Quaternary Science Reviews 101 (2014) 111–123

Contents lists available at ScienceDirect

Quaternary Science Reviews

journal homepage: www.elsevier.com/locate/quascirev

Analysis of vegetation and climate change during Late Pleistocene from Ziro Valley, Arunachal Pradesh, Eastern Himalaya region

Amalava Bhattacharyya [a], Nivedita Mehrotra [a, *], Santosh K. Shah [a], Nathani Basavaiah [b], Vandana Chaudhary [c], Indra Bir Singh [d]

[a] *Birbal Sahni Institute of Palaeobotany, Lucknow, Uttar Pradesh, India*
[b] *Indian Institute of Geomagnetism, Navi Mumbai, Maharashtra, India*
[c] *Ministry of Earth Sciences, Prithivi Bhawan, New Delhi, India*
[d] *Centre of Advanced Studies in Geology, Lucknow University, Lucknow, Uttar Pradesh, India*

A R T I C L E I N F O

Article history:
Received 21 March 2014
Received in revised form
1 July 2014
Accepted 2 July 2014
Available online

Keywords:
Late Quaternary
Pollen
Isotope
Magnetic susceptibility
MIS-3
LGM

A B S T R A C T

Vegetation and climate during later part of Late Pleistocene have been reconstructed from Ziro valley, Arunachal Pradesh, Eastern Himalaya based on pollen data along with carbon isotope and magnetic susceptibility data The study reveals that the area and the vicinity is occupied by mixed broad leaved – conifer forest and pine grass savanah at variable densities at least since 66,000yr BP. The phases of expansions and declines of Oaks with decline and increase of Pines and grasses probably occurred under increase (warm–moist) and decrease (cool–dry) of S.W. monsoon precipitation respectively. The increasing trend of S.W. monsoon and temperature is recorded during ~44,000 to 34,000 cal yr BP synchronizing with the peat development, and which peaked at around 35,000 cal yr BP. This may link to the interstadial phase during the last major glacial cycle in the Himalayan region. It is also reflected in the decline of δ^{13}C value indicating dominance of C-3 type of vegetation. The increased values of χFD%, and lower values χLF magnetic susceptibility, recorded during the phase of the peat deposit, further advocate's higher monsoon intensity. Impact of expansion of glacier felt with peak (LGM) around 20,000 cal yr BP is perceived. Tree line had moved to lower altitudes due to increased aridity and low temperature. During this time existence of savannah type of vegetation is also evident by the increase of C4 taxa. Decreased FD% and increased χLF susceptibility also indicate reduced S.W. monsoon intensity.

1. Introduction

Analysis of climate of the Himalaya is important not only in understanding the monsoon dynamics of the Indian subcontinent (Prell and Kutzbach, 1992; Li and Yanai, 1996; Boos and Kuang, 2010, 2013) but also for the whole Southeast Asia, and to know its tele–connection with other global climate systems (Bhattacharyya, 1989; Gupta et al., 2003, 2005; Cane, 2010; Molnar et al., 2010). In the Himalaya itself a great variability in climate exists from one region to other (Mani, 1981; Kumar and Pant, 1997). The eastern part is under the extreme influence of South–West Monsoon, due to closeness to the Bay Bengal and as a result climate in eastern part is considerably more humid than in the western part. Thus, it is crucial to understand cause, timing and spatial extent of millennial scale climate events of this region for understanding the tele–connections among various climate systems. Analysis of various proxy records (viz. pollen, tree rings, lake and marine sediments etc) are indispensable to retrieve long–term paleoclimate data (Bradley, 1999). It has been recorded that pollen and carbon isotope as proxy data have broader perspective towards climatic reconstruction through analysis of vegetation change. In addition magnetic susceptibility data in sediments also provide clue for the climatic change. The records of Quaternary palaeoclimate vis–à–vis palaeo–vegetation analysis based on varied proxy data are sparse from the Eastern Himalaya (Chauhan and Sharma, 1996; Bhattacharyya et al., 2007). However, such records are available in good numbers from the Western Himalaya (Krishnamurthy and DeNiro, 1982; Bhattacharyya, 1983, 1988, 1989; Dodia et al., 1985; Kotlia et al., 2000, 2010). On the contrary from the Eastern Himalaya (except one viz., from Jore–Pokhari, Darjeeling (Chauhan and Sharma, 1996), the climate records are mainly from early Holocene (Sharma and Chauhan, 2001; Bhattacharyya

* Corresponding author.
E-mail address: nivedita_mehrotra23@hotmail.com (N. Mehrotra).

http://dx.doi.org/10.1016/j.quascirev.2014.07.008
0277-3791/

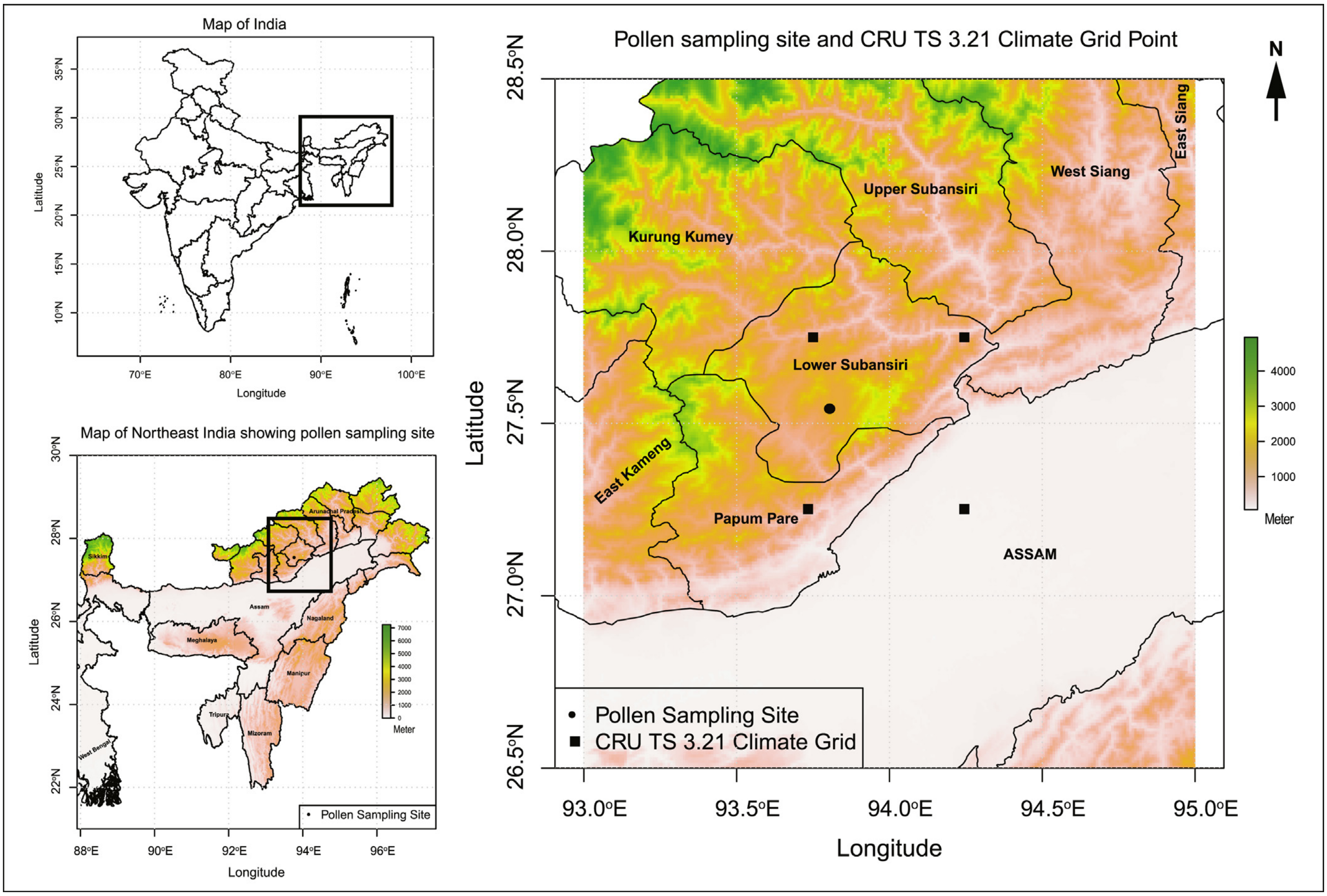

Fig. 1. Site Map showing location of sampling site in Ziro Valley, Arunachal Pradesh, NE India and nearest climate grid points used to represent modern regional climate.

et al., 2007). Even paleoclimatic scenario from the low elevation sites of north east part of India beyond Holocene are scarce (Bhattacharyya et al., 2011; Mehrotra et al., 2014).

This study attempts to reconstruct the changes in vegetation vis–-à–-vis climate during the Late Quaternary period based on palynological analysis supplemented with environmental geomagnetic and isotopic studies from subsurface sediments from the Ziro valley, Lower Subansari District in the state of Arunachal Pradesh, Eastern Himalaya.

2. Temporal record of Himalayan past vegetation and climate change

Paleoenvironmental studies commenced since the early part of 20th century with pioneering work from Western Himalaya (Wodehouse and De Terra, 1935; Deevey, 1937). Subsequent work, except for a few (Bhattacharyya, 1989; Kotlia et al., 2000, 2010) mostly was concerned vegetational changes vis–à–vis climate covering Holocene time (Bhattacharyya, 1988; Ranhotra et al., 2001; Bhattacharyya et al., 2006 and others). Some of the longest records of climate change from this region are from the Tsokar lake (4572 m amsl) in Ladakh, based on pollen analysis of 23 m core of about 30,000 yr BP–9000 yr BP, revealed phases of increase in *Junperus* communities in the continued alpine steppe vegetation cover. Four phases at 28,000 yr BP–30,000 yr BP, 21,000 yr BP–18,375 yr BP, before 15,800 yr BP and 10,000 yr BP were considered as climate amelioration events during the last glaciations in the Trans– Himalayan region (Bhattacharyya, 1989). Later from the same lake, Demske et al. (2009) reported Lateglacial and Holocene vegetation covering time span since 15.2 BP. Ranhotra et al. (2007) studied a palaeolake profile in the semi arid climate of Lamayuru, Ladakh, and provide a broad idea of temporal succession of vegetation vis–à–vis climatic changes during major part of the Last Glacial period. Paleoclimate record from Bhimtal–Naukuchiatal Lake basin in south–central Kumaun in western Himalaya indicated at least two phases of arid climate and one phase of humid climate in Late Pleistocene–Holocene period (Kotlia et al., 1997). Palynological records from another sediment profile from Wadda Lake in western Himalaya preserve three temperate humid and two arid climate phases during 36,000–10,000 yr BP (Kotlia et al., 2000). In the eastern Himalaya, longest pollen record is from the Mirik lake, Darjeeling which extends up to about 20,000 yr BP (Sharma and Chauhan, 1994). Vegetation vis–-à–-vis climate of Late Holocene (since 1800 yr BP) was made based on pollen and carbon isotope from a sediment profile in Paradise Lake near Sela Pass, Arunachal Pradesh (Bhattacharyya et al., 2009). This review of palynological analysis shows that except some stray reports, a detailed palaeoclimate records covering even major part of the Last Glacial period from the diversified geographical regions of the Himalaya especially from its eastern part are yet to come.

