Palaeoclimatic scenario during Holocene around Sangla valley, Kinnaur northwest Himalaya based on multi proxy records

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Pollen, C/N ratios and $\delta^{13}C_{OM}$ from a 1.2 m thick palaeolake deposit at Sangla, Kinnaur, Himachal Pradesh provide records of climatic changes during the past 10,000 years. The C/N ratios together with pollen data indicate high lake level between 10,000 and 4,000 yrs BP. Following this, an increase in $\delta^{13}C$ (+2‰) indicates stressed climatic conditions, whereby $\delta^{13}C_{OM}$ attained a value of –23‰, being the maximum for the available record. This event is bracketed between 3500 and 1500 yrs BP. Subsequently, the lake underwent a few dry spells ca. 1000 yrs BP. Finally, it got completely desiccated around 800 yrs BP.

Keywords: Carbon isotope, C/N ratio, holocene, palaeoclimate, pollen.

QUATERNARY stratigraphy of Lahaul–Spiti–Kinnaur is represented by glacial, fluvio-glacial, fluvial and lacustrine deposits that have preserved records of Quaternary climate change. However, considering the better preservation and near continuous sedimentation in lacustrine environment, the relict lake deposits provide detailed records of climate change.

Here we present the climatic reconstruction, based on a 1.2 m sediment profile collected from a palaeolake deposit at Sangla, Kinnaur, Himachal Pradesh. Multi-proxy data, viz. pollen, C/N ratios and $\delta^{13}C_{OM}$ along with well-constrained radiocarbon dates provide records of climatic changes during the Holocene.

Location of study area

The palaeolake is located at the Sangla Kanda on the left bank of river Baspa (31°N, 77°45′E) in the northern part of India at a height of about 3500 m amsl (Figure 1). The site can be approached from Sangla town along the left bank of Rukti river, which is a tributary of river Baspa. The common name of the site is Sangla Kanda Yala Seyring (SKYS). In local parlance, 'kanda' is a generic term for meadow. The area is characterized by a meadow within the conifer–broadleaved forest represented mainly by trees of *Cedrus deodara*, *Pinus wallichiana*, *Juglans regia*, etc.

Materials and methods

Collection of sediments and pretreatment

A 130 cm deep trench was dug from the surface of a dried lake and 26 samples were collected at every 5 cm interval. The sediments are characterized by brown silty-clay from the surface to a depth of 85 cm with two comparatively dark-brown, organic-rich layers at depths 40–45 and 80–85 cm. Few minute pieces of charcoal were also observed in the sediments from a depth of 60 to 80 cm. From a depth of 85 to 125 cm, the sediments are yellowish sandy-clay. For ^{14}C dating, bulk amount of sediments was collected at three horizons.

Radiocarbon dating

Three organic-rich layers at depths 40–45, 80–85 and 125–130 cm were collected for radiocarbon dating. The

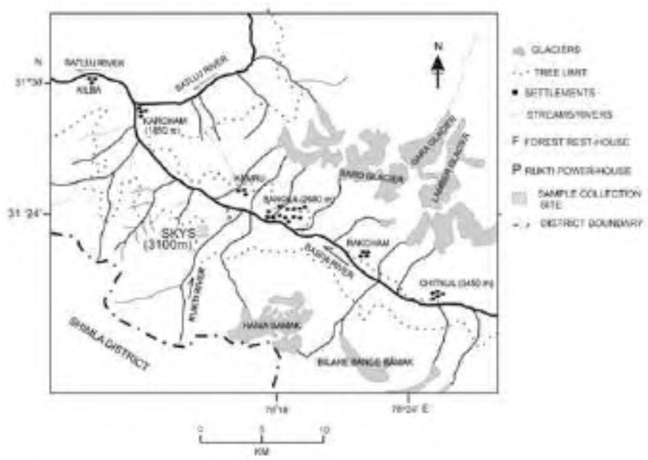

Figure 1. Location of sampling site in Sangla Valley, District Kinnaur, Himachal Pradesh, India.

