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Posted Date: 14 March 2025

doi: 10.20944/preprints202503.1042.v1

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Article

Climatic and Paleoenvironmental Conditions of the Kashmir Valley During the Pleistocene-Holocene Transition: Insights from Lithostratigraphy, Geochemical Analyses, and Radiocarbon Chronology of Palaeosol Sequences

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Abstract: The Kashmir Valley, characterized by its rich loess-palaeosol sequences (LPS), provides a unique geo-archive for reconstructing Late Quaternary climate and paleoenvironmental dynamics. This study presents an extensive multi-proxy study, integrating high-resolution lithostratigraphy, geochemical analyses, stable isotope analysis of soil organic matter ($\delta^{13}\text{C}$ -VPDB), and radiocarbon (^{14}C) chronology of a sediment sequence approximately 200 cm thick, to unravel the complex interplay of climatic, pedogenic and environmental processes shaping the region spanning the Pleistocene-Holocene transition. The results establish a precise chronology of the sediment sequence between 13.4 ka and 7.2 ka, covering the transition from the Pleistocene to the Holocene Epoch. The results reveal distinct climatic and environmental conditions during this epoch. The study reveals substantial loess deposition during the cold and dry glacial climate towards the end of the Pleistocene, followed by a shift to a warmer and wetter interglacial climate at the onset of the Holocene Epoch. This climatic shift led to the development of soil units with pronounced fluvial characteristics around 10 ka, eventually transitioning to fluvial deposition. Geochemical indices such as Ca/Ti, Al/Ti, Si/Ti, and K/Ti indicate low weathering intensity prior to 11 ka, followed by a noticeable increase around 11 ka, possibly driven by enhanced precipitation. $\delta^{13}\text{C}$ values, ranging from -26.2‰ to -22.5‰ , suggest C_3 -dominated vegetation during the Late Pleistocene, indicating wetter climatic conditions. This study provides valuable insights into the intricate interactions between climate, soil development, and vegetation dynamics during the critical Late Pleistocene-Holocene transition in the Kashmir Valley.

Keywords: Pleistocene; Holocene; ^{14}C AMS dating; Kashmir Valley; palaeoclimate; stable isotope

1. Introduction

Palaeosols serve as one of the important records of the past landscape dynamics and have been extensively studied throughout the globe [1–6]. These sedimentary archives provide a unique window into the past, offering valuable insights into climatic, ecological, and geomorphic changes that have shaped our planet over the millennia [7–9]. Among the crucial periods in Earth's relatively recent history, the Pleistocene–Holocene transition stands out as a critical Epoch marked by significant climatic and environmental shifts. The Pleistocene Epoch, characterized by extensive

glaciations and ice ages, transitioned into the Holocene Epoch around 11.7 ka ago [10,11]. This transition witnessed a remarkable transformation in climate, vegetation, and faunal assemblages, setting the stage for the development of modern ecosystems [12–14]. Palaeosols, with their ability to preserve evidence of past soil-forming processes, organic materials, and environmental conditions, offer a unique opportunity to reconstruct the intricate description of this transition. Through meticulous examination of palaeosols, researchers are able to discern changes in vegetation patterns, soil properties, and the influence of climatic factors during the Pleistocene–Holocene transition [15]. Understanding the dynamics of this critical period holds significance not only for unravelling the Earth's geological history but also for gaining insights into the mechanisms that have influenced biodiversity, human evolution, and the development of contemporary landscapes [13,14,16].

Research on loess-palaeosols in the Kashmir Valley offers an excellent perspective for comprehending the paleoclimatic and environmental changes that have shaped this region over the Quaternary Period [2,5,9,17–20]. The intermontane Kashmir Valley has witnessed development and deposition of loess-palaeosols comprising predominantly silt-sized grains, forming distinctive plateau like topography [2,5]. The distinctive loess-palaeosol sequences that characterize this region have been developed by the dynamic interplay of Quaternary glacial-interglacial cycles [7,19].

The western disturbances (WD) have a substantial influence on the climate dynamics in the Kashmir region with a minor influence of the Indian summer monsoon (ISM). The ISM, which is characterized by seasonal wind reversals and moist winds from the Bay of Bengal and the Arabian Sea, greatly increases yearly precipitation, especially from June to September [21]. In contrast, the westerlies, bring winter precipitation from extratropical cyclones that move eastward. In certain portions of the northern India, especially the Kashmir region, the WDs account for approximately one-third of the yearly rainfall during the months of December through February [22,23]. Interestingly, the climate patterns archived in the loess-palaeosols of the Kashmir valley have potential to reveal variations in precipitation intensity, just like continental proxies in areas currently heavily impacted by the ISM. Similar data from the Central Himalayas and the Tibetan Plateau show that the climate was warm-humid and cold-dry termed as Marine Isotope Stage (MIS), which sheds light on previous climatic cycles [24]. Recent studies [2,5] have attempted to examine climate variations by analysing loess-palaeosol sections in the north-western Kashmir Valley using multi-proxy approach, incorporating geochemistry, mineral magnetic, stable isotope and clay mineralogy. These studies suggest that a cold, dry environment prevailed after the Last Ice Age, there was facilitating loess deposition. This was followed by multiple warm, humid intervals that supported soil formation, with a particularly notable warm-humid phase occurring approximately 35 ka [2]. Dar et al. [25] studies three loess-palaeosol sections at Shankerpora (SP), Khan Sahib (KS) and Pattan (PT) in the Kashmir Valley through detailed lithostratigraphic fieldwork and micromorphological analysis of thin sections. Additionally, several other studies have examined the litho-stratigraphy, chronology, magnetic susceptibility, and morphological properties of loess-palaeosols sequence in Kashmir Valley [19,20,26–28].

The previous investigation of the Makaibagh loess-palaeosol section [2] is centred on the palaeosol development in a 6-meter vertical section (2 to 8 m depth). The section, originating solely from aeolian processes, underwent evolution between 65.8 ± 7.2 ka and 14.7 ± 5.4 ka. Notably, the upper 2 meters of the section, younger than 14.7 ± 5.4 ka, show mixed fluvial sedimentation, which has remained unexplored in the previous studies. The novelty of this research therefore lies in its comprehensive exploration of the previously unexplored upper 2-meter section (0–2 m), which represents a critical transition from predominantly aeolian sedimentation during the Pleistocene to mixed fluvial deposition in the Holocene. Unlike earlier studies focused on palaeosol development within aeolian-dominated sediments, this research integrates stratigraphic profiles, new geochemical, isotope and geochronological data to investigate the climatic and sedimentological shifts occurring during the Pleistocene-Holocene transition. By reconstructing palaeoenvironmental conditions during this period, the study not only establishes a detailed timeline of sedimentary processes but also provides unique insights into the interplay of climatic variability and landscape

evolution in the Kashmir Valley. This approach fills a significant gap in understanding the region's response to late Quaternary climate dynamics.

