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Core drilling of the basin-fill sediments in the Kathmandu Valley for palaeoclimatic study: preliminary results

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ABSTRACT

Core drillings in ancient lake sediments of the Kathmandu Valley, central Nepal Himalaya were carried out in order to clarify the past Indian monsoon climate and its linkage to the uplift of the Himalaya. This is the first large-scale drilling project in the valley with full core recovery, and solely dedicated to academic research purpose. The drilling penetrated the whole sequence of 208 m thick Kalimati Clay, newly defined as the Kalimati Formation.

Based on the drill-core study, the sediments are divided into three formations: 1) Bagmati Formation, 2) Kalimati Formation, and 3) Patan Formation in ascending order. These formations have very distinct sedimentary characteristics: Bagmati essentially gravelly, Kalimati clayey and Patan sandy. The lower part of the Kalimati Formation, showing marginal lake facies, has been designated as the Basal Lignite Member. Judging from the lithology and sedimentary facies and previous studies on the Lukundol Formation, the Bagmati Formation is interpreted to have been deposited by the Proto-Bagmati River prior to the appearance of the lake before 2 Ma. The clay-predominant Kalimati Formation lying over the Lignite Member was deposited in an open lacustrine environment, which is mainly composed of carbonaceous clay yielding abundant fossil leaves and diatomaceous laminite. The fluvial sand of the Patan Formation rests on the Kalimati clay bed with an marked erosional base. The ^{14}C age of the uppermost part of the Kalimati Formation suggests that the lake water of the Kathmandu Basin was drained out later than 10 kyr B.P. (Fujii and Sakai 2002). Based on comparison of the present altitude of the ancient lake floor and topset beds of the lacustrine delta sediments (dated as 29 kyr B.P.), the water-depth of the Palaeo-Kathmandu Lake in the central part of the valley is estimated to be about 70 m.

INTRODUCTION

It is generally agreed that the rise of the Himalaya and the Tibetan Plateau resulted in the development of Indian monsoon climate. The rapid and large-scale denudation and erosion of this newly formed highland gave rise to a great deal of change in the global carbon cycle, which brought about the global cooling and onset of glacial age (e.g. Ruddiman and Kutzbach 1989; Raymo and Ruddiman 1992; Prell and Kutzbach 1997). This scenario implies that the concentration of huge continental mass in Asia formed by the continent-continent collision was responsible for the change in global climate system. Though this view looks very attractive, there are many problems that remain to be solved. For a better understanding of the ancient climate system in Asia, it is very important to find longer and continuous palaeoclimatic records of monsoon from more locations.

From this viewpoint, the Kathmandu Valley seems to be the most potential location in Asia having preserved a precious archive of ancient climate history in its sediments. The valley is ideally located in the central part of the Himalayan Range which lies in strong influence of Indian monsoon and preserves a thick basin-fill sediments (Sakai 2001). Recently we have started the studies on the sediments of Palaeo-Kathmandu Lake, in order to throw a new light on the linkage between the uplift of the Himalaya and Indian monsoon (Sakai et al. 2000). The surface geological investigation and analyses of sediment slimes that were previously obtained from a drill-well in the Kathmandu Basin amply showed that the study of basin-fill sediments of the Kathmandu Valley has very high potential in bringing out new and important data pertaining to the history of Indian monsoon (Fujii and Sakai 2002, Sakai et al. 2001). We were also convinced that little progress could be expected, unless analyses of continuous drill-cores penetrating the whole sedimentary sequences are carried out.

Recently, we have successfully completed three core drillings in the sediments of the Kathmandu Valley under the "Paleo-Kathmandu Lake Project" (Fig. 1). The research project is being carried out in collaboration with the Department of Geology, Tribhuvan University, Kathmandu. The deepest hole that was drilled in this study was 222 m and we were successful in recovering a full core of the clayey sediments. In addition, short cores of 45 and 65 m in length were also recovered from other two drill-holes (Fig. 2). This is for the first time continuous drill cores of the Kathmandu basin-fill sediments have been obtained for the purpose of an academic research. In this paper, we report the characteristics and lithology of drill-cores, and propose the stratigraphic division of the basin-fill sediments in the central part of the valley.

