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Loess-Palaeosol Sequences in the Kashmir Valley, NW Himalayas: A Review

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Loess deposits and intercalated palaeosols are widespread in the Quaternary record, and these have been extensively used to gain insights into continental paleoclimatic and paleo-environmental conditions and changes. Especially over Eurasia, loess geoarchives play an important role for our understanding of past changes. Loess covers almost 500 km^2 of the Kashmir Valley in north-western India, it occurs dominantly in plateau positions, but also on terraces and sometimes forms slope deposits with thicknesses ranging from several to more than 20 m. For the time being, however, the timing of the initiation of the loess accumulation, the provenance, the grain size composition and also the paleo-environment have not been studied systematically and yet only little quantitative data is available. Yet it is clear that deposition rates are at least comparable to European loess, and that the presence of multiple palaeosols intercalated in the loess can provide valuable information on the history of the region. The limited available data hinders regional and continental correlation, and tapping its value as archive of past environmental changes in this sensitive region with influence from Westerlies and the Indian Monsoon. However, several characteristic palaeosol patterns can be traced throughout the Kashmir valley, which provide stratigraphic information. Several studies investigate physical and chemical properties of the loess-paleosol sequences and conclude to its aeolian origin and recording of past climates. The intensity of soil formation phases is traced through various proxies in low resolution and yet without conclusive age control. Here we review the exiting literature, available data, and interpretations from loess-palaeosol sequences in the Kashmir Valley. These are placed in the context of our own observations and loess from the Indian subcontinent.

Keywords: Kashmir, loess, paleoclimate, Pir-Panjal Range, Karewa, quaternary

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INTRODUCTION

Loess-Palaeosol Sequences

Since the middle of the 19th century, the term loess has become common in Earth Sciences and many researchers have tried to define it (Sprafke and Obreht, 2016 and references therein). Among them, Pye (1995) has given a simple definition of loess as “terrestrial clastic sediment, composed predominantly of silt-size particles, formed essentially by the accumulation of wind-blown dust.” Loess mainly consists of quartz, micas, feldspars, clay minerals, and varying amounts of calcium carbonate.

The processes of particle formation, transport, deposition, and post-depositional modification to the formation of sometimes thick loess deposits are argued to be closely linked to glacial geomorphic processes and changes in regional and global climate (e.g., Muhs, 2009, 2018; Újvári et al., 2016). Both glacial and non-glacial sources (mainly rivers and deserts) have been envisaged as the source regions for loess (e.g., Smalley, 1972; Wright, 2001; Sun et al., 2002; Smalley et al., 2009). Since loess is deposited directly from the atmosphere, it forms one of the few geological archives that can record atmospheric circulation (e.g., Porter, 2001; Muhs and Bettis, 2003; Smalley et al., 2011; Muhs et al., 2013; Obreht et al., 2015, 2017; Zeeden et al., 2015), and can be used for assessing the role of dust in climate change (e.g., Harrison et al., 2001).

The accumulation of loess requires both aeolian material and a trap for deposition; it has been argued that at least a sparse vegetation cover or topographic barriers are necessary for the trapping of aeolian dust (see e.g., Tsoar and Pye, 1987; Mason et al., 1999; Iriondo and Kröhling, 2007). In Kashmir, the topography has probably always been diverse enough for trapping of material. Also it may be assumed that the area was covered by sparse vegetation (C_3 and C_4types) over the last glacial/interglacial cycles (Krishnamurthy et al., 1986; Dar et al., 2015b). Here we assume a similar substrate for pedogenesis throughout the Kashmir valley and through time. Although this is not a known, nothing indicates a spatial or temporal difference.

Loess deposits have been reported from around the globe, and Quaternary loess deposits in China are the thickest, preserving records of the entire Quaternary and reaching further back in time (e.g., Ding et al., 2002a; Vandenberghe et al., 2004; Sun et al., 2006; Hao and Guo, 2007). In the Indian subcontinent, loess deposits are reported in a paleoenvironmental context from the Kashmir Valley, Potwar Plateau, Peshawar Basin (e.g., Kusumgar et al., 1980; Bronger et al., 1987b; Pant et al., 2005). Holocene loess deposits are reported from the several valleys in the western to central southern Himalaya and the Central Himalaya (Williams and Clarke, 1984; Basavaiah and Khadkikar, 2004; Pant et al., 2005), and recently aeolian silt-size deposits are reported from the Indo-Gangetic Plain (Liu et al., 2017) and Deccan Plateau (Liu et al., 2019). Studies on Quaternary climate change have fostered the interest in loess research because of sometimes high accumulation rates allowing for temporally highly resolved studies on the paleoenvironments. Further, the relatively well-developed chronological framework in Asia and the widespread occurrence over Eurasia (e.g., Chlachula et al., 1997; Ding et al., 2002b; Hao et al., 2012; Yang and Ding, 2014; Zeeden et al., 2016, 2018b; Veres et al., 2018; Vlaminck et al., 2018; Wang et al., 2018) make loess-paleosol sequences the most widely distributed geoarchives for studying past climate dynamics. Loess intercalated with palaeosols is a valuable source for studying paleoclimate dynamics because soil properties and features depend on the environmental conditions at the time of formation (e.g., Dodonov et al., 2006; Buggle et al., 2011). The presence of palaeosols within the loess deposits indicates relative landscape stability. It is well established that loess deposits are common in the mid-latitude Quaternary geological record covering ~10% of the Earth's surface (Pécsi, 1990; Muhs and Bettis, 2003; Muhs, 2013), and loess has a special preservation potential for archeology (Händel et al., 2009).

Aeolian loess deposits occur as sediments overlying the widespread fluvial and lacustrine sediments in the intermontane Kashmir Valley. The dust parent material is assumed to be dominantly formed by glacial erosion and/or erosion by other geomorphic processes within the valley and its surrounding mountain ranges. Whether further transport from outside the valley plays a major role is subjects of ongoing debates. In either case, the loess deposits of Kashmir provide a unique opportunity to investigate paleoclimate change and monsoon variations in the NW Himalayas in the context of uplift of the Himalayas and central Asian high mountains.

Geological Setting of Kashmir and the Loess-Palaeosol Sequences

The oval shaped Kashmir Valley is located at an average altitude of 1800 m above sea level and lies between 33°20′ and 34°41′ N latitude and 73°55′ and 75°37′E longitude (**Figures 1**, **2**) in the western Himalayas. It is located between the Greater Himalaya in the northeast and the Pir-Panjal Ranges in the southwest. Formation of the valley and its sedimentary filling deposits are attributed to the rise of the Pir-Panjal Range, associated with the Himalayan orogeny, which impounded the ancient drainage into the lake known as Karewa Lake (e.g., Bhatt, 1976; Singh, 1982; Kotlia, 1985a,b; Bronger et al., 1987b; Singh Kotlia and Dayal Mathur, 1992; Basavaiah et al., 2010; Dar et al., 2013, 2015b). The Karewa Lake sediments, known in geological literature as Karewa Group, range in age from lower Pliocene to middle Pleistocene (Bhatt, 1976; Singh, 1982; Basavaiah et al., 2010). The sediments of the Karewa Group are underlying the loess, and are divided into different formations based on their stratigraphy and lithology. The sediments of the Hirpur Formation (Lower Karewa) comprise a thick succession of conglomerate beds, gray clays and medium to coarse grained sand beds. It can be further sub-divided into the Dubjan, Rembiara, and Methawoin Members. With the continuous uplift of the Pir-Panjal Range and the onset of Pleistocene glacial aridity, the Nagum Formation (Upper Karewa) deposits were exposed after draining and desiccation of the lake, and were subsequently overlain by aeolian loess (Burbank and Johnson, 1982; Agrawal et al., 1989; Babeesh et al., 2017). The sediments of the Nagum Formation are again divided into Shopian, Pampore and Krungus Members. The Dilpur Formation represents loess (like) deposits, occurring as overlying the paleo-landscape in the form of terrace-, slope- and plateau-deposits with thickest sequences preserved in plateau and terrace settings. Loess deposits show variable thickness along and across the Kashmir Valley with thickness ranging from > 20 m in the south-western side to several m in the north-eastern side of the valley (Bronger et al., 1987a and also own observations). While loess in higher positions of the south-western flank is mostly of plateau-type and shows a laterally continuous character, toward the basin more reworking and channeling can be observed in several gravel- and clay pits west of Srinagar. In some slope positions, loess-paleosol sequences are covering the previous morphology. The

