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Late Quaternary Palaeoclimate and Contemporary Moisture Source to Extreme NW India: A Review on Present Understanding and Future Perspectives

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The *trans*-Himalayan region of NW India including the western part of Tibet, Karakoram, and Hindukush range host thousands of glaciers ensuring perennial freshwater supply to the Indian subcontinent and supports a large fraction of the global population. The peculiar physiography not only limits the entry of water enriched Indian Summer Monsoon winds to this region but also give passage to dry winds of barren desert of the Taklamakan, the Aksai Chin, and western Tibet, to qualify it as a cold desert. The Himalayan Orogen linked structural elements and the Quaternary glacial, and interglacial phases define the geomorphological setup of the region, which subsequently modified by the fluvial-lacustrine-aeolian processes. Over the years, our understanding in drawing climatic inferences from the sedimentary archives has improved significantly but the discrepancy in chronology, among and within different dating techniques, poses a serious challenge and therefore requires more work to address the issues. Similarly, till recently, it was argued that the major source of moisture to the Ladakh region is contributed from the Mediterranean Sea because the region falls under the rain shadow zone for the water-laden Indian summer monsoon winds. Our recent water isotopic study of upper Indus River Basin, however, emphasized that Indian summer monsoon source is also an equally important supplier. The present review highlights that the disturbed chronology and inadequate data support on moisture sources are two gap areas for further research.

Keywords: sedimentary archives, climate proxy records, ^{14}C radiometric dating, OSL and ^{10}Be dating, monsoon, westerlies

INTRODUCTION

The *trans*-Himalayan region of NW India bears immense significance, primarily because it hosts thousands of glaciers, which ensures perennial fresh water supply to the Indian subcontinent and in turn supporting a large fraction of the global population. Secondly, it is the only region that experiences semi-arid to arid cold desert climate, whereas the rest of the subcontinent falls under the tropical to subtropical warm and humid monsoon climate and therefore provides an opportunity to understand different phenomenon associated with the lower and upper atmospheric circulations. Additionally, it serves as an open laboratory for understanding the geological processes related to the Himalayan orogeny (Henderson et al., 2010; Singh et al., 2015). The associated tectonics also has a profound impact on weathering and erosional processes having wider implications toward modulating the global climate and needs to be studied more systematically to meet the challenges of global climate change (Ruddiman and Kutzbach, 1989; Raymo and Ruddiman, 1992; Singh et al., 2005).

Ever since the northward-moving Indian plate struck with the relatively stable Eurasian plate, this gives birth to the mighty Himalayas (Molnar and Tapponnier, 1975; Steck et al., 1993; Yin, 2006). In the process, the climate of the Indian subcontinent keeps modulating with time (Edmond and Huh, 1997; Guo et al., 2002; Clift et al., 2008). The Himalayas is the youngest mountain belt of the world, and because of significant height, it hosts the largest glacier mass outside the Polar Regions. Therefore, the Himalaya is often considered as the third pole as well as the water tower of the Indian subcontinent (Viviroli et al., 2007; Immerzeel et al., 2010; Bookhagen, 2012; Mukherji et al., 2015). The role of Himalaya is not only important in determining the physiographic distinctions of the Indian landmass where it acts as a barrier for the northward-moving moisture-laden monsoon winds during the summer season but also restricts the entry of icy winds coming from the north during the winter season (Mayewski et al., 1980; Goudie et al., 1984; Searle, 1991).

The extreme north-western part of India, also known as *trans*-Himalaya, falls under the rain-shadow zone for monsoon clouds and therefore experiences cold desert climate (**Figure 1**) (Pant et al., 2005; Phartiyal et al., 2005, 2018). Our own, as well as several other authors, work suggest that the major atmospheric systems responsible for bringing moisture to the *trans*-Himalaya are the Indian summer monsoon (ISM) and the westerlies (Ramesh and Sarin, 1992; Pande et al., 2000; Karim and Veizer, 2000, 2002; Hren et al., 2009; Ahmad et al., 2012; Halder et al., 2015; Rai et al., 2016; Sharma et al., 2017). The Inter-Tropical Convergence Zone (ITCZ) governs the spatial extent and the strength of these two systems. Besides, there are several other forcing factors, which includes solar insolation and surface albedo (linked to sunspot activity), the North Atlantic Oscillation (NAO), Atlantic sea-surface temperatures (SST), Bond cycles, that also cause short-term oscillations in the monsoon intensity (e.g., Gupta et al., 2003; Lang and Barros, 2004; Sinha et al., 2006).

Monsoon is a very important atmospheric phenomenon of the Afro-Asian region and also a very important component of the global climate (Kutzbach and Otto-Bliesner, 1982; Kutzbach et al., 1993; World Clim Res Programme [WCRP], 2009; Zhisheng et al., 2015; Sharma et al., 2017). Therefore, directly or indirectly, it attracted several workers to study the palaeoclimatic history of the *trans*-Himalaya (Bhattacharyya, 1989; Sekar et al., 1994; Gasse et al., 1996; Brown et al., 2002; Shukla et al., 2002; Demske et al., 2009; Dortch et al., 2010, 2013; Wünnemann et al., 2010; Phartiyal et al., 2013, 2015; Blöthe et al., 2014; Kumar et al., 2017; Lal et al., 2018). Studies based on sedimentary archives, which include glacial (Fort, 1983; Dainelli, 1922; Kuhle, 1998; Owen et al., 2006; Achenbach, 2010), fluvial (Sharma et al., 1998; Shi et al., 2001; Dortch et al., 2011; Sangode et al., 2011; Scherler et al., 2014; Nag and Phartiyal, 2015), lacustrine (Gasse et al., 1996; Shi et al., 2001; Wünnemann et al., 2010; Phartiyal et al., 2013, 2015) and aeolian (Kumar et al., 2017) deposits, significant work has been carried out. Climate proxies that include biotic proxies mainly pollen-spore based studies (Bhattacharyya, 1989; Demske et al., 2009; Wünnemann et al., 2010) and various abiotic proxies (Fort et al., 1989; Gasse and Van Campo, 1994; Fontes et al., 1996; Bhushan et al., 2018) were employed to retrieve palaeoclimatic signals preserved in the sediments. Besides, several chronological techniques such as conventional and accelerated mass spectrometry (AMS) carbon radiometric dating (Phartiyal et al., 2005, 2013), optical luminescence dating (OSL) (Dortch et al., 2010, 2013; Blöthe et al., 2014) and cosmogenic radionuclide dating (Brown et al., 2002; Dortch et al., 2010, 2013; Blöthe et al., 2014) have also been applied. Based on the works mentioned above, a fairly good understanding over the palaeoclimate of the mid-late Quaternary, more so the period extending from Last Glacial Maxima (LGM) to recent, is developed for the NW *trans*-Himalayan India.

In the present work, we are revisiting to some of our work as well as reviewing the works carried out by other workers highlighting the discrepancy observed in chronology, which has serious implications toward the palaeoclimate record of the NW India (primarily the Ladakh and Spiti regions). Similarly, we also discuss the quantitative estimation of contributions from different moisture sources to this region.

