

# Analysis of Late Quaternary dunefield development in Asia using the Accumulation Intensity model

## Abstract

Asia possesses many extensive desert dune systems within the northern hemisphere subtropical belt and more northerly continental drylands. Collectively these may preserve important sedimentary records of dune system responses to climatic and environmental changes in the Quaternary period. We use the Accumulation Intensity (*AI*) methodology, which quantifies dune accumulation using luminescence-dated sedimentary records, to provide the first composite and comparable analysis of Asian dune system development in the Late Quaternary. The INQUA dune atlas database contains 826 age records for Asian dune systems, of which 284 meet the criteria for *AI* analysis. These are from the Negev, Rub' al Khali, Thar and Hunshandake dunefields, and provide dune accumulation records of up to 150ka. The majority of accumulation peaks occur within the late glacial to early Holocene (c20-10ka) and in the late Holocene, but with limited coincidence in the timing of peaks between dune systems, such that coeval dune accumulation drivers are not proposed. However, some important data gaps are identified, and presently robust accumulation histories are only achievable for the Negev and eastern Rub' al Khali.

## Key words

Dune accumulation; Accumulation Intensity; Asia, dunefields; Quaternary

## Introduction

The application of luminescence dating to aeolian sediments has revolutionised the analysis of desert dune system development during the Quaternary Period. Since Thermoluminescence (TL) dating was applied to eight dune samples from archaeological contexts at Amarpura, Langhnaj and Bagor in the Thar Desert India, by Singhvi *et al.* (1982), at least 724 original research papers in international peer-reviewed journals have been published that use TL or Optically Stimulated Luminescence (OSL) dating to produce chronologies of dune development, in continental and coastal contexts, over  $10^5$ - $10^2$  timescales (Thomas 2013; updated using Scopus records to December 2018). This averages 60-70 outputs a year in the last decade, with several thousand luminescence ages from dune sediments being published.

It is in continental desert dune systems that luminescence dating has had its greatest impact. Prior to TL/OSL applications to quartz and feldspar grains from dune sands, the common absence of materials on which to apply other radiometric dating methods to has limited the generation of robust chronologies of landscape change and sediment accumulation. Arguably the use of

luminescence dating has ‘transformed the science of deserts and drylands [necessitating] a revision of conventional interpretations of sedimentary records and stratigraphic correlations’ (Singhvi and Porat 2008: 536). This has turned palaeoenvironmental investigations in these areas ‘from a qualitative science to a quantitative one’ (*ibid*).

Numerical analysis of age records has led to the testing, and abandonment, of global models of desert dune development (Thomas and Bailey, 2017). Luminescence dating of desert dunes sediments has provided the means to recognise temporally-complex dunefield accumulation records and multi-phase constructional histories within regional dune systems (Singhvi and Porat, 2008; Thomas and Burrough, 2012). Luminescence ages have also been employed in studies of long-term dune dynamics, extending the temporal range over which dune behaviour can be monitored from the seconds-to-weeks timescales of process studies to centuries (e.g. Bristow *et al.*, 2005). More recently, new developments in field sampling and data processing are allowing interim, decade-to-century aspects of aeolian landscape responses to external forcing to be explored through luminescence age data (Buckland *et al.*, 2018).

#### *Issues in interpreting desert dune system age records*

While the widespread application of luminescence dating to dune sediments has boosted the quantitative dimension of dunefield Quaternary studies over the past four decades, this has not been without analytical difficulties (Hesse 2016). Aside from technical issues with the dating protocols themselves, there are at least five major uncertainties that have emerged in the literature.

First is the impact that sampling can have on the ages that are produced. Sampling-dependency simply means that the ‘true’ dune record is aliased by the choice of sampling location (both in vertical and horizontal dimensions) in a dune body. What is *not* sampled will also contain an undetected age record, well-illustrated by Stone and Thomas (2008) and Leighton *et al.* (2013a, 2014a). Second is a potential to over-sample the younger (but perhaps not the very youngest: Hesse, 2016) and more readily preserved and easily accessible sedimentary units in dunes - the so-called ‘Sadler effect’ (Sadler, 1981) - at the cost of underrepresenting older units. Sediments deposited in older accumulation events may in turn have been reworked, in part if not totally, by subsequent aeolian episodes and thus form a small component of the total preserved dune body (Bailey and Thomas, 2014). The use of probability density function graphs to present age data may add to the problem of misrepresentation as these graphics are not independent of sampling issues (Galbraith, 1998). Third are debates regarding whether dune systems actually preserve records of exogenic (e.g. climatic) forcing or whether sedimentation is dominated by autogenic (internal system) drivers (Jerolmack *et al.*, 2012). Recently evaluated by Thomas and Bailey (2017), there is good evidence for the preservation of exogenic signals where the sediments of extensive continental dune systems are concerned. Fourth, taphonomic effects mean that not all older deposits are preserved, as deposited sediments can be removed in subsequent dune activity events or periods (Bailey and Thomas, 2014). Finally, even with age control, the palaeoclimatic interpretation of dune records is complex and aeolian sediment accumulation cannot simply be ascribed to drier conditions in the past, as changes in windiness and sediment supply also contribute significantly to aeolian activity and aeolian deposition (Chase, 2009).

#### *Improving the use of dune system age records*

Collectively the issues above suggest that the potential of dune age records to contribute to Quaternary research has not always been achieved. While a luminescence dating revolution has occurred in terms of the application of dating to continental dune sediments, it has not always been matched by an increase in the widespread incorporation of dune records in regional palaeo-environmental and palaeoclimatic analyses. This has at least partially been a consequence of the ages themselves been treated *a priori* as a proxy record rather than being clearly associated with a sedimentological or stratigraphical aspect of the dune record that can be linked to aspects of past environmental and climatic conditions.

