Late Holocene climatic changes in Garhwal Himalaya

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Geochemical study of a 3.55 m long lake sediment core from the Badanital Lake (Garhwal Himalaya) reveals Late Holocene centennial-scale climatic changes. The ecosystem of the tectonically formed lake seems to be controlled by natural and anthropogenic factors. The imprints of four major global events, e.g. 4.2 ka event, Medieval Warm Period (MWP), Little Ice Age (LIA) and modern warming are observed. By using the geochemical parameters, e.g. major oxides and their ratios (CaO/MgO, CaO/TiO_2, MgO/TiO_2, Na_2O/TiO_2, TiO_2/Al_2O_3, Na_2O/K_2O and Fe_2O_3/TiO_2), major elements, chemical index of weathering, chemical index of alteration and loss on ignition, the core profile is divided into six major climatic zones. The sediment accumulation rate was extremely slow during a cold/dry phase from ca. 5.1 to 3.5 ka BP. This was followed by wetter/moist phase from ca. 3.5 to 1.8 ka BP and the area further remained under arid conditions from ca. 1800 to 920 years BP. Almost wet/moist environment prevailed around 920–440 years BP, corresponding to the MWP. The LIA (440–160 years BP) was somewhat cooler, whereas post LIA, particularly from 160 years BP points to modern warming.

Keywords: Climatic changes, geochemical parameters, lake core, palaeoclimate.

Introduction

THE Indian summer monsoon (ISM) is crucial to the large population of South Asia and variation in monsoon through time has a profound impact on the economy of this region[1]. The modern lakes are ideal to study the imprints of monsoonal variation and climate in the past. The lakes are subject to interacting external and internal forcing, e.g. climate, tectonics and geomorphologic activity[2] and are strongly influenced by the natural and anthropogenic factors[3]. Geochemical analysis is useful to understand the environmental change, tectonic setting of lake surroundings and reconstruction of the past climate[4,5] and serves as an effective proxy to demonstrate the intensity of chemical weathering in the catchment[6–12]. The major elements in the sediment generally depend on weathering, diagenesis, sorting and sedimentary recycling[13]. A warm and humid climate generally produces highly weathered elements from chemical reactions and thus the rate of weathering is higher than that under dry climate setting[6,8,14]. The geochemical parameters, subjected to the modern lake cores of the Indian Himalaya, have been found suitable for palaeoclimatic reconstruction, as in the Tsokar Lake[15,16], Renuka Lake[17,18], Rewalsar Lake[19], Mansar Lake[4] and Nainital Lake[20]. In addition, the geochemical parameters, combined with lithological and sedimentological information, have also been used in the ancient lake sediment profiles, e.g. the Garbyang basin[21], Dulam palaeolake[11], Goting basin[22] and Phulara palaeolake[23]. Here, we present the dataset relating to variation in the lithology and geochemical parameters through the lake core with respect to changing climate in a part of the Garhwal Himalaya.

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Study area and core lithology

Badanital Lake (30°29′50″N : 78°55′26″E; altitude 2083 m; Figure 1 *a*) is situated in the Rudraprayag district of Garhwal Himalaya. Located on the top of a mountain (Figure 1 *b*), this closed basin (Figure 1 *c*) is 120.5 m long, 55 m wide and 2 m deep with a total circumference of 290 m and has no outlet. The slopes around the lake are covered with temperate forests. Along the periphery, there are large grasslands, small swamps and marshes. The lake is situated close to the Jutogh (MCT-II) Thrust[24] and a number of geomorphological features, e.g. waterfalls, active landslide fans, gorges, cliffs and the lake itself positioning on a mountain top point towards a possible tectonic activity which may have created the lake. The main source of the sediment input is from surrounding hills, consisting of biotite gneiss. At present, the lake receives sediments from surrounding hillocks and cultivated area and it is expected that the small lake may witness more of a local climate. Presently, the area receives about 80% of annual precipitation from the ISM and the remaining from winter rains.

