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# Changes in C<sub>3</sub>/C<sub>4</sub> vegetation in the continental interior of the Central Himalayas associated with monsoonal paleoclimatic changes during the last 600 kyr

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## Abstract

A continuous lacustrine sediment core obtained from the Kathmandu Valley in the Central Himalayas revealed that cyclical changes in  $C_3/C_4$  vegetation corresponded to global glacial-interglacial cycles from marine isotope stages (MIS) 15 to MIS 4. The  $C_3/C_4$  vegetation shifts were reconstructed from significant changes in the  $\delta^{13}C$  values of bulk organic carbon. Glacial ages were characterized by significant  $^{13}C$  enrichment, due to the expansion of  $C_4$  plants, attributed to an intensification of aridity. Thus, the southwest (SW) summer monsoon, which brings the majority of rainfall to the Central Himalayan southern slopes, would have been weaker. Marine sediment cores from the Indian Ocean and Arabian Sea have demonstrated a weaker SW monsoon during glacial periods, and our results confirm that arid conditions and a weak SW monsoon prevailed in the continental interior of the Central Himalayas during glacial ages. This study provides the first continuous record for the continental interior of paleoenvironmental changes directly influenced by the Indian monsoon.

## 1 Introduction

The climate of East and South Asia is controlled greatly by the highly seasonal monsoonal climatic system, with wet summers and dry winters (Hastenrath, 1985; Webster, 1987). The Indian monsoon system is characterized by strong southwest (SW) monsoon winds blowing from the ocean toward the continent and carrying moisture and rain over the land during summer; northeast dry winds, blowing from the continent toward the ocean, dominate during winter. Climate model simulations have demonstrated that the Asian monsoon system and its evolution are closely linked to the uplift of the Tibetan plateau (Manabe, 1974; Hahn and Manabe, 1975; Kutzbach et al., 1993; Kitoh, 1997; Ruddiman, 1997; Abe et al., 2003; Kitoh, 2004). Geological data obtained from both the continent (Quade and Cerling, 1995; Dettman et al., 2001) and ocean (Kroon et al., 1991; Prell et al., 1992) also suggest a linkage between monsoonal climate

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change and the uplift of the Himalayas and Tibetan plateau.

During the late Quaternary, monsoon strength differed between glacial and interglacial periods. Many paleoclimatic records from Indian Ocean and Arabian Sea marine sediment cores indicate that the SW monsoon was stronger during interglacial periods and weaker during glacial periods (Van Campo et al., 1982; Prell and Van Campo, 1986; Sarkar et al., 1990; Muzuka, 2000). Although monsoonal climate change affects both continents and oceans, terrestrial information on these changes in the Indian subcontinent is very limited (Krishnamurthy et al., 1986; Agrawal et al., 1989; Sakai, 2001). An arid climate is presumed to have prevailed on land during glacial periods, because of the weak SW monsoon. However, Niitsuma et al. (1991) concluded that the climate of the Arabian Peninsula was more humid during glacial periods than during interglacial periods, on the basis of the paleoclimatic record contained in sediment cores obtained on ODP Leg 117 (Neogene Package). Thus, the continuous monsoonal climate change record during the Quaternary glacial-interglacial period is still uncertain. Continuous climatic records from the continental interior are needed to clarify how the Indian monsoon system changed during the Quaternary.

The Kathmandu Valley is a key site for tracing the terrestrial climate effects of changes in the Indian monsoon. The valley is an intermontane basin, located on the southern slopes of the Central Himalayas, and is under the direct influence of the present monsoon. The dry lakebed of Paleo-Kathmandu Lake (PKL) is filled with thick lacustrine and fluvial sediments from the late Pliocene to Quaternary (Sakai, 2001). PKL was about 25 km in diameter, with a water depth estimated at 75 m or more (Sakai et al., 2001a). In 2000, a core-drilling program was undertaken in the lacustrine basin-fill sediments, which were expected to record long-term, continuous paleoenvironmental changes in the region (Sakai, 2001). A continuous 218-m-long core was obtained at Rabibhawan, in central Kathmandu Valley (Fig. 1). We used this core (RB core), composed mainly of clayey and muddy lacustrine sediments, for multi-proxy paleoenvironmental analyses.

One approach to clarifying past climate change is the reconstruction of terrestrial

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vegetation changes controlled by climatic changes. Land plants are classified as C<sub>3</sub> or C<sub>4</sub> on the basis of different photosynthetic pathways. The C<sub>3</sub> (mainly trees) and C<sub>4</sub> (herbs) plants can be clearly distinguished by their carbon isotopic compositions ( $\delta^{13}\text{C}$ ). The average  $\delta^{13}\text{C}$  value for C<sub>3</sub> plants is about  $-28\text{‰}$ , whereas that for C<sub>4</sub> plants is  $-14\text{‰}$  (O'Leary, 1988). C<sub>3</sub>/C<sub>4</sub> vegetation shifts are controlled mainly by precipitation, temperature, and the partial pressure of atmospheric carbon dioxide (pCO<sub>2</sub>) (Collatz et al., 1998). Although identifying the underlying causes of C<sub>3</sub>/C<sub>4</sub> vegetation shifts is complex, C<sub>4</sub> plant expansions have been recognized in the Cretaceous, late Miocene, and last glacial maximum (LGM) (Cole and Monger, 1994; Cerling et al., 1997; Street-Perrott et al., 1997; Kuypers et al., 1999).

