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Composition and Provenance of Clay Minerals in the Northern Part of Lake Tonle Sap, Cambodia

Masafumi OKAWARA * and Shinji TSUKAWAKI **

Abstract

Unique sedimentary processes under the control of drastic seasonal fluctuations in its water level and area are expected in Lake Tonle Sap, the largest lake in Southeast Asia. As a part in a series on pursuing the sedimentary processes and their temporal changes of the lake, sediments and soils were collected and examined from the northern part of the lake and its adjacent water systems and areas in order to reveal composition and provenance of clay minerals distributed in the northern part of the lake.

Illite, kaolin minerals, smectite and chlorite were commonly identified from the surface and suspended sediments of the lake. Judging from illite and chlorite are not detected in the sediment and soil samples from rivers and the Alluvial plains around the lake but the bottom sediments from the Tonle Sap River that connects the lake with the Mekong River yield a certain amount of them, it is stated that illite and chlorite recognized in the lake sediments were derived from the Mekong River. Since illite and chlorite are not detected in the lower part of the cored sediments from the northern part of the lake in spite of the upper part contains them, appearance of illite and chlorite in the upper part of the core indicates that a change of sediment transport in water systems around the lake took place at about 5,000 years BP.

Key words : Cambodia, Lake Tonle Sap, Mekong River, clay minerals, sedimentation

I. Introduction

Lake Tonle Sap, the largest lake in Southeast Asia, lies in central Cambodia. Since the lake is known as "the mud ocean" that refers to deep brown colour of the water all year round due to a large amount of muddy suspended sediments in water, clay minerals would act an important role of the sedimentary processes of the lake. Further, the water area of the lake expands drastically in rainy seasons due to a great amount of water supply mainly from the Mekong River through the Tonle Sap River that connects the lake with the Mekong River. Such setting holds out a promising prospect for investigations of unique sedimentary processes in the lake under the control of seasonal fluctuations in water

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level and area due to alternating rainy and dry seasons, characteristics of the tropical monsoon region. However, only a little number of limnological and sedimentological studies has been carried out in the lake and the adjacent river systems in Cambodia (*e.g.*, Carbonnel and Guiscafré, 1962 - 63; Mitusio *et al.*, 1970; Lao, 1992, 1993; Tsukawaki *et al.*, 1994; Tsukawaki and Lao, 1995).

Details of the sedimentary sequence of the lake bottom were first reported by Carbonnel and Guiscafré (1962 - 63). They recognized the upper "*vase actuelle*" and the lower "*vase ancienne*" within the bottom sediments on the basis of lithological investigation of several cored sediments obtained from the lake, and the base of the upper sequence was dated at 5720 ± 300 years BP. They also noted that illite and montmorillonite are the prevailing clay minerals in the upper sequence in spite of kaolinite is common in the lower sequence. Tsukawaki *et al.* (1994) preliminarily illustrated sediment transport in the water system in Lake Tonle Sap and the adjacent river systems in Cambodia based on compositional features of both sandy sediments and clay minerals in the sediments from the lake and the adjacent rivers, and surface soils around the lake. They concluded that within all sediments derived from the Mekong River to the lake through the Tonle Sap River by back currents during the rainy season, sandy sediments are settled restrictedly in the southern marginal part of the lake but clay minerals reach to the northernmost part of the lake as suspended sediments.

Taking the above-stated previous studies into account, the "Tonle Sap 96" project was carried out as the first step to grasp the present sedimentary processes of the lake and to reconstruct environmental history of the lake over a certain period. Lithological features and the results of radiocarbon datings of the cored sediments were already reported (Mildenhall, 1996MS; Tsukawaki, 1997; Tsukawaki *et al.*, 1997). On the bases of these analytical results, the present article describes composition and provenance of clay minerals in the surface sediments from the northern part of the lake and illustrates their temporal changes.

II. Environmental Settings of Lake Tonle Sap

Figure 1 shows the topographic features of Cambodia. Lake Tonle Sap lies in the central part of a gentle topographic depression with a NE-SW trend in central Cambodia. The Cardomon Chain and the Elephant Mountains with the highest peak of 1,744m above sea level, and the Dangrek Escarpment, 765 m above sea level, all composed mainly of sedimentary rocks of the Upper Indosinias Formation ranging from Cretaceous to Palaeocene in age (Gubler, 1933; Saurin, 1935; United States Geological Survey, 1971; ESCAP, 1993a) form the western, southern and northern boundaries of the depression, respectively. The overwhelming part of the depression is covered with unconsolidated clay, silt, sand and gravel and a variety of soil types such as acidic lithosoil and lateritic clay which are typical soil types in a humid tropical region (United States Geological Survey, 1971). Several topographic highs such as the Kuleng Mountains and Mt. Krom are distributed in the northern part of the depression.

Lake Tonle Sap is a long, narrow and gourd-shaped lake, having a NW-SE longitudinal axis of 120 km and the maximum width of 40 km at the lowest water level in the end of the

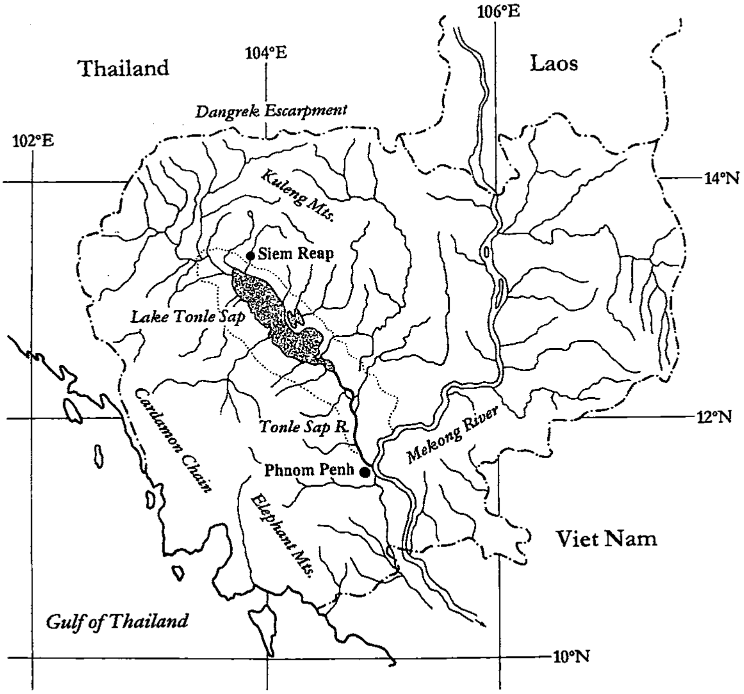

Fig. 1 Location of Lake Tonle Sap and topographic features of Cambodia. Dotted line indicates presumable water area at the highest water level (partly modified from Tsukawaki *et al.*, 1994).

dry season. The water area is about 3,000 km^2 at the lowest water level swells more than fivefold at the high water level in the end of rainy season thus the lake lacks fixed coastal lines. At the lowest water level, the depth is very small less than one metre wholly and the high water level the deepest parts are no more than 10 m (Ministry of Public Works and Transport, Kingdom of Cambodia, 1999). Forests in the coastal areas of the lake are inundated during the high stands of water level as well as paddy fields.

