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Two times lowering of lake water at around 48 and 38 ka, caused by possible earthquakes, recorded in the Paleo-Kathmandu lake, central Nepal Himalaya

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Abstract

Sedimentary facies and micro-fossil analyses, and AMS^{14}C dating were performed in order to reveal the water-level fall events and draining process of the lake (Paleo-Kathmandu Lake) that existed in the past in the Central Nepal Himalaya. The sedimentary facies change from the lacustrine Kalimati Formation to the deltaic Sunakothi Formation in the southern and central Kathmandu basin, and the abrupt and prominent increase of phytoliths *Bambusoideae* and *Pediastrum*, and contemporaneous decrease of sponge spicule and charcoal grains around 48 and 38 ka support the lowering of water level at these times. According to the pollen analysis, both events occurred under rather warm and wet climate, thus supporting that they were triggered by tectonic cause and not by climate change. The first event might be linked to a possible occurrence of a large earthquake with an epicenter in the vicinity of the Paleo-Kathmandu Lake. The occurrence of a mega landslide in Langtang area close to the north of the Kathmandu Valley producing pseudotachylite dated at 51 ± 13 ka could be linked to this earthquake. Finally, the water was completely drained out from the remnant lake at the central part of the Kathmandu basin by ca.12 ka.

Keywords: Central Nepal, Paleo-Kathmandu lake, Lacustrine sediments, Deltaic sediments, Draining of lake water, AMS^{14}C age

Background

Basin-fill sediments of intermontane basins are good archives of past climate changes, tectonics, and depositional environments within the valleys and surrounding mountains. The basin-fill sediments of the Kathmandu Valley in Central Nepal Himalaya (Fig. 1) are excellent archives of changes in monsoonal climate, terrestrial depositional environments, and tectonics of the Himalaya (Sakai 2001a). From a view point of the past earthquake in Central Nepal, the basin-fill sediments of the Kathmandu Valley is a valuable archive which recorded crustal deformation and fault rupture caused by large earthquakes such as the Gorkha earthquake in 2015 (Kobayashi et al. 2015).

In order to reconstruct geologic history of the Kathmandu Valley, we undertook core drilling of the sediments under the name of Paleo-Kathmandu Lake project, and have conducted multi-proxy analyses of the cores. As a result, changes of various kind of proxy during the last 600 kyr were reconstructed: history of vegetation and monsoon climate (Fujii et al. 2004a; Maki et al. 2004), ecological changes of diatom (Hayashi et al. 2009), and changes in TOC, C/N, δ^{13}C of organic matter (Mampuku et al. 2008). Mineralogical study of lacustrine clay during the last glacial period revealed that amount of clay fraction, clay mineral assemblage, and crystallinity were strongly controlled by paleoclimate (Kuwahara et al. 2010). Stratigraphic and sedimentological study of the basin-fill sediments revealed that the lake was born at around 1 Ma by damming of the Paleo-Bagmati river, and

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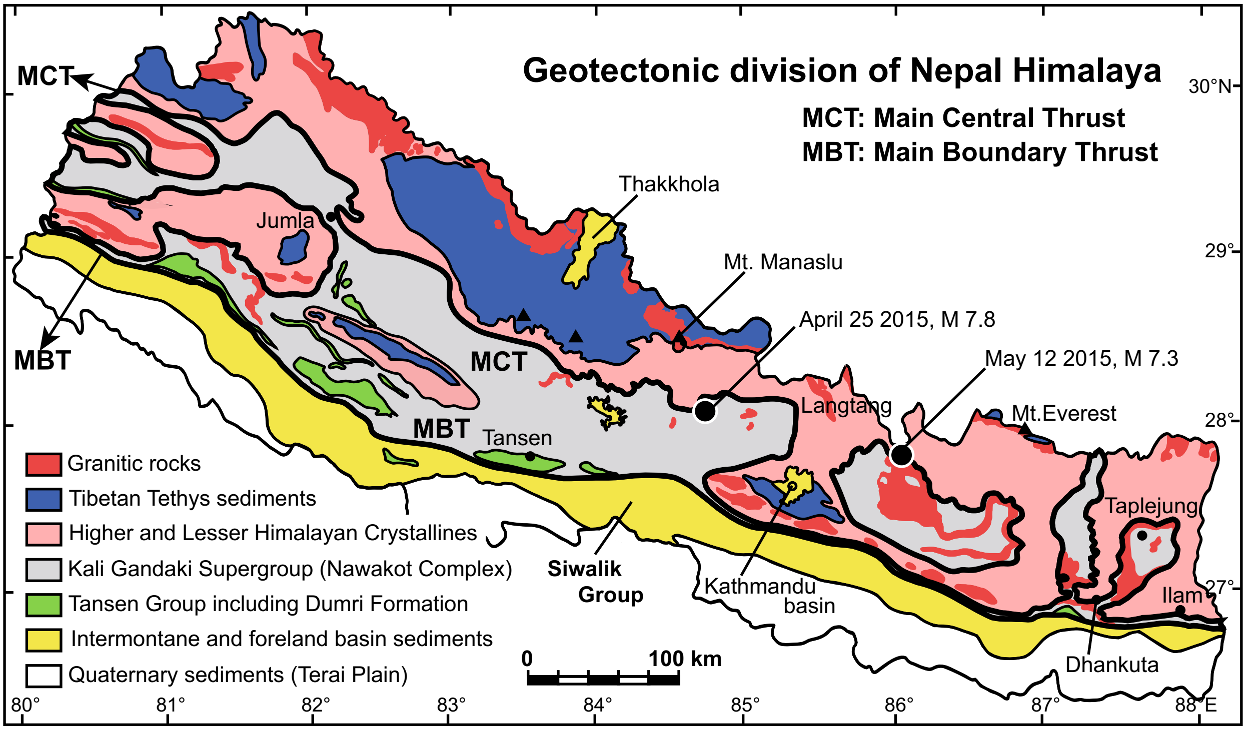

Fig. 1 Geotectonic division of Nepal Himalaya. Location of the Kathmandu basin and epicenters of the Gorkha earthquake are shown

lake water started expanding, following the growth of the dam through supply of fanglomerate from the uplifting of the Mahabharat range to the south (2006).