*For correspondence. (e-mail: supriyo_chakraborty@yahoo.com) organic fraction of carbon in the sediment was dated by means of liquid scintillation counting following the standard procedure (S. Chakraborty, unpublished thesis). The ages obtained are 1800 ± 64, 4310 ± 56, and 10450 ± 310 yrs BP at depths of 42.5, 82.5 and 127.5 cm respectively. Using the depth and corresponding ^{14}C age, an age model was fitted to understand the sedimentation pattern. An exponential growth curve was plotted which yielded the following equation.

$$y = -554.5 + 1089*\exp(0.01814x),\ r^2 = 1,$$

where y is the radiocarbon age in yrs BP, x is the depth (cm) positive downward and r is the correlation coefficient. The ages obtained at three sediment horizons were fitted to an exponential curve because the calculated ages based on this equation agreed well with the measured ages. However, the calculated ages (at 42.5 and 127.5 cm) based on a linear equation differ significantly from the measured ages. Thus the above-mentioned equation was used to calculate the radiocarbon ages at all sampling points of 5 cm interval. Typical error on radiocarbon ages is 2–3%, less than 400 years in absolute terms. Since the sampling resolution is over 600 years, the error on radiocarbon ages was not taken into account in interpreting the data. All the parameters reported here, are plotted against uncalibrated radiocarbon age.

The y-intercept gives a negative ^{14}C age of 554.5 years. This age, when converted to $\Delta^{14}C$ gives a value of 70‰. This value is in good agreement with the atmospheric $\Delta^{14}C$ for the year 2002 (the year when samples were collected) for the northern hemisphere, as reported by Hua and Barbetti[1]. This is the characteristic value (in terms of $\Delta^{14}C$) of the modern vegetation and plant litter that is in equilibrium with the atmosphere. Since the lake currently holds no water, the surface soil has a radiocarbon age similar to that of the modern vegetation. The age model appears to be an appropriate representation of the sedimentation pattern. This is based on the fact that the extrapolated value at the surface precisely represents the radiocarbon age of the surface vegetation.

Carbon isotope and elemental analyses

These analyses were performed on sediment organic matter taken at 5 cm interval down the core. The samples were dissolved with 2N hydrochloric acid for 2 h on a steam bath and left for 8 h at room temperature to facilitate complete removal of carbonates. The samples were then rinsed several times with deionized water until the solution turned neutral. Then the samples were oven-dried at 50°C.

Carbon and nitrogen were measured using Fisons NA1500 NC Elemental Analyser (Fisons Inc, Italy). Nearly 10–20 mg of decarbonated sample was packed in an aluminum cup and introduced into a combustion tube through an autosampler for carbon and nitrogen analysis. Samples were completely combusted at a temperature of 1800°C using the flash combustion technique in the presence of high-purity oxygen. The evolved gases were purified to get pure CO_2 and N_2. A three-point calibration sequence was made following K-factor method using a Deer River Shale Standard as reference material containing 2.53% carbon and 0.12% nitrogen. The analytical precision for measurement of carbon and nitrogen is 4 and 6% respectively, based on repeat measurements of the sample and standard.

For carbon isotopic measurements, the samples were combusted at 800°C in sealed quartz tube under vacuum in the presence of copper oxide and silver wool. The liberated CO_2 was then purified and introduced in a Geo 20–20 isotope ratio mass spectrometer. Isotopic data were expressed in conventional delta notation relative to PDB. The standard deviation of replicate analysis of cellulose standard was 0.05‰.

Carbon isotopes

The carbon isotope ratio provides an opportunity to study the biological processes of the algal and planktonic community of lakes that contributes to the organic component of the sediment[2]. In general, the carbon isotope ratio of organic matter derived from lacustrine primary production depends on the availability of dissolved CO_2 mediated by photosynthesis and respiration. Ambient environmental conditions additionally influence growth and productivity of lacustrine algae through the control of nutrient availability, light, climate and water temperature[3]. Hence these parameters leave their signature in the carbon isotope ratio of the lake organic matter. Lake algae $\delta^{13}C$ values are typically –28‰, similar to the C_3 land plants, while tundra and wetland (C_4) plants[4] have much higher values, –9‰.

Total organic carbon

The amount of total organic carbon is controlled by the primary production in the lake, the detrital input, and preservation/degradation processes[5]. Usually most of the organic matter (OM) is autochthonous, i.e. produced by phytoplankton and aquatic macrophytes in the lake[6]. Autochthonous OM is enriched in proteinaceous, low molecular weight compounds high in H and N, with low C/N ratios (typically less than 10). Allochthonous terrestrial OM has abundant high molecular weight, humic compounds rich in C with much higher C/N ratio[7], typically 20 to 30.