We analyzed the terrestrial C<sub>3</sub>/C<sub>4</sub> vegetation changes associated with monsoonal climatic changes in the valley during the middle to late Pleistocene. Here, we present changes in total organic carbon (TOC), total nitrogen (TN), the stable carbon isotopic composition ( $\delta^{13}\text{C}$ ) of TOC, and the n-alkane compositions recorded in the RB core. This is the first report on the continuous terrestrial record of paleoenvironmental changes on the southern slopes of the Central Himalayas obtained from an organic geochemical study.

## 2 Samples and methods

### 2.1 Study area and samples

The Kathmandu Basin, located around lat.  $27^{\circ}40'$  N, lies in warm temperate-subtropical climatic zones and has an annual average temperature of  $18^{\circ}\text{C}$ . The annual average precipitation is 1500 mm. More than 80% of rain falls in the three summer months. The basin is surrounded by 2400–2800-m-high mountains, and the average elevation of the valley floor is about 1340 m above sea level. The Kathmandu Valley is an isolated, closed basin, and basin-fill sediments are supplied only from the mountains surrounding the valley (Sakai, 2001). The valley floor vegetation is characterized by

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*Shima-Castanopsis* forest, but index plants of subtropical climates, such as *Bombax* in the southern area of the valley, are also present. *Quercus* is predominant on mountain slopes from 1800 to 2700 m in altitude (Stainton, 1972; Malla et al., 1976).

The RB core drilled by percussion method up to 83 m (core diameter: 6.5 cm) and by wire-line method below 89 m in depth (core diameter: 4.5 cm). The core was composed mainly of continuous clayey and muddy lacustrine sediments (Sakai et al., 2001a). From 12 m to 180 m, the Kalimati Formation was predominant. This clay bed was rich in organic matter and yielded carbonaceous fragments and plant and animal remains (Sakai et al., 2001a). The Kalimati Formation showed open lacustrine facies, judging from the presence of laminated clay with abundant fossil leaves and diatomaceous laminite (Sakai et al., 2001a). From 83 m to 89 m was a sand bed, interpreted as an event-deposit, caused by a sudden lowering of the lake level for a short period (Sakai et al., 2001b).

Throughout the whole sequence of the clayey and muddy sediments, the core recovery rate was >95% (Sakai et al., 2001a). The core with 6.5 cm in diameter was split into two vertical halves, one half of the core was archived. Another half and the whole 4.5 cm diameter core were used for multi-proxy analyses. The cores for analyses were cut at 5-cm intervals. Then, each 5 cm sample was subdivided into three parts and one of them was for chemical analyses. The samples were stored in a freezer until analysis. The upper 10 m of the core was not collected, as the sediments had been artificially disturbed.

## 2.2 TOC, C/N, $\delta^{13}\text{C}$ , and accelerator mass spectrometry $^{14}\text{C}$ dating

The sediment samples were analyzed at 1-m intervals for depths from 10 m to 180 m (excepting the sand bed at 83–89 m). The surface of the core sample was removed to avoid contamination. The discrete samples were freeze-dried and powdered. Prior to analysis, TOC and TN concentrations were measured by the dry combustion method with an elemental analyzer (NA-1500, CE Instruments, Italy), using ~20 mg powdered dry sample treated with 1 N HCl to remove carbonate. The precision of the TOC and

TN measurements was better than  $\pm 5\%$  for all samples analyzed. The C/N ratio was defined as the weight ratio of TOC to TN, as measured by the above method.

The carbon isotope of the total organic carbon in the acid-treated samples was measured using a mass spectrometer (Delta Plus, Thermo Quest, USA) in line with an elemental analyzer (NA-2500, CE Instruments). Each sample was run in duplicate. All carbon isotopic ratios were expressed in ‰, relative to the Vienna Pee Dee Belemnite (VPDB) standard. The precision of the  $\delta^{13}\text{C}$  measurements was  $\pm 0.1\text{‰}$ .

Accelerator mass spectrometry (AMS)  $^{14}\text{C}$  dates were used to construct the chronology of the top part of the RB core. AMS  $^{14}\text{C}$  dating was conducted on bulk organic carbon. The inorganic carbon fraction in the sample was removed using 1 N HCl. Radiocarbon measurements were performed at the Institute of Accelerator Analysis (IAA), Ltd. (Japan). Sample graphitization was carried out using the procedure of Uchida et al. (2004). Calibrated ages were calculated against INTCAL04 (Reimer et al., 2004), using CALIB5.0 software and the equation of Bard (1998).