However, when and why did the Paleo-Kathmandu Lake water started draining and when the lake was finally completely drained out was unknown. Then, we carried out geological field survey in the southern Kathmandu basin, and performed AMS ^{14}C dating of carbonaceous sediments. The results of these survey revealed that there were two events of lowering of lake water at around 48 and 38 ka, and final disappearance of the lake occurred at 12 ka. In this paper, we report our new data and discuss on the process and possible cause of draining of the lake.

Methods

We performed micro-fossil analysis by means of microscopic observation of smear slide of clayey sediments, taken from three drilled cores of the Kalimati Formation at Rabibawan (R), Tri-Chandra campus (T), and Pulchok (D) at 1 m interval (Fig. 2). Number of sponge spicules, phytoliths, pollen including spore, plant fragments, excepting diatom, were counted until a total of 200 pieces were reached under a magnification of 400, using Nikon ECLIPSE 50i POL, and each ratio was calculated.

In order to determine depositional age, 5–15 g homogeneous clay with very fine grained carbonaceous fragments were collected from the cores (Fig. 3) and exposures. Accelerator mass spectrometer (AMS) radio carbon ages were measured by Paleolabo Co. Ltd., Japan, and the obtained Libby ages were calibrated to calendar year using a calibration program of CALIB 7 (Stuiver et al. 2013).

Changes from lacustrine Kalimati Formation to deltaic Sunakothi Formation

The Sunakothi Formation (Sawamura 1994; Sakai 2001b) is distributed in the southern Kathmandu basin, forming lacustrine terraces (Fig. 4a). They are gently inclined toward the center of valley starting from an altitude of 1395 m in the south to 1302 m in the north (Fig. 3a). The total thickness of the formation decreases toward the north from 35 m at Jorkhu to 15 m at Ekantakuna (Fig. 3b). The northern limit of the Sunakothi Formation is along the Manohara and Hanumante rivers flowing from E to W in the center of the basin (Fig. 2a).

The top of the Kalimati Formation was eroded before the deposition of Sunakothi Formation, and the erosion surface is marked by the presence of lag deposits of meta-sandstone granule and carbonaceous wood fragments (Fig. 4b). Terrace gravel bed of a few meter thick is unconformably lying on the top of the uppermost bed of the Sunakothi Formation (Fig. 3b).