There is a network of numerous rivers and streams flowing directory into the lake from its surrounding areas, but their flow is adequate only in the rainy seasons, except for a certain number of rivers such as the Siem Reap River originating in the Kulěng Mountains that are a salient topographic high. Small rivers and streams around the lake partly flood in the rainy season. Again in the rainy season, water through this group of rivers that contains a large amount of muddy suspended sediment derived mainly from surface soils distributed around the lake flows into the lake. On the other hand, water of the Mekong River, originating in and bringing much melted snow from the northern slopes of the Himalayas in the western part of China together with the heavy monsoon rain also flows into the lake. Therefore, water of the Tonle Sap River flows backwards to the lake in the rainy season, and water level of the river increases more than eight metres in comparison with it in the dry season. The actual amount of sediment supply to the lake through the Tonle Sap River has not been still known, but Delvert (1993) estimated that water of the river carries about 1.7 × 10^7 grammes of suspended sediments per second to the lake during its highest water level. The inflow from the rivers and streams around the lake decreases markedly in dry season and water flows out from the southern part of the lake to the Mekong River through the Tonle Sap River.

The lake water is reddish brown to yellowish brown in colour all year round due to a large amount of muddy suspended sediments contained in the water, and extremely low in transparency even in the dry season (Mitusio *et al.*, 1970). The temperature of surface water is extremely high, 26 - 30 ℃, all year round and the pH is almost neutral (Mitusio *et al.*, 1970; Lao, 1992, 1993; Tsukawaki *et al.*, 1994).

III. Sampling Method and Analytical Procedures

The sediment and soil samples used for the present study were collected in May 1996 from Lake Tonle Sap, the Siem Reap River and in and around the West Baray water reservoir, and in August 1997 from the Siem Reap River and in and around the East Baray water reservoir (Fig. 2). The Siem Reap River flowing all year round is judged as one of the important source of sediment to the northern part of the lake, since most rivers supplying sediments into the lake flow only in the rainy seasons. The West and East Baray water reservoirs were constructed north of the lake both at about 1,000 years BP in the Khmer Dynastic period. Since water of the Siem Reap River were used for filling up the reservoirs, there is a possibility that sediments derived from the river have been accumulated in the bottom of them over a thousand years. The bottom sediments from the Tonle Sap River in Phnom Penh City collected in March 1993 (Fig. 2, upper left, Tsukawaki *et al.*, 1994; Tsukawaki and Lao, 1995) were reanalyzed in the present study to make a precise comparison with results of the above-mentioned samples.

An 130 cm-long stainless-steel pipe Phleger-type core sampler with a 16 kg weight and a small dredge sampler, 20 cm in width, were utilized to obtain cored and surface sediments from the lake, respectively. Two cored sediments, TS96-1 and 2, both about one metre in length, and four surface sediments, TS96-1, 2, 3 and 4 were obtained in the northern part of the lake. On the other hand, the surface sediment sample TS96-5 were collected from the surface emerged at the sampling. Surface water from the northern part of the lake (TS96-9) was scooped directly by a sampling bottle to grasp clay mineral composition of the suspended sediments in the water. Surface soil samples south of the West Baray water reservoir (TS96-7), north of the East Baray water reservoir (EB97-AD) and the bottom sediments of the Siem Reap River (TS96-6 and EB97-SR) were obtained by scooping. The bottom sample of the West Baray reservoir (TS96-WB1) was obtained using by the core sampler. On the other hand the soil samples from the East Baray reservoir (EB97-S) were recovered by a six metres long hand auger.

The core TS96-1 used in the present study was cut first vertically into two halves by a fishing line immediately after the sampling. One of the cutting surface was shaved and brushed well by a stainless-steel spatula and a spraying water atomiser for detailed visual

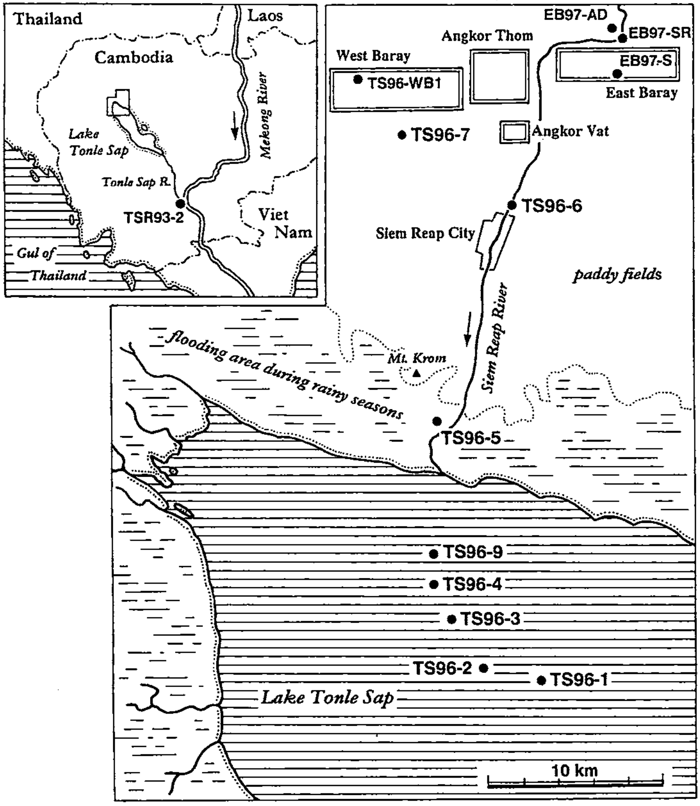

Fig. 2 Bottom surface sediment and lake water sampling sites in the northern part of Lake Tonle Sap, bottom sediment sampling sites in the Siem Reap River and sampling sites of surface soils in the Alluvial plain, and bottom sediment sampling sites in the Tonle Sap River in Phnom Penh City (upper left).

observations. After visual observations and core descriptions were made, a certain centimetres thick slices were sectioned for clay mineralogical investigations and radiocarbon datings.

