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Micromorphological Study of Kashmir Loess-Paleosol Sediments: A Tool for Stratigraphic and Paleoclimatic Reconstruction

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ABSTRACT

Integrated lithological, micromorphological and SEM studies of the Quaternary loess-paleosol sediments of the Kashmir Valley were carried out in order to reconstruct paleoclimatic history of the Kashmir valley during Middle to Late Pleistocene period. The pedological observations revealed that these paleosols are weak to moderately developed representing cold arid to warm semi-arid climatic conditions. Various pedological features also indicate that numbers of loess-paleosols events in the sequences reflect subtle climatic changes that affect relative rates of material supply and weathering rates and these paleosol profiles are formed when both loess deposition and pedogenic processes were taking place simultaneously during either phase of the loess/soil formation cycle. However, balance between the rate of sedimentation and rate of pedogenesis changed in cyclic fashion. Four periods of relatively higher precipitation and temperature conditions occurred in the Kashmir Valley. These periods are observed in paleosol profiles DS2, DS3, DS5 and DS7 of Dilpur Village section and their stratigraphic equivalent at Karapur and Burzahom Village sections. These periods of relatively higher precipitation and temperature conditions do not each represent complete interglacial period. The paleosols DS3, KS4 and BS4 are relatively well developed and record maximum thickness, which may represent one full interglacial period. The loess horizon DL1 and paleosols DS1, KS1 and BS1 probably represent the last glacial maximum (LGM) in Kashmir valley and the Last Glacial was interrupted by arid and warm semi-arid intervals when BS3 and BS2 paleosol profiles and their stratigraphic equivalent are formed. Also the lower part of the sections below the DL2 and KL1 is interpreted as the fluctuation probably within the last interglacial period. Overall the climate of the valley for most of the times fluctuated between cold arid to warm semi-arid during the recent past.

Keywords: Loess-Paleosols; Kashmir; Dilpur; Micromorphology, SEM

INTRODUCTION

In recent years there has been greater emphasis on micromorphology for recognition, description and interpretation of various pedogenic and sedimentary events of geological records from Precambrian to Recent (*e.g.* Mucher and Morozova, 1983; Fedoroff *et al.,* 1990; Retallack and Wright, 1990; Kemp *et al.,* 1994; Kemp, 1985; 2001). The value of loess as a

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paleoclimate proxy has been documented in many parts of the world (Kukla *et al.,* 1988; Hovan *et al.,* 1989; Verosub *et al.,* 1993; Vlag *et al.,* 1999; Muhs and Zarate, 2001; Beget, 2001; McDowell and Edwards, 2001; Muhs *et al.,* 2001b; Lagroix and Banerjee, 2002; Muhs *et al.,* 2003b). Kashmir loess, like that of China, is of particular interest for paleoclimate studies because of its widespread extent and lengthy depositional history (Singhvi *et al.,* 1987; Gardner *et al.,* 1989; Agrawal *et al.,* 1989).

Numerous radiocarbon and thermoluminescence (TL) dates from the loess–paleosol sequences were published over the last few decades by various researchers (*e.g.* Singhvi *et al.,* 1987; Rendell and Townsend, 1989; Agrawal *et al.,* 1989). On the basis of TL dating, Singhvi *et al.* (1987) proposed that loess deposition in Kashmir Valley commenced around ~0.3 Myr. The loess deposits on the southwestern part of the valley are dated >81 kyr and <81 kyr on the northeastern side of the Kashmir Valley. However, Rendell and Townsend (1989) and Agrawal *et al.* (1989) proposed a consistent and relatively shorter framework. According to them the loess deposition started about ~0.2 Myr in the Kashmir Valley.

Recent studies have documented the existence of numerous buried paleosols within loess deposits across Kashmir Valley (*e.g.* Singhvi *et al.,* 1987; Ahmad and Chandra, 2010, 2013; Ahmad, 2012). Their presence indicates significant periods of relative landscape stability when loess deposition rates were significantly reduced. This repeated layering of loess and paleosols are suggestive of changes from colder to warmer periods (Wang *et al.,* 1990). However, there are uncertainties as to what degree pedogenic processes may have occurred during paleosol formation and therefore what climate may have prevailed at the time of pedogenic modification of each paleosol profile. Some workers have previously attempted to deduce the Quaternary climate changes in the Kashmir valley using micromorphological approach (Bronger *et al.,* 1987; Gardner, 1989). On the basis of the micromorphological studies of the top three paleosols across the basin, Bronger *et al.* (1987) concluded that warm and mostly humid climatic conditions prevailed during their formation in the Kashmir Valley. Similarly, Gardner (1989) suggested that paleosol profiles represent similar climatic condition except the topmost two paleosols formed in the later part of the last glacial period. However, none of these studies have integrated the detailed field evidences, micromorphic and SEM study to interpret the pedogenic maturity and paleoclimate of the Kashmir Valley. In this paper, an attempt has been made to consider the role of pedogenic processes in modifying the loessic sediments, focusing on the resulting properties as indicators of past climatic conditions using detailed field/macromorphic, micromorphic and SEM studies.

GEOLOGICAL SETTING

Kashmir Valley occupies a very important place in the geotectonic of Kashmir Himalaya. It lies between the Great Himalayan Range to the northeast and the Pir-Panjal Range to the southwest. The valley possesses almost complete stratigraphic record of rocks of all ages from Archean to Recent. The geomorphic setting of the Kashmir Valley reveals that due to rise of the Pir-Panjal Range, the drainage was impounded as a vast lake (Karewa Lake or Nagum Lake) in which Plio-Pleistocene glacio-fluvio-lacustrine sediments up to 1300 m thick were deposited which are generally known as the ‘‘Karewas’’ or the ‘‘Karewa Group” (Bhatt, 1982,1989). The Plio-Pleistocene sequence of Karewa Group is broadly classified into two divisions as Lower (Hirpur Formation) and Upper Karewa (Nagum Formation), separated by an angular unconformity (Bhatt, 1976, 1982, 1989). Lower Karewa is subdivided into Dubjan, Rambiara and Methawoin members. The Upper Karewa is subdivided into Shopian, Pampore and Krungus members. This formation (Nagum) exhibits a lateral facies change from the Shopian Member in the southwestern part to the Pampore member in the central part and to the Krungus member in the northeastern part of the Karewa Basin. The soft unconsolidated sand, clay and conglomerate sediments characterize the Karewa Group. These sediments are capped by mantle of loessic sediments of Dilpur Formation which is independent of the glacio-fluvio-lacustrine environment and is aeolian in origin (Pant *et al.,* 1978, 2005; Kusumgar *et al.,* 1980, 1986; Singh, 1982; Bhatt, 1982; Agrawal *et al.,* 1985, Ahmad, 2012). These sediments occupy a major part of the present day valley floor.

The climatic pattern in northwestern part of the Himalaya is related to the rearrangement of the regional heat and moisture distributions, which, in turn, is related to the formation and evolution of Kashmir Valley which is attributed to the uplift of high mountains in Asia and buildup of the Northern Hemisphere Ice. The uplift of the Tibetan Plateau at ~14 Ma is regarded as the causative factor for monsoonal system in Asia (Edwards *et al.,* 1996). This uplifted mountain range has resulted in a change in precipitation and monsoonal climate within the Indian region (Ganjoo and Shaker, 2007) and is responsible for the strong latitudinal gradient of increasing aridity towards the central parts of the Himalaya and Tibetan Plateau (Wunnemann *et al.,* 2008; 2010). However, upliftment of the Pir Panjal Range has played locally a major role in determining the climatic changes in the Kashmir Valley. The 1400-5000 m uplift since the past ~4 Ma in the Pir Panjal Range (Burbank and Johnson, 1983; Agrawal, 1987) has effectively blocked the southwestern monsoon winds and changed the climatic conditions from sub-tropical to more arid and windy in the valley (Raza *et al.,* 1978). Only strong Indian monsoon winds can cross the Pir Panjal and reach the valley which may also be responsible for the transport of dust in Kashmir Valley as witnessed during the devastating flood in September, 2014. However, Ahmad and Chandra (2013) proposed that the westerlies might have brought fine-grained sediments to Kashmir Valley and contribution from the nearby sources also not excluded, because the katabatic winds blowing down from the mountain slopes could have also picked up fine material from the glacial front and redeposited them on valley floor.