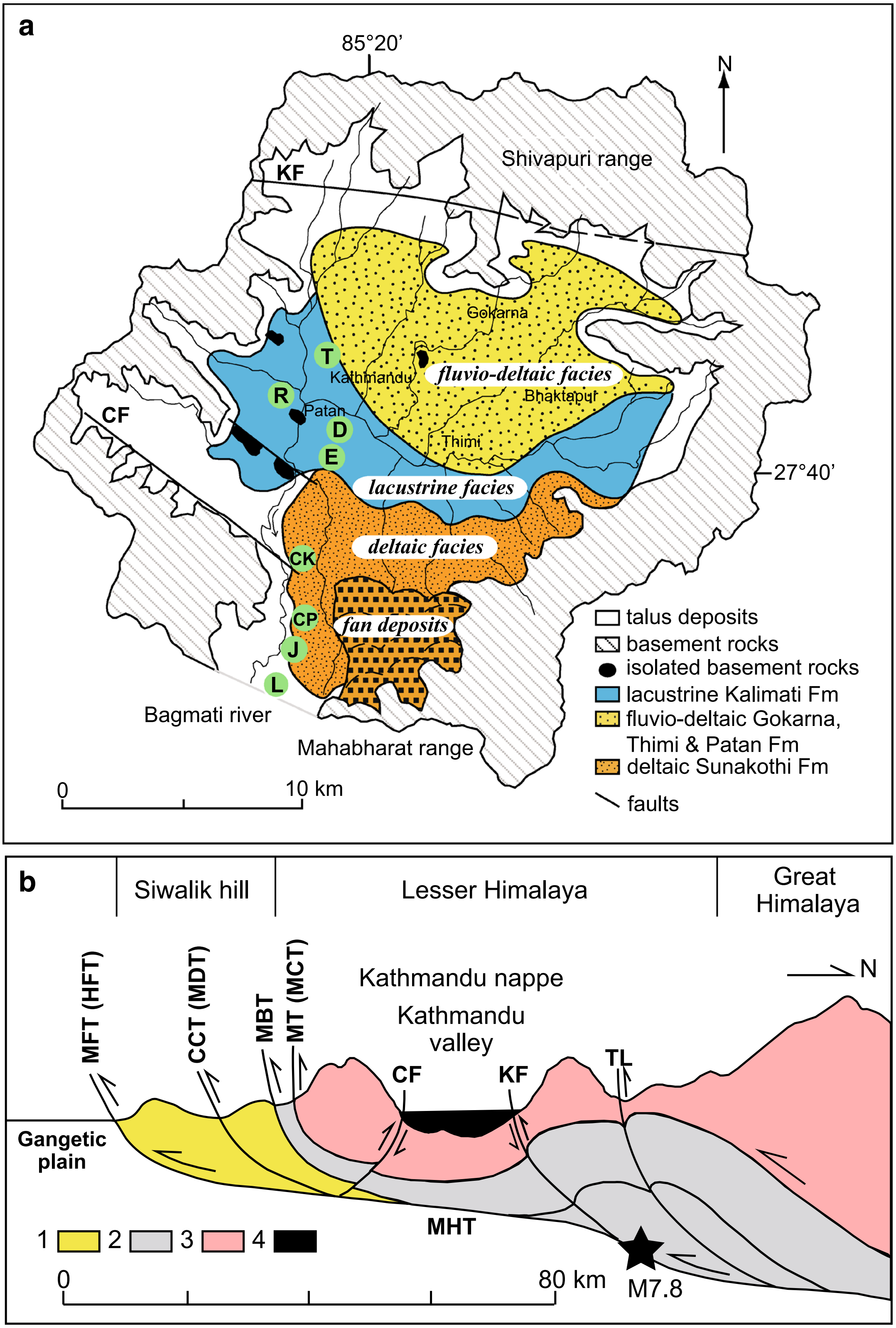

Fig. 2 **a** Sedimentary facies distribution map of the Kathmandu basin. Drill sites are also shown. **b** Schematic geological cross section of the Kathmandu Valley and surrounding mountains. Modified after Sakai (2001a). *R* Rabibhawan, *T* Tri-Chandra campus, *D* Pulchowk, *E* Ekantakuna, *CK* Chhayasikot, *CP* Chhampi, *J* Jorkhu, *L* Lukundol

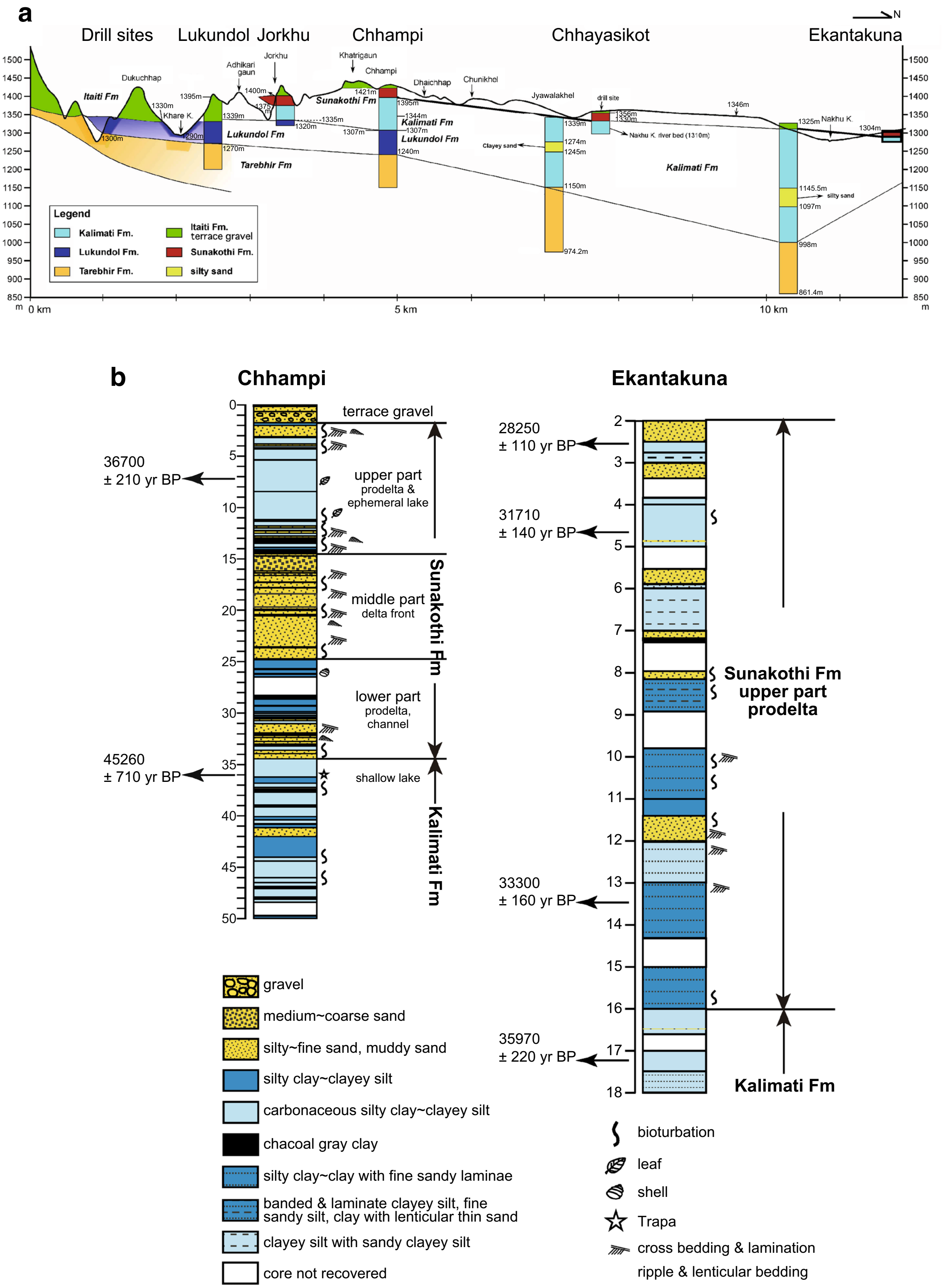

Fig. 3 **a** Lithostratigraphic comparison of seven columnar sections of the drill cores in the southern Kathmandu basin. Modified after Sakai et al. (2012). **b** Lithostratigraphy of the drill cores of the Sunakothi Formation at Chhampi and Ekantakuna in the southern Kathmandu basin

