Dune Ages in the Sand Deserts of the Southern Sahara and Sahel

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Abstract

In this paper we aim to document the history of aeolian processes within the southern Sahara as part of the INQUA Dune Atlas. We review available luminescence ages for sand dunes across the southern Sahara to develop an improved understanding of the dune chronology on a regional basis and attempt to correlate periods of sand accumulation. This was achieved by analysing dune age by country, as well as by latitude and longitude. The results show a very patchy spatial distribution of dune ages with large gaps that encompass some of the largest sand seas. Despite these gaps, some related patterns in dune morphology and stratigraphy appear to be consistent between northern Nigeria and southern Mali where older linear dunes are distinct from younger Late Holocene transverse and barchanoid dunes. Elsewhere in Mauretania linear dunes with different orientations appear to have accumulated at different times, most likely in response to changes in atmospheric circulation. Regional climatic changes are identified where dunes are transgressed by lake deposits within endorehic basins. We identify four locations where dune accumulation is terminated by lacustrine transgressions, two of which, in Lake Chad and the Bodélé Depression, occur shortly after the last glacial maximum (LGM). The third example at Gobiero in Niger occurred later, in the early Holocene, around 8.4 ka and a fourth marks a later transgression of Palaeolake MegaChad after 4.7 ka. Larger-scale latitudinal and longitudinal distributions in dune ages across the southern Sahara do not show any consistent patterns, though this may be due to the small sample size relative to the study area. In addition, local variations in external controls such as wind regime, rainfall, vegetation and sand supply need to be considered, sometimes on a site by site basis. Limiting the analysis to dune ages determined using the single-aliquot regenerative-dose (SAR) protocol indicates a lack of dune preservation during the LGM and the Younger Dryas, times associated with increased dust input to the oceans which is assumed to indicate increased aeolian activity. The SAR dune dates suggest that preservation of dunes at the onset of succeeding humid intervals is an important component of the dune record. The most striking examples of this phenomenon occur where dunes are preserved within endorehic basins by lacustrine transgressions.

1.0 Introduction

In their 1968 paper on “Quaternary landforms and climate on the south side of the Sahara” Grove and Warren note that the limits of the desert have shifted long distances north and south in the later stages of the Quaternary. They review the relative chronology of coastal, fluvial, lacustrine and dune landforms across the African continent from Mauritania in the west to Sudan in the east and establish alternating wetter and drier intervals marked by the appearance of different generations of sand dunes and their relationships to fluvial and lacustrine sediments. Grove and Warren (1968) established the now widely accepted chronology for late Quaternary climate change in North Africa, whereby the late Pleistocene was characterised by a drier climate with more extensive dune systems, followed by a wetter climate in the early Holocene, and a return to more arid conditions from the middle Holocene to the present day. They suggest that vegetated dunefields south of the Sahara indicate that the 500 mm isohyet lay some 500 km south of its present position (Grove and Warren, 1968). The expansion of the Sahara during the last glacial maximum (LGM) was supported by Sarnthein (1978) who asserted that active sand dunes were most extensive 18,000 years ago and that sand dunes were generally dormant 6000 years ago. The cause of the latitudinal shift in the desert is linked with the strength of the West African monsoon and the latitude of the intertropical convergence zone (ITCZ). Tracing the low salinity zone associated with the marine ITCZ, Arbuszewski et al. (2013) estimate that the ITCZ moved latitudinally over the ocean and shifted at least 7° south during the LGM to a latitude of 2° South. During the early Holocene there was a northward shift in the ITCZ and the monsoon rain-belt towards 10° or 12° North, from which it has subsequently shifted south to around 5° North at the present day (Haug et al., 2001).