A 3.55 m long sediment core was retrieved from the lake in January 2008 by using piston corer of Stitz Gmbh Mebgerate. The lower part of the core is composed of carbonaceous mud with occasional small rock fragments and woody material, while the upper part is dominated by sticky and micro-laminated cohesive mud. The lowermost

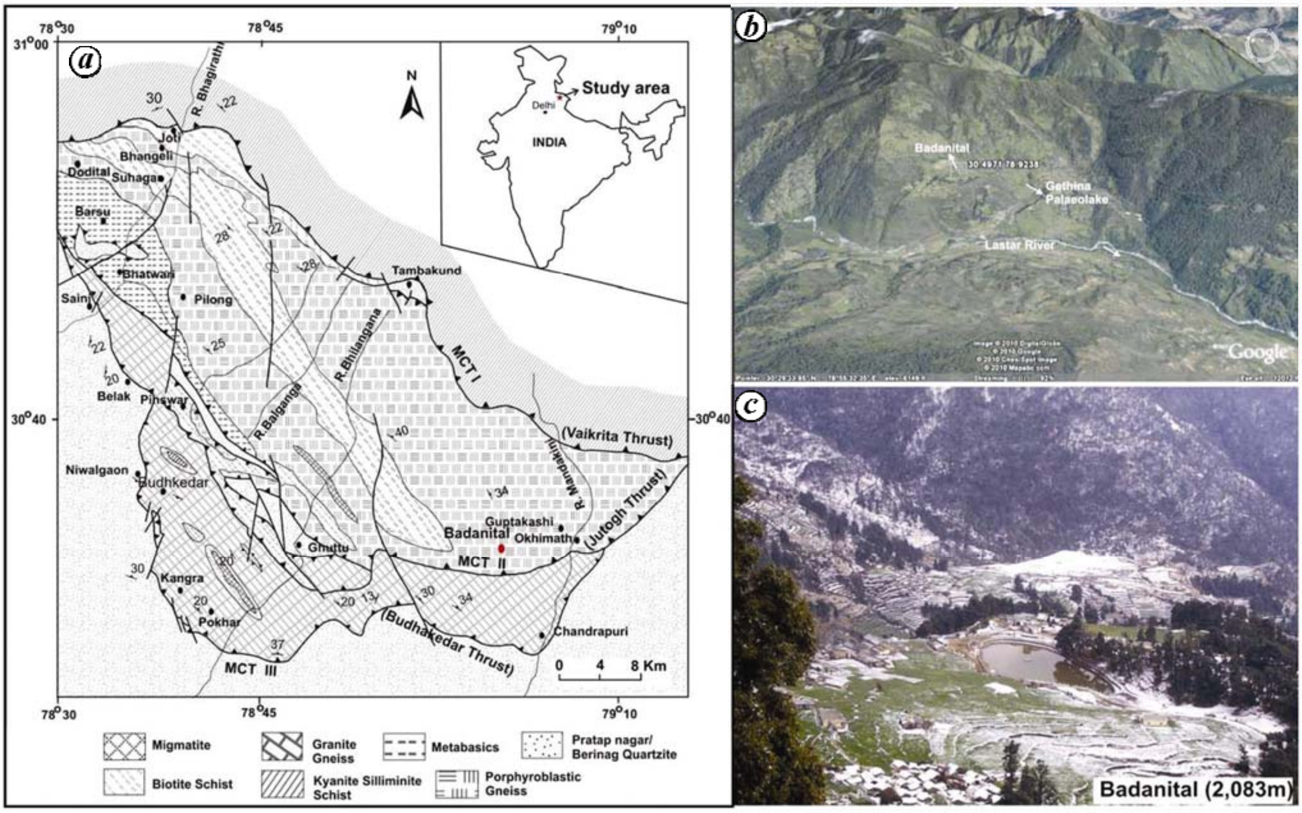

Figure 1. ***a***, Location of Badanital Lake showing geological and tectonic details (after Saklani and Bahuguna[24]). ***b***, Google image of Badanital (note the lake setting on top of the mountain). ***c***, Panoramic view of Badanital Lake.

8 cm (3.55–3.47 m) is thick sandy clay horizon, underlain by a thin layer of small rock fragments from 3.47 to 3.39 m. Very fine horizons of rock fragments mixed with woody material are found at various depths. Sub-rounded to sub-angular pebbles are aligned within the mud succession at 3.35–3.28 m and 1.55–1.49 m, which may be a result of debris flow received from the catchment during enhanced precipitation.

