

Holocene palaeoenvironmental changes in the Thar Desert: an integrated assessment incorporating new insights from aeolian systems

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Abstract

Due to the scarcity of geochemical and palaeoecological proxies in drylands, dunes have often been used as geoproxies for late Quaternary palaeoenvironmental reconstruction, with chronologies commonly provided by luminescence dating. Owing to their widespread occurrence and location in a monsoonal regime, dunes in the Thar Desert in South Asia act as important archives of past landscape change. Previous reviews have assimilated dune age data from the Thar and suggested a temporally and spatially complex record of sediment accumulation over the last ~70 ka. New luminescence age data presented in this study and from recent dunefield based investigations demonstrate a stronger Holocene record of dune building in parts of the Thar than previously suggested.

In this study, the Accumulation Intensity (AI) methodology is applied to new and old data sets, providing records of dune accumulation that can be analysed alongside

other palaeoenvironmental records. *AI* analysis demonstrates the significance of Holocene dune accumulation in the Thar landscape, with accumulation peaks observed between ~12 and ~8 ka, centred around ~7, ~5 and ~3.5 ka, and in last two millennia. The strengthening of the Indian Summer Monsoon remains a significant influence on widespread dune accumulation in the early Holocene, but dunefields have also shown diverse and spatially intensive responses to sediment supply and anthropogenic disturbances during the late Holocene. Additionally, aeolian-fluvial sequences associated with the Ghaggar-Hakra palaeochannel along the northern margin of the Thar also display dynamic geomorphic behaviour during the Holocene. The integration and interpretation of the *AI* data with published, highly resolved geochemical proxies of palaeoclimate, shows a complex relationship between geoproxy and geochemical records. We suggest that process studies of geomorphologic systems and their diverse responses to the same environmental stimuli must be given due consideration before deriving palaeoenvironmental interpretations. Despite the presence of over a hundred Holocene dune records from the Thar, there still remains marked spatial and temporal gaps. Further intensive investigations of distinct dunefields with a strong chronometric framework and geomorphological grasp are required to gain significant insights into wider Thar landscape and palaeoenvironmental dynamics.

Keywords: *Thar Desert, Holocene; Dune accumulation; Accumulation Intensity; palaeoenvironmental change*

1. Introduction

The landscape of the Thar Desert in South Asia is dominated by sand dunes of different types including parabolic, linear, and transverse, of up to 30 m in height (Kar, 1993; Singhvi and Kar, 2004; Moharana et al., 2013). These features have long been viewed as offering insights into landscape and climate change during the Quaternary period. Based on dune orientation, earlier studies proposed a dominant role of south-westerly Indian Summer Monsoon (ISM) winds in dune development in the Thar (e.g. Goudie et al., 1973; Allchin et al., 1978; Wasson et al., 1983; Kar, 1987). The ISM winds, based on meteorological observations, have been shown to exceed the threshold for sand movement in the pre-monsoon period (March to June) before the onset of rainfall (Wasson et al., 1983; Kar, 1993). Aeolian activity is strong during this period when vegetation is dry, and wind erosion of the terrain and subsequent sediment transportation and deposition are more pronounced (Wasson et al., 1983; Kar, 1993). It is only after this period of increased wind intensity that precipitation (~80% of the total annual amount) is delivered to the region, between the months of June and September, resulting in positive precipitation minus evaporation conditions. Therefore, whilst periods of more intensive monsoon activity can be associated with increased precipitation, they can also represent phases of more intensive aeolian activity. However, there was an absence of temporal control on Thar dune development until Singhvi et al. (1982) used thermoluminescence (TL) dating to provide the first chronometric perspective, with eight ages calculated from three dune sites. Since then over 150 dune samples in the Thar have been investigated and dated using both TL and optically stimulated luminescence (OSL) dating techniques (e.g. Andrews et al., 1998; Kar et al., 1998; Thomas et al., 1999; Kar et al., 2001; Juyal et al., 2003). Singhvi and Kar (2004) summarised these

investigations and concluded these records provide a first-level understanding of aeolian episodes in the Thar, with Singhvi and Porat (2008) further assessing and briefly summarising key results from the Thar dunefield age data. Lancaster et al. (2016) collated all the Thar dune luminescence ages published in peer reviewed studies (>150) in the INQUA dune atlas chronologic database.

Despite a relatively large published luminescence age data set, the interrogation of the Thar dune records in the context of understanding past landscape dynamics has been challenging. The aeolian records need to be assessed alongside other proxy data if environmental dynamics and their drivers are to be determined. Two main reasons explain the challenges that have occurred. First, there has been a lack of spatial and temporal coverage in the available aeolian data set until recently, as shown in Figure 1. For instance, the central Thar dune record was represented by just three Holocene ages from two sites, Chamu and Shergarh Trijunction (Andrews et al., 1998; Dhir et al., 2010). In contrast, the southern and northern Thar areas were the subject of several dune-based investigations, which identified major early and late Holocene dune accumulation phases respectively (Figure 1b). Consequently, single dune sites were often considered representative of the wider region, although they inevitably failed to capture dunefield development history and inhibited analyses of the drivers of dune accumulation. Recent dunefield based studies by Srivastava et al. (2019a; 2019b) have revealed significant Holocene aeolian accumulation, and presented 50 new OSL ages from a mixture of parabolic and linear dunes, demonstrating that dune accumulation was persistent throughout much of the Holocene, adding a significant late Holocene data set which was infrequently identified in earlier studies. Second, it has been difficult to integrate the aeolian age records, which have been discontinuous with other proxy records, an

issue observed in other dryland contexts worldwide (Thomas and Bailey, 2017). Therefore, reconstructions of Holocene palaeoenvironments in the Thar rely on other terrestrial archives including fluvial records from the Thar margins (e.g. Jain and Tandon, 2003; Jain et al., 2004; Giosan et al., 2012; Durcan et al., 2019), and lacustrine sediments from various interior and marginal lakes (e.g. Wasson et al., 1984; Singh et al., 1990; Kajale and Deotare, 1997; Enzel et al., 1999; Deotare et al., 2004; Sinha et al., 2006; Dixit et al., 2014a; Dixit et al., 2014b; Dixit et al., 2018). These records are often supplemented by regional palaeoclimatic proxies, including sedimentary and productivity records from marine sediments (e.g. Sarkar et al., 2000; Staubwasser et al. 2002; Gupta et al., 2003; Ivanochko et al., 2005; Ponton et al., 2012) and isotopic records from speleothems in central or north-eastern India (Sinha et al., 2007; Sinha et al., 2011a; Dutt et al., 2015; Berkelhammer et al., 2012; Band et al., 2018) and the Arabian peninsula (e.g. Neff et al., 2001; Fleitmann et al., 2003; Fleitmann et al., 2007) (Figure 2). These records present high resolution data, but due to their limited spatial context, diverse methodologies and different temporal ranges, landscape scale response interpretations arising from these geochemical proxies are often conflicting in nature (e.g. Prasad and Enzel, 2006; Macdonald, 2011, Band et al., 2018; Kaushal et al., 2018; Misra et al., 2019). Dunes, whilst widespread in the Thar landscape, remain under-utilised in environmental reconstructions, representing a valuable archive of change.