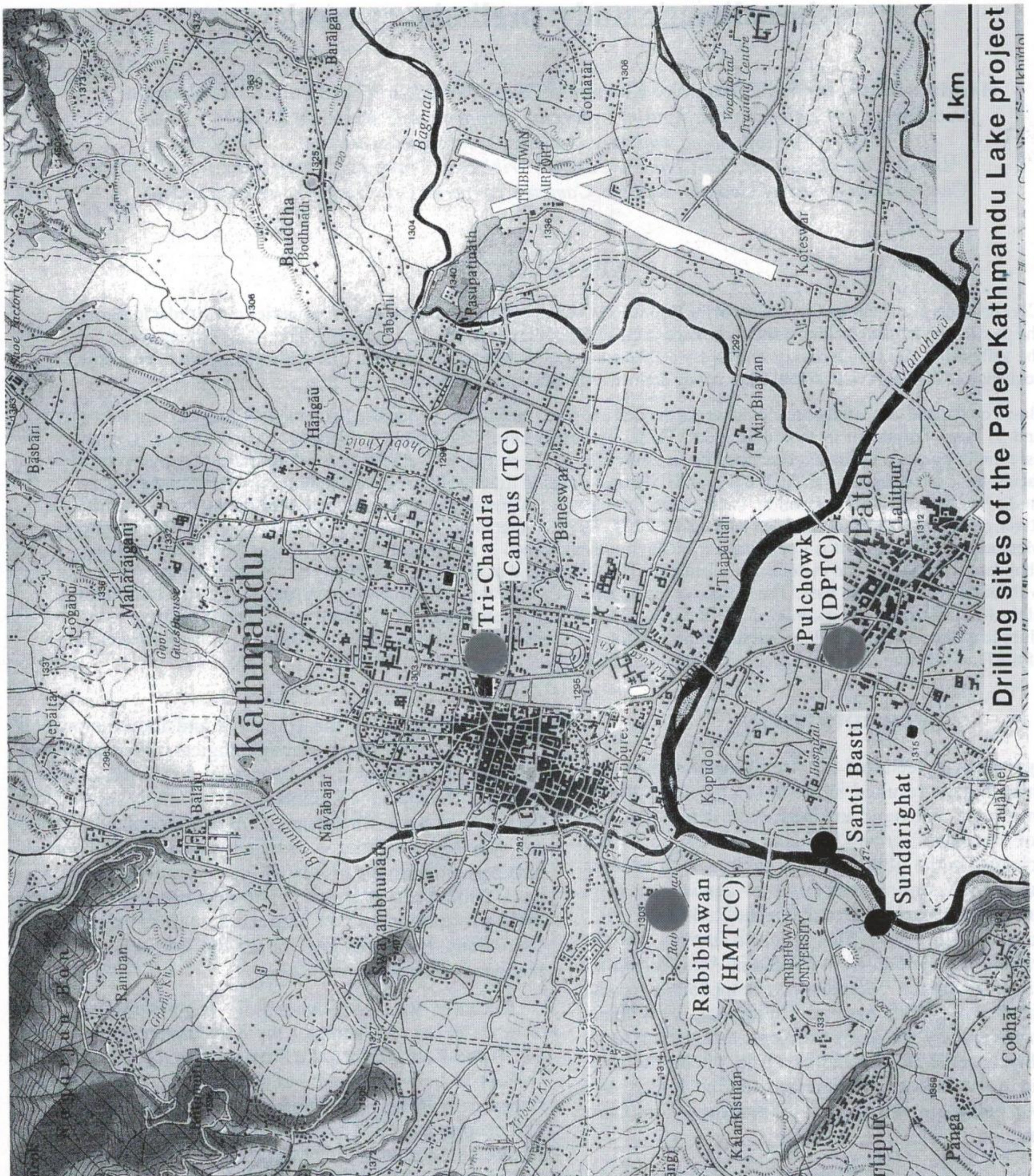

Fig. 1: Location map of three drill sites of the Paleo-Kathmandu Lake Project. Two previous drill-well sites of JW-3 at Sundarighat and SB-1 at Santi Basti are also shown.

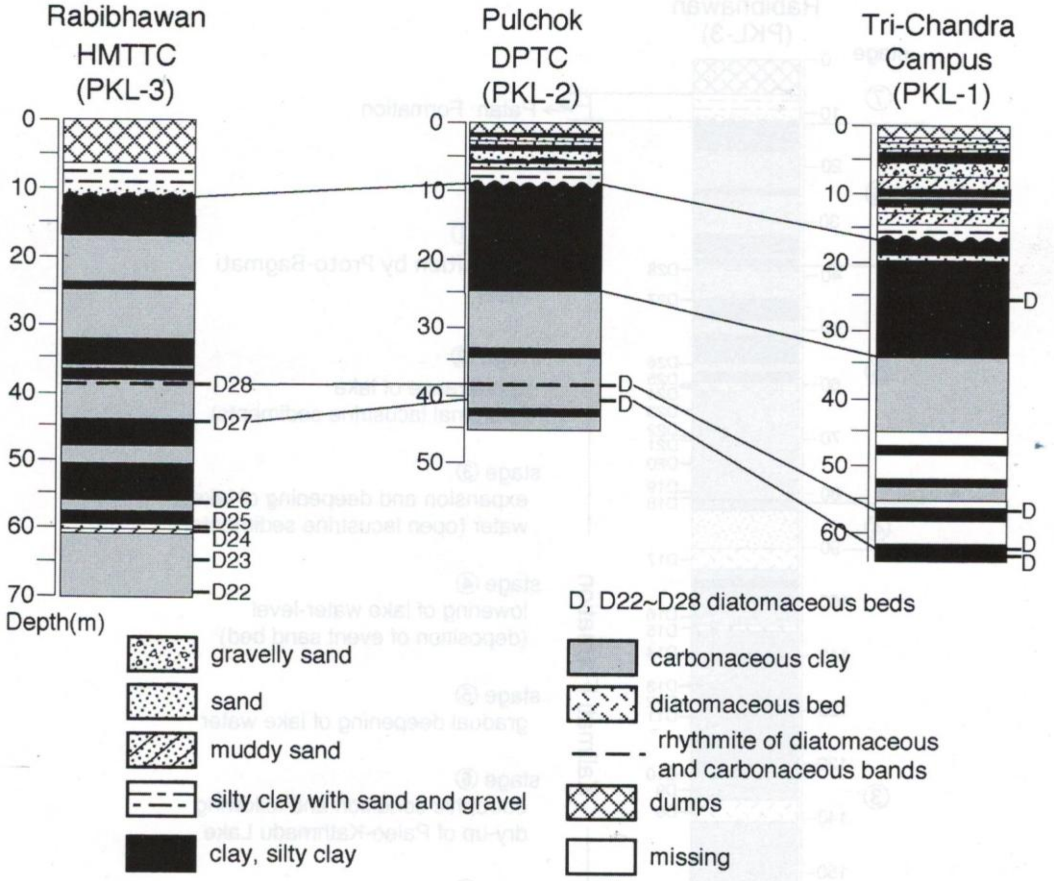

Fig. 2: Geologic columns of three cores obtained in 2000 by the Paleo-Kathmandu Lake Project. PKL-1 at Tri-Chandra Campus, PKL-2 at Pulchok, PKL-3 at Rabibhawan.

