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Redefining the timing of Tongul glacial stage in the Suru valley, NW Himalaya, India: New insights from luminescence dating

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The present study investigates latero-frontal moraines to reconstruct the pattern of glacier advances and associated climate variability in the Suru valley, southwestern Zanskar Himalaya. Impressive sets of latero-frontal moraines and discontinuous morainic ridges (recessional) represent the records of the past glacier advance and retreat. The northerly trending latero-frontal moraines that descend down the tributary valleys and terminate at the trunk Suru valley are the geomorphic expression of one of the oldest preserved record of glacier advance and is named as Tongul glacial stage. Previous studies (based on ^{10}Be and ^{14}C ages) defining the chronology of Tongul glacial stage are either limited in number (^{14}C ages) or have a large spread (^{10}Be ages) and hence demand further investigation. Optically stimulated luminescence (OSL) dating suggests that the Tongul glacial stage responded to the global last glacial maximum (gLGM) dated between ∼20 and 24 ka. We suggest that the Tongul glacial stage was driven by enhanced mid-latitude westerlies and reduced temperature (viz., continental cooling) during MIS 2 and facilitated by corresponding long winters.

Keywords. Optically stimulated luminescence (OSL) dating; Global last glacial maximum (gLGM); Southwestern Zanskar.

1. Introduction

Despite a large number of dated glacial landforms, glacier advances during the global last glacial maximum (gLGM); a time period of maximum global ice volume (∼19 to 23 ka; Marine Isotope Stage 2) are limited and in conundrum from the ecologically diverse Himalayan region (Ali and Juyal 2013; Eugster *et al.* 2016; Ganju *et al.* 2018). Chronological difficulties like paucity of organic matter for radiocarbon dating, low sensitivity and partial bleaching for optically stimulated luminescence dating, underestimation/overestimation of ages by cosmogenic exposure dating and uncertainties associated with the erosional rates (Benn and Owen 2002; Fuchs and Owen 2008; Heyman *et al.* 2011; Godard *et al.* 2012) make dating of glacial and associated sediments a challenge (Hu *et al.* 2015). Despite these, reasonable attempts have been made to bracket the glacial events that has refined our understanding of the glacier behaviour and also helped in ascertaining the forcing factors of glaciation (Eugster *et al.* 2016; Sharma *et al.* 2016; Ganju *et al.* 2018; Shukla *et al.* 2018). The chronological data generated from the Himalayan-Tibetan region suggests an asynchronous and complex glacial behaviour and has been ascribed to different sensitivities of glaciers situated in contrasting climatic compartments of the orogen (Scherler *et al.* 2010; Owen and Dortch 2014; Ganju *et al.* 2018; Sharma and Shukla 2018). The complexities get further amplified by significant discrepancy in ages obtained using different dating techniques (Dortch *et al.* 2010; Nagar *et al.* 2013; Lee *et al.* 2014; Ganju *et al.* 2018) and hence further research is warranted to resolve the chronological discrepancies. On a regional scale, luminescence ages have shown that the Himalayan glaciers have responded sensitively to the enhanced mid-latitude westerlies (MLW'S) during the gLGM (Bush and Philander 1999; Ali *et al.* 2013; Nagar *et al.* 2013; Eugster *et al.* 2016; Bisht *et al.* 2015; Sharma *et al.* 2016; Ganju *et al.* 2018; Shukla *et al.* 2018). This is contradicting to the earlier suggestions of a less extensive glacier advance in Himalayas during the gLGM (Owen *et al.* 2002) and its virtual absence in Ladakh (Owen *et al.* 2006; Dortch *et al.* 2010). Although inadequate (Eugster *et al.* 2016), the large discrepancies in the ages obtained on a single moraine using multiple dating techniques raised concerns on the precise timing of the event and thus its climatic interpretations (Nagar *et al.* 2013; Ganju *et al.* 2018) which preclude establishing the forcing factors of glaciation. The NW Himalayan region is dominantly nourished by the MLWs (Owen and Benn 2005; Leipe *et al.* 2014; Ganju *et al.* 2018); however, owing to the location of the Zanskar–Suru region, it also gets little nourishment by the ISM along with MLWs (Mayewski *et al.* 1984; Lee *et al.* 2014; Saha *et al.* 2016; Sharma *et al.* 2016). Further, the south to north precipitation gradient of the ISM and west to east gradient of the MLW's in the Zanskar region is likely to have influenced the glaciation in this region (Taylor and Mitchell 2000; Lee *et al.* 2014; Saha *et al.* 2016; Sharma *et al.* 2016; Sharma and Shukla 2018). Therefore, it is reasonable to invoke that the Suru valley located at the transitional boundary between the ISM and the MLWs, would exhibit a fragile 'edge of the range' environment (Mayewski *et al.* 1984; Bothe *et al.* 2011; Bellwood 2013; Lee *et al.* 2014; Sharma *et al.* 2016; Wang *et al.* 2016). Hence, it is expected that the glaciers will respond to the temporal changes in any of these two weather systems. Globally, the maximum extent of ice during the gLGM (peak glacial conditions) is reported to be around ∼26.5 to 19 ka (Mix *et al.* 2001; Lisiecki and Raymo 2005), a period also characterized by –4 and –7°C continental cooling (Bush and Philander 1999). Earlier chronometric data obtained using ^{10}Be and ^{14}C suggested that the prominent moraines preserved at the mouth of the tributary valleys correspond to the early part of late glacial period (∼16.7 to 17.4 ka; Tongul glacial stage), whereas the gLGM seems to be missing or the glaciers did not respond to the gLGM cooling event. Considering that there are growing evidence from the northwestern Himalayan region indicating appreciable glacial advance during the gLGM (e.g., Nagar *et al.* 2013; Eugster *et al.* 2016; Sharma *et al.* 2016; Ganju *et al.* 2018; Sharma and Shukla 2018), absence of gLGM from Suru valley is intriguing. Could it be because (i) the region did not respond to global cooling event? (ii) the moraine corresponding to the gLGM are concealed or eroded? or (iii) was it an artifact of the chronological constraints? The present study therefore, is an attempt to answer these questions by employing reasonable well established optically stimulated luminescence (OSL) dating technique.

2. Study area

The relict glacial deposits (moraines) have been investigated in two tributary glaciers near Tongul village in the Suru valley, Ladakh (figure 1). The Suru valley located to the north of the Nun-Kun massif and situated between the NW-trending Greater Himalaya and the far southwestern Zanskar ranges (Lee *et al.* 2014; Sharma *et al.* 2018) lies in the transitional climatic zone between the ISM and the MLW's (Sharma and Shukla 2018 and references therein). The valley is drained by the Suru river that originates from the Pensi-La (La=pass; 4400 m asl) which is a watershed divide between the Suru and the Zanskar valleys (i.e., between Suru and Doda rivers; Ali *et al.* 2018). The upper reaches of the valley has preserved extensive glacial and fluvial landforms, including prominent moraines (Lee *et al.* 2014; Sharma *et al.* 2018). Geologically the area consists of the Zanskar crystallines and is overlain by the Sankoo Formation representing the base of the Palaeozoic–Mesozoic sequence of the Zanskar Tethys Himalaya (Nanda *et al.* 1969; Dèzes 1999).