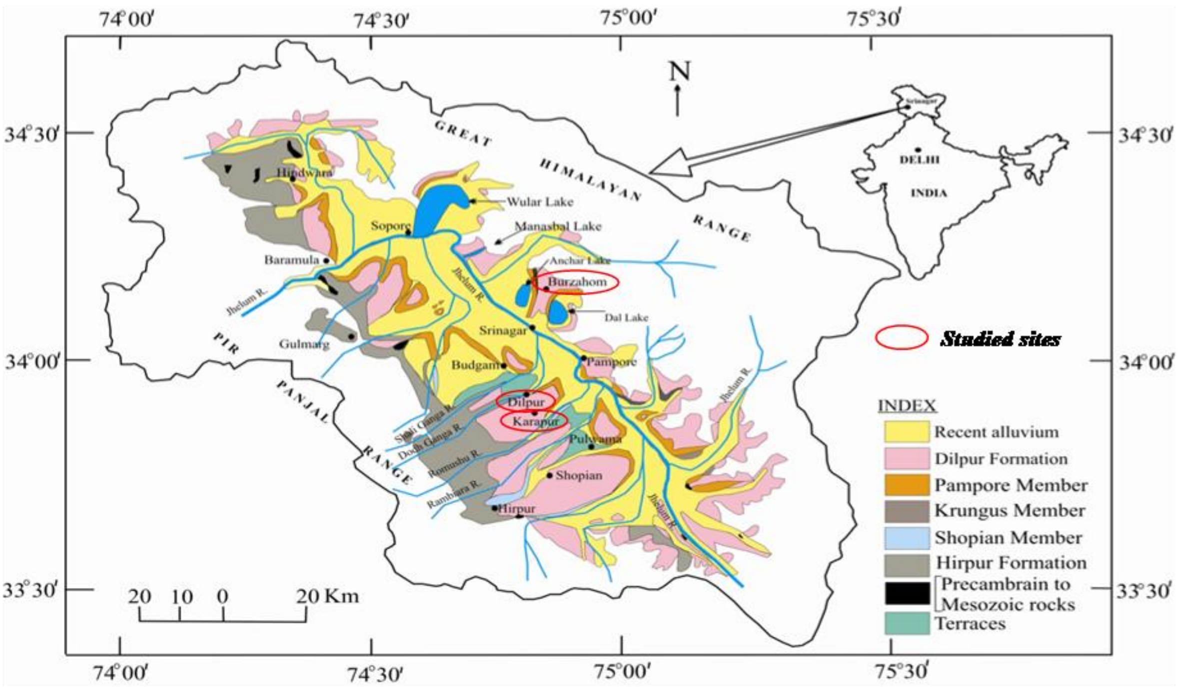

Fig. 1: Geological map showing distribution of loessic deposits of Dilpur Formation, Karewa Group and studied sites (after Bhatt, 1982).

Presently, Kashmir Valley has a Mediterranean type of climate, characterized by a marked seasonality with four well developed seasons *i.e.* spring, summer, autumn and winter. The present-day rainfall pattern in the valley is dominated by winter precipitation brought by western disturbances and trough in the westerlies as opposed to the southwestern monsoons in most of peninsular India. These disturbances are most active during winter and spring seasons and decrease substantially as summer progresses. The average annual precipitation in the Kashmir Valley is 710 mm and the average annual temperature is 13.5ºC.

MATERIALS AND METHODS

Detailed geological fieldwork has been carried out across the Kashmir Valley to locate the various loess-paleosol sections; such as at Dilpur Village (33°56´N and 74°47´E), Karapur Village (33°50´N and 74°57´E), Pakharpura Village (33°48´N and 5374°56´E), Hayatpur Village (33°53´N and 74°50´E), Romu Village (33°53´N and 74°50´E), Tsrar-e-Sharief Town (33°51´N and 74°46´E), Krungus Village (33°45´N and 75°15´E) and Burzahom Village (34°10´N and 74°53´E). After the detailed field investigations, three representative loess–paleosol sections at Dilpur and Karapur Village sections along the southwestern part and Burzahom Village section along the Northwestern part of the Kashmir Valley were selected for present research work (Fig. 1). At all the three localities, the loess–paleosols occur on plateau settings, built up by the continuous accretion of the aeolian dust. The topographic framework suggests that repeated denudation parallel to the surface is very unlikely because no erosional evidence such as incision unconformity, angular truncation of strata, buried rill, pond micro-topography, and local pavement of coarse fragments was found (Fig. 2).

Fig. 2: Panoramic view of Kashmir loess-Paleosol sequence (dark, blue and red arrows represent A-horizon, B-horizon and loess horizon respectively) showing horizontal parallel strata with no erosional evidence.

The loess and the intercalated paleosols were differentiated on the basis of various macrostructures (*e.g.* decayed organic matter, bioturbation features, blocky aggregates, clay coatings, root traces, $CaCO_3$ in the form of leaching and nodules) in the field. The nomenclature for lithostratigraphy is assigned by letter 'L' to loess and 'S' to paleosol. The paleosols are numbered from top to bottom of the section. The acronyms D, K and B are used for Dilpur, Karapur and Burzahom sections respectively. At a field scale, the sequence is divided mostly into A, B and C-horizons. The field logs of the studied sections are summarized and correlated in Fig. 3 on the basis of various pedological features and the available chronology of the loess–paleosols (Rendell and Townsend, 1989; Agrawal *et al.,* 1989). It revealed spatial variation in thickness and number of loess–paleosol profiles. The earliest records of the loess deposition in Kashmir Valley are available on the Pir-Panjal flank where land surface was available for the deposition of windblown loessic material after the lake had shifted towards the Himalayan flank due to the rise of the Pir-Panjal. Subsequently, when the land surface emerged in the central and northeastern parts of the valley along the Himalayan flank following the draining of the lake, the deposition of loess took place along the northeastern part of the valley at Burzahom Village section subsequent to the deposition of DL2 and KL1 loess horizons of the Dilpur and Karapur Village sections respectively. Therefore, the loess-paleosol sequence above these loess horizons between 0.00 m to ~6.75m at Dilpur Village section and between 0.00 m to 8m at Karapur Village section is stratigraphically equivalent to the whole sequence of Burzahom Village section. However, some parts of the lacustrine sediments of Pampore Member in the central part of the Kashmir Valley and on the Himalayan flank are contemporaneous with the loess deposits on the Pir-Panjal flank at Dilpur and Karapur Village sections (Agrawal *et al.,* 1988).

After scraping away, the outer layers exposed to light, 150 undisturbed blocks at ~30cm interval were collected and brought to the laboratory. Intact samples were left in a well-ventilated room for several days until they lost the moisture and maintained constant weight. The samples were subsequently dried in an oven at 40ºC for 48 h. Sample were impregnated with a clear epoxy, trimmed and bonded to a glass microscope slide measuring 75 × 55 mm, and polished to a final thickness of 30 microns (0.03 mm), rendering them translucent. A total of 300 thin sections were prepared from samples collected. The resulting thin sections were examined by the authors at Wadia Institute of Himalayan Geology, Dehradun, India using NIKON E600 Polarizing microscope attached with image Pro-image analysis system at 2-100X magnification. The descriptions follow the terminology of Bullock *et al.* (1985) and Stoops (2003). The most indicative samples were also studied under a scanning electron microscope (SEM). For this purpose, portion of interest from the samples of paleosol are separated and air dried to remove the moisture contents. The dried undisturbed samples were mounted on stub using durafix adhesive mixed with acetone (5:50). The mounted samples were coated with vapours of gold under high vacuum evaporator (HITACHI HUS-5GB). The samples were then studied under SEM (HITACHI S-3000H) in University Scientific Instrument Centre (USIC) at University of Kashmir, Srinagar. The age estimates were secured as part of a separate study conducted for these sites by Rendell and Townsend (1989) and Agrawal *et al.* (1989).

RESULTS

Loess Stratigraphy

The loessic deposits of the Dilpur Formation form an important litho-unit in the Karewa stratigraphy. These sediments are distributed throughout the valley and occur as terraces, slope and plateau deposits. The detailed lithological study is beyond the scope of this paper; however, some important characteristics of different horizons and studied sequences from the pedological point of views are highlighted here. On the basis of detailed field observations, four loess horizons with seven embedded paleosol profiles have been identified at Dilpur Village section. Karapur Village section contains three loess horizons with ten embedded paleosol profiles. However, at Burzahom Village section four paleosol profiles have been found (Fig. 3). Virtually no paleosol is overlain or underlain by fresh (unmodified) loess horizons. Instead all loess horizons are affected by pedogenesis (except DL4 at Dilpur and KL3 at Karapur sections) to a varying degree by structural alteration such as formation of granular structures or blocky aggregates, root traces, clay coating and secondary carbonate emanating from the superjacent horizons. The parent loess horizons are mostly absent at the base of these paleosol profiles (Fig.3). This indicates relative stable land surface conditions when the pedogenic processes become more dominant and the parent loessic material transformed into illuvial ('B') horizon (Yakimenko *et al.,* 2004).