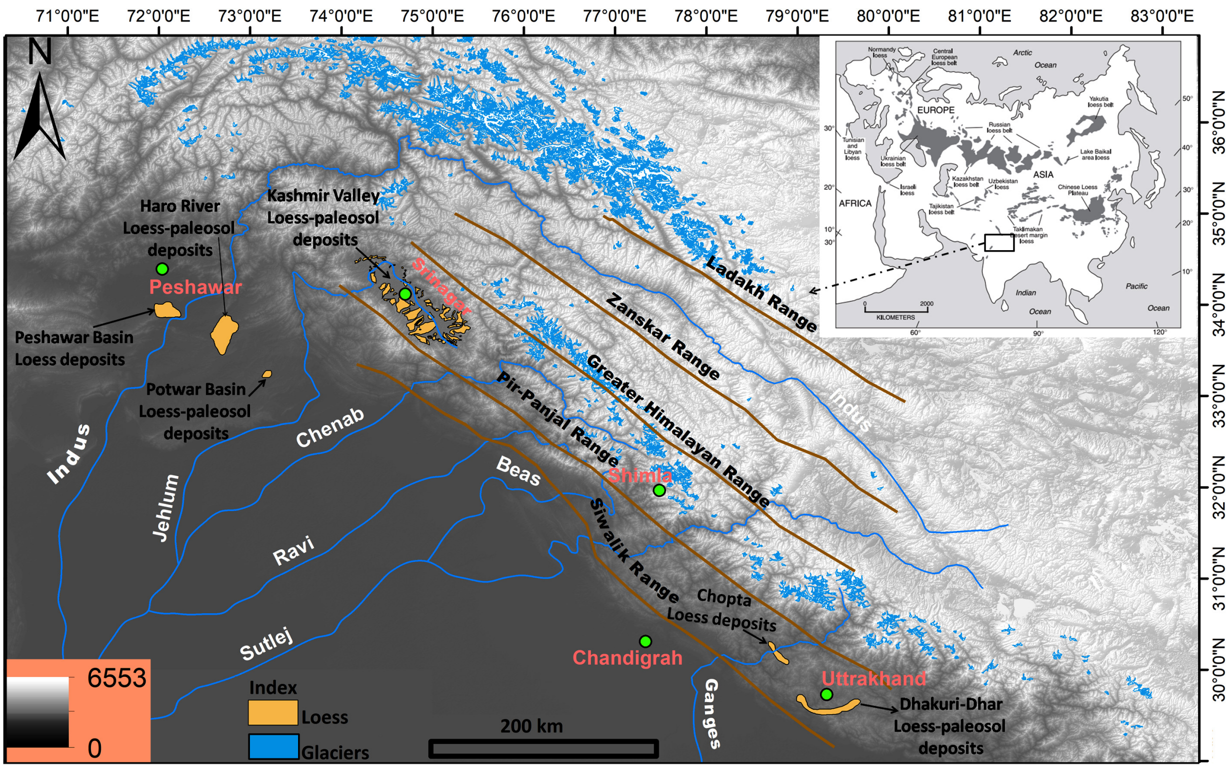

FIGURE 1 | The upper right inset is showing the distribution of loess in Eurasia after Muhs and Bettis (2003) with focus on the region around Kashmir. Enlarged (SRTM DEM derived hill shade) map showing the distribution of loess in India and Pakistan (as reported), modified after (Bhatt, 1982; Akram et al., 1998; Pant et al., 2005). Glacier cover is taken from RGI Consortium (2017) and major rivers and sub-Himalayan mountain ranges are after Brookfield (1998).

main areas of loess deposition are on the south-western side of the Kashmir valley, this is linked to the drying of the lacustrine environment which gave space to terrestrial conditions and thus loess accumulation space earlier on this side, where the Pir-Panjal Range is uplifting. Also the gentle morphology contributes to the higher preservation potential. Several outcrops allow assessment of the spatial homogeneity of the deposits over 10s–100s of meters. Especially toward the Pir-Panjal flank, the loess is often homogenous over such distances (and possibly wider). In contrast, toward the Valley the loess tends to become incised in some instances, so that care must be taken when sampling for palaeo-studies. Loess deposits of the Kashmir Valley provide one of the most valuable paleoenvironmental archives in the Quaternary of the Indian subcontinent but are yet little studied.

Climate and Its Evolution

Currently the rainfall pattern in the Kashmir valley (~710 mm/year) is dominated by western disturbances (WDs), and also has contributions from SW monsoons (Dar et al., 2015b). Variations in precipitation and temperature within the valley are mainly the result of altitude and aspect. Meteorological data shows that the annual temperature in the Kashmir Valley varies from -10 to 35°C (Zaz et al., 2019).

The onset of the monsoon climate system in Asia is by some authors attributed to the uplift of the Tibetan Plateau (TP) which started ~14 Ma ago (Edwards et al., 1996), although this is subject of ongoing debate. The formation of tectonic basins along the Himalayan and Kunlun mountain ranges is accompanied by deposition of thick gravel beds (500–1000 m in thickness), especially in lacustrine and fluvio-lacustrine sediments during the Late Miocene-Pliocene-Early Pleistocene also reflect the intensive tectonic movements around the Qinghai-Xizang TP (An et al., 1999). The uplift resulted in the formation of a well-established latitudinal gradient of increasing aridity toward the central parts of the TP and Himalayas (e.g., Wünnemann et al., 2008, 2010). The uplift of the TP accelerated during the Plio-Pleistocene epoch, accompanied by global atmospheric reorganizations, global cooling and loess sedimentation, which was probably also triggered by enhanced wind activity associated with the connection between the great east Asian trough and the Siberian anticyclone (Zhao and Morgan, 1985). This phenomenon has also been responsible for changes in precipitation and intensification of monsoon climate within the Indian region (Ganjoo and Shaker, 2007). However, the uplift of the Pir-Panjal Range on the southwestern side of the Kashmir Valley has locally played a major role in determining the climatic conditions. The Pir-Panjal Range attained a height of 1400–5000 m over the last 4 Ma due to tectonic uplift (Burbank and Johnson, 1982; Agrawal, 1985) and has acted as a barrier for southwestern monsoon winds and precipitation, thus changing the climatic conditions of the valley from tropical to more arid (Basavaiah et al., 2010). The Tibetan Plateau uplift (and coeval global CO_2 drawdown)

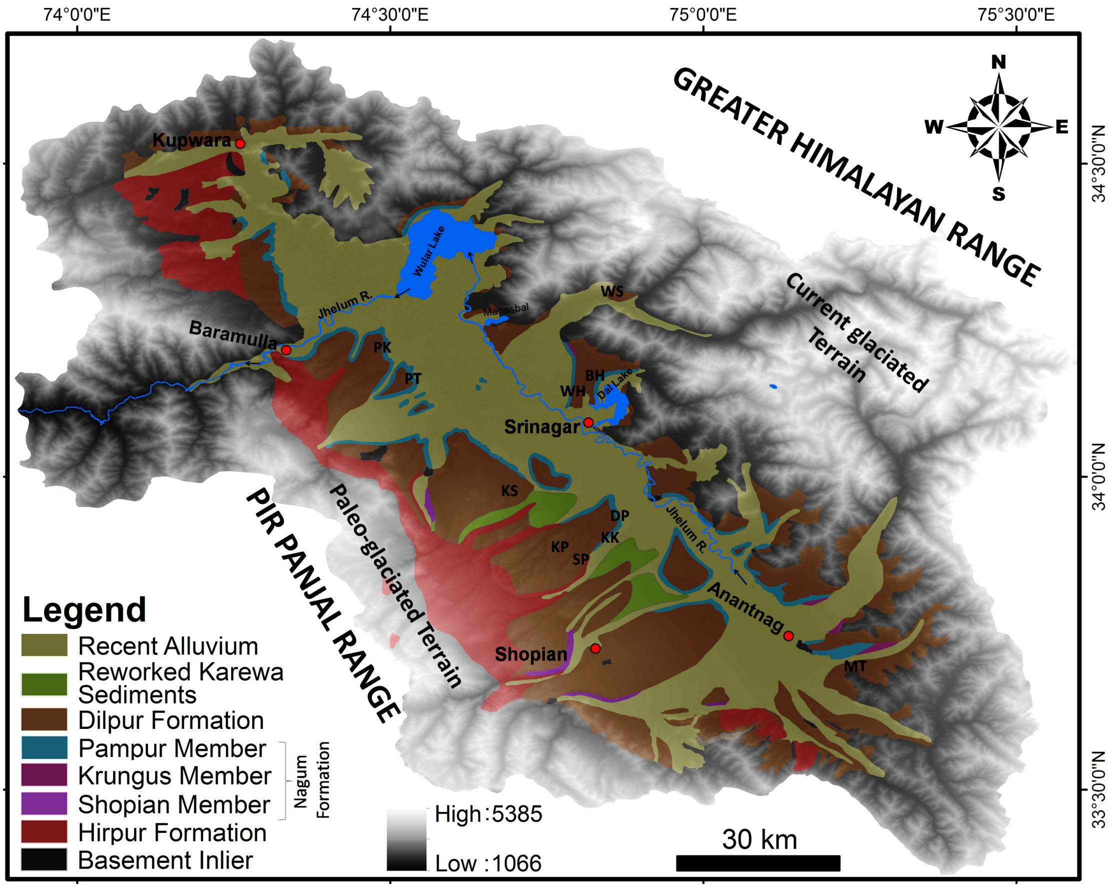

FIGURE 2 | Spatial distribution of various sediments of the Karewa Group in the Kashmir Valley after Bhatt (1982). Abbreviations MT, SP, KS, PT, PK, DP, KP, KK, BH, WH, and WS indicate the localities Mattan, Shankerpora, Khan Sahib, Pattan, Putkhah, Dilpur, Karapur, KhanchiKol, Burzahom, Wanihama, and Wuyil Sind, respectively. The Dilpur Formation represents loess and loess like sediments. The altitude is derived from SRTM (DEM; Farr et al., 2007).