CORE DRILLING

Drilling sites and method

The core drillings were carried out at the following three sites in the central part of the Kathmandu Valley (Fig. 1) lying almost at the same altitude (1,303~1,307 m above sea level). Each site is located at a little west of central part of the Palaeo-Kathmandu Lake (fig. 1 of Sakai 2001).

(1) Just south of the Clock Tower adjacent to the Department of Geology, the premise of Tri-Chandra Campus (TC), Tribhuvan University. Altitude: 1,304 m

Drilled by percussion method up to 45 m deep (core diameter: 6.5 cm).

Drilled by wire-line method from 45 to 65 m (core diameter: 4.5 cm).

(2) Adjacent to the office building of Suspension Bridge Division and north of the Department of Water Induced Disaster Prevention (DWIDP) formerly known as Water Induced Disaster Prevention Centre (DPTC), within the premise of Shri Mahal, Pulchok, Patan. Altitude: 1,307 m.

Drilled by percussion method up to 40 m deep (core diameter: 6.5 cm).

Drilled by wire-line method from 40 to 45 m (core diameter: 4.5 cm).

(3) East of Lincoln School, in the compound of Nepal Academy of Tourism and Hotel Management, Rabibhawan (RB). Altitude: 1,303 m.

Drilled by percussion method up to 82.8 m deep (core diameter: 6.5 cm).

No recovery of cores from the unconsolidated sand between 82.8 to 89.45m.

Drilled by wire-line method from 89.45 to 221.75 m (core diameter: 4.5cm).

A previous drill-well at the same site had hit the basement rock at 253 m (Fig. 3).

Condition and sampling of cores

Throughout the whole sequence of clayey sediments, core recovery rate was almost 95 to 100% (Plate I-1 and I-2). However, it decreased 80 to 90% in silty to sandy mud beds. Though sand and gravelly mud beds could not be recovered as cores, they were collected as washed-out sand and gravel when drill-well was cleaned. Up to a depth of 52 m, several clayey beds showed the presence of