In the context of these considerations, this paper aims first to systematically analyse the both new and existing dune age data set from the Thar Desert using the numerical Accumulation Intensity (*AI*) analysis approach of Thomas and Bailey (2017; 2019). Then, focussing on the Holocene, the dune accumulation records are assessed alongside other published proxy data sets to re-evaluate landscape

dynamics and change in the Thar. Finally, the new analysis is assessed in terms of potential drivers of climate, along with consideration of data gaps and issues within the existing portfolio of dune records.

2. Accumulation Intensity modelling

Several studies have highlighted difficulties in using dune age records in palaeoenvironmental and paleoclimate analyses. These difficulties include sampling issues (Hesse, 2016), taphonomic issues related to reworking of sediments (Bailey and Thomas, 2014), data presentation issues (Thomas and Burrough, 2012; Thomas and Burrough, 2016), and the definitive identification of controls on dune sediment transportation (Chase, 2009). To address these issues, Bailey and Thomas (2014) first developed the dune Accumulation Rate Variability model, identifying and quantifying the drivers of dune accumulation. This was subsequently modified to the *AI* model which utilises information on the actual sedimentation process in dunes to produce temporal *AI* curves through time, which can be compared with other palaeoenvironmental proxy data sets (Thomas and Bailey, 2017). In principle, the model integrates and analyses central ages, their associated one sigma uncertainties, and sampling interval depth data, and then iteratively resamples these ages (within their uncertainties) to calculate accumulation rates. The dispersion in the resampled accumulation rates acts as a proxy for the estimated accumulation rate (Thomas and Bailey, 2017; 2019). Full mathematical detail of the model is explained in Thomas and Bailey (2017).

The model has several advantages. It calculates temporal changes in dune accumulation through time, independent of the number of samples included in the analysis, allowing the retrieval of continuous palaeoenvironmental information from

dated dune sequences. Further, as the model incorporates age certainties into analyses, any apparent age inversions are handled appropriately. The *AI* method is applied to data from dunefields rather than individual dunes, and hence allows a more systematic testing of landscape-scale responses and relationships to external drivers at global and regional scales.

The model has been successfully used to compare and explain dunefield accumulation histories in the context of other deserts in southern Africa and Australia in conjunction with other continental and marine records (Thomas and Bailey, 2017). Recently, Thomas and Bailey (2019) applied the *AI* methodology to the Asian dune age data sets included in the INQUA dune atlas (Lancaster et al., 2016), focusing on the last 50 ka, including the records for the Thar. The authors highlighted the shortage of paired stratigraphically related ages from investigated dune sections and absence of locational/depth data. The resultant *AI* curve was therefore noted for its relatively limited spatial coverage, as well as containing insufficient data to provide a nuanced assessment of Thar dune accumulation in the late Quaternary. This paper addresses this shortfall by incorporating recently published age records into a new *AI* analysis.

2.1 Data included in AI analysis

There were 146 Thar dune luminescence ages in the first version of the INQUA dune atlas database (Lancaster et al., 2016), which after updates, now includes a further 26 ages from Shitaoka et al (2012) and Durcan et al (2019). Recent studies have expanded the available luminescence age data set by providing 50 new dune ages (Srivastava et al., 2019a; Srivastava et al., 2019b) from the central and northern Thar.

In addition to these published ages, 10 new dune accumulation records from parabolic dunes in the central Thar and from a source-bordering dune associated with the Ghaggar-Hakra palaeochannel in the north have been determined and are included in this study. These new OSL ages, from the early to middle Holocene, have been determined using small aliquots of coarse quartz grains (180-210 μm) following the luminescence dating methods outlined in Srivastava et al. (2019a) (Table 1). The full details regarding sampling and luminescence dating results are provided in the Supplementary Information. Figure 1 displays the full set of available luminescence Holocene records from the database and new studies, categorised in four regions: northern, central and southern Thar, and Ghaggar-Hakra palaeochannel following geographical contexts described in original publications.

This combined data set for the Thar provides an opportunity to enhance the spatial and temporal detail of dune accumulation, to the point where Thar dune data can contribute more robustly to palaeoenvironmental analyses for the region. The full data set for this new *AI* analysis, using the methodology of Thomas and Bailey (2017), therefore comprises (see Supplementary Information for details of all records):

1. 73 dune ages, generating 59 accumulation intervals, from a total of 146 ages presented in the database from sites Thirana, Jamsar (Thomas et al., 1999), Chamu (Dhir et al., 2010), Amarsar (Singhvi and Kar, 2004), Dharoi (Juyal et al., 2003) and Khudala (Thomas et al., 1999; Kar et al., 2001). Many ages did not meet the required criteria for *AI* analysis due to an absence of locational or depth data, or the occurrence of age reversals which meant net accumulation could not be identified (Thomas and Bailey, 2017). Further, ages from mobile transverse dunes (e.g. Khara, Bharmasar; Figure1; Kar et

al., 1998) were excluded on the account of lower likelihood of sediment preservation (Bailey and Thomas, 2014).

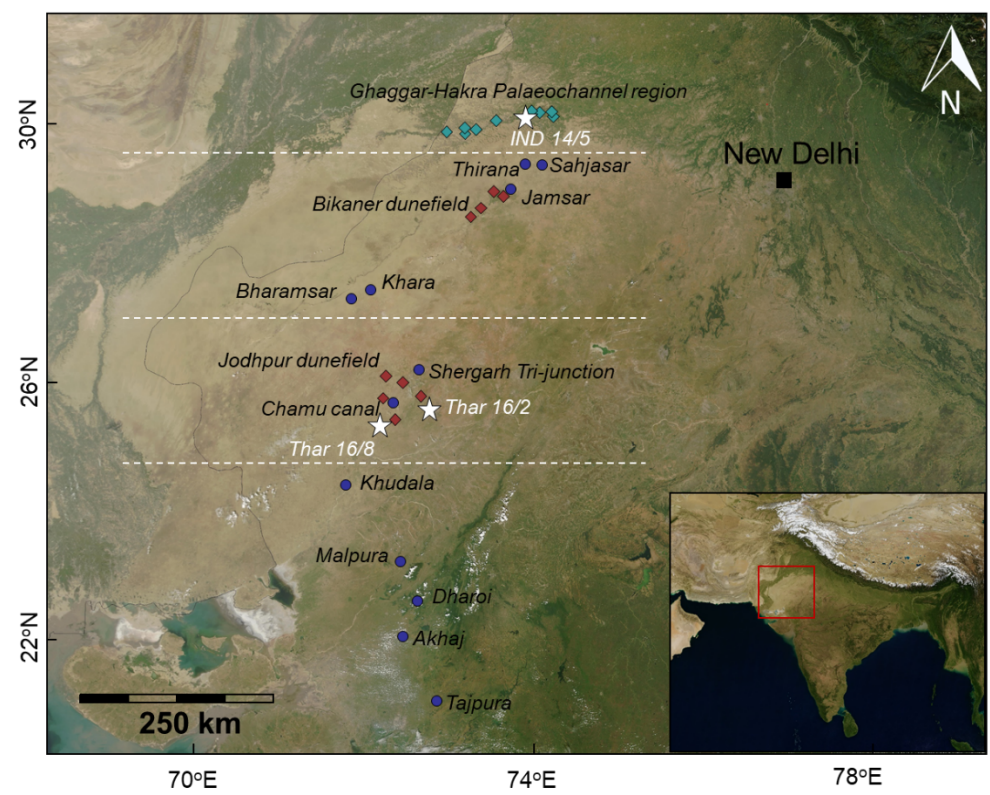
2. 83 of 86 newly published ages, from two dunefields in the central Thar (Jodhpur; Srivastava et al., 2019b; this study) and the northern Thar (Bikaner; Srivastava et al., 2019a), and aeolian sequences in Shitaoka et al. (2012) and Durcan et al., (2019), generating 58 accumulation intervals.