2. Study Area

The Kashmir Valley has a unique and varied lithological composition that spans multiple geological ages, from metamorphosed Precambrian rocks to more recent sediments [29]. It is located between the Pir Panjal Range in the southwest and the Great Himalayan Range in the northeast. The lithology that predominates the areas between the two mountain ranges is made up of Karewa deposits (Figure 1), which are dominant in the central part of Kashmir, and Permian Panjal traps, which are primarily composed of basaltic rock [18,25,26,30]. Terrigenous Plio-Pleistocene Karewa sediments span an area of 2500 km² and have a significant thickness of about 2000 meters [2]. These sediments are divided into the lower and upper Karewas and are composed of unconsolidated gravel, sand and mud successions that form vast terraces that resemble plateaus. These deposits cover the Triassic limestone and the Late Permian Panjal traps. They are distinguished by horizontal bedding and a small inclination toward the Pir–Panjal range [31]. Moreover, a number of Quaternary loess-palaeosol sequences (LPS) that span the valley vary in thickness on an average from roughly 22 m in the southwest to roughly 5 m in the northeast [2]. As the youngest member of the upper Karewa group, the Dilpur formation covers an area of approximately 500 km² covering the Karewa sediments. Its maximum thickness varies from 22 m in the southeast to 10 m in the northeast of the Kashmir Valley [32]. On the Pir-Panjal side, the nearly horizontal loess layers rest directly over the gravel bed of the Shopian member [33]. The Himalayan and Pir Panjal ranges significantly influence the climate of the Kashmir Valley.

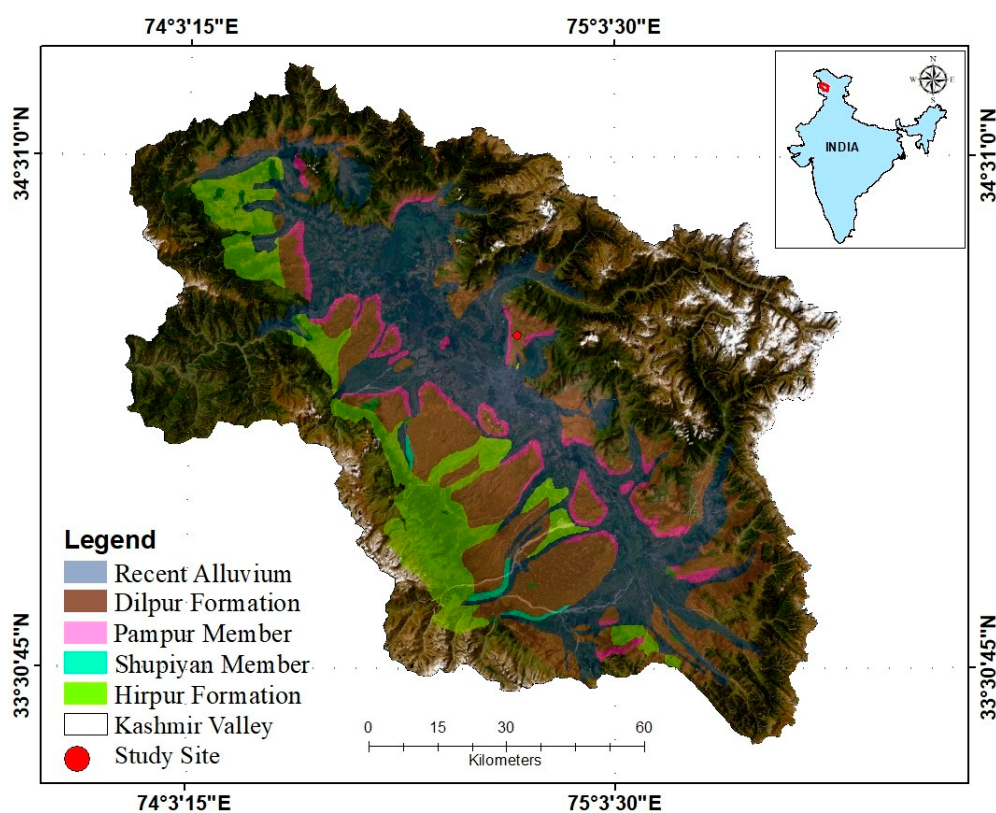


Figure 1. Distribution of Karewa sediments across the Kashmir Valley and the location of the Makaibagh study site.

The Kashmir Valley's subtropical climate is mostly determined by its physical location and is heavily impacted by the westerlies. Annual temperatures range from -10°C in winter to 35°C in summer [34]. Westerly winds from the North Atlantic and Mediterranean Seas contribute to the precipitation that falls throughout the winter months in the form of rain and snow [35]. Due to the western disturbances, more than 60% of the precipitation falls during winter and spring, with the ISM partly responsible for the remaining 40% of the precipitation during the warm summer months [30]. The Kashmir valley floor currently experiences around 710 mm of mean annual precipitation and 13.5°C of mean annual temperature [30]. The autumnal months of September and October are usually dry, and the summers are somewhat hot with sporadic showers of mostly convective rains. Monsoon winds also provide summertime rains in the Pir-Panjal range and the plains that surround it. However, the Southwest Monsoon (SWM) has little effect on the total amount of precipitation in the Kashmir Valley [34,35]. Although the vegetation in the Kashmir Valley shows distinct altitudinal zonation, C₃ type vegetation is generally dominant in the region [36].

The present study was conducted on the Makaibagh section, near Nagbal village in the central Kashmir, a key part of the extensive loess-palaeosol sequence (LPS). This 800 cm thick deposit features five well-developed palaeosol horizons, consisting of wind-blown (aeolian) sediments interbedded with palaeosols (ancient soil layers), formed due to alternating dry and wet climate phases over thousands of years [9]. These distinct layers provide valuable insights into past environmental conditions, with loess layers indicating arid periods of high wind activity, while palaeosols represent wetter intervals with increased vegetation [15].

The Makaibagh section serves as an important archive for studying Late Quaternary climate shifts, offering a record of wind patterns, precipitation changes, and landscape evolution in the Western Himalaya [9]. Optically stimulated luminescence (OSL) dating has placed its formation between $\sim 65.8 \pm 7.2$ ka at base level and $\sim 14.7 \pm 5.4$ ka at 205 cm depth from top [2]. The lower 600 cm primarily consists of aeolian loess interspersed with palaeosol layers, reflecting climate variations, while the upper 200 cm contains redeposited mixed loess and fluvial sands, indicating a transition from aeolian to fluvial deposition, likely caused by increased precipitation or glacial melting post- 14.7 ± 5.4 ka [2]. The Makaibagh LPS plays a crucial role in reconstructing Late Quaternary palaeoenvironmental changes and correlates with other regional loess deposits in central Kashmir, enhancing our understanding of past climate dynamics in the Western Himalaya.

3. Materials and Methods

3.1. Mapping and Sampling of Palaeosol Section

The ~210 cm thick section underwent a detailed field investigation to identify and distinguish various soil and palaeosol horizons (Figure 2). Despite the absence of vegetation on the exposed vertical cliff, the entire section was carefully scraped to reveal fresh soil horizons for mapping and sampling. The section was meticulously mapped during fieldwork, and key attributes such as color, texture, sedimentary structure and other notable features were recorded. Sediment samples were systematically collected at 10 cm intervals for geochemical analyses, while targeted samples were collected within 1 cm sections at specific depths for radiocarbon dating. A total of 21 samples, each weighing between 400 to 500 grams, were collected in airtight zip-lock polybags from the entire section (Figure 2), oven-dried in laboratory and subsequently analysed for geochemical analyses. Soil and sediment color and texture variations were determined using the Munsell color chart. Grain-size distribution was assessed using the sieve and pipette method [37], enabling the estimation of sand, silt, and clay percentages.