STUDY AREA

We are studying the geomorphological signatures and concentrating mainly on the lacustrine and fluvial sediments of the Ladakh and the Spiti regions of the NW Himalaya (**Figure 1**). The Tethyan sedimentary zone (TSZ) is the region between Main Central Thrust (MCT) and the Indus Suture Zone (ISZ), and further north is the *trans*-Himalaya (**Figure 1A**). The Ladakh Batholith, the Zanskar, and the Karakoram are the major mountain ranges in the area, and the Indus with its major tributary rivers, e.g., Zanskar and Shyok flow within these ranges. The Ladakh and the Spiti regions display characteristic geomorphology that is largely governed by the reworking and redistribution of Quaternary glacial deposits along with frost-shattered rocks draping the hills through stream runoff and mass movement (more on geomorphology is discussed in a later section). Sedimentary archives lying all along the Indus and its tributary rivers such as Shyok-Nubra, Tangtse and Zanskar in Ladakh (Phartiyal et al., 2005, 2013, 2018; Phartiyal and Sharma, 2009; Nag and Phartiyal, 2015) and along the entire stretch of the Spiti River (Phartiyal et al., 2009a,b, 2005; Srivastava et al., 2013) have been mapped and studied for their palaeoclimatic implications.

Similarly, the isotopic study of the main Indus, tributaries and first–second order streams water have also been carried out for ascertaining the source of the moisture to this region (Sharma et al., 2017). Similar study over the isotopic composition of the Spiti river water is in progress, and this would help us to compare as well as generalize the results over contributions received from

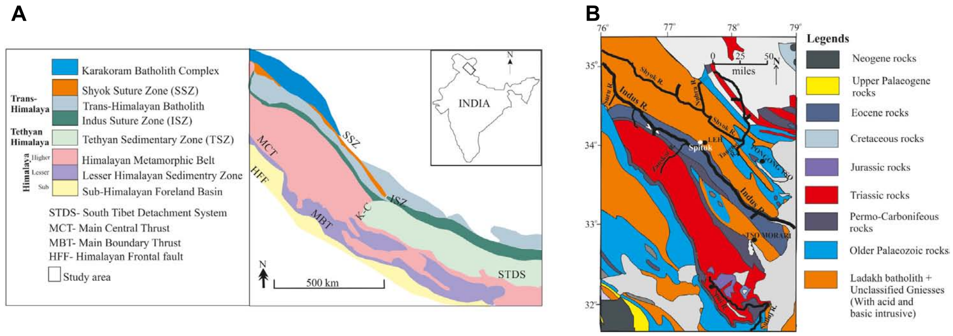

FIGURE 1 | (A) Map showing major mountain ranges and rivers of the NW India, and **(B)** Geological map of the Ladakh and Spiti valley of NW Himalaya including major rivers (please see text for lithological details). The figure also shows the Spituk site, situated near Leh City (solid white and black color circles, respectively), to highlight the discrepancy in the chronology under different dating techniques.

different moisture sources. To have a comprehensive idea of the study area, including the climate, geomorphology, and geology, these are discussed briefly in the following subsections.

Climate

Both Ladakh as well as the Spiti valley are located in the NW Himalaya at an altitude of >3000 m above sea level (asl) and experience arid to semi-arid continental climate (Schmidt and Nüsser, 2017). The region remains under snow cover for 3–4 months (November to February); however, experiences prolonged winters extending from October to May. The average annual rainfall in the area varies from <150 to ∼40 mm from west to east (Blöthe et al., 2014). The vegetation is sparse and scanty restricted to river valleys only (Phartiyal et al., 2005). Due to high altitude, the intensity of solar radiation is significant resulting in large diurnal temperature variation. Overall, the cold and arid environment, >5000 m relief, lack of vegetation (responsible for lower oxygen levels), rarefied atmosphere, large variation in seasonal temperature (varying from −20°C in winter to 35°C in summer), and extremely low rainfall, all these attributes qualify to make Ladakh and Spiti regions a high altitude cold desert.

Geomorphology

The Ladakh and the Spiti are the highest altitude regions of India. Two sets of geological processes govern the overall geomorphological evolution of these regions: (1) Continental-scale geological processes, which include the collision of the Indian plate with Eurasian plate resulting into the closer of the Tethys Sea. The collision not only responsible for the birth of Himalayas but also the major force behind other geological features such as thrust belts, suture zones, nappes, volcanic arc (Molnar and Tapponnier, 1975; Klootwijk et al., 1985; Steck et al., 1993; Yin, 2006). All these have primarily provided the basic framework for the landscape evolution and (2) Regional/local scale geological processes in which the role of climate and tectonics is significant wherein the glacial (**Figures 2a–d**), fluvial (**Figures 2e,f**), lacustrine (**Figures 2g–k**), and aeolian (**Figures 2l,m**) processes (Shukla et al., 2002; Dortch et al., 2013; Blöthe et al., 2014; Nag and Phartiyal, 2015; Kumar et al., 2017) are important agencies of landscape evolution. Among these all, glaciers are the most effective agent because of their enormous mass and volume and can alter the existing, and in some cases completely new set of the landscape has been formed (Koppes and Montgomery, 2009; Bennett and Glasser, 2011). Other agencies, i.e., fluvial, lacustrine and aeolian bring changes at relatively smaller levels, however, govern the earth surface expressions in the form of various landforms such as U/V shape valleys, moraines and outwash plains, fluvial including strath terraces, aeolian landforms represented by dunes and sand ramps, and lakes and their deposits distributed all along the large rivers and so on (**Figure 2**).

The large difference in diurnal temperature facilitates intense frost action (physical/mechanical weathering) responsible for abundant supply of unconsolidated sediments, which are blanketing the mountain ranges and forming debris cones and piles in the valleys (**Figures 2a,e,h**) (Phartiyal et al., 2013; Srivastava et al., 2013; Kumar et al., 2017). Daming of major rivers that are believed to be an outcome of glacier retreat followed by a tectono-climatic activity (Fort et al., 1989; Phartiyal et al., 2005), has a profound impact on the geomorphology that is easily evident in the region. Among several types, the lake sediments are the most characteristic feature in the entire Ladakh and Spiti regions. Mass movement activity also supported the formation of complex diamicton depositional landforms (Owen and Derbyshire, 1989; Owen and Sharma, 1998). At higher altitudes 'U'-shaped cirque glaciers are present (Holmes, 1993) having periglacial environments (Fort, 1983), however, in lower regions, the valleys are 'V'-shaped with mean slopes of 25–30° (Jamieson et al., 2004). The slopes are cut by gulleys helping debris and snowmelt-runoff and responsible for alluvial fans formation in the river valleys. The altitude, slope, and drainage distribution pattern adequately support the river channels steep bedrock reaches that transform to low angle braided alluvial landforms at relatively plainer areas (**Figure 3**). The drainage also shows that how in mere ∼400 km stretch the river Indus attained 7th stream order (**Figure 3**). Besides, the evidence of various glaciation stages can also be noticed at Leh and its close vicinity, e.g., at Phyang, Tharu, and Basgo (Fort, 1983). All these agencies, mentioned above, with associated processes individually as well