Carbon and nitrogen ratio

Carbon/nitrogen ratio is a reliable proxy in identifying the sources of terrestrial and aquatic OM. Organic nitrogen occurs preferentially in proteins and nucleic acids[8], which are relatively abundant in lower plants such as aquatic phytoplankton and in bacteria. Autochthonous lacustrine OM is therefore characterized by relatively low C/N ratio[9], typically less than 10. Lignin and cellulose, which are the dominant components of terrestrial higher plants (nitrogen-poor) allochthonous OM thus has C/N ratios[10] which are normally higher than 20 and may sometimes exceed 200. Mixing of carbon sources, alteration from nutrient cycling and decomposition, and production of ammonia alter the C/N ratios so that lake sediments[2] have ratios of 10–15.

Pollen analysis

For pollen analysis, total number of pollen grains (150 to 250 per sample) was counted. Many of the subsurface sediments macerated have been found either low or devoid of pollen grains. The whole profile, from the surface to a depth of 45 cm and between depths of 85 cm and the bottom of the profile (five samples) has yielded sufficient pollen. Sediments between depths 90–105 cm and 115–125 cm were found sporadic, whereas the middle of the profile, i.e. from a depth of 45 to 85 cm is devoid of pollen grains.

For interpretation of the pollen diagram in terms of vegetation, the diagram has been divided into four zones (Figure 2). This zonation was based on the variation in pollen frequencies of important taxa.

Pollen zone-1

This lowermost zone at a depth of 130 to 85 cm from the surface and dated between 10,000 and 4535 yrs BP, is characterized by non-arboreal taxa of Chenopodiaceae (1%), Asteraceae (1–33%), *Artemisia* (1–4%), Ranunculaceae (1–4%), Fern (29–63%), Cyperaceae (2–4%), Poaceae (4–11%) and *Impatiens* (4–7%). Pollen of *Typha* (1%) has also been reported in one sample at the base. Other herbs have 7–39% higher values towards the top of the zone. Among conifers, *Pinus* (4–49%) is represented with lower values in the middle of the zone. Other conifers are 2–29%. *Betula* (4–6%) and *Juniperus* (7–12%), with temperate broadleaved taxa (4–7%) show good values.

Pollen zone-2

This zone at a depth of 85 to 45 cm from the surface and dated between 4500 to 1900 yrs BP, is palynologically barren.

Pollen zone-3

This zone at 45 to 20 cm from the surface and assigned interpolated ages between 1910 and 1010 yrs BP, is characterized by high percentage of Chenopodiaceae (4–9%) and Asteraceae (23–36%). *Artemisia* (1–4%) shows almost the same trend. Ranunculaceae (1–2%) and Saxifragaceae (sporadic) show little input. Among other taxa, Poaceae (2–9%) represents declining trend starting with a maximum value at the base of this zone. Cyperaceae (2%) shows its presence in the upper part of this zone only, whereas fern spores (27–39%) exhibit little variation. Amongst arboreal taxa, *Pinus* (3–8%), *Juniperus* (1–4%), *Betula* (1%) and overall temperate broadleaved taxa, viz. *Alnus*, *Quercus*, *Corylus*, *Carpinus*, *Juglans* and *Celtis* show sudden decline (2%).

Pollen zone-4

This zone from 20 cm depth to the surface covers an age of about 1000 yrs BP. The zone shows increasing trend in Chenopodiaceae (7–11%) with dominance of Liguliflorae (13–24%) and *Artemisia* (2–4%). Asteraceae (18–26%) shows declining trend compared to zone-3. *Ephedra* is absent throughout the profile, with 1% presence in one sample only. Ranunculaceae (1–3%) remained the same. Cyperaceae (1–4%), Poaceae (5–7%) and fern spores (37–44%) show some increase. *Pinus* (12–40%) shows sudden increase in this zone with other conifers (4–11%). The higher values of conifers are concentrated close to the surface. *Juniperus* and *Betula* (1–2%) show a decline and temperate broadleaved elements (4–11%) registered an increase in their frequencies in comparison to zone-3.