3. Ziro valley, Arunachal Pradesh, Eastern Himalaya

3.1. Physiognomy, modern environment

Arunachal Pradesh, is a state in the northeastern extremities of the Eastern Himalaya extending from the southern ends of snow covered Tibet to the plains on of Brahmaputra valley, Bhutan on the western edge and Myanmar near its eastern borders (Fig. 1). The undulating topography with altitudes ranging from 100 m to 7000 m increases from south to north (Baishya et al., 2002). The Himalayan Mountain ranges influence and contributes to the climatic pattern of this region. The state receives a huge share of the monsoon winds rising from the Bay of Bengal. The variable weather conditions and topography are clearly accountable for the distribution of the wide range of vegetation extending from Alpine to Sub Tropical forests. For this study we have selected Ziro valley (Fig. 1) which is an elongated sediment filled topographic low (93°49′ E–93°51E: 27°32′N–27°37′N) nestled within high hills of Lower Himalaya in Arunachal Pradesh. The N–S extent of the valley is about 8 km while E–W spread being 3–4 Km. The Kale river, flowing longitudinally, forms the trunk drainage of the valley and tributaries joining it from east and west. The valley itself is having a very gentle gradient towards south with an average elevation of 1570–1580 m amsl. The surrounding hill ranges have variable elevations between1700–1800 m amsl. Quaternary sediments are underlain by Upper Siwalik group of sediments of the Kimin Formation of Mio–Pliocene age comprised of sandstone, claystone, shale, pebbly deposits and boulder beds made of quartzite, gneiss, granite, schist etc (Kesari, 2010). The Main Frontal Fault marks the boundary of post–-Siwalik Quaternary sediments that are mainly fluvial deposits are identified into Older Alluvium (Middle to Upper Pleistocene) and Newer Alluvium of Holocene to Recent age (Laskar, 1949; Banerjee, 1973; Kesari, 2010.

3.1.1. Modern climate

Meteorological data close to study site were available from the meteorological station located at Ziro town. However no data is available for the year 1963–1968 and 1977 and more than six months data of the years 1901, 1962, 1971 and 1975 are missing (Shah and Bhattacharyya, 2012). To attain a lucid understanding of the modern climate in the region the authors selected CRU-TS 3.21 climate data (Harris et al., 2014). This data set extends from the year 1901–2012 and is an interpolation of 5 degrees of latitude-longitude climate data. Four grid points (Fig. 1) around the present sampling site were selected for calculation of regional mean temperature and precipitation. The resulting mean temperature showed that the highest and lowest mean temperatures were 25.5 °C and 13.4 °C during the month of July and January respectively. The precipitation data indicated that the months of May–September were the monsoon months where July (395.3 mm) and December (12.1 mm) had the highest and lowest average precipitation records. According to the Walter and Leith Climate diagram (Walter and Lieth, 1967) based on CRU TS 3.21 climate records the average maximum and average minimum temperature of the warmest and the coldest month of the region were 29.4 °C and 6.8 °C respectively and total annual precipitation is 1942 mm during the years 1901–2012 (Fig. 2). This climate diagram represents a tropical summer rain type curve according the Walter and Lieth (1967) thus indicating that the modern climate in the region is closer to tropical warm and humid conditions.

3.1.2. Modern vegetation

A great diversity in the flora of Arunachal Pradesh is mainly due to its varying topography climate and phytogeographical position. It comprises a rich amalgamation of Chinese, Malaysian and western Himalayan elements (Sahni, 1969). Based on vegetation type and their altitudinal distribution flora of this region has been divided in to Tropical, Subtropical, Pine Forests, Temperate, Alpine and Secondary forests (Malhotra, 1983; Chowdhery, 1996; Baishya et al., 2002). The Tropical vegetation comprises Evergreen and Tropical Semi–evergreen elements;

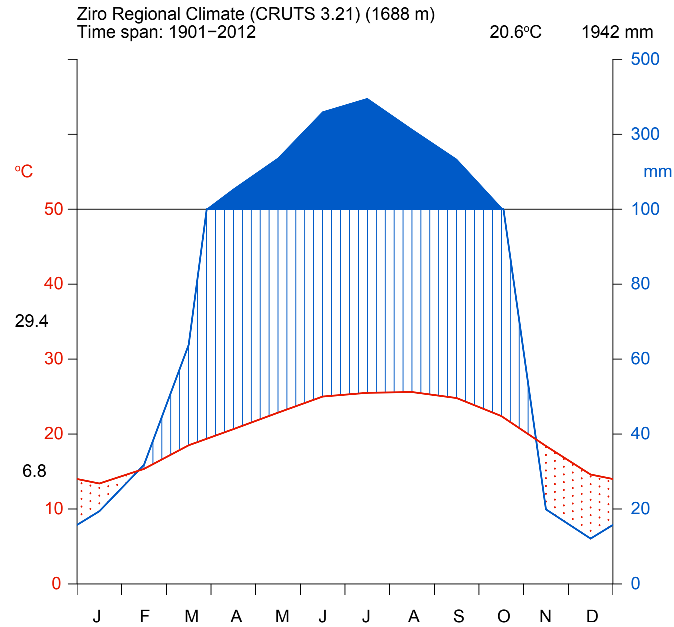

Fig. 2. Climate diagram of regional climate data based on CRU TS 3.21 climate records. Blue line represents precipitation curve and red line represent temperature. The diagram shows mean maximum temperature (29.4 °C) of the warmest month, mean minimum temperature (6.8 °C) of the coldest month. Upper right corner of the diagram is showing annual average of temperature and annual total precipitation. Climate diagram is based on Walter and Lieth (1967). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

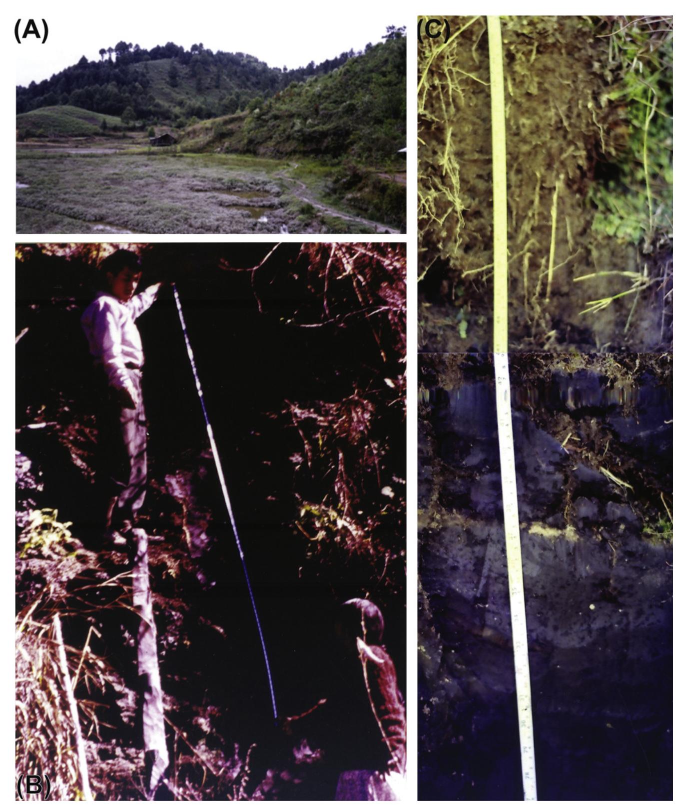

Fig. 3. A) Image of the sampling site in Ziro valley Arunachal Pradesh. B) Image of the exposed surface from where sediment profile was collected. C) Image of the top part of the sediment profile section having excessive grasses, fern and mosses cover near upper surface and vertical wall.

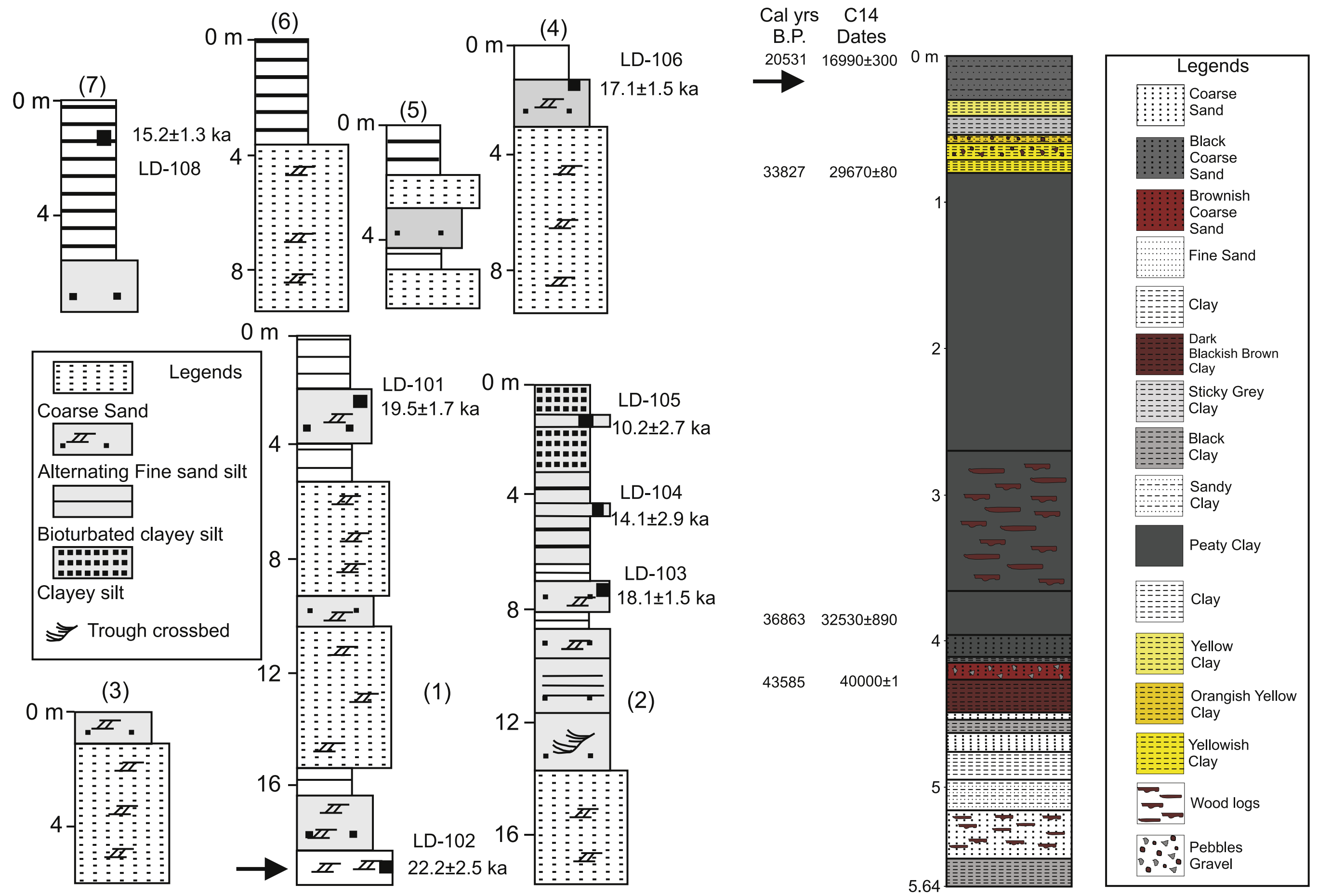

Fig. 4. Lithology of the sediment profiles from Ziro valley as in Srivastava et al. (2009) modified and compared with the lithology of the present sediment profile (shown in color) from Ziro valley Arunachal Pradesh. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

latter has been subdivided in to Low hill & Plains Semi evergreen and Riverine Semi–evergreen type. The Temperate vegetation includes both Broad leaved and Coniferous forest. The secondary forests were also classified as Degraded forests, Bamboo forests and Grasslands. Ziro valleys under Subansiri District of this region have given importance for its rich biodiversity. The vegetation in and around this site has been enumerated by several workers (Sahni, 1969; Malhotra, 1983; Behera et al., 2002; Dollo et al., 2009) who suggested that the modern vegetation comprised of a rich amalgamation of both temperate and tropical plant taxa. Malhotra (1983) provides a detailed vegetational scenario of Subansari district covering altitudes ranging of 900–4400 m amsl. This region encompasses Tropical Evergreen forests, Sub–tropical Savannah lands, Sub–tropical forests, Temperate forests and Sub–alpine vegetation.