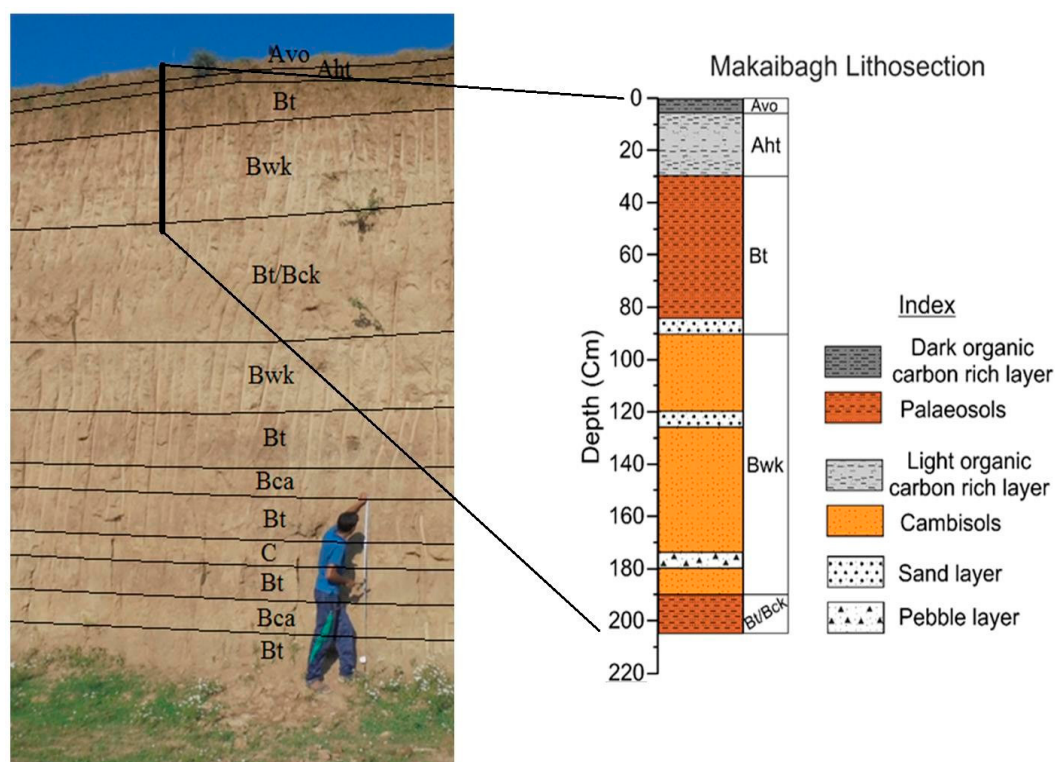


Figure 2. High-resolution photograph and litholog of the Makaibagh section.

3.2. Chronology: Accelerator Mass Spectrometry (AMS) Dating (^{14}C)

Radiocarbon (^{14}C) dating of bulk organic-rich sediments was carried out on four samples at the Inter University Accelerator Centre (IUAC), New Delhi, using 500kV Accelerator Mass Spectrometry (AMS) system [38]. The methodology employed for chronology followed the procedures outlined by Shah et al. [1]. Initially, the samples underwent an acid-base-acid treatment involving the sequential application of 1M HCl and 0.5N NaOH solutions. At each step, the samples were thoroughly washed and neutralized with deionized water before being freeze-dried. A measured quantity of the dried samples was then carefully packed into tin capsules and combusted at 900°C in the presence of high purity oxygen environment inside the combustion tube of the elemental analyser. The resulting carbon dioxide was carried by helium gas to a graphitizing machine, where it was converted into graphite using iron as a catalyst and the hydrogen as a reducing agent [1].

The AMS- acquired ^{14}C dates were calibrated using OxCal v 4.4.4 and the IntCal 20 atmospheric calibration dataset [39]. The age-depth model was also generated using the same software. The calibrated ages were expressed in kilo years before the present (ka BP) with a 2σ uncertainty (95.4% probability). For age modelling, a P-sequence deposition model was employed to account for the intricacies of the actual processes involved in sediment deposition [40].

3.3. Major Oxide Analysis

Geochemical analyses of major oxide concentrations were conducted using the X-ray fluorescence spectrometry technique (Axios, Panalytical). For this procedure, finely powdered samples (10 g) were thoroughly mixed with 1 gm of wax binder in an agate mortar. The resulting mixture was then placed in standard aluminium cups (30 mm) and compressed at 150 kN pressure using a hydraulic press to form XRF sample pellets. Data reproducibility was verified and ensured through repeated analyses of USGS (MAG-1) and laboratory (SDO-1) standards, with analytical precision for major oxides maintained below 5% at the 2σ level.

The obtained major oxide composition was used to compute the Chemical Index of Alteration (CIA) following equation 1 proposed by Nesbitt and Young [41], and the Chemical Index of

Weathering (CIW) using equation 2 according to Harnois [42]. This analytical approach provides understanding of chemical weathering intensity and mineral alteration within the sediments, yielding valuable insights into the impact of source rock composition, the duration of weathering, prevailing climatic conditions, and the rates of tectonic uplift in the source region.

$$CIA = \frac{Al_2O_3}{Al_2O_3 + CaO + Na_2O + K_2O} \times 100 \quad (1)$$

$$CIW = \frac{Al_2O_3}{Al_2O_3 + CaO^* + Na_2O} \times 100 \quad (2)$$

In Eq. (2), CaO* represents the content of CaO constituting silicate fractions. The measured CaO values in the studied soil and sediments range between 2% to 10%, suggesting that a notable portion may be attributed to pedogenic carbonates within the sediments [43].

3.4. Total Organic Carbon (TOC), Nitrogen (N), CaCO₃ and Stable Isotope ($\delta^{13}C$) Analysis

Total Organic Carbon (TOC), nitrogen (N) and stable isotopic compositions ($\delta^{13}C$) of bulk organic matter were analyzed using a continuous-flow isotope ratio mass spectrometer (Delta V–Thermo Fisher) coupled with an elemental analyzer (Flash 2000). Sample preparation involved treating dry and finely powdered samples with 1 M HCl solution at 70–80°C for 2 hours to remove carbonates. After treatment, samples were washed with double deionized water, followed by centrifugation to neutralize samples.

The CaCO₃ content in the sediments was determined employing a titration method, following the procedure outlined by Loring and Rantala [44]. In this process, 5 grams of dried sample was placed in a 250 ml beaker, and 100 ml of 1M HCl solution was added. The mixture was stirred at intervals of 3 to 5 minutes for 45 minutes, followed by a resting period of 15 minutes. Then, 20 ml of the supernatant from the sample solution was transferred to a 250 ml conical flask, and 7–8 drops of Bromothymol blue indicator were added. The supernatant was then titrated against sodium hydroxide (NaOH) until the appearance of a blue color, indicating the endpoint. Each sample underwent two replicate titrations, and as a control, two blank solutions without sediment samples were titrated. The CaCO₃ was calculated using Eq. 3.

$$CaCO_3 = \frac{(\text{Blank Value} - \text{Titrated Value})}{\text{Total weight of the sample}} \times 0.05N \times 100 \quad (3)$$

For $\delta^{13}C$ analyses, approximately 5–10 mg of carbonate-free samples were combusted in the Flash 2000 elemental analyzer at 1020 °C under an oxygenated environment. The resulting CO₂ gas was then analyzed online using a Delta V Plus IRMS. Data were normalized to the Vienna Pee Dee Belemnite (VPDB) reference scale using International Atomic Energy Agency standards (LSVEC, NBS-19, and CH-3), following the method outlined by Paul et al. [45]. Analytical precision was assessed and monitored by analyzing Oxalic Acid (IAEA-C8), yielding a standard deviation of $\pm 0.12\%$, (1σ , $n = 5$). Repeated standard measurements yielded $\delta^{13}C$ precisions of less than 0.2‰, while TOC and N content measurements maintained an analytical precision of $\pm 10\%$.