Taking the quantitative approach to understanding dated dune stratigraphies of Bailey and Thomas (2014), a numerical model has been developed to utilise chronometric and sedimentological data from individual dunefields to generate 'Accumulation Intensity' (AI) records of dunefield sediment accumulation through time (Thomas and Bailey, 2017). In this paper we apply the AI methodology to dune age records from Asian dune systems (Figure 1), allowing for the first time both a systematic analysis and comparison of the timing of dune accumulation through the continent's drylands and an assessment of the quality of regional data sets. We focus on dune age records from four dryland contexts that fall within the northern hemisphere subtropical belt: the Thar Desert in India, where luminescence dating was first applied to dune deposits (Singhvi *et al.* 1982), from Arabia, where Leighton *et al.* (2014b) developed an earlier age-based accumulation model, from the Negev Desert which possesses a unique suite of full-dune profile dated records (Roskin *et al.*, 2011a), and from China, where there is a rapid and significant growth in the application of luminescence dating to dune deposits.

[Figure 1 around here](#)

## Methodology and data

The Accumulation Rate Variability Model (ARV: Bailey and Thomas, 2014) was developed to capture the integrated effects of the stochastic and climate drivers of aeolian dune sedimentation, and the filters that affect sediment preservation. The model is relevant mostly to linear dune accumulation, since these are both the most common desert dune type worldwide (Lancaster 1982) and have the propensity, compared to more mobile (migratory) dune forms to store sediment (Thomas and Shaw, 1991), and therefore to capture a history of dune accumulation events. ARV was run with various environmental scenarios to simulate the effects of long term changes in aeolian dynamism on subsequent deposition, preservation and erosion on dune sedimentary bodies, which are the source of sediments for dating. The revised AI model (Thomas and Bailey, 2017) was expressly developed to allow temporal changes in dune accumulation to be calculated through time from empirical data, in a manner independent of the number of samples included in an analysis, but representative of changes in accumulation rates present within a dataset. The method can be applied to records integrated over a landscape scale, i.e. data collected from within a dunefield rather than simply from studies of individual dunes.

To do this, published luminescence age records are collated for a dunefield, along with associated data on sampling depths. AI integrates the central ages and one sigma errors (the dating uncertainty) of luminescence ages, and associated stratigraphic depth data from the sedimentary

profiles sampled for dating, to calculate the temporal variability of accumulation represented in the total dunefield age data set. To be included in a dunefield *AI* analysis, age data must be derived from sampled dune profiles or sediment cores, with a requirement of a minimum of two ages from each profile and depth data for each sample, so that the thickness of sediment between samples points in a profile (called ‘accumulation intervals’) can be calculated. Therefore, *AI* analysis excludes published ages that are single ‘spot’ samples, since the apparent accumulation rate cannot be determined, or that lack other data including the sampling location and the one sigma statistical error associated with the central age. The *AI* model was applied to the extensively dated dune systems of southern Africa and Australia, allowing for the first time the effective comparison of Late Quaternary dune accumulation records with other proxy data records, including those of potential dune activity forcing factors. The method is detailed in Thomas and Bailey (2017).

#### *Data source*

The INQUA dune atlas database (<https://www.dri.edu/inquaduneatlas>) project collated all published age records from desert dunes, incorporating key data on sampling location, dune type, sampling depth, the age method applied, final ages and one sigma errors, and other georeferenced data, including links to the original source literature (Lancaster *et al.* 2016). On initial publication this open-source database contained 3948 individual dune luminescence age records. This includes 155 dune age records from India, 253 from Arabia, 194 from the Negev and 311 from Chinese dunefields. Data were then filtered to ensure the requirements for *AI* analysis were met: 1) records from accumulatory dune forms or equivalent contexts (linear dune, parabolic dune and sand sheet records were retained); 2) records with central age and one sigma error data included; 3) records from profiles or cores that report sampling depth data. To provide a sufficient volume of data, a minimum number of 30 accumulation intervals was set for subsequent inclusion in the analyses. Table 1 provides summary data for each dunefield included in the subsequent analysis, with the records incorporated in the analysis described in detail in the respective sections that follow.

**Table 1. Dune age data for Asian dunefields in INQUA dune age database**

Dunefield/region	No. of ages in database	No. of linear dune, parabolic dune, sandsheet ages with relevant strat. context & depth data	No. of Accumulation intervals	Included in analysis?
Negev Desert <sup>a</sup> , Israel	97	61	42	y
Rub’ al Khali, Arabia	253	102	89	y
Thar Desert, India	145	73	59	y
China:	331, <i>including:</i>			
Taklamaklan	20	7	4	n
Badain Jaran	19	7	4	n
Wuhlanbuhe	19	12	8	n
Horqin	70	34	26 <sup>b</sup>	n
Hunshandake	62	48	34	y
Qaidam, Tibet	53	18	11	n

<sup>a</sup> In the INQUA dune database Negev records are included within a wider Eastern Mediterranean grouping.

<sup>b</sup> Though almost meeting the minimum 30 interval threshold, most ages are in fact 20<sup>th</sup> century and derived from very shallow sampling.