4. Materials and methods

4.1. Lithology and collection of samples

For the present study subsurface sediments were collected from a sediment profile along the crest of mount slope at Ziro. We cleared the exposed upper surface and vertical wall which are clothed by grasses, fern and mosses (Fig. 3 A, B) and 45 samples were collected. The profile (Fig. 3C) is of 5.64 m depth and we could not go further deep due to oozing of water. The lithology of the section (Fig 4) given in details in Table 1.

4.2. Radiocarbon dates

Sediments of the profile have been dated at the Radiocarbon laboratory, Birbal Sahni Institute of Paleobotany, Lucknow. These date at the depth of 30 cm is 16,990 ± 300 (Ziro –3 BS–2389), at 80 cm (Ziro–7 BS1922) is 29,670 ± 80, at the depth of 3.8 m (Ziro30) is 32,530 ± 890; at the depth of 4.30 m (Ziro –34 BS2390) is 40,000 ± 1 and at the depth of 5.50 m (Ziro–45 BS–1927) is 30,750 ± 660 (Table 2). Rate of sedimentation for this whole exposed section could not be calculated due to heterogeneous nature of sediments and insufficient number of ^{14}C dates. Suitable dating materials in the upper part of the section, was not available where as the lower part is beyond the range of conventional C14 dating. The date at the bottom most of the section seems to be erroneous due to contamination.

4.3. Pollen analysis

For palynological analysis sediments were macerated using the standard procedure of acetolysis. Minimum 300 pollen grains per sample were counted which is taken as 'Total Pollen Count' which includes pollen of arboreal and non arboreal taxa along with fern spore. In pollen sum we excluded fern, algal and fungus spores. Pollen percentage diagrams were constructed using the TILIA version. 2.0.2 (Grimm, 2004). Pollen of extra local elements which are not growing at the site of investigation, viz. *Abies*, *Alnus*, *Carpinus*, *Corylus*, *Juglans*, *Larix*, *Picea*, *Pinus*, *Quercus*, *Rhododendron*

Table 1
Detailed lithology of the sediment profile from Ziro Valley, Arunachal Pradesh.

Sample number(s)	Depth range (cms)	Lithology
1–2	0–30	Black sandy clay
3	30–41	Sticky yellow colored clay
4	41–54	Light grayish clay
5	54–60	Orange yellowish grit (sand, gravel and clay)
6	60–71	Yellow clay mixed with gravel and pebbles
7	71–79.5	Yellowish clay
8–30	79.5–396	Dark black peaty clay (270–366 cm good no of wood logs are visible)
31	396–411	Coarse black sand
32	411–415	Black clay band
33	415–427	Coarse sand gravel brownish
34–37	427–449	Dark blackish brown clay in which last 9 cm is less black
38	449–454	Coarse sand
39	454–463	Sticky clay less black in colour In between a small 2 cm fine sandy layer
40	463–476	Coarse sand
41–42	476–495	Clay, in last 10 cm very dark in color
43	495–516	Sandy clay layer
44	516–549	Coarse sand with wood logs
45	549–564	Sticky clay

and Tsuga are also included in the "Pollen sum". These taxa are growing at comparatively higher elevations at temperate and upper level of sub–alpine Fir forest. These pollen grains have been carried at the site by wind and water and get deposited there. Since mountain slopes are at steep gradient, the provenance of these trees are not far from the sampling site .The variation in percentage of these taxa in diagram is due to the shifting of forest belt and expansion of taxa which is much controlled by climate though role of wind direction and speed could not be ruled out for their preferential deposition. To make the pollen diagram more realistic some of the pollen taxa, which are represented by very low quantities (lower than 0.5%) throughout the profile are shown by "+" sign in the pollen diagram. For the interpretation of fossil pollen spectra, the pollen diagram has been divided in to pollen zones. These zones are made by CONISS multivariate method using square root transferred data (Grimm, 1987). These pollen zones are prefixed with the abbreviations after the name of Blue Pine Lodge, a lodge located close to the sampling site.

4.3.1. Quercus Pinus index

An index was calculated to assess the relationship of the most dominating taxa viz., *Pinus*, *Quercus* and Poaceae in the pollen diagram as they were considered as a key taxa for the vegetation dynamics in and around Ziro valley. *Pinus*, *Quercus* are presently found at higher elevated sites of Arunachal Pradesh and also around Ziro valley and Poaceae is found in the Savannah type of mixed vegetation at the proximities of the forest belt. To understand the variation in the extent of the tree element of both conifer and broad leaved taxa and the domination of grasses in a mixed savannah type of vegetation we followed the approach by Mensing et al. (2012) and developed the Index based on the formula $[(P + Q) - Po]/[(P + Q) + Po] + Po$ where P is percent *Pinus*, Q is percent *Quercus*, Po is percent Poaceae. Values approaching 1 represent high levels of *Pinus* and *Quercus* good development of conifer broad leaved taxa, while values approaching -1 represents abundant grasses, expansion of the savannah.

Table 2
^{14}C Dates of five samples at different depths within the sediment profile BPL from Ziro Valley Arunachal Pradesh generated at ^{14}C Laboratory at Birbal Sahni Institute of Palaeobotany, Lucknow India. (B.S. Number being the laboratory code given to each sample submitted).

Sample number	Depth range (cm)	B.S. number	^{14}C dates (yr BP)
1	30	Ziro –3- BS-2389	16,990 ± 300,
2	~ at 80 cm	Ziro-7- BS1922	29,670 ± 80
3	~3.8 m	Ziro30- BS-1831	32,530 ± 890
4	~4.30 m	Ziro 34- BS-2390	40,000 ± 1
5	5.50 m	Ziro 45- BS-2663	30,750 ± 660

4.4. Environmental geomagnetism

Environmental geomagnetism based analysis consider that the magnetic properties of magnetic mineral that occur naturally within sediments, the surrounding environmental conditions and geomorphic process determine their magnetic mineralogy (Verosob and Roberts, 1995; Pant et al., 2005). The measure of concentration of magnetic particles are estimated through parameters namely magnetic susceptibility (χ) and isothermal remnant magnetization (IRM) where as the extent of ultra–fine super paramagnetic and ferromagnetic particles are estimated through the coefficient of concentration of frequency dependent susceptibility (χ_{fd}) (Verosob and Roberts, 1995; Pant et al., 2005). Magnetic mineralogy from the subsurface sediments from fluvial environments have been recognized a potential climatic proxy record. It is proven now that several of its parameters such as susceptibility (χ) and frequency dependant (χ_{fd}) and isothermal remanence ratio (S) are dependent on the intensity of weathering of rocks along the fluvial environment. Susceptibility is mainly a measure of the concentration of ferromagnetic minerals and S ratio is diagnostic of the abundance of magnetite in the expense of hematite. Thus variation in these parameters would provide information regarding weathering that lead to incorporation of ferromagnetic minerals, which would indirectly provide information regarding climate and precipitation which has a great role in weathering. Environmental geomagnetism analysis of the sediment samples used in this study was conducted using standard techniques and instrumentation at the Environmental Geomagnetism Laboratory at Indian Institute of Geomagnetism, Navi Mumbai, India.

4.5. Isotopic analysis

Carbon isotopic study is made to examine variations of $\delta^{13}C$ values towards the understanding of C-3, C-4 plants productivity from the corresponding sediments analyzed for pollen and magnetic susceptibility. This provides logical inference to pollen based vegetational vis–à–vis climate reconstruction. Earlier studies have established that the lower values of $\delta^{13}C$ indicate dominance of C-3 plants which prefer cool– moist climate whereas higher $\delta^{13}C$ values specify C-4 plants confine under drier climate (Galy et al., 2008; Sarkar et al., 2009; Agrawal et al., 2012; 2013). For carbon isotope analysis of total organic carbon, sediment samples were treated with 1N HCl in order to dissolve any carbonate. When visible reaction ceased, the residues were washed several times with distilled water. The residues were dried at 50 °C and homogenized. The carbon isotopic composition was measured by combusting the samples in a Carlo–Erba element analyzer connected to a Thermo Finnigan Delta plus mass spectrometer. All isotopic values are reported in the standard d–notation in per–mil relative to V–PDB.

5. Results:

5.1. Chronology

There are several geomorphological reconnaissance of Subansari District of Arunachal Pradesh which indicate that lacustrine deposits of this region are analogous to the Karewa sediments of Kashmir (Banerjee, 1973; Acharyya, 2005). The thick sediment deposit is mostly of fluvial origin and classify in to older alluvium (middle to upper Pleistocene) and new alluvium (Holocene to Recent age). But regarding the absolute age of the sediments, except sporadic information (Srivastava et al., 2009) much of the Quaternary sediments of this region remain yet to be dated. We have dated exposed 5. 56 m sediment profile that cover a time span from about 66,000 cal yr BP to around 11,000 cal yr BP. In this section the 3m peat layer chronologically cover time span from 35,407 cal yr BP to 33,918 cal yr BP (32,530–29,771 ^{14}C) (Fig. 4) It corresponds to the Marine Isotope Stage 3 (MIS 3). This layer is underlying an oxidized yellowish sediment unit which is dated from 33,827 cal yr BP to 11,165 cal yr BP (29,670–8058 ^{14}C). In an another study several sections at the range of more or less 5 m–20 m depth from the Ziro lake valley are dated through IRSL dating which cover time ranges from 22,000 to 5000 yr BP (Srivastava et al., 2009). Based on sedimentology it is concluded that in Ziro Lake basin, the fluvial aggradations took place between 22 and 0 Ka with seismic activity and faulting during 21ka yr BP .This indicated that major sedimentation took place in the Ziro valley during the Last Glaciation followed by strong monsoon activity in the valley (Srivastava et al., 2009). A shallow profile 3.4m Soro Nala, Ziro Lake Basin, Arunachal Pradesh having two ^{14}C dates viz. 1370 ± 71 B.P. (at 20 cm) and 3540 ± 150 B.P. (60 cms) and the other dates extrapolated merely by broad matching of sediments with IRSL dates of other profiles (LD–101 and LD–105 dated as 19.5 ± 1.7 and 10.2 ± 2.7 ka respectively) given by Srivastava et al. (2009), and provided the vegetation history since LGM to recent period (Ghosh et al., 2014). Chronologically the upper oxidized layer in our section represents the bottom layer of their sections (Fig. 4). Thus, the section we have analyzed represent the lower part of their sections and extends the records back to nearly 66,000 cal yr BP based on extrapolated ^{14}C dates (Fig. 4).

5.1.1. Age model

Age–depth models were prepared using OxCal ver. 4.1.7 (Ramsey, 2009) (Fig 5). For which we used IntCal09 calibration curve (Reimer et al., 2009) and the P_Sequence depositional model with the k–value set to 0.5 (Ramsey, 1995, 2001, 2008, 2009; Reimer et al., 2009). The outliers have been designated as such within the program. Calendar year BP (cal BP) is used to indicate calibrated ^{14}C years (Fig. 6). The curve generated by Ox Cal k = 0.5 confidence limit appear to be acceptable but it included sharp slope changes, that is, abrupt changes in sedimentation rates in lower part and the upper part (Fig. 6).