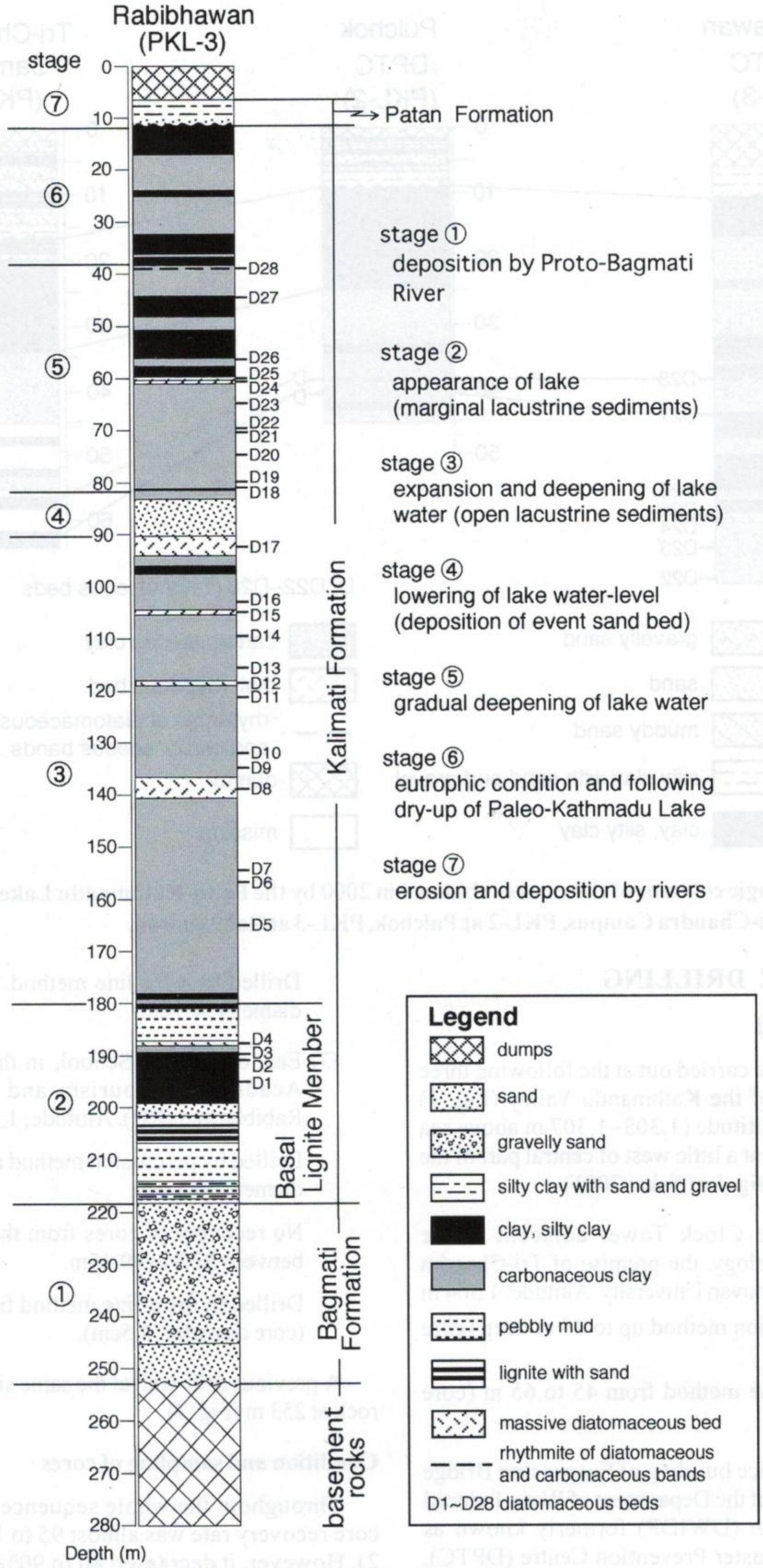

Fig. 3: Litho-stratigraphic division of the Kathmandu Basin Group in central part of the valley, on the basis of drill-cores collected by the Paleo-Kathmandu Lake Project in 2000. A columnar section below the depth of 218 m at Rabibhawan is after unpublished report of a drill well at the same site.

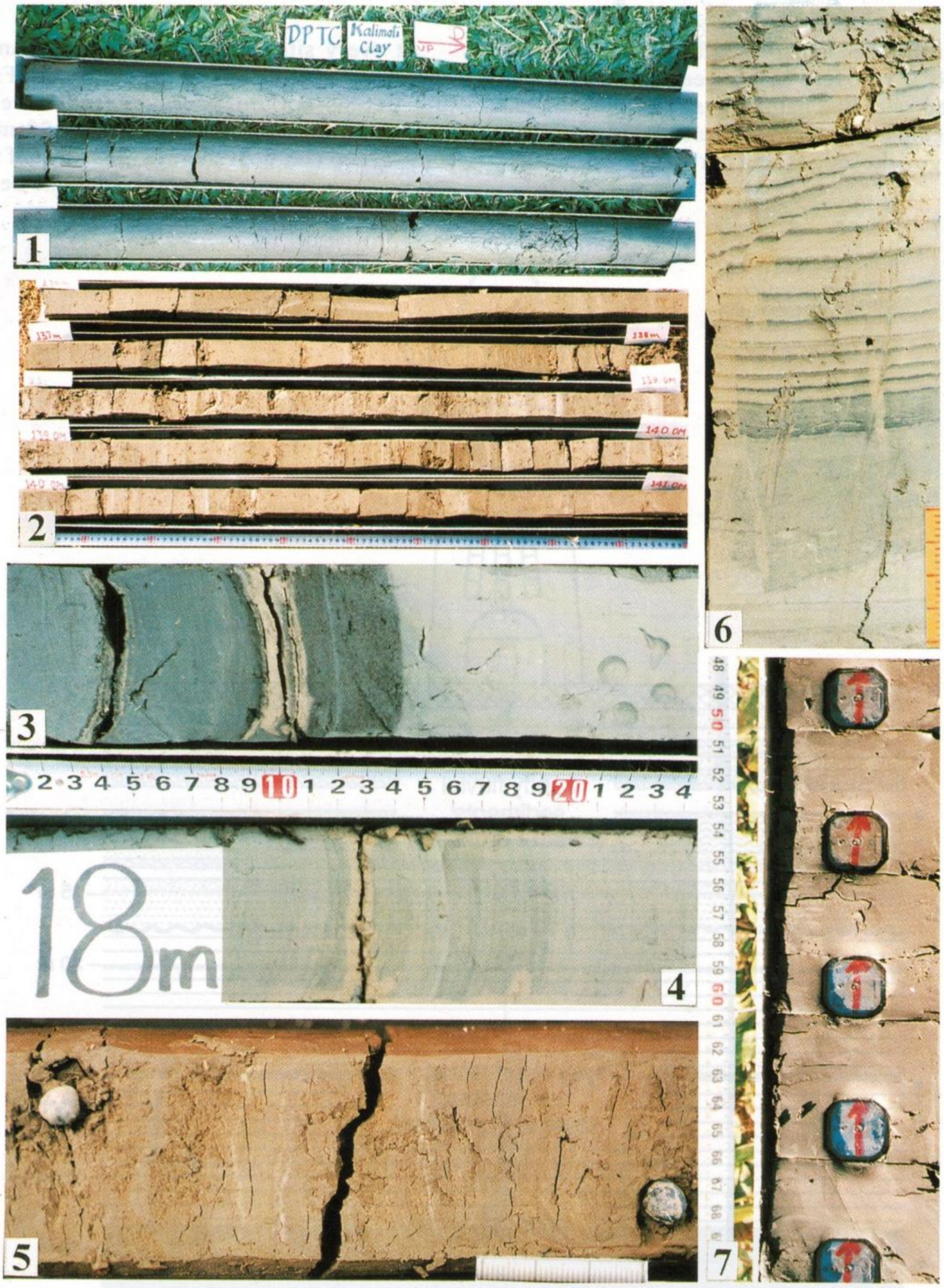

Plate I: 1: Drill-cores of the Kalimati clay from 30 to 33 m depth at DPTC, Pulchok (Fig. 1). Note homogeneous lithology of black, carbonaceous clay and its good recovery, 2: Half-cut drill-cores of 4 m-thick diatomaceous bed in the Kalimati clay from 137 to 140.5 m depth at HMTCC, Rabibhawan (Fig. 1). A close-up view is shown in Plate I - 5, 3: Black carbonaceous laminated bed (left) and light grey diatomaceous bed (right) from 17 to 17.25 m depth at Rabibhawan, 4: Fine laminated carbonaceous and diatomaceous clay from 18 to 18.25 m depth at Rabibhawan, 5: Spherules of vivianite in 4-m-thick massive diatomaceous bed from 93.28 to 93.4 m depth at Rabibhawan, 6: Diatomaceous laminite with carbonaceous black bands, from 60.8 m depth at Rabibhawan. Note synsedimentary minor normal faults, and 7: Half-cut core of the Kalimati clay was cut into small samples at 5 cm interval, and oriented samples were collected by plastic cube for palaeomagnetic study. The core is from 26 to 27 m depth at Pulchok.
The smallest divisions on the scale bar are 1 mm.

natural gas. Such cores expanded after lifting up to the surface, and their recovery rate exceeded 100%. Some cores continued releasing natural gas for a few minutes even after reaching to the ground surface. Some others showed sponge-like degassing structure on cutting surface.