## Negev

[Figure 2 around here](#)

We focus first on the age record from the Negev Desert, Israel. This relatively small dunefield of c.1300km<sup>2</sup> forms the NW part of the Sinai-Negev complex at the eastern end of the Mediterranean basin. The dunefield is dominated by low linear dunes up to c15 m high that, despite regional aridity (150-80mm mean annual rainfall pa) are largely inactive today unless disturbed due to the presence of biogenic crusts and a partial vegetation cover (Tsoar et al., 2008). The first luminescence ages from the system were derived from the application of TL to nine samples from two sites in the northern part of the dunefield (Rendell et al., 1993). The Negev accumulation record has subsequently benefited from a detailed OSL-based chronometric analysis by (Roskin et al., 2011a). Development of the dunefield has been interpreted to have resulted from several 'incursion phases' from western coastal sources, including three corridors of accumulation from north to south (Figure 2; Roskin et al. 2011a).

Our reanalysis of Quaternary dune accumulation in the Negev focusses on the Roskin et al. (2011a) data set for several reasons. First is that the Roskin *et al.* study employed extensive spatial coverage from 34 locations through the dune system, including records from all three accumulation corridors. Second is that in the main the record is derived from full-dune profile sampling sites, including from immediately above basal non-aeolian sediments (Figure 2), reducing any potential bias in the record towards younger deposits. Together these factors provide a third reason: an opportunity to compare directly the results of our AI analysis with the presentation and interpretation of data by Roskin et al. (2011a), who utilise relative probability (probability density) graphs. While the use of this presentational approach has been criticised in the context of its application to dunefield age data sets (see Thomas and Burrough 2012, 2016 and Hesse 2016 for discussion of partial sampling of aeolian sedimentary records and age data presentation methods), there is arguably little sampling bias in the data-rich Negev age record of Roskin et al. (2011a). This comparison in turn provides an independent test of the utility of the AI methodology.

Roskin et al. (2011a) include ages from transverse dunes that have formed in interdune areas between linear ridges in some parts of the Negev, and samples from sedimentary units beneath linear dune ridges including fluvial loam. These records were removed from the total of 97 OSL ages, though ages from quartz sand regarded as aeolian but within palaeosol units were retained. In total therefore our analysis focuses on ages derived from linear sand dune bodies and the lower aeolian sands preserved at some interdune sample sites. This resulted in 61 OSL ages with associated sample depth data, leading to the generation of 42 dated accumulation intervals, being included in the AI analysis (Table 1).

Figure 3 around here.

The Negev dune accumulation intensity (*AI*) plot for the full dataset, is shown in Figure 3, along with the relative probability plot of Roskin et al. (2011a) derived from the same underlying OSL age data. The record for the last 30ka through to the Holocene is shown in detail in Figure 3b. The overall record shows an accumulation peak at 14-15 ka and within the last 2ka. The post-30ka record accords well with the probability plots of Roskin et al. (2011a) in terms of identifying the principal times of dune accumulation, though the minor peak at c3ka that Roskin *et al.* (2011a) identified is not present in the *AI* curve. We can explain the 'missing' 3ka peak from the *AI* plot relative to the probability plots as a function of two aspects of the manner in which the latter are produced. First is that probability plots over-emphasise times recorded by multiple age records – i.e. the 3ka peak in Roskin *et al.* is influenced by the occurrence of four ages with small one sigma errors (samples NS1, 3.2 +/-0.5 ka; NS5, 2.9+/-0.4ka; DF75, 3.0+/-0.6ka; ISR13, 3.4+/-0.2ka) that centre around 3ka. Second, probability plot treats ages themselves as proxy records, rather than as recording evidence of an actual environmental process (Thomas and Bailey, 2017). The *AI* method focuses on the period of time over which sediments have accumulated. In this case, the four ages falling around 3ka, each from a different location in the dunefield, mark the *beginning* of a period of dune accumulation, which is subsequently ended at each sampled location by a younger (upper) age. The *AI* analytical process interrogates the period over which the sediment accumulated, rather than treating each individual age as a significant (and discrete) time of dune activity. Hence c.3ka indicates the beginning of a phase of accumulation, not the peak of a phase of activity.

Figure 3 also shows three ages with errors at around 100ka in the original Roskin *et al.* (2011a) analysis, though these do not generate a peak in the probability density curve (Figure 3a, upper). The ages are from the lowest units of two vegetated linear dunes in the northern incursion corridor (Figure 2). Sample DF-308 at 6.9m depth records 116+/-116ka at site Haluzit 4, with the next sample in vertical succession, DF304 at 5.1m depth, recording 12.8+/-1.5ka. At the Haluzit 1 dune site, DF-85 at 8.5m records 108+/- 22ka and DF-83and 7.5m records 106+/-19ka. Above this at 6.8m, DF-81 dates to 15.5+/-2.2ka. Though recorded as ages from palaeosol units by Roskin *et al.* (2011), these lower samples are also referred to as being aeolian in origin. We have included these ages and their associated accumulation interval data in the *AI* analysis, which results in a shallow peak in the resultant curve (Figure 3a, lower). Roskin *et al.* (2011a) noted that 'field and geochronological evidence indicates that aeolian sands have existed in the Negev Desert at least since 100ka....however there is no evidence for dune remnants in the NW Negev earlier than 23ka' (p1668). The *AI* approach to age analysis demonstrates this from the existing data in a manner that the use of probability plots does not because of the large errors associated with the small number of older ages.

Figure 4 around here.