Chronology of sediment core

Five AMS ^{14}C dates were obtained (Table 1) and calibrated using on-line Cal Pal program. A somewhat heterogeneous nature of the deposits and chronological uncertainties do not allow us to precisely calculate the mean accumulation rate. However, the approximate rate of sediment deposition can be estimated by calibrating the dates. The topmost negative date (due to excessive carbon) is considered as 0 years BP for calibration. By extrapolating the dates, we assume the accumulation rate as 1 cm/28.5 years for the period ~ 4.2–2.5 ka BP, 1 cm/11.7 years between ~ 2.5 and 0.62 ka BP, 1 cm/2.75 years from ~ 620 to 530 years BP and 1 cm/7.9 years from 530 years BP to the Present (Figure 2). The likely ages of the key boundaries of different climatic zones may be assumed as ~ 5.1 ka BP (3.55 m level), ~ 3.5 ka BP (2.97 m level), ~ 1.8 ka BP (2.00 m level), ~ 920 years BP (1.25 m level), ~ 440 years BP (0.55 m level) and ~ 160 years BP (0.2 m level). The age–depth model (Figure 2) shows remarkably slow deposition in the lowermost part, perhaps due to less erosion in the catchment, whereas the higher accumulation in the central part may have been a result of high precipitation and consequent landslide activity in the catchment.

Methodology

The core was cut into two halves and sampled at every ~ 8 cm for geochemical study and a total of 45 samples were analysed in the present work. The samples were initially powdered with agate mortar and the fine powder (about 6 g each) was again transferred to the mortar after adding two drops of polyvinyl alcohol for thorough mixing. The mixture was then placed in a pressure machine (at about 14 tonne pressure) and pellets were made on the borax base. These pellets were placed in sample holders of analytical equipment (Bruker S8 Tiger X-ray spectrometer) for measurements. For loss on ignition (LOI), about 1–2 g sample was used for weight loss before and after heating[25]. The analysis was carried out in the Wadia

Table 1. ^{14}C AMS dates of Badanital core sediments (calibration by on-line Cal Pal program)

Laboratory reference	Sample no.	Sample depth (cm)	^{14}C age (years BP)	Error (±)	Calibrated ages (years BP)	Error (±)
UCIAMS 61369	BT 355	1	0	20	0	0
UCIAMS 61370	BT 288	68	495	20	528	8
Poz-43655	BT 256	100	650	25	616	41
Poz-43656	BT 92	264	2450	30	2539	125
Poz-43657	BT 33	323	3815	35	4221	58

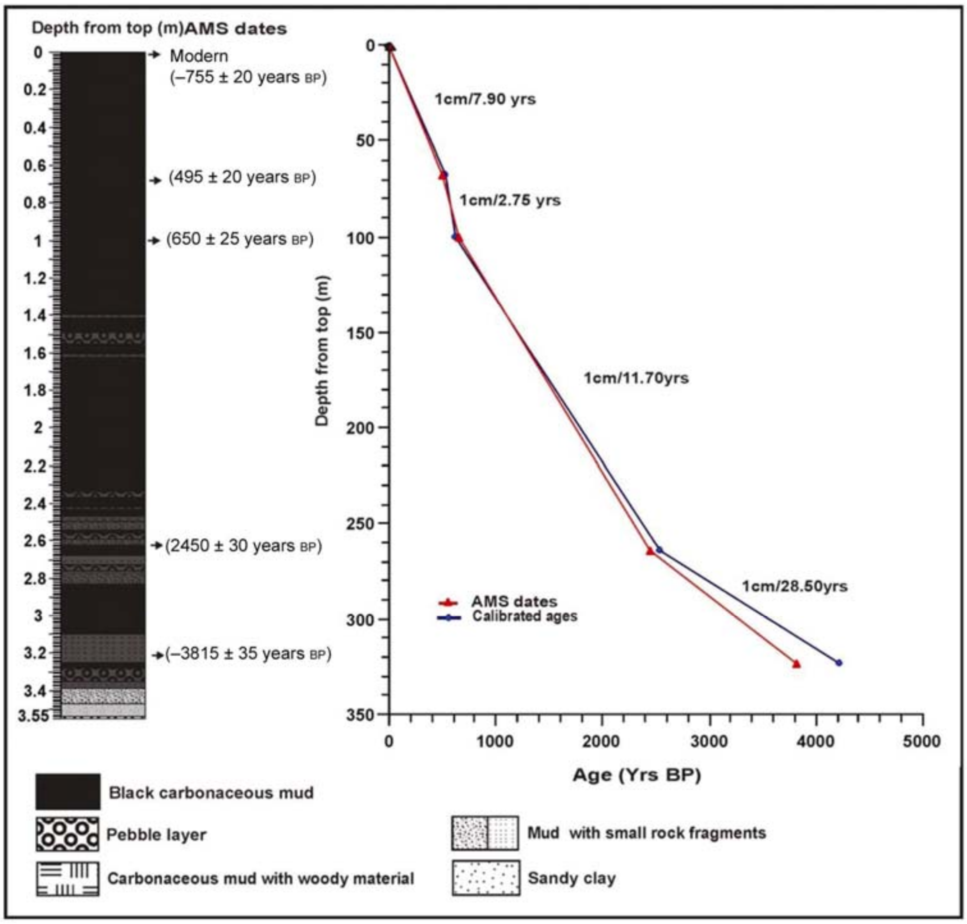

Figure 2. Age–depth model of the Badanital Lake profile.