The Sunakothi Formation is divided into three parts: lower prodeltaic part, middle delta front part, and upper prodeltaic part (Fig. 3b). The lower part at Sunakothi Formation is characterized by thin interlayered bed of fine sand and carbonaceous silty mud (Fig. 4d), showing longitudinal cross-bedding, and wave- and current-ripple bedding. Those sedimentary structures are ubiquitously destroyed by bioturbation. The middle delta front part is characterized by large-scale cross-stratified thick sand bed and convoluted bed of slump origin (Fig. 4c). Large-scale planar cross-stratification shows northward paleo-current directions (Fig. 4e). The upper prodeltaic part comprised rhythmic sequence of thin lenticular and cross-laminated sand bed and carbonaceous mud bed. The lower half is sand dominant and upper half is mud dominant and has rhythmic sequence (Fig. 4f) with destructive bioturbation.

In the northern margin of the southern Kathmandu basin at Ekantakuna, there lacks the lower and middle parts of the Sunakothi Formation (Fig. 3b). The Kalimati Formation gradually changes into the mud-dominant rhythmite beds of the upper prodeltaic sediments of the Sunakothi Formation with 1-m-thick transition zone (Fig. 3b).

A coarsening upward sequence from the Kalimati to the Sunakothi Formation represents an environmental change from lacustrine to prodelta and delta front, indicating a progradation of lacustrine delta after erosion of the Kalimati Formation.

The beginning of deposition of Sunakothi Formation

In order to determine the age of erosion of the top of Kalimati Formation and beginning of deposition of the Sunakothi Formation, we preformed AMS^{14}C dating for different samples taken from four localities at Jorkhu (J), Chhampi (CP), Chhyasikot (CK), and Ekantakuna (E) (Figs. 2a, 3a).

A carbonaceous mud sample taken from 5 cm above the base of the Sunakothi Formation at Jorkhu (Fig. 4b) yielded 44,120 ± 460 yr. BP (46,729–47,904 cal yr. BP), and that from the Kalimati Formation 3 m below the base of the Sunakothi Formation yielded 42,190 ± 370 yr. BP (45,149–45,829 cal yr. BP). A sample collected from the Kalimati Formation at 6 m below the base of the Sunakothi Formation in a drilled core at Chhampi yielded 45,260 ± 710 yr. BP (47,870–49,491 cal yr. BP). At Chhayasikot, one lacustrine clay sample was collected at 50 cm below the base of the Sunakothi Formation, and this sample yielded 44,700 ± 650 yr. BP (47,184–48,804 cal yr. BP). These data indicate that the depositional age of sediments at the base of the Sunakothi Formation in the southern area of the Kathmandu Valley is ca. 48 ka.

On the other hand, AMS^{14}C age of the basal part of the Sunakothi Formation at Ekantakuna near the center of the basin shows 33,300 ± 160 yr. BP (37,187–37,922 cal yr. BP) and that of the uppermost part of the Kalimati Formation shows 35,970 ± 220 yr. BP (40,321–40,902 cal yr. BP). It suggests that deposition of the lacustrine clay has continued at least till ca. 40 ka in the central part of the basin.

When the Paleo-Kathmandu lake completely drained out?

As the answer to the above question lies in knowing the age of the youngest Kalimati Formation, we collected a carbonaceous clay sample of this formation from 1 km to the south of southern edge of the Tribhuvan International Airport of Kathmandu (Fig. 2a) at an altitude of 1296 m, and lying near the bank of the Manohara river in the central part of the basin to perform AMS^{14}C dating. The dated sample gave the youngest age of 10,485 ± 40 yr. BP (12,405–12,531 cal yr. BP). This data narrowly constrain the date of the final drying out of the Paleo-Kathmandu Lake to ca.12 ka and also indicates that the deposition of the Kalimati Formation in the central part of the basin continued till this date.

Changes in micro-fossils assemblage in lacustrine sediments

Microscopic observation and counting of ratio of four proxy [phytoliths, sponge spicule (Fig. 5b), plant fragment, pollen] and number of *Pediastrum* (Fig. 5c) were performed (Fig. 6), in order to reveal environmental changes in and around the Paleo-Kathmandu Lake. In addition, charcoal grain (Fig. 5a) analysis was carried out to clarify the paleoclimatic changes during the late Pleistocene. A 60-m-long core between 9.4 and 61.4 m in depth of drilled cores recovered at Rabibhawan was used for the study. Additional study was carried out for two drilled cores at Tri-Chandra campus (TC core) and at Pulchok (DPTC core).

Phytoliths of *Bambusoideae* (Fig. 5d) abruptly increased its number at depth from 37.4 to 31.4 m and that from 26.4 to 24.4 m, and their peaks are at ca. 48 and 38 ka, respectively (Fig. 6). The ratio in four proxy drastically increased more than 90 % and attained 98 % at maximum, though it is usually less than 10 %.