On the basis of the OSL age data Roskin et al. (2011a) proposed spatial differences in the timing of the main Late Quaternary aeolian sand incursion phases into the Negev region (Figure 4a), with initial incursion confined to the western part of the southern corridor at 23-20ka, the last glacial maximum, an expanded phase with a northwards extension into the central corridor at 19-17ka followed by dunefield-wide accumulation from 16-13.7ka. The eastern-most expansion of dune

development was confined to the central corridor between 12.4-11.6ka, while a late Holocene period of accumulation in western areas commenced around 2ka. Roskin *et al.* (2011b) associate the 16-13.7ka event with Heinrich Event 1 and the 12.4-11.6ka episode with the Younger Dryas. For both these phases they argue that although precipitation was increased, sand transport potential also rose because of the high wind strengths associated with the influence of winter westerly cyclonic systems.

In Figure 4 we plot the *AI* curves from the respective OSL age and depth data for the three Negev accumulation corridors. We can first note that by integrating accumulation thickness data and the one sigma errors of individual ages, the *AI* plots suggest little difference in southern and central corridor accumulation onset timing, but a likelihood that the central corridor was the focus of accumulation from the outset, rather than the process commencing in the more southerly corridor. Second, Roskin *et al.* (2011a) proposed 'several major and rapid [sand] incursion events' (p1668) from 16ka onwards. Our *AI* analysis suggests a modified interpretation. Rather than incursion events, a more persistent period of accumulation took place, lasting up to 6000 years from 16ka, but with its origins up to 10ka earlier in the central and southern corridors. Accumulation also peaks, and ceases, earlier in the north than in the central and south corridors, with the timing of peak accumulation at 14ka being 2ka later than the incursion peak of Roskin *et al.* (2011a). Our Late Holocene data agrees with Roskin *et al.*'s (2011a) interpretation, with post 2ka accumulation focussed on the central corridor.

## Arabia (Rub' al Khali)

### Figure 5 around here

Over 300 luminescence ages have been published from the dune systems of Arabia (Leighton *et al.*, 2014b), although the INQUA dune database contains 253 age records (Lancaster *et al.*, 2016). The majority of these are from the 560,000 km<sup>2</sup> (Wilson, 1973) Rub' al Khali, particularly its northeastern sector in the United Arab Emirates (UAE) (Figure 5), where dune sediments are likely to have been derived from the Arabian Sea basin during periods of lower sea level (Glennie, 1998). The relatively high CaCO<sub>3</sub> content of dated dune sands (Aitkinson *et al.*, 2012) is likely to be a consequence of the incorporation of marine shell material in these sediments. 70 ages in the dune atlas database come from the smaller (10,000km<sup>2</sup>) Wahiba Sands in Oman, including 33 and 20 TL ages respectively from two long drill cores up to 144m deep through accumulated aeolian deposits that overlie MIS 5e fluvial sediments. The aeolian deposits yield a 160ka record of accumulation (Pruesser *et al.*, 2002). This dataset is not reanalysed here given it is a record derived from two sites only. Other dunefields, including the 57,000km<sup>2</sup> An Nafud Desert in northern Saudi Arabia (Edgell, 2006), and the Ad Dahna which links to the Rub' Al Khali and An Nafud and in effect designates a contiguous Arabian dune system, are currently undated but contain areas of extensive linear ridges that may preserve longer term accumulation histories.

The Rub' Al Khali record includes 25 OSL ages from transverse dunes and 18 from associated sand sheet units at the Liwa Oasis (Stokes and Bray, 2005). The remainder of the published record has emerged primarily from the analysis of deep sand quarry pit exposures in the northern UAE (Atkinson *et al.*, 2011, 2012), Leighton *et al.*, 2013a&b, 2014 a&b). These have allowed access to the



internal sedimentary units of major southwest-northeast trending linear mega-ridges that are up to 70m high. These are in turn overlain by often-sinuuous, partially vegetated, secondary linear dunes up to 20m high and orientated NW-SE, parallel to the modern dominant wind direction. These have also been sampled, from pit exposures and auger cores (Atkinson *et al.*, 2012). Accumulation ages from upper mega-ridge deposits and the secondary linear features do not fall into distinct groupings but overlap, demonstrating coevolution and transport interactions in the accumulation of upper mega-ridge sediments, rather than development in distinct palaeoclimate phases (Atkinson *et al.*, 2012).

The total age data set from the northern UAE linear forms, which includes dates from earlier studies by Goudie *et al.* (2000), Parker *et al.*, 2004 and Parker and Goudie, 2007), comprises 102 OSL ages that generate 89 accumulation intervals (Table 1). These have provided a rich and stratigraphically-detailed data set that has been used to examine local and within-dune accumulation variability and the effects of sampling strategies on resultant chronologies (Leighton *et al.*, 2013a, 2014a). These studies in turn led to the development of a net accumulation rate model for interpreting dune age data (Leighton *et al.*, 2014a, b).

**Figure 6 around here.**

Figure 6a presents the *AI* curve produced for the UAE linear dune age and accumulation interval data for the last 30ka. This is compared with the previously published ‘minimum interval’ and ‘as sampled’ net accumulation rate outputs of Leighton *et al.* (2014b), generated from the same data set. Leighton *et al.* (2014a) were the first to consider a systematic approach to presenting and interpreting clusters of dune ages derived from proximal sites within a dunefield where sampling depth information was available, without relying on the frequency of sampled ages as the main mechanism for record interoperation. For each cluster of ages from adjacent sites, their approach took the difference in sampling depth between the uppermost and lowest samples in a spatial cluster, and divided this by the time difference between the oldest and youngest samples, to produce a net accumulation rate, in m/ka, for that location. The ‘as sampled’ or mean interval approach used the central ages of upper and lower samples. To take account of the one sigma errors of individual age calculations, the ‘minimum interval’ approach considered the minimum time interval accumulation could have taken place over by considering the youngest possible age of the upper sample (the mean age minus the one sigma error) and the maximum age of the lowest sample (the mean age plus the one sigma error) (see Leighton *et al.*, 2014a for a graphical representation of the procedures used).