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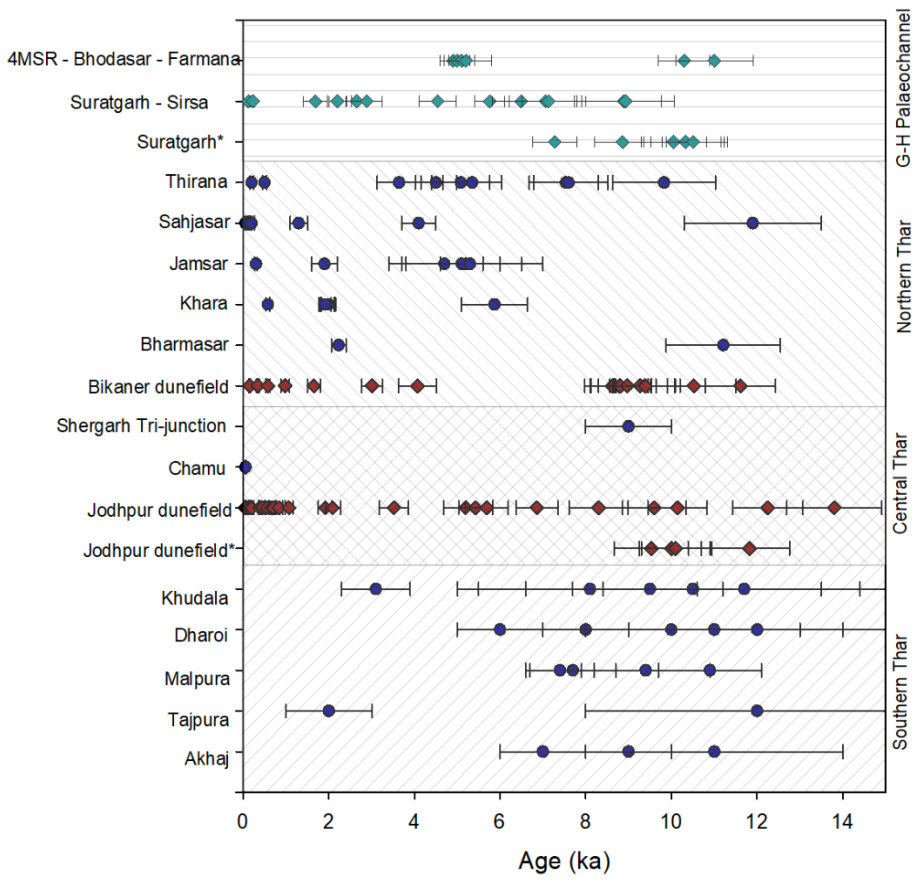
218 **Table 1. Summary OSL data of new ages included in this study. Equivalent doses (D_e), dose rates (\dot{D}), and ages are shown**
 219 **to two decimal places, with all calculations made prior to rounding. All ages were calculated using Central Age Model**
 220 **(CAM) and are relative to the year 2018.**

Sample	Depth	Discs accepted	Overdispersion	CAM D_e	Beta \dot{D}	Gamma \dot{D}	Cosmic \dot{D}	Envir \dot{D}	Age
	(m)	(measured)	(%)	(Gy)	(Gy.ka ⁻¹)	(Gy.ka ⁻¹)	(Gy.ka ⁻¹)	(Gy.ka ⁻¹)	(ka)
Thar 16/2/1	21	23 (50)	32.7 ± 4.3	24.55 ± 1.84	1.43 ± 0.11	1.12 ± 0.08	0.03 ± 0.02	2.58 ± 0.14	9.53 ± 0.87
Thar 16/2/3	22	23 (42)	26.7 ± 4.1	25.28 ± 1.43	1.25 ± 0.10	0.86 ± 0.06	0.03 ± 0.02	2.14 ± 0.12	11.83 ± 0.93
Thar 16/8/1	2	28 (48)	24.3 ± 3.5	21.82 ± 1.04	1.16 ± 0.09	0.86 ± 0.06	0.16 ± 0.02	2.18 ± 0.11	10.01 ± 0.70
Thar 16/8/2	3	23 (68)	31.9 ± 4.9	24.43 ± 1.66	1.33 ± 0.10	0.96 ± 0.06	0.14 ± 0.02	2.43 ± 0.13	10.04 ± 0.85
IND 14/5/1	2	20 (30)	21.8 ± 3.8	18.99 ± 0.97	1.43 ± 0.11	1.02 ± 0.07	0.16 ± 0.02	2.61 ± 0.13	7.28 ± 0.52
IND 14/5/2	3	20 (46)	22.4 ± 5.4	22.60 ± 1.21	1.42 ± 0.11	0.99 ± 0.07	0.14 ± 0.02	2.55 ± 0.13	8.86 ± 0.66
IND 14/5/3	10	34 (48)	22.6 ± 3.2	23.02 ± 0.96	1.31 ± 0.11	0.81 ± 0.05	0.07 ± 0.02	2.19 ± 0.13	10.51 ± 0.73
IND 14/5/4	11	18 (28)	12.6 ± 2.8	28.75 ± 1.01	1.48 ± 0.11	1.19 ± 0.08	0.06 ± 0.02	2.74 ± 0.14	10.51 ± 0.64
IND 14/5/5	25	29 (60)	28.8 ± 4.3	28.90 ± 1.65	1.54 ± 0.11	1.31 ± 0.09	0.02 ± 0.02	2.88 ± 0.14	10.05 ± 0.76
IND 14/5/6	26	18 (28)	30.0 ± 5.9	25.78 ± 2.04	1.41 ± 0.11	1.07 ± 0.07	0.02 ± 0.02	2.50 ± 0.13	10.33 ± 0.97

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223 **Figure 1. (a) The locations of studied Holocene dune sites in the Thar. Blue circles denote sites as described in Singhvi**
224 **and Kar (2004) and listed in the first version of the INQUA dune database (Lancaster et al., 2016): Thirana, Sahjasar,**

225 Jamsar, Malpura (Thomas et al., 1999), Khara, Bharmasar (Kar et al., 1998), Chamu (Dhir et al., 2010), Khudala (Kar et al.,
226 2001), Dharoi, Tajpura and Akhaj (Juyal et al., 2003); red diamonds denote sites investigated in Bikaner dunefield in the
227 northern Thar (Srivastava et al, 2019a) and Jodhpur dunefield in the central Thar (Srivastava et al., 2019b); blue diamonds
228 denote sites along the Ghaggar-Hakra palaeochannel further along the northern Thar margin (Shitaoka et al., 2012; Durcan
229 et al., 2019), white stars represent new sites included in this paper (see Supplementary Information). (b) Associated
230 Holocene dune ages reported from the investigated sites. (*) represents the new ages presented in this study.

