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Late Pleistocene - Holocene vegetation and climate from the palaeolake sediments, Rukti valley, Kinnaur, Himachal Himalaya

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ABSTRACT

Vegetation and climate during later part of Pleistocene to major part of Holocene (~16.6–3.5 ka) has been reconstructed based on the palynological and magnetic susceptibility proxies from an exposed section of lacustrine deposit at Rukti, Sangla valley, Kinnaur, western Himalaya. Study shows that along with the general tree line succession to higher altitudes since early Holocene, the area has also captured the major climatic events of late Pleistocene to early-mid Holocene time. The area exhibits a continuation of mixed conifer - broadleaved forest at least since ~16.6 ka with intermittent phases of expansions of broadleaved tree taxa especially Oaks (*Quercus*) or invasion of conifers especially Pine (*Pinus*) with an increase (moist) or decrease (dry) of Indian Summer Monsoon (ISM) respectively. This is also supported by the variations in the magnetic susceptibility values. The climate was warm and moist during ~16.6 ka and changed to cool ~13.3 ka, followed by increasing ISM since ~11.5 ka. Distinct spike in the magnetic susceptibility values between ~8.7 and ~7.8 ka could correspond to global 8.2 ka cool event thus indicating strengthening of westerly influence and low evaporation. Subsequent warm conditions could be generalized by the advancement of Birch (*Betula*) line to higher altitude following the resultant retreat of the glacial body. Study has put forth the potential of such Himalayan sites to uncover the major climatic events of global correlation captured by various proxies within a region.

1. Introduction

The major climatic events during the late Pleistocene – Holocene are well reconstructed and teleconnected in many parts of the globe using various proxies (Alley et al., 1997; Alley, 2000; Alley and Agustsdottir, 2005; Cheng et al., 2006, 2009 and others). However, from the Indian Himalayan and Trans-Himalayan regions the data on such globally related climatic events is still limited (Juyal et al., 2004; Singh and Agrawal, 1976; Sinha et al., 2005; Owen et al., 2001; Rawat et al., 2012, 2015) that might restrict the better understanding of the dynamics of the south Asian climatic system and its teleconnection with the other climatic events occurring globally. The Indian Himalayan and Trans-Himalayan region is well characterized by the Quaternary sediments of glacio-fluvial and lacustrine depositional environments providing good archives for the multi-proxy palaeoclimatic reconstructions of the late-Quaternary time (Bhattacharyya, 1988; Brown et al., 2003; Pant et al., 2005; Phartiyal et al., 2005; Ranhotra et al., 2007; Demske et al., 2009 etc.). But very few study area from the Indian region covering the time frame since beyond Holocene has unraveled and discussed such major climatic events in global aspect (Demske et al., 2009; Dixit et al., 2014; Rawat et al., 2015). The Himalayan periglacial areas bear thick lacustrine deposits that might had formed by the impounding conditions of drainage either by reactivation of faults or due to debris flow and later got exposed by the lake-burst and subsequent entrenchment of the rivers. Many such Himalayan lakes covering a mapable area came into existence or terminated around LGM, such as in Kashmir (Agrawal et al., 1989), Kumaun (Kotlia and Phartiyal, 1999; Kotlia et al., 2010), Ladakh (Bhattacharyya, 1989; Fort et al., 1989) etc. Such deposits preserving the various biotic and abiotic proxies could be potential to reconstruct the past vegetation, climate vis-à-vis glacial episodes. Sangla Valley in Kinnaur district

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of Himachal Pradesh (Fig. 1) preserves the glacio-lacustrine deposits exposed to a large extent around the Sangla Town, Kamru and Kuppa villages that suggest the presence of a huge lake during past, which was formed due to the damming of the Baspa River. Ganjoo and Koul (2005) and recently Draganits et al. (2014a, b) studied these glacio-lacustrine deposits classifying them into various depositional facies suggestive of glacio-fluvial to lacustrine depositional environments developed by the ponding of glacial melt water. Probably, the lake was progressively filled and revived under the influence of climate as well as neo-tectonic activities, as evidenced by the presence of incised and eroded glaciogenic-lacustrine deposits by the entrenched Baspa River.

During recent years few studies (Bhattacharyya et al., 2006; Chakraborty et al., 2006; Ranhotra and Bhattacharyya, 2010) have been carried out from various tributary valleys within the main Sangla valley that relate to the palaeoclimatic reconstruction based on palynology and other proxies. The studies either cover the earlier part of Holocene, as taken from the Naradu glacier valley by Bhattacharyya et al. (2006), or not continuously resolved in the Holocene time due to palynological breaks in the records from the Rukti valley (Chakraborty et al., 2006). From the upper reaches of the Rukti valley, Ranhotra and Bhattacharyya (2010) attempted the reconstruction of past glacial extent during Holocene based on the tree line fluctuation. The recent study by Draganits et al. (2014a&b) shows the existence of huge lake since ~8000 till ~2000 ka when the lake got terminated. The later study is mainly focused on the tectonic settings and seismicity of the area as well sediment load and volume of lake considering the engineering aspects of the present running 300 MW hydroelectric projects I and II few kms downstream of Sangla town. In the same focus the climate part has also been discussed by Draganits et al. (2014a) using palynology, but with sample limitations. The present work, emphasized on the analysis of pollen and environmental magnetic data, unravels the vegetation history and major climatic events during late Pleistocene to mid Holocene from an exposed section of lake sediments along the Rukti stream and also discussed any teleconnection exists with the globally known climatic events of the time frame.

2. Study area

Kinnaur Province in the extreme east of Himachal Pradesh comes under the transition zone of the Greater and Trans-Himalayan Regions and experiences the effect of both Indian Summer Monsoon (ISM) as well as Western Disturbances (WD), the later being stronger compared to ISM. Geologically as a part of Tethys Himalaya (Bassi et al., 1983), the area is considered as a continuation of Lahaul-Spiti basin and south-east extension of Zanskar basin of Ladakh, Trans-Himalaya (Bhargava and Bassi, 1998). Sangla valley (31° 10′ to 31° 40′ N Lat. and 78° 05′ to 78° 45′ E Long.), also known as Baspa valley, is situated in the north-west part of Kinnaur district. The valley is intersected by the Baspa River that originates from the Arsomang and Baspa Glaciers at an altitude of ~4200 m amsl and after traveling the distance of ~72 km it joins the River Satluj at Karcham (~1890 m amsl). The Baspa glacier with a length of ~18 km is the largest glacier in the Beas and Sutlej valleys of Himachal Pradesh (Sangewar and Shukla, 2001). The basin holds

