvial condition
Lower part of profile type A	Fresh water to marine sediment which contains low sulfidic material	Tidal flat with mangrove vegetation condition
Lower part of profile type B	Marine sediment which contain high sulfidic material	Tidal flat to swamp with grasses or reeds condition
Surface of profile type C and D	Brackish water to marine sediment which contains low sulfidic material	Recent tidal flat condition
Middle to lower part of profile type C	Brackish water to marine sediment which contain low sulfidic material	Shallow marine to open bay with restrict condition of mangrove thriving condition
Middle to lower part of profile type D	Brackish water to marine sediment which contain high sulfidic material	Tidal flat with mangrove vegetation condition

grasses or reeds, then the environment changed to a fresh-water environment, with recent alluvium deposited over the layers. In contrast, sediments of the lower part of profile type C were deposited in a shallow marine to open bay area with limited mangrove vegetation; then the environment of the area changed to a more recent tidal flat. Sediments of the lower parts of profile type D were deposited in a tidal-flat with mangrove-vegetation environment, then the environment of the area changed to a more recent tidal-flat environment.

Regarding sedimentary conditions, sequences of types A and B had fresh-water sediment in the upper parts of their sequences overlying brackish-water to marine sediment. In contrast, sequences of types C and D had no fresh-water sediment; they are brackish water to marine sediments deposited in sequences. This signifies that fresh-water conditions were a weak influence in the areas of the profiles of types C and D. The thickness of the fresh-water sediments in the sequences of types A and B indicate areas where the profiles of types A and B were distributed may be related to rapid deltaic progradation, whereas the areas where profiles of types C and D were created occurred after this time.

Regional Differences of Acid Sulfate Soil Development

The variety of characteristics of profile types was a result of further development later accumulation of sulfidic materials in soil profiles. And the differences were caused by differing influences of soil-forming processes. This confirmed the previous work of Pons and van Der Kevie (1969) that there are two processes of acid sulfate soil formation; geogenetic and pedogenetic processes. The geogenetic process is related to the environment of the sedimentation of sulfidic material in soil. After the geogenetic process, which is when the initial soil formation ends, progressive pedogenesis begins, as shown by e.g., the formation of a vertical horizon.

There were distinct profile forms of acid sulfate soils in profile types A, B and D. Those profiles showed an absence of active acid sulfate soil in their representative soils. This indicated that most of acid sulfate soils in the Lower Central Plain of Thailand have well development. Oxidation occurred intensively in the plain because the sulfuric acids have been produced and leached out from these soil bodies. Each profile type is distributed in a particular area and their locations in the Lower Central Plain of Thailand are shown in Fig. 4.

The four profile types distributed in particular separate zones of the plain indicate the distinct environment of each area. To study regional differences of acid sulfate soil development, oxidation products are good indicators for marking the stage of profile development. In this study, the relevant oxidation products are the concentrations of jarosite