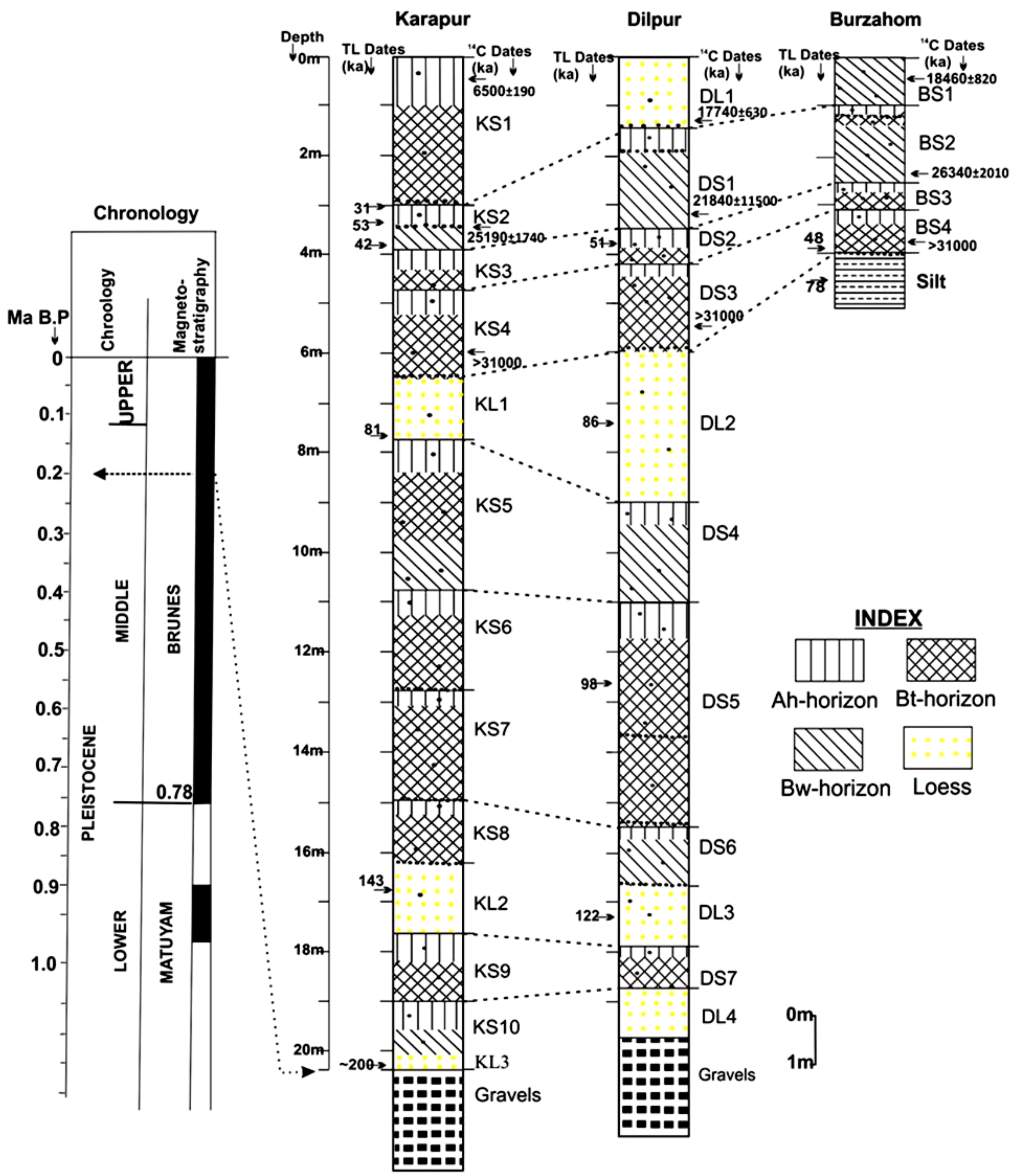

Fig. 3. Lithostratigraphic correlation of Kashmir loess–paleosol sequences of Karapur, Dilpur and Burzahom sections. Correlation is based on pedological similarity and available ^{14}C dates (Agrawal *et al.,* 1989) and TL dates (Rendell and Townsend, 1988).

Key macromorphological characteristics and features of the Kashmir loess-paleosol sediments are illustrated in Fig.4. Morphologically, loess layers distinguishable from the paleosol because of pale-yellow color, resistant to erosion, strong effervescence with HCL and absence of organo-clay cutans. Generally, the pedological properties of the underlying and overlying paleosols horizons are amalgamated and it is difficult to locate a precise boundary between both phases of soil formation. Therefore, all the paleosols horizons show genetic contact with the adjacent horizons (*e.g.* Fig.3). The root traces are observed even in B_{wk} horizons (*e.g.* Fig. 4a-b). The main diagnostic features of the B-horizons are generally ocher colour, clayey textures and clay coatings on ped surfaces (*e.g.* Fig.4c-d), and labeled as "B_t" horizon. Sometimes these horizons show powdery calcitic infilling along the root traces, nodules or encrustation beside clay coatings and labeled as "B_{tk}" horizon (Fig.4e). However, the weakly developed illuvial horizons are designated as B_w-horizon. These horizons show weakly developed structures, massive hard, moderate to strongly calcareous (*e.g.* Fig.4f). They are transitional horizons between loess (C-horizon) and B_t-horizons. Clay concentration features are generally absent in these horizons. However, thin clay coating is observed along root traces in paleosol DS1, DS6, BS2 and KS10 (*e.g.* Fig.4g). Loess typically has a light brownish gray (2.5Y 6/2), light yellowish brown (2.5Y 6/3) or grayish brown (2.5Y 5/2) color (Fig. 4g-h). It shows massive structures. Pin pores are diagnostic features of these horizons. These pores sometimes also show calcitic infillings (Fig. 4h). Most interestingly, A-horizons always preserved and consist of dark colour (10YR 4/6, 5/4) which is clearly visible in field indicating the presence of humus material (*e.g.* Fig. 2), hard, slightly to strongly calcareous and show diffuse contact with the upper soil profile. Root traces are abundant and sometimes coated with $CaCO_3$ (*e.g.* Fig. 4i-j). Burrows are present in most of the A-horizons (*e.g.* Fig. 4j). A thread like network of $CaCO_3$ coating is also present which is known as pseudomycellia (*e.g.* Fig. 4k).

Fig.4. Macromorphological features of the Kashmir loess-paleosols sections: (a) the paleosol KS5 showing blocky aggregates (Bt-horizon) $CaCO_3$ nodules in circle (B_{wk} horizon), (b) close-up view of B_{wk}-horizon of paleosol KS5showing root traces (red arrows) and CaO_3 nodules (blue arrows), (c) B_t-horizon of paleosol DS7 showing clayey texture, (d) clay coatings on the ped surfaces in B_t-horizon of paleosol KS7, (e) B_{tk}-horizon of paleosol DS3 showing fine root traces and channels filled with $CaCO_3$, (f) showing weakly developed structures and $CaCO_3$ infillings in B_{wk}-horizon of paleosol DS4, (g) paleosol KS10 showing clay coating along root traces in B_{wk}-horizon, (h) DL3-altered

loess showing massive structures and precipitation of $CaCO_3$ in pores, (i) root traces coated with $CaCO_3$ in A_{hk}-horizon of paleosol KS4, (j) burrows (red arrow) and root traces (black arrow) filled with $CaCO_3$ in A_{hk}-horizon of paleosol KS1, and (k) humus material and pseudomycellia in A_{hk}-horizon of paleosol DS1.

MICROMORPHOLOGY

Key micromorphological features of the Kashmir loess-paleosol sediments are illustrated in Figs. 5-7. Micromorphological characteristics of the loess–paleosol from the three sections are summarized in Table-1. The loess–paleosol sequences at the three locations across the Kashmir Valley are described separately in order to evaluate the response of individual loess–paleosol sections to the Late Quaternary climate change across the Kashmir Valley.