5.2. Palynological analysis

5.2.1. Description of the pollen diagram

For the convenience of the interpretation, the pollen diagram has been divided in to five pollen Zones (Fig. 7) based on variation of percentages of major pollen taxa and is numbered BPL–I to BPL–V from bottom to top of the profile and described below.

Zone BPL I–Pine–*Tsuga*–Juglandaceae–Oak–Poaceae : This zone extends from 556.50 cm to 375.36 cm covering time span 65,977 to 36,294 cal yr BP (63,303–32405 ^{14}C). This zone is subdivided in to BPL I(a) (65,977 cal yr BP to 43,585 cal yr BP) and BPL I(b) (42,039 cal yr BP to 36,294 cal yr BP). In zone BPL I (a) among temperate forest elements, except *Tsuga* (0.77–14.29%) and *Pinus* (7.56–*56.58%*) other conifers viz., *Juniperus*, *Abies*, *Larix*, and *Picea* are represented by almost less than 1%. In the broad leaved taxa, except Juglandaceae (1–16%), *Quercus* (1–24%) and *Betula* (0.4–7%)); the other taxa viz., *Alnus* (0.1–5%) *Rhododendron* (<1%),

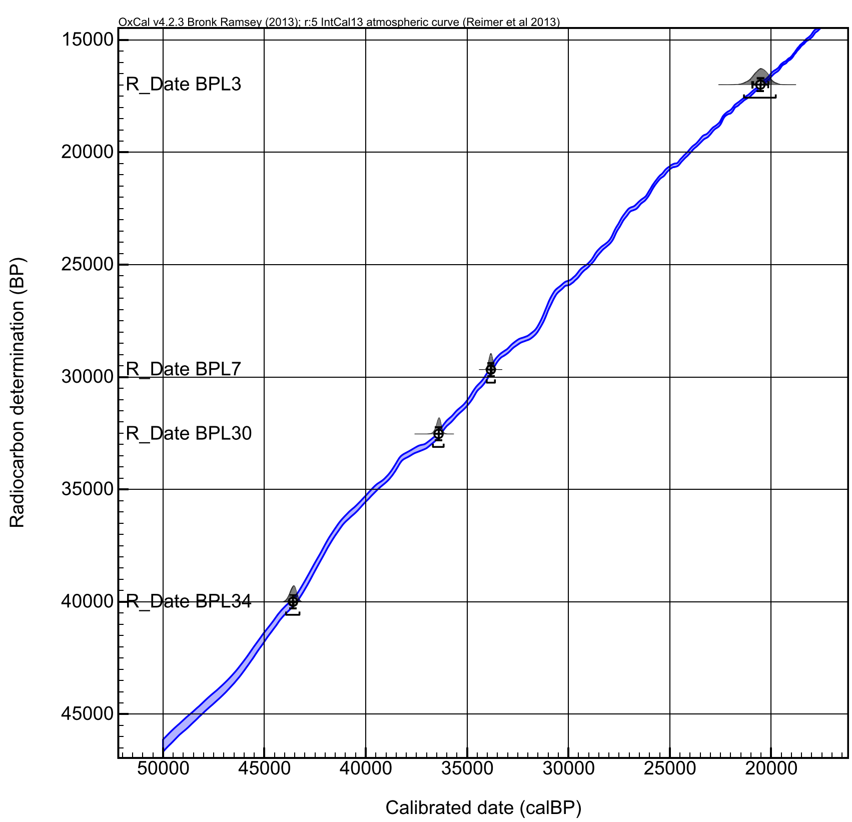

Fig. 5. Calibrated Age curve viz,. IntCal 13 atmospheric curve Reimer et al., 2013.

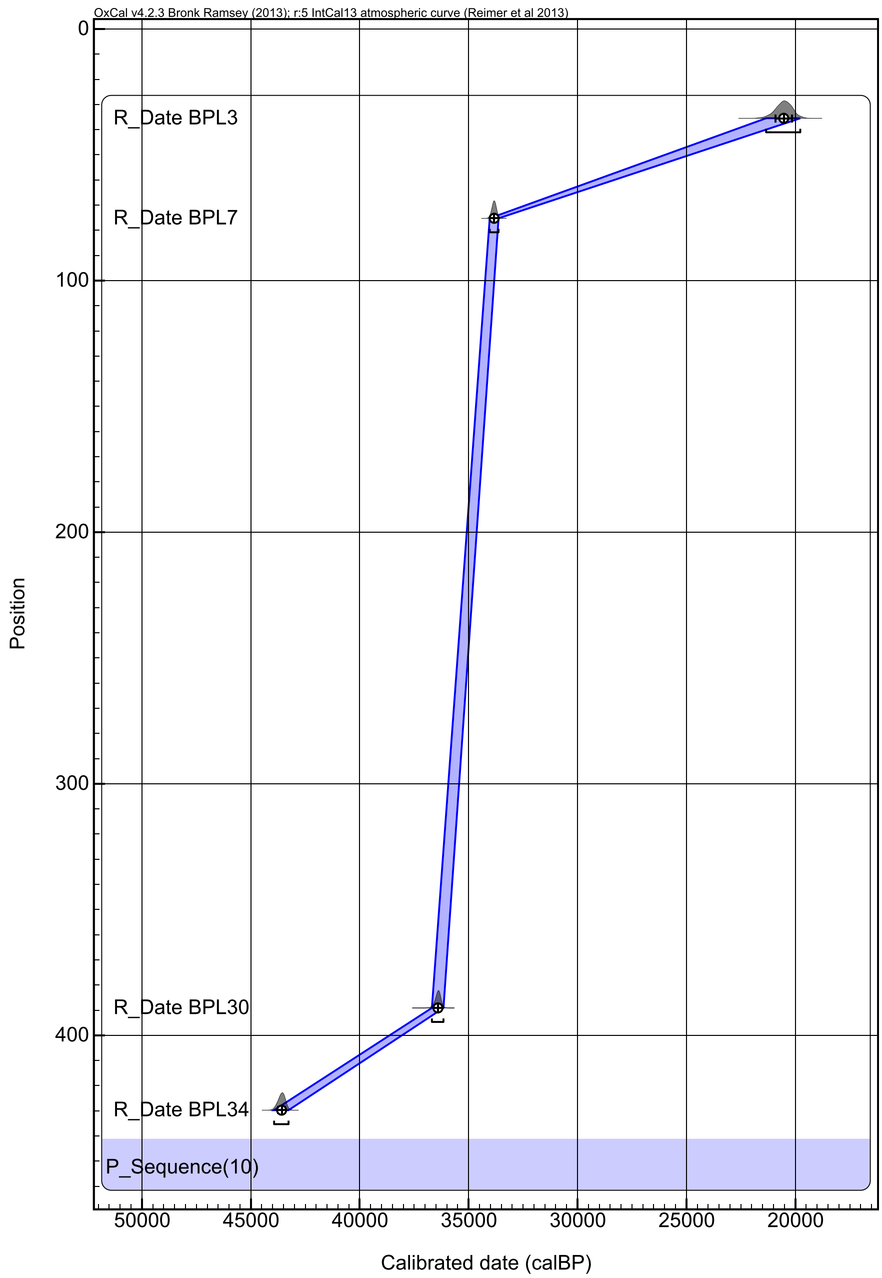

Fig. 6. Age–depth model of sediment profile from Ziro Valley.

Corylus (0.4–7%), *Acer* (<1%), *Salix* (<1%) etc. are not much represented. The elements of sub-tropical and tropical belt are represented by Tiliaceae (<2%) along with 1% each of Elaeocarpaceae, Oleaceae, *Aesculus*, Lytheraceae etc. Elements of Savanah taxa, except Poaceae (<40µ size 14–63% and >40µ size 0.99–10.53%), Caryophyllaceae (1–4%), Asteraceae (Liguliflorae <1%, Tubiliflorae <5%), Malvaceae (<2%), *Arecaceae* (<3%); other taxa represented by low values. The aquatic or marshy taxa present in this zone are represented by Cyperaceae (<2%), *Impatiens* (<3%), *Potamogeton* (2–44%), *Eriocaulon* (<1%). Apart from these taxa, pteridophytic spores are exhibited by fern (Monolete 8–19%, Trilete 1–27%) and Lycopodium (<2%).

Pollen zone BPL I(b) around 42,039–36249 cal yr BP (38,391–32405 ^{14}C) exhibits a significant increase in broad leaved taxa of temperate and subalpine belts such as *Quercus*, *Betula*, *Rhododendron*, etc,. The Poaceae (<40µ 5–41%, and >40µ 2–8%) has also increased. Similar increase is also in the aquatic taxa, *Potamogeton* (23–54%). The pteridophytic spores both fern (Monolete 5–20%, Trilete 0.3–2%) and *Lycopodium* (<1%) decline than previous pollen zone BPL I(a).

Zone BPL II– *Rhododendron*–Pine– Oak Zone: This zone extends from 361.60 cm to 265.27 cm covering time span of 36,181 cal yr BP to 35,389 cal yr BP (32,279–31,401 ^{14}C). This zone is also subdivided in to BPL II (a) (36,181 cal yr BP to 35,841 cal yr BP) and BPL II (b) (35,728 cal yr BP to 35,389 cal yr BP). In zone BPL II (a) there is a slight decline of pollen percentage of *Pinus* (10–29%) whereas values of other conifers viz., *Juniperus* (1%), *Abies* (<1%), *Larix* (<1%), *Picea* (<1%) and *Tsuga* (<1%), do not show much change. Broad leaved taxa show a mixed response, a drastic increase in *Rhododendron* (9–23%), *Quercus* (9–31%), where as percentage of *Betula*, *Corylus*,, *Salix*, *Alnus*, Juglandaceae and others decline. Elements of Savanah trees viz., Arecaceae (3–13%) Elaeocarpaceae, Oleaceae,

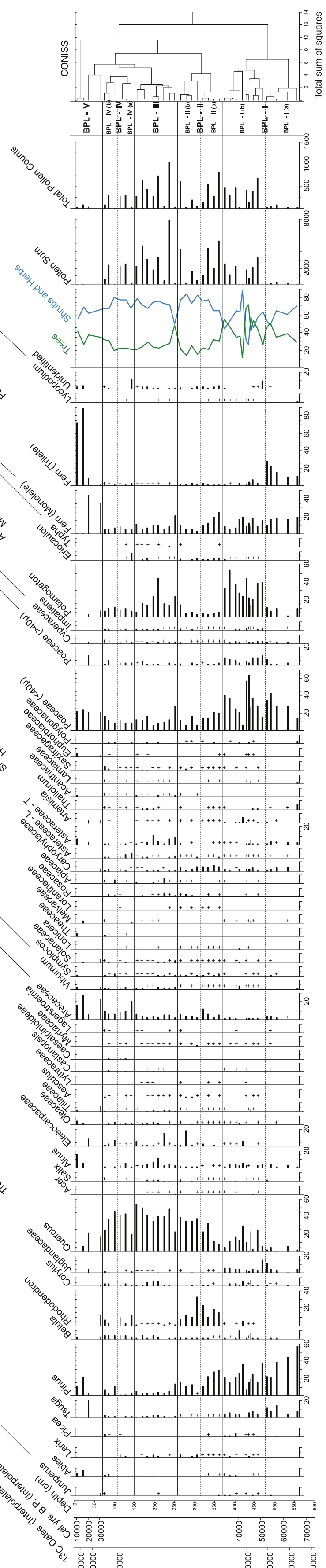

Fig. 7. Pollen diagram of sediment profile from Ziro valley, Arunachal Pradesh, NE India.