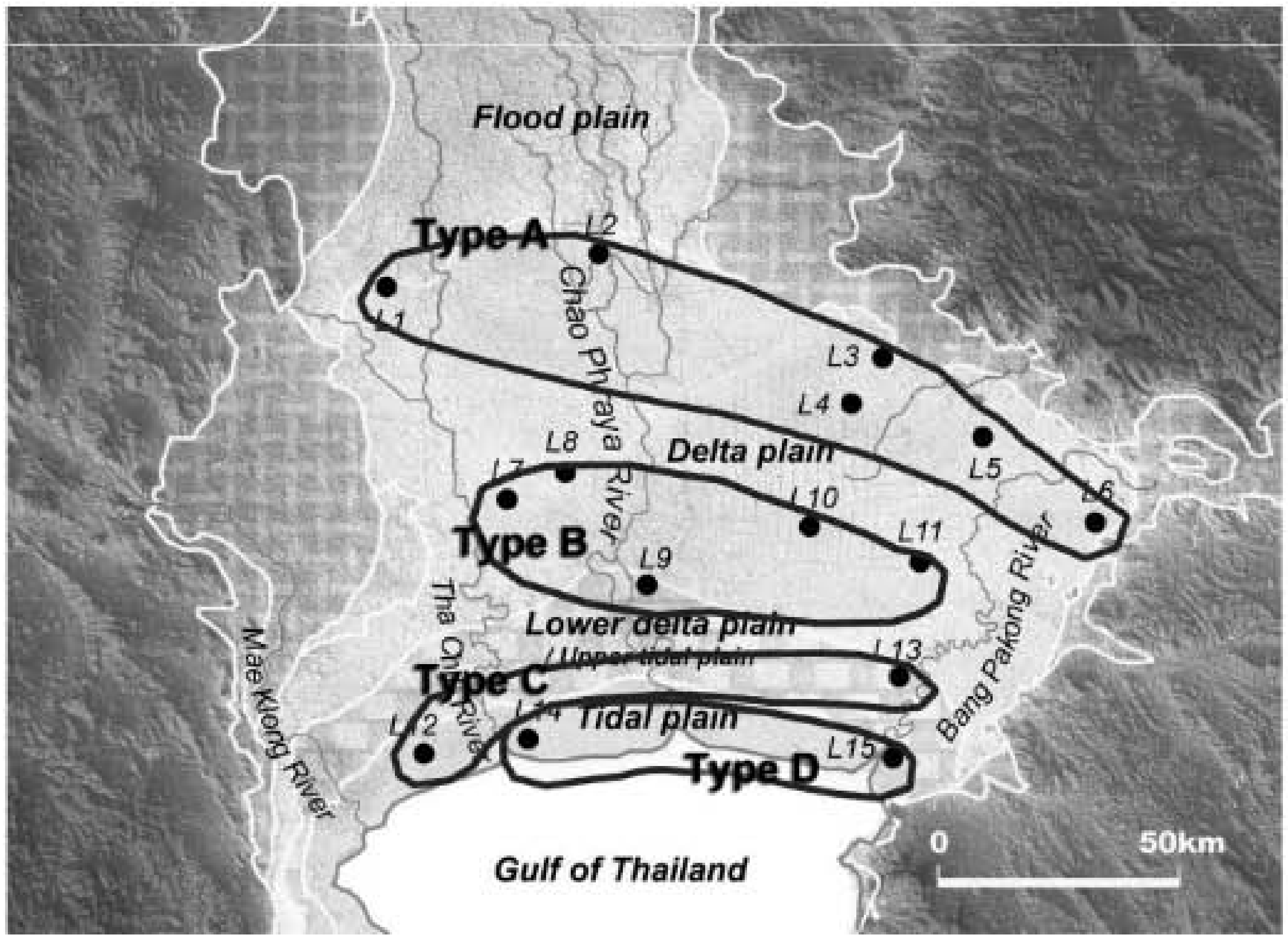

Fig. 4: Distribution of acid sulfate soil groups and associated soil groups; white lines are the boundaries of landforms

and other redoximorphic features and the decrease of pH value. To compare the degree of acid sulfate soil development by emphasis on the degree of oxidation and acidity of the profiles, profile type A has highest degree of development due to oxidation and acidification occurring among all the profiles, where ripening ultimately produced abundant redoximorphic features in a thick layer and oxidation occurred directly in sulfidic material. Profile type B has a lower degree of development due to the deep oxidation in the profile but sulfidic material is not exposed, rather it is still in a reduced condition under groundwater. Profile type C has a slightly lower degree of development than profile type B as it also has a thick oxidized layer and a reduced layer in the lower part. However, the lower red mottle content shows moister conditions and less oxidation. Profile type D is a young soil judging by the few genetic horizons developed in the profile. This soil has the lowest degree of development, with a thin oxidized layer and the oxidation has not reached the shallow sulfidic material.