has most probably contributed to the cooling processes and the onset of strong Quaternary glaciations. Quantifying the timing and extent of glaciation and the ensuing aridity of the Kashmir Himalayas and in the broader Himalaya is a prerequisite for linking Himalayan climatic fluctuations to global climate changes. Loess-palaeosol sequences, being sensitive to changes in configuration and intensification of atmospheric circulation, can provide valuable information on the local environmental change (e.g., An et al., 1999; Obreht et al., 2016).

Loess and lake sediments form the substrate for the most fertile soils in most of the Kashmir Valley and its enormous agricultural potential. The alluvial soils, derived mostly from the erosion of loess capped landscapes, cover most of the valley floor and the river flood plains. As per the United States Department of Agriculture [USDA] (1999) soil taxonomy classification, soils developed on loess in the valley are of thick organic rich mollisol and alfisol type soils, sometimes partly eroded at the top. The valley flanks comprise inceptisols as forest soils, and the upper reaches of the Pir-Panjal range are grass-covered entisols under pastures (Mahapatra et al., 2000). Various high-quality crops are grown on loess and loess-derived soils. In the higher reaches mixed broad-leaved and coniferous forest vegetation including Pinus excels, *Populus* sp., *Ulmus* spp., and Cedrus deodara etc. are prevalent. Entisols are used as pastures.

STRATIGRAPHY AND CHRONOLOGY

Available Data

Accurate chronological data is essential to understand and establish the timing of events documented within geoarchives in general and also loess deposits (e.g., Singhvi et al., 1987; Zeeden et al., 2018a,b). A number of techniques, including relative and radiometric dating techniques, have been used to understand the chronology of loess-palaeosol sequences. However, in the Kashmir Valley the initiation of loess deposition has remained a matter of debate and direct chronologies have been established so far only for the upper part of the loess-palaeosol formations (**Table 1**). The Loess-palaeosol sequences of the Dilipur Formation are clearly occurring in the Brunhes normal chron and are for sure younger 781 ka (Ogg, 2012).

Rendell and Townsend (1988) provide a minimum age from luminescence dating of ∼143 ka for the loess in Kashmir. Singhvi et al. (1987) date the uppermost thick Bt horizon, occurring below

TABLE 1 | Stratigraphic data and ideas as in literature, ordered by year.

Aim of study/data	Outcome/interpretation	References
Magnetostratigraphy, Luminescence dating	Loess of Brunhes Chron age, younger 780 ka	Agrawal et al., 1979
^{14}C dating	The last deglaciation started at ca. 18 ka	Kusumgar et al., 1980
Magnetostratigraphy	Lake deposits in Kashmir are spanning ∼4 Ma	Burbank and Johnson, 1982
^{14}C dating	Loess in Kashmir is younger 100 ka and has sedimentation rate of∼26 m/100 ka	Kusumgar et al., 1986
Pedostratigraphy	Loess in Kashmir comprises 4 glacial/interglacial cycles, and is older ∼350 ka	Bronger et al., 1987a
Luminescence dating	The topmost well developed soil is related to the last interglacial	Singhvi et al., 1987
Identification of glacials and interglacials	Loess in Kashmir is younger 200 ka	Agrawal et al., 1988
Luminescence dating	Loess in Kashmir is dated to ∼100 ka at ∼10 m, ages are probably too young	Rendell and Townsend, 1988
Identification of glacials and interglacials, ^{14}C dating	Loess in Kashmir spans the last ∼200 ka	Agrawal et al., 1989
Rock magnetism and correlation to marine d^{18}O data	Loess is older 200 ka	Gupta et al., 1991
OSL dating	Manasbal section is dated to MIS 3-2	Babeesh et al., 2017
^{14}C dating	Kashmir loess encompasses 1–2 glacial/interglacial cycles	Meenakshi et al., 2018

a triplet of "humus rich soil horizons" to the last interglacial (∼100–120 ka). The three humic horizons above this thick Bt horizon are dated to ∼80–50 ka. Babeesh et al. (2017) use optically stimulated luminescence to date the upper 8.7 m of the Manasbal section to the last 40 ka.

Agrawal et al. (1988) proposed the loess-palaeosol sequences to date back to ca. 200 ka, based on field observations and previous literature. Based on extrapolating sedimentation rates of a part of loess-palaeosols from the last glacial cycle, the reinterpretation of TL dates by Rendell et al. (1989) and correlation of loess to the marine oxygen isotope stratigraphy, Gupta et al. (1991) suggested that the base of the loess sequence is approximately 225 ka. Their correlation approach, however, is inconsistent with luminescence data by Singhvi et al. (1987), and an underestimation of the ages is probable.

Bronger et al. (1987a) states that at least four well developed soils are preserved in loess-palaeosol sequences in the Kashmir valley. Based on convincing dates of the uppermost one representing the MIS5e, Singhvi et al. (1987) suggest a time span of >300 ka based on thermoluminescence (TL) dating is a minimum age.

Lithostratigraphy and Pedostratigraphy

It is evident that thicker and older loess-palaeosol sequences are present at the Pir-Panjal flank than at the Himalayan flank and in the center of the Kashmir valley (e.g., Bronger et al., 1987a; Singhvi et al., 1987; Agrawal et al., 1988, and also own observations). Below the recent soil complex, which includes a humic topsoil and a thick Bt horizon, four gray-black soils are present in a (more or less pedogenetically altered) upper loess package. While previous studies were unsure whether three or four gray/blackish soils are present in this package, the recent literature and our own observations (at Wanihama near Burzahom, the Khan Sahib area and Shankerpora) strongly suggest four differently expressed gray/blackish soils in this loess package (**Figure 3**) above the first dark brown palaeosol (K-S1; **Figure 3**). Three gray/black soil horizons at the base of the upper loess package (K-L1) are present. Of these the uppermost one is weakest expressed, and the lower two ones are separated by an ochrish pedogenetically overprinted loessy material. This triplet represents an excellent marker package which is consistently observed in the Kashmir valley. The K-L1 is present in most places and confined at the base by a thick and dark brown Bt horizon (K-S1), which may (or may not) be genetically connected to the humic horizon above (Bronger et al., 1987a; Singhvi et al., 1987; Agrawal et al., 1988; also own observations).

The loess-palaeosol sequences below the K-S1 are not exposed in many places, making an equally consistent and reliable stratigraphic description challenging. Further, stacking of palaeosols into pedocomplexes and little separating loess is complicating a description and interpretation (Bronger et al., 1987a), our observations support this. However, the following older and second loess complex (K-L2) contains a (weak) grayish double-soil present at least in Shankerpora and the Khan Sahib area (Dar et al., 2015c; own observations; see **Figures 3**, **4C,D**), and is followed by another brown soil. Below this interval we refer to the describing literature (i.a. Bronger et al., 1987a; Gupta et al., 1991; Dar et al., 2015b; Chandra et al., 2016; Ahmad and Chandra, 2018). Literature and own observations suggest at least two further well-developed soils and loess package between these (Bronger et al., 1987a; Dar et al., 2015a).

The loess generally overlies fluvial or lacustrine sediments (**Figures 4B,C,F**). We observe the lowermost loess being overlain by non-aeolian sediments in the transition from fluvial/lacustrine to aeolian sedimentation. The transition of fluvial/lacustrine and aeolian sedimentation is not always sharp, but may start with (pedogenetically overprinted) loess, then go back to a limnic environment and then become fully aeolian. This is the result of changing water levels of water bodies and may be expected form a sedimentological and sequence stratigraphic point of view.