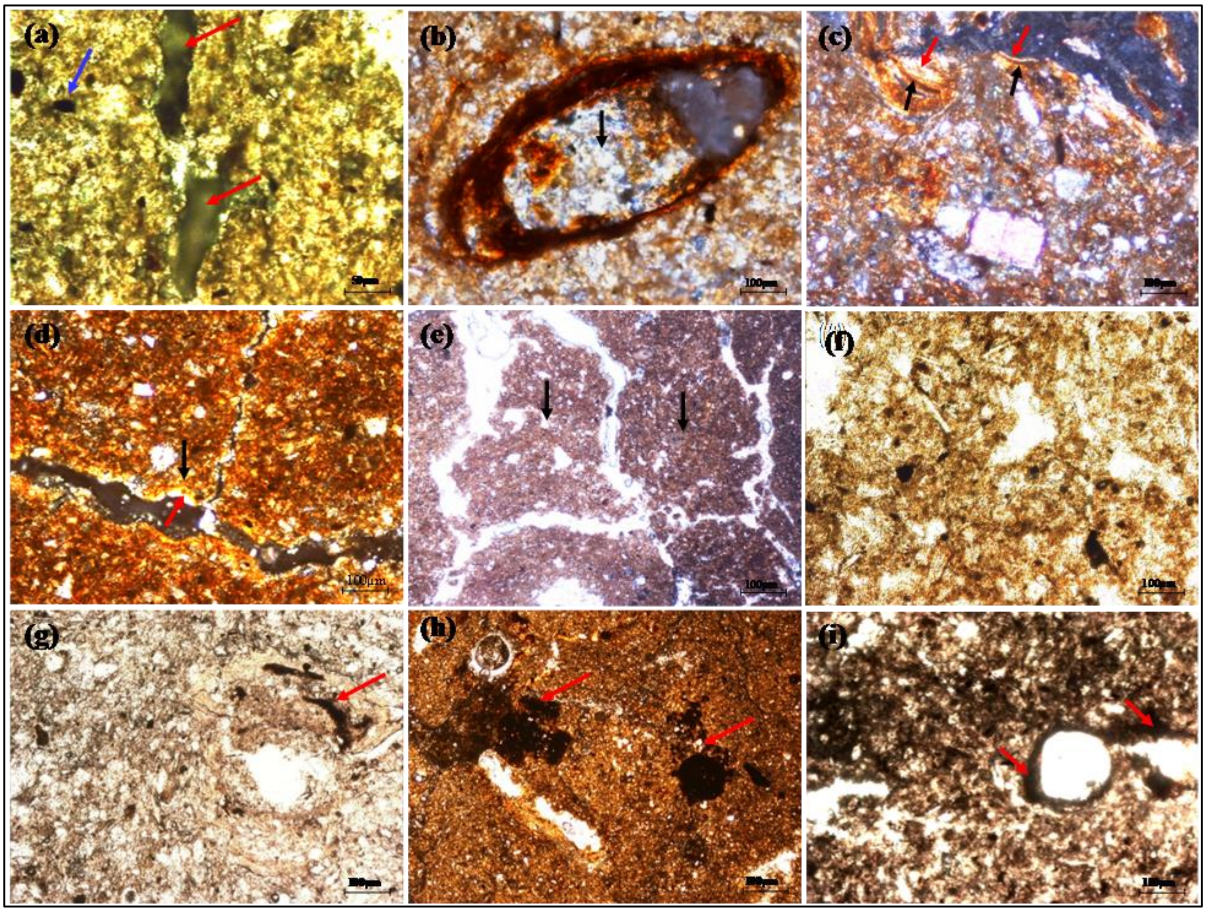

Fig.5: Representative photomicrographs of the key pedogenic features from the loess–paleosol sequences of Dilpur section (a) showing $CaCO_3$ in channels (red arrow) and iron impregnation (blue arrow) in B_{wk}-horizon of paleosol DS1, (b) root channels filled with $CaCO_3$ in A_{htk}-horizon of paleosol DS2, (c-d) B-horizons of paleosol DS3 and DS6 respectively showing channels coated with alternate clay (black arrows) and micritic $CaCO_3$ (red arrows), (e) strongly expressed subangular blocky structure in paleosol DS5, (f) Spongy microstructure is observed in paleosol DS2, (g) partially altered root in A_{hk}-horizon of paleosol DS1, (h) Fe/Mn oxides in A_{ht}-horizon of paleosol DS5, (i) humus rich clay accumulations in B_t-horizons of the paleosol DS7.

1. Dilpur Section

The main micromorphological features of the loess–paleosol sequences at Dilpur section are very frequent $CaCO_3$ coatings. $CaCO_3$ features are generally present as coatings or infillings (*e.g.* Fig. 5a) or nodules. Root channels are totally or partially filled with $CaCO_3$ (*e.g.* Fig. 5b). Channels are sometimes coated with alternate clay and micritic $CaCO_3$ (e.g. Fig. 5c-d). The paleosol profiles at Dilpur village section are characterized by weak to strongly developed pedal microstructures and very strongly expressed subangular blocky structure (*e.g.* Fig. 5e). Spongy microstructure is observed in paleosols DS2, DS5, and DL3 (*e.g.* Fig. 5f). The paleosol profiles are also characterized by partially altered root (*e.g.* Fig. 5g). The concentrations of Fe and Mn oxides (and/or oxyhydroxides), are also observed in these paleosol (*e.g.* Fig. 5h). Quartz and feldspar are the dominant minerals both in paleosols and parent loess materials. They range from angular to sub-angular or even sub-rounded. Quantity of coarse minerals such as micas, biotite, and hornblende is generally lower. The mobilization of iron has produced reddish yellow to strong brown colour in the matrix (*e.g.* Fig. 5d, h). The humus rich clay accumulations are observed in B_t horizons (*e.g.* Fig. 5i). These humus rich clay coatings are often dark brown in colour. These paleosols have much higher proportions of fine clay fractions. The c/f related distribution is porphyritic in all the paleosols, with quartz grains as the main coarse constituents. The loess horizons are somewhat altered, mainly composed of angular to sub-angular quartz and mica flakes.

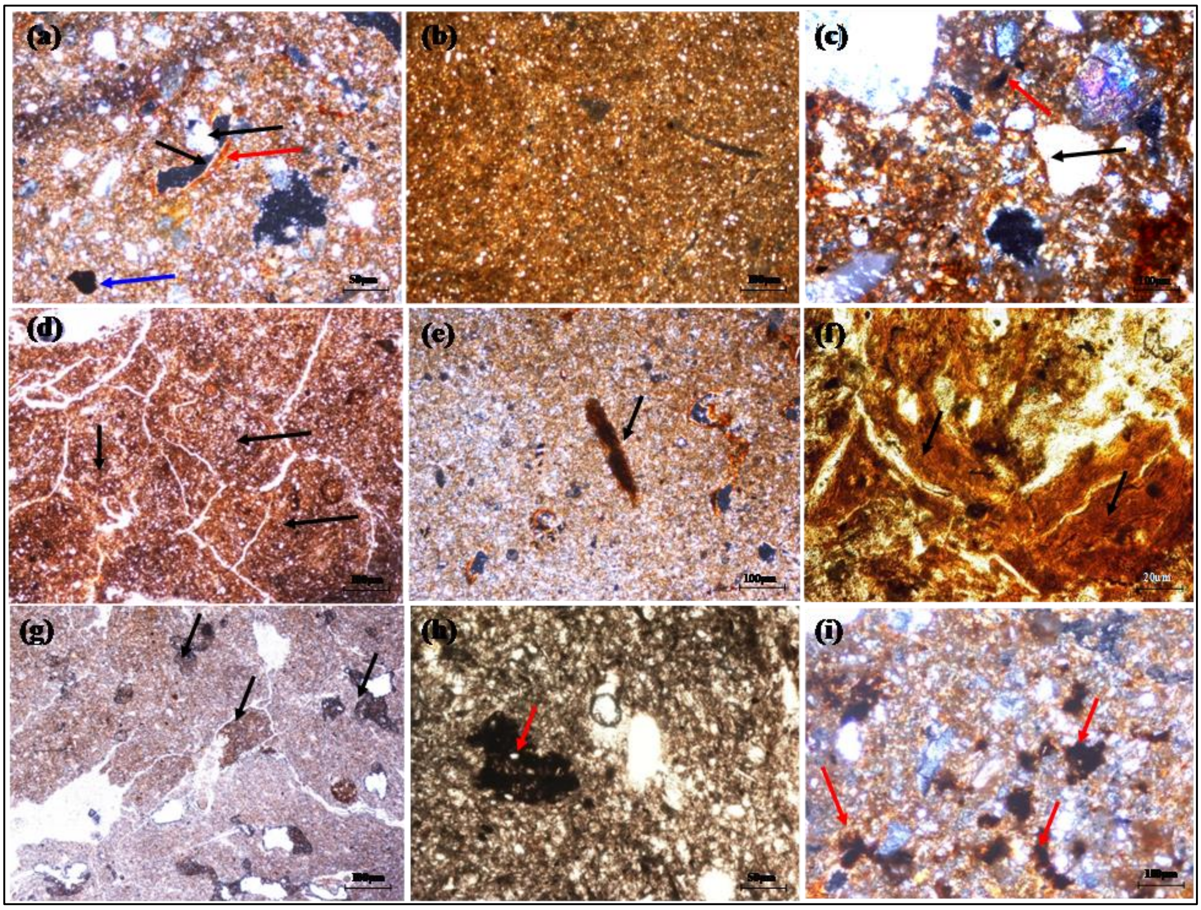

Fig.6: Representative photomicrographs of the key pedogenic features from the loess–paleosol sequences of Karapur section (a) Voids are coated with clay (red arrow) and $CaCO_3$ (black arrow) in B_t-horizon of paleosol KS1, (b) Apedal microstructure in B_t-horizon of paleosol KS4, (c) Thin clay coating around the plagioclase feldspar grain (black arrow) and partially altered biotite (red arrow) in B_{wtk}-horizon paleosol KS10, (d)

pedal microstructure in Bt-horizon of paleosols KS5, (e) Apedal structures with disseminated organic matter and fine root traces (black arrow) in A_{htk}- horizon of paleosol KS5, (f) B_t-horizon of the paleosol KS6 showing clay accumulation, (g) $CaCO_3$ precipitated in the form of nodule and concretions in A_{hk}-horizon of paleosol KS7, (h) Spongy microstructure and Fe/Mn oxide in the paleosol profile KS3, and (i) Fe/Mn oxides in A_h-horizon of paleosol KS6 with sharp boundaries.