Figure 6b and c respectively show the minimum interval and ‘as sampled’ net accumulation plots for Arabia of Leighton *et al.* (2014b). By clustering records from adjacent sites, the bar plots are presented for age clusters from individual locations (named in the legend) rather than providing a single dunefield record. The width of bars reflects the age span of clusters, with narrower bars representing shorter accumulation phases. By default, the minimum interval approach produces shorter phases compared to the ‘as sampled’ plots. While the temporal pattern of accumulation, and the peakedness of individual intervals of accumulation, are comparable between methods, the net accumulation rates (*y* axis) differ due to the different methods of determining the age span of each episode, which then acts as the denominator in the rate calculation.

In order to examine the potential forcing factors for dune accumulation, Leighton *et al.* (2014b) used the net accumulation graphs as a means to compare dune records with other regional



palaeoenvironmental proxies: marine core data for monsoon strength (Gupta *et al.*, 2003), speleothem records for rainfall (Neff *et al.*, 2001; Fleitmann *et al.*, 2007) and lake geochemical data for aridity (Preston *et al.*, 2012, 2015) as well as considerations of sediment supply changes linked to sea level changes in the Arabian Gulf. The focus of dune accumulation 16-9ka was attributed both the high sediment availability and monsoon-driven transport capacity, with anomalously low accumulation in the preceding late glacial seen as a function of high wind speeds limiting preservation. A wetter early and mid-Holocene, recorded in various proxies, coincides with an absence of recorded dune accumulation. Drier, relatively stable conditions post-6ka and through the late Holocene are represented by accumulation through the system but with site-to-site differences in preservation, that may also reflect sampling attributes.

The *AI* curve (Figure 6a) replicates the 30ka temporal pattern of dune accumulation of the Leighton *et al.* (2014b) analysis, but has the additional advantage of being able to integrate data from multiple sites in the Rub 'Al Khali linear dunefield and, as the *AI* methodology resamples from within the age errors of each pair of ages bracketing an accumulation interval (Thomas and Bailey, 2017), to probabilistically smooth the record of accumulation. The increase in the size of accumulation peaks as ages become younger is a combined function of the narrower one sigma error ranges (which focuses accumulation towards central ages), and the probabilistic likelihood of younger accumulation phases being preserved in sedimentary records (Sadler, 1981) as autogenic processes can affect the ability of dune deposits to preserve equally records of all activity phases (e.g. Kocurek and Lancaster, 1999).

### **Thar Desert**

The Thar or Rajasthan Desert extends over c.200,000km<sup>2</sup> of northern India, much covered by sand dunes. The Thar saw the first application of luminescence dating to sand dunes (Singhvi *et al.*, 1982) and has subsequently received the attention of several studies that include luminescence-derived chronometric data (Chawla *et al.*, 1992; Juyal *et al.*, 2006; Singhvi *et al.*, 1982, 1994; Thomas *et al.*, 1999). The dune landscape of the Thar contains a variety of dune forms that have been mapped in detail by Kar (1993). These include small areas of linear, transverse and star forms but over large areas the dominant dune type comprise 'rakes' of interlinked parabolic dunes, commonly ranging from 10m-30m in height, often with long linear-like arms and steep high, downwind noses. Potential sand transport today is associated with the southwest monsoon, though much of the Thar is well vegetated under natural conditions, with mean annual rainfall ranging from c200mm in the drier northwestern parts to over 500mm in wetter eastern areas. Singhvi and Porat (2008) note that the location of the Thar towards the eastern margin of the Sahara-Arabian desert belt gives rise to a high preservation potential for records of past aeolian activity.

In the INQUA dune atlas database, 145 luminescence ages are included for dunes in the Thar Desert, derived from the studies identified in Figure 5 and summarised in Singhvi and Kar (2004). All of these ages were the product of the now-rarely used multiple aliquot additive dose laboratory protocol, and a significant number are derived from TL dating of quartz grains or IRSL (infra-red) dating of feldspars from the sand bodies. The published age records are frequently from specific locations where only one sample for dating was collected, or which lack precise sampling depth data. Consequently the dataset suitable for application of the *AI* methodology is reduced to 73 ages that generate 59 accumulation intervals. Within this are included 15 ages from a 20m deep sand sheet pit

at Chamu (Singhvi and Kar, 2004), seven ages from a 7m deep pit in a parabolic dune at Dharoi in the southern Thar (Juyal *et al.*, 2003) and nine ages from a 16m parabolic dune at Khudala (Thomas *et al.*, 1999)

Figure 7 around here.

Figure 7a shows a 70ka record of dune luminescence ages from Singhvi and Porat (2008). This illustrates the difficulties of representing age records from multiple sites and the problems of including records that comprise a single age, which is the case for several of the narrow bars in the diagram. Wider bars are either derived from the upper and lower ages of a sequence, or in the case of older records, represent individual ages that have wide errors.

The *AI* curve, Figure 7b, shows that when depth data are included in the analysis along with suitable age data, two distinct peaks of accumulation can be clearly recognised in the Thar dataset. One is a broad peak extending from c 50ka to c 20ka, centred on c30ka, and the other at c10ka. The more subjective interpretation of Singhvi and Kar (2004) proposed accumulation phases at 115-110ka, c75ka, c55ka, c30ka and 13-11ka. They noted, following Wasson *et al.* (1983), that a suppressed monsoon in the late glacial limited aeolian sediment transport in the last 25ka until its reestablishment c 13ka.