Palaeovegetation reconstruction

Based on pollen data and available radiocarbon ages, it can be suggested that the steppe vegetation represented mainly by Chenopodiaceae, *Artemisia*, Asteraceae and *Ephedra*, indicators of drier climate was low during 10,450 to 4310 yrs BP. Presence of Cyperaceae and *Impatiens* and good amount of fern spores also suggests that comparatively moist environment prevailed during this period with the proximity of tree line, as indicated by the presence of *Juniperus* and *Betula* pollen. Fair amount of conifers along with low concentration of temperate broadleaved taxa indicate that Conifer–broadleaved temperate forest was located further downstream and the pollen must have been transported by wind. In addition, the presence of aquatic elements (*Typha* and *Potamogeton*) in one or two samples at the base suggests that deposition took place under relatively shallow lacustrine conditions. Summarizing the above evidences it can be suggested that warm and moist climate prevailed in the area during 10,450 to 4310 yrs BP.

The vegetational history ca. 4310 to 1800 yrs BP (85–45 cm depth) could not be reconstructed as sediments during this period are recorded barren in spore/pollen content. However, this horizon yielded abundant micro-

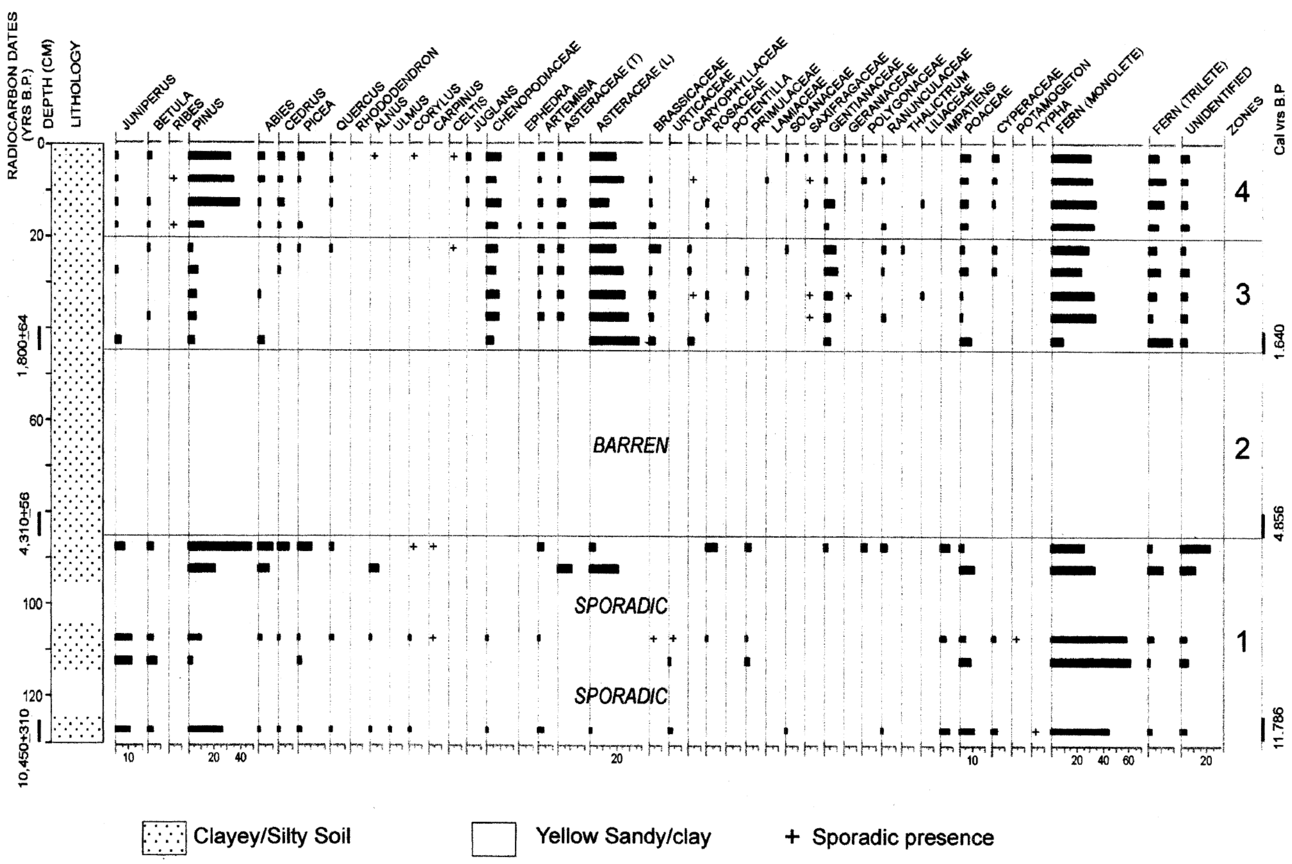

Figure 2. Pollen diagram of profile from Sangla Kanda, Kinnaur, Himachal Pradesh.