### 2.3 Analysis of n-alkanes

Thirteen samples, representing major peaks and troughs in the  $\delta^{13}\text{C}$  curve (see Fig. 2), were selected for n-alkane analysis. The freeze-dried and powdered sediment samples (approx. 5 g) were extracted several times by ultrasonication in 20 ml toluene:methanol (6:4, v/v). The combined extracts were concentrated by rotary evaporation and then separated by silica-gel column chromatography into four fractions: aliphatic hydrocarbons (F1), aromatic hydrocarbons (F2), aliphatic ketones (F3), and acids and alcohols (F4).

For gas chromatographic analysis, the samples were concentrated under a gentle stream of nitrogen to 0.1- to 0.2-ml volumes in a warm sand bath. The F1 fraction was analyzed using a gas chromatograph (GC-17A, Shimadzu, Japan) with a flame ionization detector and a non-polar capillary column (TC-1, GL Science, Japan; length, 30 m; i.d., 0.25 mm; film thickness, 0.25  $\mu\text{m}$ ). Helium was used as the carrier gas. The initial oven temperature of 50°C for 2 min was followed by progressions from 50°C to

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120°C at 10°C/min and then to 300°C at 5°C/min. The n-alkanes were identified by comparing their retention times with known standards (Supelco Inc., USA).

### 3 Results

#### 3.1 Bulk organic analyses of RB core sediments

5 Figure 2 shows the vertical profiles of TOC, C/N, and  $\delta^{13}\text{C}$  values in the RB core, and Table 1 lists the AMS  $^{14}\text{C}$  ages. The TOC concentration changed periodically, ranging from 2% to 7% by weight. The TOC concentration decreased abruptly in sand-rich layers at depths of approximately 11 m and 90 m, perhaps owing to dilution with inorganic sandy clastics. The C/N ratio ranged from 7 to 20 below 89 m in depth and  
10 from 5 to 14 at depths of 10 to 83 m. The C/N ratio changed periodically, especially below 89 m in depth. The C/N ratio is widely used to distinguish between land plant and algal origins of sedimentary organic matter (Prahl et al., 1980; Ishiwatari and Uzaki, 1987; Silliman et al., 1996). Land plants have high C/N ratios because of abundant nitrogen-free organic matter, such as cellulose. In contrast, autochthonous organisms  
15 such as algae show low C/N ratios, because amino acids, proteins, and other nitrogen-containing compounds are relatively abundant in the organic matter. In the RB core sediments, the TOC concentration was well correlated with the C/N ratio. Thus, the TOC increases probably resulted from increases in organic matter input from the land around the lake.

20 The  $\delta^{13}\text{C}$  value ranged from  $-30.0\text{‰}$  to  $-19.4\text{‰}$  throughout the core, averaging  $-23.6\text{‰}$ . High and low values varied greatly from 51 to 180 m in depth. At 10 to 51 m, the amplitude of the  $\delta^{13}\text{C}$  variation was small compared with that at the lower part of the core, although the  $\delta^{13}\text{C}$  value changed periodically. The  $\delta^{13}\text{C}$  value was inversely correlated with both the TOC concentration and C/N ratio. The timing of the changes  
25 in the  $\delta^{13}\text{C}$  value generally coincided with the changes in the TOC and C/N values.

Based on the periodic changes in the  $\delta^{13}\text{C}$  value, the muddy core section was di-

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vided into 14 zones, as shown in Fig. 2. The odd-numbered zones (dark-shaded) showed high  $\delta^{13}\text{C}$  values, and the even-numbered zones showed low  $\delta^{13}\text{C}$  values. The sand bed (light-shaded area) was included in Zone 7.

### 3.2 Compositions of n-alkanes

5 We used the compositions of the n-alkanes extracted from the core sediments to evaluate the origin of the organic matter. The n-alkanes were predominately long-chain n-alkanes, especially  $\text{C}_{29}$  and  $\text{C}_{31}$ . Table 2 lists the ratio of short-chain (i.e., low-molecular weight: L,  $\text{C}_{15}\text{--}\text{C}_{24}$ ) to long-chain (H,  $\text{C}_{25}\text{--}\text{C}_{33}$ ) n-alkanes (L/H). The contributions of lipid matter from vascular land plants and algae are distinguished principally by differences in the chain lengths of their molecular suites (Meyers, 2003). For example, vascular plants contain large proportions of  $\text{C}_{27}$ ,  $\text{C}_{29}$ , and  $\text{C}_{31}$  n-alkanes in their waxy coatings (Eglinton and Hamilton, 1967; Cranwell and Eglinton, 1987; Rieley et al., 1991). Algal contributions, in contrast, are indicated by the presence of n- $\text{C}_{17}$  (Blumer et al., 1971; Giger et al., 1980; Cranwell and Eglinton, 1987) and the lack of long-chain alkyl-hydrocarbons. As shown in Table 2, all the samples from the RB core had low L/H values ( $<0.34$ ), without regard to high or low  $\delta^{13}\text{C}$  zones, suggesting that the main origin of organic matter in the RB core was probably land plants.