Myrtaceae have good representation. The grasses of all size range (13–20%) and the aquatic or marshy elements (3–6%) are low in comparison to the previous zone BPL I (b). In pollen zone BPL II (b) except *Quercus* (34–39%), other broad leaved taxa and *Pinus* decline though there is not much change in broad leaved taxa growing at tropical and sub tropical belt. There is also a decline in the grass (6–18%) and fern (5–10%) elements.

BPL III– Oak– –Birch –*Alnus*– *Corylus*: This zone extends from 251.51 cm to 155.18 cm covering time span 35,276 cal yr BP to 34,484 cal yr BP (31,778–30,398 ^{14}C). In this pollen zone *Pinus* (2–13%) declines. There is not much change in the representative of broad leaved taxa of both high and low elevation level except *Quercus* (22–54%) has increased drastically. Poaceae including both sizes (4–27%) has shown almost similar variation as pollen zone II, whereas there is an increase in aquatic taxa viz., *Potamogeton* (6–44%). But fern (6–20%) does not exhibit much change.

BPL IV– Oak– Alder–*Corylus*–Birch – Pine: This zone extends from 141.42 cm to 75.25 cm covering time span of 34,371 cal yr BP to 33,827 cal yr BP (30,273–29670 ^{14}C). This zone is also subdivided in to BPL IV (a) (34,371 cal yr BP to 34145 cal yr BP) and BPL IV (b) (34,032 cal yr BP to 33,827 cal yr BP). In pollen zone BPL IV (a) *Pinus* (<3%) and other conifers viz., *Larix* (1–2%), *Picea* (<1%), *Tsuga* (1–2%) decline. But there is increase in broad leaved taxa growing both higher elevations viz., *Quercus* (20–42%), *Betula* (2–5%), *Alnus* (2–6%), *Corylus* (2–3%) and also Arecaceae (8–20%), Oleaceae (1–2%), *Caesalpiniodeae* (<2%), *Castanopsis* (<1%) growing at lower elevations.

In zone IV (b) high values of *Quercus* (23–46%) decline in sediments form lower to upper depths, the other broad leaved taxa *Betula* (3–4%), *Rhododendron* (2–7%), *Corylus* (2–3%), Juglandaceae (1–2%) growing at higher elevations at temperate and alpine belt decline. There is an increase in Poaceae (<40μ, 8–16%), (>40μ, 1–5%) observed.

Zone BPL V – Fir –Pine Oak– Poaceae: This zone extends from 65.50 cm to top covering time span 30,566 cal yr BP to 11,165 cal yr BP (26,560–8058 ^{14}C). This zone is also subdivided in to BPL V (a) (30,566 cal yr BP to 20,531 cal yr BP) and BPLV (b) (16,183 cal yr BP to 11,165 cal yr BP). Palynologically this part is not well represented as sediments are either with poor pollen contents or even devoid pollen grains.

In zone V (a) representation of pollen of *Quercus* (17–21%), *and Pinus* (2%) still has a lower value in sediment, where as other conifers show slight increase. Broad leaved taxa growing at lower elevation have sudden increase followed by decline. Poaceae increases (10–21%) and aquatic taxa decline abruptly.

In zone V (b) *Pinus* (10.53–21.35%) and other conifers slightly increase. *Quercus* (5%) and *Betula* (3%) are in lower values There is a sudden change in pteridophytic assemblage which is reflected by high values of fern (Trilete 72–87% and Monolete 0.71%), and *Lycopodium* (0.62%). There is an overall increase in representation of pollen grains of taxa growing in the Savanah viz., Arecaceae (17–28%), Poaceae (22–23%), Theaceae (4%), Euphorbiaceae (4%), Asteraceae (Tubiliflorae 6.58%), Malvaceae (2.25%), Acanthaceae (1.32%),etc are observed in this zone.

5.2.2. Past vegetation

We reconstructed vegetation history covering time span of around last 66,000 cal yr BP to 11,000 cal yr BP and onwards based on the interpretation of the pollen diagram (Fig. 7) in terms of extant vegetation and climate in and around of this region. Pollen assemblage of this region is characterized by deposition of pollen from local taxa (subtropical) as well as extra local taxa (trees growing at higher elevations comprising both conifers and broad–leaved taxa). A good amount of pollen (both local and extra local) in sediments suggests that site has good vegetation cover under amelioration of climate (warm–moist). Alternatively, an increase of local taxa especially grass and other steppe elements in the pollen spectra suggests existence of cooler–drier climate. Based on this principle past vegetation of the region has been interpreted temporally in terms of broad climate changes. During 66,000 to 36,300 cal yr BP the area was occupied by the temperate conifer broad leaved forest in which Pine and *Tsuga* are the major constituents of conifers and are growing at much lower elevation. In this the broad leaved trees are mostly represented by *Juglans* and Oak. The much of the area in the vicinity of the site was covered by savannah in which grasses were prominent. Lake was shallow and supported by a good growth of *Potamogeton*. During pollen zone II covering time span of 36,181 cal yr BP to 35,389 cal yr BP there was expansion of oaks, *Rhododendron* and *Juglans* within the Pine, *Tsuga* conifer zone. There was increase in tree elements within the savannah also. This might have happened with the corresponding increase of S.W. monsoon. During pollen zone III around time 35,276 cal yr BP to 34,484 cal yr BP (31,778–30,398 ^{14}C) there was further increase in the broad leaved elements viz., Oak– *Rhododendron*–Birch with the decline of pine in the temperate forest with the further increase of SW monsoon. There was invasion of more tree taxa in the Savannah. The pollen zone IV covering time span 34,371 cal yr BP to 33,827 cal yr BP temperate forest elements of broadleaved taxa viz., Oak–*Rhododendron*– Alder–*Corylus*–Birch Pine showed maximum development within conifer broad leaved forest. This forest was much closer to the site with increase of both temperature and precipitation. However, Pine forest dwindled during this time due to increase of S W monsoon precipitation and these trees might have occupied at the comparatively drier site of southern aspects of the mountain. The area of savannah is much reduced with the proliferation subtropical and tropical elements in it. During pollen zone V, covering a time span of 30,566 cal yr BP to 11,165 cal yr BP, there is expansion of Oak–Rhododendron– Birch–Pine forest when temperature might have declined to from cool moist loving trees. Around 20,531 cal yr BP to 11,165 cal yr BP, there was decline of temperature and precipitation which favored adoption of conifers, Pine–Fir when Oak forest decline. Moreover increase of Arecaceae in the savannah is noteworthy; this may be due to proliferation of *Calamus leptodix* which is a common palm growing at this region (Sahni, 1969). Increased number of grasses and other non arboreal taxa, especially sudden increase of fern, more strikingly Trilete spore bearing fern also supports the expansion of Savannah in the vicinity of the site.

5.3. Carbon isotope

Carbon isotope data can be used as a reasonable supportive evidence of vegetation changes vis–à–vis climatic variability construed by the pollen data. The $\delta^{13}C$ record of this sediment profile has values ranging from −24 to −30‰ with the highest value of −24.39‰ occurring at around 30,566 cal yr BP (26,560 ^{14}C); and the lowest value is −29.34‰ at 347.84 cm around 36,068 cal yr BP (32,154 ^{14}C). In general, low $\delta^{13}C$ values in (i.e. zone BPL I and V (b)) between elevated $\delta^{13}C$ values at the bottom and upper part of the sediment profile (i.e. BPL II, III and IV). In conjuncture with the pollen zones the isotope data significantly matches the vegetation changes recorded throughout the sediment profile (Fig. 8). Thus, this data provides supportive evidence of climatic variability recorded by the pollen data The pollen Zone BPL I has relatively high $\delta^{13}C$ values averaging up to about −27.74‰ depicted by the predominance C-3 plants. There is further decline of $\delta^{13}C$ values in Zones BPL I (b), BPLII, and BPL III, BPL IV (a) with average values of $\delta^{13}C$ being −28.45‰, −28.92‰, −28.30‰, −28.82‰ respectively, the vegetation seems to be in and around the study site mostly of C-3 type of plants. During this time period the pollen assemblages coherently had higher percentages of broad leaved taxa representing a warm and moist phase in the region. Subsequently increased of $\delta^{13}C$ values within the Zone BPL IV (b) averaging about − 27.38‰ signifying addition of C4 type of plants within the C-3 type of dominated vegetation. The increase of $\delta^{13}C$ i.e., from C3 toward C4 values is expected due to changeover of vegetation patterns from to broad leaved conifer forest to grassland under deterioration of climate. During this period there might have been an occurrence of Savannah and subsequently at Zone BPL V (b) further expansion of Savannah with more C-4 type plants. This changing vegetation trends are evident in the pollen assemblages where grassland elements coherently dominate the arboreal taxa.

5.4. Magnetic susceptibility

The χlf or the low frequency measurements of magnetic susceptibility of the sediments show significant variations. The magnetic susceptibility values are not completely synchronous with the palynological data (Fig. 8.). In pollen zone BPL I (a) or the oldest zone the χlf values were relatively higher than the other overlying zones but the values comparatively were low range susceptibility values. Similar trend continues in Zones BPL I (b), II, and III where there was variability in the χlf data but the estimates are increasingly low. In Zone BPL IV the χlf values were the lowest signifying the driest phase in the region which was similar to the pollen and isotope records of this profile. In Zone BPL V the χlf values are again variable and shift towards relatively higher orders but the overall range being of low values. The estimates in this zone were not significantly similar to the pollen and isotope records as they depicted a much drier environment during that period.

The non–synchronous nature of the susceptibility records is probably due to the nature of the vegetation cover in the region. The palynoassemblage records around ~43,000 cal yr BP to ~34,000 cal yr BP have the highest values of taxa recorded and hence reflect a dense vegetative cover during this period especially in Zones BPL I, II, III and IV (a). Thus the erosion rate in the valley was controlled or checked and can be attributed to much vegetation cover during that time. Moreover during this period there was probably an intensification of S.W. monsoon which is also supported by rising lake levels spread in wider area like western China, Tibet and many other regions (Rhodes et al., 1996; Zhang et al., 2000; Zheng et al., 2000; Shi et al., 2001; Yang and Scuderi, 2010). Hence the low susceptibility values might be probably due to the diminished content of ferromagnetic minerals as these depict the erosion and deposition environment of the sediment in which they accumulate. The reduced content of mineral magnetite in the sediment has lead to the reduced χlf values and a rise in hematite and other supra paramagnetic minerals have caused the variations in the Frequency Dependent (FD %) percentages ratios of χlf and χhf. These estimates of susceptibility of the sediment profile are evidence for the changing vegetation scenario of the region during that time.

