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The Younger Dryas cold event in NW Himalaya based on pollen record from the Chandra Tal area in Himachal Pradesh, India

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Pollen record of an AMS radiocarbon dated lacustrine sediment profile underlying the Chandra peat deposit in Himachal Pradesh, yielded signatures of the globally reported Younger Dryas (YD) cold event. This report of the YD event in NW Himalaya, substantiated by mineral magnetic variations, also records significant wet and warm conditions prior to 12,880 cal yrs BP, depicting the Ållerød interstadial preceding YD. The notable decrease in local (meadow) and regional (desert steppe) vegetation indicates major climate shift towards cold and dry conditions marking the onset of YD that intensified progressively till 11,640 cal yrs BP. The YD terminates with gradual reappearance of local and regional flora, indicating initiation of the Holocene wet and warm conditions. The pollen-inferred floristic changes and mineral magnetic variations

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suggest that in NW Himalaya the initiation and termination of the YD cold event was probably gradual.

Keywords: Cold event, lacustrine sediment, pollen record, radiocarbon dates.

AN abrupt climate turnover that marks the late Pleistocene–Holocene transition is widely reported in the Northern Hemisphere palaeoclimate records[1–3]. This sudden climate change, known as the Younger Dryas (YD) cold event named after Arctic or Alpine tundra *Dryas octopetala* (Rosaceae family), was recently dated between 12,860 and 11,650 cal yrs BP in the Greenland ice core record[4]. The event triggered by rapid turnover of the global atmospheric and oceanic circulation, resulted in a series of abrupt climate changes on centennial to millennial timescales[1–3]. However, the extent and response of the YD event in the lower latitudes in general and in the Himalayan realm in particular is still debatable due to insufficient high-resolution studies[4–8]. Delineation of the YD event under various geographic domains is therefore significant to understand the global tele-connections of rapid climate turnover like the late Pleistocene–Holocene transition. The available Himalayan records lack sufficient age control between 13.0 and 10.0 ^{14}C kyr BP for precise delineation and climate interpretation of the YD event[5–12]. Therefore, new records are imminent to improve our understanding on this aspect.

During a recent field study, a peat sequence and underlying lacustrine sediments deposited near the Chandra Tal in Lahul–Spiti area of NW Himalaya, was trenched and sampled at regular intervals for pollen analysis and mineral magnetic measurements. This 53-cm thick sequence is constrained with nine accelerator mass spectrometry (AMS) radiocarbon dates. In the present study, we have used only 44–53 cm interval of lake sediments that bracket the 13,000–9500 cal yrs BP period of climate record. This period also covers the YD event.

The study area is situated in Lahaul and Spiti District of Himachal Pradesh, NW Himalaya (Figure 1). This entire district comprises mountain belts bordering the southern part of the Ladakh cold desert. Except for restricted agricultural activities confined to river terraces and adjoining scree deposits, the major landscape is occupied by perennial snow and glaciers above ~4500 m altitude. The remaining lower altitude area (below 4500 m) is covered by the seasonal mountain steppe[13]. The natural forest comprising mainly Himalayan cedar (*Cedrus deodara*) and tree juniper (*Juniperus polycarpos*) in isolated pockets, is presently confined to inaccessible rocky cliffs below 3600 m altitude.

The Chandra Tal (i.e. moon lake) situated at 4302 m altitude (Figure 1) is located in the rain-shadow zone immediately north of the east-west oriented Rohtang Range, which restrains the entry of the Indian Summer Monsoon (ISM) in NW Himalaya. Rainfall record of the nearest weather station at Koksar (977 m altitude, 32.40°N and 77.20°E, WMO station # 42065.1) located at the base of Rohtang Pass, shows that it receives ~1000 mm annual precipitation mainly as winter snow. However, the occasional spillover of ISM during its increased strength in North India, significantly contributes to the subsistence of the Chandra Tal meadow[13].

The scenic alpine meadow has developed on the lateral moraine situated between the Chandra Lake and left bank of Chandra River (Figure 1). The present vegetation of this meadow is dominated by a variety of sedges, grasses and alpine herbs[13].

The 53-cm thick sequence of lake sediments and overlying peat deposit was trenched and sampled as 1 cm thick continuous slices. Around 9 cm thick lake sediments studied here represent the basal part of this profile. Each sample was analysed for its pollen content and mineral magnetic properties.