There are insufficient data for the *AI* approach to identify either nuanced peaks of aeolian accumulation or episodes of dune accumulation earlier than 50-20ka. The broad accumulation episode within this 30 thousand year period, while this generalised peak is in itself a facet of a record that is populated by limited accumulation interval data. Juyal *et al.* (2006) noted the spatial disparities in dune age data in the Thar, with the most robust records derived from the southwestern part of the extensive dune system and resulting from dune building predicated by enhanced sediment supply from coastal areas attributable to lower sea levels. The strongest peak in the Thar Desert *AI* record commences in the Early Holocene. Singhvi and Porat (2008) report this as a c.2ka long period of dune building, with sporadic records of accumulation in the mid-Holocene (Figure 7a). By integrating records throughout dunefield, the *AI* analysis suggests a more continuous phase of dune accumulation from 13ka through to c5ka. Early Holocene dune accumulation has been widely associated with the high sand transport potential linked to the reestablishment of the southwestern monsoon.

### Chinese dunefields

The mid latitude desert belt of China between 36°N and 50°N (Figure 8), includes eleven sand seas with a total area of 566,000km<sup>2</sup> (Li and Yang, 2016). Six of these, the Taklamakan, Kumtag, Badain Jaran, Wulanbuhe and Kubuqi, possess active dunes in a variety of forms and are cold desert systems influenced by the Mongolian anticyclone (Yang *et al.*, 2012). The remainder, under the influence of the East Asia Monsoon, are largely vegetated to varying degrees and are regarded as largely inactive. These are sometimes referred to in the literature as 'sandylands' (e.g. Yang *et al.*, 2008). The locations of active and inactive sand seas is heavily influenced by sediment supply, and are closely associated with endoreic drainage systems supplying sand-sized material from the Tibetan Plateau and other mountain zones.

Figure 8 around here.

The INQUA dune atlas database contains 331 records from Chinese dune systems, the majority being OSL ages. In their review, Li and Yang (2016) note that ages have been generated from ten of the eleven dune systems, the exception being the Kumtag Desert. The Badain Jaran dunefield contains dunes up to 300m high with interdune lakes that together generate interbedded aeolian and lacustrine sequences (Yang and Williams, 2003), but to date chronometric data have been derived from only a small part of the system (Yang, 2004, 2006). The active Taklamakan Desert has also received relatively limited chronometric analysis, with only 20 published OSL ages (Yang *et al.*, 2006; Zhang *et al.*, 2011). Stabilised sandyland sediments have received more attention however, with 70 ages published from the Horqin Sandyland (Yang *et al.*, 2012) and 62 from Hunshandake (Li *et al.*, 2002; Mason *et al.*, 2008, 2009; Yang *et al.*, 2008, 2013).

When the requirements of *AI* analysis are considered, including dune type and especially the inclusion of known sampling depth data and a stratigraphic relationship between pairs of samples, the dune age dataset for China is further restricted. None of the presently active dune systems yield sufficient records for *AI* analyses to be undertaken. The Horqin Sandyland has 34 suitable ages, but these only generate 26 accumulation intervals, below the acceptance threshold, and many of these are derived from very shallow samples that generate ages within the last millennium (Yang *et al.*, 2012). Zhou *et al.*'s (2012) record from the linear dunes of the Qaidam basin, Tibet Plateau, provides an age dataset for the last 3ka, but despite comprising 53 OSL ages, only generates eleven accumulation intervals (Table 1).

**Figure 9 around here.**

The Hunshandake Sandyland, including the Otindag dunefield (the name used by Mason *et al.*, 2008, and entered in the INQUA database as Hunshandake by Li and Yang, 2016), is located in the eastern part of the desert belt (Figure 8). Within the database, 48 OSL ages generate 34 accumulation intervals for *AI* analysis. These sandsheet and parabolic dune ages incorporate six from Yang *et al.* (2008), 14 from Mason *et al.* (2008), 16 from Mason *et al.* (2009) and 12 from Yang *et al.* (2013). The *AI* plot, Figure 9, shows a disjointed record of accumulation from c 13ka onwards, with the most prominent peaks a c.10-9ka and notably in the Late Holocene. Minor accumulation peaks also occur in the record at c.12.5ka, 7ka and 4ka

The Hunshandake age record is relatively difficult to interpret environmentally (Li and Yang, 2016), while original data sources also include OSL ages from palaeosol units within aeolian sediments that are interpreted as evidence of landscape stability in the mid-Holocene (e.g. Mason *et al.*, 2009). There are also few aeolian accumulation ages prior to 13ka, with one age of 20.1+/- 0.8 ka reported by Yang *et al.*, 2013). The paucity of late glacial ages has been interpreted as a consequence of permafrost inhibiting sand transport during very cold but dry times (Li and Yang (2016) and to a weak monsoon (Lack of transport energy) by Mason *et al.* (2008). Several proxy sources point to a strengthening of monsoon conditions in the early Holocene (e.g. Wang *et al.*, 2005), leading to stronger winds but not increased precipitation over the eastern desert margin area, including Hunshandake (Mason *et al.*, 2008). Yang *et al.* (2013) suggest that the region was much wetter than today's semi-arid conditions between 9.6-3ka, driven by enhanced insolation. The *AI* record broadly concurs with this interpretation. Late Holocene activity may be associated with reduced monsoon precipitation in this sensitive threshold region and/or growing human pressures.