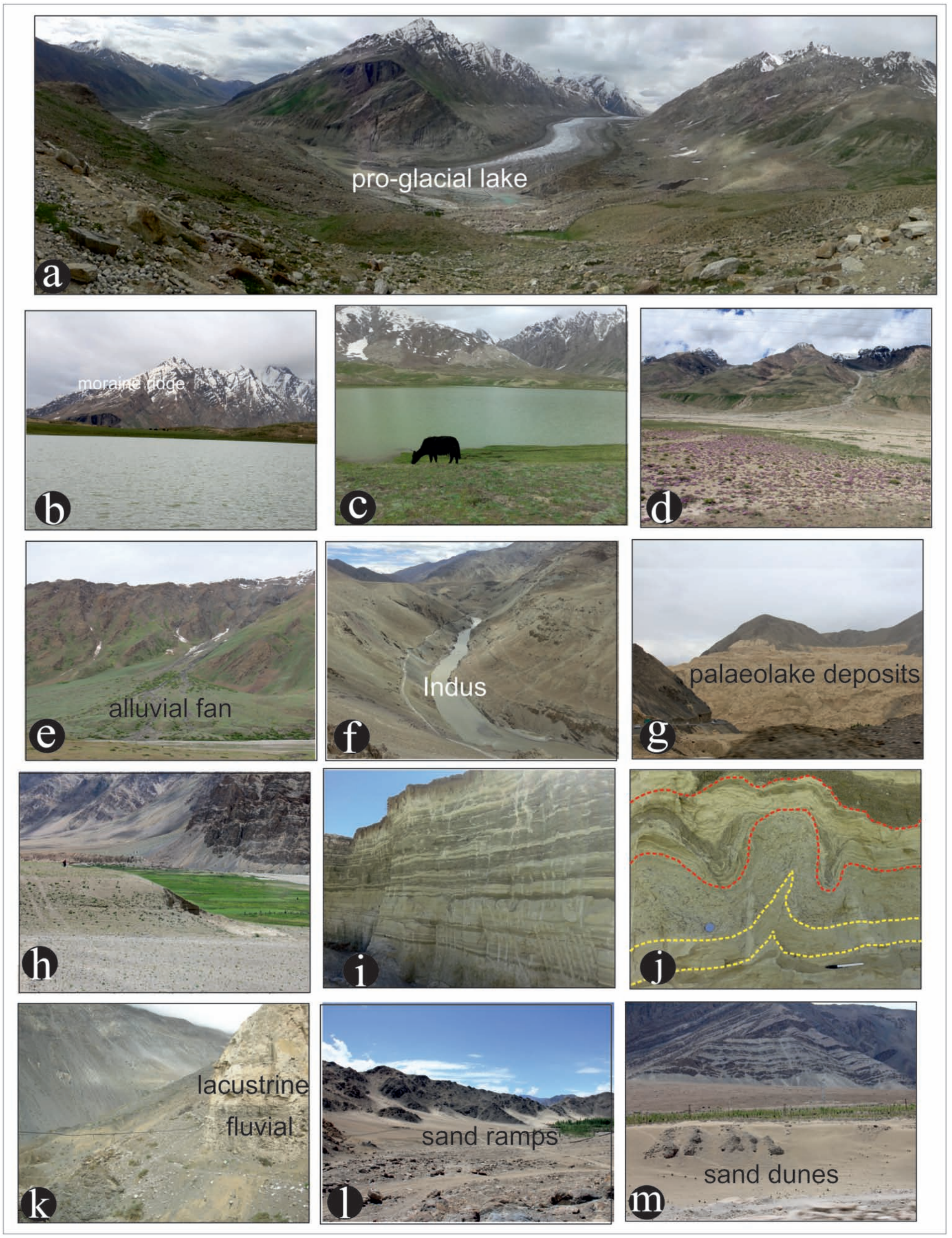

FIGURE 2 | Field photographs are showing the geomorphological features and overall landscape of the Ladakh and Spiti regions of NW Himalaya. **(a)** A Synoptic view of the Zanskar valley, a typical valley glacier (Photograph was taken from Penzi La), showing the Drang- Drung glacier. The curvilinear, recessional latero-frontal moraines present in front of the glacier snout have been dated to 4.8 ± 0.4 ka (Ali et al., 2018). The broad U shaped Zanskar valley is a manifestation of glacial erosion in the past. **(b,c)** Field photographs taken at Penzi-La (La = Pass; ∼4400 m asl) showing some recessional moraines and a high altitude lake supported by glacial meltwater. **(d)** At Padum village, the Zanskar valley has preserved the traces of right lateral moraine corresponding to the oldest stage of glaciation (stratigraphically). The meltwater stream coming from the tributary valleys have cut across this moraine and form the fans in the trunk valley. Younger moraines also seen along the tributary glacier valleys. **(e)** A huge alluvial fan emanating from the left slope and extending into the Zanskar valley. **(f)** Narrow gorge along the Indus River between Leh and Nimu in Ladakh. **(g)** Synoptic view of the Lamayuru palaeolake deposits in the Ladakh region. **(h)** Field photograph taken along the Zanskar valley (downstream of Padum) showing that the vegetation is restricted to the river valley, however, mountains are almost barren and blanketed by the weathered rock material, a very common freeze and thaw process responsible for breaking (physically/mechanically) the rocks into finer detritus. **(i)** One among many, fluvio-lacustrine deposit present near the confluence of Doda and Tsarp rivers near Padum. Such deposits are a direct manifestation and evidence of river impounding. The relict lake deposits also seen at many places along the Zanskar valley. **(j)** Close-up of the relict lake sequence showing well developed Synsedimentary/seismic deformation (shown by yellow dotted lines) and ice wedges (shown in red dotted lines). **(k)** A well-preserved relict lake section showing a sharp contact between fluvial and lacustrine facies near the Nako Village (Spiti Valley) and samples were collected for multiproxy studies. The lake section is around 100 m thick, and we have collected 9 OSL samples for dating the section and 660 samples for palaeoclimatic reconstruction; and **(l,m)** Field photograph showing sand accumulation by the dry winds near Leh.

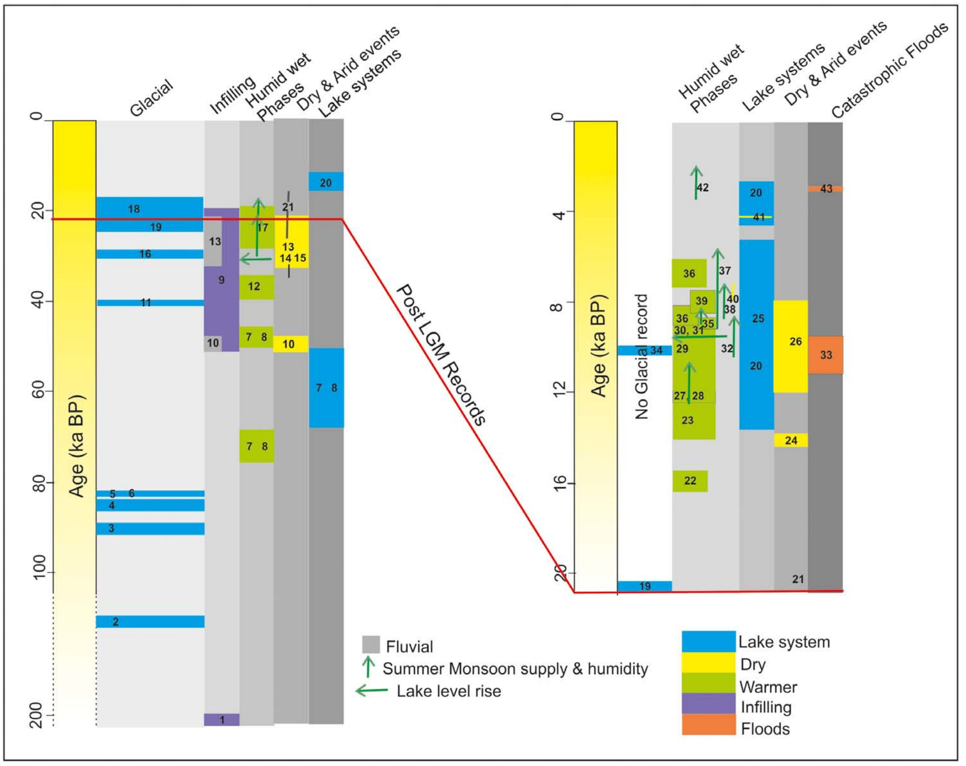

FIGURE 3 | Summary diagram showing different climatic regimes based on **Table 1** in chronological order. The numbers shown in the diagram are taken from **Table 1** as reference numbers to show the study referred, and the proxy used to infer the climatic regime as well as the dating technique applied by the respective authors. The vertical and horizontal arrows are used to show an increase in monsoon supply and lake level rise, respectively. The length of the different color boxes is indicative of the time duration to which the climate was in a particular mode, respectively.

as jointly, have governed the geomorphological evolution, mainly during the Quaternary period in this region.