Pollen extraction was carried out by the conventional laboratory technique (20% hydrochloric acid followed by 10% freshly prepared potassium hydroxide treatment)[14]. Before final preparation of the slides, the recovered residue was subjected to ultrasonic wet sieving (10 μm mesh) to remove the unwanted finer organic debris, improve clarity, and concentrate the pollen and spores. For calculation of absolute pollen concentration (grains/g), the weighted quantity of the sample (200 mg–5.7 g) added with *Lycopodium* spores (10,680 spores/tablet) as an exotic marker[15] was used for chemical treatment.

The mineral magnetic analysis was carried out at Paleomagnetic Laboratory, Wadia Institute of Himalayan Geology, Dehradun by filling ~10 g of freeze-dried samples into non-magnetic pots. The saturation isothermal remanent magnetization (SIRM) was measured by imparting subsequently higher DC magnetic fields (using ASC IM 10-30 pulse magnetizer) in excess of 1000 mT and measured by Molspin's fluxgate magnetometer. All the samples saturated well below 1000 mT. Further, based on close-interval backfield data, a ratio of IRM backfield (at –300 mT) and SIRM called *S*-ratio was used, adapting its classic version[16] after attempting other versions discussed in Heslop[17]. The *S*-ratio was employed here to provide a relative measure of the high and low coercivity minerals within its SIRM.

The chronology of this profile was based on four AMS radiocarbon dates (Table 1) generated at Poznań Radiocarbon Laboratory, Poland. All the dates ideally satisfy the stratigraphic order. In the present study we have used only 44–53 cm interval of lacustrine sediments constrained with three radiocarbon dates encompassing the period between 12,880 and 9500 cal yrs BP (Table 1). The uniform lithology indicating uninterrupted sediment deposition at constant rate helped us in the interpolation of intermediate ages.

The identification of pollen and fern spores was facilitated by pollen morphological keys[14,18], Austrian