## Discussion

A major limitation on the inclusion of dune age data in integrated palaeoclimatic and palaeoenvironmental research has been the incapacity to analyse point age data, which incorporate one sigma errors, alongside other data sets that provide continuous records of change through time (Thomas and Burrough, 2016). As a result age plots have often appeared as bars (see e.g. Figure 7a), representing a cluster of central ages, or as plots of individual ages showing the central age and one sigma errors (see for example Thomas and Bailey, 2017, including their Figure 1, for discussion). In both cases, unless aeolian sediments are bracketed by other deposits, the luminescence ages themselves are treated as proxy records *per se*. For most thick aeolian deposits, for example those contained within a sand dune body, sedimentary units definitively attributable to other environmental processes or bracketing units, such as palaeosols, are commonly absent. The AI modelling approach, integrating central ages, age one sigma errors and stratigraphical data in the form of the thickness of sediment accumulated between two ages, provides a method that both overcomes the limitations of other age data presentation methods, and utilises information on the actual sedimentation process in dunes, to provide a method that allows the maximum palaeoenvironmental information to be gained from dated aeolian sequences (Thomas and Bailey, 2017).

#### *Data inclusion*

Inclusion of luminescence age records within the INQUA dune atlas database required several quality control considerations to be met (Lancaster *et al.*, 2016). These included being published in peer-reviewed sources, the presence of georeferenced spatial data to allow precise locations to be plotted, the inclusion data on sampling context and depth within the dune body, and at least basic information on age generation laboratory protocols. For the luminescence ages in the dune atlas database, we applied additional criteria to facilitate inclusion in our AI analysis. Only ages derived from accumulatory dune systems (primarily linear dunes, parabolic dunes and sand sheets) have been considered, with ages from more mobile/migratory features, such as transverse and barchan dunes, excluded because they have a lower likelihood of preserving sediments deposited from earlier accumulation events (see Bailey and Thomas, 2014). Additionally, ages only qualified for inclusion if they were generated from contexts where a minimum of two samples in vertical succession were dated, supported with accompanying sampling depth information. These parameters generate the accumulation interval data necessary for analysis in the AI model.

Implementing these requirements led to a significant body of published records being excluded from the study. For example, the dataset of ages for China is large, but many records represent single 'spot' samples, and frequently these are from upper, younger, dune sediments to the detriment of sampling deeper, older deposits (Li and Yang, 2016). In India, the locational data for some records are imprecise or differ from one publication to another, creating doubt of the locations from which ages were derived. While we recognise that the intentions of the original primary research that generated ages has undoubtedly varied from study to study, these and other factors have restricted the suitability of some dune atlas database ages for incorporation in this investigation. To this end, Table 1 indicates the number of ages that it has not been possible to use to contribute to the AI analysis in this investigation.

#### *Spatial distribution of records*

A key point that emerges from an Asia-wide assessment of dunefield development is the spatial unevenness of the age records available for conducting a continental-scale assessment and comparison of the timing, and causes, of dune building episodes. The Negev Desert is exceptionally well dated, both in terms of the spatial coverage of records through the dunefield and in the presence of multiple full-profile records that extend to the substrates lying beneath dunes. But this is a small dunefield relative to the other regions assessed here, and in itself is also part of the much more extensive Sinai-Negev system that extends west into Egypt and from where Negev dune sand has originated (Roskin *et al.*, 2011b).

The Rub' al Khali is well represented in the database in the sense that there is a large pool of age records, many of which are derived from profiles that, uncharacteristically when compared to other dunefield records, embrace deep profiles from very large linear dune ridges. These records, however, are in the main from a small part of this exceptionally extensive dunefield that covers a considerable swathe of southern-central Arabia. The dated component of the dune system is largely restricted to the more accessible northeastern part of a system which embraces less than 5% of this extensive sand sea. In all, other sand seas within Arabia are unrepresented within the total record, save for the Wahiba Sands, such that an Arabia-wide assessment of Quaternary dune development requires significantly larger spatial coverage than is currently available. Given the scale of the system, and the spatial variability in accumulation phases noted through the extensive Kalahari dune systems (Thomas and Bailey, 2017), we would anticipate a more complex Late Quaternary record of dune building to emerge should future records generate wider coverage, particularly if this extended to the linear dunefields in the southwestern 'Uruq ar Rumaylah (Breed and Grow, 1979) area of the Rub' al Khali. These spatial differences may have impacted on sediment supply for dune building (Garzanti *et al.*, 2013): while northeastern dune sands may have a marine origin (Glennie, 1998), those to the southwest may be derived from the basement rocks of the tectonic basin in which the dunefield sits (Besler, 1982; White *et al.*, 2001), though Garzanti *et al.* (2013) note that a degree of homogenisation has occurred through multiple transport and reworking over time. Modern wind regimes also differ through the extensive Rub' al Khali (Breed and Grow, 1979), reflecting differential influences of the southwesterly Indian Ocean summer monsoon and the winter shamal trade winds that arc in an clockwise direction over Arabia (Leighton *et al.*, 2014). Changes in monsoon dynamics, which were important for driving temporal and spatial variations in humidity (Parker *et al.*, 2006; Lezine *et al.*, 2010), can be postulated to have impacted on the spatial dynamics of dune accumulation including in regions as yet undated.

In contrast, at face value India's Thar Desert is represented by records that have wide spatial coverage through the system from south to north and east to west (Figure 5). However, only part the total dataset is suitable for application of the *AI* methodology due to the absence of paired, stratigraphically related, ages from many sampled and dated locations. As a consequence, 31 of the 73 ages that meet *AI* requirements are derived from only three locations, one of which is in the extreme south of the Thar (Jumal, *et al.*, 2006, site 8 on Figure 7) and two in the northern-central region (Thomas *et al.*, 1999, Singhvi and Kar, 2004) so that the resultant spatial coverage represented in the *AI* record is again relatively limited.