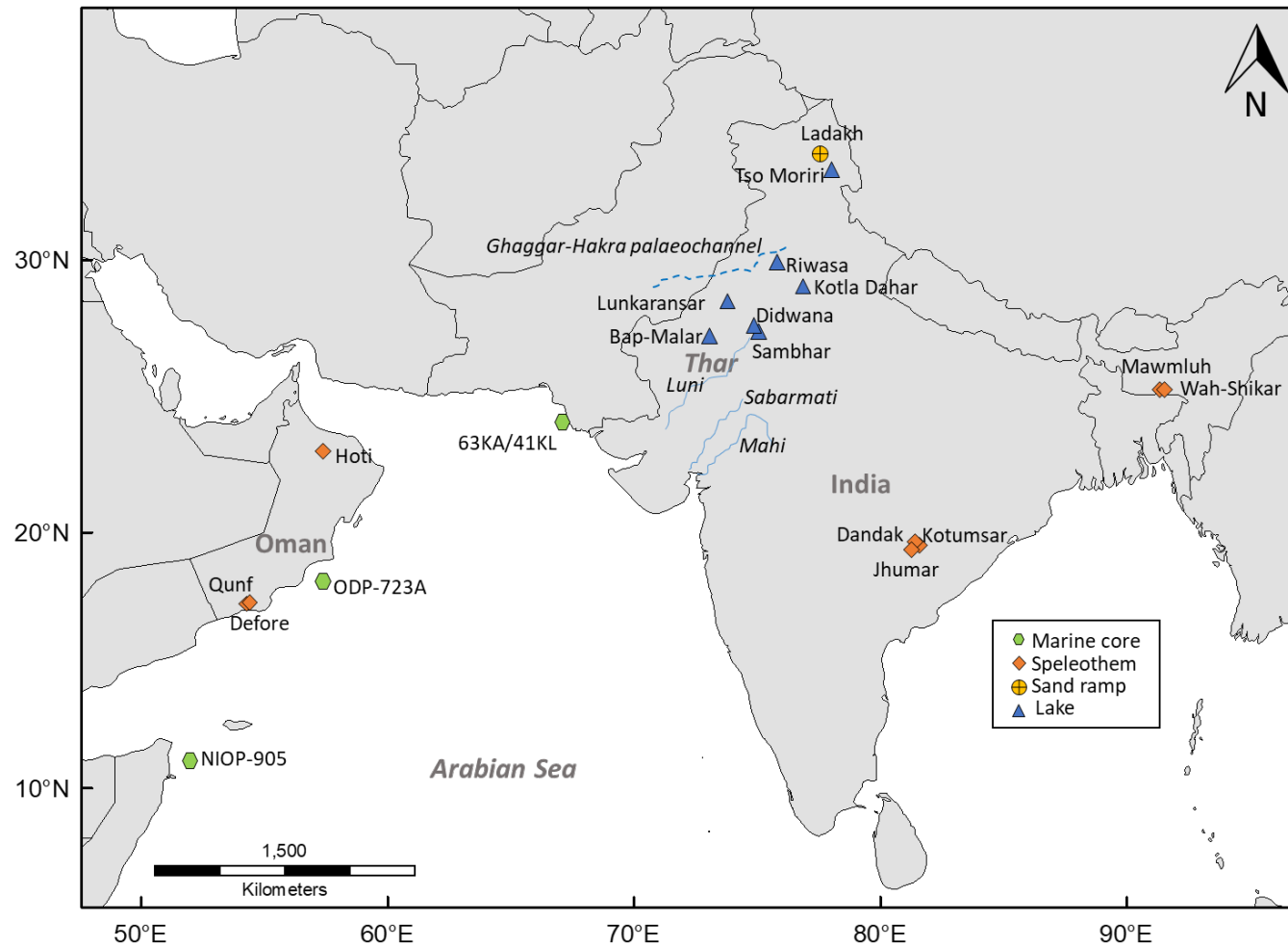


Figure 2. The locations of different types of proxy records from north-western India and beyond, as discussed in this paper.

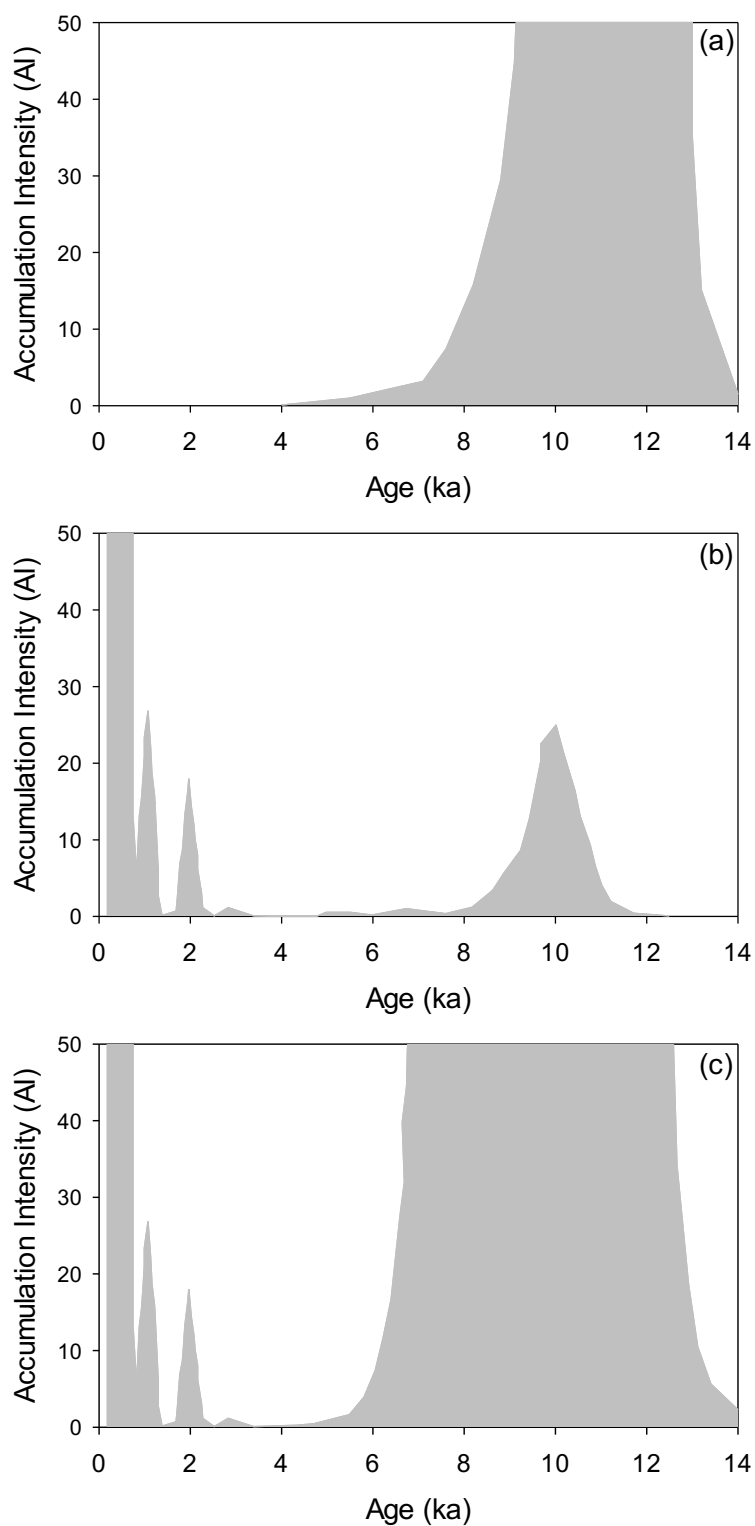
2.2 A new *AI* record for the Thar Desert