According to the information above, there is a good relationship between the characteristics of the profile types and their positions on the plain. Therefore, the characteristics of a profile type could be described as a typical soil in an area. As a result, area of profile type A is severely dry and the water level is below the sulfidic material, while the area of profile type B is also in a very dry condition, but here the water level is above the sulfidic material, preventing acidification. The area of profile type C is similar to the area of profile type B but slightly moister. The area of profile type D is relatively wet and the water table is close to the surface, with water submerging the sulfidic material.

Illustrations of phases of profile development are shown in Fig. 5. Soils of profile type A are well developed or old acid sulfate soils and are developing in the stage of weathering after extremely acid conditions have passed. Soils of profile type B are younger acid sulfate soils; they could further develop into soils of profile type A if aeration occurs continuously

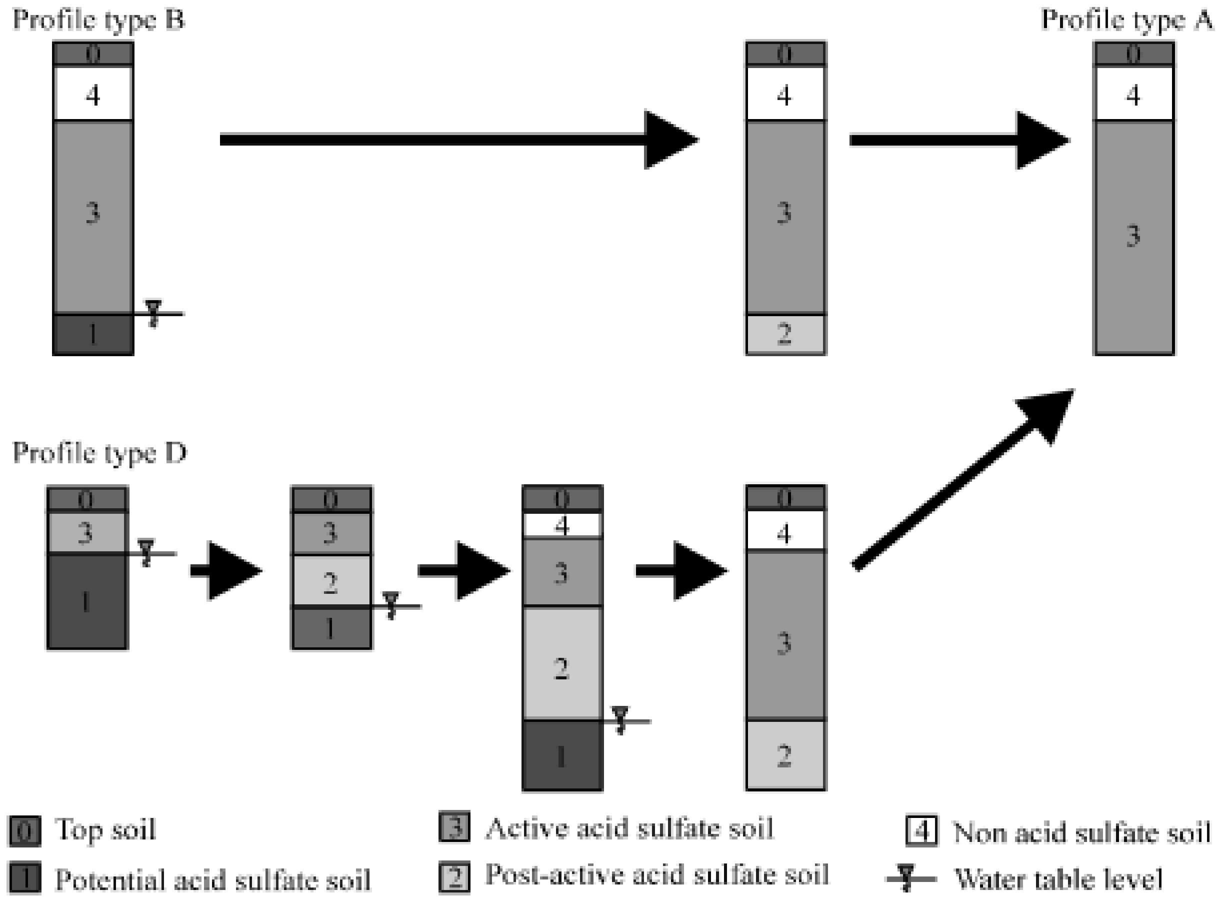

Fig. 5: Illustrations of the steps of acid sulfate soil-profile development

until the sulfidic materials in these profiles are fully exposed to oxidation. Soils of profile type D are the youngest acid sulfate soils; they could further develop into soils of profile type B and A if the area is drained or there is a lowering of the water table. In the later stages of development, the potential acid sulfate soil would be oxidized and developed into active acid sulfate soil; concentrations of jarosite and redoximorphic features and extremely acid conditions would be generated. Subsequently, if the oxidation process continued, active acid sulfate soil would