2. Karapur section

The thin sections from Karapur village section displayed pedological features like illuval clay coatings, pedotubules, disseminated organic matter and $CaCO_3$ coatings. Voids and channels are coated with clay and $CaCO_3$ (*e.g.* Fig. 6a). Apedal microstructure characterized by randomly and uniformly distributed fabric units were also observed (*e.g.* Fig. 6b). Thin clay coating was seen around the skeleton grains and voids in 'B_t' horizons (*e.g.* Fig. 6c). Pedal microstructure was also observed in the studied paleosols (*e.g.* Fig. 6d). The c/f related distribution is porphyritic in all the paleosols, with quartz grains as the main coarse constituents. The groundmass sometimes showed finely disseminated humus material assimilated in to the matrix. The 'A' horizons of the paleosols are relatively rich in organic matter, voids and root channels (*e.g.* Fig. 6e). The illuvial horizons (B_t) of the paleosol profiles are rich in clay (*e.g.* Fig. 6f). Paleosols KS3, KS4, KS5, KS6 and KS7 are also characterized by thick and laminated clay coatings. The $CaCO_3$ rich solution got precipitated in the form of nodule and concretions (*e.g.* Fig.6g). Spongy microstructure was observed in the paleosol profile KS2, KS2 and KS1 (*e.g.* Fig.6h). The Fe/Mn sesquioxides are also abundant in these paleosols showing sharp boundaries (*e.g.* Fig.6i). The loess horizons showed presence of altered biotite, feldspar, angular quartz, and calcite grains in association with the flaky micaceous minerals. Quartz, feldspar and sesquioxides are the important coarse constituents followed by micas, biotite and hornblende both in paleosols and parent loess materials.

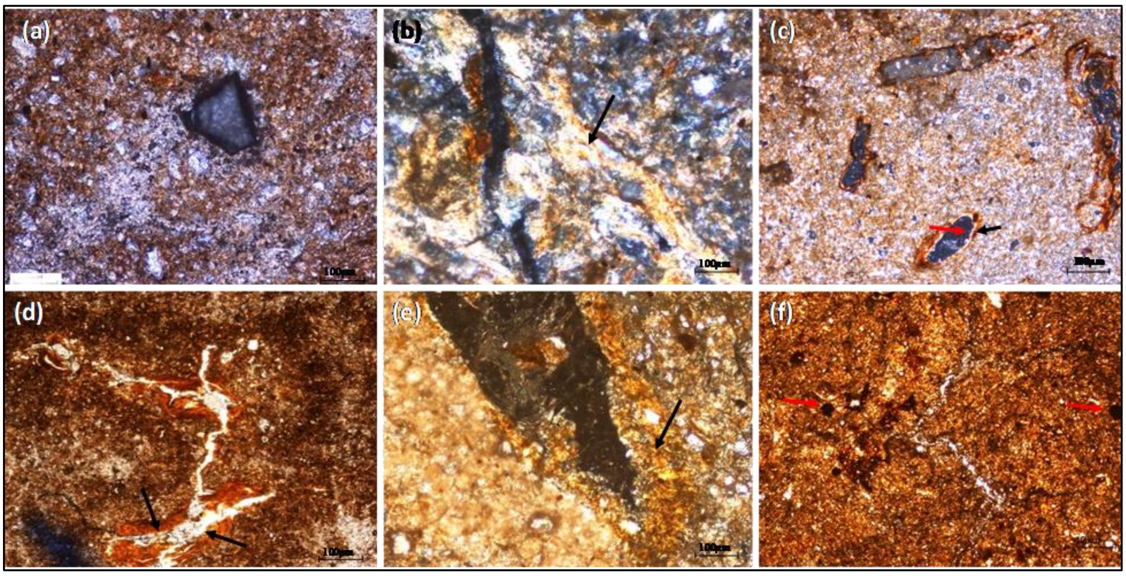

Fig.7: Representative photomicrographs of the key pedogenic features from the loess–paleosol sequence of Burzahom section (a) Massive structure in the weakly altered B_{wt}-horizons of the paleosol BS2, (b) $CaCO_3$ coatings and hypo-coatings along channels in the weakly altered B_{wk}-horizons of the paleosol BS1, (c) thin clay and $CaCO_3$ coatings along root channels in A_{hk}-horizon of paleosol BS3, (d-e) Root traces with thick laminated clay coatings in B_t-horizon of paleosols BS3 and BS4 respectively, (f) show angular pedal microstructures and iron impregnations (red arrow) in A_{ht}-horizon of paleosol BS4.

3. Burzahom section

The main micromorphological features of the loess–paleosol sequences at Burzahom section are frequent $CaCO_3$ and clay coatings. Massive structure is generally observed in the weakly altered 'B_w' horizons of the sequence (*e.g.* Fig. 7a). $CaCO_3$ features are also common in the form of coatings and hypo-coatings in channels and voids (*e.g.* Fig. 7b). Various partially altered biotite grains observed in these paleosols indicate weak to moderate pedogenesis. Root traces are characterized by thick and laminated clay coatings (*e.g.* Fig. 7c-e). These paleosols also show angular pedal microstructure (*e.g.* Fig. 7f). The sesquioxide complexes are also observed in these paleosol profiles (*e.g.* Fig. 7f). Quartz and feldspar are the dominant minerals both in paleosols and parent loess materials. They range from angular to subangular or even sub-rounded. Quantities of coarse minerals such as micas, biotite, and hornblende are generally lower. These paleosols have much higher proportions of fine clay fractions. The c/f related distribution is porphyritic in all the paleosols, with quartz grains as the main coarse constituents.

SEM study

Carbonate accumulations are the basic pedogenic features in soils and paleosols of arid/semiarid regions of the world (Kuznetsova and Khokhlova, 2010). Pedogenic carbonates are an accurate proxy of soil formation and functioning because the morphology of $CaCO_3$ accumulations is directly bound up with the processes of dissolution–precipitation, consequently they contain information about climate and water regime dynamics. Hence, special attention has been given to the SEM micromorphology of $CaCO_3$ and clay pedofeatures as a proxy for reconstruction of paleoenvironment/ or the conditions and processes under which these paleosols are formed. Electron microscopy allowed the discovery of cryptocrystalline coatings of $CaCO_3$ and clay (Fig. 8a). Most of these paleosols show smooth $CaCO_3$ coating along the walls of channels which mask the relief of the soil matrix (Fig. 8b). The scanning electron micrograph of paleosol shows continuous carbonate coating on the matrix and encrustation on the surface of sub-rounded quartz grain (Fig.8c). Fine particles are observed attached to the surfaces of larger (Fig.8d). These particles represent fine dispersed quartz and carbonates. The irregular accumulations both in shape and distribution most probably represent carbonates. The micromorphology of these paleosols suggests that these are primarily consisting of abundant quartz grains of clay fraction. Fairly uniform distribution of these grains may indicate their aeolian transportation (Grabowska-Olszewska, 1975). The degree of roundness and sorting of this material also support the assumption about the origin of this loess under subaerial conditions, fairly slow transportation and rather distally situated derivation area of this loess material. The continuous $CaCO_3$ coatings are also observed around the aggregates (Fig. 8e). The origin of these carbonate accumulations is chemical: they were formed by processes of dissolution–precipitation of calcite from the overlying horizon. In dry periods, $CaCO_3$ accumulations with perfect crystals and sharp borders were found (Fig. 8b). Perfect crystals grow in undisturbed conditions without abrupt changes from solution of normal concentration (Grabowska-Olszewska, 1975; Khokhlova and Kuznetsova, 2002; 2004). The scanning electron micrographs also show desiccation cracks in these paleosols, suggesting that these are formed under drier and seasonal climate (Fig.8f). The stacked and overlapping clay plates in BS3 paleosol profile show doming, curl or sheets like structure with openings on top of the surface (Fig.8g). These doming, curl or sheets like structures are the characteristics of clay mineral smectite (Rokosh *et al.,* 2009). The laths of illite clay minerals are also present in traces (Fig.8h). The presence of clay minerals smectite and illite in these paleosols is consistent with the results of XRD study (Chandra *et al.,* 2016). The presence of clay mineral illite is directly related with the prevailing cold climatic conditions (Bryant and Dixon, 1964; Millot, 1970; Chamley, 1989). It is considered to be the precursor mineral for the formation of clay mineral smectite under arid-semiarid environment. The presence of illite in the loess can be used to delineate the glacial periods and proved to be a valuable paleoclimatic indicator (Emadi *et al.,* 2008). It is admitted that the above interpretations may be oversimplified as the observational SEM material is yet too scarce. However, further studies are required to determine whether it is the case.