Chronostratigraphic Information

Magnetostratigraphy places the loess of the Kashmir Valley in the Brunhes normal polarity chron, younger 780 ka (Basavaiah et al., 2010 and references therein). Due to lacustrine sediments above

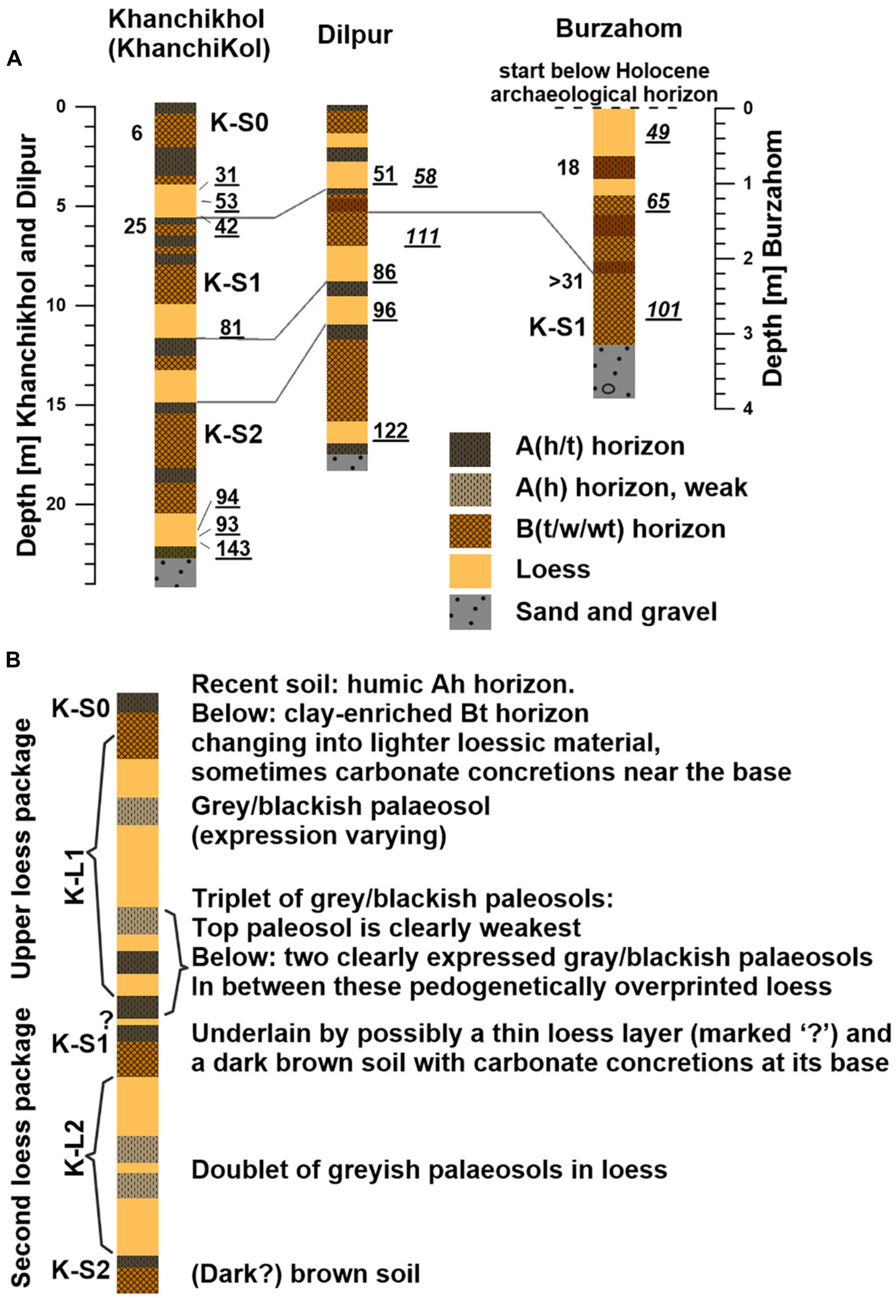

FIGURE 3 | (A) Comparison of selected loess-paleosol sections which have been dated. Ages are rounded and given in ka. Stratigraphic positions are indicated as good as possible, correlation to stratigraphic unit is correct but the exact positioning is only indicative here. Logs are summarized and simplified from Kusumgar et al. (1986), Bronger et al. (1987a), and Singhvi et al. (1987). Thermoluminescence ages are plotted right of section logs, here after Rendell and Townsend (1988; bold and underlined), and from Singhvi et al. (1987; bold, underlined and italic). ^{14}C ages from Kusumgar et al. (1986) are included left of the stratigraphic columns. Note that other dates are available but cannot be placed in the stratigraphies unambiguously. Correlations are after Bronger et al. (1987a) and Singhvi et al. (1987) and Gupta et al. (1991). Note that ^{14}C ages are systematically younger than thermoluminescence ages. Please see the here introduced nomenclature for loess and palaeosol sequences as K-S0 to K-S2 and K-L1 to K-L2. At the Himalayan Flank only the K-S1 is present, while older loess is described from the Valley toward the Pir-Panjal flank. **(B)** Generalized stratigraphy of the upper/younger Kashmir loess–palaeosol sequences across the Kashmir Valley. At some localities, loess below these two packages is outcropping, but we can at this point not describe a general pattern. Below the here generalized stratigraphy, the stratigraphy is less clear to us. Several (2 at least, possibly more) well expressed paleosols follow. These are not always separated by loessy material. We name the Soils K-S0 (recent soil) to K-S2 (second thick brows soil) and the upper two loess units K-L1 and K-L2. These are descriptive terms here and are no indication of time or glacial/interglacial cycles due to a lack of reliable chronology. Please note the maker triplet of soils in **(B)**, which sometimes represents the upper part of an amalgamated K-S1 pedocomplex, and sometimes is separated by loess layers, see also **Figures 4D,E**.

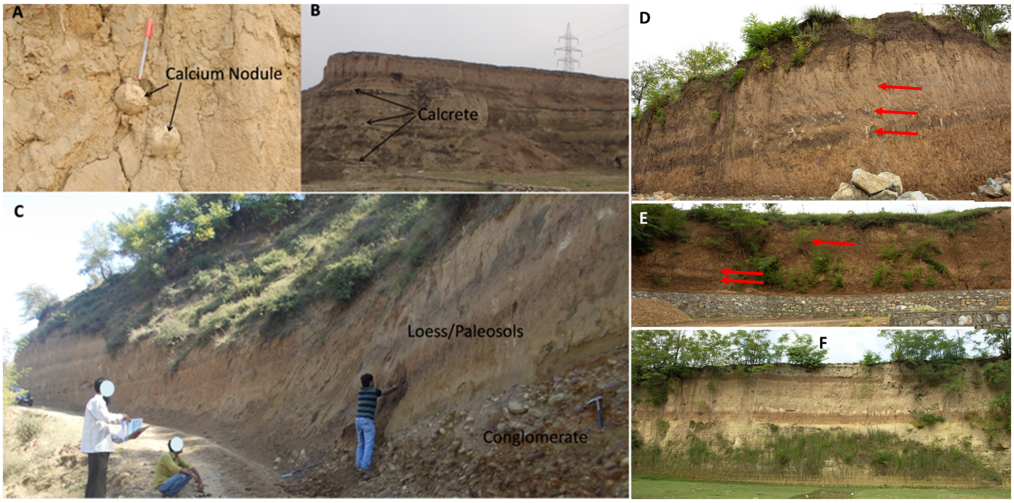

FIGURE 4 | Field photographs showing **(A)** calcium carbonate nodules in the 5th well developed palaeosol at the Shankerpora village section **(C)**, **(B)** three calcrete layers in lacustrine sediments near the town of Pampore underlying loess, reflecting dry and arid climatic conditions. These calcrete layers in Central Kashmir are chronologically and stratigraphically equivalent to the loess in the south-western Kashmir Valley (see Dar et al., 2015a for further explanation), **(C)** loess palaeosol sequence section near Shankerpora Village directly overlying the conglomerate bed of the Shopian Member of the Karewa Group. **(D, E)** Are images of the marker triplet, which is exposed in a road cut near Khan Sahib, in a plateau position **(D)**, and a slope position **(E)**. **(F)** Shows the loess overlying lacustrine deposits at Wanihama. The lower vegetated part of the wall shows clear layering of lacustrine carbonates.

the Matuyama-Brunhes boundary, one may expect a considerably younger age. Generally, luminescence dating and ^{14}C dating suggest inconsistent ages for the Kashmir loess-palaeosol deposits with ^{14}C dates suggesting younger ages. ^{14}C dating is generally accomplished using microscopic organic matter extracted from palaeosols, and not on macro remains. Luminescence dates from the 1980s may also be difficult when compared to recent data.