3. Landform mapping

Detailed geomorphological mapping of the two tributary valleys (Tarangoz and Sentick) near Tongul village (figures 2, 3) was undertaken using Google Earth Pro Imagery and a three arc-second

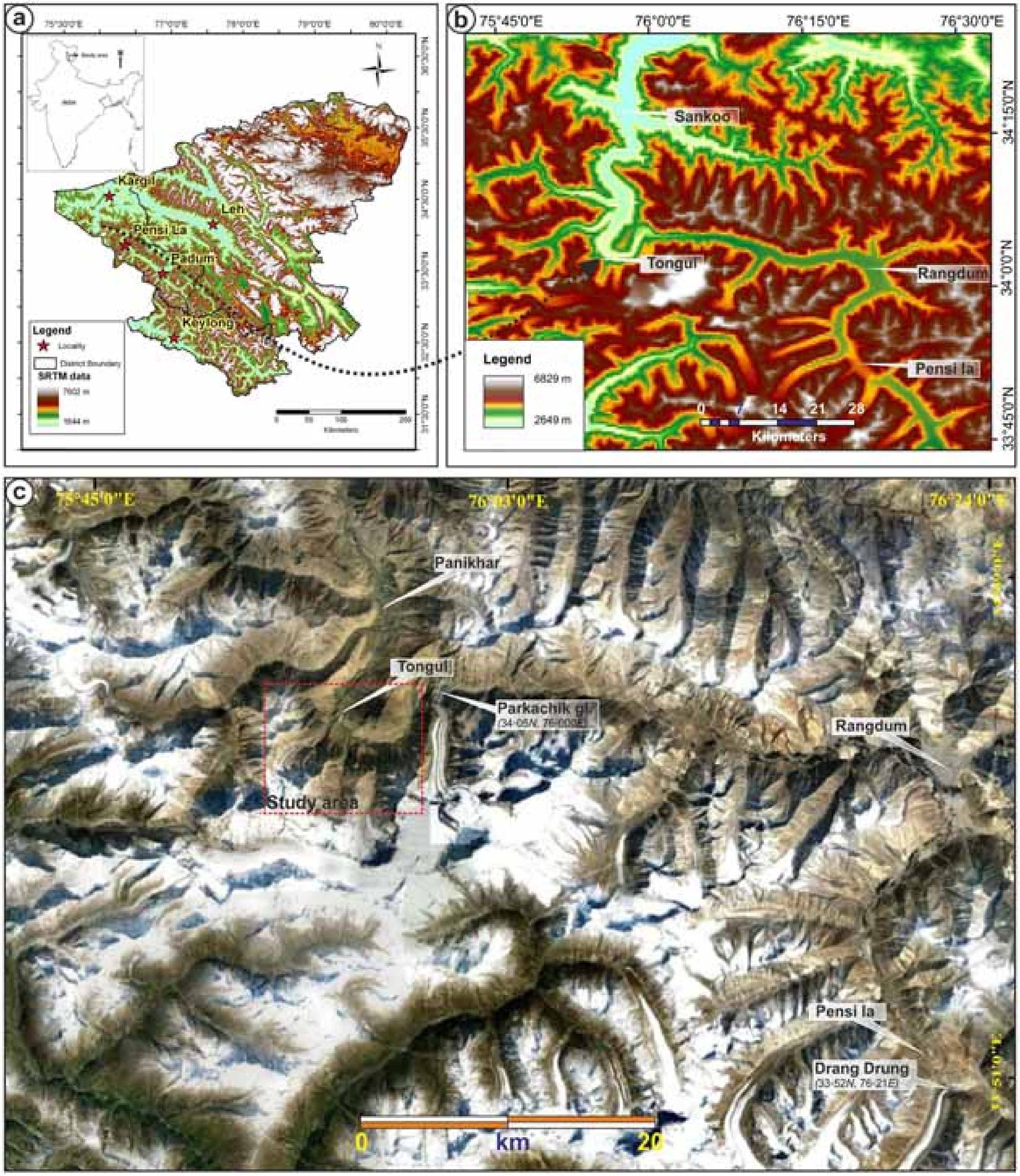

Figure 1. (**a**) Location of the Northwestern Himalayan region shown on Shuttle radar topographic mission (SRTM) digital elevation map (DEM), (**b**) shuttle radar topographic mission (SRTM) digital elevation map (DEM) showing the location of study area, and (**c**) synoptic view of the study area (Google Earth Pro image) with important locations along Suru-Zanskar valley.

(90 m) Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM) supported by detailed field mapping. The field data was used as a reference to facilitate mapping using satellite imageries (Seong *et al.* 2009). The presence of wide U-shaped valleys and moraines suggests that the area has been extensively glaciated in the past.

Geomorphological mapping of the glacio-fluvial landforms was carried out following the observations of Lee *et al.* (2014) and further improved upon by using field observations, Shuttle Radar Topography Mission (SRTM) Digital Elevation Models (DEMs) and the Google Earth Pro images. The names and locations of glaciers and glacial features followed the existing terminology used by

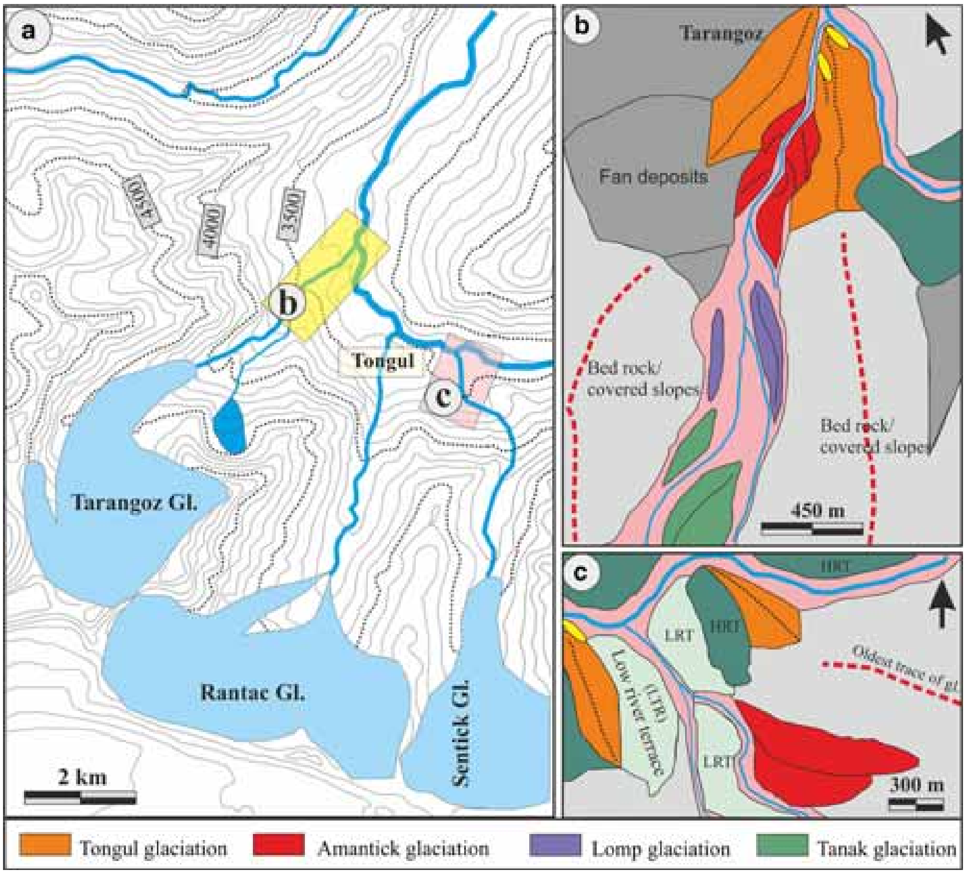

Figure 2. Map compilations showing the (**a**) Contour map of the study area, (**b, c**) detailed glacio-geomorphic maps of the Tarangoz and Sentick valley and the sample locations shown by yellow ecliptics. Different landforms and glacier stages are shown in different colors (after Lee *et al.* 2014).