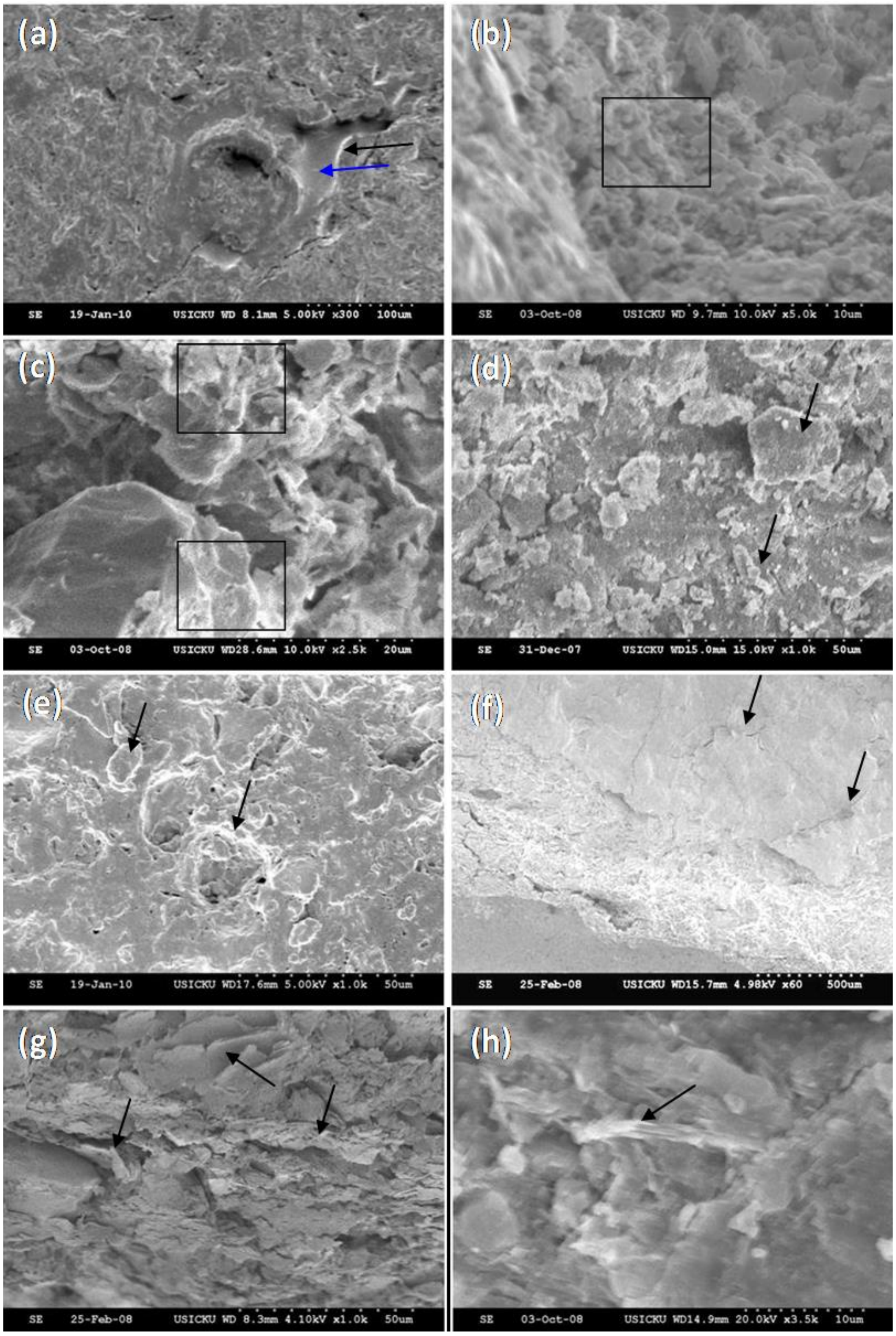

Fig.8: Showing alternate clay (blue arrow) and $CaCO_3$ (black arrow) coating along void, (b) continuous thickening of the $CaCO_3$ coating that hides the aluminosilicate matrix, (c) continuous coating and encrustation on the surface of quartz grain, (d), fine particles attached to the surfaces of larger, (e) continuous $CaCO_3$ coatings around the aggregates, (f) desiccation cracks dividing a feature into parts, (g) showing doming of smectite clay minerals in paleosol BS3, and (h) Illite lath in paleosols DS4.

DISCUSSION

Stratigraphic Implications of Loess–Paleosols

Lithostratigrphic study reveal that the earliest records of the loess deposition in Kashmir Valley are available on the Pir-Panjal flank where land surface was available for the deposition of wind-blown loessic material after the lake had shifted towards the Himalayan flank due to the rise of the Pir-Panjal. Subsequently, when the land surface emerged in the central and northeastern parts of the valley along the Himalayan flank following the draining of the lake, the deposition of loess took place along the northeastern part of the valley at Burzahom Village section subsequent to the deposition of DL2 and KL1 loess horizons of the Dilpur and Karapur Village sections respectively (Fig.3). Therefore, the loess-paleosol sequence above these loess horizons between 0.00 m to ~6.75m at Dilpur Village section and between 0.00 m to 8m at Karapur Village section is stratigraphically equivalent to the whole sequence of Burzahom Village section. However, some parts of the lacustrine sediments of Pampore Member in the central part of the Kashmir Valley and on the Himalayan flank are contemporaneous with the loess deposits on the Pir-Panjal flank at Dilpur and Karapur Village sections (Agrawal *et al.,* 1988; Ahmad, 2012). This revealed spatial variation in thickness and number of loess–paleosol profiles. Most interestingly, A-horizons are always preserved and consist of dark colour (10YR 4/6, 5/4) which is clearly visible in field (*e.g.* Fig.2) indicating that repeated denudation parallel to the surface is very unlikely because no erosional evidence such as incision unconformity, angular truncation of strata, buried rill, pond micro-topography, and local pavement of coarse fragments and the like was found.

Decayed organic matter, bioturbation features, blocky aggregates, clay coatings, root traces, $CaCO_3$ in the form of coatings and nodules are the characteristic lithological features of these paleosols. Irregular, downwardly bifurcating root traces are commonly preserved in paleosols with no diffuse, drab-colored mottles or haloes associated with micro-reducing environments around former plant roots were found. The presence of pseudomycellia suggests high evapotranspiration or by the local redistribution of carbonate rich water from lower topographic position to the drier higher positions by capillary movements (Sobecki and wilding, 1983; Knuteson *et al.,* 1989). The presence of $CaCO_3$ nodules in paleosol profiles indicate drier climatic condition, in which translocated $CaCO_3$ rich solution got precipitated in the form of nodule and concretions. The presence of organic matter and calcium carbonate in the A-horizons of paleosol profile indicates some degree of aridity associated with less precipitation. The dark colour of surface horizons as visible in these paleosols due to presence of humus material also suggests low precipitation, which otherwise might have leached out from the horizon (Duchaufaur, 1982; Sheldon and Tabor, 2009). Paleosols cannot be differentiated from the loess (altered loess) horizons in terms of size of the particles. These sediments have much higher proportions of fine clay fractions with homogeneous fine to medium silty textures. This vertical homogeneity in lithology confirms uniform sedimentary regimes as proposed by Ahmad and Chandra (2013). In paleosols, the thickness of horizons, color change and pedogenic structures likely reflect the degree of pedogenic development. Clay coatings result from the typical illuvial process under relatively moist and wet environmental conditions. Lower organic matter contents and weak to moderately developed illuvial clay pedofeatures, suggests subtle climatic changes that affect relative rates of material supply and weathering rates. This further suggests that these paleosol profiles are formed when both loess deposition and pedogenic processes were taking place simultaneously representing cold arid to warm semi-arid climate (Verosub *et al.,* 1993; Rendell *et al.,* 1989; Gardner, 1989).