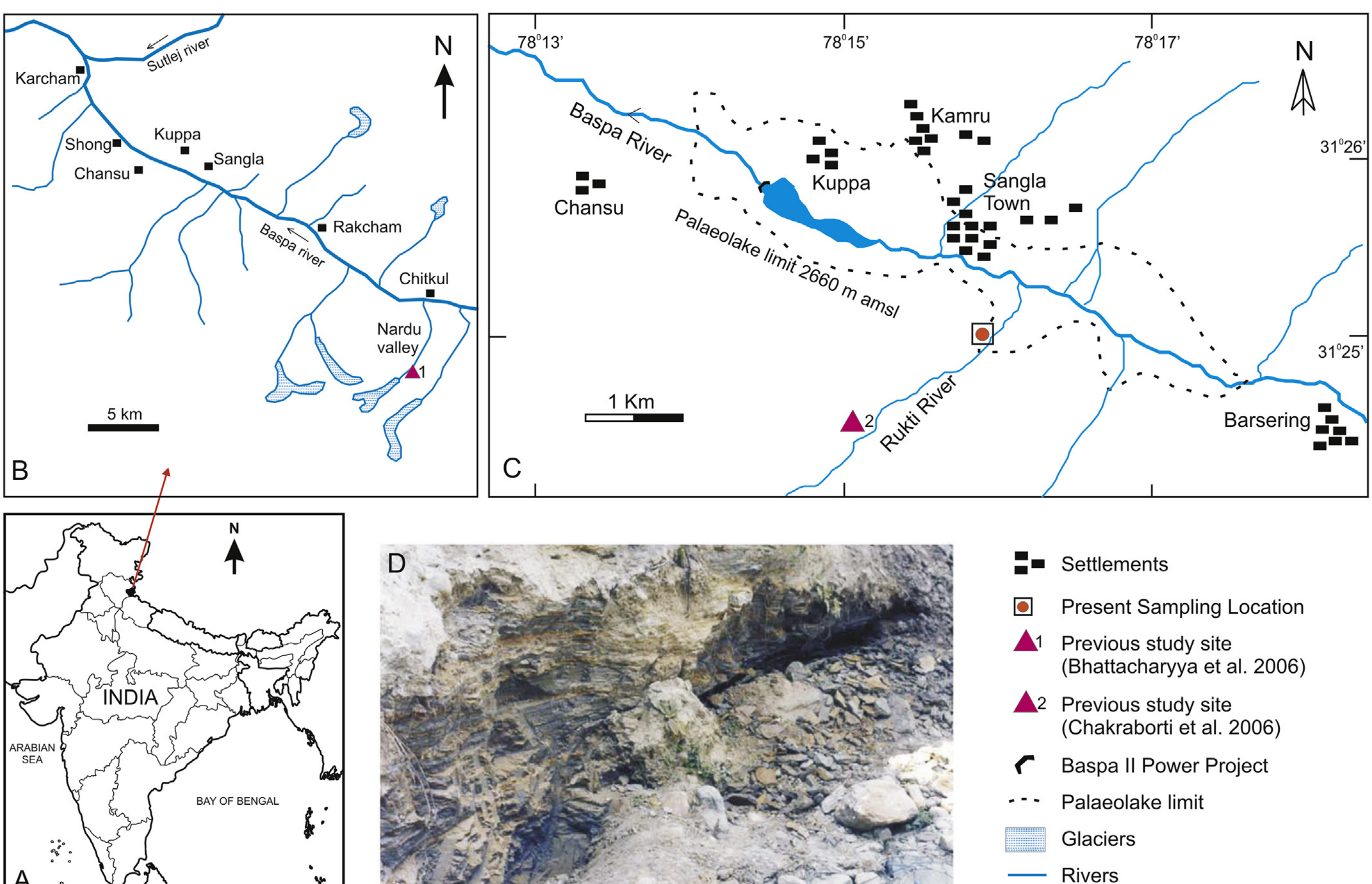

Fig. 1. A) Map of India with the location of Kinnaur. B & C) Site map of Baspa valley showing the sampling location along the Rukti river for present study and also the sampling location of previous studies. D) View of the exposed section of the lacustrine deposits along the Rukti river.

small tributary glaciers between the altitudes of ~4000–6000 m amsl, the melt waters of which feed the main Baspa River before its confluence with the River Satluj. Rukti is one such tributary valley that streams in the main Baspa River at its left bank at an altitude of ~2600 m amsl near the Sangla Town under Sangla Tehsil, about 235 km NE of Shimla in Himachal Pradesh (Fig. 1).

2.1. Present vegetation

The area is surrounded by the upper temperate broadleaved - conifer forest characterized by *Cedrus deodara, Pinus wallichiana, Quercus* etc. This forest, towards its upper limit at ~3400 m amsl, merges into the sub-alpine forest with major elements of *Picea smithiana* and *Abies spectabilis* along with the *Betula utilis*. Later one forms the tree line at ~3800 m amsl. The alpine meadow, which succeeds the tree line, is characterized predominantly by the patches of stunted *Juniperus*, *Ephedra*, and diversified herbaceous taxa. These herbaceous taxa mostly are represented by members of Asteraceae including *Artemisia*, Primulaceae, Crassulaceae, Scrophulariaceae, Ranunculaceae, Saxifragaceae, Brassicaceae, Caryophyllaceae etc. Towards its lower level i.e. around Sangla town at ~2600 m amsl, the area is characterized by the temperate broadleaved - conifer forest with spp. of *Quercus*, *Acer caesium*, *Ulmus wallichiana*, *Juglans regia*, *Celtis australis*, *Carpinus viminea* along with conifers viz., *Pinus gerardiana* and *Cedrus deodara*.

2.2. Climate

Most of the Kinnaur enjoys a temperate climate due to its high elevations, with long winter from October to May, and short summer from June to September. Though the lower parts of the Sangla and Sutlej valleys receive monsoon rains but higher areas of these valleys are in the rain-shadow zone considered to be arid regions. Most of the precipitation in the catchment occurs as snow contributing to glacier and consequently to the river flow during the period April to October (Draganits et al., 2014a). Detailed climate data for longer time span is not available from the area. However, climate data only for two years 1990–91 AD has been recorded from the Automatic Weather Station installed above the tree line (~3800 m amsl) near the glacier snout in the Naradu, a nearby tributary valley of the Baspa River. It shows that mean maximum temperature ranges from 14 °C to 18 °C during July and the mean minimum temperature ranges from −18 °C to −20 °C during February. Wind direction 25°–45° due North with speed of 1–20 km/h is recorded; average wind speed is 5.5 km/h. Precipitation varies greatly within the short distance, which is in the form of rainfall at lower altitudes and at the higher altitudes i.e. above 4200 m amsl, precipitation is mainly in the form of snow (Bhattacharyya et al., 2006). Based on data from the weather stations at Sangla, Rakcham and Chitkul, Wulf et al. (2010) calculated 310 mm average summer precipitation and 370 mm average winter precipitation. At Chitkul (~3440 m amsl) 380 mm annual mean snowfall was observed between 1976 and 1990.

3. Material and methods

3.1. Sampling location and lithology

For the present study the sediments were collected from a small section of the lacustrine deposits exposed at the left cutting of the Rukti stream near Rukti micro power plant at altitude around 2600 m amsl, (Fig. 1C&D). Sediments at some intervals were collected for the various proxy study viz. palynology and environmental magnetism by clearing the outer surface of the exposed deposits. From the 140 cm thick exposed section (Fig. 4), 17 samples were collected at the bulk interval of 10 cm each, with exception at certain depths where the bulk interval is 5 cm. The upper 10 cm part of the collected sediment section is fine sand to silt followed by a 30 cm thick clay layer rich in organic content. Sediment layers below the depth of 40 cm are characterized by the alternations of sand and clay of varying thickness.

Earlier, based on the textural analysis Ganjoo and Koul (2005) divided the deposits of Sangla palaeolake into four facies viz. basal conglomerate, cohesive debris flow, sheet/water flow and laminites. According to them the basal conglomerate facies signifies the maximum extent of the glacier advancement episode, which may probably correspond to LGM time. Draganits et al. (2014a) further modified and discussed six facies associations deposited under different depositional environments. Laminites of 1–3 mm thickness, also referred as varve deposits, well exposed at several places around the Sangla town within the valley are described under two facies as - facies A of horizontally laminated clay to silt size sediments deposited under the lacustrine conditions; and facies B of horizontally laminated, mm to cm-thick, medium sand layers, deposited under marginal lacustrine environment. These laminate deposits are exposed at many places within the valley and show soft sediment deformation structures due to earthquake induced liquefaction (Bagati, 2001; Ganjoo and Koul, 2005). The sediment section taken for the present study seems to correspond the laminitic facies B (Draganits et al., 2014a) deposited under the marginal lacustrine conditions.