Geology

The geology of the study area is highly complex as it marks the boundary between the relatively stable Eurasian plate and the northward subducting Indian plate (Searle et al., 1990; Henderson et al., 2010). The Indus River largely follows the ISZ; however, at places, it cuts the Ladakh Batholith, which represents the *trans*-Himalayan granodioritic belt of subduction-related intrusions (**Figures 1A,B**) (Fuchs, 1981; Garzanti and Van Haver, 1988). The major lithologies of the Ladakh region are tonalitic to granodioritic intrusives with mafic enclaves. However, the Indus basin sedimentary rocks represent forearc-basin sediments (Henderson et al., 2010; Singh et al., 2015). Further south of ISZ and toward the continental margin of India, the Neoproterozoic to Eocene time Tethyan sediments, e.g., sandstones, mudstones, and carbonates are exposed (Gaetani and Garzanti, 1991).

The general trend of the Spiti River is NW-SE, which is more or less parallel to the major faults such as MCT, ISZ, and Karakorum Fault (KF), (**Figure 1B**). However, the local N and NNE trending Kaurik-Chango (K-C fault) and fault associated with Leo-Pargil horst in downstream reaches of the Spiti River are responsible for the abrupt change in its course (Molnar and Chen, 1983). In the Spiti valley, Tethyan sediments of Neoproterozoic to Cretaceous are exposed (Sinha, 1989; Bhargava and Bassi, 1998; Srivastava et al., 2013).

SEDIMENTARY ARCHIVES AND PROXIES FOR PALAEOCLIMATE

The Quaternary sedimentary archives preserve palaeoclimatic signatures, and this becomes even important in areas having an abundant supply of sediments with unstable tectono-climatic setup, e.g., NW India. Vegetation based proxy, e.g., Pollen, Spore, Phytolith, are robust climatic tool to draw inferences over the climatic set up of the particular region (Bhattacharyya, 1989; Demske et al., 2009), however, the scope becomes rather limited if the region is a desert with scanty vegetation cover. Except for some lake sequences, it is very difficult to get biotic proxy signals in the Quaternary sediments because the organic matter gets readily oxidized (Sekar et al., 1994; Shukla et al., 2002). Interestingly, the Ladakh and Spiti regions, however, have widely distributed variety of landforms of glacial, fluvial, lacustrine, and aeolian origin (**Figure 2**) and have been exploited for extracting the palaeoclimatic information by applying physical and geochemical proxy parameters (Fort et al., 1989; Phartiyal et al., 2005; Dortch et al., 2013; Srivastava et al., 2013; Kumar et al., 2017). Among glacial landforms, moraines and large erratic stones (moraine boulders) are used widely for estimating the glacial stages by geomorphic field mapping, remote sensing and ^{10}Be terrestrial cosmogenic nuclide surface exposure dating (Brown et al., 2002; Dortch et al., 2010, 2013). Similarly, fluvial terraces, the sedimentary structures preserved therein and also the texture, mineralogy, geochemistry and environmental magnetic parameters are successfully used for the palaeoclimatic reconstructions by several workers in different parts of the subcontinent (Chauhan et al., 2013; Prasad et al., 2014; Raj et al., 2015; Bhushan et al., 2018). Pro-glacial, glacial, freshwater and even saline lakes distributed in the Ladakh and Spiti regions are also exploited using both biotic and abiotic proxies to draw climatic inferences (see **Table 1**).

A 23 m sediment core of Tsokar lake dated by ^{14}C radiocarbon technique and studied for the its pollen record elaborates four phases of climate amelioration at 28,000–30,000 yr B.P., 21,000–18,375 yr B.P., slightly before 15,800 yr B.P. and 10,000 yr B.P. On the basis of *Juniperus* communities expansion within alpine steppe (Bhattacharyya, 1989). Sekar et al. (1994) also suggested similar climatic conditions based on the analysis of elemental, organic and mineral content variations with slight asynchronous events from the Tsokar lake, Ladakh. After two decades, Demske et al. (2009) revisited the Tsokar Lake and using the same palynological and chronological techniques, fine-tuned the records indicating increased moisture conditions between ca. 12.9 and 12.5 kyr BP, followed by extremely weak moisture conditions at ca. 12.2–11.8 kyr BP. They also reported peak monsoon between ca. 10.9 and 9.2 kyr BP. A moderate reduction in moisture from ca. 9.2 to 4.8 kyr BP, but noted high lake levels around 8 kyr BP. They also recorded an abrupt shift to arid conditions after ca. 4.8 kyr BP that continued till ca. 2.8–1.3 kyr BP. The interplay of Monsoon and Westerly wind systems were probably governing the climatic fluctuations. Similar palaeoclimate results were derived by Wünnemann et al. (2010) by geomorphological, geochemical and palynological investigations. This study also discusses the hydrological evolution of Tsokar Lake Basin in past 15 kyr. High resolution isotopic (δ^{18}O and δ^{13}C) investigations on endogenic carbonates from Tso Moriri Lake, Ladakh concluded an increasing ISM precipitation between ca. 13.1 and 11.7 cal ka and highest ISM precipitation during the 11.2–8.5 cal ka (Mishra et al., 2015). Detailed geochemical, mineralogical and sedimentological analysis reveals that Tso Moriri witnessed several short-term fluctuations with seven major palaeohydrological stages since ∼26 cal ka (Mishra et al., 2014). Recently, the OSL dating of aeolian deposits, particularly the sand ramps of the Ladakh area suggest that the aggradations in valley occurred in three pulses, at ∼52, ∼28, and ∼16 ka, and these pulses broadly coincide with periods of stronger ISM (Kumar et al., 2017).

In a relatively recent work Blöthe et al. (2014) reviewed the earlier works as well as did field mapping including lithology and chronology of glacial, fluvial and lacustrine deposits of the Indus and Zanskar confluence and adjoining areas. Accordingly, they concluded that the region experienced at least two episodes of massive infilling during the late Pleistocene. The older episode may have occurred after 530 ka, followed by pronounced incision at ∼200 ka. The remnants of the former valley floor, which is currently lying up to 200–300 m above the present river levels, are signs of the older episode. The younger episode of infilling, however, occurred between 50 and 20 ka BP. They also suggested that lakes existed for longer time periods (10^3—10^4 yr) than the previously estimated. However, the causative factor behind the lake formation was the same as proposed by Phartiyal et al. (2005).

Interestingly, Blöthe et al. (2014) also concluded that there is no direct relationship between the sequence of late Quaternary valley incision and backfill with proxies of the ISM. However, post and inter-glacial sediment pulses are relatively better correlated. Additionally, they emphasized that tectonics is not the major player in the landscape evolution of the *trans*-Himalayan region because the drainage configuration has not changed significantly during the last ∼120 ka. However, soft sedimentary deformation structures indicating tectonic activity are also reported from several fluvio-lacustrine deposits (Phartiyal and Sharma, 2009), concentrating mostly ∼10 ka and 6 ka BP (Nag and Phartiyal, 2015).