While there is general consensus that the Sahara changed from a humid "green" to an arid "brown" since the mid Holocene, there is some debate over the timing of the change and whether it was gradual or abrupt. Talbot (1981) suggested that the onset of the drier windier conditions occurred around 4,500 years ago with desert expansion between 4,500 and 3,800 years ago. Subsequent research on lake sediments across the southern Sahara has supported and refined this chronology e.g. (Gasse, 2000). In 2000, deMenocal et al. suggested that the change occurred a little earlier, around 5.5 ka and asserted that the change was abrupt. Subsequent papers have questioned the abrupt change (Kröpelin et al., 2008, Eggermont et al., 2008), although the case for an abrupt change was reiterated by McGee et al. (2013) who refine the onset and end of the AHP as 11.8 ± 0.2 and 4.9 ± 0.2 ka respectively based upon a review of the marine record. In addition, there is potential for different proxies to respond in different ways and~~However,~~ in their ~~recent~~ review of palynological and palaeohydrological data across the Sahara and Sahel Lézine et al. (2011) point out that there will be a lag within wetland response due to groundwater recharge which is likely to have influenced the record of endorehic lake basins as well as ground water fed systems such as Lake Yoa, the source of the gradual change hypothesis. Most recently, Shanahan et al. (2015), suggest that the termination of the African humid period was locally abrupt, but occurred progressively later at lower latitudes accompanied by both declining rainfall intensity and gradual southward migration of the tropical rainbelt.

Swezey (2001) provides a review of the Late Quaternary aeolian stratigraphy in the Sahara even though, at that time (2001), few aeolian sediments in the Sahara had been dated directly. As a consequence there were, and still are, numerous uncertainties regarding the timing of aeolian sediment mobilisation and stabilisation (Swezey 2001). Despite these limitations, Swezey concluded that "although the data are relatively sparse, when viewed as a whole, they reveal a general pattern of widespread eolian sediment mobilisation during the Late Pleistocene, eolian sediment stabilisation during the early Holocene, and a return to widespread eolian sediment mobilisation in the later Holocene" (Swezey 2001, p.128). At the same time, Swezey predicted that "further use of luminescence dating and more precise mapping of stratigraphic relationships should make it possible to resolve Quaternary eolian chronologies with greater resolution and to create more precise models of eolian sediment response to climate change" (Swezey 2001, p.127).

Amongst the most outstanding debates on North African climate in recent years is that concerning the rate at which change has occurred and the degree of synchronicity across the continent. In his classic 1978 paper on sand deserts during the LGM, Sarnthein (1978) commented that "climatic changes from desert to vegetated land and vice versa are very rapid, spanning no more than a few hundred years" (Sarnthein 1978, p.46). Further evidence for abrupt change is found in the dust record of offshore cores (deMenocal et al. 2000, McGee et al. 2013). The main aim of this paper is to review the progress that has been made during the past decade, concentrating on the record that we now have from optical dating of dune sands in the southern Sahara, to try to elucidate the aeolian record of dune activity and response to climate change.

1.1 The Sahara

The Sahara is the largest warm desert on Earth. It covers an area of approximately 9 million km^2, similar to that of the USA and spans latitudes 15° to 34°N in North Africa. In this paper we are considering only the southern half of the Sahara which is divided from the north by elevated plateaus and mountains that straddle the Sahara including the Adrar des Iforas, Hoggar, Ajjer, Tibesti and Eneddi. However, there is interaction between the north and south because hydrological connections have operated during the Holocene (Drake et al., 2011) and northeasterly winds transport sand through these highland areas (Wilson 1971, Mainguet 1978) into basins on the southern side of the highlands. Along the way, upland areas divert and deflect the northeasterly trade winds and sandflow is diverted around and between the upland areas locally converging and diverging (Mainguet 1978). In his review of ergs Wilson (1973) mapped the distribution of 56 ergs larger than 12,000 km^2. Around a half of these, 27 are located in Africa north of the Equator, of which 16 are located within the southern and western Sahara area covered by this review.