For clay mineralogy, samples were first disaggregated in distilled water for four hours, and clay fractions, approximately less than 2μm in diameter, were concentrated by a centrifuge. Then, clay fractions were dried at room temperature and prepared for X-ray analysis. X-ray analysis was carried out on oriented samples on glass slides. X-ray diffraction patterns of the samples were recorded with a Mac Science (MXP-3 AHF) X-ray powder diffractometer equipped with a graphite monochromator, using Cu-Kα radiation, tube voltage 40 kV, tube current 20 mA, slit system of 0.5° − 0.30 mm and scanning speed of 2.00° /min. X-ray analysis was performed for untreated specimens and such treated specimens after ethylene glycol-solvation, Mg-saturation and glycerol-solvation, HCl-treatment, K-saturation, and one hour heating at 300℃ and 600℃.

IV. General Features of Samples and Sampling Sites

General features of the samples used in the present study are as follows. The surface soils in the East Baray water reservoir and the surface sediments from the Tonle Sap River in Phnom Penh City are described based on Tsukawaki *et al.* (1998) and Tsukawaki *et al.* (1994), respectively.

1) Surface sediments of Lake Tonle Sap

Four bottom surface sediments TS96-1, 2, 3 and 4 were obtained from the northern part of Lake Tonle Sap at water depths of all around 0.9 m. One surface sediment sample TS96-5 was collected from the land area on the north of the lake, but the sampling site becomes a part of the lake floor when the water level is high.

The sediments from the former four sites consist of light olive grey or reddish brown soft or soupy mud. Mud contents of them are more than 90% in weight. Yellowish brown clays predominate muddy sediments with small amounts of quartz and biogenic materials such as sponge spicules, pollens and diatoms. Sandy sediments are composed mainly of very fine- to fine-grained quartz with a little amount of lateritic rock fragments. Plant debris and molluscan shell fragments are commonly contained in the sediments. Freshwater ostracodes, and squamae and teeth of fish are occasionally recognized in the sandy sediments.

On the other hand, the latter is composed of pale orange sandy mud. Sandy sediments consist mainly of very fine- to fine-grained quartz with a little amount of lateritic rock fragments. Muddy sediments consist mainly of yellowish brown clays with a certain amount of quartz.

2) Surface sediments of Tonle Sap River

The sample TSR93-2, one of the five bottom surface sediments recovered from the Tonle Sap River in Phnom Penh City (Tsukawaki *et al.*, 1994; Tsukawaki and Lao, 1995), is moderately brown mud. The mud content is about 80% in weight. Moderately brown clays predominate muddy sediments with small amounts of quartz and biogenic materials such as diatoms and sponge spicules. Almost of all sandy sediments are very well sorted fine-grained sand, predominantly irregular-shaped quartz, feldspars, muscovite and biotite with a small amount of magnetite and lithic fragments.

3) Surface sediments of Siem Reap River

Surface sediments from the Siem Reap River at Siem Reap City (TS96-6) and on the north of the East Baray water reservoir (EB97-SR) are both composed chiefly of yellowish pale orange muddy fine- to medium-grained sand. The mud content of the former is less than 20% in weight. Sandy sediments consist of fine- to medium-grained quartz with a small amount of lateritic rock fragments Most of quartz grains are stained in reddish colour. Muddy sediments are composed chiefly of pale yellowish brown clays.

4) Alluvial soils in and around West and East Baray water reservoirs

Soil sample from the Alluvial plain south o the West Baray water reservoir (TS96-7) is composed of pale orange clay in which almos no sandy sediments are contained. On th other hand, the bottom surface sediment from the deepest part of the reservoir at th water depth of 8.0 m (TS96-WB1) consis mainly of pale orange coloured sandy clay Fine- to medium-grained quartz predominate sandy sediments in addition to a smal amount of lateritic rock fragments.

The samples from the East Baray water reservoir taken at three horizons of an auger hole (EB97-S) consist of yellowish brown clayey sand (160–180 cms), light grey sandy clay (360–380 cms) and yellowish grey clayey sand (560–580 cms). The sandy sediments of them are composed mainly of fine- to medium-grained quartz with a small amount of lateritic rock fragments. The radiocarbon age of sediments from 160 - 180 cms is 2540 ± 100 years BP (Tsukawaki *et al.*, 1998). The surface soil sample on the north of the reservoir (EB97-AD) consists of pale orange clay. Almost no sandy sediments are contained in the sample.

5) Cored sediments of Lake Tonle Sap

The cored sediments TS96-1 was obtained from the flat lake floor almost in the centre of the northernmost part of Lake Tonle Sap about 10 km southwest off the rivermouth of the Siem Reap River. The water depth at sampling was 0.9 m. Sediments from six horizons of the core were analyzed in the present study. Lithological features of the core based on Tsukawaki *et al.* (1997) and Tsukawaki (1997) are as follows (Fig. 3).

The core, 125 cm in length, is composed of ight olive grey soupy mud in the upper 22 cm and homogeneous or bioturbated muds in the ower. In the lower part, a 25 cm thick light olive grey homogeneous mud overlies a 55 cm hick dusky yellowish green bioturbated mud, followed by an about 25 cm thick greyish olive green homogeneous mud. The lower bioturbated and homogeneous muds are relatively compact rather than overlain homogeneous mud. Parallel laminations are rarely developed in part of the bioturbated mud. The sand is composed mainly of very fine-grained quartz, lateritic rock fragments and charred wood debris. The mud consists mainly of clays with a small amount of biogenic materials such as diatoms and sponge spicules. A molluscan shell and shell fragments layer is intercalated at 26 cm below the lake floor. The radiocarbon ages of sediments from 42 - 48, 100 - 106 and 110 - 116 cms are 5081 ± 86, 6233 ± 84 and 6505 ± 88 years BP, respectively (Mildenhall, 1996MS).

In addition, the core TS96-2 obtained about 2 km WNW of the site TS96-1 is lithologically correlatable with the core TS96-1. A slight but clear increase of sandy sediment contents from 0 to 10% is recognized at the horizon about 55 cms below the lake floor in the core. The radiocarbon ages of sediments from 48 - 53 and 103–108 cms are 5620 ± 120 and 6070 ± 90 years BP, respectively (Tsukawaki *et al.*, 1997).

V. Results

Figures 4, 5, 6 and 7 show selected X-ray diffraction patterns for the untreated and treated specimen of the surface sediments from Lake Tonle Sap (TS96-3), the Tonle Sap River (TSR93-2), the Siem Reap River (TS96-6), and the surface soils south of the West Baray water reservoir (TS96-7). The patterns for the untreated specimen of the cored sediments from the lake are also shown in Fig. 8.