At the same depth, number of sponge spicule abruptly decreases its number from average 193.4 pieces/g to less than 50 pieces/g at around 48 and 38 ka. The ratio of sponge spicule also decreases up to 2 %. In addition, number of charcoal grain also decreases from average 2675 pieces/g to less than 100 pieces/g at the same periods. The ratio of plant fragments including charcoal grain also decreases to less than 10 % and minimum ratio is 1 % at 34.4 m in depth.

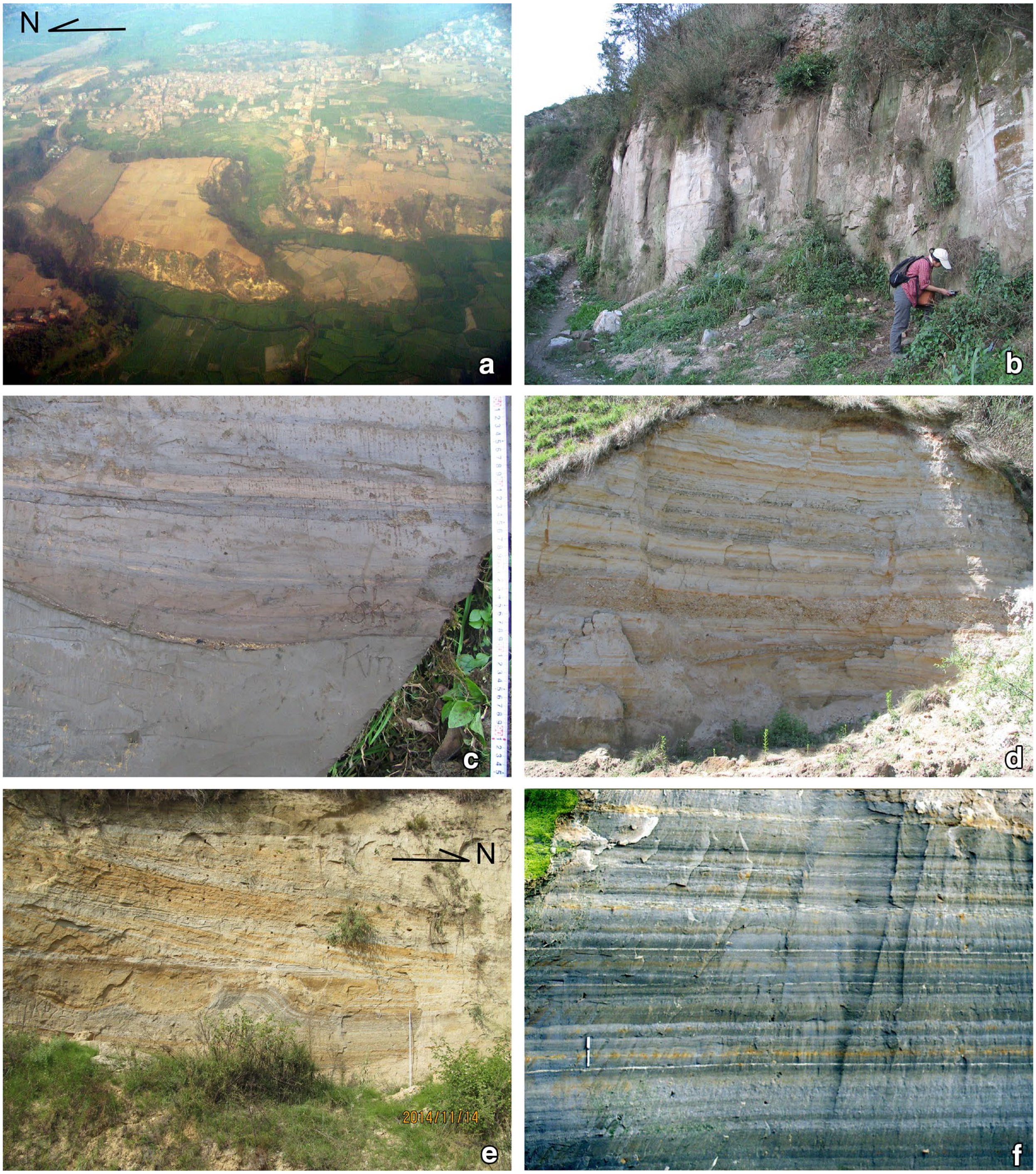

Fig. 4 Photograph of the Sunakothi Formation showing its topographic features and representative sedimentary facies. **a** Aerial photograph of terrace-forming Sunakothi Formation and Kalimati Formation exposed on the eroded valley floor, east of Sunakothi. **b** Vertically jointed, lacustrine clayey mudstone of the Kalimati Formation, at Khokana. **c** An exposure showing the boundary between Kalimati Formation comprising massive clay and Sunakothi Formation of fine banding of carbonaceous mud and silty clay, at Jorkhu. Note the erosion surface of the Kalimati clay and lag deposits on it. **d** Alternated beds of sand and mud of the lower part of the Sunakothi Formation at Sunakothi. **e** Large cross-stratified sandstone of the middle part of the Sunakothi Formation, at Sunakothi. **f** Prodeltaic rhythmite of rippled and laminated sandstone and black carbonaceous mudstone at the uppermost section of the Sunakothi Formation at Ekantakuna