6. Reconstruction of vegetation and climate change

Data derived from Pollen analysis, Magnetic susceptibility and carbon isotopic analysis cumulatively (Fig. 8) provide a better understanding of climatic changes in Ziro valley during later part of Pleistocene. A good amount of grass pollen along with broad leaved conifer forest elements throughout the deposition suggests that the nearby area was savannah with close by conifer–broad leaved forest. However there are certain intervals (35,050 cal yr BP to 34,842 cal yr BP and 34,371 cal yr BP to 34,145 cal yr BP) when

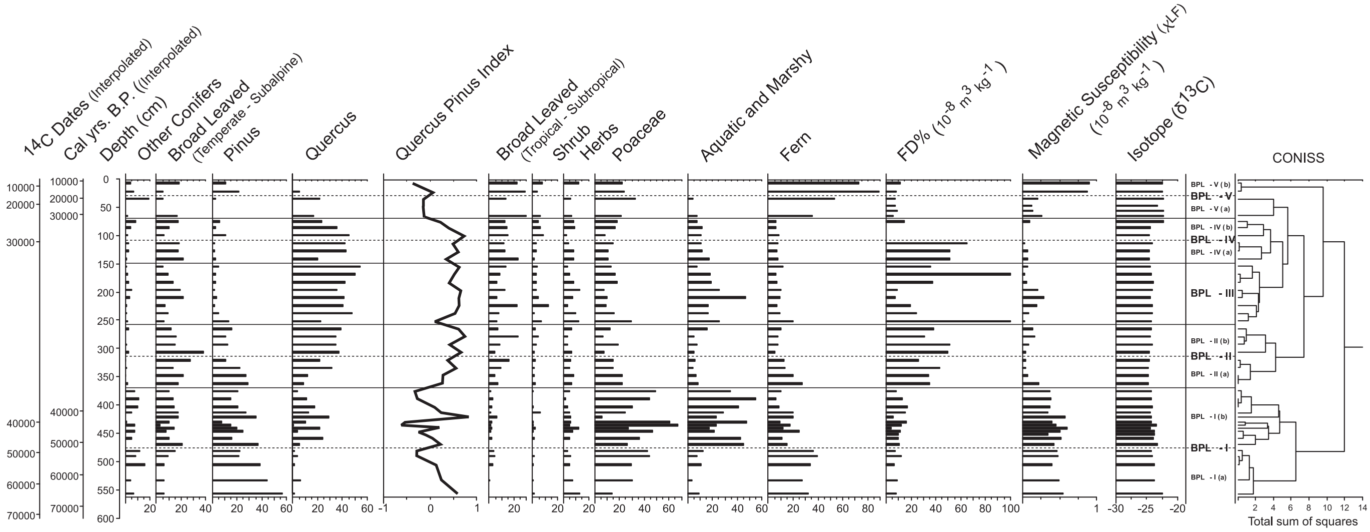

Fig. 8. Diagram showing *Quercus* –*Pinus* Index, Magnetic Susceptibility, δ^{13}C Isotope variations in the sediment profile and its comparison with major palynomorphic elements which comprise the vegetation in Ziro valley Arunachal Pradesh.

grasses decline, with an increase of broad leaved conifer taxa. This is also evident from the high value of Quercus – Pinus Index. In general pollen and carbon isotope data reveal that during last glaciations a phase of interstadial with domination of C-3 broad leaved tree elements are present within the sequence dominated by Pine grass savannah. The carbon isotopic data shows variation of in δ^{13}C values in the range of C-3 plants which lead to conclude that the area was mostly occupied by C-3 plants in mixed vegetation of C3 and C4 types. The changes in values towards higher or lower may be incorporation of C4/C3 plant community. More over such variation in δ^{13}C values within the range -3‰ also suggest that the site undergone several changes in hydrological regime, from swamp, marsh to dry–land. Palynological, Isotopic, and Magnetic Susceptibility data all are harmonized depicting that in the beginning the climate was comparatively cooler and drier. The most salient feature in the present study is the increase of magnetic parameters and decrease of δ^{13}C values around ~36,000 cal yr BP to ~33,000 cal yr BP corresponding to the peat deposition of the profile when the area have comparatively good forest cover. This might be impact of short time span of interstadial phase when both rainfall and temperature were higher during Last Glacial period. Maximum development of *Rhododendron* in 36,294 cal yr BP and 34,597 cal yr BP also synchronize with the lower δ^{13}C indicating the expansion of broadleaved C3 vegetation. The other significant feature in the present study is the sharp rise of magnetic parameters and also increases of δ^{13}C values around 30,566 cal yr BP and afterwards when glacier environment reverted again. Palynologically, this period has been characterized by drier climate when much of the area was colonized by grasses under savannah and at higher elevations conifer broad–leaved forest was became diminutive. Thus the magnetic susceptibility data also supports the palynological view that the area had experienced drier climate at that period.

7. Regional correlations

We have recorded changes in climate based on multi proxy data, viz., pollen, δ^{13}C values and magnetic susceptibility data during the Late Pleistocene (corresponding to Marine Isotope Stage 3, MIS 3) from the sub–surface sediment from Ziro valley. During Last Glacial period at 66,000 cal yr BP the Eastern Himalayan region might have been occupied by a lager extent of glacier as evidenced from the Garhwal Himalaya (Benn, and Owen, 1998). Numerical climate modeling records from the Himalaya of the Late Quaternary indicated an increase in snow cover in the Eastern Himalaya during Last Glacial Maximum probably due to the variation in the wind pattern in the summer and winter south Asian monsoon (Bush, 2002, 2004). During last glaciations, glacier may not descend to low elevations as close to Ziro valley since it was weak in the comparison to earlier ones in the Himalaya (Rashid et al., 2011), but position of snout and average snow line was much lower during that period than today and that varied with the changes of climate. Moreover, during Last Glacial period SW monsoon in general was weak with the corresponding increase of NE monsoon, but latter does not bring much rain (Owen et al., 2008). The impact of these climate changes and glacier environment influences vegetation scenario of not only at the higher elevations but also be felt even at the lower elevations. Pollen data suggests that climate of this region has been comparatively cool and dry around 66,000 cal yr BP which is evident by the expansion of the Pine –*Tsuga* savannah comparable to present day dry temperate forest of the Eastern Himalaya. Subsequent development (around 43,000 cal yr BP) of broad leaved forest especially expansion of Oak within it took place when climate was changing to moister than before. Further expansion of broad leaved conifer forest around 35,000 cal yr BP suggests comparatively more favorable climatic conditions. Thus overall scenario of the present study indicates that there was gradual rise of S.W. monsoon since 66,000 cal yr BP onwards and reached to peak at around ~36,000–34,145 cal yr BP (32,530–30,022 ^{14}C) which subsequently weakened when climate turned to be comparatively cooler and drier with coeval of increased aridity during LGM, which favored the expansion of Pine and grass land. However because of non–availability of samples suitable for pollen analysis and dates in the upper part of the profile impact of these events could not be precisely recorded. But δ^{13}C values indicate expansion of C4 plants in response to increased aridity. This is also supported by pollen data from adjacent upper Assam where temperate and subtropical elements are reported at lower elevations (Bhattacharya and Chanda, 1992). Thus in the present study the optimum expansion of broadleaved conifer forest in response to increased S.W. monsoon records around 34,145 cal yr BP (30,022 ^{14}C) may correspond to interstadial period which have extensive supportive evidences of corresponding climate ameliorations in other parts of the Himalaya, Tibetans Plateau and also in marine records. From the western Himalayan region several periods of ameliorations during 34 ka, 32 ka, 30.7 ka, and 29 ka are recorded from Kumaun, Lesser Himalayan (Kotlia et al., 1997, 1998, 2000) and also from Ladakh, Trans–Himalayan regions (Bhattacharyya,1989), and seem to correspond to the events of Ziro valley, Eastern Himalaya. Isotope studies from Karewa sediments, Kashmir reveal that palaeosols dating beyond 30,000 yr BP have lower values of $\delta^{13}C$ values ranging from −21.9to16.2‰ whereas palaeosol dated about 18,890 yr BP having −25.3‰ $\delta^{13}C$ values (Krishnamurthy and DeNiro, 1982) Thus in the Karewa deposit regions of Kashmir Himalaya C-4 type vegetation dominated beyond 30,000 yr BP signifying a cold dry phase whereas C-3 type vegetation persisted around 18,000yr BP when the climate was more warm and humid (Krishnamurthy and DeNiro, 1982). These results exhibited the difference in the vegetation scenario in the contemporaneous deposits of Ziro valley where C-3 vegetation dominated around 30,000 (^{14}C dated). This variation may signify the difference in the moister conditions in both the regions were dissimilar during this period of enhanced monsoon strength. The amelioration of climate during interstadial phases occurring in the Trans–Himalayan region concur with the increased Western disturbance/ northeast monsoon in the Indian subcontinent (Bhattacharyya, 1988; Bhattacharyya et al., 2006; Demske et al., 2009). However, based on carbon isotope study from Nilgiri Hills almost similar trend of climate changes (the southern Indian montane region) are recorded, which is also under domain of S.W. monsoon region. This study showed that the moist conditions around 40,000 to 28,000 yr BP followed by increase of aridity and more arid conditions around 16,000 yr BP (Rajagopalan et al., 1997) .The extreme arid conditions in this region during the LGM have also been evidenced in another carbon isotopic analysis earlier from the same region when there were higher values of $\delta^{13}C$ suggesting mostly existence of C-4 plants, which are indicator of arid climate. Thus, 16,000 yr BP onwards there is more negative signature of $\delta^{13}C$ indicating dominance of C-3 vegetation, which reached optimum at around 10,600–9000 yr BP (Sukumar et al., 1993) However, for most of our data from Ziro valley a precise correlation with existing data from other regions is not possible so far, due to the low number of samples and age constrain. In the Tibetan Plateau an extremely strong event of summer monsoon was recorded during the later part of marine isotope Stage 3 (MIS 3), which corresponds to the later phase of the mega–interstadial of Last Glacial period during 30,000–40,000 yr BP (Shi et al., 2001). During this period the warm and humid conditions with 2–4 °C higher temperature and 40%–100% more precipitation were estimated to have prevailed causing higher lake levels in the Plateau as evidenced in the ice–core, pollen and lake–level records (Shi et al., 2001). The strong summer monsoon managed to reach the interior of northwest China such as the Qaidam basin during late MIS 3 where higher lake levels were recorded (An, 2000). The Weinan Loess and Luochuan Loess in the Loess Plateau of China show evidences of increased precipitation during MIS 3 which also correlates with the SST changes in a South China Sea core (An and Sun, 1995; Wang et al., 1995; Gu et al., 1997; An, 2000). Equivalent to Ziro valley, a similar interstadial period was described at about 30 ka characterized by slight increase of tree pollen in the long lacustrine core sample from Lake Urmia, North West Iran (Djamali et al., 2008). These climatic ameliorations have also wide impact in many other geographical regions of Northern Hemisphere. The warm–moist phase around 36–34 ka reported in the present study may correspond to the Interstadial of 34–28 ka which is widely known from SW Europe (Veres, 2007), NW Europe as Denekamp Interstadial (Van der Hammen et al., 1971; Roger, 1976; Kolstrup, 1980), Alesunde Interstadial in Scandinavia (Baumann et al., 1995) or as Krinides Interstadial in Northern Greece (Wijmstra, 1969). There is a regional evidence for an almost fully deglaciated Scandinavia during the Middle Weichselian some 30–40 ka (Olsen et al., 1996). The glacial–geologic sea level and benthic $\delta^{18}O$ data indicates that ice volume at ~35 ka BP was approximately 50% of that of the LGM (Winograd, 2001). However the scenario is different in the southern hemisphere where the records from northern Australia indicate increase aeolian activity, desert development resulting from strengthened south–easterly trade winds during MIS 3 which might have contributed to enhanced precipitation in East Asian monsoon resulting from trans equatorial air streams effects (Wasson, 1986; De Deckker et al., 1991; An, 2000).