3.2. Radiocarbon dating

For providing chronology to the studied sedimentary section the organic rich bulk sediments from three depths were radiocarbon (^{14}C) dated. Two samples at the depths range of 1–10 cm and 120–130 cm were dated by AMS method at the AMS Laboratory, Institute of Physics, Bhubaneswar, that provided the dates 3417 ± 16 yrs BP (3700 cal yrs BP) and 12,844 ± 330 yrs BP (15,300 cal yrs BP) respectively. One sample at the depth range of 50–55 cm was dated by conventional means at the Radiocarbon laboratory, Birbal Sahni Institute of Palaeosciences, Lucknow, which provided the date of 7850 ± 300 yrs BP (8750 cal yrs BP). In the text the calibrated dates have been mentioned in 'ka'. Pretreatment of the samples included the standard acid-base-acid procedure for the removal of inorganic carbon from the sediments. The dates are converted to calendar years using the suggested method of calibration (Reimer et al., 2013) and the OxCal v4.2.4 program (Fig. 2). The calibrated dates are rounded off to the nearest decade or century (Stuiver and Polach, 1977) and represented in Table 1. To assign ages to any major changes in the pollen or other proxy data at some depths in the studied sequence, the dates at those depths are interpolated using the age-depth model through polynomial regression ($R^2 = 1$) providing the best fit curve (Fig. 3).

3.3. Palynological analysis

For extracting the pollen-spores from the sediment samples, common maceration procedure (Erdtman, 1943; Faegri and Iverson, 1989) has been followed with slight modifications, which included the acid-base-acid treatment and acetolysis process for the removal of carbonate and silicate sand and also making the pollen grains morphologically clear for identification. Few slides were scanned under the light compound microscope to raise the total count of pollen grains between 350 and 700 per sample. Pollen frequency diagrams were prepared by using TILIA 1.7 software (Grimm, 2004). The total number of pollen-spores counted per sample is taken as "Total Pollen Count" (TPC). Two pollen diagrams (Figs. 4 and 5) are prepared, in which first one represents the pollen frequency or

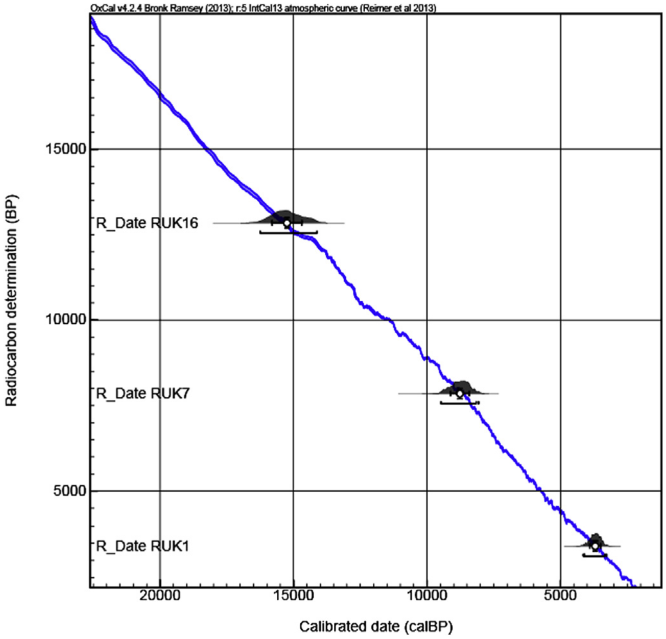

Fig. 2. Calibration plot of the radiocarbon (^{14}C) dates using OxCal v4.2.4 for the profile RUK, Rukti valley, Sangla, Kinnaur.

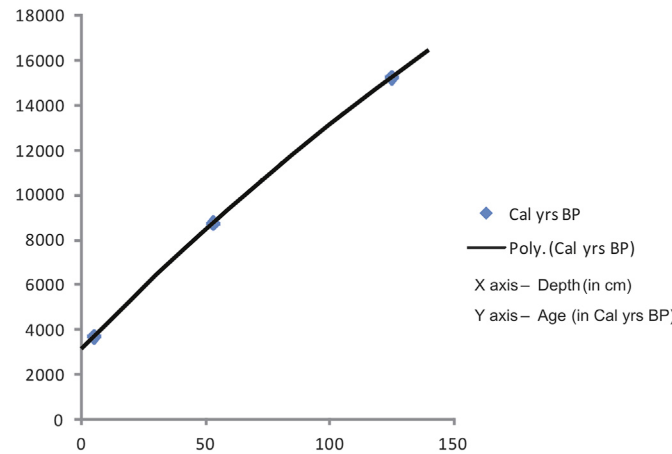

Fig. 3. Age-Depth model of the profile RUK, Rukti valley, Sangla, Kinnaur.

percentage of all individual taxon calculated on TPC. In the other diagram plant taxa are grouped in broad ecological aspects viz., Sub-alpine, Conifers, Temperate broadleaved, Other herbs/shrubs and Marshy/aquatic taxa. These groups are displayed along with the magnetic susceptibility parameters. Lithology of the section is shown on the extreme left side of the diagrams along with the radiocarbon dates. The pollen frequency lower than 1% is shown by "+" sign in the pollen diagram. In conjugation with the changes in the frequency of some important arboreal and non-arboreal taxa at certain depths, the Pollen diagram has been divided into different pollen zones for which determination has been done by stratigraphically constrained cluster analysis, using CONISS, available in Tilia 1.7 software (Grimm, 1987, 2004). Pollen zones and the cluster diagram are displayed on the extreme right of the pollen diagrams.

3.4. Environmental magnetic study

Variations in the magnetic mineralogy parameters reflect changes in climate, which has vital role in weathering along with other non-climatic factors (Thompson and Oldfield, 1986; Fang et al., 1999; Basavaiah et al., 2004; Basavaiah and Khadkikar, 2004; Deotare et al., 2004; Shankar et al., 2006). Several of its parameters such as magnetic susceptibility 'χ' (Chi), anhysteretic remanent magnetization (ARM), isothermal remanent magnetization (IRM), saturation IRM (or SIRM), S-ratio $_{(-300mT)}$ etc., are dependent on the intensity of weathering of rocks in the catchment area (Thompson and Oldfield, 1986). Here these parameters have been carried out to supplement the pollen based climatic oscillations. For magnetic susceptibility measurements, sediment samples were prepared by oven drying at temperature below 40 °C overnight. Dry samples were crushed-disaggregated gently using agate pestle-mortar, wrapped in a clean cling foil and packed tightly into standard 10 cc cylindrical plastic holders. For mass specific magnetic parameters, the mass of sample was calculated by taking the weight difference between empty bottles along with thin cling foil and bottles packed with sample material. The most frequent approach to establish magnetic concentration in samples involves measurement of magnetic susceptibility 'χ' in low frequency (χlf), followed by the measurement of frequency dependant susceptibility ('χ'fd), ARM, IRM and SIRM. S-Ratio$_{(-300mT)}$ determines the concentration of magnetic minerals of magnetite/haematite in the samples. S-ratios close to +1.0 are indicative of ferrimagnetic minerals, while low S-ratios are caused by the presence of antiferromagnetic minerals (Bloemendal et al., 1992; Basavaiah and Khadkikar, 2004).

4. Data interpretation and results

4.1. Palynology

For the convenience of interpretation, the pollen diagrams (Figs. 4 and 5) have been divided into three Zones (RUK-I to RUK-III) based on the variations of some key pollen taxa. However the pollen zone RUK-II has been further sub-zoned as IIa and IIb in Fig. 5 based on the frequency changes of few ecological groups.