4. Results

4.1. Sedimentological Features

A detailed description of the studied sediment section is given in Table 1. The different soil and palaeosol horizons show marked variations in color, texture, and grain size. On the basis of physical and chemical characteristics, five polycyclic palaeosol units were identified: Avo (5–1 cm), Aht (30–6 cm), Bt (90–31), Bwk (190–91 cm), Bt/Bck (205–191 cm) (Figure 3a). The uppermost 5 cm thick soil horizon (unit-5, Avo) is characterized by dark brown color (10YR 2/2, 4/2) due to high organic carbon content. This horizon manifests high silt and moisture content, with abundant plant root traces and

is porous. The 25-cm thick (unit-4, Aht) layer is dark brown in color (10YR 3/2, 3/1), enriched in organic carbon, and features visible root channels filled with fine silt. This layer is also characterized by well-developed peds with gradual transition to the lower horizon. The 60-cm thick horizon (unit-3, Bt) appears dull brown in color (7.5 YR 5/3, 5/4) and contains more sand content than silt and clay fraction (Figure 3b-d). The layer is characterized by a moderately developed palaeosol interbedded with sand layers and has low CaCO₃ content. Reddish-brown coloured Fe/Mn nodules are scattered within this horizon. A 5-cm thick (85–90 cm) sand layer at the bottom of the third horizon suggests prominent fluvial activity. A 100-cm thick layer (Unit-2, 90–190 cm) is light grey in color (7.5 YR 8/1), contains weakly altered sediments and has high CaCO₃ and pedogenic nodules. A distinct sand horizon (120-125 cm) indicates high fluvial reworking of aeolian sediments. Furthermore, a 5-cm thick pebble/ gravel bed (175-180 cm) at the base suggests high fluvial activity due to high-energy meltwater deposition from nearby mountains, marking the end of loess deposition. A sharp contact with the overlying horizon is also observed. The 15-cm thick (190–205 cm) basal layer (Unit-1, Bt/Bck), is grey is brown to grey in color (7.5 YR 8/2), and is characterized by a weakly developed palaeosol with very high CaCO₃ content. The horizon indicates reduced weathering and the final stage of sediment deposition within the section.

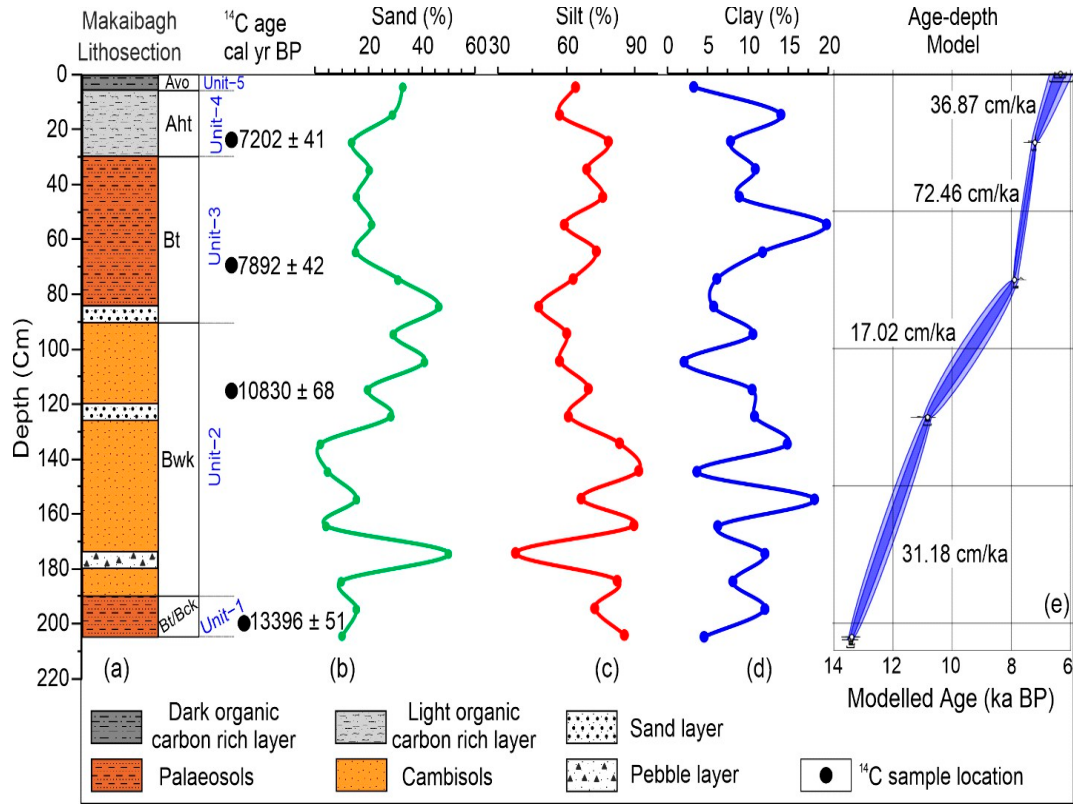


Figure 3. (a) Detailed lithosection with ages, depth-wise variation in sediment grain size, (b) sand %, (c) silt %, (d) clay %, and (e) age-depth model showing sedimentation rates.

Table 1. Depth-wise stratigraphic description of the Makaibagh litho-section.

Depth (cm)	Thickness (cm)	Age (ka)	Horizon	Description
1–5	5	<6.5	Avo	Dark brown (10YR 2/2, 4/2), organic carbon rich, silt with root traces and pores, with high moisture content.
6–30	25	12 – 6.5	Aht	Dark brown (10YR 3/2, 3/1) with higher organic carbon content, with visible root channel filled with fine silt. Well-developed ped with a gradational contact with the lower horizon.
31–90	60		Bt	Dull brown (7.5 YR 5/3, 5/4), moderately developed palaeosol with bedded sand layers, low CaCO ₃ content and contains

				significant amount of sand content. This horizon developed during MIS-1.
91–190	100	Bwk	Light gray (7.5 YR 8/1), Weakly altered sediments with high CaCO ₃ and pedogenic nodules, N ₂ nodules and bedded sand horizons. A pebble/ gravel bed (3–4 cm thick) is deposited at the base of this unit. A sharp contact with the lower horizon.	
191–205	15	13.4 – 12	Bt/Bck	Greyish brown or gray (7.5 YR 8/2), weakly developed palaeosol with very high CaCO ₃ content

4.2. Chronology and Sedimentation Rate

The calibrated AMS ¹⁴C dates are presented in Table 2, indicating that the top two meter of the section represent sediment deposition from the Late Pleistocene to Mid–Holocene. All analysed sediment samples maintain stratigraphic order, with no observed age reversals. Aht horizon sample (unit–4) at 25-cm depth yielded an age of 6422 ± 41 ¹⁴C yr BP (7202 ± 41 cal yr BP). The Bt horizon (unit-3) palaeosol sample at 75-cm depth yielded an age of 6849 ± 41 ¹⁴C yr BP (7892 ± 42 cal yr BP). The cambisol (unit–2) sample at 125 cm depth provided an age of 9639 ± 53 ¹⁴C yr BP (10830 ± 68 cal yr BP). The Bt/Bck horizon (unit–2) sample from 205 cm depth yielded an age of 11521 ± 48 ¹⁴C yr BP (13396 ± 51cal yr BP).

Table 2. Calibrated AMS ¹⁴C dates with 2σ uncertainty (95.4 % Probability).