## 4 Discussion

20 The  $\delta^{13}\text{C}$  value of organic matter in sediments is important in assessing the organic matter source. In the RB core, the  $\delta^{13}\text{C}$  value fluctuated markedly throughout the core; the odd-numbered zones were characterized by high  $\delta^{13}\text{C}$  values (Fig. 2) that averaged about  $-22\%$ , whereas the values in the even-number zones averaged about  $-27\%$ . High  $\delta^{13}\text{C}$  values in marine sediments can be interpreted as its origins in marine algal and/or terrestrial input containing  $\text{C}_4$  plant, as both (marine algal and  $\text{C}_4$  plant) typically have high  $\delta^{13}\text{C}$  values ( $-22.4$  to  $-20.3\%$  for marine algae (Prahl et al., 1980;

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Gearing et al., 1984; Rodelli et al., 1984)). On the other hand, typical lake algae show relatively low  $\delta^{13}\text{C}$  values ( $-30.9$  to  $-26.8\%$  (Meyers, 1990, 1994; Prokopenko et al., 1993)), which are generally indistinguishable from those of  $\text{C}_3$  plants (Meyers, 1999). In both lakes and oceans, since benthic algae (common in littoral food webs) are enriched in  $^{13}\text{C}$  compared to planktonic algae, the  $\delta^{13}\text{C}$  values that reflect a contribution from littoral food webs are relatively higher than those from pelagic food webs (e.g. France, 1995). However, in the RB core drilled at the center of the Paleo-Kathmandu Lake, the muddy and clayey lacustrine sediments showed open lacustrine facies (Sakai et al., 2001a). Moreover, benthic diatoms, which are common in littoral food webs, were not abundant in the core sediment (Hayashi et al., 2006).

The C/N ratio, which is another source indicator, had relatively low values in the high  $\delta^{13}\text{C}$ -value zones, decreasing to about 10. Although the low C/N values indicated that autochthonous organic matter most likely contributed to the sediments, the high  $\delta^{13}\text{C}$  values in the odd-numbered zones could not be accounted for without the contribution of  $\text{C}_4$  plants. Thus, we suggest that the significant contrast between the high and low  $\delta^{13}\text{C}$  values of organic matter in the RB core is attributable to shifts in the proportions of  $\text{C}_4$  and  $\text{C}_3$  land plants. The proportion of  $\text{C}_4$  plant input to total organic matter is most likely high in the odd-numbered zones but negligible in the even-numbered zones. This interpretation is strengthened by an analysis of pollen from the RB core samples (Fig. 3, Fujii et al., 2004; Maki, 2005). Variations in the  $\delta^{13}\text{C}$  value correlated well with changes in the proportion of non-arboreal pollen (NAP) to total pollen and spore throughout the core. The high NAP ratios in the odd-numbered zones suggest that the flora around the lake was dominated by herbs during high  $\delta^{13}\text{C}$  periods; thus, the proportion of  $\text{C}_4$  plant increased at that time.

Some environmental constraints on the growth of  $\text{C}_4$  plants have been proposed,  $\text{C}_4$  plants are more water-efficient than  $\text{C}_3$  plants (Ehleringer et al., 1991). Teeri and Stowe (1976) demonstrated that  $\text{C}_4$  plants are more tolerant of aridity than  $\text{C}_3$  plants, if the minimum growing-season temperature does not drop below  $8^\circ\text{C}$ . P'yankov and Mokronosov (1993) reported that aridity in Central Asia is closely related to the ratio

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of C<sub>4</sub> plants to total plants. If aridity were the primary climatic factor favoring C<sub>4</sub> over C<sub>3</sub> plants in the Kathmandu valley, then <sup>13</sup>C-enriched sediments in the odd-numbered zones of the RB core would have been deposited under an arid climate regime, and sediments in the even-numbered zones would have been formed in more humid conditions. Moreover, the even-numbered, <sup>13</sup>C-depleted zones are also characterized by relatively high C/N ratios and high TOC concentrations, suggesting that the input of terrestrial organic matter was greater in the even-numbered zones than that in the odd-numbered zones. Given that terrestrial organic matter was mainly transported by rivers into the lake, the increase of terrestrial organic matter in the even-numbered zones suggests an increase in river flow. Thus, the even-numbered zones may plausibly correspond to wetter periods.

Previous palynological study on the lacustrine sediments in the Kathmandu Basin (Fujii and Sakai, 2002) reported at least seven repetitions of warm and cold climates, corresponding to the global glacial-interglacial cycles. The study suggested that a dry climate prevailed during cold-glacial periods and a wet climate during warm-interglacials in the Kathmandu Valley. Consequently, the dry and wet climate recurrences we deduced from the  $\delta^{13}\text{C}$  variations most likely corresponded to the global glacial-interglacial cycles.