1) Surface and suspended sediments of the northern part of Lake Tonle Sap

Figure 4 shows the X-ray diffraction patterns for untreated and treated specimen of the 1 cm thick surface sediments TS96-3 from the northern part of Lake Tonle Sap. The untreated specimen has a broad reflexion peak around 15.1 Å, relatively sharp peaks at 10.0, 7.1 and 3.34 Å. The sharp peak at 3.34 Å is attributed to quartz. The broad peak at 15.1 Å shifts to about 17.0 Å by ethylene

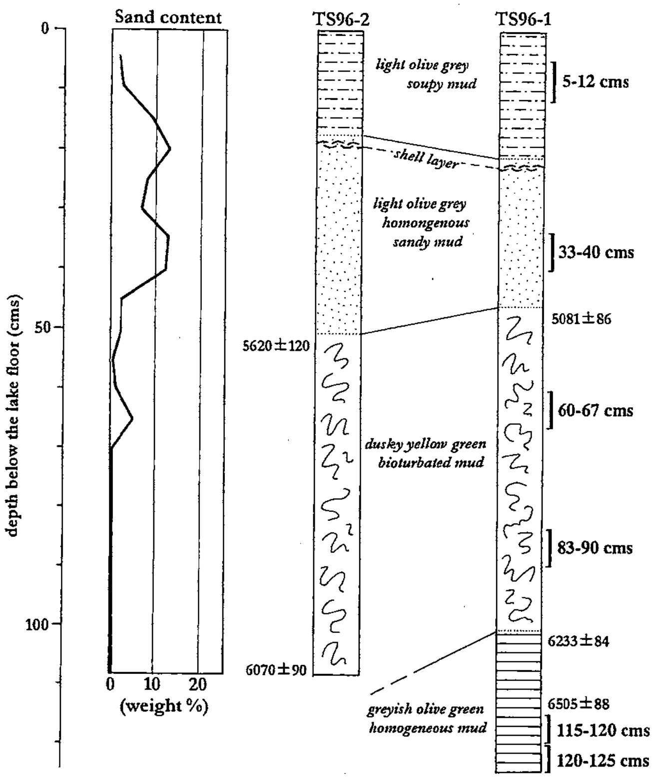

Fig. 3 Simplified lithological columnar sections of the cored sediments TS96-1 and 2 from the northern part of Lake Tonle Sap with radiocarbon datings (Simplified from and adapted to Tsukawaki, 1997). Thick lines beside the column indicate sampling horizons for clay mineralogy.

glycol-solvation and it shifts to about 18.0 Å by Mg-saturation and glycerol-solvation. This indicates that the broad peak is attributed to smectite. However, small peaks around 14.5 Å are observed in untreated, ethylene glycole-solvated, and Mg-saturation and glycerol-solvated specimens, and the peak does not change by K-saturation. These facts suggest the presence of a small amount of chlorite in the sample. The sharp peak at 10.0 Å and its high order reflexion do not change by glycolations, HCl-saturation and 300℃ heating tests, indicating that the peak at 10.0 Å is attributed to illite. The basal peak at 7.1 Å that is not affected by HCl-treatment is attributed to kaolin minerals. The X-ray diffraction patterns of untreated and treated specimen of other four samples (TS96-1, 2, 4 and 5) from the lake surface and those of the suspended sediments in the lake water (TS96-9) show very similar to those of TS96-3. Thus, clay minerals of the surface sediments from the northern part of Lake Tonle Sap and the suspended sediments in the lake water are composed mainly of smectite, chlorite, illite and kaolin minerals.

2) Surface sediments of Tonle Sap River

Figure 5 shows the X-ray diffraction patterns for untreated and treated specimens of 2 cms thick surface sediments of sample TSR93-

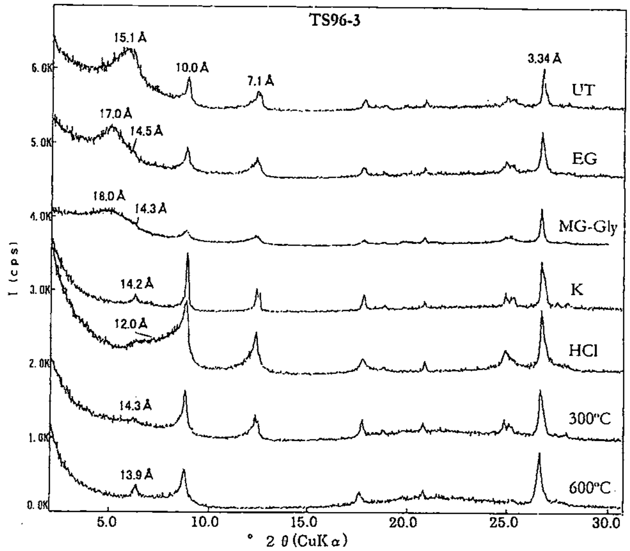

Fig. 4 X-ray diffraction patterns for oriented aggregates of untreated and treated surface sediment sample TS96-3 from the northern part of Lake Tonle Sap.
UT : untreated sample, EG : ethylene glycol solvated sample, MG-Gly : Mg-saturated and glycelrol-solvated sample, K : K-saturated sample, HCl : HCl-treated sample, 300℃ and 600℃ : thermal treated samples for one hour at 300℃ and 600℃, respectively.

2 from the Tonle Sap River in Phnom Penh City. The untreated specimen has reflexion peaks at 14.4, 10.1, 7.2 and 3.34 Å. The peak at 3.34 Å is attributed to quartz. After ethylene glycol-solvation, the peak at 14.4 Å separates into two weak peaks at 17.0 and 14.0 Å, and the former peak shifts to about 18.0 Å by Mg-saturation and glycerol-solvation, thus the diffuse peak are attributed to smectite. On the other hand, the latter weak peak at about 14.0 Å increases its intenseness and is slightly contracted in space after heating at 600℃ while higher order reflexion disappeared. In addition, the peak at 14.4 Å does not change by K-saturation, indicating that the peak is attributed to chlorite. The basal peak at 7.2 Å is not affected by HCl-treatment although the intensity weakened slightly. Therefore, the basal reflexion peak at 7.2 Å is attributed to chlorite overlapping with kaolin minerals. The 10.1 Å reflexion peak does not change by HCl-treatment and 300℃ heating tests, indicating that the reflexion peak is attributed to illite. Accordingly, clay minerals of the surface sediments from the Tonle Sap River in Phnom Penh City are composed mainly of smectite, chlorite, illite and kaolin minerals.