Here we introduce a palaeosol numbering K-S1, K-S2, and K-S2 The gray/blackish and humus-rich soils in the K-L1 show no strong Bt horizons and are interpreted to represent short and/or weak soil formation phases. The thick Bt K-S1 has been suggested to represent MIS 5e by Singhvi et al. (1987). ^{14}C dates are in contrast to this suggestion and imply much younger ages for the K-S1, and imply higher sedimentation rates of ∼26 m for the last 100 ka (Kusumgar et al., 1986). The ^{14}C-dating of the marker triplet (see **Figure 3**) of grayish soils preserved across the Kashmir Valley yielded ages of ∼9, 15, and 20 BP (Meenakshi et al., 2018) from the Shankerpora section. However, the marker triplet clearly lies below the topmost blackish palaeosol dated to ∼22,500 ka BP (Krishnamurthy et al., 1982) and 14–21 ka PB (Agrawal et al., 1989). Meenakshi et al. (2018) also calibrated the age of the local LGM to 18.6–22.3 ka. This apparent inconsistency still suggests a rather high sedimentation rate, but does not give confidence in the ^{14}C dates.

Two studies (Bronger et al., 1987a; Gupta et al., 1991) attempt a comparison of the Kashmir loess-palaeosol sequences with global climate evolution, and conclude that the loess-palaeosol sequences of the Kashmir valley span at least several glacial/interglacial cycles. While Bronger et al. (1987a) suggests at least 4 glacial-interglacial cycles and a minimum duration of 350 ka, Gupta et al. (1991) suggest an age of >200 ka based on (tentative and possibly questionable) correlation to marine d^{18}O data.

Stratigraphic Summary

Although it may be argued that an adequate chronological database is available for Kashmir loess, the inconsistency between the chronologies makes it challenging to interpret the soil forming episodes in the context of global climatic events and evolution. The difference between the luminescence and ^{14}C ages may be due to the high inorganic carbonate content of up to >20%, and the visible carbonate movement in the profiles. This may alter the carbonate isotopic composition in samples and explain the inconsistencies between ^{14}C dating studies. Also processes of loess deposition and soil formation may play a role, as the former gives the age of the initiation of loess accumulation and the latter the age of soil formation. Therefore, differences between these chronologies may be expected, but not in the reported magnitude and inconsistency. There is a clear need for the establishment of a reliable chronology of the loess-palaeosol sequences for placing these reliable in a regional and global context. There is a clear need for the establishment of a reliable chronology of the loess-palaeosol sequences for placing these reliable in a regional and global context.

PALEOENVIRONMENTAL PROXY DATA AND INFERENCES

Paleoenvironmental proxy data are so far available in a limited quantity from the loess deposits of Kashmir (**Table 2**). Although the semi-quantitative early studies (e.g., Agrawal et al., 1979, 1988; Bronger et al., 1987a; Singhvi et al., 1987) are very valuable, no quantitative and reproducible high-resolution studies of any proxy data have been carried out. The following sections provide an overview of the existing paleoenvironmental proxy studies in Kashmir loess.

Rock Magnetic Properties

Yet, two studies report on the magnetic susceptibility and its frequency dependency from loess in Kashmir. Kusumgar et al. (1986) dates the ~25 m long Khanchikhol-I and Burzahom sections by ^{14}C, and also provide data for the magnetic susceptibility (χ, reported in a range from 10 to 50 without dimensions) and the frequency dependent magnetic susceptibility (χ_{fd}, in a range from 2 to 12%). Also Gupta et al. (1991) report χ ranging from $2*10^{-6}$ and $2*10^{-7}$ SI units and χ_{fd} of 2–12% for several loess sections, and use the rock magnetic data and the soil stratigraphy for correlation between these profiles. They also suggest that the χ_{fd} is increased in soils relative to palaeosols in a similar fashion as in eastern Asia, although by now it is clear that there are clear differences within Asian records (e.g., Ding et al., 1999). It is relevant to notice that there seems to be a higher magnetic susceptibility in soils for most of the upper ~10 m of profiles. Below, this relationship seems less clear and especially B-horizons show partly lowest magnetic susceptibilities. This is similar to loess from Pakistan, where no clear magnetic enhancement could be detected (Akram et al., 1998).

A study including the temperature dependent magnetic susceptibility and also isothermal remanent magnetization is available from the Central Himalaya (Pant et al., 2005). Their study suggests the presence of magnetite and maghemite in palaeosols, and a dominance of magnetite and hematite in loess with a minor maghemite contribution. If this is representative also for Kashmir loess is to be tested in the future.

Grain Size Data

The available literature reveals that the grain size of Kashmir loess is dominated by silt-size particles in the range from 6 to 20 μ, making up 30–40% of the total sample and the clay content ranging commonly from 25 to 35% (Bronger et al., 1987a). The grain size has mostly been used to discriminate the source of dust and quantify the degree of weathering (Bronger et al., 1987a; Babeesh et al., 2017), while no study has been published so far which has used grain size as proxy for paleoenvironments. Bronger et al. (1987a) suggest that some of the loess may be reworked local lake sediments, but also argue that the fine grain size (compared to European loess) suggests a distant source beyond the Kashmir Valley itself.

Geochemistry of Kashmir Loess

Geochemical studies did not differentiate systematically between loess and soils, and several observations cannot be related to stratigraphic information in detail. Studying the geochemistry of loess sediment is a powerful tool to understand its origins, transportation, and post-depositional modification. More importantly, geochemical studies may provide insights into Quaternary climate change (e.g., Schaetzl et al., 2018; Han et al., 2019). A fair amount of geochemical data has been generated on the loess-palaeosol sequences of the Kashmir Valley (Lodha et al., 1987, 1988; Ahmad and Chandra, 2013). Lodha et al. (1987, 1988) carried out an XRF study of loess-palaeosol sediments, and they suggested that K, Rb, Fe, Ti, Zn, Cu, and Mn are generally elevated in palaeosols, whereas Ca and Sr have relatively high concentrations in loess layers. They suggested that such concentration of elements in palaeosols is related to the pedogenic modification of the parent loess. Subsequently, Lodha et al. (1987) found that the concentration of iron and titanium are higher in loess profiles along the Pir-Panjal flank than on the Himalaya margin of the Kashmir Valley. The Pir-Panjal is dominated by basic rocks, mostly Panjal traps, compared to the Greater Himalayan flank of the Kashmir Valley which is dominated by carbonates (Dar et al., 2014).

Recently, Ahmad and Chandra (2013) analyzed the loess-palaeosol sediments for major, trace and REE elements to determine their chemical composition, provenance and intensity of paleo-weathering. Based on weathering indices such as the Chemical Index of Alteration (CIA), Chemical Index of Weathering (CIW), and Plagioclase Index of Alteration (PIA) values (71.87, 83.83, and 80.57 respectively) and the A-CN-K diagram of the loess-palaeosol sequences, they suggested that these sediments have experienced a weak to moderate degree of chemical weathering. They further suggested that these sediments reflect a similar composition and alteration history across the Kashmir valley. Their Chondrite normalized REE-patterns are characterized by moderate enrichment of LREEs, a relatively flat HREE pattern (Gd_{CN}/Yb_{CN} = 1.93–2.31), a lack of a prominent negative Eu anomaly (Eu/Eu^* = 0.73–1.01, average = 0.81) and variable amounts of total REE (ΣREE = 156–226 ppm). The lack

TABLE 2 | Summary of physical- and chemical studies on Kashmir loess.

Type of data	Outcome/interpretation	References
Rock magnetism: magnetic susceptibility and frequency dependent magnetic susceptibility	Loess is related to global climate evolution, different interpretations by authors	Kusumgar et al., 1986; Gupta et al., 1991
Element geochemistry	Provenance is stable, weathering intensity varies	Lodha et al., 1987, 1988; Ahmad and Chandra, 2013; Chandra and Ahmad, 2013; Chandra et al., 2016; Babeesh et al., 2017
Isotope geochemistry	Pleistocene climate- and precipitation changes	Krishnamurthy et al., 1982, 1986; Dar et al., 2015b
XRD clay mineralogy	Clay is mainly Smectite, illite, chlorite, and kaolinite occur	Chandra et al., 2016; Meenakshi et al., 2018
Grainsize	Varying depositional processes	Babeesh et al., 2017
Micromorphology	Intensity of soil formation, relation to paleoclimate	Bronger et al., 1987a; Chandra and Ahmad, 2013; Dar et al., 2015a,b; Chandra et al., 2016

of a negative Eu anomaly reflects partial weathering of plagioclase feldspar, which also reflects its paucity in the source area.

Clay Mineralogy

On the basis of an XRD study (Chandra et al., 2016) concluded that the palaeosols' clay mineral composition is dominated by smectite, illite and chlorite-kaolinite with contributions of chlorite. It should be noted that smectite is commonly found in arid to semi-arid climatic regions. Under intense weathering conditions it can alter halloysite and kaolinite (Cai et al., 2008). Its presence in soils represents poorly drained environments and a climate characterized by strong seasonal precipitation (Bellotto et al., 1995).