Therefore, on the basis of detailed field studies at various exposures across the Kashmir Valley, the loess-paleosol sequences demonstrate broadly similar pedological characteristics. Mobilization of calcium carbonate is observed as the dominant process during the development of these paleosols. The calcitic features are formed by the precipitation of solutes present within groundwater or leached down from accretionary surfaces. The surfaces horizons leached with significant amounts of secondary carbonate accumulating lower down in the profile. In places, the migrating solutes have been unable to infiltrate significantly downward into the profile and have thus formed discontinuous layer of carbonate nodules at the base of some paleosols (Fig.3). The presence of such layer at the base of paleosols is a function of precipitation from the soil solution near the depth of wetting front under warm semi-arid climate (Sobecki and Wilding, 1983; Gunal and Ransom, 2006). Gunal and Ransom (2006) suggest that the less quantity of precipitation favour the accumulation of this carbonate within the profile rather than leaching out from the soil profile. Bronger (2003) stated that more strongly developed paleosols in the exposures of the SE Central Europe and especially in the East and Central Asia have distinct calcareous nodules layers which indicate the presence of hiatuses in loess-paleosol sequence. Bronger *et al.,* (1987) also suggest that the presence of this layer is associated with the erosional gap or with sheet wash due to intense rainfalls during the prevailing summer seasons. However, this interpretation did not explain the weak elluviation process in the underlying paleosols horizons. This is further supported by the fact that all the paleosol horizons show genetic contact with the adjacent horizons and almost parallel strata (0º-5º slope). Detailed field observations preclude the post depositional reworking and there is no doubt that all the pedogenic units of the Kashmir loess-paleosol sequences are in situ formations. Thus, it is interpreted that the presence of calcareous nodules layer at the base of these horizons is the consequences of arid climate as sufficient moisture was available for the partial depletion of calcite from the horizon.

The absence of parent C-horizon (loess) in most of the paleosols may be attributed to relative stable land surface conditions when the pedogenic processes become more dominant and the parent loessic material transformed into illuvial ('B') horizon (Yakimenko *et al.,* 2004). As a result, loess horizon changes into B-horizon whereby loess was modified by leaching process. The stratigraphically equivalent of paleosol profile KS7 at Karapur Village section is absent at Dilpur Village section (Fig.3). Teruggi and Imbellone (1987) introduced the possibility that such horizons might simply be unrecognizable due to the masking effect of subsequent episode of loessic deposition which must have amalgamated the characteristics of A-horizon at Dilpur village section. Hence, the A-horizon is transformed into illuvial horizon, which is further suggested by almost equal thickness and presence of calcium carbonate nodules layer in lower part of the paleosol profile DS5. This layer of $CaCO_3$ corresponds to the layer of $CaCO_3$ nodules developed at the base of KS6 paleosol (Fig.3).

The lithological characteristics such as organic matter, illuvial pedofeatures and granularity of soil are relatively weakly developed at Dilpur Village section as compared to Karapur and Burzahom Village sections. However, the different types of calcretes such as $CaCO_3$ coating, infilling, platy concretions and nodules are relatively well developed at Dilpur Village section than Karapur Village section. Lithological characters reveal that the Dilpur Village section experienced relatively more arid climatic conditions as compared to the Karapur and Burzahom Village sections. This is because the Dilpur Village section is lower in altitude than Karapur and Burzahom Village sections and hence has high potential for evapo-transpiration. Hence, it experiences relatively dry climatic conditions than the Karapur and Burzahom Village sections. Therefore, the soil-water balance of these locations differs which affects the rate of pedogenesis (Bronger *et al.,* 1987). This suggests that the local geographical conditions also played vital role in the pedogenic modification of these sediments (Bronger *et al.,* 1987).

PALEOCLIMATIC IMPLICATIONS OF LOESS–PALEOSOLS

This study is mainly concentrated on those micro-features, which are useful to investigate past-climatic conditions (Fig. 5-8). The most common micromorphological features reported from loess–paleosol sequences are microstructures (vugs/void channels, pedal and massive microstructure), biological features (root traces/pedotubules), textural features and calcitic features, the characteristics of clay accumulation horizons and hydromorphic reactions, and decomposed organic matter, revealing postpedogenetic processes after burial are of great importance for obtaining reliable information on the nature and intensity of weathering processes in loess-paleosol sediments in terms of past climatic conditions (Courty and Fedoroff, 1985; Courty *et al.,* 1987, 1989; Fedoroff *et al.,* 1990; Zhengtang *et al.,* 1996; Kemp, 1998). In studied paleosols, micromorphology is discussed mainly in terms of microstructures, clay coatings, disseminated organic matter, secondary $CaCO_3$, Fe/Mn oxides and biological features.

Pedogenic $CaCO_3$ features were found most common in the form of coatings and hypo-coatings in bioturbation channels. The presence of pedogenic $CaCO_3$ in the form of coatings, infilling and nodules is due to the precipitation of leachates washed down from the overlying horizons (Kemp *et al.,* 1996).

According to Retallack (1994) carbonates are retained in soil profiles only where the annual precipitation is <1000 mm. The present day average annual precipitation of the Kashmir Valley is 710 mm and the average annual temperature is 13.5ºC. Mean Annual Precipitation (MAP) and Mean Annual Temperature (MAT) values for these paleosols are also determined (Ahmad and Chandra, 2018). MAP values range from ~59 to 564, with average values ~419 mm/yr whereas MAT values range from ~10.55 to 12.57, with average values ~11.73. The MAP values of these paleosols are significantly lower than this threshold which therefore favors pedogenic $CaCO_3$ accumulation in paleosol profiles. Studies of the oxygen isotope ratios of the pedogenic $CaCO_3$ nodules from other sections of the valley revealed seasonal variation of rainfall with $\delta^{18}O$ values ranging from 6.37‰ to 7.75‰ (Dar *et al.,* 2015a). It is believed that these climatic conditions favored the precipitation of $CaCO_3$ within the soils rather than it's leaching away from the soils. The results of the thin section analysis show that calcium carbonate is less than ~10% in the paleosol profiles. The percentage gradually increases up to 20% in the B_{tk} horizons and in altered/unaltered loess horizons. This is because of the consequence of the migration and accumulation process. The higher concentration occurs in B_{tk} horizons. The relatively shallower depth of calcium accumulation indicate that the climate was progressively drier as corroborated by carbon isotopic studies of pedogenic carbonate nodules (Dar *et al.,* 2015a).

Thick illuvial clay coatings are observed in the illuvial horizons of paleosols DS2, DS3, DS5, DS7, KS3, KS4, KS6, KS7, KS9, BS3 and BS4, consistent with the field observations. In rest of the paleosols, the overall clay content is less. We inferred that these paleosol profiles are relatively well developed and record maximum thickness. Therefore, these paleosol profiles can represent one full interglacial period. Kusumgar *et al.* (1980) proposed that the top most paleosol profile at Burzahom Village section is ca 18000±1000 years old and represents warm-humid climate during last interglacial stage. However, Gupta *et al.* (1991) proposed that 18ka ago is regarded as the last glacial maximum (LGM) globally and warm-humid climate as suggested by Kusumgar *et al.* (1980) is an enigma. The clay coatings represent the gradual accumulation of clay translocated in suspension under seasonally dry climatic condition (Kemp, 1998). However, clay pedofeatures are not only the function of climate but there are evidences which might suggest that the clay formation also depends upon landscape stability and time (Bronger *et al.,* 1998). The thin section study revealed a considerable amount of the fine clay plasma, with a high birefringence, occurring as thick seams along the voids and the conductive channels. The presence of clay in the paleosol profiles is consistent with the results of geochemical studies, which indicates that these sediments are rich in inherent clay (Ahmad and Chandra, 2013).

Illuvial clay and $CaCO_3$ coatings are sometimes superimposed (*e.g.,* DS3, DS6). The presence of pedogenic $CaCO_3$ coatings superimposed on the clay coatings in paleosols probably suggests relatively wetter conditions were followed by arid climatic conditions when secondary carbonates get precipitated (Kemp and Zarate, 2000). This postulation is supported by smaller amounts of total $CaCO_3$ observed in the surface (eluvial) horizons and larger amounts found in the lower (B_{tk}) horizons (Table-1). Badia *et al.* (2009) have found similar features in the oldest terrace (Early Pleistocene) of the Segre River northeast Spain, which were interpreted as caused by Quaternary climatic changes. SEM study also confirms these microscopic observations. Alternate cryptocrystalline coatings of $CaCO_3$ and clay are also observed (Fig. 8a) that develops in conditions of contrasting climate with clearly express dry and wet seasons. These coatings occurred in a wide number of semiarid/arid soils in different regions of the world (Kuznetsova and Khokhlova, 2010). The main peculiarities of $CaCO_3$ coating are their smooth surfaces, suggesting precipitation from colloidal solutions. Its thickness is greater than 1 μm and they mask a relief of soil matrix (Fig. 8b), suggesting arid climatic conditions (Kuznetsova and Khokhlova, 2012). During the humid period, these coatings become thinner and fragmentary and soil matrix usually aluminum silicate grains become partly free of the coatings. Clay is usually translocated in moister climatic conditions and subsequently gets engulfed by carbonate when climate becomes drier (Khormali *et al.,* 2003). Pal *et al.* (2003) have suggested that clay illuviation and pedogenic $CaCO_3$ formation are two concurrent pedogenic processes in semiarid climatic conditions.