8. Conclusions

We describe changes of vegetation and climate during the major part of the Last Glacial period in the vicinity of Ziro valley, Arunachal Pradesh, Eastern Himalaya based on multi proxy data. Increase of SW monsoon from ~43,000 cal yr BP to 34,000 cal yr BP (40,000–30,022 ^{14}C) and decline thereafter is recorded. The area experienced a peak warm and humid phase around 36,181 cal yr BP–34,145 cal yr BP (32,279 to 30,022 ^{14}C) during last glaciations. During this time span the influence of enhanced SW monsoon was evident in the pollen and isotope records when wet evergreen confer mixed vegetation covered at altitude gradient, enhanced in the valley. Around 20,000 cal yr BP i.e., during LGM the decline of monsoon is evident when forest turn to be Savannah type, which is also evident by the lower Quercus- Pinus Index. However, for the higher resolution and detailed paleoclimate analysis there is a need for longer and complete record from the region. Ziro valley, Arunachal Pradesh, Eastern Himalaya seems to be one of the promising sites for paleoclimatic analysis using multi proxy of long Quaternary sequence. Due to typical physiographical position at Lower Eastern Himalaya this area can provide us a complete picture of past climatic variations especially monsoon dynamics. Such long records would be useful to understand the climatic variation and its tele–connections not only from the Himalaya but also throughout the globe.

Acknowledgment

The authors are highly indebted to Prof. Sunil Bajpai, the Director Birbal Sahni Institute of Palaeobotany Lucknow for providing the necessary support and facilities to the authors for the compilation of this work. The paper is outcome of the Department of Science and Technology Sponsored Project No. ESS/44/01/98 and highly acknowledged for the financial support. Thanks are also due to Dr. B. Sekar for providing us C-14 dates done at the C14 laboratory of the Birbal Sahni Institute of Palaeobotany. One of the authors N.M. is highly grateful to the C. S. I. R., Government of India for providing her financial support. The authors are also grateful to the Institute of Geology and Mineralogy, University of Erlangen–Nuremberg, Erlangen for the support they provided during the isotope analysis for this study and Institute of Geomagnetism for providing facilitate to work on magnetic susceptibility. The authors are also thankful to the reviewer for the valuable suggestions given to improve this manuscript.

References

Acharyya, S.K., 2005. Eastern Himalayan stratigraphy and tectonics. In: Saklani, P.S. (Ed.), Himalaya (Geological Aspects). Satish Serial Publishing House, Azadpur, Delhi, pp. 619–643.
Agrawal, S., Sanyal, P., Sarkar, A., Jaiswal, M.K., Dutta, K., 2012. Variability of Indian summer monsoon over the past 100 ka and its implications to C3–C4 vegetational change. Quat. Res. 77, 159–170.
Agrawal, S., Sanyal, P., Bera, M.K., Dash, J.K., Balakrishnan, S., 2013. Paleoclimatic, paleovegetational and provenance change in the Ganga Plain during the late Quaternary. J. Earth. Sys. Sci. 122, 1141–1152.

An, Z.S., 2000. The history and variability of the East Asian paleomonsoon climate. Quat. Sci. Rev. 19, 171–187.

An, Z.S., Sun, D.H., 1995. Discussion of the monsoon variation over the Loess Plateau in the Last Interglacial cycle. In: Ye, D.Z. (Ed.), China Contribution to Global Change. Science Press, Beijing, pp. 122–124.

Baishya, A.K., Balodi, B., Pal, G.D., 2002. Floristic diversity of Arunachal Pradesh an overview. In: Sundriyal, R.C., Singh, T., Sinha, G.N. (Eds.), Arunachal Pradesh: Environmental Planning and Sustainable Development, pp. 173–206. HIMAVI-KAS Occasional Publication No. 16.

Banerjee, S., 1973. A note on the geology of Arunachal Pradesh. J. Mines, Met. Fuels 21 (8), 225–229, 236.

Baumann, K.H., Lackschewitz, K.S., Mangerud, J., Spielhagen, R.F., Wolf–Welling, T.C.W., Henrich, R., Kassens, H., 1995. Reflection of Scandinavian Ice sheet fluctuations in Norwegian Sea sediments during the past 150,000 years. Quat. Res. 43, 185–197.

Behera, M.D., Khushwaha, S.P.S., Roy, P.S., Srivastava, S., Singh, T.P., Dubey, R.C., 2002. Comparing structure and composition of coniferous forests in Subansiri district, Arunachal Pradesh. Curr. Sci. 82 (1), 70–76.

Benn, D.I., Owen, L.A., 1998. The role of the Indian summer monsoon and the mid–latitude westerlies in Himalayan glaciation: review and speculative discussion. J. Geol. Soc. Lond. 155, 353–363.

Bhattacharya, K., Chanda, S., 1992. Late–Quaternary vegetational history of Upper Assam, India. Rev. Palaeobot. Palynol. 72, 325–333.

Bhattacharyya, A., 1983. Studies in the Vegetational History of the Alpine Region of North–West Himalaya (unpubl. Ph D thesis). Lucknow University, Lucknow, p. 278.

Bhattacharyya, A., 1988. Vegetation and climate during postglacial period in the vicinity of Rohtang Pass, Great Himalayan Range. Pollen Spores 30 (3&4), 417–427.

Bhattacharyya, A., 1989. Vegetation and climate during the last 30,000 years in Ladakh. Palaeogeogr. Palaeoclimatol. Palaeoecol. 73, 25–38.

Bhattacharyya, A., Ranhotra, P.S., Shah, S.K., 2006. Temporal and spatial variations of Late Pleistocene–Holocene climate of the western Himalaya based on pollen records and their implications to Monsoon dynamics. J. Geol. Soc. India 68, 507–515.

Bhattacharyya, A., Sharma, J., Shah, S.K., Chaudhury, V., 2007. Climatic changes last 1800 years BP from Paradise lake, Sela pass, Arunachal Pradesh, Northeast Himalaya. Curr. Sci. 93 (7), 983–987.

Bhattacharyya, A., Sharma, J., Shah, S.K., Chaudhary, V., 2009. Climatic changes during the last 1800 yrs BP from Paradise Lake, Sela Pass, Arunachal Pradesh, Northeast Himalaya. Curr. Sci. 93 (7), 983–987.

Bhattacharyya, A., Mehrotra, N., Shah, S.K., 2011. Holocene vegetation and climate of South Tripura based on palynological analysis. J. Geol. Soc. India 77, 521–526.

Boos, W.R., Kuang, Z., 2010. Dominant control of the South Asian monsoon by orographic insulation versus plateau heating. Nature 463, 218–222.

Boos, W.R., Kuang, Z., 2013. Sensitivity of the South Asian monsoon to elevated and non–elevated heating. Sci. Rep. 3, 1192.

Bradley, R.S., 1999. Paleoclimatology: Reconstructing Climates of the Quaternary. Academic Press, San Diego, pp. 129–436.

Bush, A.B.G., 2002. A comparison of simulated monsoon circulations and snow accumulation during the mid–Holocene and at the Last Glacial Maximum. Glob. Planet Change 32, 331–347.

Bush, A.B.G., 2004. Modelling of Late Quaternary climate over Asia: a synthesis. Boreas 33, 155–163.

Cane, M.A., 2010. A moist model monsoon. Nature 463, 163–164.

Chauhan, M.S., Sharma, C., 1996. Late–Holocene vegetation of Darjeeling (Jore Pokhari), Eastern Himalaya. Paleobotanist 45, 125–129.

Chowdhery, H.J., 1996. Arunachal Pradesh. In: Hajra, P.K., Sharma, B.D., Sanjapa, M., Sastry, A.K. (Eds.), Flora of India (Introductory Volume) Part I, Botanical Survey of India. Publ. Director B.S.I., Calcutta, pp. 238–250.

De Deckker, P., Corré ge, T., Head, J., 1991. Late Pleistocene record of cyclic aeolian activity from tropical Australia suggesting the Younger Dryas is not an unusual climatic event. Geology 19, 602–605.

Deevey, E.S., 1937. Pollen from the interglacial beds of Pangong valley and its climatic interpretation. Am. J. Sci. 33, 44–56.

Demske, D., Tarasov, P.E., Wünnemann, B., Riedel, F., 2009. Late glacial and Holocene vegetation, Indian monsoon and westerly circulation in the Trans–Himalaya recorded in the lacustrine pollen sequence from Tso Kar, Ladakh, NW India. Palaeogeogr. Palaeoclimatol. Palaeoecol. 279, 172–185.

Djamali, M., de Beaulieu, J.L., Shah–Hosseini, M., Andrieu–Ponel, V., Amini, A., Akhani, H., Leroy, A.S., Stevens, L., Alizadeh, H., Brewer, S., 2008. An Upper Pleistocene long pollen record from the Near East, the 100 m–long sequence of Lake Urmia, NW Iran. Quat. Res. 69, 413–420.

Dodia, R., Agarwal, D.P., Vora, A.B., 1985. New pollen data from the Kashmir bogs: a summary. Curr. Trends Geol. 6, 101–108.

Dollo, M., Samal, P.K., Sundriyal, R.C., Kumar, K., 2009. Environmentally sustainable traditional natural resource management and conservation in Ziro Valley, Arunachal Himalaya, India. J. Am. Sci. 5 (5), 41–52.

Galy, V., Francois, L., France–Lanord, C., Faure, P., Kudrass, H., Palhol, F., Singh, S.K., 2008. C4 plants decline in the Himalayan basin since the Last Glacial Maximum. Quat. Sci. Rev. 27, 1396–1409.

Ghosh, R., Paruya, D.K., Khan, M.A., Chakraborty, S., Sarkar, A., Bera, S., 2014. Late Quaternary climate variability and vegetation response in Ziro lake basin, eastern Himalaya: a multi proxy approach. Quat. Int. 325, 13–29.

Grimm, E.C., 1987. CONISS: a FORTRAN 77 program for stratigraphically constrained cluster analysis by the method of incremental sum of squares. Comput. Geosci. 13, 13–35.

Grimm, E.C., 2004. TILIA and TG View 2.0.2. Illinois State Museum, Springfield IL.

Gu, Z.Y., Lal, D., Liu, T.S., Guo, Z.T., Southon, J., Caffee, M.W., 1997. Weathering histories of Chinese loess deposits based on Uranium and Thorium series nuclides and cosmogenic ^{10}Be. Geochim. Cosmochim. Acta 61, 5221–5231.

Gupta, A.K., Anderson, D.M., Overpeck, J.T., 2003. Abrupt changes in the Asian southwest monsoon during the Holocene and their links to the North Atlantic Ocean. Nature 421, 354–357.

Gupta, A.K., Das, M., Anderson, D.M., 2005. Solar influence on the Indian summer monsoon during the Holocene. Geophys. Res. Lett. 32 (L17703), 1–4.

Harris, I., Jones, P.D., Osborn, T.J., Lister, D.H., 2014. Updated high-resolution grids of monthly climatic observations–the CRU TS 3.10. Int. J. Climatol. 34, 623–642.

Kesari, G.K., 2010. Geology and Mineral Resources of Arunachal Pradesh. Geological Survey of India, Arunachal Pradesh. Geological Survey of India, Miscellaneous Publication, 30 (IV) (I) (i).

Kolstrup, E., 1980. Climate and Stratigraphy in North Western Europe between 30,000 yr BP and 13,000 yr BP with special reference to the Netherlands. Meded. rijks Geol. Dienst 32 (15), 181–253.