1.2 The Database

In this paper we review the existing luminescence age data for dunes in the southern Sahara which have been entered into a global digital database and atlas of Quaternary dune fields and sand seas; see http://inquaduneatlas.dri .edu for further details of the INQUA dune atlas. Within the database each sample has a unique identification number e.g. (AFNL000n) which is reported in this paper in parentheses. Initially the dune ages are considered regionally, country by country from Sudan in the East to Mauretania in the West. This is followed by an overview investigating latitudinal and longitudinal dune age distributions across the southern Sahara; firstly using all available luminescence ages, and secondly considering only those luminescence ages produced using the SAR method which is considered to produce more reliable age estimates.

2.0 Available data sets

Luminescence ages from 13 papers are incorporated into this review (Armitage et al., submitted, Berking and Schütt, 2011, Bubenzer et al. 2007, Bushbeck and Thiemeyer 1994, Felix-Henningsen et al. 2009, Gumnior and Preuser 2007, Holmes et al. 1999, Lancaster et al. 2002, Mauz and Felix-Henningsen 2005, Rendell et al. 2003, Sereno et al. 2008, Stokes and Horrocks 1998, Stokes et al.

2004, Theimeyer 1995), with sample locations shown in figure 1. These papers use a variety of different methods for calculating the equivalent dose, reflecting the development of luminescence dating methods over the past twenty years. The earliest results come from Buschbeck and Thiemeyer (1994) using thermoluminescence (TL) to date dunes in northeastern Nigeria. Their results indicate ages in the range from 1.1 ± 0.85 ka to 12.6 ± 5.6 ka, with very large uncertainties, and the authors themselves describe the dose rate as “not very reliable”. In addition, TL is no longer considered an appropriate method for dating young sedimentary samples and Thiemeyer (1995) questions the validity of the calculated TL ages for the Lantewa and Gudumbali dune fields, concluding that he is “not able to relate the TL ages of NE- Nigerian dunes to certain phases of dune formation” (Thiemeyer 1995, p.105). Furthermore, the papers by Buschbeck and Thiemeyer (1994) and Thiemeyer (1995) do not provide coordinates for their sample locations, making it difficult to incorporate their data into the atlas format. Consequently, the TL ages from Buschbeck and Thiemeyer (1994) and Thiemeyer (1995) are not be considered further in this paper.

The papers by Stokes and Horrocks (1998), Holmes et al. (1999) and Lancaster et al. (2002) all use the multiple aliquot additive dose (MAAD) technique, while Rendell et al. (2003) used the single aliquot additive dose (SAAD) technique. Although comparison of the MAAD and SAR techniques indicates that MAAD ages are likely to be significantly in error e.g. Duller and Augustinus (2006) they have been retained within the atlas because they include around half of the available dune ages for the southern Sahara. The MAAD technique has been superseded by SAR and this is the technique used in more recent publications including Berking and Schütt (2011), Felix-Henningsen et al. (2009), Gumnior and Preusser (2007), Mauz and Felix-Henningsen (2005) and Stokes et al. (2004). While the SAR technique is widely applied and considered to be reliable, there are still some issues that the reader/user needs to be aware of. The paper by Stokes et al. (2004) does not include location details for seven out of the 16 samples, locations for the atlas have been estimated from published maps and Google Earth™. Gumnior and Preuser (2007) date fluvial sediments in northeastern Nigeria but within the floodplain sediments they also located and dated one aeolian sand which has an age of 4.8 ± 0.4 ka and is duly incorporated into the database (AFNL00128). Bubenzer et al. (2007) report dune ages from Wadi Howar in Sudan which include 17 ages derived using three different methods; Multiple Aliquot Additive Dose (MAAD) Protocol, Infrared Stimulated Luminescence (MAA IRSL) dating of potassium feldspar; Multiple Aliquot Regenerative Dose Protocol, Green-Light Stimulated Luminescence (MAR GLSL) dating of quartz; and Single Aliquot Regenerative Dose Protocol, Blue-Light Stimulated Luminescence (SAR BLSL) dating of quartz. Despite the reservations of Duller and Augustinus (2006) the ages derived from different techniques appear to be reasonably consistent. In their study at Gobero, Sereno et al. (2008) do not provide details of the dating methodology or the samples locations, the lack of location information is an attempt to prevent damage to an archaeological site and approximate coordinates based on location descriptions in Sereno et al. (2008), and co-workers have been used to estimate an approximate location which will suffice for the level of interrogation required in this paper. In addition we discuss ages for fossil dunes in the Bodélé Depression in northern Chad and dune islands within Lake Chad which are reported by Armitage et al. (submitted) (Table 1).