Stable Isotopic Studies on Kashmir Loess

Paleoenvironmental studies using the stable C and O isotopic compositions of organic matter, calcium nodules (see **Figure 4A**), and other material preserved in the loess-palaeosols have been carried out on material from the Kashmir Valley. The work by Krishnamurthy et al. (1982, 1986) and Dar et al. (2015b) studies the paleovegetation and paleoenvironmental setting using stable oxygen and carbon isotopic signatures (**Table 3**). The nodules of 1–3 cm size were handpicked from the Bk horizons of the paleosol profiles from three loess-paleosol sections (Shankerpora, Khan Sahib and Putkhah), and have been analyzed for C and O isotopic signatures (Dar et al., 2015b). The overall $\delta^{13}C$ values of the pedogenic carbonates from three loess-palaeosol sections Shankerpora (SK), Khan Sahib (KS) and Putkhah (PK) range from -4.96 to -8.28‰. The reported $\delta^{13}C$ values suggest that the C_4 fraction of the local flora has gradually increased in the valley during the formation of most of the palaeosols analyzed in the study with the exception of palaeosols SK-7 (-7.64‰) and KS-2 (-8.28‰; see Dar et al., 2015b) and palaeosol-1 (18 ± 2 ky) at Burzahom (Krishnamurthy et al., 1982), which reflect less arid climate and the presence of more C_3 type plants.

The $\delta^{18}O$ values of the pedogenic carbonates suggest that cooler and possibly drier than present conditions prevailed at the time of nodule formation (Dar et al., 2015b). The observed relationship between $\delta^{13}C$ and $\delta^{18}O$ is consistent with carbonate precipitation at times of enhanced westerly precipitation influence.

Micromorphological Studies of Kashmir Loess

The imprint of pedological features related to different environmental conditions is strongly influenced by climate. Palaeosols often preserve records of the paleoenvironment in their pedogenic features (e.g., Kemp and Zárate, 2000; Kemp, 2001; Scarciglia et al., 2003; Srivastava et al., 2010). In this framework, understanding of the local pedogenetic response to climate change can be improved by micromorphological analysis. In the Kashmir Valley few studies have reported the micromorphological investigations of loess-palaeosol sequences. Initially these deposits were misinterpreted as loessic loam, loamy silt and brown silty clay (de Terra and Patterson, 1940). However, Pant et al. (1978) were the first to perform a Scanning Electron Microscopic (SEM) study of the quartz sand grains of these deposits and suggested their eolian origin. Thereafter, several studies have been carried out to deduce Quaternary climate changes in the Kashmir Valley using thin section micromorphology of paleosols (Bronger et al., 1987a; Gardner, 1989; Dar et al., 2015a; Chandra et al., 2016). On the basis of micromorphological studies, Bronger et al. (1987a) suggested that warm and mostly humid climatic conditions prevailed during the formation of the top three palaeosols across the Kashmir Valley. Similarly, Gardner (1989) proposed that the palaeosols represent similar climatic conditions except for the two palaeosols formed in the later part of the last glacial period. The most common micromorphological features reported from Kashmir loess-palaeosols are channel/void- and ped-microstructures, massive microstructures, clay coatings, concentrations of calcite in the form of coatings and nodules, iron staining, iron manganese oxides, pedotubules, and disseminated organic matter (Dar et al., 2015a). A study also reported the co-existence of pedogenic $CaCO_3$ and clay coatings, suggesting decalcification followed by clay illuviation (**Figure 5**). This is interpreted as reflecting progressive drier climatic episodes following the partially moist climate associated with Quaternary climate changes, as has been found elsewhere (Badía et al., 2009). Khormali et al. (2003) suggested that clay gets translocated in moist climatic conditions and is covered by carbonate as the climate gets drier. Besides, the ped microstructures formed by shrinking-swelling reveal seasonal wetting and drying conditions (Dar et al., 2015a).

Paleopedology in the Context of Chronology

Loess-palaeosol sequences in Kashmir have traditionally been used for studying stratigraphic and relative paleoenvironmental variations expressed by the intensity of soil formation. The paleosoils intercalated in loess can be seen throughout the Kashmir valley with some regional variations (Bronger et al., 1987a; Agrawal et al., 1988). Changes in the paleoclimatic conditions during pedogenesis are reflected by lithological features such as the amount of organic matter, different clay minerals and their content, color, presence/absence of calcium carbonate and the depth of carbonate leaching in the loess palaeosol sequences. The palaeosols generally show elevated organic matter contents compared to the loess, and weak to moderately developed illuvial clay pedofeatures, suggesting subtle to substantial climatic changes that influence the relative rates of material supply, pedogenesis and weathering (Dar et al., 2015a). According to Dar et al. (2015a), the palaeosols formed under stable landscape conditions when loess deposition was episodic, or accumulation decreased to the point where pedogenesis could outpace the eolian input.

A semi-quantitative pedological assessment helps understanding past environments and their variability. For example, three humus rich "Aht" horizons representing three warm and humid climatic conditions (between 80 and 50 kyr) were recognized (Bronger et al., 1987a). They also suggested

TABLE 3 | Pedological and isotopic characteristics of the top three palaeosols preserved across the Kashmir valley, and reference to key papers.

Site/Location	Material	Depth (m)	$\delta^{13}C$ (‰ VPDB)	$\delta^{18}O$ (‰ VPDB)	Horizon	Color	Age in years	References
Khan Sahib (KH)	KH-S1	1.90	−4.96	−6.55	Aht	10YR6/4	NA	^Agrawal et al., 1989; Dar et al., 2015a,b
					Btk	7.5YR5/3		
	KH-S2	3.60	−6.22	−6.47	Aht	10YR6/4	17,740 ± 630^	
					Btk	10YR5/4		
	KH-S3	5.50	−4.88	−6.78	Aht	7.5YR5/3	21,840 ± 1150^	
					Btk	7.5YR8/2		
Putkhah (PK)	PK-S1	1.50	−5.50	−7.3	Ah	10YR7/3	NA	^Agrawal et al., 1989; Dar et al., 2015a,b
					Bt	10YR6/3		
	PK-S2	3.00	−5.27	−7.93	Aht	10YR6/3	18,550 ± 600^	
					Bt	10YR47/3		
	PK-S3	4.25	−6.31	−5.75	Aht	10YR5/3	25,800 ± 1110^	
					Btk	10YR5/4		
Burzahom (BZ)	BZ- S1	1.29	−25.3# OM	−7 ± 0.3# (Avg.)	Bwk	10YR7	42,452–45,877* 18,890 ± 830 750#	#Krishnamurthy et al., 1982; Chandra and Ahmad, 2013; Meenakshi et al., 2018
		1.79				10YR 6/3	45,877–47,726*	
	BZ- S2	2.06	−16.2# OM	−7 ± 0.3# (Avg.)	Ahk	10YR 6/3	47,726–49,438*	
		2.31			Bt	10YR7/3	49,438–53,205*	
	BZ- S3	2.86	−21.9# OM	−7 ± 0.3# (Avg.)	Aht	10YR 6/3	53,205–55,945*	
		3.26			Bt	10YR 5/4	55,945–62,657*	
Shankerpora (SP)	SP-S1	1.00	–	–	Aht	10YR4/2	8648–9016*	Dar et al., 2015b; Meenakshi et al., 2018
		1.63			Bwt	10YR5/4	9833–10,229*	
	SP-S2	2.65	–	–	Ah	10YR5/2	18,468–18,868*	
		3.15			Bw	10YR6/4	22,001–22,511*	
	SP-S3	3.88	–	–	Aht	10YR5/6	28,189–28,972*	
		4.1			Bwt	10YR4/4	33,565–34,357*	

The asterisks "^" "#," and "" respectively indicate the source of chronological and isotopic data from Krishnamurthy et al. (1982), Agrawal et al. (1989), and Meenakshi et al. (2018).*