At every site, water-saturated mud and sand beds were found to occur up to a depth of 40 m (Fig. 4). Below this depth, the thick clayey sequence was under half-consolidated condition. Below 100 m, these half-consolidated clay beds show development of vertical joints and weak cleavages obliquely cutting the bedding planes.

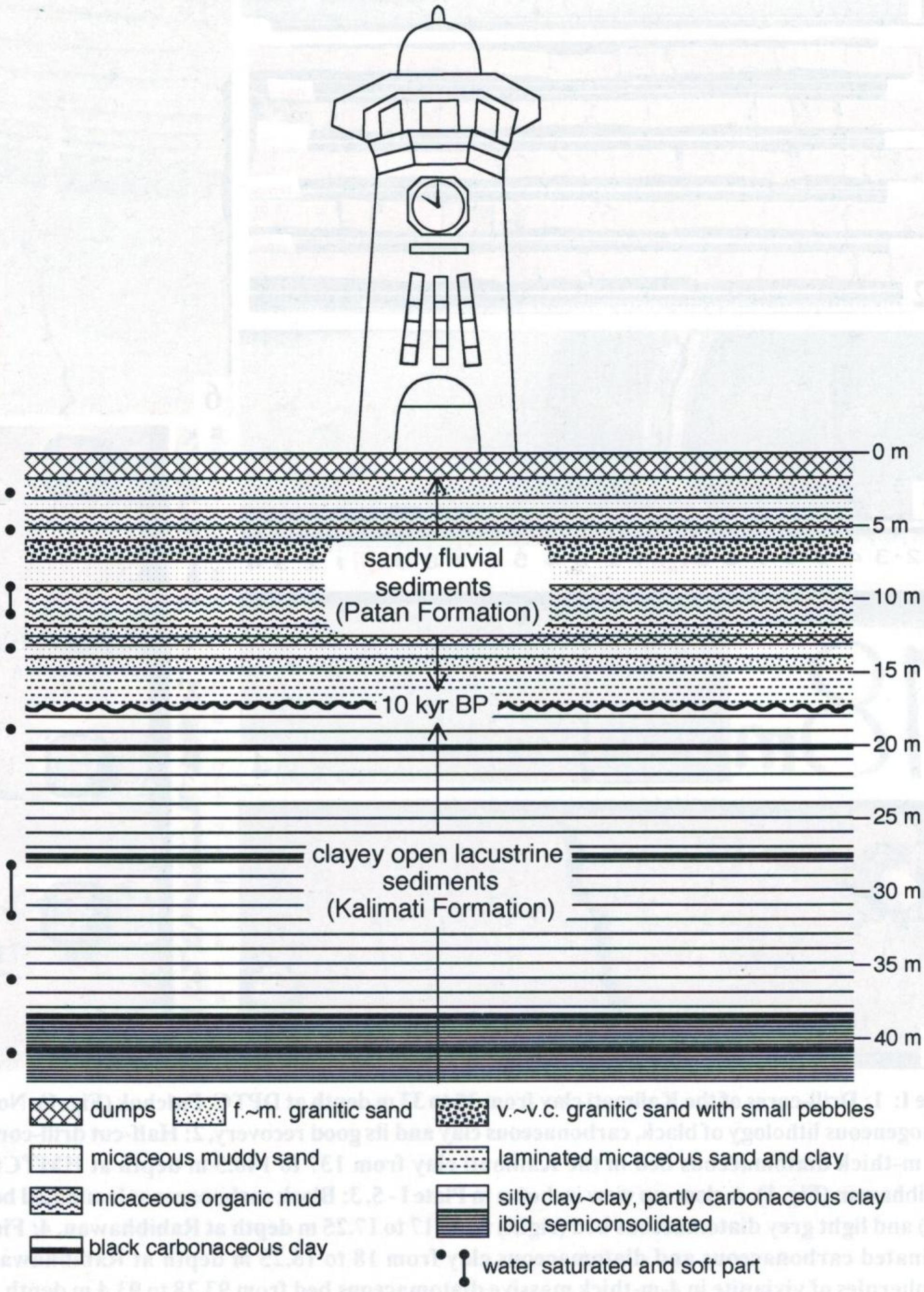

Fig. 4: A schematic geologic cross-section beneath the Clock Tower at Tri-Chandra Campus. Sediments are unconsolidated. Silty and sandy beds up to 20 m in depth show high water content. The Kalimati clay gradually hardens in proportion to depth and becomes semi-consolidated condition below 40 m.

The sand and gravelly beds show high water content even below 200 m depth.