develop into post-active acid sulfate soil. Moreover, acid in the upper part of post-active acid sulfate soil would be weathered and leached out. Then, the post-active acid sulfate soil would become non-acid sulfate soil and the form of profile type D would become similar to of profile type B. Subsequently, the oxidation would likely reach the sulfidic material and the form of profile would be similar to of profile type A.

The paleogeography and evolution of the Chao Phraya Delta or the Lower Central Plain were studied by Tanabe *et al*. (2003) they presented a paleo-shoreline with mangrove area in six periods. The report was confirmed that sulfidic materials were accumulated in the plaeoenvironment. Based on this study, we can show that profiles of type A are distributed in the areas where mangrove thrived in the period of 8-6 cal kyr BP and continued until 4 cal kyr BP. Profiles of type B are distributed in the areas where mangrove adjusted in the period of 3-2 cal kyr BP. Profiles type C and D are distributed in the areas where mangrove developed after 2 cal kyr BP until the present. This shows that mangrove was developed in area of profile type A for long periods, thus, abundant of wood fragments were accumulated in these profiles. In comparison, the areas having profiles of type B were developed as tidal flat with mangrove vegetation for a short period. At that time, fewer mangrove fragments were accumulated in the sediment, so wood fragments were not observed in these profiles. For a similar reason, in the development in the area having profiles of type C the period for mangrove growth and accumulation in sediment was limited. In contrast to the area with profiles of type D, mangrove has only recently been developed and deposited in the sediments as wood fragments.