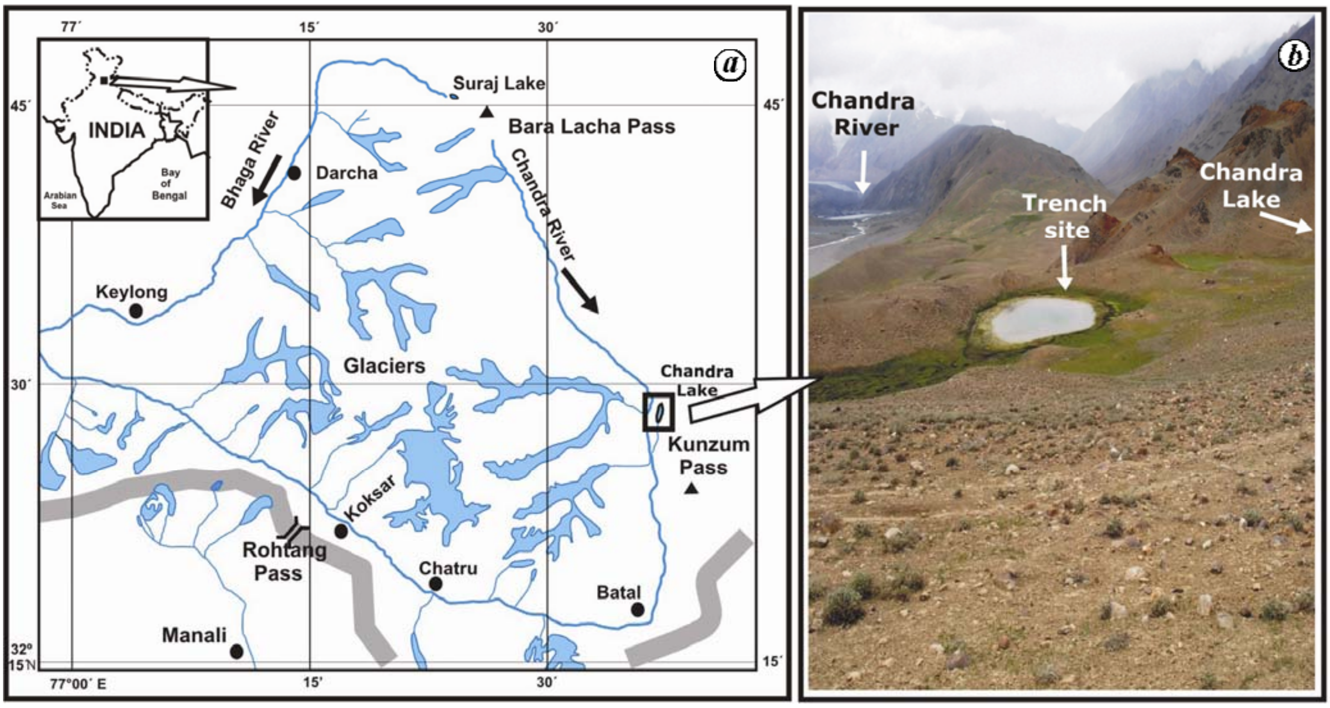

Figure 1. ***a***, Map of the study area showing the Chandra Tal locality. Thick grey line marks the Rohtang ridge, which acts as an orographic barrier preventing the normal entry of the Indian Summer Monsoon in NW Himalaya. ***b***, Field photograph showing the trench location from the pond developed on the lateral moraine occurring between Chandra Tal and left bank of the Chandra River.

Table 1. AMS radiocarbon dates of lake sediments based on bulk samples

					Age (cal yrs BP) (2δ)	
Sample #	Depth (cm)	Lab. #	Material	AMS ^{14}C date	Range	Middle
CT-7	6–7	Poz-34721	Bulk TOC	102 ± 0.33	224–254	250 (= 1710 cal AD)
CT-45	44–45	Poz-34723	Bulk TOC	8520 ± 50	9,453–9,550	9,500
CT-48	47–48	Poz-37818	Bulk TOC	8790 ± 50	9,601–9,954	9,778
CT-53	52–53	Poz-34724	Bulk TOC	10990 ± 60	12,682–13,078	12,880

Calibration refers to the Intcal09.14c program of Reimer *et al.*[17].

palynological database (http://www.paldat.org), and Australian pollen and spore atlas (http://apsa.anu.edu.au). The species-level identification was made possible by local floristic literature[13,19].

Pollen taxa present across the 12,880–9500 cal yrs BP interval that includes the YD event, are incorporated in the pollen diagram (Figure 2) and discussed for the vegetation and climate interpretations. The pollen grains of Cyperaceae (sedges) and Poaceae (grasses) were identified only at the family level confounding their distinction as the pollen grains of local meadow or more distant desert steppe. For regional climate interpretation, however, the increased presence of sedge and grass pollen usually indicates an improved availability of moisture and increased temperature. Pollen grains of Chenopodiaceae and Amaranthaceae are normally undistinguishable under the optical microscope. In the Lahaul and Spiti area, the amaranth family represented by a solitary genus *Amaranthus* (with two species, namely *A. retroflexus* and *A. cruentus*) is restricted to the cultivated area[13]. Therefore, the polyporate pollen grains of Cheno/Am affinity are considered to be of Chenopodiaceae, a characteristic family of arid habitats (dry slopes and sandy areas) in the Himalayan cold deserts[13]. Similarly, the presence of *Ephedra*, a typical sand binder commonly found in the cold deserts of NW Himalaya[13], also indicates the improved moisture and temperature. The presence of *Thalictrum* pollen and fern spores, which are usually derived from the moist sites, indicates wet and warm conditions. The aquatic members represented by pollen of *Myriophyllum spicatum* and *Potamogeton* sp. are usually found in shallow freshwater lakes, whereas plants growing in the marsh adjoining the lake, are documented by the pollen of Onagraceae (mainly *Ludwigia* and *Oenothera*).

Pollen grains of arboreal taxa (*Myrica esculanta*, *Pinus wallichiana*, *C. deodara*, *Picea smithiana*, *Abies pindrow*, *Alnus nepalensis*, *Quercus semecarpifolia* and *Betula utilis*) are likely derived from the upper tree-line and