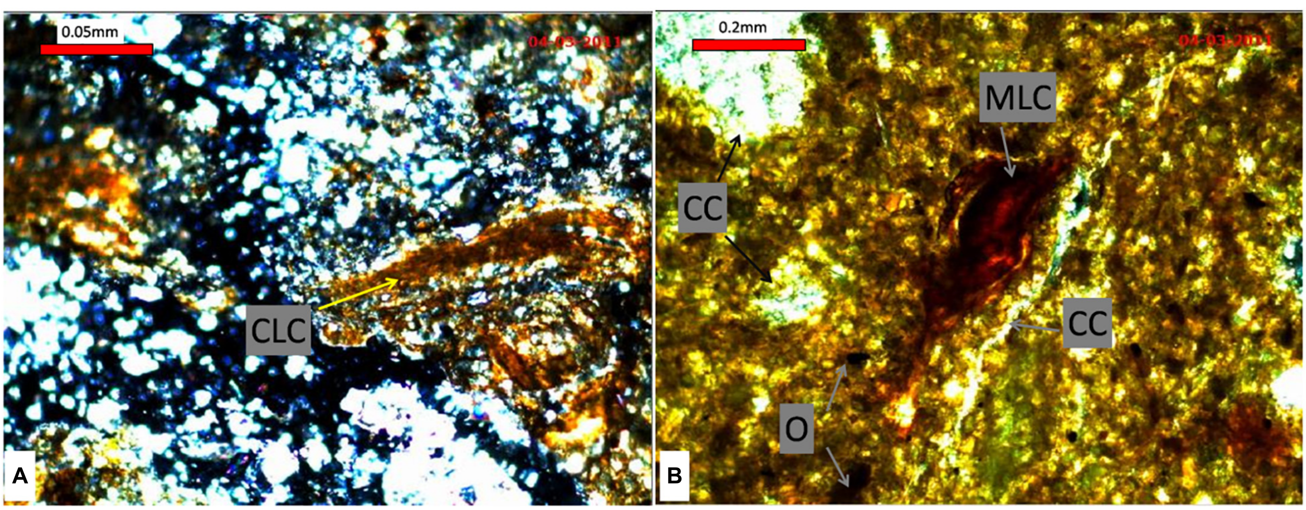

FIGURE 5 | Photomicrographs of the Khan Sahib section showing **(A)** clay coating (CLC) in a root cavity, quartz grains in a partly altered loess layer KS- L1 and **(B)** showing micro laminated clay coating (MLC), opaque minerals (O) channel and void filled with calcium carbonate (CC) in paleosol profile Btk (KS-S4) at the Khan Sahib (Dar et al., 2015a).

that during the middle Pleistocene at least four Bwt, or thick Bt horizons developed in loess reflecting four interglacial periods, with climates similar to the present-day. Based on the available ^{14}C dates of the Khanchi Kol-I section, Kusumgar et al. (1986) proposed that the palaeosols dated to ca. 5000, ca 18,000 and > 31,000 BP all represent major climatic oscillations indicating interglacial conditions, also around the LGM. Recently, optically stimulated luminescence (OSL) dating of loess like palaeosols in the Manasbal section (total section thickness 10.6 m) yielded ages of 41.7 ± 8.0 ka (at a depth of 8.7 m), and 14.6 ± 3.8 ka (at a depth of 2.9 m), coinciding with the age of marine isotope stages (MIS) 3 and late MIS2, respectively (Babeesh et al., 2017). The palaeosol formed during the MIS3 shows well-developed Ah/Btk characteristics, reflecting rather wet climatic conditions. A gradual increase in arid and drier climatic conditions is revealed by the $CaCO_3$ content and C/N ratio of the palaeosols at a depth of 6.50 m (Babeesh et al., 2017). They also suggested that Bwk horizons at a depth of 2.90 m represent the late MIS2 post-LGM period.

Paleopedology contributed most to the understanding of past environments in Kashmir. Despite the progress made by above mentioned studies on the paleoenvironmental signature using a pedological approach, more systematic high-resolution quantitative work is needed in this direction. In particular, the relation to a reliable chronostratigraphy can lead to a better understanding of the climate evolution and its global context.

Paleovegetation

Reconstructions of the paleovegetation from Kashmir have recently received increasing attention. Krishnamurthy et al. (1982, 1986) and Dar et al. (2015b) analyzed vegetation from loess. Previous studies are focusing on pollen-based vegetation reconstructions from the lacustrine sediments predating or associated with the loess accumulation phase (Agrawal et al., 1989 and the references therein). Stable isotopic signatures of pedogenic carbonates and organic fractions demonstrate that C_4 plants dominated the vegetation during the time of loess deposition. The $\delta^{13}C$ values suggest that the sampled palaeosols formed under hotter and drier interglacial or interstadial conditions than present and/or the last interglacial period (Krishnamurthy et al., 1986). Although the presence of wetter periods cannot be ruled out, that would require higher resolution isotopic analysis as this is not reflected by the analyzed pedogenic carbonate nodules and organic matter from the palaeosols (Krishnamurthy et al., 1982, 1986; Dar et al., 2015b). The dominance of C_4 vegetation may also be considered as a result of the strengthening of WDs as the seasonal variations of drying and wetting associated with these winds allow C_4 vegetation to survive better than C_3 plants (Dar et al., 2015b). However, the palaeosol dated 18 ± 2ka (e.g., at the Burzahom section; see **Figure 2** for location) indicates the presence C_3 type of vegetation (Krishnamurthy et al., 1982, 1986). Interestingly, the $\delta^{13}C$ values reveal that monsoon systems may have been of less intensity since the start of loess deposition. The monsoon winds may also have operated less efficiently even in the peninsular India during the last interglacial periods, thus resulting in less precipitation and hotter and drier conditions in Kashmir (Krishnamurthy et al., 1986).

On the basis of $^{13}C/^{12}C$ and C/N ratios of Karewa lake sediments, three major periods of reduced water levels with enhanced contribution from terrestrial vegetation are revealed, probably associated with the onset of Quaternary glaciation which amplified aridity that led to loess deposition (Krishnamurthy et al., 1986). The paleopedology has not yet been used to assess paleo-vegetation and its development.

Summarizing, reconstructing the paleovegetation is difficult for the Late Quaternary, as loess is not commonly preserving pollen, and the Lake Karewa dried to give place to terrestrial environments. Isotope data are probably the best way forward, although interpretations have to be taken with care (Obreht et al., 2019). Agrawal et al. (1989) reconstructed a general cooling and drying trend over the last several million years from Lake Karewa sediments, but details of the timing and patterns of this change are yet to be determined.

Paleo-Precipitation and -Temperature Reconstructions

Paleosols can be used for proving quantitative information of precipitation and temperature in the past (e.g., Kraus, 1999). However, quantitative paleo-precipitation and paleo-temperature estimates for the Kashmir Valley are yet missing. So far, the mean annual precipitation (MAP) and mean annual temperature (MAT) were investigated by Ahmad (2012) from three loess-palaeosol sequences at Karapur, Dilpurand and Burzahom. The MAP and MAT values were derived from the weathering indices (CIA values) of the loess palaeosol sequences. The concept being that high precipitation and warm temperatures enhance the extent of chemical weathering, whereas low precipitation and/or cold temperature weakens the intensity of chemical weathering (White and Blum, 1995; Sheldon et al., 2002). The availability of water and warmth enhances the depletion of alkali- and alkaline earth elements at the cost of refractory elements such as aluminum (Sheldon et al., 2002). Therefore, changes in weathering intensity with stratigraphy reflects the variation in past temperature and precipitation. The derived MAP value of the Kashmir loess and palaeosols ranges from ∼59 to 564 mm with an average of 419 mm. The reconstructed MAT values range from ∼10.55 to 12.57°C with an average of 11.73°C. On the basis of the MAP and MAT values, Ahmad (2012) advocated that the climatic conditions in the valley mostly fluctuated between cold arid to warm semi-arid during the Late Quaternary – a clear contradiction to the intense soils described by e.g., Bronger et al. (1987a). Generally it is suggested that the climate of the Kashmir Valley varied between cold-arid and warm semi-arid during the Late Quaternary (Ahmad and Chandra, 2018). The climatic variability has mainly been investigated for the Holocene (Singh, 1963; Dodia, 1983; Agrawal, 1992; Spate, 2019), and quantification of the climatic signatures preserved within soils is yet best addressed by pedology. Due to a lack in reliable chronology, millennial-scale (and or centennial-scale) climatic oscillations, which can represent very valuable for correlation (e.g., Shi et al., 2003; Zeeden et al., 2018c), are not yet reported from Kashmir. Summarizing, the timing and intensity of paleoclimatic changes in Kashmir over the late Quaternary is yet rather incomplete.

Provenance of Kashmir Loess

The provenance of the dust for Kashmir loess is poorly established and remains a matter of ongoing debate. In their pioneering work, de Terra and Patterson (1940) suggested the source dust for loess beyond the Pir-Panjal Range. Subsequently, (Lodha et al., 1985, 1987) worked on the major and trace element concentrations of these sediments using EDXRF. Based on iron and titanium concentrations in loess-palaeosol profiles along the Pir-Panjal flank and Greater Himalayan flank, they suggested that the source material of Kashmir loess is local. Similarly, Gupta et al. (1991) suggest that the source of loess is local, based on thickness and magnetic susceptibility variations among the analyzed loess layers. Dilli and Pant (1994) stated that loess was derived from the region, where both acidic and basic rocks and their metamorphic equivalents predominate. Further, the relatively high content of coarse and medium silt size particles suggests that the source of the silt is predominantly local (Gardner, 1989). The possible source of dust could be the mountain ranges delimiting the Kashmir Valley, as these are dotted with extensive glacial landforms reflecting the existence of extensive valley glaciers during the later Quaternary period (Dar et al., 2017). Therefore, it may be argued that these glaciers might have produced large quantities of glacial outwash and fine sediments through glacial grinding. However, recent geochemical studies of the loess-palaeosol sequences puts forward that these sediments are derived from mixed sources of mafic and felsic rocks suggesting larger provenance regions with variable geological settings (Ahmad and Chandra, 2013; Babeesh et al., 2017; Bhat et al., 2019). This suggests that a major contribution from outside the Kashmir valley exists. Candidate regions are the Peshwar Basin in Pakistan, from where large amounts of loess have been reported. A fine component brought form the Thar desert is also possible.