Lee *et al.* (2014; figure 2). Samples for OSL dating were collected from the sand lenses, which are cryogenically deformed and considered to be deposited along with the moraine (ice-contact sediments; Phillips *et al.* 2000).

4. Chronology

Numerical dating of glacial and associated sediments is a challenge (Hu *et al.* 2015) and there are considerable difficulties for OSL dating due to poor bleaching and poor sensitivity of quartz (Duller 2006) particularly from the Himalayan region (Ali *et al.* 2013 and reference therein). However, the ice contact sediments (sand lenses) present within the moraines are considered to be better bleached, because these sediments are transported in suspension and hence receive adequate sunlight and have successfully been utilized for establishing glacier chronologies across (Richards *et al.* 2000a, b; Tsukamoto *et al.* 2002; Shukla *et al.* 2018). Samples were collected in opaque metallic pipes with an O-ring fitted in the cap to shield against light exposure and prevent moisture loss. For the extraction of quartz, the samples were treated with 1N HCl and 30% H_2O_2 to remove carbonates and organic matter respectively. The samples were oven dried (∼45°C) and sieved to obtain 90–150 μm grain size. Isodynamic separation was used to separate the heavy minerals (at 0.5 A) and feldspar (at 1.5 A; Porat 2006) from the quartz. The quartz fraction was etched with 40% HF for 80 min, to remove the outer alpha skin (∼20 μm) and residual feldspar, followed by 12N HCl treatment for 30 min to remove fluorides. Purity check of the quartz, in terms of feldspar contamination, was done by infrared stimulated luminescence (IRSL). Further, we have tested the contribution of OSL components in all the samples and found that the fast OSL component contribute ∼40 to 60% of signal (figure 4). Pre-heat and dose recovery test were performed to optimize the pre-heat and validate the protocol used respectively. Both the pre-heat plateau and dose recovery tests were performed

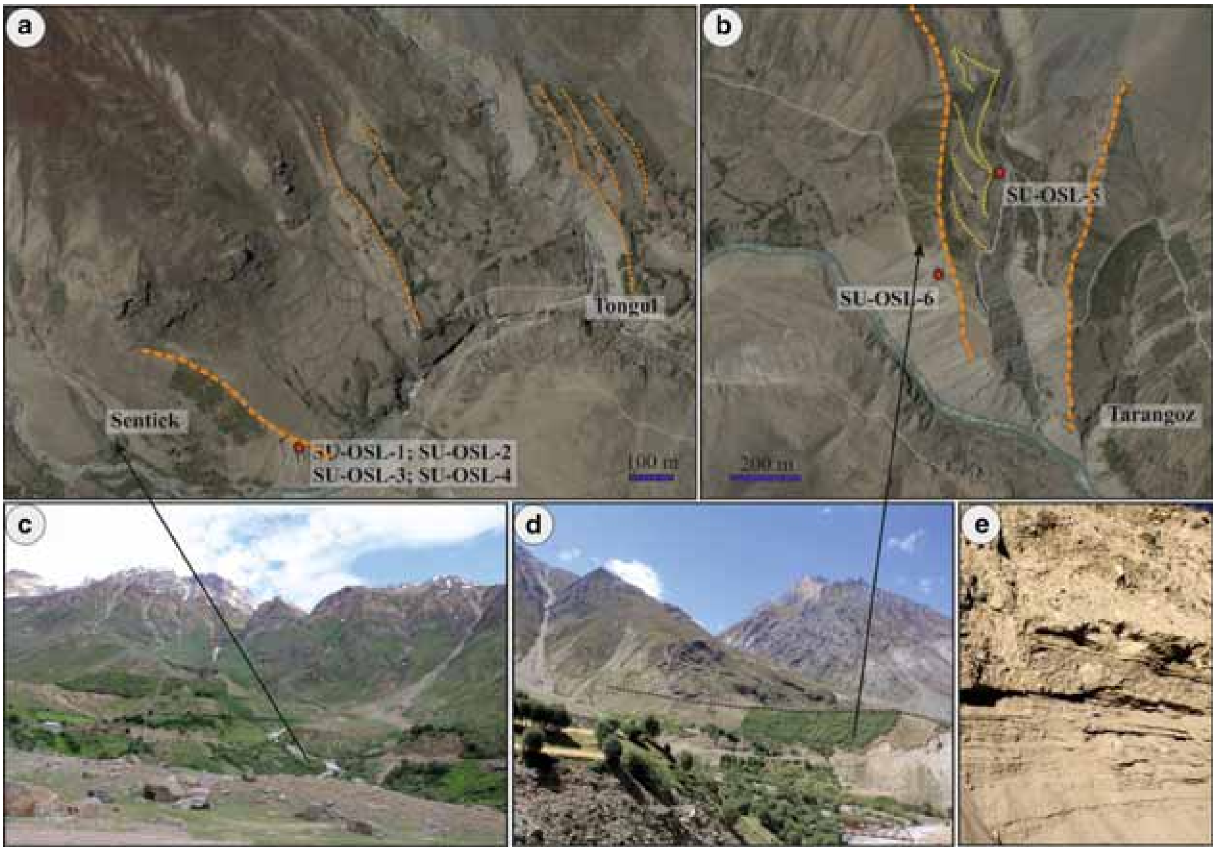

Figure 3. (**a**, **b**) Synoptic view shown on a Google earth Pro image showing (highlighted-orange lines) the lateral moraine and the location of OSL sample collection sites (**c, d**) Field photographs of the Sentick and Tarangoz valleys, (**e**) Close-up of a sand lens from where OSL sample has been collected.

on the Sun bleached (5 hrs) quartz grains. Considering the plateau region of measured to given dose ratio (M/G dose ratio), near unity recycling ratio and lower recuperation (%) collectively, the pre-heat temperature of 240°C was selected (figure 5a). Using this pre-heat temperature, dose recovery test recovered a laboratory administered dose of 50 Gy within 5% accuracy (figure 5b). For measurements, an automated Risø TL-OSL reader (TL/OSL-DA-20; Bøtter-Jensen *et al.* 2010) was used. The samples were irradiated using an on-plate ^{90}Sr/^{90}Y beta source with a dose rate of 5.96 Gy/min. Further, to avoid any contribution from feldspar, equivalent doses (D_e) were carried out through modified single aliquot regeneration (Murray and Wintle 2000; Banerjee *et al.* 2001; Jain and Singhvi 2001) protocol. The annual dose of the samples was calculated using measured radioactive material concentrations and the conversion factor by Adamiec and Aitken (1998). The U, Th, and K concentrations were measured by an X-ray fluorescence elemental analyzer with an accuracy and precision of ∼5 and 10%, respectively (Galson *et al.* 1983; Das *et al.* 2017). Cosmic ray contributions were calculated using the method suggested by Prescott and Hutton (1994). An average water content of 15±5% was used.