Kotlia, B.S., Bhalla, M.S., Sharma, C., Ramesh, R., Rajagopalan, G., Chauhan, M.S., Mathur, P.D., Bhandari, S., Chacko, S.T., 1997. Palaeoclimatic conditions in the Upper Pleistocene and Holocene Bhimtal–Naukuchiatal lake basin in south–central Kumaun, North India. Palaeogeogr. Palaeoclimatol. Palaeoecol. 130, 307–322.

Kotlia, B.S., Hinz–Schallreuter, I., Schallreuter, R., Schwarz, J., 1998. Evolution of Lamayuru palaeolake in the Trans Himalaya: palaeoecological implications. Eiszeitalt. Ggw. 48, 23–36.

Kotlia, B.S., Sharma, C., Bhalla, M.S., Rajagopalan, G., Subrahmanyam, K., Bhattacharyya, A., Valdiya, K.S., 2000. Palaeoclimatic conditions in the Late Pleistocene Wadda lake, eastern Kumaun Himalaya (India). Palaeogeogr. Palaeoclimatol. Palaeoecol. 162, 105–118.

Kotlia, B.S., Sanwal, J., Phartiyal, B., Joshi, L.M., Trivedi, A., Sharma, C., 2010. Late Quaternary climatic changes in the eastern Kumaun Himalaya, India, as deduced from multi–proxy studies. Quat. Int. 213, 44–55.

Krishnamurthy, R.V., DeNiro, M.J., 1982. Isotope evidence for Pleistocene climatic changes in Kashmir, India. Nature 298, 640–641.

Kumar, R., Pant, G.B., 1997. Climates of South Asia. Wiley, Chichester.

Laskar, B., 1949. Notes on Traverse in Subansiri Valley in Outer Himalayas in Assam (Unpublished G.S.I. report).

Li, C., Yanai, M., 1996. The onset and interannual variability of the Asian summer monsoon in relation to land–sea thermal contrast. J. Clim. 9, 358–375.

Malhotra, C.L., 1983. Observation of the botanist member of the Subansiri expedition 1974–1975. In: Proceedings of the Symposium on Geology and Mineral Resources of North Eastern Himalayas. Misc. Publ., Geol. Surv, India, pp. 26–28, 43.

Mani, A., 1981. The climate of the Himalayas. In: Lall, J.S., Moddie, A.D. (Eds.), The Himalayas–aspects of Change. Oxford University Press, pp. 3–15.

Mehrotra, N., Shah, S.K., Bhattacharyya, A., 2014. Review of palaeoclimate records from Northeast India based on pollen proxy data of Late Pleistocene–Holocene. Quat. Int. 325, 41–54.

Mensing, S., Korfmacher, J., Minckley, T., Musselman, R., 2012. A 15,000 year record of vegetation and climate change from a treeline lake in the Rocky Mountains, Wyoming, U.S.A. Holocene 22 (7), 739–748.

Molnar, P., Boos, W.R., Battisti, D.S., 2010. Orographic controls on climate and paleoclimate of Asia: thermal and mechanical roles for the Tibetan Plateau. Annu. Rev. Earth Planet. Sci. 38, 77–102.

Olsen, L., Mejdahl, V., Selvik, S.F., 1996. Middle and Late Pleistocene Stratigraphy, Chronology, and Glacial History in Finnmark, North Norway. Norges Geologiske Undersøgelse, p. 429.

Owen, L.A., Caffee, M.W., Finkel, R.C., Seong, Y.B., 2008. Quaternary glaciation of the Himalayan–Tibetan orogen. J. Quat. Sci. 23 (6–7), 513–531.

Pant, R.K., Basavaiah, N., Juyal, N., Saini, N.K., Yadava, M.G., Appel, E., Singhvi, A.K., 2005. A 20–ka climate record from central Himalayan loess deposits. J. Quat. Sci. 20 (5), 485–492.

Prell, W.L., Kutzbach, J.E., 1992. Sensitivity of the Indian monsoon to changes in orbital parameters, glacial and tectonic boundary conditions and atmospheric CO_2 concentration. Nature 360, 647–652.

Ramsey, C.B., 1995. Radiocarbon calibration and analysis of stratigraphy: the OxCal program. Radiocarbon 37 (2), 425–430.

Ramsey, C.B., 2001. Development of the radiocarbon calibration program. Radiocarbon 43 (2A), 355–363.

Ramsey, C.B., 2008. Deposition models for chronological records. Quat. Sci. Rev. 27 (1–2), 42–60.

Ramsey, C.,B., 2009. Bayesian analysis of radiocarbon dates. Radiocarbon 51 (1), 337–360.

Ranhotra, P.S., Bhattacharyya, A., Kotlia, B.S., 2007. Vegetation and climatic changes around Lamayuru, Trans–Himalaya during the last 35 kyr BP. Palaeobotanist 56, 117–126.

Rajagopalan, G., Sukumar, R., Ramesh, R., Pant, R.K., Rajagopalan, G., 1997. Late Quaternary vegetational and climatic changes from tropical peats in southern India – an extended record up to 40,000 yr. BP. Curr. Sci. 73 (1), 60–63.

Ranhotra, P.S., Bhattacharyya, A., Kar, R., Sekar, B., 2001. Vegetation and climatic changes around Gangotri glacier during Holocene. Proc. Nat. Symp. Role of Earth Sci. –Integr. Dev. Relat. Soc. Issues, G.S.I. Spec. Pub. No. 65(III), 67–71.

Rashid, H., England, E., Thompson, L., Polyak, L., 2011. Late Glacial to Holocene Indian summer monsoon variability based upon sediment records taken from the Bay of Bengal. Terr. Atmos. Ocean. Sci. 22 (2), 215–228.

Reimer, P.J., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G., Bronk Ramsey, C., Grootes, P.M., Guilderson, T.P., Haflidason, H., Hajdas, I., HattŽ, C., Heaton, T.J.,

Hoffmann, D.L., Hogg, A.G., Hughen, K.A., Kaiser, K.F., Kromer, B., Manning, S.W., Niu, M., Reimer, R.W., Richards, D.A., Scott, E.M., Southon, J.R., Staff, R.A., Turney, C.S.M., van der Plicht, J., 2013. IntCal13 and Marine13 Radiocarbon Age Calibration Curves 0-50,000 Years cal BP. Radiocarbon 55 (4), 1869–1887.
Reimer, P.J., Baillie, M.G.L., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G., Bronk Ramsey, C., Buck, C.E., Burr, G.S., Edwards, R.L., Friedrich, M., Grootes, P.M., Guilderson, T.P., Hajdas, I., Heaton, T.J., Hogg, A.G., Hughen, K.A., Kaiser, K.F., Kromer, B., McCormac, F.G., Manning, S.W., Reimer, R.W., Richards, D.A., Southon, J.R., Talamo, S., Turney, C.S.M., van der Plicht, J., Weyhenmeyer, C.E., 2009. IntCal09 and Marine09 radiocarbon age calibration curves, 0–50,000 years cal BP. Radiocarbon 51 (4), 1111–1150.
Rhodes, T., Gasse, F., Ruifen, L., Fontes, J., Wei, K., Bertrand, P., Gibert, E., Mélières, F., Tucholka, P., Wang, Z., Chen, Z., 1996. A Late Pleistocene–Holocene lacustrine record from Lake Manas, Zhunggar (northern Xinjiang, western China). Palaeogeogr. Palaeoclimatol. Palaeoecol. 120, 105–121.
Roger, V., 1976. The vegetational evolution during the transition from the Denekamp Interstadial to the full glacial in Belgium (Abstract). In: V Int. Palynol Conf, p. 403.
Sahni, K.C., 1969. A contribution to the flora of Kameng and Subansiri districts, NEFA. Indian For. 95 (5), 330–352.
Sarkar, A., Sengupta, S., McArthur, J.M., Ravenscroft, P., Bera, M.K., Bhushan, R., Samanta, A., Agrawal, S., 2009. Evolution of Ganges–Brahmaputra western delta plain: clues from sedimentology and carbon isotope. Quat. Sci. Rev. 28, 2564–2581.
Shah, S.K., Bhattacharyya, A., 2012. Spatio–temporal growth variability of three Pinus species of Northeast Himalaya with relation to climate. Dendrochronologia 30, 266–278.
Sharma, C., Chauhan, M.S., 1994. Vegetation and climate since Last Glacial Maxima in Darjeeling (Mirik Lake), Eastern Himalaya. In: Proc. 29th Int. Geol. Congr. Part B, pp. 279–288.
Sharma, C., Chauhan, M.S., 2001. Late–Quaternary pollen record from Kupup (Sikkim), Eastern Himalaya. J. Palaeontol. Soc. India 46, 51–58.
Shi, Y., Yu, G., Liu, X., Li, B., Yao, T., 2001. Reconstruction of the 30–40 ka enhanced Indian monsoon climate based on geological records from the Tibetan Plateau. Palaeogeogr. Palaeoclimatol. Palaeoecol. 169, 69–83.
Srivastava, P., Misra, D.K., Agarwal, K.K., Bhakuni, S.S., Khayingshing, L., 2009. Late Quaternary evolution of Ziron intermontane Lake basin, NE Himalaya, India. Him. Geol. 30 (2), 175–185.
Sukumar, R., Ramesh, R., Pant, R.,K., Rajagopalan, G., 1993. A δ^{13}C record of Late Quaternary climate change from tropical peats in southern India. Nature (London) 364, 703–706.
Van der Hammen, T., Wijmstra, T.A., Zagwijn, W.H., 1971. The floral record of the late Cenozoic of Europe. In: Turekian, K.K. (Ed.), The Late Cenozoic Glacial Ages. Yale Univ. Press, New Haven. Conn, pp. 391–424.
Veres, D.S., 2007. Terrestrial Response to Dansgaard–oeschger Cycles and Heinrich Events (PhD thesis). Department of Physical Geography and Quaternary Geology, Stockholm University.
Verosob, K.L., Roberts, A.P., 1995. Environmental magnetism: past, present and future. J. Geophys. Res. 100, 2175–2192.
Walter, H., Lieth, H., 1967. Klimadiagram – Weltatlas. VEB Gautav Fischer Verlage, Jena.
Wang, P.X., Wang, L.J., Bian, Y.H., Jian, Z.M., 1995. Late Quaternary paleoceanography of the South China Sea: surface circulation and carbonate cycles. Mar. Geol. 127, 145–165.
Wasson, R.J., 1986. Geomorphology and Quaternary history of the Australian continental dunefields. Geogr. Rev. Jpn. Ser. B 59 (1), 55–67.
Wijmstra, T.A., 1969. Palynology of the first 30 meters of a 120 m deep section in north Greece. Acta Bot. Neerl. 18 (4), 511–527.
Winograd, I.J., 2001. The magnitude and proximate cause of ice–sheet growth since 35,000 yr BP. Quat. Res. 56, 299–307.
Wodehouse, R.P., De Terra, H., 1935. Pleistocene pollen of Kashmir. Mem. Conn. Acad. Art. Sci. 9 (1), 1.
Yang, X., Scuderi, L.A., 2010. Hydrological and climatic changes in deserts of China since the Late Pleistocene. Quat. Res. 73, 1–9.
Zhang, H., Ma, Y., Wünnemann, B., Pachur, H., 2000. A Holocene climatic record from arid northwestern China. Palaeogeogr. Palaeoclimatol. Palaeoecol. 162, 389–401.
Zheng, M., Meng, Y., Wei, L., 2000. Evidence of the pan–lake stage in the period of 40–28ka BP on the Qinghai–Tibet Plateau. Acta Geol. Sin.–Engl. 74.