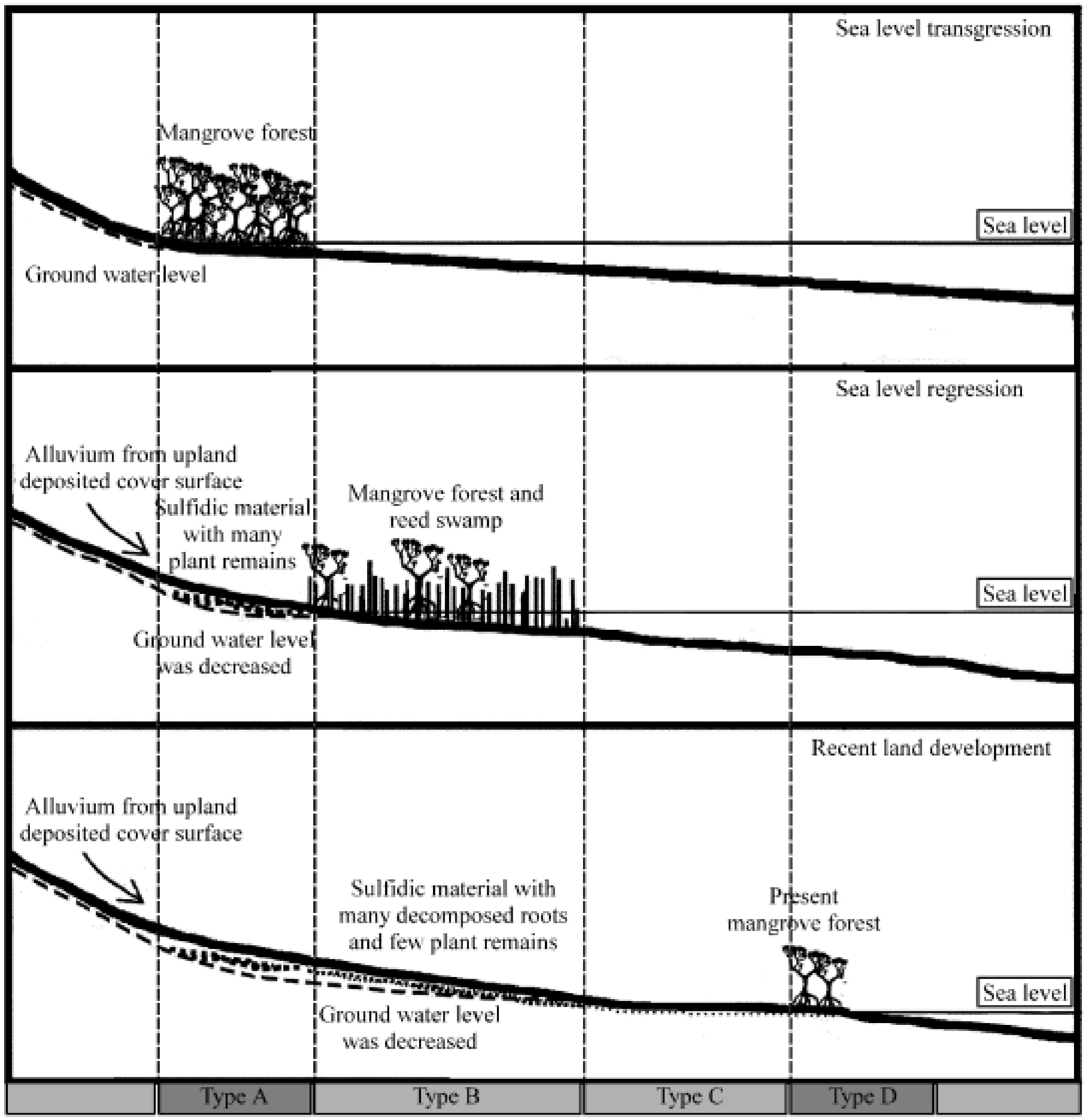

Fig. 6: Schematic cross-section of paleoenvironment of the Lower Central Plain in the Holocene

Model of the Formation of Acid Sulfate Soil in the Lower Central Plain of Thailand

A cross-sectional diagram of the Lower Central Plain is presented for three periods to illustrate the paleoenvironment of acid sulfate soil formation, showing its division into areas of profile types A, B, C and D and their distributions in Fig. 6.

During the period of the middle Holocene, sea transgression covered most of the present Lower Central Plain including the whole area of acid sulfate soil distribution. In this period, the area of the upper boundary of the delta plain, the area of profile type A, was a tidal flat under mangrove vegetation. Numerous sulfidic materials were formed under these conditions. After this time, the paleo-shoreline moved to the Gulf of Thailand and the environment of area was changed causing the death of mangrove tresses and accumulation of deltaic sediment. The dead mangroves were deposited as fragments in the sediment containing sulfidic materials and remained as abundant wood fragments in these profiles.