Zone RUK-I: The bottom part of the profile i.e., from 140 to 103 cm corresponding to around 16.6 to 13.3 ka shows a good representation of arboreal (45–60%) and non-arboreal taxa (55-40%). *Pinus* (6–20%) is the dominating conifer taxa over other conifers viz. *Cedrus* (1–2%) and *Abies* (1% and less). The local sub alpine taxa is represented by *Betula* (13–17%) in good amount. *Salix* marks its presence. The broad leaved temperate taxa are

Table 1
Radiocarbon dates with corresponding depth range, calibrated ages and laboratory identification number for the profile RUK, Rukti, Sangla Valley, Kinnaur.

Sample No.	Depth Range (cm)	^{14}C Dates (yrs BP)	Calibrated Ages (cal yrs BP)		Laboratory Identification Number
			μ	σ	
RUK-1	1–10	3417 ± 160	3700	200	IP-521
RUK-7	50–55	7850 ± 300	8750	350	BS-2442
RUK-16	120–130	12,844 ± 330	15,250	560	IP-522

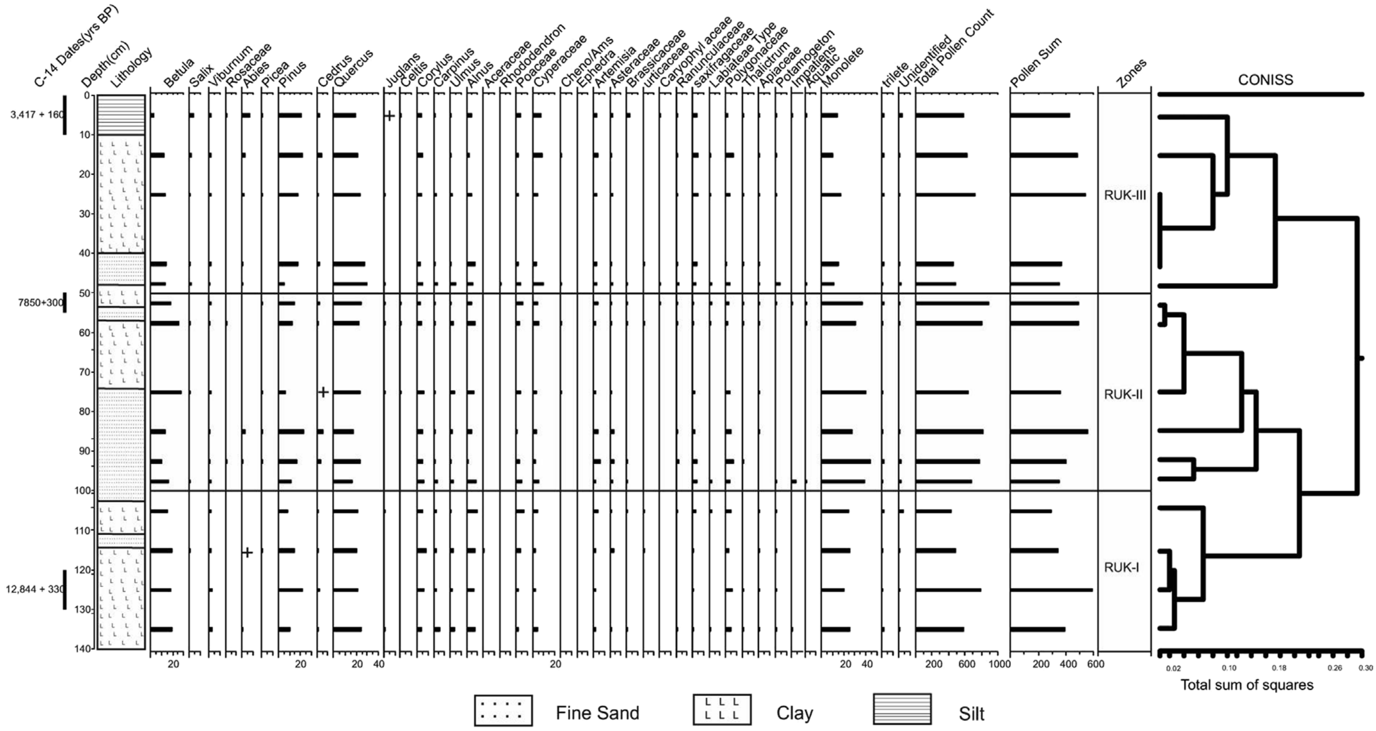

Fig. 4. Pollen diagram showing the pollen assemblages recovered from the profile RUK, Rukti valley, Sangla, Kinnaur.

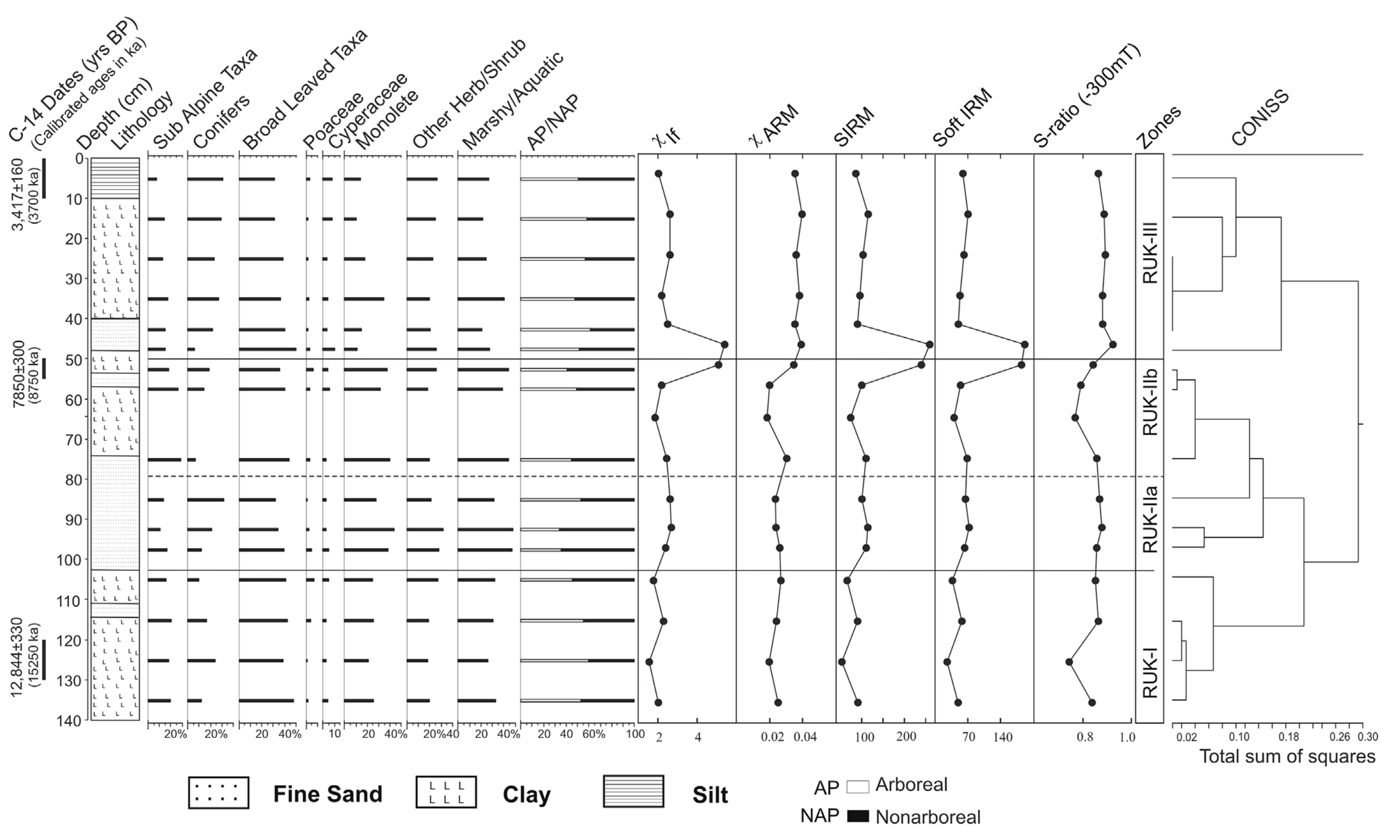

Fig. 5. Pollen diagram showing the various ecological groups of the pollen taxa along with the environmental magnetic data for the Profile RUK, Rukti valley, Sangla valley, Kinnaur.