scopic charcoal pieces. After 1800 yrs BP, the presence of a good amount of steppe taxa indicates overall dry conditions. Low values of temperate broadleaved taxa during this period with higher values towards the recent time indicate the gradual shift of temperate elements to higher elevations in this valley. This is also supported by the presence of sub-alpine taxa, *Betula* and *Juniperus* in lower values since 1800 yrs BP to recent than that recorded between 10,450 and 4310 yrs BP. These elements might have shifted to higher elevations with the retreat of glaciers under warm conditions. This shifting is also indicated by the rise of conifers, especially *Pinus* that had also migrated from lower to higher elevation. Increase of steppe elements, especially Chenopodiaceae and sudden rise of *Pinus*, all suggest a change towards drier climatic conditions.

Results and discussion

Variations of $\delta^{13}C$, N%, C% and C/N ratio of the sedimentary OM are shown in Figure 3. The range of variability in the case of carbon is from 0.3 to 1.6%, nitrogen is from 0.03 to 0.1%, and C/N ratio lies between 9 and 17. The $\delta^{13}C$ of the sedimentary OM ranges from –25 to –23‰. These values are typical of lacustrine sediments that represent relative abundances of the C_3–C_4 type of vegetation.

The C/N ratio reflects the relative proportion of carbon and nitrogen incorporated into vascular plants versus plankton, and carbon losses during decomposition[2]. The observed range of values in this case is 9 to 18, which presumably reflects that of lake algae and/or the C_3 type of vegetation. The values most probably indicate the absence of C_4 type of land plant, as their C/N ratios[4] typically exceed 35.

The presence of allochthonous source of OM may be ascertained from the apparent correlation between C/N atomic ratios and that of percentage of carbon. With increased supply of terrestrial plants (low N content), the C/N ratio is increased resulting in a rise in carbon content of OM. Hence the C/N ratio and organic C should show a positive trend[11]. Such a relation was not found in our case until 4000 yrs BP, indicating that the lake system was relatively stable and did not receive extraneous materials from the catchment. However, from around 3500 to 940 yrs BP, these two parameters show strong correlation ($r^2 = 0.74$, $n = 12$). This probably suggests transport of allochthonous OM to the lake system. This is the time when %C and C/N ratio showed enhanced values with a rising trend in $\delta^{13}C$. The increase in C/N ratio may also arise due to preferential loss of nitrogen-rich fraction of OM. However, the nitrogen content does not show any significant