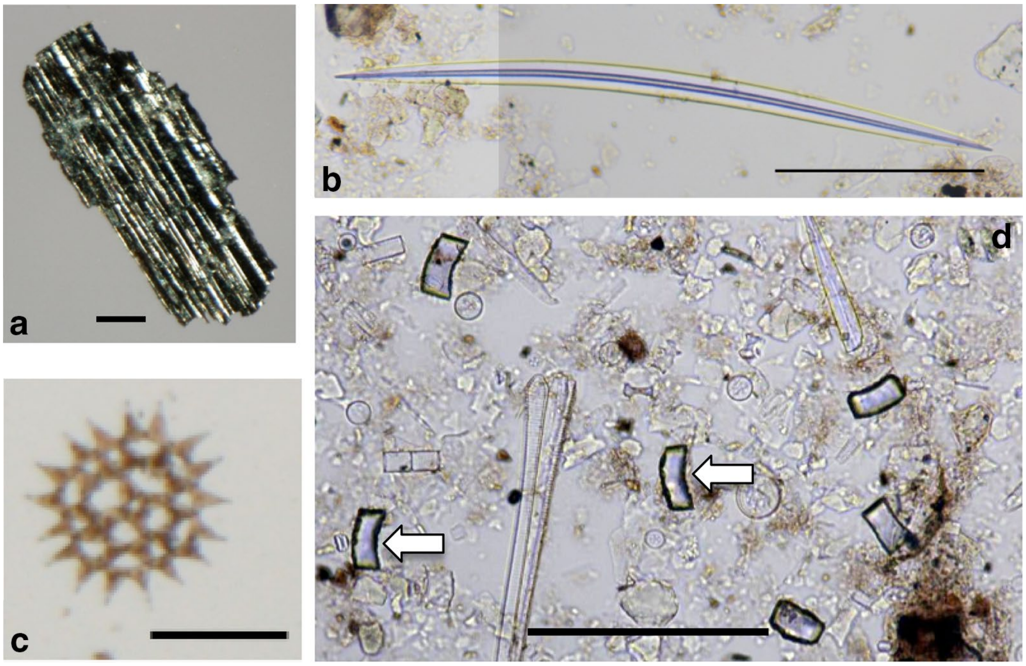

Fig. 5 Photomicrograph of micro-fossils obtained from cores of the lacustrine Kalimati Formation. **a** charcoal grain, **b** sponge spicule, **c** *Pediastrum*, **d** phytoliths and diatom. *Arrow* shows *Bambusoideae*. A *scale bar* is 100 µm

Pediastrum is an inhabitant of shallow water environment, because it produces energy by photosynthesis. It was also detected from RB core at the same depth, and its number reaches maximum of 45 pieces/g at 35.5–34.5 m depth.

Similar abrupt increase of Phytoliths of *Bambusoideae* at two horizons are detected at 54–52 and 47–44 m in depth of TC, and at 35 and 31–30 m in depth of DPTC cores (Fig. 2a). When Phytoliths of *Bambusoideae* is dominant, number and ratio of sponge spicule and plant fragment decrease same as in RB core. Thus this event is not a local phenomenon but widespread in the whole lake.

Discussion

Lowering of lake-water level at 48 and 38 ka indicated by micro-fossils

Abrupt and prominent increase of Phytoliths *Bambusoideae* at 48 and 38 ka is interpreted to indicate lowering of lake-water level, because preferable habitat of *Bambusoideae* is swampy lowland where it is not submerged under water. Contemporaneous increase of *Pediastrum* also indicates expansion of swampy environments around the lake margin. Decrease of sponge spicule is interpreted that shallow water environments along the lake margin shrunk, because freshwater sponge usually live a life attaching a gravel, stem of waterside plants, and decayed tree in submerged lake margin. Decrease of both charcoal grain and ratio of plant fragment suggest that depositional area of terrestrial material supplied from surrounding mountains shrunk at 48 and 38 ka.

Lowering of lake-water level at around 48 ka

In addition to the micro-fossil evidence, abrupt termination of deposition of clayey lacustrine sediments, marked by deposition of fluvial and prodeltaic sediments in the southern Kathmandu basin, clearly indicates a lowering of lake-water level. There are two possible explanations for this: (a) the climatic and (b) the tectonic. On the basis of pollen analysis (Fujii et al. 2004a, b) and crystallinity of clay mineral (Kuwahara et al. 2010), it has already been shown that the climate of Kathmandu basin area at around 48 ka was rather warm and wet. This will imply that there was plenty of rainfall and the lake-water level will remain high. But despite that kind of climatic condition, the present study on microfossils indicates a water-level fall, and suggests that climate has played no part in the lowering of the lake-water level. Therefore, tectonics could be the only reasonable cause of the fall in water level.

Lowering of lake-water level at around 38 ka

Gradual facies change from the lacustrine Kalimati to prodeltaic Sunakothi Formation recorded in a drilled core at Ekantakuna also indicates lowering of water level in the central part of the basin at ca.38 ka. All