KASHMIR LOESS IN A REGIONAL CONTEXT

Loess in the Indian Subcontinent and Kashmir

From India loess data is sparse, and although the distribution can be expected to be widespread (Smalley et al., 2009), loess has hardly been reported from India for unclear reasons. Smalley et al. (2016) state (for both India and Pakistan) "the conditions appear to be perfect for the formation of large deposits." Juyal et al. (2000) report aeolian sandy silt with ∼60% silt and ∼40% fine sand from the last glacial cycle in the Mahi Basin, western India. (Liu et al., 2017) report rather coarse loess from southwest of Delhi, and suggest a more widespread occurrence in the Indo-Gangetic plain in the triangle of Delhi, Jaipur and Agra. Our observations confirm the presence of silty aeolian material as described by Liu et al. (2017) near Delhi airport. Further, Liu et al. (2019) suggest an aeolian origin of lateritic soils in the Deccan Plateau. These studies from India south of the Himalayas show a similar Rare Earth Element (REE) geochemistry as loess from China and also Kashmir, but a silt grain size dissimilar from the Kashmir loess (Ahmad and Chandra, 2013). However, because loess in India and China can be expected to have different sources, the similarity of REEs in loess in India and Kashmir cannot be taken as indication for a common source. Also for some Himalayan and Tibetan valleys loess is reported (Dill et al., 2003; Sun et al., 2007; Jones and Pal, 2009).

The topic of loess, and other Late Quaternary paleoclimate archives, has not been investigated more in Pakistan than in India during the last decades, and Muhs (2018) states that the extent of loess in Pakistan is only vaguely known. Several loess areas are reported from the Peshwar Basin, specifically the area around Nowshera west of the confluence of the Kabul and Indus Rivers (Din and Yoshida, 1997), the Haro River Loess-Palaeosol deposits (Din and Yoshida, 1997), the area of Islamabad (Calkins et al., 1975; Warwick and Wardlaw, 2007).

The most valuable literature containing hard data are Din and Yoshida (1997) and Akram et al. (1998), who report on grain size properties and further rock magnetic properties from a ∼17 m loess-palaeosol profile from the Haro loess area in Pakistan. No systematic magnetic enhancement is observed (Akram et al., 1998; their **Figure 7**) which led Akram et al. (1998) to the statement "The loess-palaeosol sequence in Attock basin, Pakistan does not show "Chinese Loess Plateau type" correlation between magnetic susceptibility and loess/palaeosol facies." The fact that the magnetic susceptibility is enhanced in the topmost soils and meters, but follows no clear patterns in older soils and deeper parts of profiles seems a similarity between the loess in Pakistan and Kashmir. To our knowledge no study on loess in Pakistan relates physical sediment properties to age, preventing any robust conclusions on the timing of past environmental change. The grain size may be similar or coarser for loess from the Attock Basin in Pakistan than for Kashmir loess. Most data from the Attock Basin have a median grain size of ∼30 μm (Din and Yoshida, 1997). Especially because the Peshwar Basin in northern Pakistan is located in a similar geographic situation as the Kashmir Valley in India, extensive loess areas spanning at least the last glacial cycle may be expected. Bibi et al. (2019) report on loess from the Peshwar Basin for the last glacial maximum with a maximum thickness of ∼5 m. They also found loess intercalated with lacustrine sediments. Also in Kashmir non-aeolian sediments occur on top of loess in some positions (own observation in the Khan Sahib area).

We agree that a much more widespread occurrence of both typical and fine loess and also rather coarse "desert loess" is expected in the Indian subcontinent. Yet, descriptions are missing, but we are optimistic that more research will be conducted in this direction in the future. This is also because of a general scarcity of well understood paleoenvironmental reconstructions from the Indian subcontinent beyond the Holocene.

An Eurasian Context

While numerous studies report on loess from the Eurasian loess belt, in the last decades a shift toward establishing quantitative records for comparison between areas and sections is apparent. This facilitates comparison of terrestrial loess archives over Eurasia and with marine proxy data (e.g., Hovan et al., 1989; Zhou et al., 1995; Vlaminck et al., 2016; Lauer et al., 2017; Zeeden et al., 2018b; Perić et al., 2019), also for loess in Kashmir (Gupta et al., 1991). For loess in Kashmir and the whole Indian subcontinent, yet only rather little quantitative data are available in low resolution compared to studies from Europe (e.g., Antoine et al., 2009; Obreht et al., 2017), Central Asia (e.g., Ding et al., 2002b; Cheng et al., 2012; Wang et al., 2018; Jia et al., 2019) and East Asia (e.g., Ding et al., 2005; Hao and Guo, 2005; Yang and Ding, 2014). The topic of loess in India has been discussed during the last decades without much actual data, and Smalley et al. (2009) highlight this knowledge gap by stating "Loess in India has been neglected". Especially because the loess in Kashmir has potential to show the interaction of Westerlies with the Indian Monsoon system this is surprising and probably also caused by political difficulties in the last decades.

The patterns found in the Kashmir loess-palaeosol sequences are considerably different from other places in Eurasia. Because ^{14}C dates are mostly inconsistent between studies and with luminescence ages, the age of loess is interpreted differently by several authors (e.g., Bronger et al., 1987a; Singhvi et al., 1987; Agrawal et al., 1989). The correlation to the marine oxygen isotope record by Gupta et al. (1991) needs to be taken with caution in our opinion, and reliable work on the chronology of the Kashmir loess is necessary.

OUTLOOK

With the emergence of various methods allowing for reconstructing the paleoenvironment reproducibly from loess-palaeosol sequences, a growing number of quantitative studies on loess have been published worldwide. Our review reveals that only few studies, aimed at addressing the composition, timing and extent of past climatic variations, have been carried out on the Kashmir loess-palaeosol sequences so far. Since these are important archives for answering questions related on Kashmir and the wider Himalayas including the interaction of westerlies and the Indian Monsoon system, a wealth of information can be expected in these geoarchives when investigated in detail.

Paramount to the understanding of the loess is a better knowledge of its origin. The palaeosols are well developed and stratigraphically distinctive in the Kashmir Valley and have yet been used for local correlations, mainly due to their nature different from many other northern hemisphere geoarchives. Although some initiatives have been taken in this direction, the lack of well-established chronologies prevented this from being informative. The timing and extent of aeolian loess deposition in the Kashmir Himalayas, and in the broader Himalaya, is a prerequisite for understanding Himalayan climate fluctuations in the context of Eurasian and global climate change. Identifying the principal dust source is to be accomplished, and both grain size and geochemical data may help solve this question. Only the application and consistent interpretation of multiple proxies will allow a robust interpretation regarding the Quaternary evolution of the area, as shown e.g., by Hošek et al. (2015), Krauß et al. (2016), and Obreht et al. (2016). An integrated approach involving the use of rock magnetic studies, stable carbon and oxygen isotopes, phytoliths, grain size analysis and mollusk-based paleoclimatic studies may improve our understanding of the Quaternary climatic conditions of the region. We suggest obtaining chronometric dates, and obtain climate proxy data in high resolution from several sections for a reliable understanding of the deposits. In addition, geochemical data needs to be collected from possible sources to understand the dust source(s).

SUMMARY

Loess in Kashmir comprises several 10s of meters, and probably represents the last several 100 thousand years in some places. While most research focused on the last glacial cycle due to better dating possibilities, the onset of loess deposition is controversial and seems to begin much later than in most of Asia and Europe and in the Brunhes Chron.

This review gives a detailed account of past studies and available data from loess-palaeosol sequences in the Kashmir valley (NW Himalayas), and we point out caveats in research to be filled. Yet, both proxy data and dating of Kashmir loess is very limited. While pedological investigations have been carried out throughout the valley, almost no quantitative climate proxy data is available. Although the loess-palaeosol sequences show clear alterations, their relationships with hemispheric and global climate evolution is yet based on limited data and is therefore unsolved at least on an orbital time scale. The inconsistency between the published chronologies (luminescence and ^{14}C) makes it difficult to interpret the driving mechanisms of soil forming episodes.

We highlight the need for high-resolution multi-proxy studies as from other loess areas, and a reliable understanding of the chronology.

AUTHOR CONTRIBUTIONS

RD and CZ wrote this review manuscript.

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