The area of the lower boundary of the deltaic plain, the area of profiles of type B, was submerged as a shallow marine area during the sea transgression. Subsequently, in the period of the late Holocene, the area of profile type A emerged and the environment of area of profiles type B became tidal flat, which was dominated by swamp with grasses or reeds. The progradation rate during this stage was rapid because of the inappropriate condition for mangrove development. Other vegetation such as salt grasses and reeds were better able to survive in this period. Sulfidic materials in the profiles of type B were accumulated in this environment. Then, the paleo-shoreline mitigated and deltaic sediment was deposited, covering the surface of this area and causing the death of salt grasses and reeds. Their roots were preserved in the sediment containing sulfidic materials, remaining as decayed roots in the profiles.

Profiles of type C and D are distributes in the area of the present tidal plain. This area was submerged as an open bay environment in the period of the middle Holocene and a shallow marine environment in the period of the late Holocene. Subsequently, the area has changed to a tidal plain environment in recent times. In the period closest to the present, rapid deltaic progradation occurred in the area with profile type C; the rate was relatively fast compared with that of the area of profile type B. Rapid progradation brought inappropriate conditions for plant growth; only a small amount of sulfidic material was accumulated due to the lack of organic source material for its formation. The conditions restricted the development of acid sulfate soil in the area of profile type C.

Finally, profiles of type D are distributed in the area of the present shoreline at the head of the Gulf of Thailand. The area is commonly occupied with mangrove vegetation, at least where it has not yet been removed for land reclamation. The locations of profiles L14 and L15 are in the estuaries of the Tha Chin and Bang Pakong Rivers, respectively. This is a recent environment of sulfidic material formation due to the influence of the tidal flat with mangrove vegetation. Sulfidic materials have been accumulated in a shallow zone below the surface including the remains of mangrove as wood fragments. Below this, sediment from the uplands has been deposited on the surface as a thin layer but the area is still controlled by marine conditions.

CONCLUSIONS

We found a good correlation for the characteristic of forms of soil profile types and sediments with their distributions. This correlation well described acid sulfate soil formation and the evolution of the Lower Central Plain of Thailand. The characteristics of the profile types and their distributions validated the known paleogeography of regional conditions in the plain.

Acid sulfate soils in the Lower Central Plain have been formed according to the environmental change of the plain. Sulfidic materials accumulated in relation to the coastal change of the plain during the period of the middle to late Holocene. Developed acid sulfate soils; soils of profile type A and B, are distributed in the deltaic plain in the inner part where there was tidal flat with mangrove vegetation to grass and reed swamp in the middle to late Holocene. Sulfidic materials were accumulated in this environment. Mangrove and plant roots were the sources of organic material for the sulfidic formation process in the soils. Non acid sulfate soils; soils of profile type C and young acid sulfate soils; soils of profile type D, are distributed in the tidal flat along the present coast. This area where once shallow marine to open bay area in the middle to late Holocene. At that time, the conditions were inappropriate for terrestrial plant growth. Sulfidic material did not form intensively in the area of profile type C due to a lack of organic material for sulfidic material formation and the shell fragments and calcareous concentration, which caused base-rich condition preventing acidification. In contrast, plentiful sulfidic material was recently accumulated in the area of profile type D; here, the soils have been developing in the present estuary conditions, which are appropriate environments for the accumulation of sulfidic materials.

The related characteristics of profile types A, B and D reveal that the soils in the Lower Central Plain of Thailand have gradually passed through phases of development. Presently, soils of profile type A have the highest degree of development, followed by soils of profile types B and finally D with the lowest degree of development. The different developments of the soil profiles were caused by differing influences of oxidation and depth variations of the sulfidic material and the water table level of the area. Increasing of penetration of oxygen into the reduced horizon can cause a young acid sulfate soil to further developed into extremely an acidic condition and a higher degree development.

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REFERENCES

Beek, K.J., W.A. Blokhuis, P.M. Driessen, N. van Breemen and L.J. Pons, 1980. Problem Soils: Their Reclamation and Management. In Land Reclamation and Water Management. ILRI Publication 27, ILRI, Wageningen, pp: 43-72.

Berner, A.R., 1984. Sedimentary pyrite formation: An update. Geochim. Cosmochim. Acta, 48: 605-615.