represented by dominance of *Quercus* (16–22%) followed by *Alnus* (5–7%), *Corylus* (3–6%), *Carpinus* (3–6%), and *Ulmus* (1–3%). The non arboreal taxa are Poaceae (1–5%), Asteraceae (1–2%), *Artemisia* (1–3%), Saxifragaceae (1–2%), Polygonaceae (1–2%), etc. Aquatic and marshy taxa include Cyperaceae (2–5%), *Potamogeton* (1–2%) and monolete (21–26%).

Zone RUK-II: This zone extending from 103 to 50 cm depth covers a time span from ~13.4 to 8.5 ka. Compared with zone RUK-I, this zone shows decrease in the arboreal pollen taxa (from 45% to 36%). *Betula* is fluctuating (10–25%) with higher values at upper part of this zone. The conifers viz. *Pinus* (4–18%), *Cedrus* (2–4%) and *Abies* (1–2%) and the broad leaved taxa *Quercus* (11–16%), *Alnus* (3–5%), *Corylus* (2–4%), *Carpinus* (1–2%) and *Ulmus* (2–3%) show an overall decrease as compared to previous zone. Amongst the non arboreal taxa *Artemisia* (1–3%), Saxifragaceae (1–2%) and Poaceae (2–5%) show almost similar trend. Other herbs/shrubs represented are Asteraceae (1–2%), Polygonaceae (2–4%), Ranunculaceae, etc. Cyperaceae (3–6%), *Potamogeton* (1–2%) and ferns viz. monolete (28–44%) and trilete (1–2%) show increased values together from 32% to 48% as compared to zone RUK-I. The demarcation between zones RUK-IIa and RUK-IIb in Fig. 5 is based on the dominance of the conifers in the IIa as compared to IIb whereas the subalpine and boadleaved taxa show increase in their frequencies from IIa to IIb.

Zone RUK-III: This zone starts from 50 cm depth and continues up to the top of the exposed section, aged between ~8.5 and 3.5 ka. This zone shows the dominance of arboreal pollen (51–61%) over the non arboreal pollen (49-39%). As compared to the earlier zone, *Betula* (2–11%) shows a noticeable decline. The temperate taxa viz. *Pinus* (3–20%), *Cedrus* (2–6%), *Abies* (2–5%) and *Quercus* (16–25%) show an overall increase in the frequency, whereas *Carpinus* (1–2%), *Corylus* (2–4%), *Juglans* (1%), *Alnus* (2–6%), *Ulmus* (2–4%) show more or less similar values. Poaceae (2–3%), Polygonaceae (2–5%), Saxifragaceae (2–4%) also do not show much variation in the pollen content but there is a marked decline in the percentage of fern spores (11–35%) and other aquatic and marshy taxa (21–41%) with slight increase in the frequency of Cyperaceae (4–10%).

4.2. Environmental magnetic study

Temporal variation in magnetic parameters in the sediments provide information regarding the intensity of weathering leading to incorporation of low or high amount of ferromagnetic minerals. Magnetic Susceptibility (χ), ARM, SIRM are concentration dependent, hence to eliminate this dependency, the ratios between individual magnetic parameters of S-ratio and ARM/SIRM can be used to assess the magnetic assemblage grain size in sediments. In present study the values of magnetic susceptibility (χlf), χARM, SIRM, soft IRM and S-ratio range between 1.5 and 5.4, 0.018 to 0.039, 65 to 259, 36.9 to 53.2 and 0.76 to 0.92 respectively (Fig. 5). The maximum values of χlf, χARM, SIRM and S-ratio are recorded for the two samples between depth range 55–45 cm corresponding to age range of ~8.7 to 7.8 ka.

5. Palynological and magnetic susceptibility data analysis

Palynological analysis (Figs. 4 and 5) shows that since ~16.6 till ~13.3 ka the climate was favorable for the flourishment of conifer-broadleaved oak forest. Amongst conifers, *Pinus* was dominant followed by *Cedrus* and *Abies*. For broadleaved taxa, the subalpine species of *Betula* was in good frequency, whereas for temperate taxa *Quercus* is found abundant along with low proportions of *Carpinus, Corylus, Juglans, Ulmus, Viburnum*. The ground vegetation was poor, comprising of *Artemisia*, elements of Asteraceae, Cyperaceae, Poaceae, Polygonaceae etc. The Pteridophytic (fern) spores (mainly monoletes) found in good frequency, might have occupied the moist margins of the lake. The situation seems to be similar to the proglacial conditions resulted by the recession of the glacier from the place. The high pollen amount of *Betula* (a tree line forming element) in the zone RUK-I (Fig. 4) indicates comparatively lower tree line levels during the end Pleistocene time as compared to present. The overall dominance of arboreal taxa over non-arboreals along with the dominance of *Quercus* over *Pinus* might indicate the moist conditions. Ground vegetation was also less represented. Since ~13.3 ka the conditions indeed were suitable for *Pinus* to invade the area and its invasion gradually increased till ~11.5 ka (zone RUK-IIa in Fig. 5) with the corresponding decline of *Betula* and *Quercus*, thus indicating decline of moist conditions. Subsequently after ~11.5 ka there was a noticeable increase in the pollen frequency of *Betula* and *Quercus* at the expense of *Pinus* (subzone RUK-IIb in Fig. 5). The fern spores also remained high as compared to previous zone RUK-I thus indicating the early Holocene moist conditions that could be linked with the increased ISM. The maximum pollen concentration of *Betula* in subzone RUK-IIb might indicate the dense growth of *Betula* trees near the site along with the *Quercus* during the time frame ~11.5 to ~8.5 ka. Also *Pinus* became to its minimum during this time frame. Though there is no noticeable change in the ground vegetation but the good amount of fern spores (monolete) in subzone RUK-IIb also supports the good growth of ferns along the lake margins indicating high moisture. In the zone RUK-III i.e. since ~8.5 ka there is a continuous decline of *Betula* and increase in the *Pinus* and *Quercus* pollen frequency though the *Pinus* remained lower than *Quercus* at the early part of this zone and became more dominant during the later part of this zone i.e. till ~3.5 ka. This might indicate the gradual shift of the tree line forming element (*Betula*) towards higher elevation following the glacial retreat under the general warming trend of climate and the colonization of the *Pinus* along with other conifers as well as temperate broad leaved taxa at the study site with the gradual filling of lake. However ~8.2 ka the fair amount of *Potamogeton* pollen might suggest the high lake stand when evaporation was low. The lowest value of *Pinus* pollen could be due to decline in Pine growth because of cool conditions. A fair increase in the cyperaceae ~8.2 ka and presence of *Quercus* pollen also indicate cool conditions.