3) Surface sediments of the Siem Reap River

Figure 6 shows the X-ray diffraction patterns for untreated and treated specimens of the surface sediments TS96-6 from the Siem Reap River in Siem Reap City. The untreated specimen shows a broad and weak reflexion peak around 14.6 Å, a weak peak at 10.0 Å, a sharp and strong peak at 7.2 Å, and sharp peaks at 3.58 and 3.34 Å. The sharp peak at 3.34 Å is attributed to quartz. The weak reflexion peak around 14.6 Å diffuses about

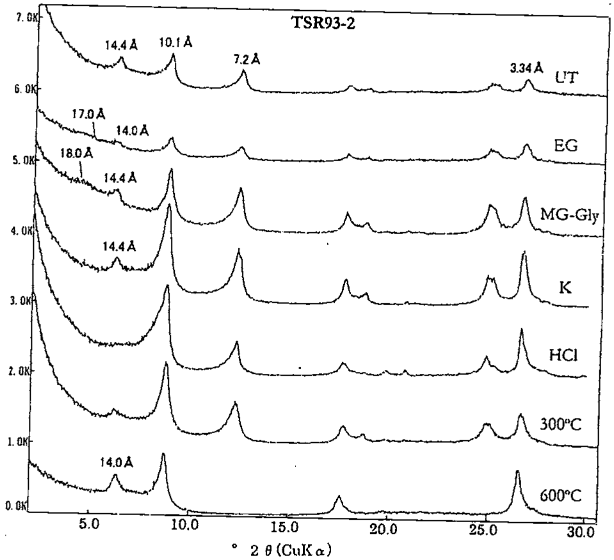

Fig. 5 X-ray diffraction patterns for oriented aggregates of untreated and treated surface sediment sample TSR93-2 from the Tonle Sap River in Phnom Penh City.
UT : untreated sample, EG : ethylene glycol solvated sample, MG-Gly : Mg-saturated and glycelrol-solvated sample, K : K-saturated sample, HCl : HCl-treated sample, 300℃ and 600℃ : thermal treated samples for one hour at 300℃ and 600℃, respectively.

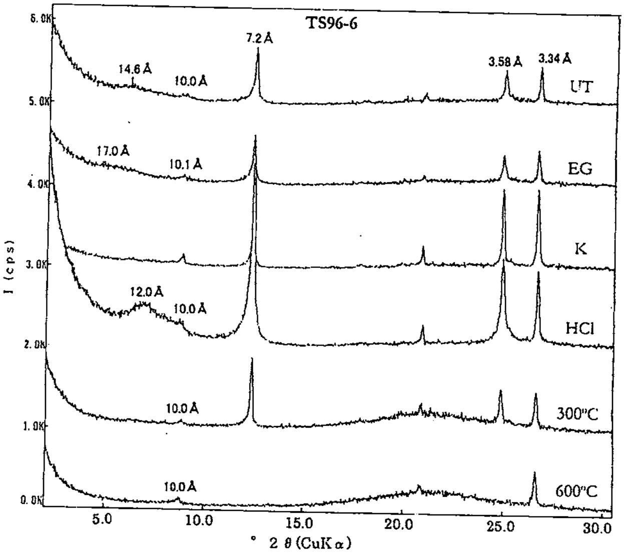

Fig. 6 X-ray diffraction patterns for oriented aggregates of untreated and treated surface sediment sample TS96-6 from the Siem Reap River in Siem Reap City.
UT : untreated sample, EG : ethylene glycol solvated sample, K : K-saturated sample, HCl : HCl-treated sample, 300℃ and 600℃ : thermal treated samples for one hour at 300℃ and 600℃, respectively.

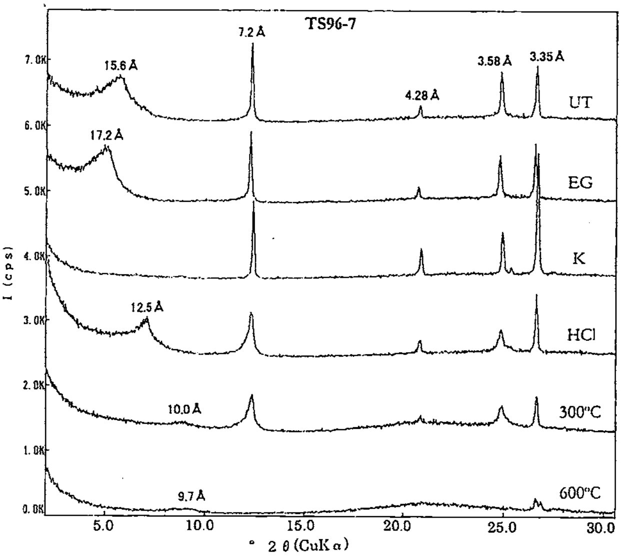

Fig. 7 X-ray diffraction patterns for oriented aggregates of untreated and treated soil sample TS96-7 from the Alluvial plain south of the West Baray water reservoir. UT : untreated sample, EG : ethylene glycol solvated sample, K : K-saturated sample, HCl : HCl-treated sample, 300℃ and 600℃ : thermal treated samples for one hour at 300℃ and 600℃, respectively.

17.0 Å by ethylene glycol-solvation and it shifts to around 12.0 Å by HCl-treatment. Thus, this diffuse peak is attributed to smectite. The weak peak at 10.0 Å is assigned to a very small amount of illite by glycolations, HCl-treatment and heating tests. The strong peak at 7.2 Å does not change by HCl-treatment, but collapses after heating at 600 ℃. This phenomenon implies that the 7.2 Å reflexion peak and its higher order reflexion (*e.g.*, 3.58 Å) are mainly attributed to kaolin minerals. The X-ray diffraction patterns of the untreated and treated specimens of the sample EB97-SR from the river on the north of the East Baray water reservoir are very similar to those of TS96-6. Therefore, it is stated that clay minerals of the surface sediments from the Siem Reap River consist mainly of kaolin minerals and a very little amount of smectite and illite.