Institute of Himalayan Geology, Dehradun and a number of geochemical parameters, e.g. Na, Al, P, Fe, Ca, Na_2O, Al_2O_3, Fe_2O_3, K_2O, Cao, Fe/Mn, Na/K, Na/Al, Na/Ti, Al/K, CaO/MgO, CaO/TiO_2, MgO/TiO_2, Na_2O/TiO_2, TiO_2/Al_2O_3, Na_2O/K_2O, Fe_2O_3/TiO_2, chemical index of weathering (CIW), chemical index of alteration (CIA) and LOI were studied. CIA and CIW were calculated using the formulae given by Nesbitt and Young[7], and Harnois[26]

$$CIA = [Al_2O_3/(Al_2O_3 + CaO + Na_2O + K_2O)] \times 100,$$

$$CIW = [Al_2O_3/(Al_2O_3 + CaO + Na_2O)] \times 100.$$

Significance of geochemical parameters used in this study

The LOI is generally used as a measure of organic content of the sediment material[27,28] and the organic matter, determined by LOI, has a linear relationship with the total organic carbon (TOC) in the sediment[29]. The elevated LOI mainly reflects biomass and hence improved vegetation cover[30]. The Fe/Mn ratio is a sign of former redox conditions, thus, the higher ratio points to more barren mineral soils, favouring aridity[31,32]. The higher values of Ca, Mg, Na and K reflect arid conditions[33]. Ca and Na are major elements occurring in most lakes, generally as allogenic clastics, eroded from the catchment[11]. During active erosion, Na concentration is increased, whereas during the period of stable soils, the condition is reversed[34]. The higher Ca and Na contents show increased intensity of droughts[11,35].

Warm and humid climate generally produces highly weathered elements from chemical reactions, and thus the rate of weathering is higher than that under cold and dry climate setting[6,8]. Abundance of Al has been used as a proxy of weathering and erosion in the catchment[22]. High CIA and CIW values suggest relatively more intense weathering from the source area[36] and are responsible for elemental mobilization during the weathering processes[37]. Improved Al/K ratio is a signal of high chemical weathering[38]. Similarly, Al_2O_3 also indicates a gradual rise in weathering under warm and humid conditions[39,40]. Phosphorus (P) may reflect levels of past lake productivity and its level is lower in those sediments where Fe shows strong reducing conditions[29]. The amount of P released from the sediment is called internal phosphorus, leading to enhancement of the lake eutrophication[41]. Considering the above parameters as valuable proxy for palaeoclimatic reconstruction, our data are interpreted as below.

Results and interpretation

Based on the concentration and distribution of various oxides and elements in the sediment core, six possible climatic zones can be proposed.

Zone 1 (3.55–2.97 m; ca. 5.1–3.5 ka BP)

This zone is represented by comparatively lower accumulation rate probably due to less erosion in the catchment, higher values of Na, Fe, Fe/Mn, Na/K, Na/Al, Na/Ti, Na_2O, Fe_2O_3, Na_2O/TiO_2, TiO_2/Al_2O_3, Na_2O/K_2O, Fe_2O_3/TiO_2 and CIA (Figures 3–5). The values of Ca, P, Al, Al/K, Al_2O_3, CaO, CaO/MgO, CaO/TiO_2 and MgO/TiO_2 are initially low, but gradually increase upward in the zone. In contrast, CIW is initially higher but reduced in the upper part. K_2O is poorly represented. Such a combination may call for decreased chemical weathering under stressed climatic condition. This is further supported by higher Fe/Mn, indicative of somewhat arid climate. Low concentrations of P and LOI are suggestive of low organic productivity under reduced precipitation due to which the lake may have become oligotrophic. Higher ratios of Na/Al, Na/K and Na/Ti also point to unfavourable climate setting[42]. Furthermore, an increase in Na and Ca may represent change in soil composition, accompanied by accelerated erosion under adverse conditions in the catchments.