OSL ages have been produced from the majority of China's sand seas, but for many systems yielding ages, Li and Yang (2016) report limited spatial coverage and shallow sampling as common data attributes, often linked to issues of accessibility. While largely-stabilised sandylands are better-

dated, we have only been able to apply the *AI* approach to one, Hunshandake, because of issues of data suitability. In many respects it is loess records that dominate the aeolian Quaternary landscape of China, with Yang and Li (2016: 60) noting that ‘considering the extensive distribution of dunefields in north China, these chronologies are far from satisfactory for a thorough understanding of palaeoclimatology and Quaternary environmental changes’.

**Figure 10 around here. Record comparison**

Noting these limitations of spatial coverage, Figure 10 compares the *AI* plots for the four systems that we have been able to produce records for. For three of these, the accumulation intensity record extends back to 150ka, but with only small number of ages contributing to interpretations older than 50ka. The Hunshandake record from China does not extend back beyond 25ka. Actual *AI* values (the y axes in Figure 10) are not scaled and are a function of the attributes of the specific data set being analysed. While this might in some regards be a limitation with the methodology, as it does not facilitate inter-dune field accumulation comparisons of a quantitative nature, it also robustly illustrates the difficulties of calculating a meaningful parameter to express accumulation trends. This is well illustrated by the differing net accumulation rate values, in m/ka, that resulted from the two different applications of the Leighton *et al.* (2014b) net accumulation rate model. Given the sampling uncertainties associated with the production of all luminescence ages, a ‘true’ accumulation rate associated with a depositional phase will always be subject to issues of calculation-derived variability, with the *AI* methodology being a more appropriate means of interpreting data for comparative purposes.

The bulk of the sediments preserved in these dunefields result from late glacial to early Holocene accumulation. While sediment supply is a fundamental factor for dune building, it has not been regarded as a limiting control in either the Negev or (Roskin *et al.*, 2011b) or the northern Rub’ al Khali, (Leighton *et al.*, 2014b). Roskin *et al.* (2011b) link dune building events to strong winds during Heinrich Event 1 (16-13.7ka) and the Younger Dryas (12.4-11.6ka), the latter coinciding with an *AI* peak in our Negev and Rub’al Khali records. Enhanced northwesterly (Shamal) winds are also proposed in the Arabian Gulf region during the Younger Dryas (Pourmand *et al.*, 2004); however the *AI* peaks for the two systems do not precisely coincide though similar trends are apparent at this time. Early Holocene reestablishment of monsoon winds are also seen as important influences on dune building in the Thar (Singhvi and Porat, 2008) and the Hunshandake Sandyland (Mason *et al.*, 2008).

In the Kalahari of southern Africa and in some dunefields of Australia, *AI* peaks (Thomas and Bailey, 2017) coincide with declining solar insolation (i.e. with the downward limbs of insolation curves). Two explanations have been provided for this: first, that insolation maxima can be associated with higher precipitation, so that declining insolation relates to drying, and second, sediment availability for aeolian transport can in some contexts be linked to antecedent fluvial supply of material for subsequent deflation by the wind (Thomas and Bailey, 2017). Figure 10 also includes the summer (July) solar insolation curve for 30°N. The most prominent peak in the *AI* record for the Thar follows the insolation maxima at c11ka, but equivalent associations are not apparent with earlier insolation peaks or for other regional records. The lack of ages contributing to the earlier parts of the *AI*

records make any comparisons with other proxy records or potential forcing factors problematic at present.

Finally, we note the late Holocene peaks in *AI* in all the records except that for the Thar. However, there are few late Holocene luminescence ages in the database for this region, particularly compared to the other Asian dunefields analysed here. This may relate to the manner and context of the generation of age records in the Thar, with the exclusion of dune upper sediments from analyses.

## Conclusion

Our analysis shows that there is no universal driver for the timing of continental dune construction in the Asian dune systems analysed in this paper. It also demonstrates the strengths and limitations of the existing dune age data sets from the continent. The accumulation intensity approach to analysing composite desert dune age records provides a methodology for relating chronometric data to the actual process of sediment accumulation (Thomas and Bailey, 2017). This has in turn the potential to utilise age data in a manner more meaningful than simply treating ages as proxy records themselves, facilitating both the visualisation of accumulation variability over time and a means to relate this variability to other proxy records of desert environmental and climatic change in the Quaternary period. A number of issues emerge, however, from the application of *AI* analysis to the Asian records in the INQUA dune age database. First, despite the large number of ages that have been published from Asian dunefields since the first application of luminescence dating to aeolian sediments in the Thar Desert by Singhvi *et al* (1982), it is surprising how little we still know about long term dune development. The spatial coverage within the dataset is relatively restricted both in terms of the dune systems that have chronological data and in terms of the coverage within the dated dunefields themselves. Second, this in turn impacts on the capacity to competently analyse dune accumulation records in the context of both other proxy records and potential climatic drivers of dune activity and accumulation in Asian deserts. Third, and positively, where detailed and robust datasets are present, such as for the Negev Desert, the potential of the method to provide an analytical competence to Quaternary studies becomes apparent.

What this study highlights is how difficult the analysis of often remote desert systems remains today. Importantly, it also demonstrates how a consistent analytical approach to investigating long-term dunefield dynamics via a reproducible methodology can allow robust analysis of datasets. What is now needed therefore is an increasingly systematic approach to the application of luminescence dating to desert dune sedimentary archives, in order to contribute effectively to analyses of dryland climatic and environmental changes and their impact on aeolian systems.

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