4) Alluvial soils in and around the West and East Baray water reservoirs

Figure 7 shows the X-ray diffraction patterns for the untreated and treated specimens of the surface soil sample TS96-7 from the Alluvial plain on the south of the West Baray water reservoir where the flooded water of Lake Tonle Sap does not reach even at the highest water level. The untreated specimen shows a broad reflexion peak at 15.6 Å, and sharp and strong peaks at 7.2, 4.28, 3.58 and 3.35 Å. The sharp peaks at 4.28 and 3.35 Å are attributed to quartz. The broad peak at 15.6 Å shifts to about 17.2 Å by ethylene glycol-solvation and it also shifts to 12.5 Å by HCl-treatment. Further, the new peaks at 10.0 Å and 9.7 Å appear after heating at 300 ℃ and 600 ℃, respectively. Thus, the broad peak is attributed to smectite. The strong peak at 7.2 Å does not change by HCl-

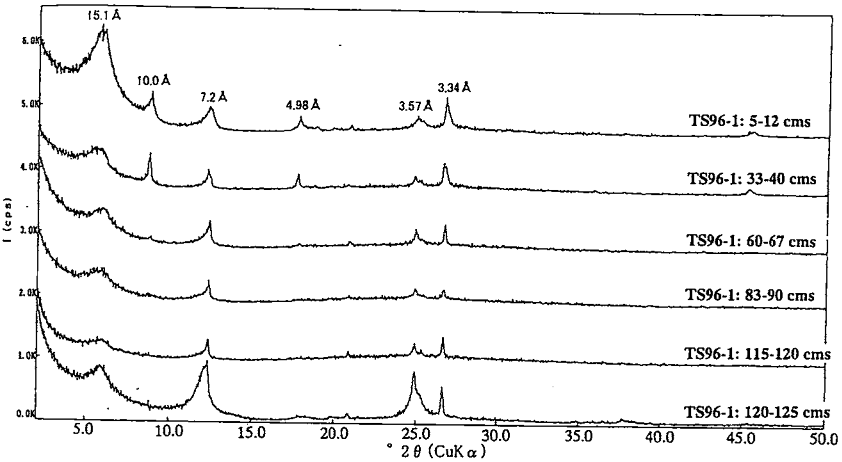

Fig. 8 X-ray diffraction patterns for oriented aggregates of untreated sediment samples from six horizons of the cored sediment TS96-1 from the northern part of Lake Tonle Sap.

treatment, but collapses after heating at 600 ℃. This indicates that the 7.2 Å reflexion peak and its higher order reflexion (*e.g.*, 3.58 Å) are mainly attributed to kaolin minerals. The X-ray diffraction patterns of the untreated and treated specimens of the samples EB97-S from the auger hole in the south of the East Baray water reservoir and those of the sample EB97-AD on the north of the reservoir, and the sample TS96-WB1 from the bottom surface of the West Baray water reservoir are similar to those of TS96-7. Accordingly, clay minerals of the Alluvial soils in and around West and East Baray water reservoirs are composed mainly of smectite and kaolin minerals.

5) Cored sediments of Lake Tonle Sap

The X-ray diffraction patterns for the untreated specimens from six horizons of the cored sediments TS96-1 are shown in Fig. 8. The untreated specimens of upper two horizons have broad reflexion peaks around 15.1 Å and sharp peaks at 10.0, 7.2, 4.98, 3.57 and 3.34 Å. The sharp peak at 3.34 Å is attributed to quartz. The broad peak around 5.0° is assigned to smectite and a small amount of chlorite by expansion tests using ethylene glycol-solvation, and Mg-saturation and glycerol-solvation, K-saturation and heating tests. The sharp peak at 10.0 Å and its high order reflexion (*e.g.*, 4.98 Å) do not change by glycolations and 300 ℃ heating, indicating that the peak at 10.0 Å is attributed to illite. The basal peak at 7.2 Å and its high order reflexion (*e.g.*, 3.57 Å) that are not affected by HCl-treatment is attributed to kaolin minerals. Thus, clay minerals of the upper two horizons of the cored sediments from the northern part of Lake Tonle Sap consist mainly of smectite, chlorite, illite and kaolin minerals.

On the other hand, the peak at 10.0 Å and its high order reflexion are not detected in the X-ray diffraction patterns of the untreated specimens from the lower four horizons of the cored sediments since other peaks that recognized in those from the upper two horizons appear. Accordingly, clay minerals of the lower four horizons of the cored sediments from the northern part of the lake are

Table 1 Results of the X-ray diffraction analysis for the samples of the surface sediments from Lake Tonle Sap, the Siem Reap and Tonle Sap Rivers, the surface soil from the Alluvial plains in and around the East and West Baray water reservoirs, and the suspended sediment in the lake water.

Sample No.	Sediment Type	Area	quartz	illite	kaolin minerals	chlorite	smectite
TS96-1	surface	Lake Tonle Sap	+ + +	+ + +	+ + +	−	+ + +
TS96-2	surface	Lake Tonle Sap	+ + +	+ + +	+ + +	−	+ + +
TS96-3	surface	Lake Tonle Sap	+ + +	+ + +	+ + +	−	+ + +
TS96-4	surface	Lake Tonle Sap	+ +	+ +	+ +	−	+ + +
TS96-5	surface	Lake Tonle Sap	+ + +	+ + +	+ + +	−	+ +
TS96-6	surface	Siem Reap River	+ +	−	+ + +		−
EB97-SR	surface	Siem Reap River	+ +		+ + +		−
TS96-7	surface	West Baray	+ +		+ + +		+ +
TS96-WB1	surface	West Baray	+ +		+ + +		+
EB97-AD	surface	East Baray	+ + +		+ + +		+ + +
EB97-S-1 (160-180)	surface	East Baray	+ +		+ + +		+ + +
EB97-S-2 (360-380)	surface	East Baray	+ +		+ + +		+
EB97-S-3 (560-580)	surface	East Baray	+ + +		+ + +		
TSR93-2	surface	Tonle Sap River	+ + +	+ + +	+ + +	+ +	−
TS96-9	suspended	Lake Tonle Sap	+ + +	+ + +	+ + +	−	+

+ + + : abundant, + + : common, + : present, − : rare

composed mainly of smectite, chlorite and kaolin minerals.

VI. Discussion

1) Composition and provenance of clay minerals in the northern part of Lake Tonle Sap

Identified minerals of surface sediments or soil samples from the northern part of Lake Tonle Sap (TS96-1 to- 5), the Siem Reap River (TS96-6 and EB97-SR), the Alluvial plain in and around the West and East Baray water reservoirs on the north of the lake (TS96-7 and -WB1, EB97-AD, and EB97-S-1 to- 3), the Tonle Sap River in Phnom Penh City (TSR93-2) and the suspended sediments in the lake water from the northern part of the lake (TS96-9) are summarized and listed in Table 1. Kaolin minerals, illite, chlorite and smectite were determined as clay minerals in these samples.

Kaolin minerals were commonly observed in every sample, and were particularly abundant in such surface soil samples as TS96-7 from the Alluvial plain north of Lake Tonle Sap. Smectite was also common in every sample with the exceptions of the samples from the Siem Reap and Tonle Sap Rivers in which a little amount of smectite was detected. In contrast of them, illite was frequently detected in all surface sediment samples of Lake Tonle Sap and the suspended sediments of the lake, and the surface sediments of the Tonle Sap River in Phnom Penh City. Further, a little amount of chlorite was observed in these samples that illite was detected.