Zone 2 (2.97–2.00 m; ca. 3.5–1.8 ka BP)

This zone shows higher Al, P, Al/K, CIA and CIW, reduced Na_2O/TiO_2 and CaO/TiO_2 and decreasing pattern in Na/Al, Na/K, Na/Ti and Na_2O/K_2O (Figures 3–5). Improved P indicates high organic productivity, whereas CIA and CIW reflect intense chemical weathering from the source area and enhanced erosion. In addition, abundance of Al also points to more weathering and erosion in the catchment. Lower values of Na_2O/TiO_2 and CaO/TiO_2 reflect increased precipitation[43] and low Na/Al, Na/K and Na/Ti values signify warmer climate[42]. Concentrations of various parameters in this zone are suggestive of improvement in lake eutrophication and higher plant productivity during the higher precipitation under wetter/ warmer situation.

Zone 3 (2.00–1.25 m; ca. 1.8 ka BP–920 years BP)

This zone records higher Na, Ca, Na/K, Na/Al, Na/Ti, Na_2O, CaO, CaO/MgO, CaO/TiO_2, MgO/TiO_2, Na_2O/TiO_2, TiO_2/Al_2O_3 values and low Al, Al_2O_3, Fe_2O_3, K_2O, CIA and CIW values (Figures 3–5). Al_2O_3, Fe_2O_3 and K_2O show positive relationship but are negatively correlated with Na_2O and CaO. The low CIA indicates absence of chemical alteration under arid condition[44]. This is supported by elevated values of Na/K, Na/Al, Na/Ti, Ca and Na. Low Al with higher Ca and Na are further suggestive of weaker erosion intensity in the catchment under the reduced monsoonal precipitation. The lower values of Al_2O_3, Fe_2O_3 and K_2O with relatively high values of Na_2O and CaO reflect a stronger hydrodynamics and poor chemical weathering under deprived precipitation and deteriorating conditions.

Zone 4 (1.25–0.56 m; ca. 920–440 years BP)

This zone is characterized by increasing Fe, Fe/Mn, K_2O, Fe_2O_3, CIW, CIA and LIO as well as declining values of Na, Ca, CaO, Na_2O, CaO/MgO, CaO/TiO_2, TiO_2/Al_2O_3, Na_2O/K_2O, Na_2O/TiO_2, Na/K, Na/Al, Na/Ti and Al/K (Figures 3–5). A drop in Na_2O/TiO_2 and CaO/TiO_2, Na/K and Na/Al values may be linked to the better precipitation during warmer/wetter conditions and this is supported by high CIA and CIW in this zone. A fall in Ca and Na also indicate the reduced erosion intensity. Increased K_2O, Fe_2O_3 and Al_2O_3 with relatively low values of Na_2O and CaO may be a sign of stronger chemical weathering from increased precipitation that would result in the loss of more soluble and mobile elements of Na_2O and CaO (ref. 12).

Zone 5 (0.56–0.20 m; ca. 440–160 years BP)

This zone is characterized by improved values in Na, Ca, Na/K, Na/Al, Na/Ti, Na_2O, CaO, CaO/MgO, Na_2O/TiO_2, TiO_2/Al_2O_3, Na_2O/K_2O with higher Fe/Mn ratio. In contrast, Al, Fe, Al_2O_3, Fe_2O_3, Fe_2O_3/TiO_2, CIA, CIW and LOI values are declined (Figures 3–5). The enhanced