3.0 Regional dune ages by country

3.1 Sudan

Luminescence ages for aeolian sands in Sudan are reported by Bubenzer et al. (2007) and Berking and Schütt (2011). Bubenzer et al. (2007) report luminescence ages for 3 parabolic dunes on the north bank of Wadi Howar (AFNL00022-32) and one site (Dune -84-13) on the south side of the Wadi Howar (AFNL00033-38) for which the morphology is not reported. The 17 ages includes 14 Early to Middle Holocene ages in contrast to Stokes et al. (1998), who found no preserved aeolian sediments of this age in the Selima Sand Sheet across the border in southern Egypt (AFNL00045-49). The preservation of the dunes at Wadi Howar is unusual, firstly the dunes have a parabolic form and secondly the dune morphology is preserved beneath a layer of artefacts including stone tools, pot sherds and animal bones. The parabolic form of the dunes is taken to indicate at least partial stabilisation of the dunes by vegetation at this time, and clearly there must have been sufficient water available for humans and animals to live in the area as indicated by the rich artefact layers covering the dunes. The early to middle Holocene ages reported for samples (AFNL00022-35) are unusual because they occur within the African Humid Period (AHP) a time of increased precipitation in the southern Sahara (Pachur and Hoelzman 2000). It is possible that the sand was derived from the neighbouring wadi which contained sufficient moisture to support human occupation but was also dry enough to act as a source of wind-blown sand, possibly on a seasonal basis. The dune ages reported by Berking and Schütt (2011) from the vicinity of Meroitic Naga in northern Sudan appear to come from sand ramps on either side of a rocky outcrop. Samples appear to come from four locations, three on the northern side of the outcrop and one on the southern side. At each location, the ages are stratigraphically coherent with younger above older. Five out of the 11 dates are latest Holocene, less than 2000 years old (AFNL00117-119, AFNL00122 and 127), there are three dates from the Early to Mid-Holocene (10.13 ± 1.51 ka, 9.93 ± 0.81 ka and 7.08 ± 0.71 ka) (AFNL00123-125), and three older ages (14.72 ± 1.6 ka, 21.05 ± 3.56 ka and 37.75 ± 5.25 ka) (AFNL00120, 121 and 126) suggesting that the sand ramps are relatively long lasting features. The oldest samples are from just 2.5m depth and the gaps between ages may represent an incomplete stratigraphy, incomplete sampling or a combination of the two.

3.2 Chad

Sandseas in Chad include the Erg du Djourab as well as parts of the Erg du Kanem. However, dune dates are sparse and the only published luminescence ages of which we are aware are those of Mauz and Felix-Henningsen (2005) who report 6 OSL ages for dunes in the Erg du Djourab that were collected along a transect between Faya-Largeau and N'Djamena following the Bahr el Ghazal (AFNL00057-62). The samples were taken from dune sands overlain by lake deposits or soils and yield ages of between 4.7 ± 0.3 ka and 1.3 ± 0.1 ka. Felix-Henningsen et al. (2009), describe the dunes as linear dunes with flattened tops. However, given the orientation of the dunes with respect to the seasonal north-easterly Harmattan wind and the south-westerly monsoon winds the dunes would be better described as transverse. The dunes close to the Bahr el Ghazal have flattened tops which might be attributed to reworking of partially stabilised dunes by the seasonally reversing winds. An alternative explanation, given the associated lacustrine sediments within interdune areas, is that the dune crests were planed off during or close to the Holocene highstand of palaeolake Megachad. Flooding of the dunes by palaeolake Megachad is indicated by diatomite deposits on top of the dune sands dated by Mauz and Felix-Henningsen (2005) at their localities 1 and 2, while the soil development on the dunes at their localities 3 -6 most likely developed during a corresponding humid interval in the late Holocene.