Illite and chlorite are not generally ascribed to the products from the other clay minerals by natural weathering even under acid conditions in humid tropical region (*e.g.*, Sudo, 1974; Nishiyama, 1985). Therefore, considering sediment transport in present water system in Cambodia, it is highly probable that the illite and chlorite in the northern part of the lake are derived from the Tonle Sap River. Judging from the sampling site of the river was closely located to its confluent point with the Mekong River, it is inferred that there is no marked difference in bottom sediment compositions between the Tonle Sap and Mekong Rivers. Accordingly, it can be stated that illite and chlorite detected in the surface and suspended sediments from the northern part of Lake Tonle Sap are derived from the Mekong River, and they are transported by back currents from the river to the lake through the Tonle Sap River during the rainy season.

Matsui *et al.* (1993) noted that there is no major difference in chemical and physical properties in water among Lake Tonle Sap, the Tonle Sap River and the Mekong River. They concluded that the water in the Mekong River flows into the lake through the Tonle Sap River in the rainy season. Tsukawaki and Lao (1995) suggested that sandy sediments of the Tonle Sap River in Phnom Penh City are derived mainly from metamorphic and granitic rock bodies distributed probably in the Mekong River basin in Viet Nam and Laos based on their compositional features. Tsukawaki *et al.* (1994) concluded that sandy sediments transported by back currents of the Tonle Sap River in the rainy season do not reach to the northern part of the lake in spite of muddy sediments reach there as suspended sediments.

On the other hand, the peaks of quartz and smectite in the X-ray diffraction pattern of the lake surface sediments TS96-3 are rather conspicuous than those of the sediments from the Tonle Sap River. The same trend recognizable in the pattern of the suspende sediments of the lake water. Smectite is t common clay mineral in the surface soils fro the Alluvial plain around the lake in spite it is rare in the sediments from the Siem Rea River as already described, and both surfa soils from the plain and sediments fro the Siem Reap River contain rather lar amounts of quartz than those of the sed ments from the Tonle Sap River. The featu described above suggests that composition both bottom surface and suspended sediment in the northern part of the lake are influence by sediment supply from the rivers an streams in the surroundings of the lake.

Taking above-discussed comparison for cla mineral compositions among the surface an suspended sediments of the northern part Lake Tonle Sap, and the surface sediments the Siem Reap and Tonle Sap Rivers, and th Alluvial soils north of the lake into considera tion, it is concluded that clay minerals of th surface and suspended sediments in th northern part of the lake are derived bot from the surface soils distributed in th Alluvial plain around the lake and th Mekong River (Fig. 9). Clay minerals fro the former consisting mainly of smectite an kaolin minerals are supplied into the lak through a network of rivers and streams suc as the Siem Reap River from the surround ings of the lake during mainly the rain season. On the other hand, clay minerals fro the latter characterized by existence of illit and chlorite are provided into the lake fro the Mekong River through the Tonle Sa River only during the rainy season by stron back currents of the Tonle Sap River.

Tsukawaki *et al.* (1994) recognized that chlorite characteristically occurred only in th

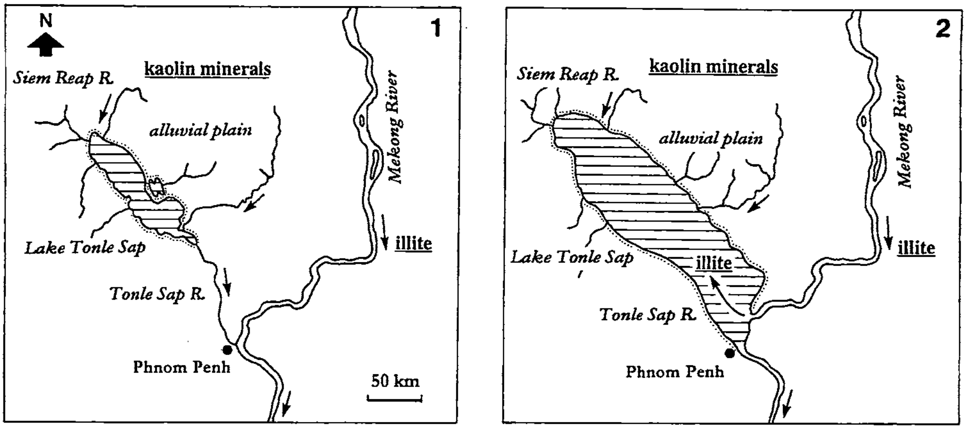

Fig. 9 Estimated transport directions of clay minerals in water systems around Lake Tonle Sap in (1) dry season and (2) rainy season (arrows indicate the direction of water flow and supply of prevailing clay minerals).

sediment samples from the Tonle Sap River and the northern part of Lake Tonle Sap, and they led the conclusion that muddy sediments of the Mekong River reach to the northern part of Lake Tonle Sap as suspended sediments in spite of the sandy sediments are settled in its southern part based on the comparison on both sandy and muddy sediment compositions. However, they could analyze only a limited amount and number of sediment samples on the course of their study since the Cambodian political unrest persisted at that time. The conclusion of the present study supports the previous result expressed by Tsukawaki *et al.* in spite of illite was also determined in the sediments from the northern part of Lake Tonle Sap as the characteristic clay mineral derived from the Mekong River.

2) Vertical changes of clay mineral composition in the cored sediments

The identified clay minerals in all analysed samples from six horizons of the cored sediments TS96-1 obtained from the northern part of Lake Tonle Sap are listed in Table 2. Kaolin minerals, illite, smectite and chlorite are determined as clay minerals in these samples. Kaolin minerals and smectite were commonly observed in every sample. In contrast to this, illite and a little amount of chlorite were obtained only in the samples from the upper two horizons of 5-12 and 33-40 cms below the lake floor. Carbonnel and Guiscafré (1962 - 63) recognized the upper "*vase actuelle*", 20 to 350 cm thick, and the lower "*vase ancienne*", more than 50 cm thick, within the bottom sediments of Lake Tonle Sap on the basis of lithological observations of several cored sediments from the lake. They reported that illite and montmorillonite are the prevailing clay minerals in the upper sequence in spite of kaolin minerals is dominant in the lower sequence. Although their study was short of a preliminary grasp on only compositional descriptions of the cored sediments, their result is in accordance with the present study.

An obvious lithological change is recognized in both cores TS96-1 and 2 at horizons about 50 cm below the lake floor (Tsukawaki, 1997).