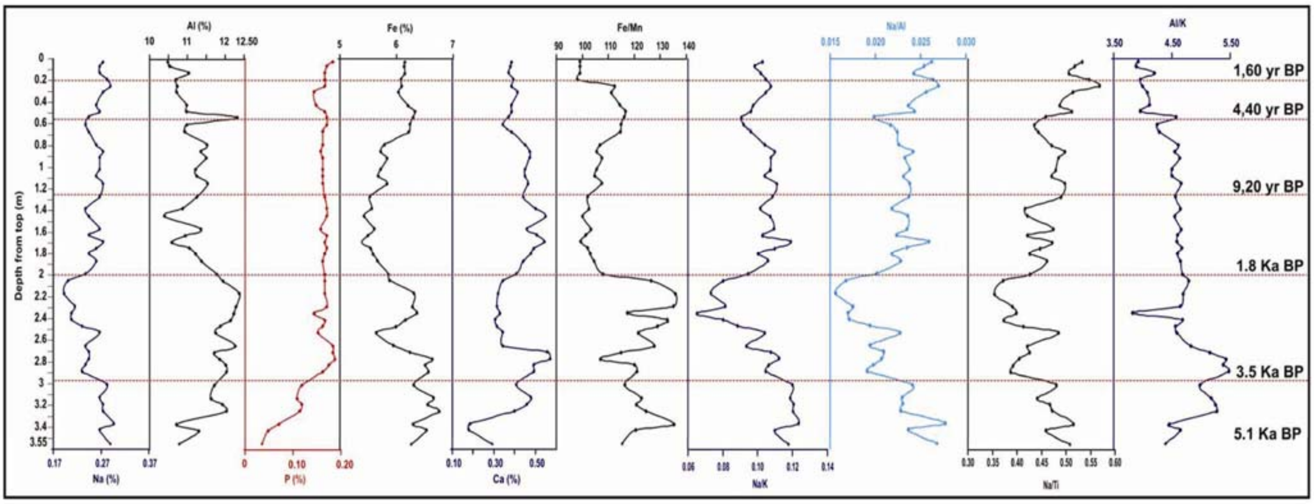

Figure 3. Concentration of various elements and their ratios through the core profile.

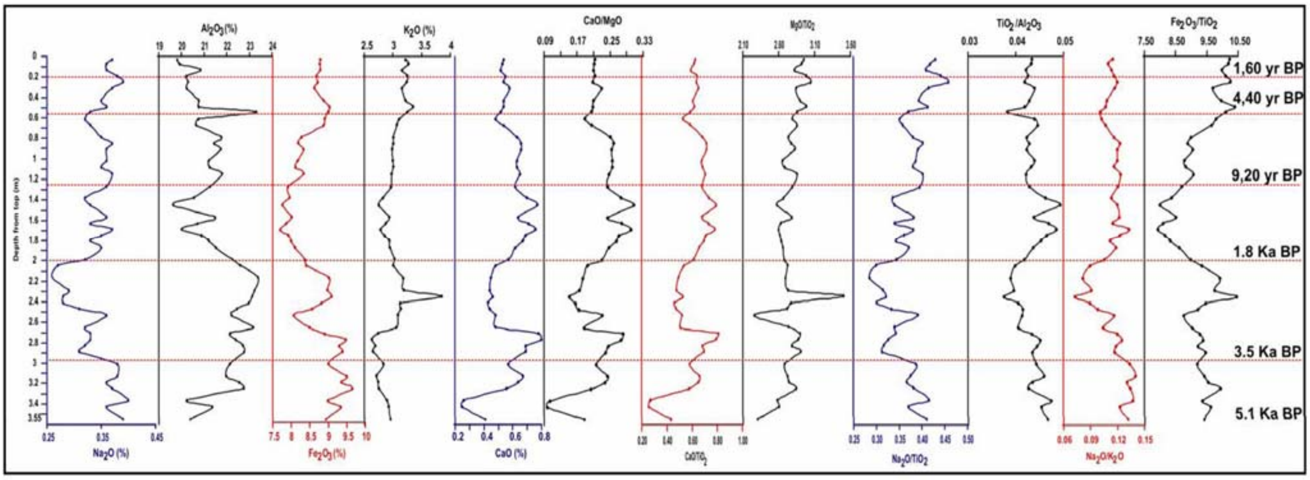

Figure 4. Concentration of various oxides and their ratios through the core profile.

sedimentary Na and Ca may represent accelerated erosion under arid conditions in the lake catchment. The high Na_2O and CaO with relatively low values in Al_2O_3, Fe_2O_3, K_2O, CIA and CIW indicate weaker chemical weathering and perhaps decreased organic content – suggestive of reduced precipitation. Compared to the preceding zone, a reduced P indicates towards oligotrophic lake environment under low rainfall.

Zone 6 (0.20–0 m; ca. 160 years BP onwards)

This zone is represented by increasing values in Al, Al/K, CIW, CIA, LOI, Al_2O_3, K_2O, TiO_2/Al_2O_3, Fe_2O_3/TiO_2 and high P. However, Na/K, Na/Al, Na/Ti and Fe/Mn values decreased in this zone (Figures 3–5). Abundance of Al may be interpreted as a proxy of weathering and erosion in the catchment, as mentioned in the text. The high CIA and CIW values suggest relatively more intense weathering from the source area. An increasing trend in P and LOI reflects high organic productivity leading to improvement of the lake eutrophication. Further, higher Al_2O_3, K_2O with declining Na_2O values may also signify stronger chemical weathering under enhanced monsoon effective precipitation. This is also supported by the low Fe/Mn ratio with reducing values of Na/K, Na/Al and Na/Ti.