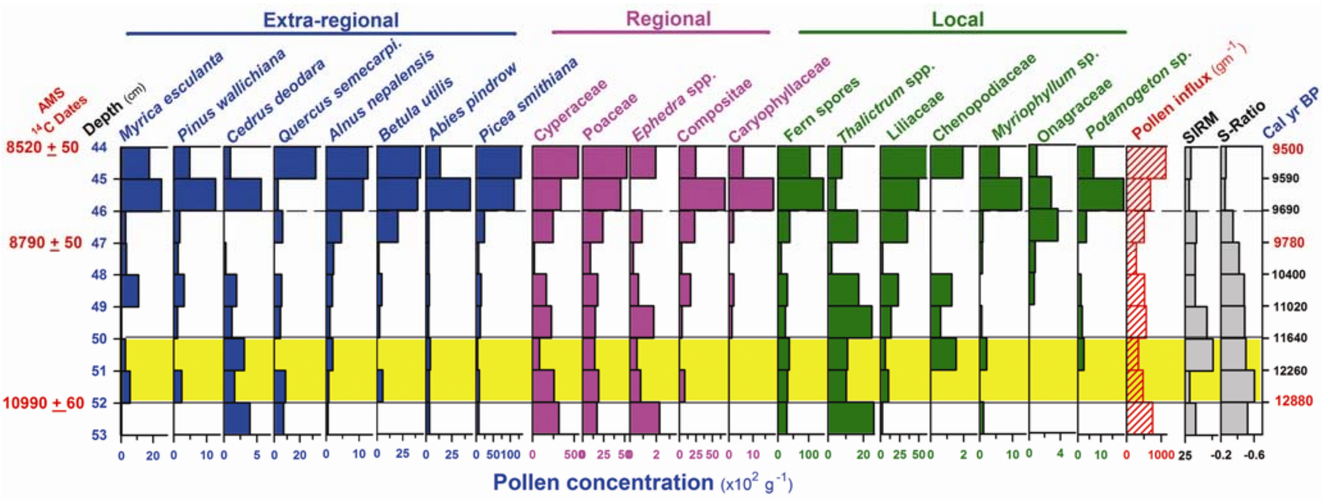

Figure 2. Diagram showing influx values of extra-regional regional, and local pollen taxa together with mineral magnetic profiles (SIRM and *S*-ratio) across the 12,880–9500 cal yrs BP interval. The horizontal (yellow) band marks the interval of cold/dry climate comparable with the Younger Dryas (YD) event. AMS radiocarbon dates of the respective samples are marked on the extreme left, while the calibrated ages are shown on the extreme right.

sub-alpine forests presently located in down valley below ~3600 m altitude. In the mountain cold deserts, the increased influx of arboreal pollen is normally attributed to increase in up-thermal winds or upward migration of alpine forests, implying the prevalence of wet and warm conditions.

Pollen spectrum of the lowermost sample (53–52 cm interval) is characterized by good presence of non-arboreal taxa derived from the local meadow and surrounding desert steppe. It is dominated by Cyperaceae (>31,000 grains/g), ferns (>2800 spores/g) and grasses (>1600 grains/g), followed by *Ephedra*. The highest presence of *Ephedra* for the entire profile is confined to this sample. Pollen grains of sedges and grasses are probably derived from the surrounding meadow, whereas those of the *Ephedra* (represented by *E. gerardiana* and *E. intermedia*) are wind-transported from the desert steppe. The local members mainly represented by pollen of *Thalictrum alpinum* and Liliaceae, are usually found in the wet alpine meadows, whereas *M. spicatum* is a typical aquatic plant that usually grows in shallow water lakes. The arboreal pollen representing mainly Deodar (*C. deodara*) and Brown oak (*Q. semecarpifolia*), is likely transported by up-thermal winds from the sub-alpine and alpine forests presently growing down valley below 3600 m altitude.

The pollen-inferred vegetation indicating good presence of local as well as regional flora clearly indicates the prevalence of significantly wet and warm climate compared to present-day extreme cold and arid conditions. This floristic scenario existed in the wet and warm conditions, particularly around 12,880 cal yrs BP (AMS ^{14}C date 10,990 ± 60), and therefore indicates the Ållerød interstadial climate.

The pollen spectrum of the immediately overlying sample (51–52 cm depth corresponding to 12,880–12,260 cal yrs BP interval) indicates a noteworthy decrease in pollen influx, suggesting the climate shift to relatively cold and dry conditions. The prominent decrease in *Thalictrum* also indicates the increased dryness in the surrounding meadow. Moreover, the decreased presence of *Ephedra* further corroborates the prevalence of drier climate in the nearby desert steppe. The apparent increase in arboreal pollen derived from the down-valley forests, however, is probably because of the intensified up-thermal winds due to drier conditions. Mineral magnetic properties indicate significant decrease in SIRM accompanied with higher negative *S*-ratio, suggesting increased detrital ferrimagnetic (multidomain) grains probably due to poor vegetation cover during drier climates. This prominent climate shift to cold and dry conditions particularly around 12,880 cal yrs BP, in all probability therefore, marks the beginning of the YD event.