A total of six samples collected from the moraines representing two tributary valleys have been dated and are listed in table 1. Out of these, four samples are from the lateral-frontal moraine of Sentick glacier and two samples from the Tarangoz valley (figure 2). The lateral moraine samples (SU-OSL-1 to 6) yielded ages of 10.1±1.0, 23.5±1.3, 20.2±1.7, 21.3±1.7, 12.0±1.4 and 23.0±1.3 ka, respectively (table 1). The 12.0±1.4 ka age is obtained from the crest of the moraine ridge which is inset within the Tarangoz lateral moraine and might represent the initiation age of deglaciation. For palaeodose estimation, central age model (CAM) and minimum age model (MAM3) were used depending on kurtosis, skewness, over-dispersion (OD, %) and the respective relative standard deviation as given in Arnold *et al.* (2007, figure 6); Galbraith *et al.* 1999; Jacobs *et al.*

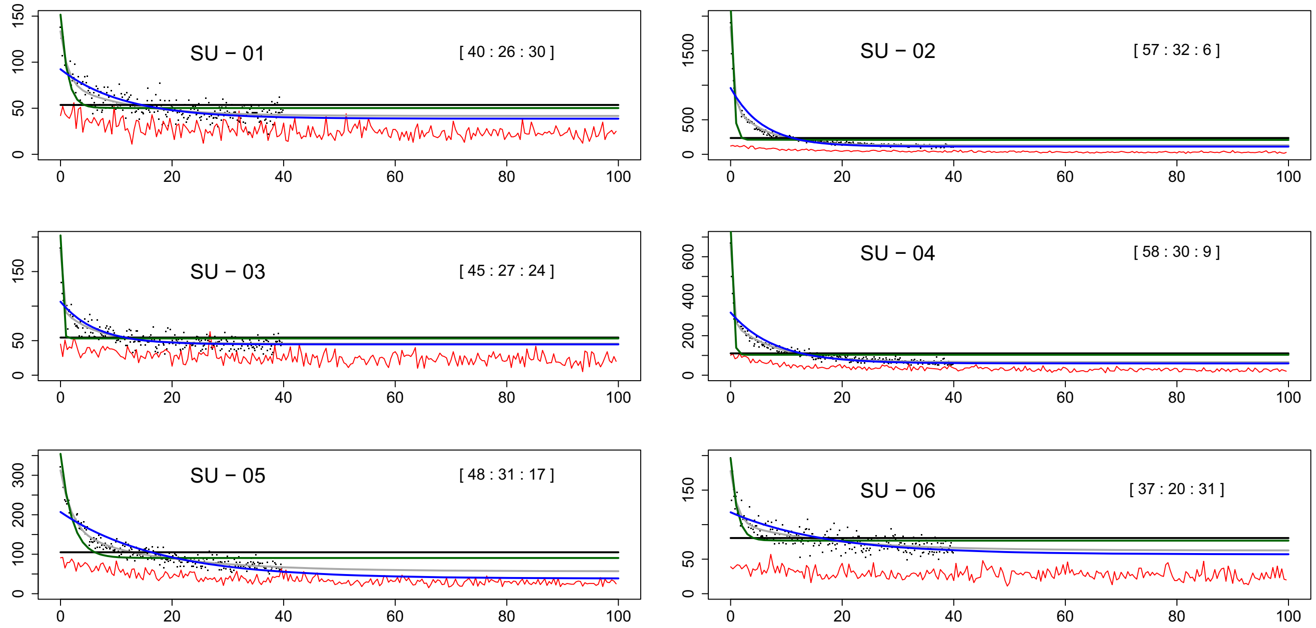

Figure 4. Graph showing the shine down curves of both OSL (black dots) and IRSL (red line) of the samples. OSL shine down curves were fitted to a combination of three exponential decay functions (dark gray line). The percentage contribution of fast (green line), medium (blue line) and slow components (black line) are shown.

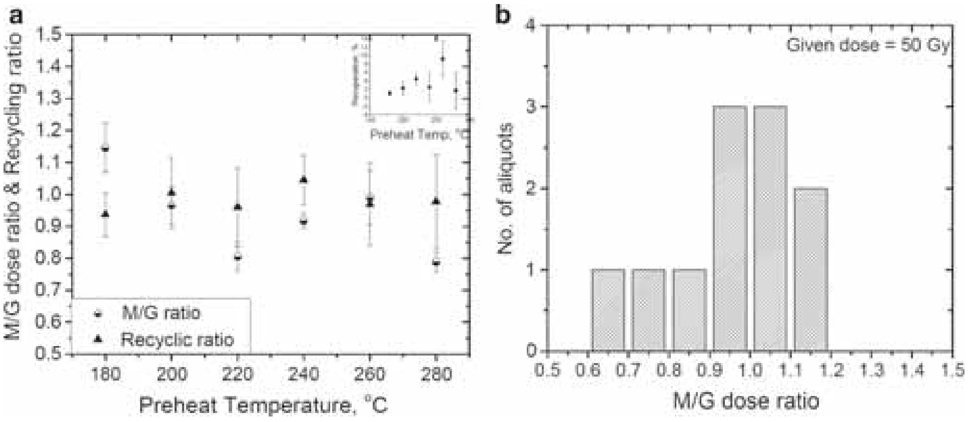

Figure 5. Graph showing (**a**) pre-heat plateau and (**b**) dose recovery test.

2006, 2008; Arnold and Roberts 2009; Galbraith and Roberts 2012).

5. Discussion

Glacio-chronological studies from the Suru valley were first carried by Röthlisberger and Geyh (1986). The study attempted radiocarbon dating of the moraines of Rantac Glacier (Suru valley) that yielded an age of ∼19490±1630 a BP (∼23396±2003 cal. a BP; a humic acid age) and ∼15670±770 a BP (∼18830±851 cal. a BP; total organic age). Subsequently, Lee *et al.* (2014) undertook a more detailed investigation of paleoglaciations in the Nun-Kun massif and used ^{10}Be exposure dating to establish the chronology of glaciations. On the basis of morphostratigraphy and ^{10}Be ages of glacial landforms, they concluded that the area has witnessed four glacial phases, viz., Achambur (∼MIS 3–4), Tongul (early part of the lateglacial; 16.7–17.4 ka), Amantick (lateglacial; 14.3 ka, 11.7–12.4 ka), Lomp and Tanak glacial stages (Little Ice Age and younger). The most spectacular latero-frontal moraines (Tongul glacial stage; Lee *et al.* 2014) which descend down to