Lab id.	Depth (cm)	Libby Age (years BP)	Calibrated Age (years BP)		(μ) Calibrated (years BP)
			from	to	
17C1149	25	6422 ±41	7307	7164	7202 ±41
17C1150	75	6849 ±41	7933	7771	7892 ±42
17C1151	125	9639 ±53	10960	10708	10830 ±68
17C1153	205	11521 ±48	13488	13308	13396 ±51

The age–depth model applied to the entire lithosection (Figure 3e) reveals fluctuating sedimentation rates during the Pleistocene–Holocene transition, with a notably high sedimentation rate during the Early to Mid–Holocene period. A significant increase in sediment accumulation rates (~72.46 cm/ka) is observed around 75 cm depth (Figure 3e), coinciding with a shift in sediment grain size, indicating changes in sediment production processes in the catchment area. Overall, diverse sedimentation rates are recorded across different units in the section (Figure 3e).

4.4. Bulk Geochemistry

The major oxide concentrations (wt%) in Makaibag palaeosol section are detailed in Table ST2. The section displays variability in normalized Al₂O₃ and SiO₂ contents, ranging from 17.09-19.59 wt % (mean: 18.15 ± 0.60) and 53.96-61.23 wt %, (mean: 57.83 ± 1.64) respectively. The abundance of Fe₂O₃ ranged from 7.01-10.75 wt % (mean: 9.13 ± 0.89), while CaO and MgO exhibited abundance ranging from 12.41-7.11 wt % (mean: 4.55 ± 1.31) and 2.95 to 6.46 (mean:4.88 ± 0.76) wt %, respectively. K₂O and Na₂O concentrations ranged from 2.04 to 3.27 wt % (mean: 2.69 ± 0.31) and 1.01 to 1.64 wt % (mean: 1.40 ± 0.16), respectively. P₂O₅ concentration ranged from 0.11–0.22 wt % (mean: 0.18 ± 0.02)), that of TiO₂ from 0.78–1.21 wt % (mean: 1.03 ± 0.11), and MnO concentration was in the range of 0.14–0.21 wt % (mean: 0.17 ± 0.02) in the Makaibag palaeosol section.

The selected geochemical ratios were calculated and are shown in Figure 4. The Chemical Index of Alteration (CIA), which ranged from 69.10 to 74.20 (mean: 70.65 ± 1.40), was used to assess the degree of chemical weathering. The Chemical Index of Weathering (CIW) showed distinct variation across different depths and varied from 69.10 to 74.20 (mean: 70.65 ± 1.40). Overall, these geochemical ratios effectively captured the Pleistocene–Holocene climatic transition, revealing diverse depositional conditions.

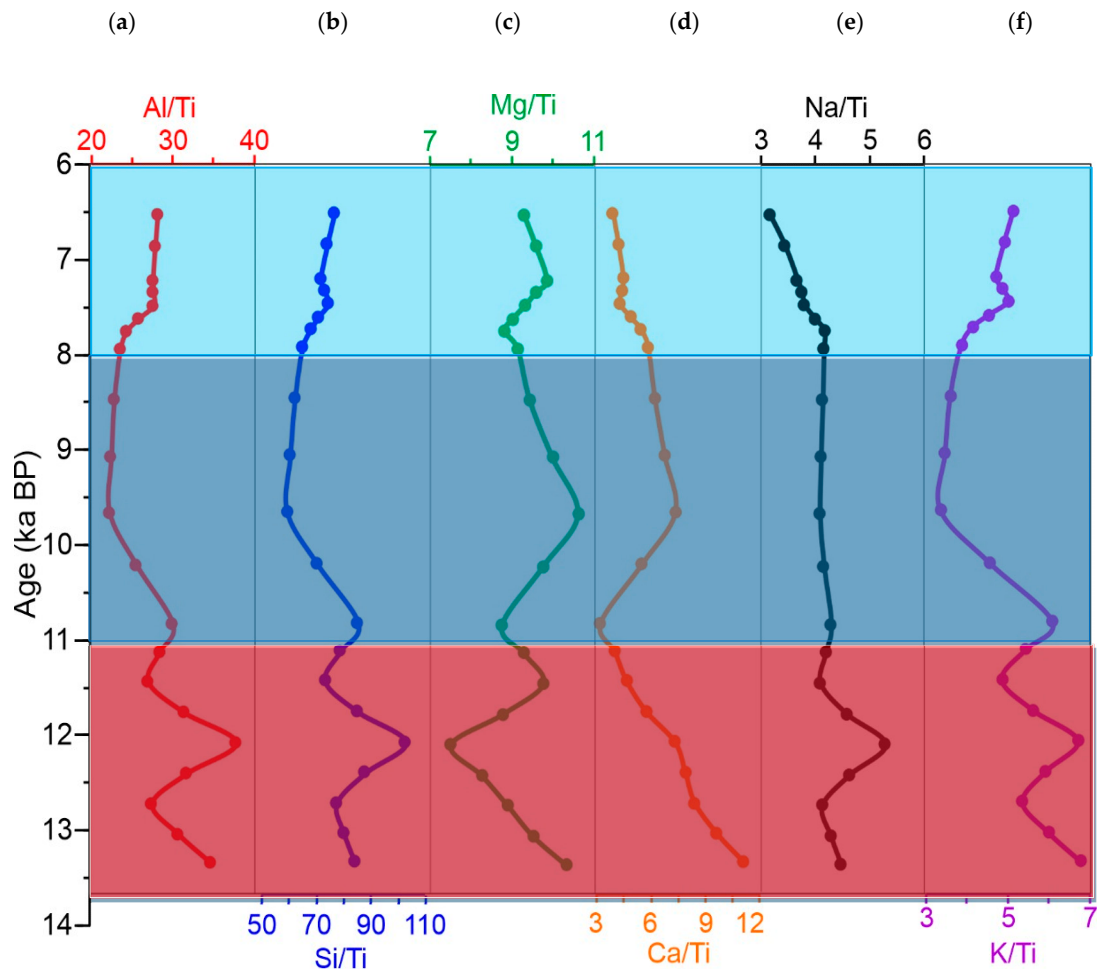


Figure 4. Temporal variation of different geochemical indices a) Al/Ti, b) Si/Ti, c) Mg/Ti, d) Ca/Ti, e) Na/Ti and f) K/Ti.

4.5. Bulk Organic Geochemistry (TOC, N) and CaCO₃

The TOC, nitrogen, and CaCO₃ percentages are presented in Table 3 and shown in Figure 5. TOC content displays variability ranging from 0.07% to 0.41% (at 91–110 cm depth), with an average of 0.21%. Particularly, higher TOC concentrations are associated with the top Avo and Aht horizons (1–30 cm depth), ranging from 0.26% to 0.37%. Original parent material (cambisols) exhibits minimal pedogenic alteration and contains a lower TOC content (<0.020%). Nitrogen content (N %) remains stable ranging from 0.04% to 0.1%, with higher values (0.1% to 0.2%) in the Avo and Aht horizons (0–30 cm depth). The depth-wise N and TOC shows a similar pattern (Figure 5). The CaCO₃ % content of the sediment samples varies from 0.50% to 13% with relatively high amounts of CaCO₃ (7% to 13%) observed at depths of 191–450 cm, corresponding to the time span from 35 ka to 13 ka [2].

Table 3. Variation in Total organic carbon (TOC) (%), Carbon (C) (%), Nitrogen (N) (%), C/N ratio, CaCO₃ content (%) and δ¹³C-VPDB (‰) in the Makaibagh litho-section.