Armitage et al. (submitted) supplement this record with three dune dates from the Bodélé Depression where barchan dunes are locally preserved beneath lacustrine diatomite (samples CH16, CH22 and CH51, table 1). The contact between the cross-stratified aeolian sand and the overlying diatomite is sharp with no evidence for plant roots or soil development on top of the dunes (Figure 3), suggesting a very rapid transgression. While the preservation beneath lacustrine sediments is similar to that reported by Mauz and Felix-Henningsen (2005) the dune ages from the Bodélé are significantly older ranging in age from 17 ± 1.7 to 14.8 ± 1.5 ka, and most likely represent an earlier lake transgression.

3.3 Nigeria

Luminescence ages for dunes in northeastern Nigeria are reported in five papers: Armitage et al. (submitted), Buschbeck and Thiemeyer (1994), Thiemeyer (1995), Stokes and Horrocks (1998), and Holmes et al. (1999). As explained above we have rejected the TL ages reported by Buschbeck and Thiemeyer (1994) and Thiemeyer (1995) because the reliability of the ages are questioned and the papers lack sample coordinates. In this paper we review the remaining luminescence chronology.

Stokes and Horrocks (1998) sampled both linear dunes and loessic soils in northeast Nigeria. Their results include ages for linear dunes which range between 20.6 ± 3.1 and 7.0 ± 1.1 ka and include a cluster of late glacial ages (20.6 ± 3.2, 18.2 ± 2.0, 17.8 ± 3.0, 17.6 ± 2.4 ka, AFNL00155, AFNL00150 and 151). They suggest that the linear dunes accumulated over a long time span, at least 6 ka, and that the accumulation was probably episodic. In addition to the linear dunes Stokes and Horrocks (1998) sampled Loessic soils within the dune field and downwind and the three oldest samples with ages of 50 ± 11, 37 ± 10 and 25 ± 10 ka,(AFNL00154, 161 and 162) are from Loessic soils and all contain a high percentage of silt and clay sediments (Stokes and Horrocks 1998).

Holmes et al. (1999) report 15 ages from the dunes in the Lantewa dunefield which includes linear and transverse dune forms although ten of the fifteen samples come from barchans or barchanoid dunes, with two samples from playa sand sheets, one from an interdune depression and one from a proto-linear dune (AFNL00097-107) (Holmes et al. 1999, table1). The sampling strategy appears to have ignored the linear dunes which were studied by Stokes and Horrocks (1998). The dune ages range from 6.98 ± 0.45 to 0.17 ± 0.03 ka, from the Middle Holocene to present day, and are invariably younger than the ages of the linear dunes from the same area reported by Stokes and Horrocks (1998) (AFNL00150-160). Thus there appear to be at least two generations of dunes in the Lantewa dunefield, an older set of linear dunes which trend ENE-WSW, mapped by Grove (1958), and a younger set of barchanoid dunes which were active from the Middle Holocene. Also in northeastern Nigeria, but sandwiched between floodplain sediments of the Komadugu River Gumnior and Preusser (2007) identified an aeolian sand with an age of 4.8 ± 0.4 ka (AFNL00128) which most likely represents increasingly arid conditions in northeastern Nigeria at that time (Gumnior and Preusser 2007).

Armitage et al. (submitted) present four new OSL ages from dune islands in Lake Chad. The islands in Lake Chad are transverse dunes that were flooded when the lake levels rose and have recently been revealed as the lake waters recede (Figure 4). Armitage et al. (submitted) collected samples from auger boreholes into the dune islands at Phulkime Island, Madayi Island and Zango 2 Island (Table 1).