Drill cores with 6.5 cm in diameter were cut into halves along the longitudinal direction. After taking photographs and detailed lithological descriptions, one half of the cores were preserved and stored for further studies, whereas the other half was cut into small pieces for analyses. As the 4.5 cm diameter cores were too small to split into two, the entire core was used for analyses and no part of the samples were preserved for future studies. The cores were cut at 5 cm interval, and thus a core of one meter could be divided into 20 pieces. Then each 5 cm long sample was divided into three parts: i) oriented samples for palaeomagnetic studies collected into a plastic cube of 7 cc (Plate I-7), ii) sample for micropalaeontological and sedimentological studies, and iii) sample for chemical analyses. If we take the average sedimentation rate of the Kalimati clay as 104 mm/kyr (Fujii and Sakai 2001), time length of one piece of sample (5 cm long) represents about 500 years.

CHARACTERISTICS OF SEDIMENT CORES

The longest core that was obtained at the Rabibhawan site can be lithologically divided into four parts: i) about 15 m thick gravelly mud at the lowermost part, ii) about 187 m thick clayey and muddy sediments, iii) about 9 m thick sand bed, and iv) cultivated soil and fillings at the top (Fig. 3). The clay predominant sediments, hitherto been called "Kalimati clay", are divided into several litho-facies on the basis of amount of carbonaceous matter and silt, attitude of laminae, diatomaceous interbeds and consolidation condition and so on (Plate I-3 and I-4).

One of the most important characteristics of the sediment core samples is the interbeds of diatomaceous sediments at different levels whose total thickness attains about 20 m. Twenty-five diatomaceous beds, thicker than 10 cm, were detected. In the middle part of the core, two diatomaceous beds of 4 m thick are interbedded, the first one between 90.2 to 94 m and the second one from 136.7 to 140.5 m in depth (Fig. 3, Plate I-5). Ten diatomaceous laminite beds were also recognized which consist of repetition of diatomaceous white laminae and clayey pale-green laminae (Plate I-6, Plate II-2).

Throughout the whole sequence of clayey and muddy sediments, small spots of vivianite are commonly observed (Plate II-6). Their shapes show several variations such as tiny spot, irregular shape, spherical (Plate I-5) and ellipsoidal shapes; and their size varies from less than 1 mm to 10 mm. The vivianite spherules in diatomaceous beds are composed of hard crystals, on the other hand spotted and irregular shaped vivianite are soft aggregates.

The topmost sand beds overlying the Kalimati clay at 12.15 m depth are generally medium- to very coarse-grained micaceous granitic sand derived from the Shivapuri Lekh to the north. Except the topmost sand beds and one granitic sand bed of 2.1 m thick at 200 m depth (Plate II-3), almost all sand and gravels are composed of detritus from weakly metamorphosed sedimentary rocks derived from the underlying Kathmandu Complex.

In addition to common occurrence of tiny carbonaceous fragments (Plate II-4), abundant fossil leaves were found in the clayey parts (Plate II-1). Especially, the lower to middle part of the core from Rabibhawan contains many fossil leaves of deciduous and evergreen trees. Fossil leaves of broad-leaved trees were detected from 160 horizons between 95 to 198 m in depth. Fossil seeds of *Trapa* (water chestnut) were found from the lower part at a depth of about 179 m. All fossil leaves and seeds were well preserved and organic part remained without decomposition.

Only one operculum of gastropod was found at a depth of 189.8 m, and tiny bone fragments were found from a depth of 178.5 m.

LITHOSTRATIGRAPHY

On the basis of lithology and sedimentary facies of sediments obtained from drill-cores and previous drill-well data, we have divided the basin-fill sediments of central Kathmandu Valley into three parts. From bottom to top they are: i) the lower sand and gravel dominant beds, named as Bagmati Formation, ii) the middle clay predominant beds, named as Kalimati Formation and iii) the upper sand dominant beds, named as Patan Formation (Fig. 3). Yoshida and Igarashi (1984) first used the name Patan Formation to include the youngest sediments in the Kathmandu Basin. The name Kalimati Formation was first used by Kharel et al. (1998) for the clayey sequence exposed in and around the Patan-Bhaktapur area, but they did not provide sufficient definition of the formation as pointed by Sakai (2001). The Bagmati Formation is newly introduced name by the present authors.

The Bagmati Formation is considered to be the northern continuation of the Tarebhir Formation, which is exposed in the southern end of the Kathmandu Valley (Sakai 2001). The overlying Kalimati Formation is distributed mainly in the subsurface area of the Kathmandu Valley and shows open lacustrine facies, judging from the presence of laminated clay with abundant fossil leaves and diatomaceous laminite. The lower part of the Kalimati Formation has a different lithology and sedimentary facies compared to the overlying clays. A 38-m-thick sequence, characterized by the presence of lignite beds (Plate II-5), bituminous pebbly mud (Plate II-7), fossil *Trapa* (water chestnut) and opercula of gastropod, is named as Basal Lignite Member (Fig. 3). These sediments are interpreted as the marginal facies of lacustrine environments in shallow water depth.

A 6-m-thick sand bed from 83 to 89 m depth can be correlated with a fossiliferous sand bed reported from a drill-well JW-3 at Balkhu (Sakai et al. 2001), though no fossils were found from this sand bed.