The subsequent younger horizon (50–51 cm covering the 12,260–11,640 cal yrs BP period), revealing continued decrease in pollen flux, indicates further deterioration of vegetation and climate. The first appearance of Chenopodiaceae pollen also indicates the escalation of dry climate until ca 11,640 cal yrs BP. The significant increase in SIRM with corresponding decrease in negative *S*-ratio indicates increasing concentration of the stable single domain grains that can develop authigenically under prolonged anoxic conditions and cooler climates. Majority of regional herbaceous plants existed prior to 12,260 cal yrs BP and again reappeared after 11,640 cal yrs BP; this indicates the increased availability of moisture and improved temperature, suggesting the initiation of Holocene warm climate. However, the lithology and sedimentary features across this time interval do not show any appreciable change. This is also well reflected in mineral magnetic parameters suggesting the gradual change. It therefore implies that the YD/Holocene transition was gradual in this region.

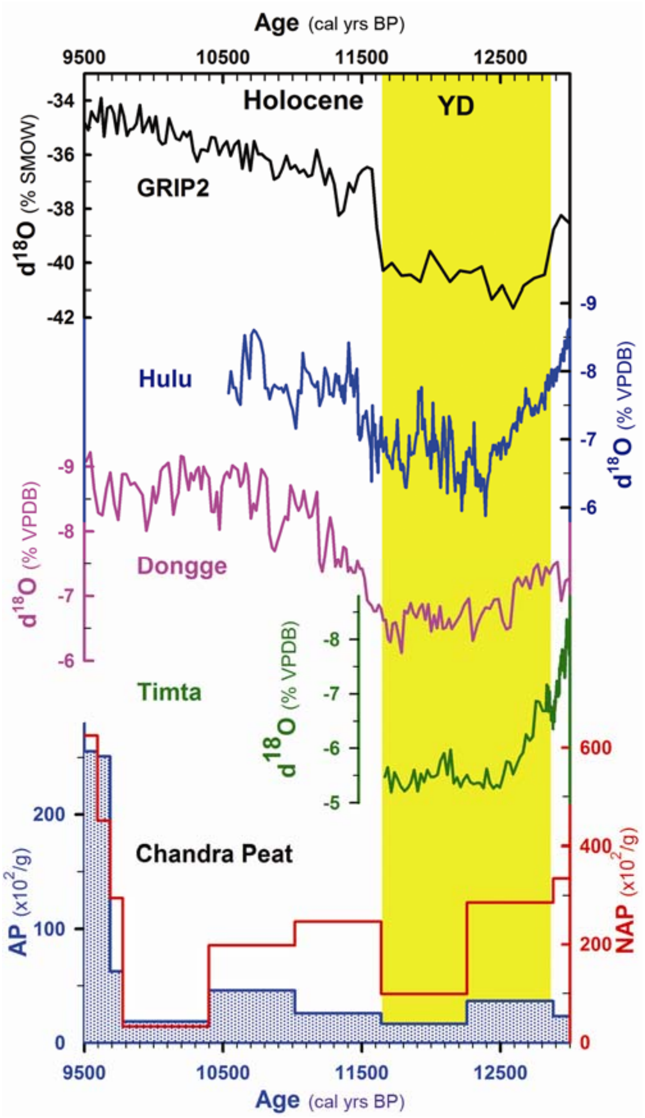

Figure 3. Comparison of pollen richness records (AP, arboreal pollen; NAP, non-arboreal pollen) spanning 12,880–9500 cal yrs BP period in Chandra peat profile with independently dated stalagmite $\delta^{18}O$ records of the Timta[7] (green), Dongge[5] (pink) and Hulu[6] (blue) caves, and Greenland ice core[25]. The shaded (yellow) horizontal bar marks the time interval of the YD event.