In general there is not much fluctuation in the magnetic susceptibility parameters of the entire studied sedimentary section except a magnetic spike near the transition of zone RUK-II to III. The slight fluctuations recorded in the susceptibility values of the sediments at various depths since ~16.6 ka might be due to the changes in the intensity of surface erosion because of changes in the local ground vegetation conditions related to soil moisture content. The slight increase in the values from zone RUK- I to II could be the effect of increased erosion either due to less vegetation cover in the surrounding areas or due to input of sediments by the inflowing streams from the upper reaches of the valley. However, the spike in the values of susceptibility corresponding to ~8.7 to 7.8 ka depicts the high erosion event that might be due to reduced vegetation cover of the surrounding area. Thereafter the values again declined suggesting the low erosion conditions.

6. Climatic events and glacial reconstruction

The small exposed section of laminites along the left cutting of the Rukti stream, probably corresponding to the laminitic facies B as described by Draganits et al. (2014a), suggest the survival of lake at least since later part of the Pleistocene till late Holocene time. During this lacustrine phase the glacial bodies within the Sangla valley might have receded to upper reaches thus feeding the lake by melt water. As suggested by earlier studies the maximum extent of glacier advance to the valley floor is evidenced by the presence of basal conglomerate facies (Ganjoo and Koul, 2005) followed by the recession of glacier and formation of lake by the damming of melt water due to rock-avalanche (Draganits et al., 2014a,b). Study by Ranhotra and Bhattacharyya (2010) from higher reaches within the same Rukti valley, suggesting that the glacial extent within the valley might be at the altitude of around 3500 m amsl during early to mid Holocene, also supports the evidence. Taking the glacier extent studies from the other adjacent regions, the maximum extent of the glacier at this corresponding altitude of ~2500 m amsl is available from the Bhagirathi valley by the dating of moraines at Jhala (~2400 m amsl) to be around 63 k yrs BP old corresponding to MIS-3 stage (Sharma and Owen, 1996; Barnard et al., 2004). At almost similar altitude of ~2500 m amsl in the Tons valley of Garhwal, the lowest glacial moraines have been dated ~16 k yrs BP (Scherler et al., 2010). Considering these glacial extent studies from the nearest valleys as analogues, the section of Sangla palaeolake deposits dated ~16.6 ka might suggest the origin of this palaeolake to be even older within the late Pleistocene part. However, Draganits et al. (2014a) based on the dates of recovered fossils suggest the age of entire deposits to be within Holocene time. The comparative age difference from the previous and the present study can be attributed to the development of this huge palaeolake area under different temporal stages with altitudinal variations. More number of dates from different locations and depths of the sections of these deposits are needed to supplement the data with more precise understanding of the deposition and age of this palaeolake.

The present analysis depicts vegetation and climatic changes for the time span of later part of Pleistocene to major part of Holocene (since ~16.6 to 3.5 ka) based on palynology and magnetic susceptibility data. Pollen analysis reveals that the site was occupied by broadleaved Oak-Conifer forest at least since the end part of Pleistocene till Holocene with evident tree line shifts at variable density. There are several phases when expansion of broadleaved taxa, especially Oaks (*Quercus*), took place at the expense of Pine (*Pinus*). This might have happened with a change to comparatively moist climate under the influence of increased ISM. Around 16.6 ka climate was favorable for the flourishment of broadleaved oak and conifer woods under the influence of moist conditions. This is followed by less moist phase since around 13.3 ka when an overall decline in the pollen taxa is noticed. The vegetation cover by the broadleaved taxa might have been reduced with the decline in Oak vegetation growing at lower altitudes. The conditions indeed were suitable for Pine to invade the area and its invasion gradually increased. The MS values also show slight increase during the phase suggesting the comparatively less vegetation cover and increase of surface erosion. This time period can be correlated with the Younger Dryas (YD) event. This comparative arid phase was interrupted ~11.5 ka as depicted by the gradual advancement of broadleaved Oak forest at the cost of Pine under the high monsoon regime, also evident by the good amount of Pteridophytes (ferns). Subalpine broadleaved taxa, *Betula,* also might have flourished not far away from the site indicating the lower altitudes of the tree line during the early Holocene time. The slight lowering in the MS values further support the increase of vegetation under moist conditions. The sudden spike in the values of MS parameters in the two samples corresponding to age bracket ~8.7 to 7.8 ka might be the result of high erosion due to less vegetation cover. However, the pollen data with slight increase of *Quercus* with decline of the *Pinus* and fern spores along with fair amount of *Potamogeton* points towards the comparative cool conditions with high lake strand, nearly coinciding ~8.2 ka global event. This might indicate the strong westerly influence and low evaporation due to cool conditions. Subsequently till ~3.5 ka there was expansion of Pine and decline of Birch thus suggesting the advancement of tree line towards higher altitude with the shifting of Birch following the resultant retreat of the glacial body under the averaged warm conditions. By the late Holocene the study site got colonized by the *Pinus, Abies* and other conifers along with the mixed temperate broadleaved taxa. Earlier Ranhotra and Bhattacharyya (2010) also discussed the tree line shift to the higher altitude based on palynological analysis from Sangla Kanda site at higher reaches than the present collection point within the Rukti valley.

7. Correlation with other palaeoclimatic studies

Climatic data derived from the present study has also been correlated with the previous published data from the same study area as well as from various other Himalayan, Tibetan and extra regions. The previous climatic studies from the Naradu and Rukti valleys within the same Baspa valley (Bhattacharyya et al., 2006; Chakraborty et al., 2006) show near temporal correlation for the YD event, also recorded in the present study, whereas the 8.2 ka event evident from the present study has not been reported from the previous two studies (Fig. 6). The study from the Naradu Glacier valley (Bhattacharyya et al., 2006), which is near Chitkul village, upstream to the Sangla town, covers the early Holocene time and has shown cool events around 12.7 ka and 10.1 ka based on the increase in the pollen of local steppe taxa. The 12.7 ka cool event could be correlated with the YD event also reported in the present study from ~13.3 to 11.5 ka. Whereas, the 10.1 ka dry event can said to be fairly corresponding with an intermittent weak ISM intensity between ca 10.3 and 9.8 ka by Rawat et al. (2012, 2015), coinciding with the bond event-7 discussed by Rawat et al. (2015). The earlier study from the Rukti valley (Chakraborty et al., 2006), upstream of the present study site location, though covers the entire Holocene time but with many breaks in the palynological records since early to late Holocene, thus restricting any correlation with the present study, except the early Holocene moist conditions found corresponding to the other studies. The recent study by Draganits et al. (2014a) also discussed about the general warm climate of the area since ~8 ka but based on reconnaissance samples from the lake deposits exposed at lower reaches near Sangla town. Also the presence of anthropogenic activities in the form of burning wood during mid to late Holocene (after ~5 ka) is evident by reported charcoal layers in the deposits near Sangla town (Draganits et al., 2014a), also supported by the reporting of charcoal in sediments between time frame of ~4.3 to 1.8 ka (uncal) from the upper reaches within Rukti valley by Chakraborty et al. (2006).

The results from the present study show a near synchronity for other regions also. The moist phase since around 16.6 to ~13.3 ka is synchronous with the Bolling-Ållerød Interstadial records from various Himalayan, Trans-Himalayan regions such as deglaciation in Kashmir valley at ca 15 ka BP (Singh and Agrawal, 1976); deglaciation of Batal glaciation stage during 15.5 to 12 ka in the Chandra valley (Owen et al., 2001) and depleted $d^{18}O$ record of stalagmites between 14 and 13 ka BP from Timta cave, Kumaun Himalaya (Sinha et al., 2005). Study by Demske et al. (2009) from Tsokar lake of Trans-Himalaya suggested the cold–dry phase between 15 and 14 ka followed by the climatic amelioration till ~12.5 ka with increased monsoon and reduced westerly winds. The later climate amelioration time frame covers some common period with our present study but the 15–14 ka cold-dry episode is not recorded, which might be due to low sample resolution in this study. The marine records from the Arabian sea showing this Interstadial Period between ~15 and 14.5 ka BP (Sirocko et al., 1993; Overpeck et al., 1996) also coincides with the present study.