The areal extent of Ladakh region is many orders more than the Spiti valley. However, the landscape evolution of the two regions is pretty similar. The signatures of neotectonic activity in the Spiti region are more pronounced, whereas in Ladakh these are rather subdued (Singh et al., 1975; Singh and Jain, 2007; Phartiyal et al., 2009a; Srivastava et al., 2013; Blöthe et al., 2014). There are many tributary valleys of Indus River such as Zanskar, Shyok, Suru, that may be independently compared with the Spiti River valley and the sediment deposits found along the longitudinal profile of these rivers are also comparable. Based on the relative stratigraphy and the geometry of fluvial and lacustrine deposits distributed across these regions, it is inferred that the channel damming is the most effective process in their formation. The damming is largely governed by the tectono-climatic factors that may either be catastrophic landslides, rainfall-induced debris flow or fan building (Fort et al., 1989; Phartiyal et al., 2005). A summary of the Quaternary palaeoclimate works carried out in the region by several workers is presented here in the chronological order in tabular form as a ready reference and illustrated for better understanding (see **Table 1** and **Figure 4**) of the subject.

SOURCE OF MOISTURE

There are two major sources of moisture in this region, *viz*. ISM and central Asian westerlies [Western disturbances (WD)/Winter Monsoon (WM)] (**Figure 5**). Monsoon is a highly complex phenomenon, and over the years, studies carried out have extended its spread from local to regional and presently to global scale. In a recent study, Zhisheng et al. (2015) summarized that "The global monsoon is the significant seasonal variation of three-dimensional planetary-scale atmospheric circulations forced by seasonal pressure system

TABLE 1 | Summary table of climatic history in the *trans*-Himalayan region (Ladakh and Spiti Valley).

Time	Climate and proxy used in the study	The technique applied and archive used for age estimation	Reference	Reference number used in Figure 6
∼200 ka	Quaternary valley infilling indicating deglacial phase	^{10}Be Exposure and optically and infrared stimulated luminescence (OSL, IRSL) ages determined on high-level fluvial terrace remnants	Blöthe et al., 2014	1
∼144 ka	Deshkit 3 glacial stage	^{10}Be Exposure ages from quartz-rich boulders and bedrocks	Dortch et al., 2010	2
∼90 ka	Major glacial advance	^{10}Be Exposure ages from moraine boulders	Brown et al., 2002	3
∼85 ka	Local Pangong-2 glacial stage	^{10}Be Exposure ages from boulders	Dortch et al., 2013	4
∼81 ka	Local Glacial stage of Ladakh Range	^{10}Be Exposure ages from boulders	Dortch et al., 2013	5
∼81 ka	Deshkit 2 glacial stage	^{10}Be Exposure dates from quartz-rich boulders and bedrocks	Dortch et al., 2010	6
∼78–46 ka	Fluvio-Lacustrine deposits of deglacial phase	OSL ages from sandy strata of fluvio-lacustrine deposits	Lal et al., 2018; Mujtaba et al., 2017	7
∼72–32 ka	Fluvio-Lacustrine deposits of deglacial phase	OSL ages from sandy strata of fluvio-lacustrine deposits	Sangode et al., 2013	8
50–20 ka	Quaternary valley infilling indicating deglacial phase	^{10}Be Exposure OSL, IRSL dating of high-level fluvial terrace remnants	Blöthe et al., 2014	9
∼48 ka	Cold and arid climatic setup with a drier phase during the fluvial depositional setting	OSL ages from sandy layers of fluvial terrace	Phartiyal et al., 2015	10
∼40 ka	Pangong-1 glacial stage	^{10}Be Exposure dates on boulders	Dortch et al., 2013	11
35–40 ka	Humid conditions	Pisidium and Succinea shells dated by the ^{14}C radiometric technique	Shukla et al., 2002	12
30–21 ka	Fluvial depositional setting	OSL ages from sandy layers of fluvial terrace	Phartiyal et al., 2015	13
∼30 ka	Tectonic quiescence and a warm–arid climate	Thick biogenic carbonate sequence dated by the ^{14}C radiometric technique	Bhattacharyya, 1989	14
>30.4 ka	Climate generally dry and arid	Elemental, organic and mineral content dated by the ^{14}C radiometric technique	Sekar et al., 1994	15
28–30 ka	Amelioration of climate within the alpine steppe during the latter part of the last (Weichselian) glaciation	Expansion of *Juniperus* communities dated by the ^{14}C radiometric technique	Bhattacharyya, 1989	16
∼28–19 ka	Amelioration of wet-humid phase during the intervening period	Elemental, organic and mineral content dated by the ^{14}C radiometric technique	Sekar et al., 1994	17
∼21–18 ka	Amelioration of climate within the alpine steppe	Expansion of *Juniperus* communities dated by the ^{14}C radiometric technique	Bhattacharyya, 1989	18
21–23 ka	Glacial conditions (LGM)	OSL ages from glacial moraines	Phartiyal et al., 2013	19
17–13 ka; 12–9 ka; 5–3 ka	Rizong palaeolake indicating interglacial phase	OSL and ^{14}C AMS radiocarbon ages from palaeolacustrine deposits	Nag and Phartiyal, 2015	20
25–17 ka	Aridity and aeolian activity	OSL ages from river/strath terraces	Kumar et al., 2017	21
16.4–15.9 ka	Amelioration of wet-humid phase during the intervening period	Analysis of elemental, organic and mineral content dated by the ^{14}C radiometric technique	Sekar et al., 1994	22
14.9–12.6 ka	Amelioration of wet-humid phase during the intervening period	Analysis of elemental, organic and mineral content dated by the ^{14}C radiometric technique	Sekar et al., 1994	23
15.2–14 ka	Dry and cold conditions	^{14}C AMS radiocarbon ages from palaeolacustrine deposits	Demske et al., 2009	24
14–5 ka	Khalsi-Saspol palaeolake indicating interglacial phase	OSL and ^{14}C AMS radiocarbon ages from palaeolacustrine deposits.	Nag and Phartiyal, 2015	25
12–8 ka	Aridity and aeolian activity	OSL ages from river/strath terraces	Kumar et al., 2017	26
12.5 ka	Summer monsoon moisture supply indicated by deposition of more profound lake facies and development of aquatic fauna and flora	^{14}C AMS radiocarbon ages from palaeolacustrine deposits	Wünnemann et al., 2010	27

(Continued)