Sample id	Depth (cm)	Age (ka)	TOC (%)	C (%)	N (%)	C/N	CaCO ₃ (%)	δ ¹³ C (VPDB, ‰)
MAK-1	5	6.5	0.28	0.28	0.19	1.47	0.50	-22.47
MAK-2	15	6.8	0.32	0.32	0.12	2.67	1.00	
MAK-3	25	7.2	0.37	0.37	0.04	9.25	1.00	-25.13
MAK-4	35	7.3	0.26	0.26	0.04	6.50	1.50	
MAK-5	45	7.5	0.15	0.15	0.04	3.75	1.50	-23.42

MAK-6	55	7.6	0.13	0.13	0.04	3.25	2.50	
MAK-7	65	7.8	0.11	0.11	0.05	2.20	1.00	-22.63
MAK-8	75	7.9	0.09	0.09	0.05	1.80	0.50	
MAK-9	85	8.5	0.08	0.08	0.05	1.60	0.50	
MAK-10	95	9.1	0.07	0.07	0.05	1.40	0.50	
MAK-11	105	9.7	0.07	0.07	0.05	1.40	1.00	-24.38
MAK-12	115	10.2	0.11	0.11	0.05	2.20	1.50	
MAK-13	125	10.8	0.14	0.14	0.06	2.33	1.00	-26.19
MAK-14	135	11.2	0.13	0.13	0.06	2.17	1.50	
MAK-15	145	11.5	0.11	0.11	0.06	1.83	0.50	-23.69
MAK-16	155	11.8	0.12	0.12	0.06	2.00	0.50	
MAK-17	165	12.1	0.13	0.13	0.06	2.17	1.50	-24.03
MAK-18	175	12.4	0.12	0.12	0.06	2.00	5.50	
MAK-19	185	12.8	0.11	0.11	0.06	1.83	6.00	
MAK-20	195	13.1	0.12	0.12	0.06	2.00	7.00	
MAK-21	205	13.4	0.13	0.13	0.06	2.17	7.50	-24.04
Minimum			0.07	0.07	0.04	1.40	0.50	-26.19
Maximum			0.37	0.37	0.19	9.25	7.50	-22.47
Mean			0.15	0.15	0.06	2.67	2.10	-24.00
SD			0.08	0.08	0.03	1.83	2.22	1.10

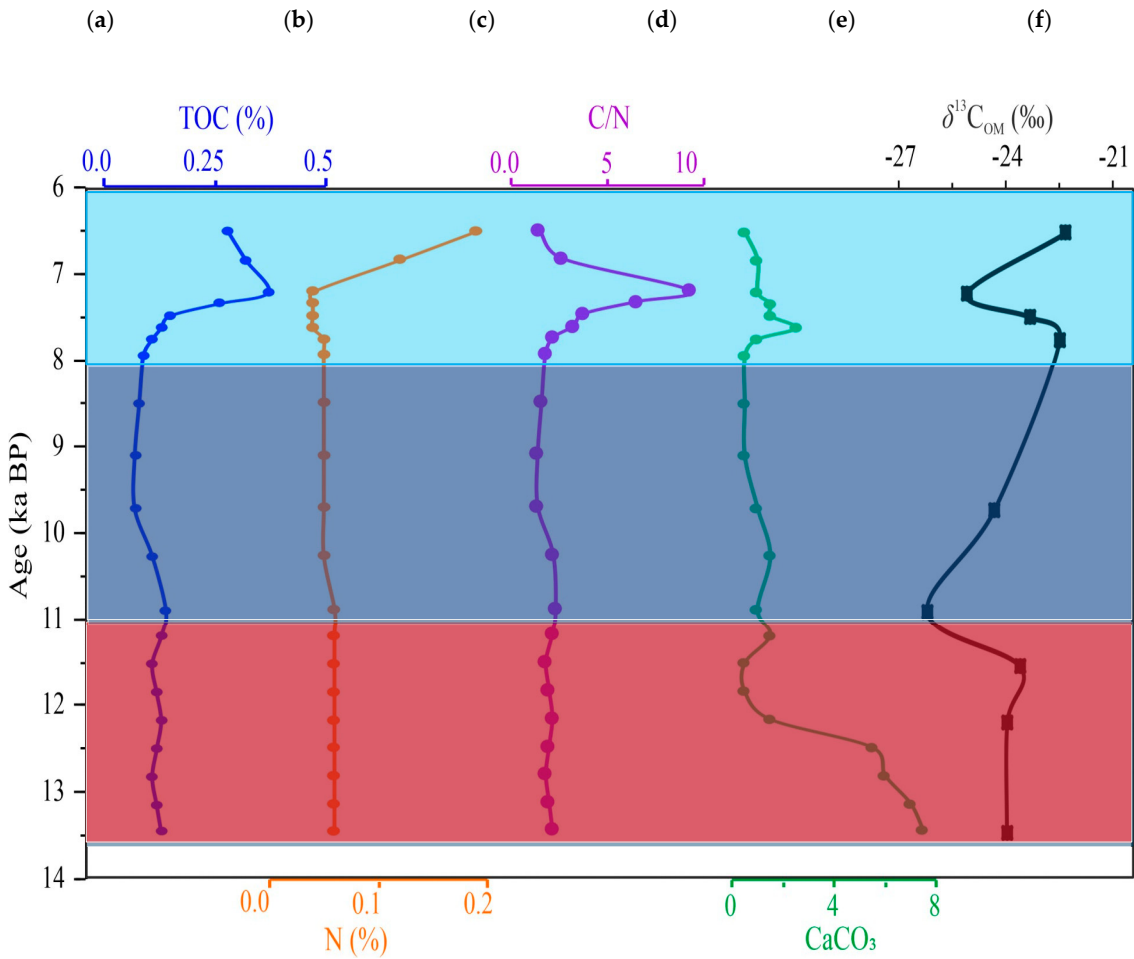


Figure 5. Temporal variation of a) TOC, b) N, c) C/N, d) CaCO₃, and e) δ¹³C values.

4.6. Stable Carbon Isotope Composition ($\delta^{13}\text{C}$)

The $\delta^{13}\text{C}$ in the bulk sediment organic matter ranges from -26.19‰ to -22.47‰ (mean: $-24 \pm 1.10\text{‰}$), with an overall variability of -4.12‰ (Table 3). This range suggests a dominant contribution of organic matter from C_3 plants. In the loess horizon (at 145 cm depth), $\delta^{13}\text{C}$ values are relatively positive, measuring -23.69‰ . The depth-wise $\delta^{13}\text{C}$ plot (Figure 5) reveals more negative values, specifically at a depth between 201–210 cm (-24.04‰) and 120–130 cm (-26.19‰), and more positive values around 20–10 cm (-22.04‰), which is associated with palaeosol formation. Despite mild variations of $\delta^{13}\text{C}$ values with depth, there is no indication of a major shift from C_3 to C_4 vegetation.

5. Discussion

5.1. Geochemical Characteristics and Palaeoweathering

Palaeosols serve as valuable sedimentary archives for reconstructing palaeoclimatic conditions, including palaeoweathering patterns and pedogenesis development [2,16,46]. Our dataset (Figure 4) highlights significant variations in major oxide concentrations across the studied sediment section. These variations can be attributed to the lithological differences between the Pir Panjal flank, dominated by basic igneous rocks and the Himalayan flank characterized by limestone dominance [18]. The palaeosol sediments, dating back to the Pleistocene and Holocene, primarily originate from the weathering of basaltic-andesite rocks of the Pir Panjal Mountain Range, which are high in Fe and low in Mg [47]. However, the lower Fe content in the Pattan loess–palaeosol section (mean Fe_2O_3 : 7.5 wt%) suggests either a shift in sediment source or the incorporation of material from the Himalayan flank [5]. Similarly, a significant change in Fe_2O_3 , Al_2O_3 and CaO content between 10 ka and 11 ka in Makaibagh palaeosol section suggests a provenance shift, significantly influencing oxides variability. Additionally, the Ca mobility, reflected in large variations in CaO content during warm periods, aligns with the findings by Shah et al. [2], suggesting dry climatic conditions in the late Pleistocene.