A drier spell from ~13.3 till ~11.5 ka here shown by pollen record and slight increase in the MS values is correlated to the Younger Dryas (YD) episode, a widespread event with the weak summer monsoon and increased westerlies, recorded from many terrestrial and marine sites. In the Lahaul Himalaya this cold event is recorded between 12.8 and 11.5 cal ka BP (Alley, 2000) and recently by Rawat et al. (2015) indicating low precipitation condition in the Chandra valley from ~12.9 to 11.6 ka. The speleothem studies from few caves

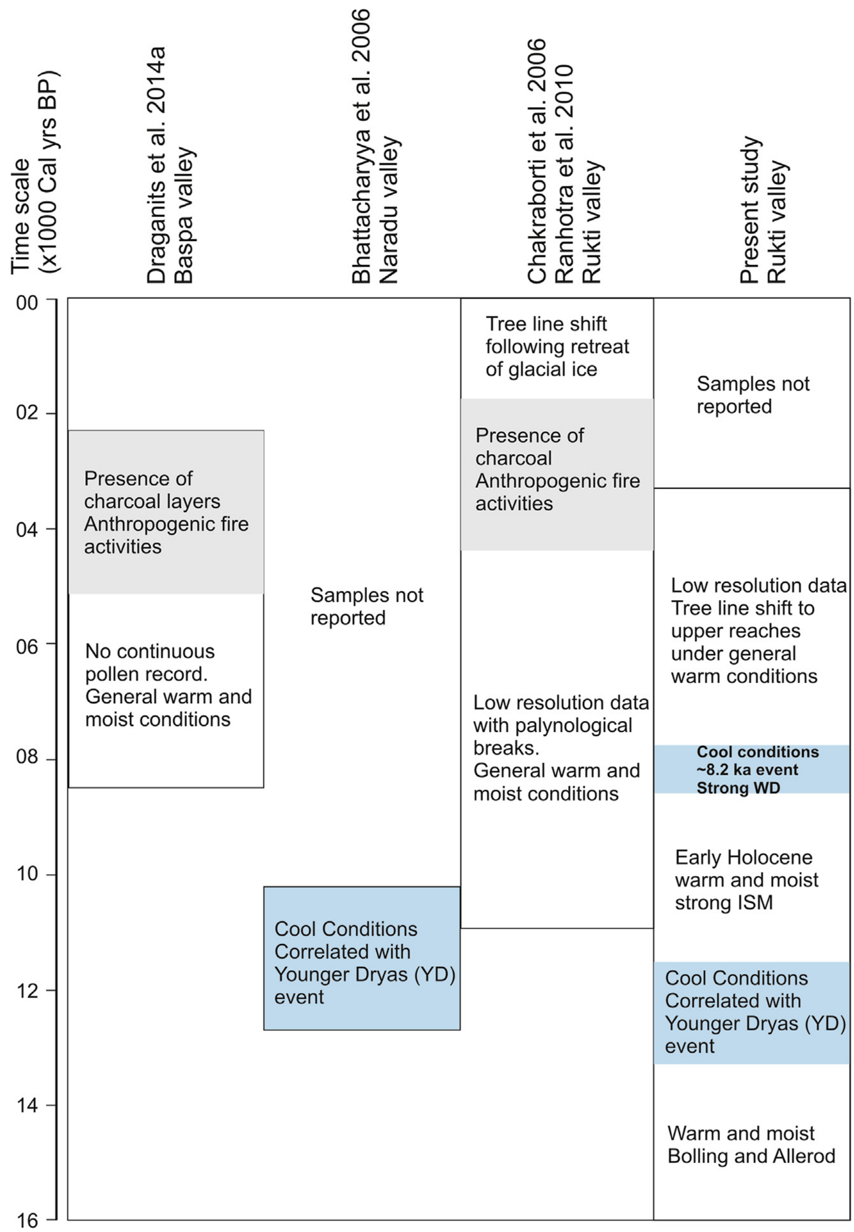

Fig. 6. Climatic correlation between the present and the previous studies from the Sangla valley.

viz. Timta cave, Kumaun, western Himalaya (Sinha et al., 2005), and other Asian monsoon dominated parts such as Dongge cave, south east China (Dykoski et al., 2005) and Hulu cave eastern China (Cheng et al., 2006) also records the decrease in the intensity of summer monsoon bracketed between 12.9 and 11.5 ka. The decrease of the summer monsoon during this YD period is also well reported from the Guliya ice core, China (Thompson et al., 1997). From the other Indian continental part, the YD comparative events showing reduced ISM are available from the lake sediment records of Garbyang Basin, Western Himalaya (Juyal et al., 2004); Naradu valley, Kinnaur Himalaya (Bhattacharyya et al., 2006); Dokriani valley, Garhwal Himalaya (Bhattacharyya et al., 2011); Ganga plain (Sharma et al., 2004); from marine cores of Arabian sea (Gupta et al., 2003) and Bay of Bengal (Chauhan and Suneethi, 2001; Chauhan et al., 2004; Rashid et al., 2011) and also in the studies from many other parts of Globe (Lamb, 1977; Birks and Birks, 1980; Bradley, 1999; Morrill et al., 2003).

Onset of the Holocene is well marked by the moist climate due to increased monsoon activity, evident by many studies from the Indian subcontinent. The higher water discharge with high influx of sediments of Ganges–Brahmaputra at that time supports strengthening of the monsoon (Goodbred et al., 2000). Similar evidences have also been reported from the lacustrine and marine sediments of other regions (Singh et al., 1974; Sirocko et al., 1993; Overpeck et al., 1996; Enzel et al., 1999; Prins and Postma, 2000; Chauhan and Suneethi, 2001; Morrill et al., 2003). From the same Baspa region the earlier study by Chakraborty et al. (2006) also suggest the relatively warm and moist conditions and lower tree line altitude (Ranhotra and Bhattacharyya, 2010) during early to mid Holocene i.e. since around 10.5 till ~4.5 uncal yrs BP, though the coarse and unproductive nature of few samples at various depths during this time frame could not resolve the climate at finer resolution. Amongst adjacent valleys of same orographic region, the Dokriani glacier valley within Bhagirathi valley of Garhwal

Himalaya Bhattacharyya et al. (2011) also revealed diversification of vegetation around 10.6 ka, following the YD phase, thus indicating the early Holocene climatic amelioration with high summer monsoon when glacier might have retreated resulting to vegetation diversification on the ice/snow free surfaces. The past hydrological study (Wünnemann et al., 2010) from the Tsokar lake of Indian Trans-Himalayan region reveals the summer monsoon moisture supply since ca 11.5 ka as evidenced by lake facies and aquatic fauna and flora. The lake reached its maximum level and extent between 8.5 and 7 ka under the moist climate, thereafter weakened monsoon and gradual shrinking of lake towards its lowest stand at about 4.2 ka. From the Tso-Moriri, Ladakh region a phase of maximum humidity was reached between ca. 11 and 9.6 ka, followed by a gradual decline in mean annual precipitation (Leipe et al., 2014). The Indus water discharge also reached maximum at ca. 9.4 ka as based on lowest $\delta^{18}O$ value (Staubwasser et al., 2002). From Tibetan region the warm-moist climate has also been recorded from Lake Bangong at the period around 9.6 to 6.2 ka based on $\delta^{13}C$ and $\delta^{18}O$ from the glacio-lacustrine sediments (Fontes et al., 1996). From the same Bangong basin based on pollen record, diatoms, detrital organic matter and other parameters maximum monsoon rainfall was recorded at time span i.e. around 9.5 to 8.7 ka and from around 7.2 to 6.3 ka, (Fan et al., 1996; Gasse et al., 1996). These moist conditions correspond to relatively high monsoon activity modelled by Prell and Kutzbach (1987) as well as high lake levels of Tso Kar in Ladakh (Wünnemann et al., 2010) when the monsoon front limit might have been further north than present. Earlier studies on foraminiferal $\delta^{18}O$ on marine sediment core (Sirocko et al., 1993); total organic carbon concentration (Schulz et al., 1998) and the terrigenous records of a gravity core supported by magnetic susceptibility and elemental concentrations (Thamban et al., 2007) from the Arabian Sea also suggest a peak of the ISM strength occurring during early Holocene ca. 10 ka. Records from lacustrine deposit of Thar Desert also show an increase in SW monsoon during 10 to 9.5 ka (Enzel et al., 1999).