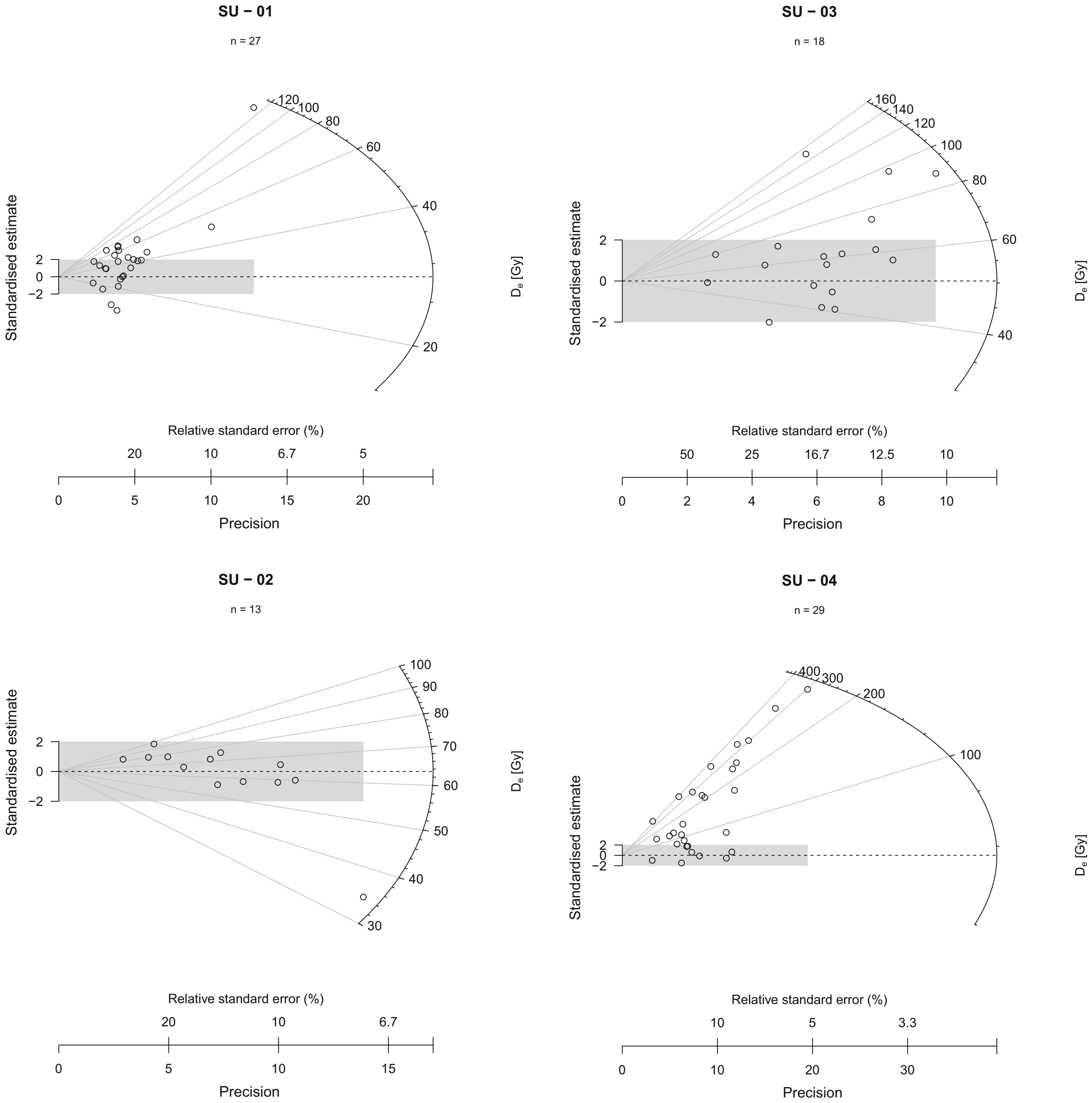

Figure 6. Graph showing the typical radial plots. The shaded portion represents the palaeodose used for age estimation.

mouth of the tributary valleys (Tarangoz and Sentick) is the geomorphic manifestation of the 2nd oldest and most prominent glacier advance in the Suru valley (figure 2). Lee *et al.* (2014) dated these moraines to ∼16.7 to 17.4 ka corresponding to the early part of the late glacial period. However, the post-gLGM was a phase of the revival of insolation driven ISM (Duplessy 1982; Sirocko *et al.* 1993) which led to the melting of glaciers, thus mobilizing the glacial sediments and deposited them as glacier beds in glacier valleys in both westerly dominated northwestern Himalayan region (Ganju *et al.* 2018) as well as ISM dominated central Himalaya (Shukla *et al.* 2018).

It is evident from the ^{14}C ages of Röthlisberger and Geyh (1986) that this phase of glaciation correlate well with the gLGM glacier advances reported in this region (Nagar *et al.* 2013; Sharma *et al.* 2016; Ganju *et al.* 2018). However, the ^{10}Be ages with a large distribution (∼8.1±3.3 to 20.0±2.3 ka) seems to be underestimated (Lee *et al.* 2014), and do not fit the local as well as regional scenario (Ganju *et al.* 2018; Shukla *et al.* 2018 and references therein). The most plausible

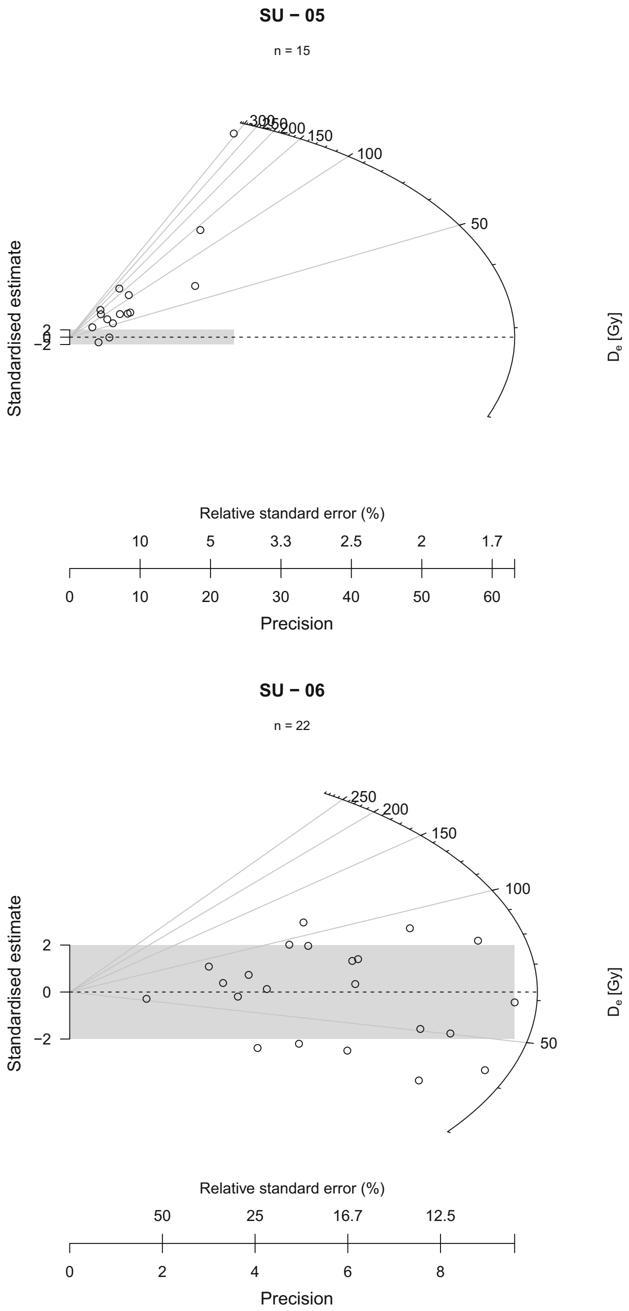

Figure 6. *(Continued.)*

explanation for younger cosmogenic exposure ages compared to OSL (present study) could be the incomplete exposure due to post-depositional shielding. Heyman *et al.* (2011), strongly suggested that post-depositional shielding is the most important geological process leading to scattering in cosmogenic exposure ages for glacial boulder groups older than a few thousand years, and might be the case with younger ages having a large spread in Lee *et al.* (2014) chronology. Contrary to their suggestion, we are able to redefine the chronology of Tongul glacier stage using OSL ages (∼20 to 24 ka), that advocate for an active response of the glaciers in this area to the gLGM (figure 2).