To assess the weathering history, we employed chemical weathering indices such as CIA and CIW. The CIA values ranged from 69.1 to 74.2 (mean: 70.7 ± 1.4), suggesting moderate weathering conditions, while the CIW values varied between 76.1 and 84.7 (mean: 79.7 ± 2.3), indicating moderate to high weathering patterns in the Makaibagh palaeosol section. These observations suggest a relatively stable climate during the Late Pleistocene. However, a higher CIW value after 9.5 ka, coinciding with the observed variations in the K/Ti ratio, suggests a shift towards warmer and wetter conditions. The Al_2O_3 – $\text{CaO}^* + \text{Na}_2\text{O}$ – K_2O (ACNK) ternary diagram (Figure 6), shows that the studied palaeosol samples follow a weathering trend parallel to the A–CN line, indicating the leaching of Ca and Na while K remains retained in clay minerals during silicate weathering [5]. Compared to southeastern sections [48], and the Pattan section in the northwestern part of the valley [5], the Makaibagh palaeosol section exhibits a relatively lower degree of weathering.

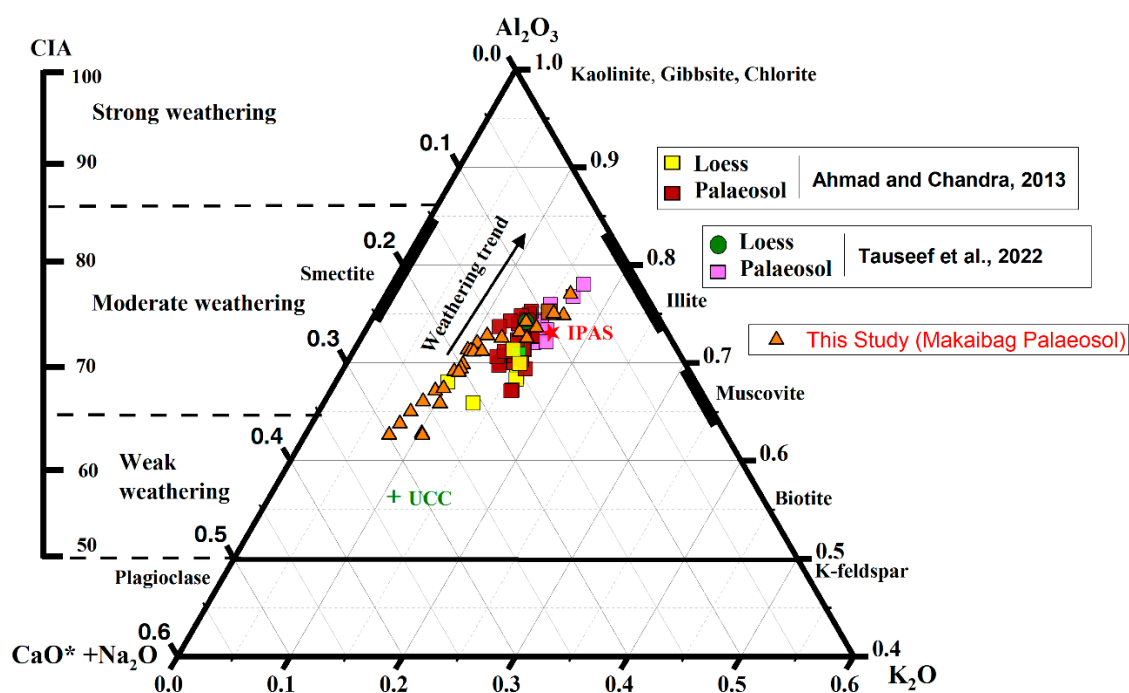


Figure 6. ACNK ($\text{Al}_2\text{O}_3\text{--CaO}^*\text{+Na}_2\text{O--K}_2\text{O}$) ternary diagram [41] for the studies section, with comparisons to other loess- palaeosol deposits [e.g., 5,48]. The diagram also includes the average composition of the Upper Continental Crust [UCC; 56] and Indian post-Archean Shale [IPAS; 57] for reference.

The removal of base elements (Ca, Na, K, and Mg) from soil profiles is primarily influenced by water availability, which is often correlated with rainfall. In a humid climate with increased rainfall, base elements are rapidly leached, whereas immobile elements like Al and Ti tend to accumulate [16,49]. Ratios of base elements (Ca, Na, K, and Mg) to Ti within a soil profile provide insights into base loss due to leaching. In the studied Makaibagh palaeosol section, Mg/Ti and Ca/Mg ratios generally exhibit an upward increasing trend with occasional sharp excursions while Na/Ti exhibit a declining trend, indicating the preferential leaching of Na, which is more mobile than Mg and Ca in a weathering profile.

5.2. Pleistocene and Holocene Transition

Phase – I: Late Pleistocene (140 cm -210 cm; 13.4 - 11 ka)

The sedimentary deposits below 210 cm in the 8-meter section under investigation were exclusively of aeolian origin, consistent with previous studies [2]. Notably, the sediments between 190 to 210 cm exhibit a greyish brown or grey hue (7.5 YR 8/2), and were initially deposited as aeolian sediments. Over time, these deposits underwent weak pedogenesis, forming poorly developed palaeosol, with relatively high CaCO_3 content (>7%). Following this phase, a cambisol horizon layer developed, characterized by light grey sediments (7.5 YR 8/1) with elevated CaCO_3 content and pedogenic nodules. At the base of this unit, a 3-4 cm thick pebbles/gravel layer marks a distinct boundary with the underlying horizon. This gravel layer represents the earliest documented fluvial activity within this aeolian section, estimated to have occurred around 12.8 ka, during the last 65 ka. The minimal pedogenic alteration observed throughout this horizon indicates a gradual transition from relatively cooler, drier environmental conditions towards a warmer climate. This environmental transition is further corroborated by variations in Ca/Ti, Al/Ti, Si/Ti, and K/Ti ratios, which show a downward progression (Figure 4). The persistent high calcium carbonate content in sediments during this phase aligns with arid climatic conditions prevalent during deposition, reinforcing the hypothesis of limited precipitation and strong aeolian influences in the region.

Phase – II: Onset of the Holocene (80 cm -140 cm; 8 - 11 ka)

During this period, recognized globally as the early Holocene, significant climatic changes occurred, marking the onset of a warmer and wetter epoch. In Phase II, distinct changes from Phase I, indicate a relatively warmer climate, reflecting in the sedimentary records. The sedimentary deposits primarily consist of reworked fluvial sediments rich in sand content, exhibiting well-developed Bwk and Bt horizons. These horizons display color variations from light grey (7.5 YR 8/1) to dull brown (7.5 YR 5/3, 5/4), indicative of progressive pedogenesis. Two prominent sand horizons at 120 cm and 85 cm depth, signify heightened fluvial activity corresponding to warm, humid and wetter climate conditions of this period. Moreover, a significant decrease in CaCO_3 content compared to Phase I is noticed, which suggests dissolution and subsequent erosion of the previously deposited CaCO_3 , further supporting the inference of enhanced precipitation and increased chemical weathering. The entire horizon exhibits significant pedogenic alterations, which is suggestive of the presence of a relatively warmer and wetter environmental conditions prevailing during this phase. These findings are further supported by geochemical variations, particularly in Ca/Ti, Al/Ti, Si/Ti, and K/Ti ratios, which display a progressive downward trend (see Figure 4), further indicating a shift towards more humid conditions.