Brinkman, R. and L.J. Pons, 1968. A pedo-geomorphological classification and map of the Holocene sediments in the coastal plain of the three Guyanas. Soil Survey Paper No. 4, Netherlands Soil Survey Institute, Wageningen.

Dawson, B., 2009. Acid Sulphate Soil. Professional Development Loughborough University, UK.

Dent, D.L. and L.J. Pons, 1995. A world perspective on acid sulphate soils. Geoderma, 67: 263-276.

Department of Environment and Conservation, 2009. Government of western Australia acid sulfate soils. http://portal.environment.wa.gov.au/portal/page?_pageid=53,34347&_dad=portal&_schema=PORTAL.

Department of Natural Resources and Water, 2009. Acid sulfate soils. http://www.nrw.qld.gov.au/land/ass/.

Dheeradilok, P. and W. Kaewyana, 1986. On the quaternary deposits of Thailand. GEOSAE V Proc. Vol. I, Geol. Soc. Malaysia Bull., 19: 515-532.

Diemont, H., L.J. Pons and D.L. Dent, 1993. Standard Profiles of Acid Sulphate Soils. In: Ho Chi Minh City Symp. on Acid Sulphate Soils, Dent, D.L. and M.E.F. Mensvoort (Eds.). ILRI Publ., Wageningen, pp: 51-59.

Fanning, D.S., 2002. Acid Sulfate Soils, Definition and Classification. In: Encyclopedia of Soil Science, Lal, R. (Ed.). Taylor and Francis, USA., ISBN: 978-0-8493-3830-4, pp: 11-13.

Funabiki, A., S. Haruyama, V.Q. Nguyen, V.H. Pham and D.H. Thai, 2007. Holocene delta plain development in the Song Hong (Red River) Delta, Vietnam. J. Asian Earth Sci., 30: 518-529.

Hara, Y., K. Takeuchi and S. Okubo, 2005. Urbanization linked with the past agricultural landuse patterns in the urban fringe of the deltaic Asia mega-city: A case study in Bangkok. Landscape Urban Plan, 73: 16-28.

Kyuma, K., 2004. Paddy Soil Science. Trans Pacific Press, Melbourne, ISBN: 9781920901004, pp: 280.

Land Development Department, 2006. Acid sulfate soil distribution map of Thailand. Land Development Department, Bangkok.

Melville, M.D., I. White and C. Lin, 1993. The origins of acid sulfate soils. Proceedings of the 1st National Conference on Acid Sulfate Soils, (ASS'93), Coolangatta, pp: 19-25.

Poleman, J.N.B., 1973. Soil Material Rich in Pyrite in Non-Coastal Areas. In: Acid Sulphate Soils, Dost, H. (Ed.). ILRI Publ. 18, Vol. 11, International Institute for Land Reclamation and Improvement, Wageningen, pp: 197-207.

Pons, L.J. and W. van Der Kevie, 1969. Acid Sulphate Soils in Thailand: Studies on the morphology, genesis and agricultural potential of soils with cat-clay. Soil Survey Report No. 81, Department of Land Development, Bangkok.

Pons, L.J., 1973. Outline of the genesis, characteristics, classification and Improvement of acid sulphate soils. Proceedings of International Symposium on Acid Sulphate Soils, Aug. 13-20, Wageningen, pp: 3-27.

Pons, L.J. and N. van Breemen, 1982. Factor influencing the formation of potential acidity in tidal swamps. Proceedings of the Bangkok Symposium on Acid Sulphate Soils, Second International Symposium on Acid Sulphate Soils, Bangkok, Jan. 18-24, Thailand, pp: 37-51.

Rau, J.L. and P. Nutalaya, 1983. Geology of Bangkok clay. Geo. Soc. Malaysia Bull., 16: 99-116.