A subsequent shift in the environmental conditions by the spike in the magnetic susceptibility data between time frame 8.7 to 7.8 ka in the present study can be related well with the 8.2 ka cool event reported globally. Alley and Agustsdottir (2005) discussing the cause and consequences pointed that this 8.2 k abrupt climate event brought a general cold and dry conditions to broad northern-hemisphere regions especially in wintertime. According to the references there in the study by Alley and Agustsdottir (2005), the Central Greenland ice-cores recorded the averaged cooling between 7 and 8 ^{O}C during the 8.2 k event; the parts of Europe also recorded the 1–0.7 ^{O}C cooling; in Africa the general dry event brackets the age interval of 8.5–7.8 ka, indicated by low lake levels and from Tibet (China) the records from Shumxi co, Xinjiang, Qinghai Lake, Dunde ice core reported the short lived dry interval around 8 ka. However, Morrill et al., in 2003 reviewed the event with no conclusive evidences for changes in the Asian monsoon during 8.2 ka. The recent compilation about the 8.2 ka climate event by Morrill et al. (2013) also suggested the cooling in the north Atlantic and Europe and decreased precipitation in the Asian monsoon region. However, the observations from few sites suggest strengthening of the Asian winter monsoon and also wet climate at some European sites (Morrill et al., 2013). Balascio et al. (2015) based on minerogenic study and other previous studies from Greenland describe the glacier advancement episodes at ~8.5 ka and ~8.2 ka, contemporaneous with the cooling event. Also the glacier advance in Swedish Lapland is probably correlative (Alley and Agustsdottir, 2005). From the South Asian region this major event indicating the cool and dry climate with reduced summer monsoon is evident from many geographical regions, viz, Riwasa (Tropics) in Haryana (Dixit et al., 2014); Chandra valley, Himachal Himalaya (Rawat et al., 2015). From Tso kar, Ladakh Demske et al. (2009) pointed the weaker ISM precipitation but high winter Westerly flow during this period. A view on the reconstructed glacial stages from various valleys of the western Himalayan region also nearly coincides with the major climatic cool events including the glacial stage ~8 ka in the Tons valley and Kedar stage (~8–7 ka) in the Gangotri valley (Scherler et al., 2010) that could be related to the enhanced winter precipitation. In the present study also the evidence of high lake level by the presence of *Potamogeton* could be due to enhanced winter westerly precipitation with prolonged cool months thus lowering the evaporation. The increase in MS values could be due to more erosion of the surface by the melting of snow at higher reaches.

The mid to late Holocene climatic phases in the present study cannot be distinctly explained due to low sampling resolution. However, there is a gradual vegetation succession to the higher altitudes that might be due to the glacial recession under general warm conditions. The intermittent dry phases during mid to late Holocene has also been recorded in the Himalaya (Bhattacharyya et al., 2006) and in many other parts of Southeast Asia (Morrill et al., 2003). A significant weak monsoon period is recorded between 6 and 5.5 ka from East Arabian sea (Thamban et al., 2007) and southwest coast of India, (Sarkar et al., 2000; Thamban et al., 2001). However the dry phase might have been preceded by the increased ISM as recorded from ~7.8 to 5 ka within the Dokriani valley (Phadtare, 2000) followed by the weakening of the monsoon. The maximum lake levels also reported in the Thar Desert during 7.2 to 5.6 ka (Enzel et al., 1999; Singh et al., 1974, 1990). Prasad and Enzel (2006) also compiled the relatively high lake levels around 7.2 to 6 ka from Indian regions with subsequent wet events possibly due to increased winter rainfall. In the Quinghai-Xizang Plateau, interval ~7.5 to 3 ka was also warm and moist with intervening dry episode from ~5.5 to 4.7 ka (Wang and Fan, 1987). Cooling recorded around 3.1 ka in the Quinghai-Xizang Plateau may correspond to the beginning of cooling of the Northern Hemisphere, which peaked around 2.5 ka (650–280 BCE) (Klimenko, 2004). This phase could not be recognized in the present study due to non-availability of sediments covering this period or constrain of date as sample had wide depth interval range of mainly 10 cm.

8. Conclusions

The various proxies analyzed in the present study from the Rukti valley, along with the analysis of previous available studies within the Baspa valley has put forth the signatures of vegetation change vis-à-vis climatic events during late Pleistocene - early Holocene. This study has opened an insight and the necessity to unravel the major but short lived late Pleistocene to Holocene climatic events from the Indian Himalayan and Trans-Himalayan regions in order to better understand the intensity and influence of such climatic events to relate it with the global scenario. The studied section of exposed laminate deposits of the Sangla palaeolake, Himachal Pradesh with chronological setup using the radiocarbon dates could suggest the origin of this palaeolake even older than ~16 ka, as the sediments are collected from the small exposed section by the cutting of Rukti river. According to the radiocarbon dates the section covers the time period since prior to Holocene (~16.6 ka) till early part of late Holocene (~3.5 ka). The absence of the late Holocene to recent part might either be due to the non exposure of the late Holocene part or due to absence of contemporaneous deposits by the desiccation of the lake during late Holocene. The later reason could be more valid as Draganits et al. (2014a) also discussed the desiccation of lake around 2 ka. Here we recorded that some climatic events have linkage with the contemporaneous globally known events. Prior to Holocene till late Holocene (~16.6–3.5 ka) the site was mainly occupied by the broadleaved Oak-Conifer forest with fluctuation of taxa under variable precipitation/temperature regime. The moist phase around 16.6 to ~13.3 ka as shown by the palynological data and low MS values, relates with the Bolling-Ållerød Interstadial records. This was followed by the cool episode of YD between ~13.3 and 11.5 ka from the present study and ~12.7 ka from the Naradu valley at upper reaches. A short 10.1 ka cool-dry event also reported from the Naradu valley has been correlated with the Bond event-7 as reported and discussed from Chandra valley by Rawat et al. (2015). However, this event has not been reported from the present and previous other studies. The intermittent early Holocene cool event between 8.7 and 7.8 ka is well reported by the spike in the MS values in the present study that might be due to the high erosion from the upper reaches. This event correlates with the 8.2 ka global event. But the pollen evidence of the high lake level could be attributed to the strong westerly affect. The wet winters are also discussed by the high lake levels from Tso kar, Ladakh and few sites from European region that might be due to low evaporation under cool conditions. The absence of the signals for the one or the other intermittent but globally known climatic events from different sites can be explain by the sensitivity of the various proxies to capture such event or also due to the temporal resolution of the studied samples linked with the age constrains.

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