Phase – III: Holocene climate Optimum (0 cm - 80 cm; 6.5 - 8 ka)

Globally recognized as the Holocene Climate Optimum, this phase is marked by predominantly warm, humid and wet climatic conditions. The sedimentary deposits from this phase exhibit dark brown hues, indicating substantial pedogenic alterations reflecting extensive pedogenic modifications, characteristic of prolonged exposure to high temperatures and high moisture. Building upon the preceding phases, sedimentation rates in this period increased substantially, reaching 72.46 cm per thousand years (ka) (Figure 3e), more than double the rates observed in earlier phases. This rapid accumulation of sediments corresponds with increased fluvial activity.

Furthermore, this phase records a significant increase in Total Organic Carbon (TOC) and nitrogen (N) content, corroborating the prevalence of warm, humid and wet climatic conditions. However, despite these overall trends, the Ca/Ti, Al/Ti, Si/Ti, and K/Ti ratios (Figure 4) exhibits a minor negative trend, likely due to the exceptionally high sedimentation rates. This rapid deposition limited extent of chemical weathering, allowing less time for alteration.

Overall, Phase III represents a period of optimal Holocene climatic conditions, marked by accelerated sedimentation rates, enhanced pedogenesis and notable geochemical shifts. These observations highlight the dynamic interplay of environmental factors during Holocene Climate Optimum, reflecting the broader climatic trends of this epoch.

5.3. Palao-Vegetation Patterns

The $\delta^{13}\text{C}$ isotopic signatures of soil organic matter provide direct insight into the dominant vegetation type, which is primarily influenced by the prevailing climatic conditions of the region [50,51]. C_3 plants, which dominate temperate and humid environments, thrive in environments with high atmospheric pCO_2 , while C_4 plants are well-adapted to low pCO_2 conditions, higher temperatures and arid climates [52,53]. Since the relative abundance of C_3 and C_4 plants varies with the local and regional environmental conditions, the $\delta^{13}\text{C}$ values of soil organic matter (SOM) serves as a widely used proxy for palaeovegetation and palaeoclimate reconstruction [2,5,24,49,54,55]. In this study, depth-wise variation in $\delta^{13}\text{C}$ values indicates a significant shift around 7.2 and 11 ka, suggesting an increased contribution from C_3 vegetation in the catchment areas during these periods (Figure 5).

6. Conclusions

The study presents a comprehensive analysis of sediment sequences from the Kashmir Valley, spanning the Late Pleistocene-Holocene transition, using a multidisciplinary approach that integrates lithostratigraphy, geochemistry, isotope analysis, and radiocarbon dating. The studied section serves as a valuable archive for understanding paleo-climatic and paleo-environmental conditions during the Late Pleistocene-Holocene period. The findings reveal a significant shift from cold, and arid

glacial conditions during the late Pleistocene to warm, humid and moist interglacial climates at the onset of the Holocene. This transition is characterized by the deposition of loess under arid conditions, followed by the development of palaeosols and fluvial sedimentation indicative of enhanced pedogenesis and climatic amelioration. The geochemical indices suggest low weathering followed by higher intensity after 11 ka due to increased precipitation. $\delta^{13}\text{C}$ values suggest increased contribution from C_3 -dominated vegetation during this time period. This study provides compelling evidence for a warm climatic transition around the start of the Holocene Epoch.

The implications of this research extend beyond reconstructing past climates. By providing a detailed chronology of sedimentation and environmental changes, this study offers valuable insights into the climatic sensitivity and sedimentary dynamics of the region, which can serve as a baseline for future studies on climate change and its impacts in the region. The findings also contribute to understanding the role of the Indian Summer Monsoon and Western Disturbances in shaping the paleoclimatic history of the Kashmir Himalayas. Future research should focus on expanding the spatial scope of this study to include other palaeosol sequences in the region. It is believed that integrating high-resolution geochemical proxies, advanced isotopic techniques, and sediment modelling can refine regional correlations and uncover finer-scale climatic variations.

Author Contributions: Rayees Ahmad Shah was responsible for conceptualization, investigation, methodology, formal analysis, data curation, and writing the original draft. Shakil Ahmad Romshoo was responsible for supervision, resource management, project administration, funding acquisition, and contributed to data analysis, interpretation and manuscript writing, review and editing. Imran Khan contributed to geochemical analysis and writing draft manuscript. Pankaj Kumar contributed to radiocarbon dating and review and editing of the manuscript. All authors have read and agreed to the published version of the manuscript.

Funding: The research work was carried out as part of a sponsored research project titled “Centre of Excellence for Glacial Studies in the Western Himalaya”, which was funded by the Department of Science and Technology (DST), Government of India. The financial assistance provided by the Department under the project to complete the research is thankfully acknowledged. Dr. Rayees Ahmad Shah duly acknowledges the funding received from University Grants Commission (UGC) through Dr. Kothari Postdoctoral Fellowship scheme grant No.F.4-2/2006 (BSR)/ES/19-20/0024.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in the study are included in the article in the form of tables and supplementary data., further reasonable inquiries can be directed to the corresponding author/s.

Acknowledgments: The research was conducted as part of the sponsored project “Centre of Excellence for Glacial Studies in the Western Himalaya,” funded by the Department of Science and Technology (DST), Government of India, whose financial support is gratefully acknowledged. Dr. Rayees Ahmad Shah also acknowledges the funding received from the University Grants Commission (UGC) through the Dr. Kothari Postdoctoral Fellowship scheme. Authors are thankful to IUAC for extending the ^{14}C AMS facility and graphitization laboratory established with funding support from the Ministry of Earth Science (MoES), Govt. of India, with reference numbers MoES/16/07/11(i)-RDEAS and MoES/P.O.(Seismic)8(09)-Geochron/2012.

Conflicts of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Abbreviations

The following abbreviations and formulas are used in this manuscript:.

Al	Aluminium.
AMS	Accelerator Mass Spectrometry.
Al_2O_3	Aluminum oxide.
Ca	Calcium.
CaO	Calcium oxide.
CaCO_3	Calcium Carbonate.
CIA	Chemical Index of Alteration.

CIW	Chemical Index of Weathering.
DST	Department of Science and Technology.
Fe ₂ O ₃	Iron oxide.
HCl	Hydrochloric acid.
ISM	Indian summer monsoon.
IUAC	Inter University Accelerator Centre.
K	Potassium.
ka	Kilo years.
K ₂ O	Potassium oxide.
LPS	Loess-palaeosol sequences.
M	Molar.
MAG	Marine Mud.
MgO	Magnesium oxide.
MIS	Marine Isotope Stage.
MnO	Manganese oxide.
N	Nitrogen.
NaOH	Sodium hydroxide.
Na ₂ O	Sodium oxide.
OSL	Optically stimulated luminescence.
P ₂ O ₅	Phosphorus pentoxide.
SDO	Standard Devonian Ohio Shale .
Si	Silicon.
SWM	Southwest Monsoon.
SiO ₂	Silicon dioxide.
Ti	Titanium.
TOC	Total Organic Carbon.
UGC	University Grants Commission.
USGS	United States Geological Survey .
VPDB	Vienna Pee Dee Belemnite.
WD	Western disturbances.
XRF	X-ray Florescence.
¹⁴ C	Carbon-14.
δ ¹³ C	Delta carbon-13.
σ	Sigma.

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