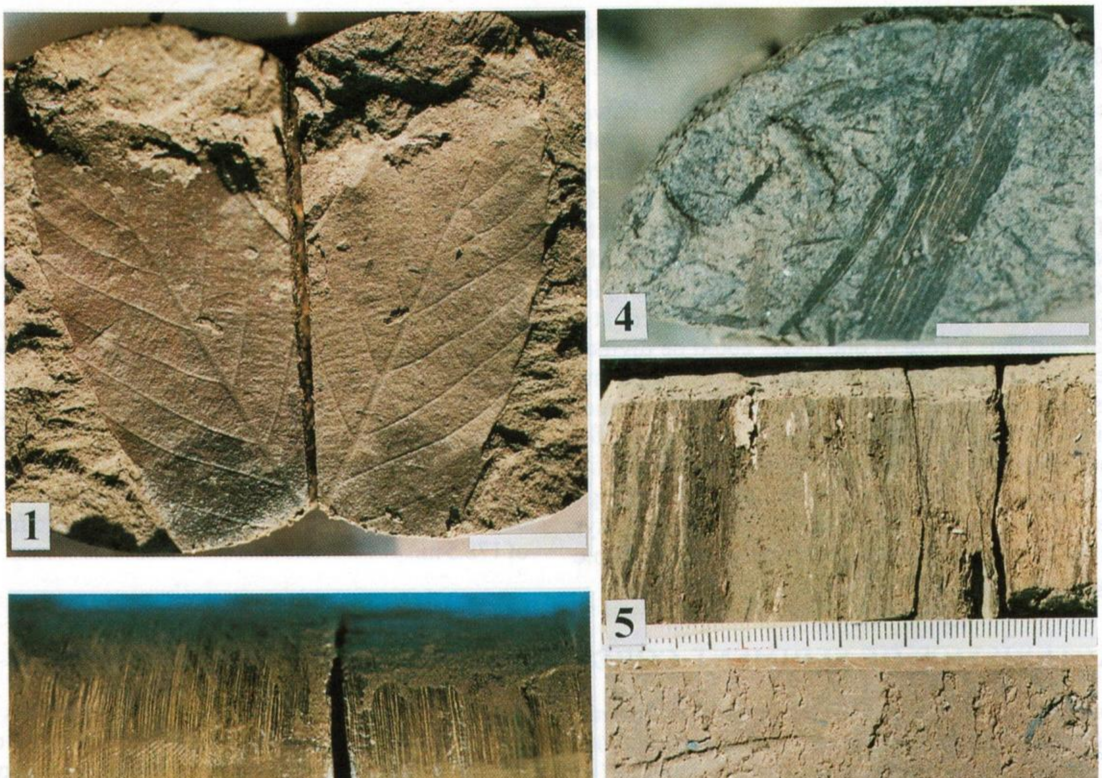

Plate II: 1: Leaf prints of evergreen oak preserved in the core of Kalimati clay, from 172.24 m depth at Rabibhawan, 2: Diatomaceous laminite composed of rhythmic alternation of white diatom, black carbonaceous and light green laminae, 40.7 m depth at Pulchok (Fig. 2), 3: Medium- to very coarse-grained granitic sands containing granules and small pebbles of granite, 199.4 m depth at Rabibhawan, 4: Tiny carbonaceous fragments in the core of Kalimati clay at Rabibhawan, 5: Lignite and carbonaceous beds of the Basal Lignite Member, 195.1 m depth at Rabibhawan (Fig. 3), 6: Spotted vivianite in dark grey clay of the Kalimati Formation, 196.9 m depth at Rabibhawan, and 7: Bituminous pebbly mud near the base of the Kalimati Formation, 207.5 m depth at Rabibhawan (Fig. 3).
All white scale bars are 1 cm and divisions on the scale are 1 mm.

Fluvial sand bed of the Patan Formation rests on the erosion surface of the lacustrine clayey beds of the Kalimati Formation in both cores from Rabibhawan and Pulchok (Fig. 2, plate I-1a of Sakai 2001). At Tri-Chandra Campus, the black Kalimati clay belonging to the Kalimati Formation is overlain by light grey diatomaceous mud and micaceous sand of the Patan Formation, (plate I-1b of Sakai 2001).

At all the three sites, both the Patan Formation and underlying Kalimati Formation are easily correlated with each other by means of diatomaceous beds (Fig. 2). Two thick diatomaceous beds in the Kalimati Formation are the key beds and are useful to construct three-dimensional structure of the sediment distribution beneath the Kathmandu Valley.

DISCUSSION

Changes in depositional environments

Changes of lithology and sedimentary facies of the sediment core from Rabibhawan outline the life of the Palaeo-Kathmandu Lake. The history of the Palaeo-Kathmandu Lake can be divided into the following seven stages.

Stage 1: Prior to the appearance of the lake, a river system transported the detritus from the Kathmandu Valley out to the Gangetic Plain in the south (Sakai et al. 2001). The detritus originated from all along the slopes of the mountains within the valley. The previous river originating in the northern slope of the Shivapuri Lekh was the trunk river to drain the valley, which corresponds to the "Proto-Bagmati River" of Hagen (1968). The deposits by the Proto-Bagmati River is now represented by the lowermost gravelly basin-fill sediments, namely the Bagmati Formation in the central part, and the Tarebhir Formation in the southern part of the basin.

Stage 2: Appearance of lake in the Kathmandu Valley is indicated by the occurrence of the marginal lacustrine sediments named as the Basal Lignite Member of the Kalimati Formation containing lignite beds and bituminous mud with fossil seed of *Trapa*.

Stage 3 :Indication of expansion and deepening of lake water is found in the overlying clayey beds of the Kalimati Formation. This facies lies between the depths of 181 m to 90 m at the Rabibhawan site. In the lower half, fine- to very fine-grained thin sand beds and laminae are commonly observed, but there are no sand interbeds in the upper half. Fossil leaves are very abundant in the lower half, but decrease in the upper half and totally lack in the uppermost part. These facts suggest that the depositional environment of the lake changed from shallow lake margin to open lacustrine environment where both sand and leaf could not reach.