Recent studies have suggested that during the cold gLGM (Bush and Philander 1999; Mix *et al.* 2001; Lisiecki and Raymo 2005), the Himalayan glaciers advanced significantly (Ganju *et al.* 2018) and have been attributed to the enhancement of the mid-latitude westerlies (Ganopolski *et al.* 1998; Ali *et al.* 2013). Therefore, the glaciers in the Suru valley cannot be an exception and would have responded in accordance with the global and regional climatic pattern. In the more eastern part of the northwestern Himalayan region (Chandra valley), Eugster *et al.* (2016) suggested that rapid melting of the glaciers initiated around 19–18 ka for which increased temperature is implicated. Similarly in the Indus valley, the post-glacial retreat is represented by widespread river aggradations (Kumar and Srivastava 2017).

The recent OSL chronology (∼20 to 24 ka) indicates that during the gLGM, glaciers in Suru valley extended to their fullest and occupied the tributary valleys. It needs to be mentioned that the underestimation in one age, i.e., SU-OSL-1 possibly due to the mixing of younger grains; however, we propose further investigation on this. Overall OSL ages are in agreement with Röthlisberger and Geyh (1986) and other recent studies (Nagar *et al.* 2013; Sharma *et al.* 2016; Eugster *et al.* 2016; Ganju *et al.* 2018; Sharma and Shukla 2018). These studies suggest that irrespective of the geographical position (northwestern to central Himalayan region), the glaciers have actively responded to the gLGM due to the deep penetration of the MLW's and corresponding temperature decrease (Ganopolski *et al.* 1998; Bhutiyani *et al.* 2010; Ali and Juyal 2013; Ali *et al.* 2013; Bisht *et al.* 2015; Ganju *et al.* 2018). Zech *et al.* (2009) suggested that the glaciers situated in orographically shielded areas with a reduced amount of moisture are suggested to be more sensitive to changes in precipitation and the ones within the domain of high precipitation are more sensitive to temperature. Although the Suru valley lies in an orographically shielded region, it is located at the northern end of the higher Himalaya thus influenced both by the ISM and the MLWs. It has been suggested that the MLWs were enhanced during the gLGM (Benn and Owen 1998; Ganopolski *et al.* 1998; Eugster *et al.* 2016; Ganju *et al.* 2018), at the expanse of the ISM (Prell and Kutzbach 1987; Herzschuh 2006; Agrawal *et al.* 2012; Dutta *et al.* 2012). As a

Table 1. *Sample details along with the equivalent dose (De), number of aliquots, over dispersion (OD), age model applied, radioactivity, dose rate, and the optical ages obtained on the recessional and lateral moraine.*

Sample identifier	U (ppm)	Th (ppm)	K (%)	De (Gy)	Dose rate (Gy ka^{-1})	Age (ka)	Age model	Glacier valley
SU-OSL-1	3.6 ± 0.18	11.5 ± 0.57	1.24 ± 0.06	28.2 ± 2.7	2.8 ± 0.11	10.1 ± 1.0	MAM3	Sentick
SU-OSL-2	3.3 ± 0.16	12.6 ± 0.63	1.17 ± 0.06	63.4 ± 2.4	2.7 ± 0.11	23.5 ± 1.3	CAM	
SU-OSL-3	2.1 ± 0.10	11.5 ± 0.57	1.27 ± 0.06	50.4 ± 3.7	2.5 ± 0.10	20.2 ± 1.7	MAM3	
SU-OSL-4	3.0 ± 0.15	10.9 ± 0.54	1.32 ± 0.07	57.4 ± 4.0	2.7 ± 0.11	21.3 ± 1.7	MAM3	
SU-OSL-5	2.8 ± 0.14	10.6 ± 0.53	1.00 ± 0.05	28.8 ± 3.3	2.4 ± 0.09	12.0 ± 1.4	MAM3	Tarangoz
SU-OSL-6	5.0 ± 0.25	10.4 ± 0.52	1.00 ± 0.04	62.2 ± 2.4	2.7 ± 0.11	23.0 ± 1.3	CAM	

Error in ages is 1σ; water content 15±5%; U, Th, and K (5–10% error).

consequence, the enhanced winter precipitation would have resulted into long winters that in turn led to more snow and hence causing positive feedback through increased albedo (Juyal *et al.* 2009 and references therein). This condition of ice-albedo feedback mechanism (Colin *et al.* 1998) which reduces radiative heating (Adams *et al.* 1999) would have created favourbale conditions in the Suru valley for the glaciers to advance and sustain during the gLGM.

6. Conclusions

The OSL chronology of the Tongul glacial stage suggests glacier expansion during the gLGM and is in accordance with other valley glaciers in northwestern Himalayan region, suggesting wider role of the enhanced MLWs which led to synchronous response of the valley glaciers with that of the Northern Hemisphere cooling. We ascribe the gLGM glacier advance in Suru valley to a combination of lower temperature and increase moisture contribution from the enhanced MLWs; however, temperature seems to have played a major role. Further the study suggests that in order to arrive at more secure inferences towards the drivers of glacier advances, it is suggested that, wherever possible multiple dating techniques should be employed.

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References

Adamiec G and Aitken M J 1998 Dose–rate conversion factors: Update; *Ancient TL* **16** 37–50.

Adams J, Maslin M and Thomas E 1999 Sudden climate transitions during the quaternary; *Prog. Phys. Geogr.* **23** 1–36.

Agrawal S, Sanyal P, Sarkar A, Jaiswal M K and Dutta K 2012 Variability of Indian monsoonal rainfall over the past 100 ka and its implication for C3–C4 vegetational change; *Quat. Res.* **77**(**1**) 159–170.

Ali S N and Juyal N 2013 Chronology of late quaternary glaciations in Indian Himalaya: A critical review; *J. Geol. Soc. India* **82**(**6**) 628–638.

Ali S N, Biswas R H, Shukla A D and Juyal N 2013 Chronology and climatic implications of late Quaternary glaciations in the Goriganga valley, central Himalaya, India; *Quat. Sci. Rev.* **73** 59–76.