Pollen spectra of the following interval (50–44 cm, corresponding to the 11,640 to 9500 cal yrs BP period) reveal the reappearance of regional flora that existed prior to 12,880 cal yrs BP. With overall gradual decrease starting from ca. 11,000 cal yrs BP, the entire vegetation (i.e. local, regional as well as extra-regional) culminated with its minimum presence around 9780 cal yrs BP. This indicates that the dry climate initiated after ~11,000 cal yrs BP, was further intensified until 9780 cal yrs BP. The prominent increase in pollen concentration of almost all taxa indicates that the climate was significantly improved after 9780 cal yrs BP and further intensified from 9690 cal yrs BP onward. The richest pollen influx together with lowest values of SIRM, low negative *S*-ratios and higher remanance coercivities ($/B_{0CR}$, not plotted for brevity; suggesting influx of anti-ferromagnetic oxides) observed after 9590 cal yrs BP reveal further improvement of moisture as well as warmer temperatures. This indicates that in the NW Himalaya, the typical early Holocene warm and wet climate was initiated around 9800 cal yrs BP, and well established only after ~9700 cal yrs BP.

Thus the pollen-inferred vegetation trend observed in this lake sequence indicates that: (i) significantly wet and warm climate prevailed around 12,880 cal yrs BP, which was shifted to cold and dry conditions that continued with further intensification until ca 11,640 cal yrs BP, and (ii) the wet and warm climate reinstated after 11,640 cal yrs BP, gradually deteriorated resulting in a significant dry episode between 10,400 and 9780 cal yrs BP. The climate again improved after 9780 cal yrs BP with further intensification of wet and warm conditions after 9690 cal yrs BP. The temporal changes in climate signatures observed around 12,880 cal yrs BP attribute to the termination of Allerød interstadial with onset of the YD cold event, whereas that around 11,640 cal yrs BP indicate the end of YD interval with gradual initiation of the Holocene warm climate.

The past 15,000-yrs high resolution and uninterrupted climate history of Ladakh cold desert is precisely documented in multi-parameter palaeoclimate record of the Tso Kar Lake[8,11]. For delineation and climate interpretation of the YD interval, however, the sediments spanning 12,800–11,010 cal yrs BP period (i.e. 191.5–175 cm interval) lack precise dates. Nevertheless, the geochemical data (e.g. titanium and Ca/Si ratio)[11] indicating significant decrease in run-off with corresponding increase in carbonate precipitation around 13,000 cal yrs BP, reveal the termination of the Ållerød interstadial with initiation of the YD cold climate. These data also indicate the termination of the YD cold interval into gradually improved Holocene climate in NW Himalaya.

The prevalence of cold and dry climate between 12,880 and 11,640 cal yrs BP in NW Himalaya, closely corresponds (within dating uncertainty) to the increased $\delta^{18}O$ in the Timta stalagmite[7], suggesting weak ISM in the Central Himalaya. The generalized (i.e. without precise dates) interpretation of Late Glacial–Holocene climate also indicates a warm climate and intensification of the summer monsoon during the Ållerød interstadial, and cold and dry conditions due to weak monsoon during the YD period in the Garhwal Higher Himalaya[9,20,21] as well as in Gangetic Plain[22]. This cold and dry climate episode also compares with depleted $\delta^{18}O$ of *Globigerinoides ruber* and *Globigerina bulloides*, indicating drier climate due to weak monsoon in the Arabian Sea[23] and Bay of Bengal[24] respectively and the YD cold interval (Figure 3) marked in Hulu and Dongge stalagmites of China[5,6] as well as the Greenland ice core record[25]. This emphasizes the regional significance of the report of the YD event in

NW Himalaya with precise dates over an undisturbed peat-lake sequence.

The age-constrained floristic changes substantiated with mineral magnetic signatures over the Chandra peat deposit in NW Himalaya indicate an undisturbed and rare record of the time duration 12,880–9500 cal yrs BP. The wet and warm climate revealed by good vegetation cover in Chandra Tal area around 12,880 cal yrs BP, had changed to cold and dry conditions that continued until 11,640 cal yrs BP when the climate improved again. This 12,880 cal yrs BP climate turnover coincides with the global event of the termination of the Allerød interstadial and the beginning of the YD event. Whereas the wet and warm conditions gradually reinstated after 11,640 cal yrs BP indicate the termination of the YD interval with initiation of the Holocene warm climate. In the high latitudes of the northern hemisphere, including the Greenland ice sheet, the YD event is reported as an abrupt cold reversal[3]. However, in NW Himalaya, both the initiation as well as termination of the YD cold interval appears to be gradual. This assertion needs to be substantiated by precision chronology and high-resolution palaeoclimate data from additional prospective sites in the Himalaya.

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