The new Holocene *AI* record for the Thar Desert is presented in Figure 3. For contrast, Figure 3a shows the initial Thar *AI* plot from Thomas and Bailey (2019), based only on the ages included in the original dune atlas database (Lancaster et al., 2016). Figure 3b shows the *AI* plot from the recently published OSL ages from parabolic and linear dunefields in the central and northern Thar (Srivastava et al., 2019a; Srivastava et al., 2019b), aeolian sequences along the Ghaggar-Hakra palaeochannel (e.g. Shitaoka et al., 2012; Durcan et al., 2019) and ten new OSL ages presented in this study (Table 1). Figure 3c shows the integrated results of *AI* analysis generated after combining all the Thar dune records included in Figure 3a and 3b.

The broadest accumulation peak falls within the late Pleistocene and early to middle Holocene period, extending from ~14 to ~6 ka based on >40 individual ages. The breadth of the peak in Figure 3a and 3c occurs as a result of the larger age uncertainties associated with the previously published ages, which are in the range ~ ±10-40 % (Table S3). The new and recently published OSL ages (this study; Srivastava et al., 2019a; Srivastava et al., 2019b) have lower uncertainties (less than ±10%), which when incorporated into the *AI* model results in a narrower accumulation peak (Figure 3b). Thomas and Bailey (2017) discuss this in their paper, commenting that as uncertainties increase, peak broadness increases and peaks become less refined (see Figure 4A, 4B of Thomas and Bailey, 2017). Regardless of the resolution, the early Holocene is a period of high aeolian accumulation in the Thar Desert.

In the middle to late Holocene, as shown in Figure 3b, peaks are centred at ~7, ~5 and ~3.5 ka. Interestingly, there are no peaks or secondary 'shoulders' observed between ~5 and ~3.5 ka despite the presence of six luminescence ages (Figure 1). It can be explained in the context of underlying principles of *AI* analysis as these six ages have been calculated from different sampling locations in the Thar and hence associated accumulation thickness cannot be calculated. Another important consideration is that due to nature of y axis resolution, sometimes minor rises may not be displayed unless magnified (e.g. southern Kalahari dunefield; Thomas and Bailey, 2017).

The late Holocene peaks are notably absent from the original analysis from dune database records (Figure 3a). Prior to the recent application of intensive sampling through full dune sediment profiles, studies tended to exclude the upper few metres of dune sediments from investigation, sampling deeper sections, and therefore potentially under-representing the late Holocene records. With the inclusion of new data in this *AI* analysis, strong peaks appear in the late Holocene centred around ~2 ka and ~1 ka, with the most nuanced one based on 14 ages representing the last two centuries. Unlike the early Holocene peaks, the late Holocene *AI* peaks increase in size due to younger ages having narrower one sigma error ranges (causing accumulation concentrated towards the central age) and probabilistic likelihood of better preservation of younger accumulation phases (Bailey and Thomas, 2014).



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278 **Figure 3. (a). Holocene AI plots for the Thar based on dune luminescence ages**

279 **first listed in INQUA dune atlas database (Lancaster et al., 2016). (b). based on**

recent studies (Shitaoka et al., 2012; Durcan et al., 2019; Srivastava et al., 2019a; Srivastava et al., 2019b; this study). (c). all combined.

3. Drivers of Thar landscape change during the Holocene

3.1 Early Holocene (~11.7 - ~8.2 ka)

As the Thar lies in a monsoonal regime, the ISM winds remain one of the major drivers of dune accumulation in the desert (Wasson et al., 1983; Kar, 1993; Singhvi and Kar, 2004; Srivastava et al., 2019a). As shown by the strongest peak in the AI plot (Figure 3) and >30 individual luminescence ages from dunefields (Figure 1), the Thar landscape experienced widespread dune accumulation during the early Holocene. At least 3 parabolic dune sites in the central Thar and 4 linear dune sites in the northern Thar have been shown to have recorded accumulation between 12.2 ± 0.8 ka and 8.7 ± 0.6 ka, with net dune accumulation up to 3.5 m per year (Srivastava et al. 2019a; Srivastava et al. 2019b). The new ages presented in this paper are also consistent with these published early Holocene records (Table 1). The basal ages from a parabolic dune near Jodhpur (Thar 16/2; Figure 1) date to 9.53 ± 0.87 ka (Thar 16/2/1) and 11.83 ± 0.93 ka (Thar 16/2/3). The samples investigated from another parabolic dune Thar 16/8 also display consistency and further give evidence of an early Holocene dune accumulation between 10.01 ± 0.70 ka (Thar 16/8/1) and 10.04 ± 0.85 ka (Thar 16/8/2). Dunes at the northern margin of the Thar, associated with the Ghaggar-Hakra palaeochannel system, also record early Holocene aeolian accumulation. Six samples from one such source-bordering dune in the northern Thar margin show a rapid ~16 m thick dune accumulation between 10.05 ± 0.76 ka and 10.51 ± 0.73 ka (site IND 14/5; Table 1). The shallower

samples at this site record dune activity at 7.28 ± 0.52 ka and 8.86 ± 0.66 ka at depths of 2 and 3 m (Table 1). Shitaoka et al. (2012) and Maemoku et al. (2012) dated sediments from nearby dunes to report accumulation between ~15-10 ka, however, the extent of accumulation cannot be compared because their studies are based on ≤ 2 samples from each dune. From the same area, Durcan et al. (2019), also used OSL dating to report aeolian accumulation dating to 8.93 ± 1.14 ka at 0.5 m and 8.89 ± 0.88 ka from uppermost 3.3 m of a dune in the same dunefield. Further to the north in the cold desert of Ladakh, Kumar et al. (2017) investigated five sand ramps using sedimentology and OSL dating and identified a phase of persistent high sedimentation rate between ~12 and ~8 ka. In the southern Thar, fluvial records from the Luni River suggest incision during this phase, which was followed by sheet flow aggradation between ~9 and ~5 ka (Jain and Tandon, 2003). Further south, records from the perennial Mahi and Sabarmati Rivers also indicate that these rivers incised during the early Holocene primarily governed by accelerated fluvial activity and large runoff as a response to enhanced ISM (Srivastava et al., 2001; Jain and Tandon, 2003; Jain et al., 2004).