Sammut, J. and R. Lines-Kelly, 2004. An introduction to acid sulfate soils. NSW Department of Primary Industries, Orange.

Sammut, J., I. White and M.D. Melville, 1994. Stratification in acidified floodplain drains. Wetlands, 13: 49-64.

Sinsakul, S., 1997. Country report: Late quaternary geology of the Lower Central Plain, Thailand. Proceedings of the International Symposium on Quaternary Environment changes in the Asia and Western Pacific Region. October 14-17, University of Tokyo, Tokyo.

Sinsakul, S., 2000. Late quaternary geology of the Lower Central Plain, Thailand. J. Asian Earth Sci., 18: 415-426.

Slager, S., A.G. Jongmans and L.J. Pons, 1970. Micromorphology of some tropical alluvial clay soils. Eur. J. Soil Sci., 21: 233-241.

Soil Survey Staff, 1993. Soil Survey Manual. 1st Edn., United States Department of Agriculture, Washington, DC.

Soil Survey Staff, 2006. Keys to Soil Taxonomy. 10th Edn., Department of Agriculture, Natural Resources Conservation Service, Washington DC., USA.

Somboon, J.R.P., 1988. Paleontological study of the recent marine sediments in the Lower Central Plain, Thailand. J. Southe. Asian Earth Sci., 2: 201-210.

Somboon, J.R.P., 1990. Geomorphology of the Chao Phraya Delta, Thailand. Ph.D. Thesis, Kyoto University.

Somboon, J.R.P. and N. Thiramongkol, 1992. Effect of sea-level rise on the North coast of the bight of Bangkok, Thailand. Malaysian J. Trop. Geo., 24: 3-12.

Tanabe, S., Y. Saito, Y. Sato, Y. Suzuki, S. Sinsakul, S. Tiyapairach and N. Chaimanee, 2003. Stratigraphy and holocene evolution of the mud-dominated Chao Phraya Delta, Thailand. Quaternary Sci. Rev., 22: 789-807.

USDA-NRCS, 1996. Soil survey laboratory methods manual. Soil survey investigations. Report No. 42, Version 3.0 USDA-NRCS.

Umitsu, M., S. Tiyapairach, N. Chaimanee and K. Kawase, 2002. Late holocene sea-level change and evolution of the Central Plain, Thailand. Proceedings of the Symposium on Geology of Thailand, 26-31 August 2002, Bangkok.

Vacharotayan, S. and T. Attanandana, 1985. Potential productivity of acid sulfate soils for crop production in Thailand. Proceedings of the International Seminar on Environmental Factors in Agriculture Production, (EFAP'85), Bangkok, pp: 389-406.

Van Breemen, N., 1973. Soil Forming Processes in Acid Sulphate Soils. In: Acid Sulphate Soils, Dost, H. (Ed.). International Institute for Land Reclamation and Improvement, Wageningen, pp: 66-130.

Van Breemen, N., 1976. Genesis and solution chemistry of acid sulfate soils in Thailand. Agric. Res. Rept. 848. PUDOC, Wageningen, pp: 263.

Van Breemen, N., 1982. Genesis, Morphology and Classification of Acid Sulphate Soils in Coastal Plains. In: Acid Sulfate Weathering, Kittrick, J.A., D.S. Fanning and L.R. Hossner (Eds.). SSSA, Madison, pp: 95-108.

Vijarnsorn, P. and S. Panichapong, 1977. Characteristics and classification of paddy soils in the Chao Phraya Delta, Thailand. Soil Survey Division, Department of Land Development Department, Bangkok.

Vlek, P., 1971. Some morphological physical and chemical aspects of acid sulphate soils in Thailand. Report SSR-84, Soil Division, Department of Land Development, Bangkok.

Yokoyama, T. and I. Koizumi, 1989. Marine transgressions on the pleistocene pecangan formation in the Sangiran area, central Java, Indonesia. Palaeogeogr. Palaeocl. Palaeoec., 72: 177-193.