A marked shift in carbon isotope ratios of bulk organic matter has been reported from African lake and swamp sediments (Hamilton, 1982; Hillaire-Marcel et al., 1989; Talbot and Johannessen, 1992; Aucour et al., 1994; Giresse et al., 1994; Huang et al., 1995; Street-Perrott et al., 1997, 1998). The glacial/interglacial shifts of  $\delta^{13}\text{C}$  values in these sediments show higher  $\delta^{13}\text{C}$  values for sediments deposited during glacial periods. Most of those studies attribute high  $\delta^{13}\text{C}$  values in sediments to the spread of C<sub>4</sub> plants, as a result of a drier climate and/or lower pCO<sub>2</sub>. We expect that such vegetation changes also occurred in the Kathmandu Valley: the odd-numbered zones of the RB core most likely correspond to glacial periods when C<sub>4</sub> plants flourished. The dry climate and/or low pCO<sub>2</sub> of the glacial period may have caused the expansion of C<sub>4</sub> plants in the Kathmandu Valley, as in Africa. Although separating the two factors is

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difficult, Huang et al. (2001) suggest that low  $p\text{CO}_2$  alone is insufficient to trigger the expansion of  $C_4$  plants, in the absence of favorable climatic conditions. Thus, even with low  $p\text{CO}_2$  during glacial periods, arid conditions in the Kathmandu Valley would be essential for the expansion of  $C_4$  plants. In short, increased aridity during glacial periods most likely induced the spread of  $C_4$  plants in the valley.

We compared the  $\delta^{13}\text{C}$  oscillation record to the SPECMAP stack (Imbrie et al., 1984) to assess its correspondence with global climate change. The upper part of Zone 1 with the AMS  $^{14}\text{C}$  dating data corresponded to cold marine isotope stages (MIS 3–2), and thus we made a comparison between MIS stages below MIS 5 and the lower part of Zone 1. The  $\delta^{13}\text{C}$  curve was consistent with the SPECMAP curve (Fig. 4). As shown in Fig. 4, the even-numbered zones of the RB core correspond to warm stages of the SPECMAP stack. The agreement between the  $\delta^{13}\text{C}$  and SPECMAP curves is supported by the correspondence of three individual minor peaks in Zone 7 to small peaks in MIS 8 and 7 (Fig. 4). We suggest that the sand bed occurring between 83 m and 89 m was deposited during a short period of a few thousand years. The cyclic paleoclimatic changes in Kathmandu Valley correspond to the global climate changes represented by  $\delta^{18}\text{O}$  curve, which was mainly controlled by the ice volume change during the late Pleistocene. Zone 14 most probably corresponds to the upper part of MIS 15; thus, we presume the age of the core at 180-m depth to be approximately 600 ka.

We propose the age-depth curve shown in Fig. 5, based on the  $^{14}\text{C}$  ages in the upper 23 m of sediment (Table 1) and a comparison of the  $\delta^{13}\text{C}$  oscillation record to the SPECMAP data below this depth (Table 3). This age-depth curve identifies sedimentation rates as follows; ca. 0.24 m/kyr, 180–60 m; ca. 0.33 m/kyr, 60–50 m; ca. 0.45 m/kyr, 50–23 m; and ca. 0.7 m/kyr, above 23 m. The sedimentation rates appear to increase gradually from the lower to the upper part of the sediment core. Sedimentological observations show that the Kalimati-clay section (12–180 m in depth) is dominated by clayey material, and, except for the sand bed between 83 and 89 m in depth, no hiatus or thick bed formed by sedimentary events has been reported (Sakai et al., 2001a).

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Therefore, the changes in the estimated sedimentation rates may be the result of compaction effects and/or dehydration of clay sediments with increasing burial depth.

In monsoonal regions, changes in precipitation are largely controlled by the intensity of the monsoon (Prell et al., 1992). The dry-wet records we obtained most likely reflect changes in the Indian monsoon intensity in the Central Himalayas during the past 600 kyr. During dry glacial periods, we infer that the SW summer monsoon weakened and produced arid conditions, whereas wet conditions in interglacial periods resulted from a stronger SW summer monsoon. Most of the paleoclimatic studies on Indian Ocean marine sediments have reported that the SW summer monsoon was stronger during interglacial periods and weaker during glacial periods (e.g. Prell and Van Campo, 1986; Sarkar et al., 1990). Although Niitsuma et al. (1991) concluded that the climate of the Arabian Peninsula was more humid during glacial periods with weak SW monsoons, our results confirmed that increased aridity on the Indian subcontinent during glacial ages resulted in the expansion of C<sub>4</sub> plants.

The increased aridity during glacial periods would have caused the water level in Paleo-Kathmandu Lake to fall. Based on sedimentological studies of lacustrine delta deposits, Sakai et al. (2006) reported that events during which lake levels fell occurred in the late Pleistocene. Although the arid conditions during glacial periods may have been too harsh for C<sub>3</sub> plants to flourish, would be favorable for the growth of C<sub>4</sub> plants in this region. Consequently, C<sub>4</sub> grasslands could have spread to the exposed shores of PKL, as the water receded. The lower water level most probably produced an extensive delta plain and expanded marsh, with a concomitant proliferation of hygrophytes, including C<sub>4</sub> grasses, during glacial periods.