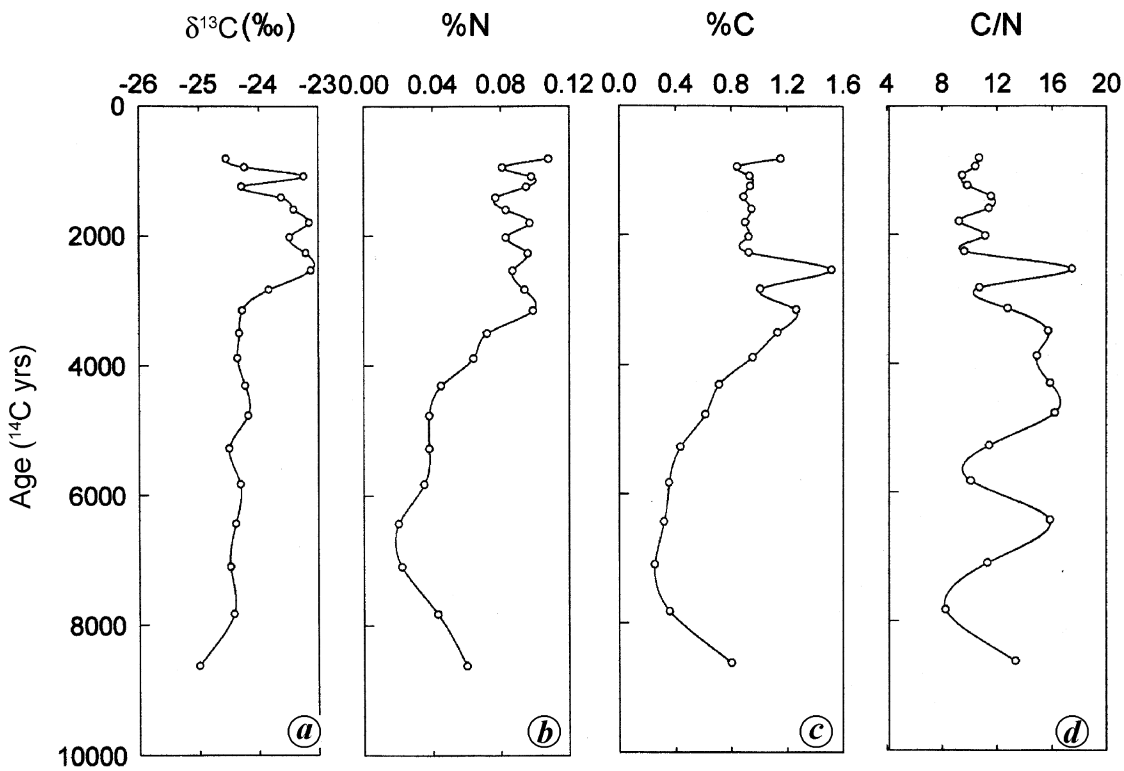

Figure 3. Geochemical proxies of sedimentary profile. (***a***) Stable carbon isotopic variation, (***b***) nitrogen fraction, (***c***) organic carbon fraction and (***d***) C/N atomic ratio. *Y*-axis represents radiocarbon age (uncalibrated) in yrs BP based on the chronology of three ^{14}C dates.

amount of nitrogen loss during this period (Figure 3). Hence this probably explains incorporation of minute amount of C_4 type of land plants as evidenced from the pollen diagram that shows marginal increase during this period, also supported by small increase in $\delta^{13}C$.

Diagenetic change of OM could alter the original isotopic signature. In view of the fact that both the carbon and nitrogen content of OM does not show any kind of decreasing trend with depth, suggests that OM has not undergone diagenetic alteration after deposition. Further, a strong correlation between %C and %N ($r^2 = 0.71$, $n = 23$) indicates that both C and N are organically bound.

The fluctuating C/N ratio during the early to middle Holocene (about 9800 to 5300 yrs BP) suggests alternate phases of dry and wet conditions. One of the lowest values at about 3000 yrs ago probably indicates the driest phase. Corresponding sediments are devoid of pollen grains, but rich in microscopic charcoal pieces. This might have been derived from forest fires when the climate was dry. There are other evidences which indicate that monsoon rainfall in general, in the Indian subcontinent was higher in the early to middle Holocene[12–14], after which precipitation started decreasing. For example, the oxygen isotopic record[15] of speleothem from Orissa indicates that rainfall started decreasing since 3400 yrs BP to about 1900 yrs BP. This was also corroborated by varve analysis done on coastal sediments, off the Pakistan coast[16]. The pollen data from the other site also suggests that a weak monsoon prevailed in the western Himalaya about 3500 yrs ago[17]. This is followed by a peak in C/N ratio at about 2780 yrs ago. This could be either due to a moist condition as a result of increased precipitation or due to cooling. However, the carbon isotope ratio does not indicate any substantial increase in precipitation. Thus the present C/N peak is attributed to the reduction in temperature (cooling). After 2780 yrs BP, the C/N ratio falls and remains stable at around 10–11 until about 1000 yrs BP, a value typical of surface soil. This was probably the time when the lake got desiccated. This is also supported by pollen data indicated by the sudden rise of *Pinus*, along with increase in Chenopodiaceae under drier climatic conditions.

Conclusion

Multiproxy analysis of a palaeolake profile in the sub-Himalayan region reveals the palaeoclimatic scenario for the past 10,000 years. The general pattern of the climate inferred from this lake profile shows good coherence with the climatic conditions of the Indian subcontinent. Combined analysis of stable isotopes and palaeobotanical proxies allows us to draw the following broad inferences:

1. Warm and moist climatic conditions persisted in Sangla basin during 10,450 to 4310 yrs BP, implying enhanced monsoonal activity.
2. Reduction in precipitation and dominance of dry climate is inferred between 4310 and 1800 yrs BP.
3. From 1800 to 1000 yrs BP (interpolated age), the climate fluctuated between dry and wet phases.
4. Lake desiccation occurred around 1000 yrs BP.

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