Table 2 Results of the X-ray diffraction analysis for the samples from the six horizons of the cored sediments TS96-1 from the northern part of Lake Tonle Sap.

Horizon (cms)	quartz	illite	kaolin minerals	chlorite	smectite
5–12	+ +	+ +	+ +	–	+ + +
33–40	+ + +	+ + +	+ + +	–	+ +
60–67	+ + +		+ + +		+ +
83–90	+ +		+ +		+ +
115–120	+ + +		+ + +		+
120–125	+ + +		+ + +		+ +

+ + + : abundant, + + : common, + : present, – : rare

Sediments above the horizon are composed of light olive grey homogeneous soft or soupy sandy mud with an intercalation of molluscan shell layer, but they below the horizon consist of greyish olive green homogeneous or bioturbated compact mud. The radiocarbon ages of sediments from 42-48 cms of the core TS96-1 and 48-53 cms of the core TS96-2 both just below the above-mentioned horizons are 5081±86 and 5620±120 years BP, respectively (Mildenhall, 1996 MS; Tsukawaki *et al.*, 1997).

Tsukawaki *et al.* (1997) recognized that sedimentation rate of the northern part of Lake Tonle Sap was decreased markedly from about 1.0 mm/yr to less than 0.1 mm/yr at the horizon of the lithological change in both cores, and they suggested that an environmental change in and/or around Lake Tonle Sap at about 5,000 years BP would trigger the sudden drop of the sedimentation rate. Tsukawaki (1997) illustrated that the sediments above the horizon of the lithological change in both cores are the products under the active environment of repeating erosion and deposition in spite of they below that formed under rather quiet condition on the basis of the sedimentological interpretation on sedimentary facies and sediment compositions of the cored sediments. Since the horizon of the lithological change is corresponded with that of appearance of illite and chlorite in the core TS96-1, it can be attributed to that the appearance of them resulted from the environmental change in and/or around the lake mentioned by Tsukawaki *et al.* and Tsukawaki.

Very little has been known about the modern tectonic movements in Cambodia, but it is inferred that no major tectonic movements have taken place in Cambodia during the last 10,000 years because no such movements have been recognized in its surrounding areas such as the eastern and southern parts of Thailand and the southern part of Viet Nam through the period (*e.g.*, ESCAP, 1993b; Salyapongse *et al.*, 1997; Fenton *et al.*, 1997). Thus, these facts support the idea that the environmental change inferred by Tsukawaki (1997) and Tsukawaki *et al.* (1997) would not be ascribed to such tectonic movements in and around Lake Tonle Sap as well as the lower course of the Mekong River Basin.

As already discussed and stated, illite and chlorite detected in both surface and suspended sediments from the northern part of Lake Tonle Sap are derived from the Mekong River. They were transported as suspended sediments from the river to the lake through the Tonle Sap River by strong back currents during the rainy season suggested also by

Tsukawaki *et al.*(1994). Apart from them, the X-ray diffraction patterns of the sediments from the upper two horizons are very similar with those of the surface and suspended sediments of the lake. On the other hand, illite and chlorite were not determined in the sediments from the lower four horizons. The X-ray diffraction pattern of the sample from the lowest horizon of the cored sediments is similar with that of the soil sample TS96-7 from the Alluvial plain north of the lake.

Considering the marked differences of clay mineral compositions, depositional settings and sedimentation rates between sediments above and below the horizon of the cored sediments, it would be inferred that the environmental change mentioned by Tsukawaki (1997) and Tsukawaki *et al.* (1997) is ascribed to a change of sediment transport in water system in Cambodia. Accordingly, it can be stated that water from the Mekong River did not flow into Lake Tonle Sap before about 5,000 years BP, and only rivers and streams from the surrounding areas of the lake flowed and supplied sediments into the lake. Inflow of water with suspended sediments from the Mekong River started to the lake about 5,000 years BP and the present sediment transport system into the lake has appeared since that time. Further, the thought behind this is that the stated change of sediment supply into the lake also means some change of fluvial system in the lower course of the Mekong River. This point should be further studied in detail.

VII. Conclusion

The following conclusions are reached during the course of the present study:

1. Clay minerals of the surface and suspended sediments from the northern part of Lake Tonle Sap, and the surface sediments of the Tonle Sap River in Phnom Penh City are composed mainly of kaolin minerals, illite, smectite and chlorite. On the other hand, the soil samples around the lake and the surface sediments of the Siem Reap River consist mainly of kaolin minerals and smectite.
2. Judging from illite and chlorite are not detected in the sediment and soil samples from the Siem Reap River and the Alluvial plains around the lake but the bottom sediments from the Tonle Sap River yield a certain amount of them, it is stated that illite and chlorite distributed in the northern part of the lake would be derived from the Mekong River.
3. In spite of a certain amount of illite and a little amount of chlorite are detected in the upper part of the cored sediments obtained from the northern part of Lake Tonle Sap, they are not recognized in the lower part. Since they are considered to be derived from the Mekong River, appearance of them in the upper part of the core indicates that a change of sediment transport in water system took place around the lake at about 5,000 years BP.

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トンレサップ湖北部に分布する粘土鉱物の組成ならびに起源

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東南アジア最大の湖であるトンレサップ湖は雨季と乾季とでその水深・冠水面積が大きく変化し，このような季節的変動に支配された特異な堆積作用の発生が予期される。そこで同湖における堆積作用の解明へ向けて，同湖に堆積物を供給する関連水系や同湖周辺に分布する沖積層の堆積物の粘土鉱物組成にもとづき，同湖北部湖底堆積物に含まれる粘土鉱物の起源およびその時間的変化を調べた。

トンレサップ湖北部の表層堆積物ならびに懸濁物からは，カオリン鉱物，イライト，スメクタイトおよび緑泥石が検出される。同湖とメコン河とを連絡するトンレサップ川の堆積物からもイライトおよび緑泥石が検出されるにもかかわらず，同湖北部周辺の水系や沖積層の堆積物にこれらがほとんど含まれないことから，同湖北部に分布するイライトおよび緑泥石はメコン河本流を起源とするものと判断される。

一方，トンレサップ湖北部湖底から採集された柱状試料では，その上部約50cmの堆積物からはイライトならびに微量の緑泥石が検出されるものの，同試料下部にはこれがまったく認められない。したがって，イライトおよび緑泥石がメコン河水系に由来するという表層堆積物解析結果にもとづき，同湖における堆積物の供給源に大きな変化が発生したことが推定され，その年代は今から約5,000年前と考えられる。

キーワード：カンボジア，トンレサップ湖，メコン河，粘土鉱物，堆積作用

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