The strong *Al* peaks, consistent with thick dune accumulation records from the Thar and beyond attest to a wider dynamic landscape response in the early Holocene. This period was marked by precessionally forced changes in insolation resulting in the intensification of the monsoon systems (Berger and Loutre, 1999; Wang et al., 2005), as evidenced in an array of terrestrial and marine proxies. In terrestrial records from north-western India, a $\delta^{18}\text{O}$ study conducted on ostracods from palaeolake Riwasa sediments (Figure 4) by Dixit et al. (2014b) showed that lake levels were high between ~9.4 and ~8.3 ka, in concurrence with the early Holocene monsoon strengthening. The other lakes in the Thar (notably Sambhar, Didwana,

Bap-Malar and Lunkaransar), however, show differences in the onset timings of fluctuations in levels and salinity throughout the Holocene (Figure 4). Lake level peaks do not directly correlate with the early Holocene ISM strength, as the high lake levels were reported to have occurred in the middle Holocene (Prasad and Enzel, 2006; Macdonald, 2011; Misra et al., 2019). Furthermore, Lake Sambhar in the eastern Thar does not record any evidence of complete desiccation (Sinha et al., 2006). These differences, which highlight the difficulties in considering individual lake records as representative of the regional picture, may be due to a multitude of reasons including differences in their geographic locations and groundwater discharges, resulting in different hydrological responses to rainfall changes as well as basin size, depth and morphology (e.g. Bowler, 1986); differences in the proxy records analysed in individual studies resulting in diverse interpretations (e.g. Burrough and Thomas, 2009); differences in employed dating methods and interpretive resolutions (e.g. Cohen, 2003) and finally the additional possibility of winter rainfall also contributing to the hydrology of some of the basins (Enzel et al., 1999; Prasad and Enzel, 2006).

The published Holocene speleothem records are scarce within the peripheral domain of the ISM in the Indian subcontinent and do not often cover the entire Holocene period (e.g. Yadava and Ramesh, 1999; Dixit and Tandon, 2016; Kaushal et al., 2018; Band et al., 2018 and references therein). Nevertheless, more negative $\delta^{18}\text{O}$ values reported from speleothem records in the Mawmluh Cave, north-eastern India suggest an enhanced ISM precipitation in the early Holocene (Berkelhammer et al., 2015; Dutt et al., 2015). The other high-resolution $\delta^{18}\text{O}$ records from speleothems in Oman also indicate a rapid increase in ISM strength between ~ 10.6 and ~ 9.7 ka in southern Oman (Qunf and Defore Caves) and between ~ 10.1 and ~ 9.2 ka in

northern Oman (Hoti Cave) (Figure 4; Fleitmann et al., 2003; Fleitmann et al., 2007) which is consistent with widespread early Holocene dune accumulation in the Thar. Holocene ISM variability has been inferred from the Arabian Sea sedimentary records as the region experiences upwelling driven by this monsoon system. Gupta et al. (2003) presented a high-resolution foraminifer (*Globigerina bulloides*) productivity record of wind strength from a core off the coast of Oman (ODP- 723). This suggested an early Holocene strengthening of the ISM marked by discrete weak intervals (Figure 4). Another productivity record based on *Neogloboquadrina dutertrei* from south-western Arabia Sea core NIOP-905 also shows broad consistency with Gupta et al. (2003)'s observations (Ivanochko et al., 2005). Staubwasser et al. (2002) presented a record of the Indus River discharge using *Globigerinoides ruber* $\delta^{18}\text{O}$ from core 63KA/41KL off Pakistan, and suggested strengthening of the ISM between ~12 and 11 ka BP with maximum Indus water discharge at ~9.4 ka. Gill et al. (2017) hypothesised teleconnections from the Pacific and based on sea surface temperature proxies from 27 locations scattered across the equatorial Pacific revealed the greatest ISM wind stress curl during this period. The correlation between upwelling and wind strength proxies from the Arabian Sea and enhanced phases of dune accumulation thus most likely suggest an in-phase relationship between general intensification of the ISM and dune accumulation in the early Holocene.

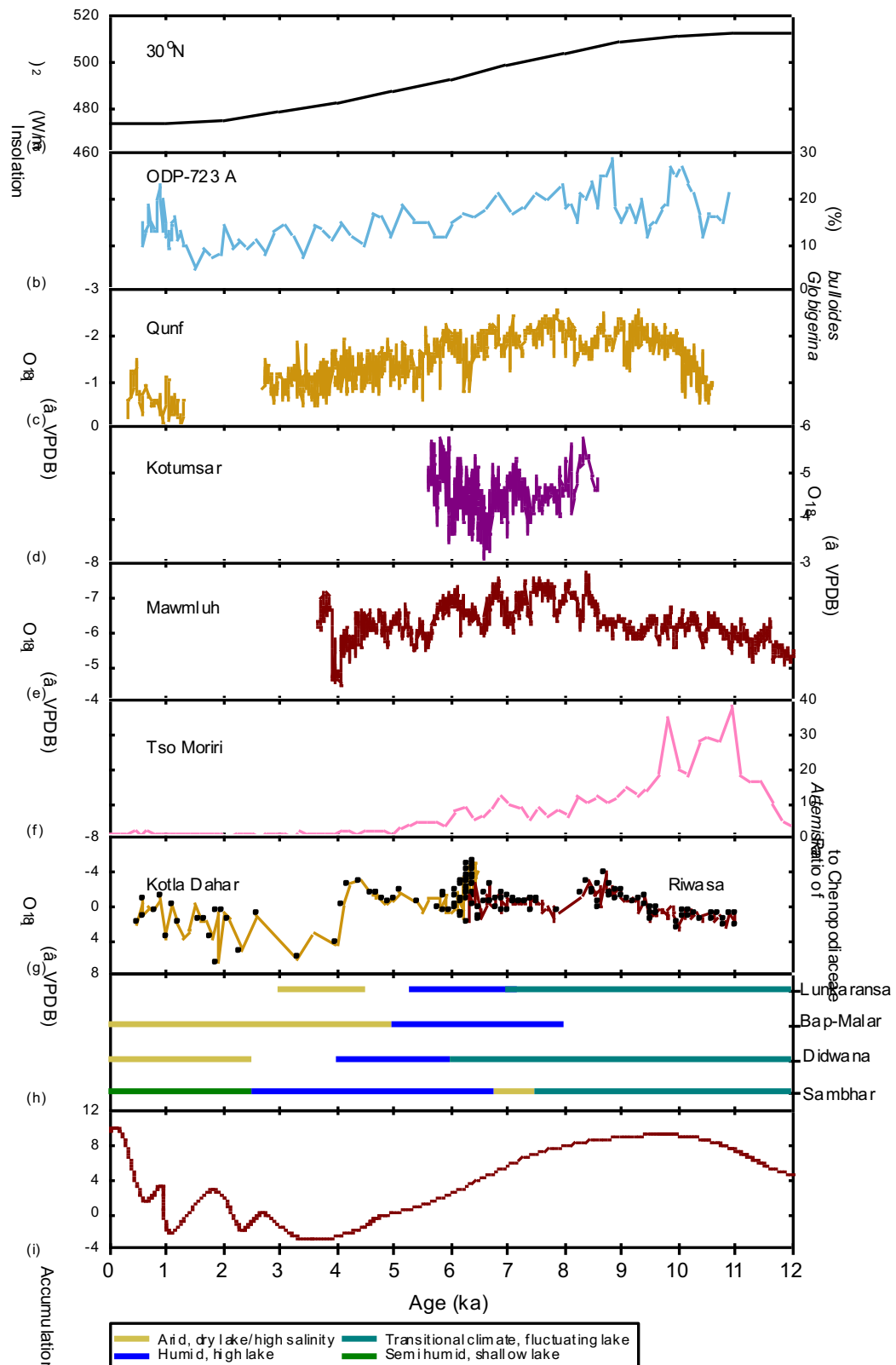


Figure 4. (a). Summer insolation (W/m^2) at 30°N (from Berger and Loutre, 1999).