Ali S N, Thakur B, Morthekai P, Farooqui S, Phartiyal B, Seth P and Sharma A 2018 Diatom diversity under extreme climate: A study from Zanaskar Valley, NW Himalaya, India; *J. Palaeontol. Soc. India* **63**(**1**) 119–126.

Arnold L J and Roberts R G 2009 Stochastic modelling of multi-grain equivalent dose (De) distributions: Implications for OSL dating of sediment mixtures; *Quat. Geochronol.* **4** 204–230.

Arnold L J, Bailey R M and Tucker G E 2007 Statistical treatment of fluvial dose distributions from southern Colorado arroyo deposits; *Quat. Geochronol.* **2**(**1–4**) 162–167.

Banerjee D, Murray A S, Botter-Jensen L and Lang A 2001 Equivalent dose estimation using a single aliquot of polymineral fine grains; *Radiat. Meas.* **33** 73–94.

Bellwood P 2013 *First migrants: Ancient migration in global perspective*; Chichester and Malden, MA: Wiley Blackwell.

Benn D I and Owen L A 1998 The role of the Indian summer monsoon and the mid-latitude westerlies in Himalayan glaciation: Review and speculative discussion; *J. Geol. Soc. London* **155** 353–363.

Benn D I and Owen L A 2002 Himalayan glacial sedimentary environments: A framework for reconstructing and dating former glacial extents in high mountain regions; *Quat. Int.* **97/98** 3–25.

Bhutiyani M R, Kale V S and Pawar N J 2010 Climate change and the precipitation variations in the northwestern Himalaya: 1866–2006; *Int. J. Climatol.* **30** 535–548.

Bisht P, Ali S N, Shukla A D, Negi S K, Sundriyal Y P, Yadava M G and Juyal N 2015 Chronology of late Quaternary glaciation and landform evolution in the upper Dhauliganga valley (Trans Himalaya), Uttarakhand, India; *Quat. Sci. Rev.* **129** 147–162.

Bothe O, Fraedrich K and Zhu X 2011 Large-scale circulations and Tibetan Plateau summer drought and wetness in a high-resolution climate model; *Int. J. Climatol.* **31**(**6**) 832–846.

Bøtter-Jensen L, Thomsen K J and Jain M 2010 Review of optically stimulated luminescence (OSL) instrumental developments for retrospective dosimetry; *Radiat. Meas.* **45** 253–257.

Bush A B and Philander S G H 1999 The climate of the Last Glacial Maximum: Results from a coupled atmosphere–ocean general circulation model; *J. Geophys. Res. Atmos.* **104**(**D20**) 24509–24525.

Colin C, Kissel C, Blamart D and Turpin L 1998 Magnetic properties of sediment in the Bay of Bengal and the Andaman Sea: Impact of rapid North Atlantic Ocean climatic events on the strength of the Indian monsoon; *Earth Planet. Sci. Lett.* **160** 623–635.

Dèzes P 1999 Tectonic and metamorphic evolution of the central Himalayan domain in southeast Zanskar (Kashmir, India) 145, Université de Lausanne.

Dortch J M, Owen L A and Caffee M W 2010 Quaternary glaciation in the Nubra and Shyok valley confluence, northernmost Ladakh, India; *Quat. Res.* **74** 132–144.

Duller G A T 2006 Single grain optical dating of glacigenic deposits; *Quat. Geochronol.* **1** 296–304.

Duplessy J C 1982 Glacial to interglacial contrasts in the northern Indian Ocean; *Nature* **295** 494–498.

Dutta S, Suresh N and Kumar R 2012 Climatically controlled Late Quaternary terrace staircase development in the fold-and-thrust belt of the Sub Himalaya; *Palaeogeol. Palaeoclimatol. Palaeoecol.* **356** 16–26.

Eugster P, Scherler D, Thiede R C, Codilean A T and Strecker M R 2016 Rapid Last Glacial Maximum deglaciation in the Indian Himalaya coeval with midlatitude glaciers: New insights from ^{10}Be-dating of ice-polished bedrock surfaces in the Chandra Valley, NW Himalaya; *Geophys. Res. Lett.* **43**(**4**) 1589–1597.

Fuchs M and Owen L A 2008 Luminescence dating of glacial and associated sediments: Review, recommendations and future directions; *Boreas* **37** 636–659.

Galbraith R F and Roberts R G 2012 Statistical aspects of equivalent dose and error calculation and display in OSL dating: An overview and some recommendations; *Quat. Geochronol.* **11** 1–27.

Galbraith R F, Roberts R G, Laslett G M, Yoshida H and Olley J M 1999 Optical dating of single and multiple grains of quartz from Jinmium rock shelter, northern Australia. Part I: Experimental design and statistical models; *Archaeometry* **41**(**2**) 339–364.

Ganju A, Nagar Y C, Sharma L N, Shubhra Sharma S and Juyal N 2018 Luminescence chronology and climatic implication of the late quaternary glaciation in the Nubra valley, Karakoram Himalaya, India; *Palaeogeol. Palaeoclimaolt. Palaeoecol.* **502** 52–62.

Ganopolski A, Rahmstorf S, Petoukhov V and Claussen M 1998 Simulation of modern and glacial climates with a coupled global model of intermediate complexity; *Nature* **391**(**6665**) 351.

Godard V, Burbank D W, Bourlès D L, Bookhagen B, Braucher R and Fisher G B 2012 Impact of glacial erosion on ^{10}Be concentrations in fluvial sediments of the Marsyandi catchment, central Nepal; *J. Geophys. Res. Earth Surface* **117**(F3).

Herzschuh U 2006 Paleo-moisture evolution in monsoonal central Asia during the last 50,000 years; *Quat. Sci. Rev.* **25** 163–178.

Heyman J, Stroeven A P, Harbor J M and Caffee M W 2011 Too young or too old: Evaluating cosmogenic exposure dating based on an analysis of compiled boulder exposure ages; *Earth Planet. Sci. Lett.* **302**(**1–2**) 71–80.

Hu G, Yi C L, Zhang J F, Liu J H, Jiang T and Qin X 2015 Luminescence dating of glacial deposits near the eastern Himalayan syntaxis using different grain size fractions; *Quat. Sci. Rev.* **124** 124–144.

Jacobs Z, Duller G A, Wintle A G and Henshilwood C S 2006 Extending the chronology of deposits at Blombos Cave, South Africa, back to 140 ka using optical dating of single and multiple grains of quartz; *J. Hum. Evol.* **51** 255–273.

Jacobs Z, Wintle A G, Duller G A, Roberts R G and Wadley L 2008 New ages for the post-Howiesons Poort, late and final Middle Stone Age at Sibudu, South Africa; *J. Archaeol. Sci.* **35** 1790–1807.

Jain M and Singhvi A K 2001 Limits to depletion of blue-green light stimulated luminescence in feldspars: Implications for quartz dating; *Rad. Meas.* **33** 883–892.

Juyal N, Pant R K, Basavaiah N, Bhushan R, Jain M, Saini N K, Yadava M G and Singhvi A K 2009 Reconstruction of Last Glacial to early Holocene monsoon variability from relict lake sediments of the Higher Central Himalaya, Uttrakhand, India; *J. Asian Earth Sci.* **34**(**3**) 437–449.