## 5 Conclusions

The organic geochemical record of a continuous core drilled in Kathmandu Valley revealed a series of paleoenvironmental changes during the past 600 kyr. We found at least seven cyclical oscillations of TOC, C/N, and  $\delta^{13}\text{C}$  values, most likely corre-

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sponding to MIS 15–4 of the SPECMAP curve. The relatively higher  $\delta^{13}\text{C}$  values of total organic carbon during glacial periods, compared with those during interglacial periods, are attributable to the significant increase in  $\text{C}_4$  plant contributions. The relative abundance of  $\text{C}_4$  versus  $\text{C}_3$  plants in this region during the past 600 kyr was most likely influenced by changes in precipitation, controlled by the SW summer monsoon strength. The arid condition produced by the weaker SW monsoon during glacial periods would have favored the spread of  $\text{C}_4$  grasslands in this region. Our study provides the first direct evidence of aridity changes on land being correlated to changes in the Indian monsoon strength during the past 600 kyr.

We conclude that over the past 600 kyr, the paleoclimate of the Central Himalayan southern slopes was controlled mainly by global glacial-interglacial cycles. Our results show that  $\text{C}_3/\text{C}_4$  vegetation changes in the continental interior of South Asia are linked to the intensity of the monsoon, suggesting important implications for possible vegetation changes in response to future climate change in the region. Although we analyzed the sediment samples at 1-m intervals, we nonetheless confirmed that the PKL sediments have the potential to provide a high-quality, high-resolution record of Quaternary climate changes in the continental interior of South Asia. We expect that further ongoing studies, combined with other proxies, will provide more detailed paleoclimatic records for the region.

*Acknowledgements.* We are grateful to H. Tsutsumi, Kumamoto Prefectural University, for providing every facility for TOC, TN and carbon isotope measurements. We are also grateful with M. Suzuki (JAMSTEC) for preparation of AMS measurement. The present study was carried out as a part of the Paleo-Kathmandu Lake drilling project in collaboration with the Department of Geology, Tribhuvan University. The core-drilling and laboratory works were financially supported by Grant-in-Aid for Scientific Research (A) (2), No.11304030 and (B) (2), 14340152 from Japan Society for the Promotion of Science. This study is also part of the “Study on the past marine environmental changes” sponsored by the Japan Agency for Marine-Earth Science and Technology (JAMSTEC).

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**Table 1.** Analytical results of the AMS  $^{14}\text{C}$  ages of the RB core.

Depth (m)	$^{14}\text{C}$ age (yr BP $\pm 1\sigma$ )	Calibrated age (cal BP, $1\sigma$ )
9.75	10 960 $\pm$ 130	12 836–13 022 (12900)
17.1	15 890 $\pm$ 120	18 954–19 197 (19 040)
19.1	17 090 $\pm$ 80	20 100–20 326 (20 220)
20.4	18 670 $\pm$ 90	22 160–22 335 (22 240)
22.05	24 010 $\pm$ 120	28 220*
23.2	27 410 $\pm$ 160	32 080*

\*Calculated using the equation of Bard (1998).

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**Table 2.** The ratios of short-chain (L, C<sub>15</sub>-C<sub>24</sub>) n-alkanes to long-chain (H, C<sub>25</sub>-C<sub>33</sub>) n-alkanes (L/H) are listed with the  $\delta^{13}\text{C}$  values and C/N ratios. The analyzed horizons of n-alkanes are shown by arrows in Fig. 2.

Zone	Depth (m)	L/H	$\delta^{13}\text{C}_{\text{TOC}}(\text{‰})$	C/N
2	52.50	0.15	-27.7	10.1
3	56.50	0.09	-22.6	10.7
4	60.50	0.10	-28.6	9.6
5	67.48	0.16	-20.6	7.5
6	77.48	0.21	-28.8	10.8
7	99.50	0.34	-19.4	7.9
8	112.50	0.21	-29.4	13.4
9	127.50	0.33	-20.0	7.9
10	139.50	0.16	-29.9	14.6
11	142.50	0.21	-19.0	11.1
11	146.50	0.21	-20.1	9.0
12	156.00	0.14	-29.0	13.7
13	169.50	0.20	-21.6	10.4

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**Table 3.** The chronological tie-points below 23 m in depth of the RB core.

Zone boundary	Depth (m)	Age (kyr)
Zone1/2	50.9	93
Zone2/3	55.5	108
Zone3/4	58.5	116
Zone4/5	60.5	122
Zone5/6	76.5	195
Zone6/7	81.5	219
Sand bed (top)	83.0	225
Sand bed (bottom)	89.0	225
Zone7/8	107.5	300
Zone8/9	115.5	330
Zone9/10	135.0	394
Zone10/11	141.5	418
Zone11/12	155.5	477
Zone12/13	165.0	518
Zone13/14	175.5	579

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**Fig. 1.** Location of RB core drilling site in the Kathmandu Valley. The separation of the valley floor from the valley-side slope (shaded) is shown by a dark line following the 1400 m contour. Arrows mark the direction of the flow of the rivers.