TABLE 1 | Continued

Time	Climate and proxy used in the study	The technique applied and archive used for age estimation	Reference	Reference number used in Figure 6
∼12 ka	Wetter conditions indicated by the intra-dunal lake formation and fluvial gullying corresponding to variations in SW monsoon strength	OSL ages from sand layers	Kumar et al., 2017	28
12–9 ka	Wetter conditions	OSL and ^{14}C AMS radiocarbon ages from palaeolacustrine deposits	Phartiyal et al., 2013	29
11.8 ka	Lake level rise due to intensified glacier melt and effective moisture supply by summer monsoon	^{14}C AMS radiocarbon ages from palaeolacustrine deposits	Wünnemann et al., 2010	30
11.6–10.7 ka	Amelioration of wet-humid phase during the intervening period	Analysis of elemental, organic and mineral content dated by the ^{14}C radiometric technique	Sekar et al., 1994	31
11.5–8.6 ka	Summer monsoon moisture supply indicated by deposition of more profound lake facies and the development of aquatic fauna and flora.	^{14}C AMS radiocarbon ages from palaeolacustrine deposits	Wünnemann et al., 2010	32
11–9.6 ka	Catastrophic flood indicating intensified monsoon	^{10}Be Exposure ages from imbricate granitic boulders and strath terraces	Dortch et al., 2011	33
∼10 ka	Events of amelioration of climate within the alpine steppe during the latter part of the last (Weichselian) glaciation	Expansion of *Juniperus* communities dated by the ^{14}C radiometric technique	Bhattacharyya, 1989	34
∼9.6 ka	Abrupt environment change from arid to wet conditions deduced from Terrestrial pollen spectra	^{14}C radiometric ages	Gasse et al., 1996	35
∼9.0–8.7 ka and 7.5–6.2 ka	"Optimum" (wetter and warmest) climatic conditions indicated by the lowest $\delta^{18}O$ content	^{14}C radiometric ages	Fontes et al., 1996	36
∼9.5–6.2 ka	Heavy monsoonal precipitation indicated by the extremely low $\delta^{18}O$ content	^{14}C radiometric ages	Gasse and Van Campo, 1994	37
9.0–8.7 ka	Maximum humidity indicated by the highest frequency of Artemisia pollen	^{14}C radiometric ages	Gasse and Van Campo, 1994	38
8.5–7 ka	Warm-moist climate conditions suggesting maximum lake level	^{14}C AMS radiocarbon ages from palaeolacustrine deposits	Wünnemann et al., 2010	39
<8 ka	Summer monsoon influence weakened indicated by sedimentological and palynological records	^{14}C AMS radiocarbon ages from palaeolacustrine deposits	Wünnemann et al., 2010	40
4.2 ka	The lowest stand of the lake with the return of permafrost activity indicated by sedimentological and palynological records	^{14}C AMS radiocarbon ages from palaeolacustrine deposits	Wünnemann et al., 2010	41
∼3.2–2.1 ka	Wet pulse of minor amplitude deduced by pollen and diatom assemblages	^{14}C radiometric ages	Gasse et al., 1996	42
3 ka	Catastrophic flooding	^{14}C AMS radiometric ages from palaeolacustrine deposits	Phartiyal et al., 2013	43

shifts driven jointly by the annual cycle of solar radiative forcing and land-air-sea interactions. The seasonal reversal of prevailing wind direction and a seasonal alternation of dry and wet conditions characterize the associated surface climate". Similarly, the central Asian westerlies are low-pressure waves embedded in the mid-latitude subtropical westerly jet that travel from West to the East bringing moisture from the Mediterranean Sea and the Atlantic Ocean (Dimri et al., 2015; Dimri and Chevuturi, 2016) and modulate the winters. Depending on the intensity of these waves, different regions receive precipitation either in the form of snow/ice, fog or showers. Most of the studies referred above discuss the meteorological parameters and related dynamics. However, the water isotopic composition based studies from the Ladakh/Upper Indus Basin are scanty, more so conflicting and dealt in the discussion section.

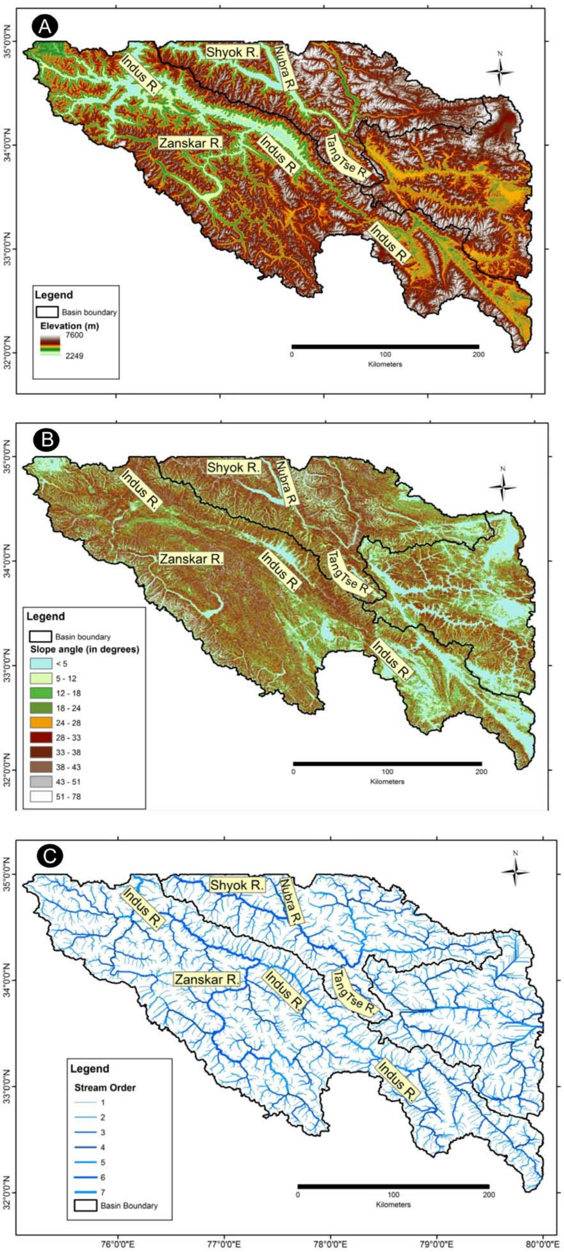

FIGURE 4 | Three maps panel of Upper Indus Basin Catchment **(A)** Map showing the altitude (DEM) variation within the catchment. **(B)** The slope map showing appreciable variation in the slope angle in a relatively limited distance of ∼400 km course of the Indus River. **(C)** The drainage map of the Indus catchment showing its major tributaries and minor streams. It is interesting to note that river Indus has attained 7th stream order, a feature usually seen in mountainous terrenes only.

It is well accepted now that the ISM is a manifestation of the seasonal migration of the Inter-Tropical Convergence Zone (ITCZ) (**Figure 5**). However, the intensity of rainfall and its latitudinal-location is still unanswered (Schneider et al., 2014; Gadgil, 2018). The region also receives relatively more rain/snow during Abnormal Monsoon Years (AMYs) due to a northward shift of the ITCZ (Bookhagen et al., 2005). Besides, the region seldom experiences unpredictable climatic conditions, e.g., in the year 2010 the Leh city and adjoining areas were devastated by the cloudburst wherein 210 mm precipitation occurred only in 3 h period causing a destructive flash flood (Juyal et al., 2010; Arya, 2011; Rasmussen and Houze, 2012). Such extreme events, in geological past, may have triggered the landslides responsible for damming the stream flow and thereby forming the lakes as suggested by several workers (Pant et al., 2005; Phartiyal et al., 2005, 2013).

CHRONOLOGY: ADVANTAGES AND LIMITATIONS

Chronology of geological events has immense significance in geological sciences. Conventional and AMS ^{14}C radiometric dating is the most widely used technique and successfully used by numerous workers (Bhattacharyya, 1989; Demske et al., 2009; Phartiyal et al., 2009a,b, 2005; Wünnemann et al., 2010). Presence of measurable organic carbon content in sediment limits the application of conventional radiocarbon method to be employed. In glaciated barren terrains, e.g., Ladakh and Spiti valley, we have used conventional ^{14}C radiometric dates in our initial publications (Phartiyal et al., 2005; Phartiyal and Sharma, 2009), however, we started facing problems due to reservoir effect (pre-aged organic carbon or ^{14}C-depleted hard water) (Doran et al., 1999; Halla and Henderson, 2001; Wagner et al., 2004; Zhou et al., 2015). To overcome this meager availability of organic carbon, as much as possible, we started using ^{14}C AMS dates. In our endeavor to revisit the palaeolake deposits of Spituk area near Leh city in Ladakh, the ^{14}C AMS dates that we have received are much younger (Phartiyal et al., 2013) than the one we have analyzed by the conventional ^{14}C dating techniques of the same sequence (Phartiyal et al., 2005). Optical ages from this sequence have yielded age estimates that are similar or older than conventional radiocarbon ages (Sangode et al., 2013; Blöthe et al., 2014; Lal et al., 2018) as shown in **Figure 6**.