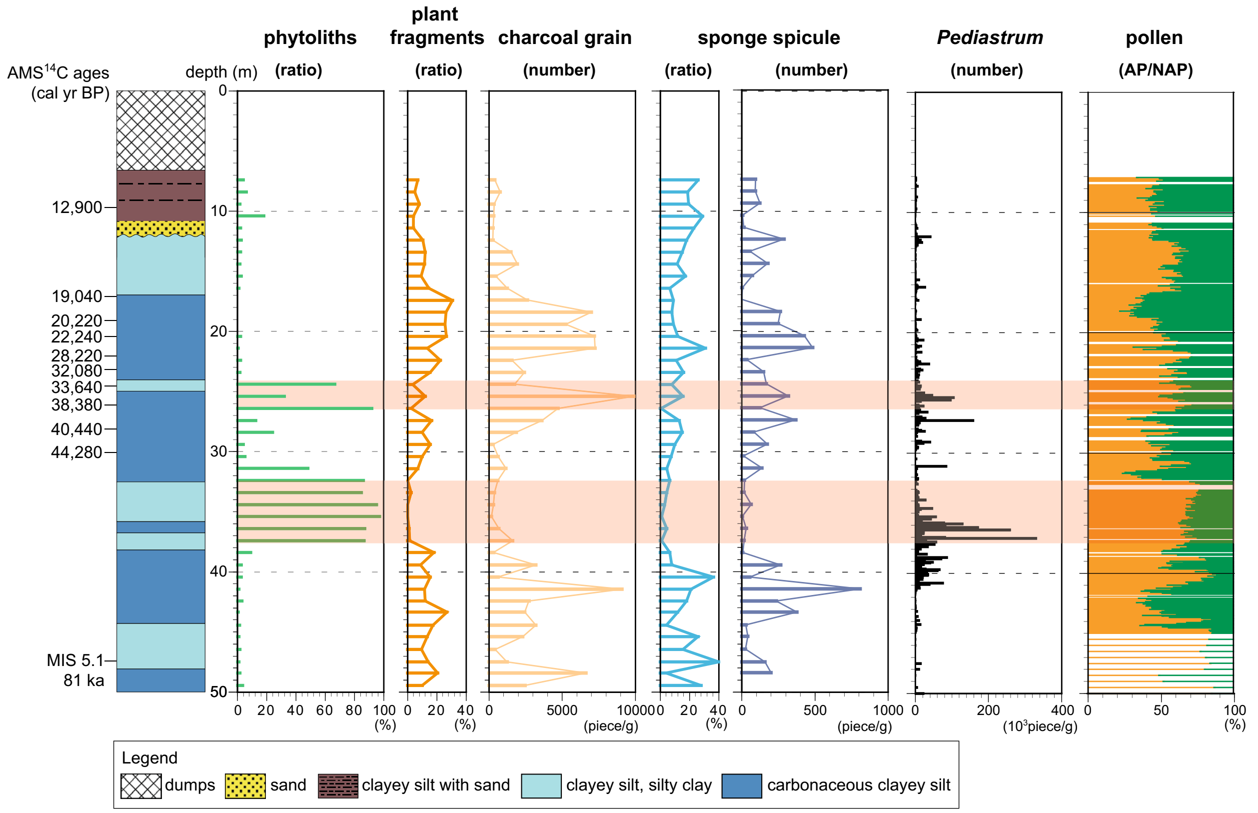

Fig. 6 Lithostratigraphy of RB core after Sakai et al. (2001), and AMS14C ages after Hayashi et al. (2009). Change in ratio of phytoliths, sponge spicule, carbonaceous fragments, pollen including spore and others are shown, and change in numbers of sponge spicule, charcoal grain, and *Pediastrum* in RB core are also shown. Possible range of lake-water fall events are indicated by *pink shadow*. *AP* arboreal pollen, *NAP* non-arboreal pollen

micro-fossil records from the younger horizon at 38 ka also indicate a similar pattern as that shown by 48 ka sediments. Paleoclimatic data obtained from pollen and clay analyses from this horizon indicate that rather warm and wet climate had prevailed in Kathmandu at around 38 ka (Fujii et al. 2004b; Kuwahara et al. 2010), and rise of water level due to increase of rainfall at around 38 ka should be expected. But on the contrary, the micro-fossil analyses indicate a lowering of water level at this time. Thus, possible cause of lowering of lake water is ascribed to tectonic movement.

Lake-water lowering events in the northern and southern Kathmandu basin

Three major events of Paleo-Kathmandu Lake water lowering spanning for nearly 30 kyr (between 50 and 20 ka) were suggested by Sakai et al. (2006, 2008) based on the sedimentary facies analysis of the deltaic sediments and dating of delta plain deposits in the northern Kathmandu basin (Fig. 7). The events were dated at 50–45, 39, and 35 ka. The first event was based on the evidence of the lowering of elevation of delta plain deposits, and the second event was identified based on the time of erosion of the Gokarna Formation at 39 ka. The third event was estimated from the evidence of about 50 m difference of altitude of delta plain between the Gokarna and Thimi Formations. Lowering of lake water at 48 and 38 ka in the southern Kathmandu basin can thus be safely correlated with those in the northern basin.

A possible cause of draining of the Paleo-Kathmandu lake at 48 ka

In Lantang area to the north of Kathmandu (Fig. 1), a pseudotachylite zone has been found which is interpreted to have been formed by friction melting along the slip surface of a mega landslide in gneisses called Tsergo-Ri landslide (Masch et al. 1985; Weidinger et al. 2002). Fission-track age of zircon taken from fault gouge around the pseudotachylite is estimated to be 51 ± 13 ka (Takagi et al. 2007). The timing of formation of pseudotachylite is contemporaneous (within the error) with that of starting of lowering of the Paleo-Kathmandu lake-water level at around 48 ka. If this landslide was caused by a big earthquake similar or much larger than the recent Gorkha earthquake on 25 April 2015 (M 7.8), it could be argued that the dam of the Paleo-Kathmandu Lake must