The clay coatings observed from thin sections is sometimes dark brown to reddish-brown and limpid yellowish brown in colour. These clay coatings are characterized by lower humus contents, containing abundant red to brown fine iron oxide/hydroxide particles and are thus described as ferric-argillans (Fig. 5d and Fig. 6f). Badia *et al.* (2013) suggested that under warmer and drier climatic conditions; the oxidization of Fe^{2+} ion forms goethite that gives the horizons their reddish yellow color. In humid climates, high groundwater level, the retention of surface water in the soil (water logging) modified the oxidation–reduction conditions of the soils, as a result iron and manganese gives rise to reduced colors, depleted zones in the matrix, different kinds of nodules, and thick and continuous coatings and consequently reduced conditions firstly due to ferrous compounds, the soil colour becomes blue-grey or grey, and secondly the rates of decomposition of organic are slow. This process is known as gleying. Iron and manganese ions are mobile and may be transported by water as it moves through the soil under reduced condition. Manganese is reduced more rapidly than iron, while iron oxidizes more rapidly upon aeration. Characteristic colors (grey and yellow/brown) are created by these processes (Soil Survey Staff, 2003; 2006). The reduced iron and manganese ions may be removed from a soil if vertical or lateral fluxes of water occur, in which case there is no iron or manganese precipitation in that soil. Wherever the iron and manganese are oxidized and precipitated, they form either soft masses or hard concretions or nodules with diffused boundaries (Soil Survey Staff, 2003; 2006). Here in our case, gleying is not enough to solubilize large quantities of iron. The concentrations of Fe/Mn oxides (and/or oxyhydroxides), are very scarce in all horizons. These are present in the form of impregnations or hypocoatings or coatings and nodules in few horizons. In thin sections of most of the paleosols, Iron oxide impregnations are massive, dark-brown or opaque and consist of dispersed detrital grains of the various size and shape as grains in the matrix and occur frequently throughout the sequence. On the basis of their irregular morphology and sharp boundaries (*e.g.* Fig.5a, Fig.6a), it is clear that these are inherited and have been transported within the sediment. In case of paleosol DS2, DS5, DS7, KS3, KS5, KS6, KS9, BS3 and BS4; these are generally regarded as formed in soils by redistribution of Fe and Mn in response to fluctuations in redox potential associated with periodic water saturation. The common superimposition of Fe/or Mn oxides in the form of coating on illuvial clay (ferruginous clay coating) that represents the warm conditions for oxidation processes to operate (Fig. 5d), however suggests that they may have formed from in situ accretion of iron oxides which occurred during a period of high but seasonally fluctuating groundwater circulation rich in chelates (in a similar manner to the calcium carbonate leached from the overlying horizon) when ion-carrying water moves through the aerated zone in the soil (Schwartzman, 1985). Most of the paleosols are rich in reddish iron oxides coating that represent the warm conditions for oxidation processes to operate.

Fissure or pedal microstructures are also present in these paleosols (*e.g.* DS5, KS5, and KS6). These microstructures are the characteristic features of the well-developed soils. Massive or apedal microstructure are the typical micromorphological features observed in loess horizons and weakly developed paleosol DS1, DS4, DS6, KS2, KS5, KS10 and BS1, implying their subjection to only weak soil-forming processes, weak biological activity, sparse vegetation and cold–arid climatic condition. The paleosol profiles DS2, DS3, DS5, DS7, KS3-KS9 are characterized by weak to strongly developed pedal structures, formed by shrink-swell activities due to fluctuations in water saturation because of seasonal wetting and drying conditions (Wilding and Tessier, 1988; Stolt *et al.,* 1994; Zarate *et al.,* 2000; Kemp and Zarate, 2000). This is well substantiated by the oxygen isotopic signatures of the precipitation which reveal seasonal variation of rainfall in the Kashmir Valley (Dar *et al.,* 2015a). The scanning electron micrographs also show desiccation cracks in these paleosols, suggesting that these are formed by shrink-swell activities under drier and seasonal climate (Fig.8f). The soil with spongy microstructure can be regarded as weakly developed steppe soils in semi-arid environments (Zhengtang *et al.,* 1996). It also suggests that the profile was rarely water-saturated (Courty and Fedoroff, 1985), thus with a relatively low soil humidity (Zarate *et al.,* 2000).

In arid and semi-arid soils, the grass and short-shrub vegetation normally has a large root system than the above-ground litter (Zhu *et al.,* 1983). Channels associated with the roots and some soil fauna, provide some of the most abundant and characteristic features in such soils (*e.g.* Parle, 1963; Ehlers, 1975; FitzPatrick, 1980; Syers and Springett, 1983; Zhu *et al.,* 1983; Courty and Fedoroff, 1985). The root density is mainly determined by the climate, particularly the precipitation. In the field, clear effects of faunal activity were observed in few paleosols where large channels in-filled with clean churned soil are easily seen with the naked eye (Fig. 4j). In thin sections, most of the paleosols studied are characterized by root channels (*e.g.* Fig. 5b g,i; Fig.6e; Fig.7b-e). The loess contains very small channels (Fig.4h); these were probably formed by roots of short grass species developed under dry-cold environments as the loess accumulated (Liu, 1985; Li *et al.,* 1992). In contrast, the channels in the paleosols are relatively large, but density is still low. This is ascribed to the effects of tall grass (Li *et al.,* 1992) during the relatively milder and moister periods of soil formation. The overall low organic contents and root traces and channels of very small dimensions in these paleosols indicate the presence of steppe type vegetation that would have acted as a highly effective sediment trap and probably suggests limited opportunity for an extensive vegetation cover to develop whilst the loess was accumulating.

CONCLUSION

Integrated macro-, micromorphological and SEM studies of the Late Quaternary loess-paleosols sediments of the Kashmir Valley during Middle to Late Pleistocene period have allowed the reconstruction of paleoclimatic conditions of the Kashmir valley. The studies carried out have revealed the following:

Pedological features of these paleosols, especially clay illuviation, $CaCO_3$ accumulation, biogenic features, Fe/Mn oxides, fissure and pedal microstructures indicate that these paleosols are weak to moderately developed representing cold arid to warm semi-arid climatic conditions. These paleosols indicate that loess sedimentation was episodic, or at least rates of deposition decreased to the point where pedogenesis could keep ahead of aeolian input. It further suggests that loess deposition and pedogenesis is likely competing processes and neither stop completely during either phase of the loess/soil formation cycle representing cold arid to warm semi-arid climate. We inferred that four periods of relatively higher precipitation and temperature conditions occurred in the Kashmir Valley. These periods are observed in paleosol profiles DS2, DS3, DS5 and DS7 of Dilpur Village section and their stratigraphic equivalent at Karapur and Burzahom Village sections. These periods of relatively higher precipitation and temperature conditions do not each represent complete interglacial period. The paleosols DS3, KS4 and BS4 are relatively well developed and record maximum thickness representing prolonged land surface stability when pedogenic processes outpace loess deposition, may represent one full interglacial period. The loess horizon DL1 and paleosols DS1, KS1 and BS1 probably represent the last glacial maximum (LGM) in Kashmir valley and the Last Glacial was interrupted by arid and warm semi-arid intervals when BS3 and BS2 paleosol profiles and their stratigraphic equivalent are formed. Also the lower part of the sections below the DL2 and KL1 is interpreted as the fluctuation probably within the last interglacial period. Overall the climate of the valley for most of the times fluctuated between cold arid to warm semi-arid during the recent past.

To summarize the results of the present research work, it is suggested that loess-paleosol sediments of the Kashmir valley formed syndepositionally when both loess deposition and pedogenic processes were taking place simultaneously. However, the balance between rate of sedimentation and rate of pedogenesis change in cyclic fashion. This also rules out sharp glacial or interglacial conditions during the development of these paleosol profiles. These paleosols are subjected to weak to moderate degree of weathering. The climate of the Kashmir Valley fluctuated between cold-arid to warm semi-arid during Middle Pleistocene to Late Pleistocene.

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