Stage 4: Deposition of the Kalimati clay is abruptly interrupted by a 6 m thick sand bed between the depth of 83 m to 89 m. The sand bed is extensively distributed in the subsurface of the Kathmandu Basin (Katel et al. 1996). A 4-m-thick fossiliferous sand bed in between 115 m and 119 m, reported from a drill-well JW-3 at Sundarighat is southern continuation of this sand bed. The sand bed is interpreted as an event-deposit caused by a sudden lowering of the lake-water level (Sakai et al. 2001). The high frequency of *Pediastrum* of green alga from the clay beds between 114 m and 98 m depth suggests that the water level remained shallow after deposition of the sand bed (Sakai et al. 2001; Fujii and Sakai 2001).

Stage 5 : Deepening of water-level from shallow water-depth is recorded in the clayey sequence from 83 to 38 m in depth. The clayey beds show open lacustrine facies similar to the clayey sequence underlying the event sand bed.

Stage 6 : The 27 m thick Kalimati clay from 38 to 11 m in depth probably record the eutrophic condition of the lake, judging from the differences of lithology and sedimentary structure from the underlying clay. The beds lack distinct laminae, diatomaceous laminite, fossil leaves, though they contain considerable amount of tiny carbonaceous fragments. The topmost 1 m part of the Kalimati Formation is characterized by thin interbeds of silt and sand. The presence of these beds suggests inflow of coarse detritus to clayey lake floor before the disappearance of the lake.

Stage 7 : Draining out of the lake-water and following erosion by rivers are indicated by erosion features on the top surface of the Kalimati Formation and the onset of the fluvial sand beds over it. The boundary between the lacustrine clay and the fluvial sand was detected at 16.82 m in Tri-Chandra Campus, at 9.15 m in DPTC and at 12.15 m depth in Rabibhawan. This indicates that the altitude of erosion surface lies between 1,287 ~ 1,297 m. While the upper part of the Kalimati Formation was being deposited in the central part of the Kathmandu Basin, thick lacusrtine delta sediments were deposited in the northern part (Natori et al. 1980; Yoshida and Igarashi 1984; Sakai et al. 2001). They are considered as late Pleistocene in age. These deltaic sediments are distributed near the foot of the northern hills and the top surface lies at altitude ranging from 1,300 to 1,386 m above mean sea level. As a delta is developed in the waterfront, altitude of topset sediment can be roughly regarded to indicate an ancient altitude of water-surface of the lake. The ^{14}C age of the Kalimati clay, 11 m below the ground surface at Santi Basti (Fig. 1; altitude is about 1,270 m) is reported to be 29,210 ± 90 yr. B.P. (Fujii and Sakai 2002). This age is very close to the youngest age of the Thimi Formation or the oldest age of the Gokarna Formation (Yoshida and Igarashi 1984), which are located between 1,340 and 1,345 m above mean sea level respectively. Thus, the altitude difference of about 70 m to 75 m between Santi Basti (1,270 m) and Thimi (1,345 m) and Gokarna (1,340 m) represents the water depth of the Palaeo-Kathmandu Lake at Santi Basti at 29 kyr. B.P.

It is difficult to discuss on the duration and age boundary of each stage at present, because we do not have yet any age data of the sediments obtained as cores. However, Sakai et al. (2002) and Fujii and Sakai (2002) estimated the ages of the sediments, on the basis of comparison of the palaeoclimatic curve obtained from pollen analyses of samples from drill-wells in the Kathmandu Basin and a variation curve of $\delta^{18}O$ from deep sea sediments in the Indian Ocean. They estimated that the birth of the lake was around 2 Ma and the lake disappeared after the last glacial period, probably during the Holocene time. The ongoing ^{14}C dating of carbonaceous fragments found in the cores will help to give an accurate date of drying up of the Palaeo-Kathmandu Lake.

Proposed geotechnical study of Kathmandu Basin sediments

The common occurrence of water-saturated mud and sand beds in the Patan Formation and the uppermost part of the Kalimati Formation was unexpected before the core-drilling. The cores obtained from all the three sites showed that the uppermost 20 m thick layer belonging to the Patan Formation and the top part of the Kalimati Formation are considerably water saturated and also filled with natural gas. Thus, in general, the sediments occur under a favorable condition for liquefaction during the shaking by an earthquake. The impermeable clayey beds of the Kalimati Formation under the porous and permeable fluvial sand beds of the Patan Formation probably give rise to form an aquifer saturated with water, and thereby making them weak against shear stress. Liquefaction of sandy beds weakens the shear strength of the beds, and results in lowering the supporting force for buildings. Many earthquake disasters caused by liquefaction were reported from all over the world, e.g. Hyogo-ken Nanbu Earthquake around Kobe in 1995, Loma Prieta Earthquake, California in 1989, Mexico Earthquake in 1985, Niigata Earthquake in 1964. In these earthquakes, collapsing of buildings, bridges and ports concentrated more in the areas of water-saturated weak sediments, such as reclaimed land, river bank and ancient lake area. The subsurface geological condition of Kathmandu City is very similar to that of Mexico City which is built on the ancient Texcoco Lake (Bolt 1993). In spite of weak subsurface condition, many tall buildings have come up in Kathmandu, and the number is constantly rising. Most of such large buildings have been constructed without adequate research of subsurface sediment condition. The natural gas field areas along the Bagmati and Manahara Rivers may be considered as one of the most dangerous zones in the Kathmandu Valley where liquefaction may take place during strong earthquakes. We have, therefore, proposed in our next research programme a systematic study on the engineering properties of subsurface sediments of the City. This will greatly help the concerned agencies in Nepal to take proper action in order to mitigate the earthquake disasters.

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