Comparison of present records with Indian Himalayan sites

ca. 5.1–3.5 ka BP

In our study, this period represents decreased chemical weathering, slower erosion and lesser organic productivity during reduced rainfall and under unfavourable

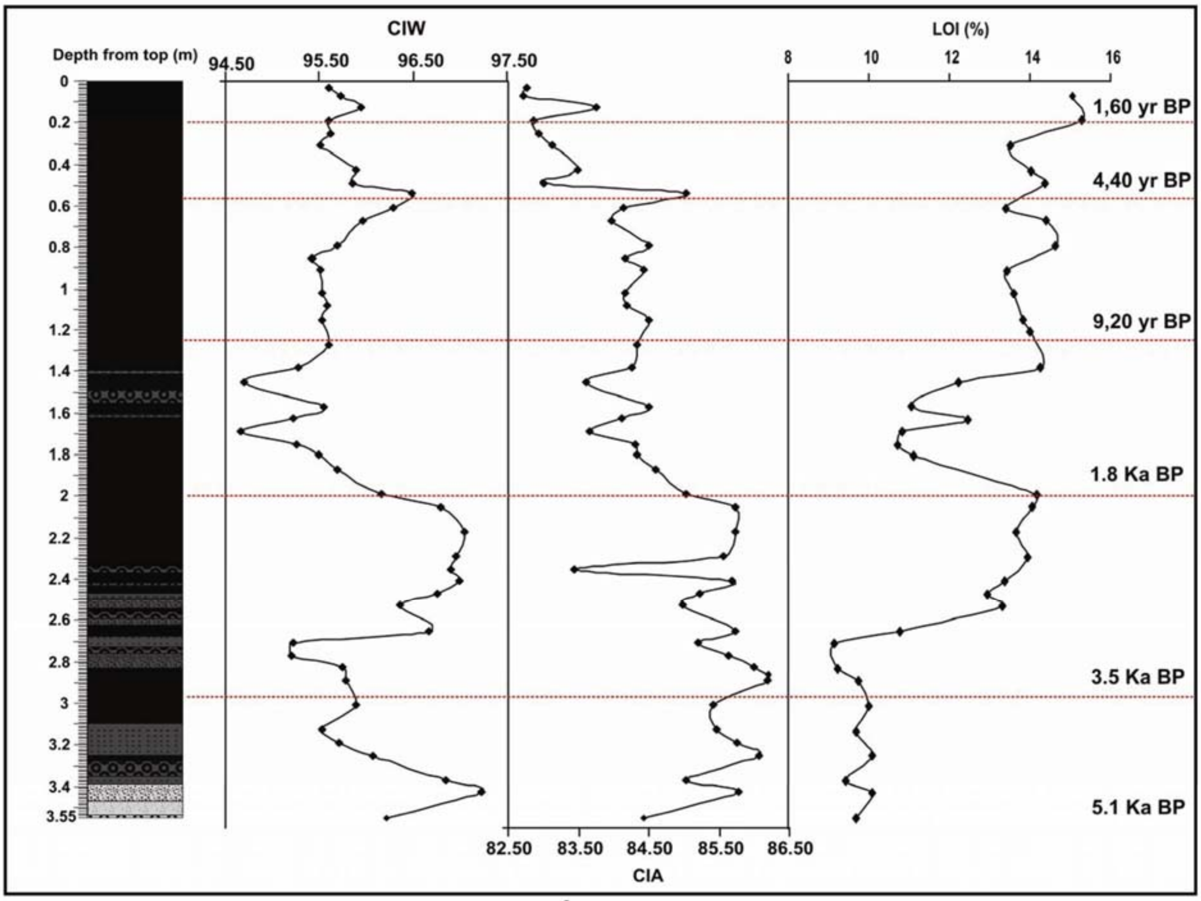

Figure 5. Comparison of chemical index of weathering (CIW) and chemical index of alternation (CIA) with loss on ignition (LOI).

climatic regime. Global in nature, the 4.2 ka arid event has also been felt in the Indian Himalaya. Dated to ca. 4.2–4.0 ka BP, this episode has been documented as a weaker south west (SW) monsoon event as well as the closure of the ancient lake around Bhimtal–Naukuchiatal area[45] as an arid period in the Central Higher Himalaya[46] and a drought pulse with a rapid shift to very dry conditions around Pithoragarh area[47]. The termination of some ancient lakes of Garhwal Himalaya after ca. 5 ka BP due to the combined effect of climate and tectonics[48] seems to be in agreement with our results.