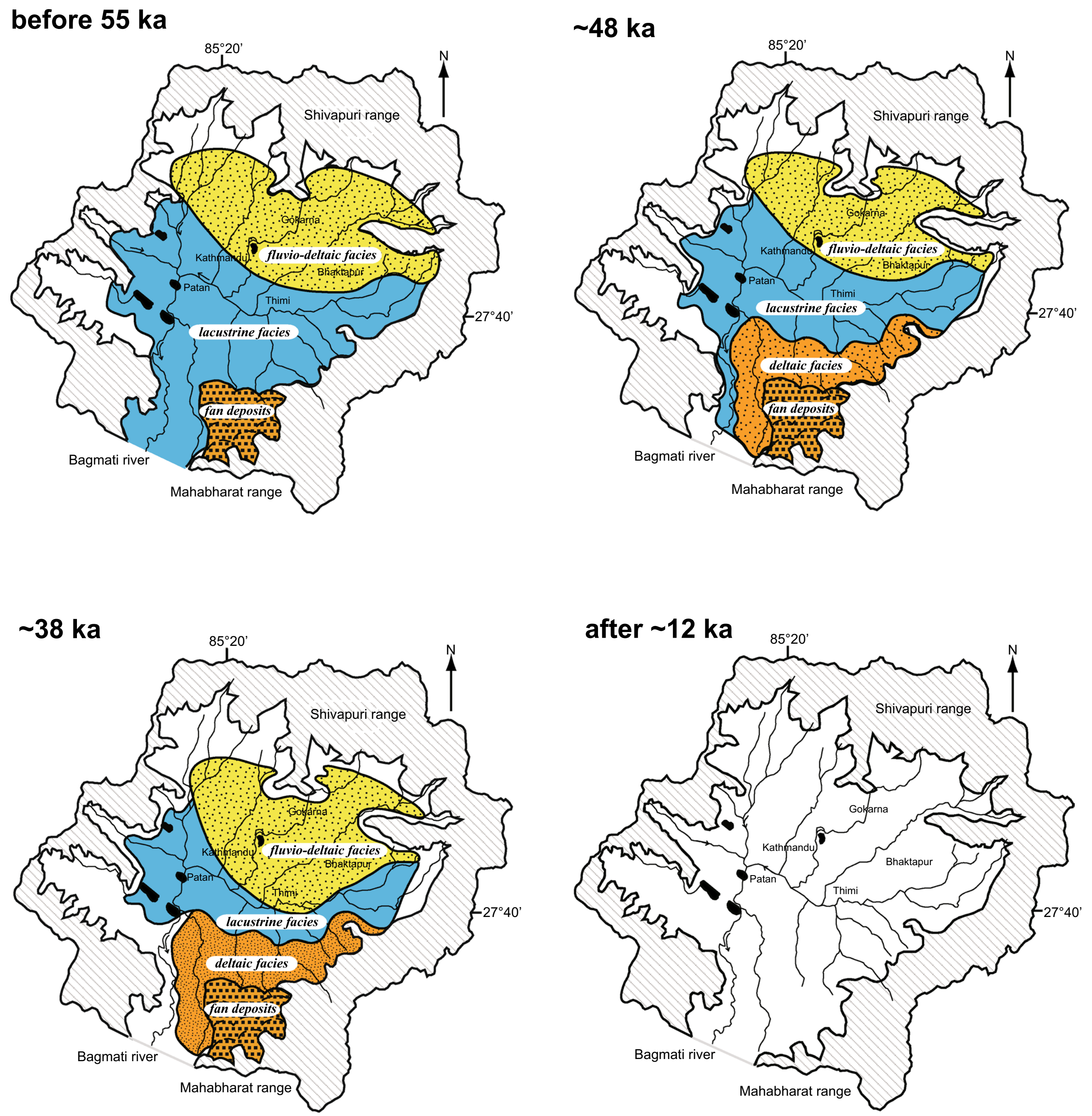

Fig. 7 A schematic paleogeographic map showing major depositional environmental changes of the Kathmandu basin during the last 60 kyr

have been broken by this earthquake shock and the lake water started to drain out from the breached portion of the dam, and thus lowering the water level of the lake occurred.

Conclusions

Lowering of lake-water events recorded in the Late Pleistocene lacustrine sediments of the Paleo-Kathmandu Lake were studied by means of micro-fossil and sedimentary facies analyses of five drilled cores dated by AMS ^{14}C method. In the southern area of the Kathmandu Valley, sedimentary facies changes from the lacustrine Kalimati Formation to prodelta and delta front sequence of the Sunakothi Formation occurred ca. 48 ka. During the same time in the central part of the basin, *Pediastrum* and Phytoliths of *Bambusoideae*, which are inhabitants of swampy environments, abruptly increased their number, and sponge spicule and charcoal grains abruptly decreased their number. This phenomenon is commonly detected in three cores, and interpreted to indicate an abrupt and rapid lowering of lake-water level caused by a tectonic event, because the climate of this period was estimated to be rather warm and wet, and lake-water level must have risen. A possible tectonic cause can be ascribed to an earthquake occurred in Langtang area to the north of Kathmandu, which generated pseudotachylite at around 51 ± 13 ka.

The similar abrupt and rapid lowering of lake-water level was commonly detected from three drilled cores in the central part of the basin at around 38 ka. At this time, sedimentary facies changed from lacustrine to prodeltaic, near the center of the basin. This phenomenon is also likely to have been triggered by a probable earthquake, because the paleoclimatic record suggests rising of lake-water level.

Authors' contributions

HS is a leader of the Paleo-Kathmandu Lake project and core-drilling program, and designed and supervised the whole project. RF is a sub-leader of this project and she was in charge of pollen and other micro-fossil analyses. MS and RS analyzed micro-fossils and charcoal grains and interpreted the data. MP did field survey and collected samples for ^{14}C dating. All authors read and approved the final manuscript.

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