Regarding optical dating, Morthekai et al. (2017) suggest that one needs to be cautious while using quartz to obtain chronology, particularly in a geological terrain like Ladakh and Spiti valley. Feldspar's inherent problem of anomalous fading affects the chronology, and hence it is avoided when quartz portion is sufficient. The reason for being cautious, as Morthekai et al. (2017) stated that quartz is not only 'dull' (low sensitivity to ionizing radiation) but also heterogeneously bleached (poor resetting of latent geological signals) and may lead to erroneous results. In this work, the authors have shown that the bigger the aliquots (with many quartz grains) yield over-estimated ages with small over-dispersion in the data.

Similarly, in cosmogenic exposure ^{10}Be chronology, certain assumptions need to be made toward understanding the geological history of the sample. These assumptions are difficult to test and therefore may cause a profound effect on the inferred age. In a review work over palaeoglaciation in Tibetan region, Heyman et al. (2011) have shown that two principal geological

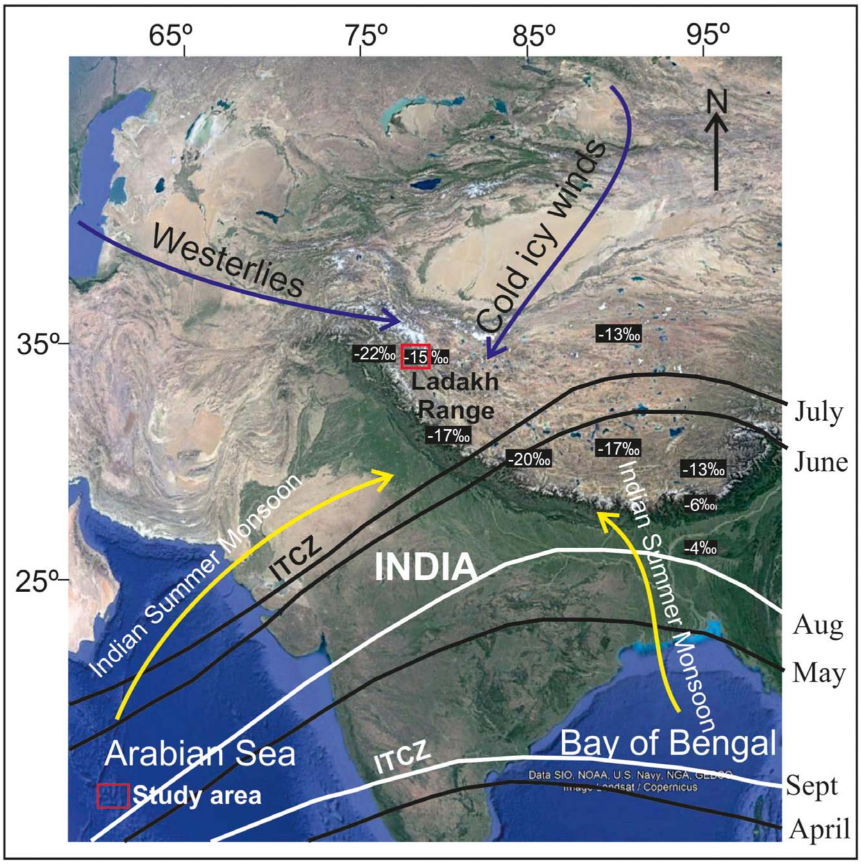

FIGURE 5 | Google image of India showing different moisture sources to NW *trans*-Himalayan regions. Also shown the position of ITCZ during ISM (source for ISM trend lines: https://www.pmfias.com/indian-monsoons-south-west-north-east-monsoons-itcz/). The solid black and white ITCZ trend-lines showing that with increasing temperature, the ITCZ keeps moving northward (April–July) and from August onwards, the direction of ITCZ trend becomes southward, respectively. It is important to note that in abnormal monsoon years (ITCZ moves further north), appreciable amounts of monsoon winds crossover the Himalayas and bring more rain and snow to *trans*-Himalayan regions. The $\delta^{18}O$ isotopic composition is also marked in the figure (for details see Sharma et al., 2017).

factors (1) Exposure before glaciation and (2) Incomplete exposure due to post-depositional shielding may yield exposure ages that are either too old or too young, respectively. Therefore, it is essential that more emphasis must be given to understand the geological features and processes to ascertain the relative stratigraphy of a region. And based on this a combination of different dating techniques is to be applied for establishing the chronology, particularly in regions like *trans*-Himalayan terrains of NW India and employing a single technique may mislead.

DISCUSSION

In our research endeavors in the Ladakh and Spiti regions of NW India, primarily dedicated to the Quaternary geomorphology and fluvio-lacustrine deposits, we have carried out extensive field reconnaissance surveys supported with laboratory-based dataset, and discussed the landscape evolution and paleoclimate of the region in our publications (Phartiyal et al., 2005, 2009a,b, 2005, 2013, 2015; Phartiyal and Sharma, 2009; Srivastava et al., 2013; Nag et al., 2016) and still continuing with it. A cursory look of the geomorphological signatures present in the entire NW Himalayan region (**Figures 1–3**) indicates that the region has experienced glacial advance (glacial phase) and retreat (interglacial phase) at different time intervals.

The fluvial and lacustrine regime was dominating in the interglacial phase. However, their timing and duration are still debatable. The aeolian activity interspersed between the glacial and interglacial phases noticed in the form of dune and sand ramps indicating dry climatic phases. A summary of climate based geomorphic expressions along with chronology is presented in **Table 1** and illustrated in **Figure 4** and readers may refer to the relevant reference for the comprehensive understanding of the subject. Although several authors have attempted to see the correlation between late Pleistocene to early Holocene fluvio-lacustrine deposits with monsoon proxies (see **Table 1** and reference therein), however, no consensus has so far evolved due to chronological issues and dealt in the following section.

To highlight the discrepancy in chronological techniques, we are presenting the case study of one of the section, among many others, the Spituk palaeolake sequence (34.13246 °N;