The Phulara palaeolake profile in the Kumaun Central Himalaya[23] has registered drier conditions at ca. 5.0–4.0 ka BP, which can be equated with the 4.2 ka arid event. A number of other Himalayan records show intensification of an arid phase at ca. 4.0–3.5 ka BP (refs 45 and 49). A sudden environmental change around 4.2 ka BP coincides with the end of Harappan civilization in the Indus Valley and collapse of other civilizations westward[50,51] and a prominent drought in the low-latitude southwestern Asia[52]. Migration of the Indus civilization to the Ganga Plains between ca. 5 and 4 ka BP is correlated with strong aridity throughout the Indian subcontinent[53].

ca. 3.5–1.8 ka BP

This duration indicates increased erosion, high organic productivity and greater chemical weathering under wetter/moist climate setting. A climatic amelioration around 2.3–2.0 ka BP has been described from Deorital area[54]. Rühland *et al.*[55] projected wet climatic conditions in Pinder valley around ca. 2.3–1.6 ka BP. The increased moisture availability at about 2 ka BP is associated with wetter climate from a number of the Central Asian sites[46,56–58]. A booming Painted Grey Ware culture in the Indus Valley between 2.7 and 2.3 ka BP (ref. 59) also seems to be a result of improvement in climate.

ca. 1.8 ka–920 years BP

Our records in this age bracket indicate absence of chemical alteration, low organic productivity, less erosion and reduced rainfall under semi-arid to arid climate. Pollen analysis of Deorital sediments[54] also points to the climatic deterioration between ca. 2.0 and 1.4 ka BP. Further, Rühland *et al.*[55] also suggested that the drier climatic conditions prevailed in the Pinder valley around 1.6 ka BP. Pollen data obtained from the Spiti region also specify cool/dry conditions between ~ 2.0 and 1.0 ka BP (ref. 60). Speleothem record from the Pokhara valley (Central Nepal) has also proved that the annually deposited aragonite layers formed between 2.3 and 1.5 ka BP were due to the reduced monsoonal precipitation and increased aridity[61].

ca. 920–440 years BP (AD 1080–1560)

This period may correspond to the Medieval Warming Period (MWP) and our results are indicative of intense chemical weathering, high organic productivity, reduced erosion intensity and increased precipitation under a wetter/moist regime. Palynological study of a peat bog in the Higher Central Himalaya indicates a wetter time around AD 1300 (ref. 55) and another similar study of the Naychhudwari bog (Himachal Pradesh) has revealed a warm/moist phase from AD 700 to 1250 (ref. 62). The *Juniper* chronologies from western high Asia (Karaoram, Tien Shan) also point to a warm period from 11th to mid 13th centuries[63,64]. An extended period of warmth has also been reported from the Tibetan Plateau between AD 800 and 1100 (ref. 65). Evidence of a warm interval from AD 1200 and 1450 is further confirmed by stable carbon isotope analysis on the subalpine *Juniper* from eastern Tibet[66,67].

ca. 440–160 years BP (AD 1560–1840)

During this time-period, our records indicate accelerated erosion, soil stability, low chemical weathering, decline in organic productivity and oligotrophic lake setting under somewhat unstable environment. This may correspond to the LIA. The cooler episode is documented from AD 1600 to 1950 in the western Himalayan tree ring records[68] and from AD 1605 to 1770 in Nepal[69]. The historical records on the frequency of droughts, dust storms and floods in China also show that the climate was highly uneven during the LIA[70]. However, this result is not in agreement with the stalagmite data of the Central Indian Himalaya[71], most likely because of the coarser sampling as well as high age uncertainty in the lake core.

ca. AD 1840 onwards

This part is characterized by strong chemical weathering, high organic productivity, enrichment of lake eutrophication and enhanced precipitation under wetter climatic conditions. This indicates the modern warming. The peat study in Pinder valley has registered a striking abrupt and synchronous shift toward a wetter state in the last 200 years[55].

Conclusion

The Badanital Lake was formed around 5.1 ka BP, most likely, due to a tectonic activity, the imprints of which are observed in form of the geomorphological features, such as waterfalls, active landslide fans, gorges and cliffs around the lake area. The sediment core reveals major climatic phases, e.g. 4.2 ka event, MWP, LIA and 20th century warming trends. Thus, the work adds to the growing evidence for the global extent of these events in the Central Himalaya. Using the geochemical parameters, we suggest that the area experienced at least six main climatic episodes as a cold/dry period from ca. 5.1–3.5 ka BP (including the 4.2 ka event), a wetter/moist phase from ca. 3.5 to 1.8 ka BP, an arid pulse from ca. 1.8 to 920 years BP, a wetter phase from 920 to 440 years BP, a cooler LIA from ca 440 to 160 years BP and a warming trend post-LIA.

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