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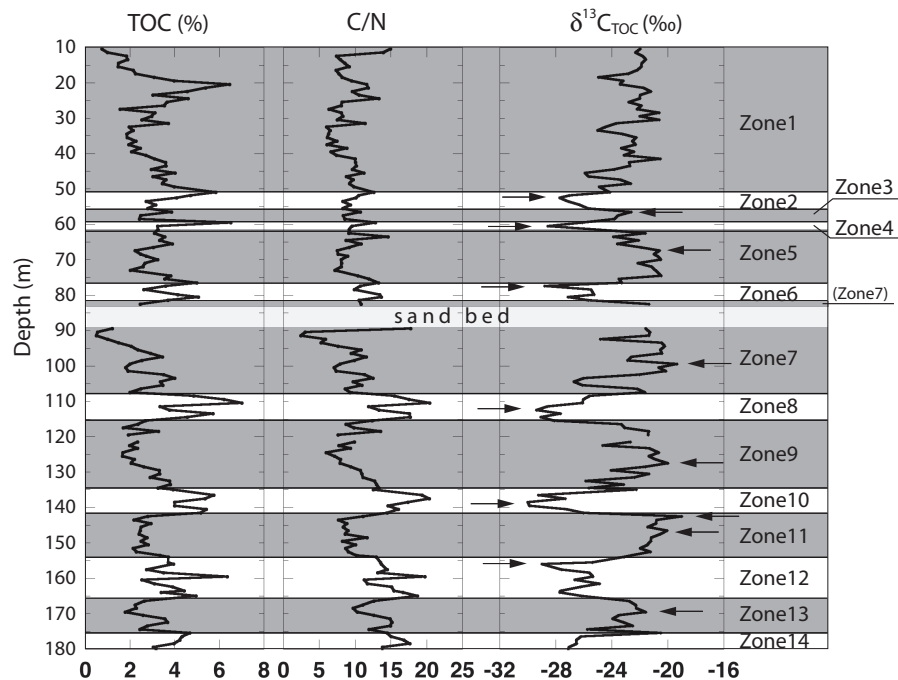
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**Fig. 2.** Concentrations of total organic carbon (TOC), weighted TOC/TN ratios (C/N) and  $\delta^{13}\text{C}$  of TOC ( $\delta^{13}\text{C}$ ) values in the RB core of muddy lacustrine sediments from the Kathmandu Valley. TOC concentration was well correlated with the C/N ratio ( $r=0.7$ ,  $n=164$ ), and the  $\delta^{13}\text{C}$  values was inversely correlated with both the TOC and C/N values ( $r=-0.6$ ,  $n=164$ ). The muddy section of the drill core was divided into 14 zones based on the periodic changes of the  $\delta^{13}\text{C}$  values. Odd-number zones (dark-shaded) correspond to high  $\delta^{13}\text{C}$  zones, while even-numbered zones correspond to low  $\delta^{13}\text{C}$  zones. The sediment between 83 m to 89 m (light-shaded area) is sand. Arrows in the figure indicate analyzed horizons for n-alkanes.

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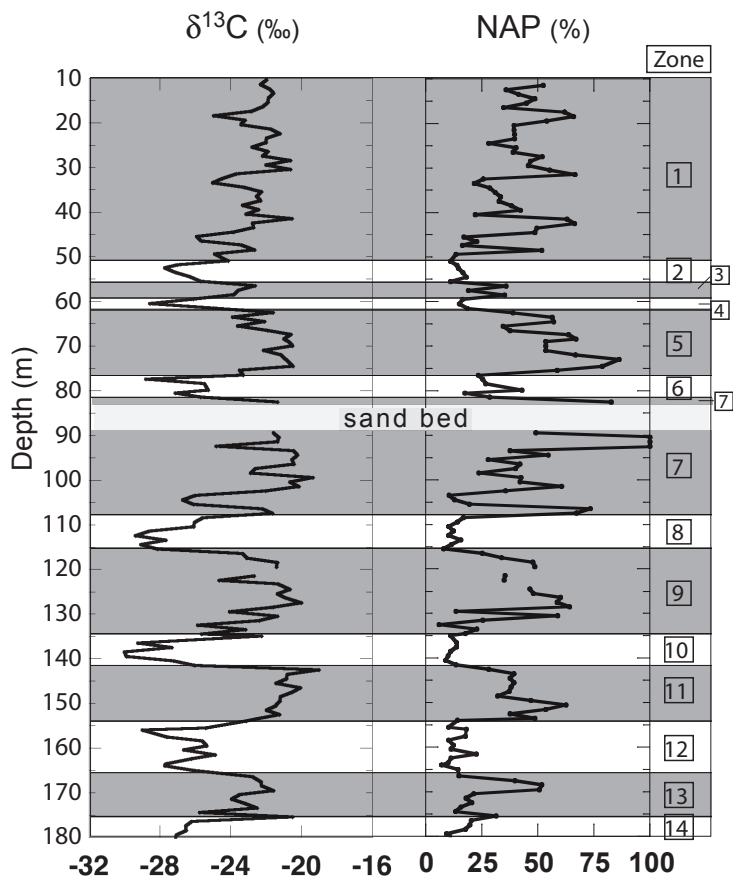
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**Fig. 3.** Comparison of the  $\delta^{13}\text{C}$  records with the non-arboreal pollen (NAP) variation curve from the RB core (Fujii et al., 2004; Maki, 2005). Variations in the  $\delta^{13}\text{C}$  value correlated well with the changes in the NAP ( $r=0.7$ ,  $n=162$ ).