Kumar A and Srivastava P 2017 The role of climate and tectonics in aggradation and incision of the Indus River in the Ladakh Himalaya during the late Quaternary; *Quat. Res.* **87**(**3**) 363–385.

Lee S Y, Seong Y B, Owen L A, Murari M K, Lim H S, Yoon H I and Yoo K C 2014 Late Quaternary glaciation in the Nun-Kun massif, northwestern India; *Boreas* **43**(**1**) 67–89.

Leipe C, Demske D, Tarasov P E, Wünnemann B, Riedel F and Members H P 2014 Potential of pollen and non-pollen palynomorph records from Tso Moriri (Trans-Himalaya, NW India) for reconstructing Holocene limnology and human–environmental interactions; *Quat. Int.* **348** 113–129.

Lisiecki L E and Raymo M E 2005 A Pliocene–Pleistocene stack of 57 globally distributed benthic δ^{18}O records; *Paleoceanography* **20**(**1**) PA1003, https://doi.org/10.1029/2004pa001071.

Mayewski P A, Lyons W B, Ahmad N, Smith G and Pourchet M 1984 Interpretation of the chemical and physical time-series retrieved from Sentik Glacier, Ladakh Himalaya, India; *J. Glaciology* **30**(**104**) 66–76.

Mix A C, Bard E and Schneider R 2001 Environmental processes of the ice age: Land, oceans, glaciers (EPILOG); *Quat. Sci. Rev.* **20**(**4**) 627–657.

Murray A S and Wintle A G 2000 Luminescence dating of quartz using an improved single-aliquot regenerative-dose protocol; *Radiat. Meas.* **32** 57–73.

Nagar Y C, Ganju A, Satyawali P K and Juyal N 2013 Preliminary optical chronology suggests significant advance in Nubra Valley glaciers during the last glacial maximum; *Curr. Sci.* **105**(**1**) 96–101.

Nanda M M, Dungrakoti B D, Singh M P, Das B K, Andotra B S, Chakarborti R K and Mohanty A K 1969 Progress report on the geological expedition to Zanskar; Geol. Surv. India Report (Unpublished).

Owen L A and Benn D I 2005 Equilibrium-line altitudes of the Last Glacial Maximum for the Himalaya and Tibet: An assessment and evaluation of results; *Quat. Int.* **138** 55–78.

Owen L A and Dortch J M 2014 Nature and timing of Quaternary glaciation in the Himalayan–Tibetan orogen; *Quat. Sci. Rev.* **88** 14–54.

Owen L A, Caffee M W, Bovard K R, Finkel R C and Sharma M C 2006 Terrestrial cosmogenic nuclide surface exposure dating of the oldest glacial successions in the Himalayan orogen: Ladakh Range, northern India; *Geol. Soc. Am. Bull.* **118**(**3–4**) 383–392.

Owen L A, Finkel R C and Caffee M W 2002 A note on the extent of glaciation throughout the Himalaya during the global Last Glacial Maximum; *Quat. Sci. Rev.* **21**(**1–3**) 147–157.

Phillips W M, Sloan V F, Shroder J F, Sharma P, Clarke M L and Rendell H M 2000 Asynchronous glaciation at Nanga Parbat, northwestern Himalaya Mountains, Pakistan; *Geology* **28** 431–434.

Porat N 2006 Use of magnetic separation for purifying quartz for luminescence dating; *Ancient TL* **24** 33–36.

Prell W L and Kutzbach J E 1987 Monsoon variability over the past 150,000 years; *J. Geophys. Res.* **92** 8411–8425.

Prescott J R and Hutton J T 1994 Cosmic ray contributions to dose rates for luminescence and ESR dating: Large depths and long-term time variations; *Radiat. Meas.* **23** 497–500.

Richards B W M *et al.* 2000a Timing of Late Quaternary glaciations in the Himalayas of northern Pakistan; *J. Quat. Sci.* **15** 283–297.

Richards B W, Benn D I, Owen L A, Rhodes E J and Spencer J Q 2000b Timing of late Quaternary glaciations south of Mount Everest in the Khumbu Himal, Nepal; *Geol. Soc. Am. Bull.* **112**(**10**) 1621–1632.

Röthlisberger F and Geyh M 1986 Glacier variations in Himalayas and Karakorum; *J. Glaciol. Geocryol.* **4** 237–249.

Saha S, Sharma M C, Murari M K, Owen L A and Caffee M W 2016 Geomorphology, sedimentology and minimum exposure ages of streamlined subglacial landforms in the NW Himalaya, India; *Boreas* **45**(**2**) 284–303.

Scherler D, Bookhagen B, Strecker M R, von Blanckenburg F and Rood D 2010 Timing and extent of late Quaternary glaciation in the western Himalaya constrained by ^{10}Be moraine dating in Garhwal, India; *Quat. Sci. Rev.* **29**(**7–8**) 815–831.

Seong Y B, Owen L A, Yi C and Finkel R C 2009 Quaternary glaciation of Muztag Ata and Kongur Shan: Evidence for glacier response to rapid climate changes throughout the Late Glacial and Holocene in westernmost Tibet; *Geol. Soc. Am. Bull.* **121** 348–365.

Sharma S and Shukla A D 2018 Factors governing the pattern of glacier advances since the Last Glacial Maxima in the transitional climate zone of the Southern Zanskar Ranges, NW Himalaya; *Quat. Sci. Rev.* **201** 223–240.

Sharma S, Chand P, Bisht P, Shukla A D, Bartarya S K, Sundriyal Y P and Juyal N 2016 Factors responsible for driving the glaciation in the Sarchu Plain, eastern Zanskar Himalaya, during the late Quaternary; *J. Quat. Sci.* **31**(**5**) 495–511.

Sharma S, Hussain A, Mishra A K, Lone A, Solanki T and Khan M K 2018 Geomorphic investigation of the Late-Quaternary landforms in the southern Zanskar Valley, NW Himalaya; *J. Earth Syst. Sci.* **127**(**1**), https://doi.org/10.1007/s12040-017-0911-2.

Shukla T, Mehta M, Jaiswal M K, Srivastava P, Dobhal D P, Nainwal H C and Singh A K 2018 Late Quaternary glaciation history of monsoon-dominated Dingad basin, central Himalaya, India; *Quat. Sci. Rev.* **181** 43–64.

Sirocko F, Sarnthein M, Erlenkeuser H, Lange H, Arnold M and Duplessy J C 1993 Century-scale events in monsoonal climate over the past 24,000 years; *Nature* **364** 322–324.

Taylor PJ and Mitchell WA 2000 The Quaternary glacial history of the Zanskar Range, north-west Indian Himalaya; *Quat. Int.* **65** 81–99.

Tsukamoto S, Asahi K, Watanabe T and Rink W J 2002 Timing of past glaciations in Kanchenjunga Himal, Nepal by optically stimulated luminescence dating of tills; *Quat. Int.* **97–98** 57–67.

Wang L, Chen W, Huang G and Zeng G 2016 Changes of the transitional climate zone in East Asia: Past and future; *Clim. Dyn.* **49** 1463–1477.

Zech R, Zech M and Kubik P W *et al.* 2009 Deglaciation and landscape history around Annapurna, Nepal, based on 10Be surface exposure dating; *Quat. Sci. Rev.* **28** 1106–1118.

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