(b). *G. bulloides* percentage from a marine core ODP-723A off Oman (Gupta et

al., 2003). (c). $\delta^{18}\text{O}$ record (‰ Vienna Peedee belemnite; VPDB) from a stalagmite in the Qunf Cave, southern Oman (Fleitmann et al., 2003). (d). $\delta^{18}\text{O}$ record (‰ VPDB) from the Kotumsar Cave, central India (Band et al., 2018). (e). $\delta^{18}\text{O}$ record (‰ VPDB) from the Mawmluh Cave, north-eastern India (Berkelhammer et al., 2012). (f) pollen percentage ratio of *Artemisia* to *Chenopodiaceae* (A/C) from Tso Moriri (Leipe et al., 2014) (g). Gastropod $\delta^{18}\text{O}$ record (‰ VPDB) from palaeolakes Kotla Dahar (Dixit et al., 2014a) and Riwasa (Dixit et al., 2014b). (h) Schematic representation of Holocene palaeolimnological history of four inland lakes in the Thar (Wasson et al., 1984; Kajale and Deotare, 1997; Deotare et al., 1998; Enzel et al., 1999; Sinha et al., 2006); (i) Summary *AI* curve for the Thar dune records as analysed in this study.

3.2 Middle Holocene (~8 - ~4.2 ka)

The middle Holocene, in contrast to the early Holocene, has fewer records of dune accumulation which come from scattered sites. In the *AI* plots, this period has therefore fewer and more minor peaks (Figure 3c). As shown in Figure 1b there is a relative lull in recorded dune accumulation between ~8.5 ka and ~7 ka in the northern and central Thar, although there are luminescence ages from dune sites in the southern Thar that show evidence of dune accumulation (Singhvi and Kar, 2004). Juyal et al. (2003) associated southern Thar dune activity with the availability of sediment from a large alluvial plain of regional rivers, notably the Mahi and the Sabarmati, in combination with lower sea-levels, increasing sediment availability to the wind, resulting in source-proximal dune accumulation despite the weaker ISM.

402 Several high-resolution records have suggested variability in ISM strength during the
403 middle Holocene (Gupta et al., 2003; Wang et al., 2005; Dixit et al., 2014a). Based
404 on stalagmite $\delta^{18}\text{O}$ records from the Kotumsar Cave in central India, Band et al.
405 (2018) showed that the intensity of ISM gradually declined between ~8.5 ka and ~6.5
406 ka, which was followed by a steady increase between ~6.3 and ~5.6 ka (Figure 4).
407 The brief period of re-intensification can also be observed in $\delta^{18}\text{O}$ records from other
408 Qunf and Mawmluh Caves (Fleitmann et al., 2003; Berkelhammer et al., 2012;
409 Figure 4). There are two dune sites in the northern (Jamsar) and central (Jodhpur)
410 Thar where dune accumulation was recorded in this phase, as reflected in the form
411 of minor *Al* peak in Figure 3b. Other geochemical records indicate further weakening
412 of the ISM after ~5 ka as evidenced from high $\delta^{18}\text{O}$ values in Kotla Dahar palaeolake
413 along the northern Thar margin (Dixit et al., 2014a; Figure 4), low *Artemisia* to
414 *Chenopodiaceae* pollen ratios from Tso Moriri Lake in northern India (Leipe et al.,
415 2014; Figure 4) and higher $\delta^{18}\text{O}$ values in speleothem record from Mawmluh in
416 north-eastern India (Berkelhammer et al., 2012; Figure 4). Despite a relatively
417 weaker ISM, dune accumulation is recorded along the Thar's north-eastern fringe
418 during the middle Holocene, coincident with enhanced fluvial activity. Saini and
419 Mujtaba (2010) and Durcan et al. (2019) dated silty sand fluvial sediments from the
420 Ghaggar-Hakra palaeochannel and reported fluvial deposition during this phase
421 which continued to ~4 ka. Multiple source bordering dunes in the vicinity, also
422 recorded dune activity (Shitaoka et al., 2012; Maemuku et al., 2012). Durcan et al.
423 (2019) suggested this concurrence of dune and fluvial activity to be related to
424 changing hydrological conditions of the palaeochannel, with the drying of the fluvial
425 system resulting an increase of sediment supply available for entrainment. They
426 hypothesised that dune accumulations on the floodplain of the Ghaggar-Hakra

channel are sourced from reworking of the fluvial sediments. Similar co-occurrence has been shown in the context of landscape dynamics near Cooper Creek in the Lake Eyre basin in central Australia where dune activity on the floodplain has direct sediment influx from the fluvial system (Cohen et al., 2010; Maroulis et al., 2007). Based on these data, it is evident that dune accumulation occurred over a large area of the Thar Desert and its margins during the middle Holocene, attributable to enhanced sediment supply from ephemeral fluvial channels set against the backdrop of a weakening ISM. Further the coeval fluvial activity records suggest that during the middle to late Holocene, the landscape along the Ghaggar-Hakra palaeochannel possibly acquired a state of balance, which Li and Coulthard (2015) describe as a geomorphic setting where both fluvial and aeolian processes operate together.

The middle Holocene palaeolimnological histories of the Thar lakes have often been compared with the timing of dune accumulation to test a potential relationship. For instance, Thomas et al. (1999) studied a palaeolake in the northern Thar (near Jamsar) and hypothesised antiphase behaviour between dune accumulation and lake aridity at ~5 ka that during a period of relatively increased aridity, lake dried up which facilitated sand mobilisation. Prasad and Enzel (2006) also compared the middle Holocene 'dune formation' episodes in the southern Thar with aridity records from nearby lakes and suggested further analyses of the available regional climate record. However, establishing any such relationship requires careful assessment of each geomorphic system individually and their response to external factors. For example, lakes that are groundwater or distant-catchment fed could be wet in locations where dunes are also active (accumulating), as the forcing factors (local wind /aridity, distant moisture source) do not conflict as evidenced in the case of dunes and lakes in Badain Jaran Desert, Inner Mongolia, China (Yang et al., 2003;

Yang et al., 2010). Further, dunes can be active, and lakes wet over annual/decadal cycles in regions with strongly seasonal climates, which is a characteristic of monsoon environments such as the Thar. For instance, when Lake Bap-Malar recorded high levels between ~8 ka and ~5 ka (Kajale and Deotare, 1997) (Figure 4), parabolic dunes in the nearby dunefield (Srivastava et al., 2019b) were also accumulating during the period. Therefore, a complex, nonlinear relationship should be expected between lake hydrological changes and dune records.