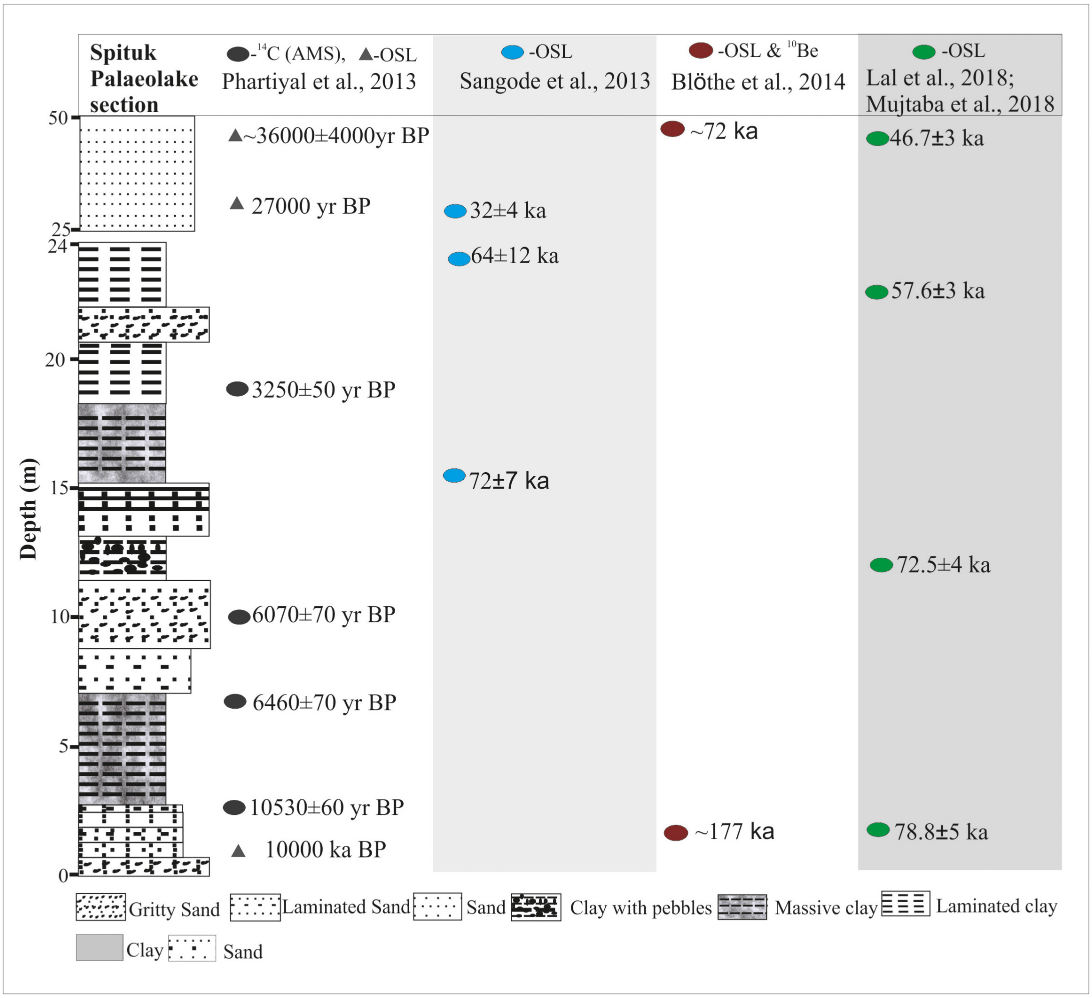

FIGURE 6 | Lithololog of Spituk palaeolake sedimentary sequence situated near Leh city on the right bank of the Indus River on Leh-Srinagar road used as an example to explain age discrepancy. The lithological description of the section is fairly consistent in studies carried out by different workers. However, there is a discrepancy in age estimated through different dating techniques (see text for details).

77.52563 °E) exposed on the right bank of the Indus river. Several workers study this sedimentary sequence and have given the chronology for the same sequence (Phartiyal et al., 2005, 2013; Sangode et al., 2013; Blöthe et al., 2014; Mujtaba et al., 2017; Lal et al., 2018) (**Figure 6**). So far as the sediment facies present in the entire >50 m sequence is concerned, there is a fairly good understanding among the authors that how incision followed by the fluvial aggradation and subsequent lacustrine facie deposition took place in the Spituk locality, however, the chronology is disturbed. Altogether three dating techniques were applied for establishing the chronology of the Spituk section, i.e., conventional ^{14}C radiometric and AMS dating by Phartiyal et al. (2005, 2013), respectively. All other authors used the OSL/IRSL technique to date this sequence (Sangode et al., 2013; Blöthe et al., 2014; Mujtaba et al., 2017; Lal et al., 2018). The conventional ^{14}C radiometric date bracketed between ~50 and ~30 ka. However, it reduced to ~10.5–3.2 ka when ^{14}C AMS technique is applied (see **Figure 6**).

Similarly, the three other age brackets using OSL/IRSL technique are ~72 to ~32 ka (Sangode et al., 2013), ~177 to ~72 ka (Blöthe et al., 2014) and 78.8–46.7 ka (**Figure 6**) (Mujtaba et al., 2017; Lal et al., 2018) showing considerable variation beyond the error range. The discrepancy observed in ages indicates that more work is required to address this issue, at least for regions like Himalaya or similar orogen. Interestingly, a solitary date obtained by OSL technique of the bottom sand of this section by Phartiyal et al. (2013) is also ~10 ka (**Figure 6**). These two dates of ~10 ka obtained through both OSL and ^{14}C AMS techniques made us believe that these are most likely the correct ages. As we have only one such set of comparable dates obtained from two different techniques, more such sets of samples are required to address this important issue and looking at the arguments by Morthekai et al. (2017) further work in this direction is under progress.

In the Quaternary palaeoclimatology study, it is a common practice that authors usually employ several climate proxy parameters over an exposed sedimentary section or a sediment core. Because multiproxy climate data generation is a tedious and time taking practice, often less emphasis is given to generate a relative stratigraphy of the region. Under such conditions, there is no choice left but to completely rely on the results obtained through the absolute dating techniques. On the contrary, often distinctly different climatic inferences are drawn in a much-localized area as is the case of Spituk section referred above. This kind of intra/inter dating technique limitations bring serious discrepancy in the climatic record, which is otherwise not possible. Therefore, adequate precaution is to be required, so as a comprehensive understanding on the processes involved, inter-linkages in different proxy parameters and the combination of dating technique with comparable ages will enable us to propose the palaeoclimatic history of a particular region.

Similarly, the contribution of dominant moisture sources to the NW *trans*-Himalayan regions is another challenging issue. It is for long believed that the moisture source is dominantly (2/3 of the total) contributed by the westerlies and ISM contribution is only 1/3 of the total precipitation received to the *trans*-Himalayan regions (Mayewski et al., 1980; Goudie et al., 1984; Searle, 1991). In a study using oxygen and hydrogen isotopic values of the Indus River in the Pakistan territory, Karim and Veizer (2002) proposed that ∼74% of the moisture comes from the Mediterranean region and the other sources contribute only 26% of the total moisture received annually. However, in our study carried out in the Ladakh region of the Indus, its tributaries and other smaller streams water isotopic composition along with two end-member mixing model and the mass balance calculations, we (Sharma et al., 2017) demonstrated that in the main Indus channel flow, only ∼26% contribution is received from the Mediterranean source, and the ISM contributes the rest. These values are fairly consistent with Pande et al. (2000) from the same region and significantly different from the Karim and Veizer (2002).

Further, it is to be noted here that if the dominant source of moisture is from the Mediterranean region, the isotopic including the d-excess values must be more depleted in Ladakh as compared to Hindukush region of Pakistan because the Ladakh is situated further east of the Hindukush and relatively more distant from the Mediterranean region (continentality effect). However, the measured isotopic composition of the Indus, its major and minor tributaries, all showing less depleted values, which implies that ISM contribution, is also a dominant source to the *trans*-Himalayan region (Sharma et al., 2017). In a recent study by Shafiq et al. (2016), wherein the authors carried out the time series analysis of precipitation recorded at Leh from the year 1901 to 2000, also reported that the summer months average precipitation is relatively more (30.67 mm) as compared to the average winters (27.38 mm). However, the trend is showing a marginal decrease in summer precipitation and complimentary increase in the winter precipitation. Since the long-term water/ice isotopic data record from this region is inadequate, efforts need to be made in this direction to generate more from this region. As mentioned earlier also, that fresh water supply to a large fraction of the global population is dependent on the Himalayan glaciers, the significance of water isotopic studies become, even more, important and have wider implications.

CONCLUSION

(1) The India-Asia collision primarily governs the geomorphological evolution of the *trans*-Himalayan region of NW India. Subsequently, the Quaternary glacial and interglacial processes modified the landscape and responsible for the present geomorphic setup of the region.
(2) Climate proxy parameters provide important information over glacial and interglacial regimes, but the discrepancy in chronology needs serious relooking for the better palaeoclimatic record.
(3) The Mediterranean and Indian Summer Monsoon winds are bringing moisture to the *trans*-Himalayan region more or less equally. More long-term work employing time series analysis is required to address the issue of moisture contribution from different sources having wider implications.

AUTHOR CONTRIBUTIONS

AS had plotted the concept of the manuscript. AS and BP had contributed in writing the manuscript.

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