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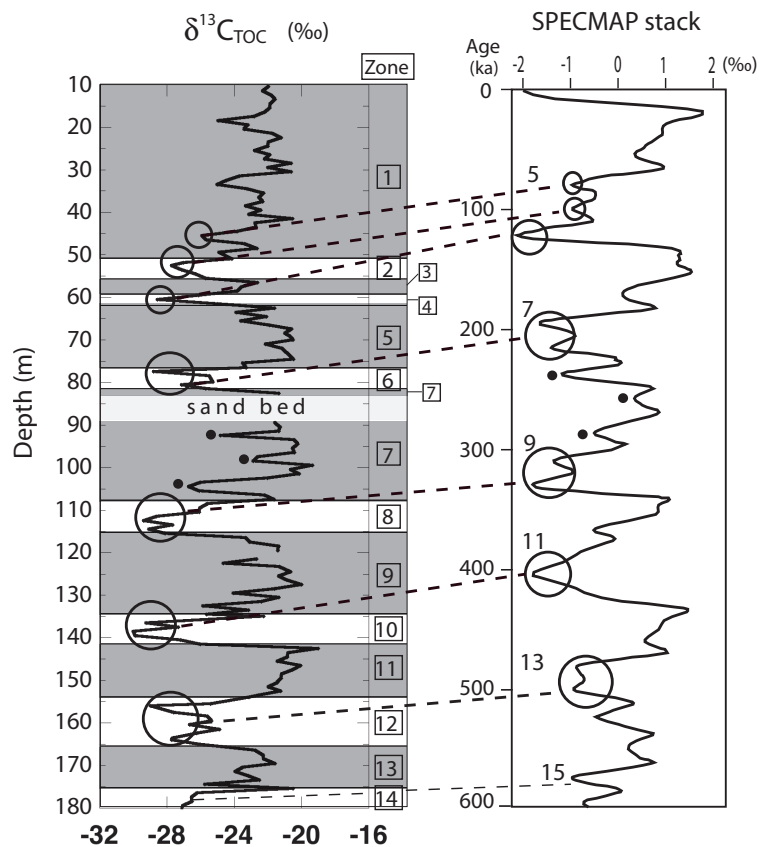
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**Fig. 4.** Comparison of the  $\delta^{13}\text{C}$  variation curve from the RB core with the SPECMAP stack (Imbrie et al., 1984). The numbers in the SPECMAP stack show marine oxygen isotope stages (MIS). Individual peaks in Zone 7 (peaks with filled circles) corresponded to the small peaks in MISs 8 and 7 in the SPECMAP stack.

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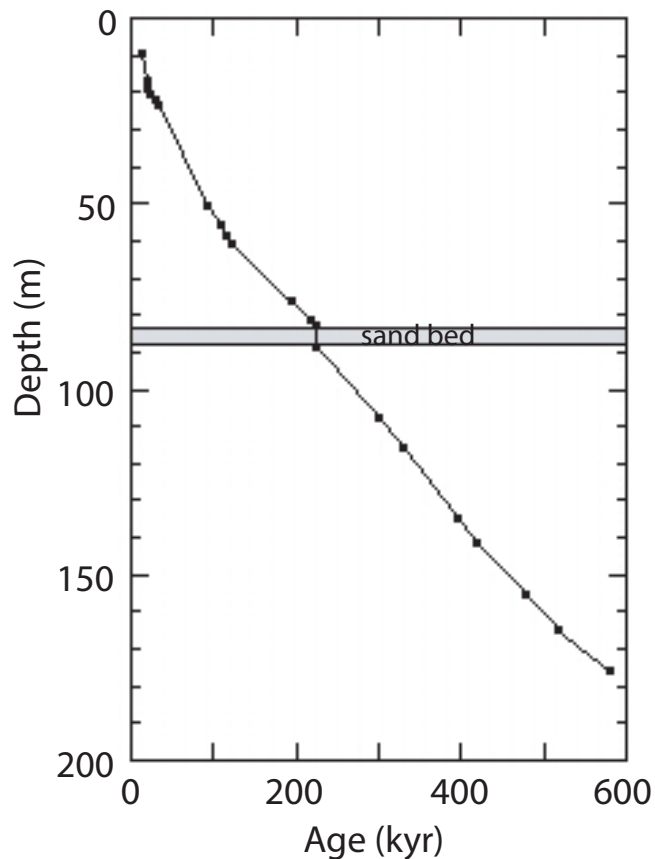
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**Fig. 5.** Age-depth curve of the RB core. The age model based on the  $^{14}\text{C}$  ages in the upper 23 m of sediment (Table 1) and a comparison of the  $\delta^{13}\text{C}$  oscillation record to the SPECMAP data below this depth (Table 3).

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