3.3 Late Holocene (~4.2 ka - ~present)

In the late Holocene, two minor peaks are observed between ~3.5 ka and ~1.5 ka (Figure 3c), calculated from dune records from the central and northern dunefields. Late Holocene dune records, however, remain scarce from the southern Thar (Figure 1), with only 2 of the 18 luminescence ages from this area recording late Holocene accumulation (Figure 1b). As the *AI* method focusses on the time period in which sediments accumulated rather than treating individual ages as discrete dune activity phases (Thomas and Bailey, 2017), peaks between ~3.5 and ~1.5 ka suggest the beginning of a phase of accumulation instead of an activity phase. Interestingly, the late Holocene, due to weakening of the ISM and reduced monsoonal precipitation, represented a phase of pronounced aridity in the Thar. Jain and Tandon (2003) and Jain et al. (2004), based on sedimentological analyses and luminescence dating, suggested that the streams of rivers in the southern Thar became defunct. Several lakes in the Thar like the Bap-Malar, Didwana, Lunkaransar also showed high salinity levels or dried up during this phase (Wasson et al., 1984; Singh et al., 1990; Kajale and Deotare, 1997; Deotare, 1998; Enzel et al.,

1999). Whilst the records of dune accumulation in the backdrop of weakening ISM are sparse, the drying lakes and river sources acted as potential local sources of sediment supply, and hence the *AI* peaks appear, even during a period of weakened ISM intensity.

In Figure 3c, two *AI* peaks are observed: one centred around ~1 ka and the other representing the recent century. In the last millennium, based on $\delta^{18}\text{O}$ values from a speleothem from the Wah Shikar Cave in north-eastern India, it has been suggested that ISM strength was variable, and coincided with intervals of droughts in the subcontinent (Gupta et al., 2019). Other speleothem studies from the Dandak and Jhumar Caves in central India (Sinha et al. 2007; Sinha et al., 2011a; Sinha et al., 2011b; Berkelhammer et al., 2010) also reported weaker ISM conditions attributable to drought conditions across large part of the country. In the Thar, there is recurring evidence from different dune sites of continuous dune activity coinciding with some of the historically reported long droughts. These droughts during 1255-1258, 1309-1313, 1868-1870, 1899-1905 and 1935-39 have been attributed to weak and erratic summer monsoons (Sharma 1966; Narain and Kar, 2005). The relationship between drought events with dune activity has been investigated in some details in the context of dunefields in the Kalahari (Thomas and Leason, 2005; Thomas and Burrough, 2012) and the Nebraska Sandhills (Miao et al., 2007; Hanson et al., 2009; Buckland et al., 2019) to demonstrate geomorphological consequences in the landscape. It could be hypothesised that during drought events, vegetation covers on dunes and groundwater levels fell affecting the stability of dunes and exposing their surfaces to reactivation.

While a strengthening of the ISM in recent centuries has been suggested based on marine productivity records (e.g. Anderson et al., 2002; Anderson et al., 2010) and

speleothem geochemistry from the Indian subcontinent (e.g. Gupta et al., 2019; Sinha et al., 2011a), Gill et al. (2017) suggest that precipitation over northwest India today is approximately 40% lower when compared to Early Holocene levels.. Instrumental meteorological data collection began during the mid-19th century in the Thar Desert, and shows that fluctuations in rainfall inter-annually, but no long term increase or decrease (Sontakke et al., 1993; Parthasarathy et al., 1994). From field observations made throughout the year, Singhvi and Kar (2004) observed increased levels of sand mobility in areas of significant human pressure, which they suggested to be greater now than during the Late Quaternary period. This is seen in the strong *Al* peaks in Figure 3c, which are comparable to the pronounced early Holocene *Al* peaks, and are more likely to be the result of significant anthropogenic disturbances in the Thar landscape. Since the subcontinent's independence seventy years ago, the human population has seen a four-fold rise in the Thar as land reforms and the construction of irrigation canals has increased access and agricultural potential (Kar et al., 2014; Dhir, 2018). Today, the population density of the Thar is over 100 people/km² which surpasses not just other arid but many temperate regions too. Increased livestock grazing, mechanised ploughing on dune slopes and excessive groundwater pumping have all led to a significant deterioration in vegetation cover and dune reactivation. Srivastava et al. (2019b) have shown that sensitive parabolic dunes in the central Thar have recorded accumulation rates up to 5 m per year in the recent century. Similar cases of anthropogenic drivers of dune activity have also been observed in semi-arid regions of China (e.g. Yang et al., 2011; Xu et al., 2019; Zhang and Huisingh, 2018) and the Negev (Tsoar, 2008; Roskin et al., 2013).

4. Conclusions

There are now more than 100 Holocene luminescence ages calculated from dunes in the Thar Desert. This new *AI* analysis identifies multiple peaks of dune accumulation, notably between ~12–~8 ka, and centred around ~7, ~5 and ~3.5 ka. The strongest peaks are observed in recent centuries. The widespread early Holocene dune accumulation is most likely to have occurred as a response to the period of strengthened ISM that is recorded in the other proxies from the subcontinent and beyond (e.g. Gupta et al., 2003; Fleitmann et al., 2003; Gill et al., 2017). During the middle to late Holocene, when the ISM started to weaken gradually, sediment supply facilitated by drying river channels in the northern Thar, and anthropogenic disturbances in the central Thar have been significant drivers of dune activity (e.g. Durcan et al., 2019; Srivastava et al., 2019b). The dune ages cannot be translated simply to derive palaeoclimatic interpretation as they display a nonlinear and complex relationship with rainfall and aridity, much like the dune records from the Kalahari (Chase, 2009), the Arabia (Atkinson et al., 2011; Leighton et al., 2014) and the Negev (Roskin et al., 2011). Thar fluvial and lacustrine records also present a picture of dynamic yet divergent responses to drivers during the Holocene. Along the northern margin of the Thar, the Ghaggar-Hakra system shows a concurrence of fluvial and dune activities during the middle to late Holocene. The lake records from the Thar also show complex relationships with ISM variations, and it is therefore unsurprising that dune accumulation periods do not necessarily relate to lake low phases. These complex geomorphic responses over time in the Thar, and the lack of clear correlations between both lake/dune dynamics and ISM changes inferred from marine records, indicates that landscape dynamics are likely driven by the complex interplay of regional and more local drivers.

This study with the application of *AI* analysis, has allowed an enhanced recognition of the complexity of landscape development in the Holocene. However, there still remain challenges in constructing a holistic picture of landscape dynamics as the Thar is under-sampled spatially and temporally with few intensive dunefield based studies. Being an extensive desert with many distinct dune types, further dunefield based studies are needed to represent the complexity of geomorphic evolution of the Thar landscape through time.

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