The optical dating used the SAR and the resulting ages range from 19.0 ± 1.9 to 15.6 ± 1.6 ka (Table 1). These ages post-date the LGM and we suggest that the area presently occupied by Lake Chad was dry during the LGM which allowed transverse dunes to migrate southwest into the lake basin driven by the northeasterly Harmattan wind. Soon after the LGM the climate changed and became more humid with an enhanced monsoon and the dune activity was halted by increased fluvial discharge into the endorehic lake basin which flooded the dunes preserving them where they stood. Thus the ages of these dunes records the onset of humid conditions in the Sahel.

3.4 Niger

Four papers provide luminescence ages for dune deposits in Niger: Rendell et al. (2003), Sereno et al. (2008), Mauz and Felix-Henningsen (2005), and Felix-Henningsen et al. (2009).

Rendell et al. (2003) report 7 IRSL ages from a climbing dune that developed on river terraces on the south side of the Niger River (AFNL00070-76). The ages range from 13.2 ± 1.1 to 0.48 ± 0.28 ka and are stratigraphically coherent with the oldest at the base and the youngest at the top of a 12 m section. Initial deposition appears to be relatively rapid with around 5 m of sand accumulating within 2.3 ka between 13.2 ± 1.1 and 11.4 ± 1.6 ka although this section also includes a palaeosol (Rendell et al. 2003). This early sand accumulation may be associated with the Younger Dryas (YD) which is associated with increased aridity in sub-Saharan Africa (Gasse 2000), although Rendell et al. (2003) indicate possible palaeosol formation at this time. A later palaeosol bracketed by IRSL ages 3.28 ± 0.74 and 0.48 ± 0.28 ka (AFNL00071 and 70) suggest dune stabilisation and soil formation during the late Holocene. Unusually both palaeosols are dated to periods associated with regional aridity in the Younger Dryas and Late Holocene, whereas much of the sand accumulation is associated with more humid conditions (Rendell et al. 2003). Rendell et al. (2003) suggest that this can be explained by changes in the sediment supply from the nearby Niger River with soil development occurring when sediment supply from the Niger River was more limited and that dune building resumed when the sand supply was more abundant. An alternative explanation for the soil formation is that it occurred within shorter humid intervals within otherwise dry periods that have not been resolved.

Sereno et al. (2008) report 9 OSL ages from barcan (sic.) dunes that were transgressed by a shallow lake (AFNL00108-116). The dune ages range from 16.5 ± 1.8 to 8.2 ± 0.6 ka indicating dune accumulation between the end of the LGM and the early Holocene. The two oldest ages 15.0 ± 1.4 and 16.5 ± 1.8 ka (AFNL00111 and 110) are from depths of 2.5 and 2.0 m respectively. While sand from the shallowest depth 0.35 m has the youngest age 8.2 ± 0.6 ka (AFNL00113). The dunes were emplaced and being used as a cemetery between 9.6 and 9.2 ka (Sereno et al. 2008). Subsequently, between around 8.5 and 8.3 ka the level of Palaeolake Gobero rose flooding the dunes and forcing relocation of the local inhabitants. Interpretation of the palaeontological record at Gobero indicates that the palaeolake highstand was probably short lived and episodic (Sereno et al. 2008). The palaeolake highstand was apparently followed by an arid phase (8.4 -8.0 ka) correlated with the "arid interruption" of Brooks (2006), and then reoccupied around 7.5 ka with conditions remaining suitable for human habitation until around 4.5 ka corresponding with widespread desiccation of the Sahara (Sereno et al. 2008).

Felix-Henningsen et al. (2009) provide five additional ages from 29.31 ± 4.9 to 9.9 ± 1.2 ka (AFNL00051-56), which appears to include one sample originally reported by Mauz and Felix-Henningsen (2005) (AFNL00053) for low dunes or sandsheets overlain by weathered soil horizons.

The ages are spread across a wide range from pre-LGM (29.3 ± 4.9 (AFNL00054), to the early Holocene. The overlying soil development most likely formed during the Early to Middle Holocene African Humid period. Felix-Henningsen et al. (2009) comment that “with such a low number of samples it cannot be proven that aeolian sedimentation occurred continuously under an arid climate between 30 and 10 kaBP”(Helix-Henningsen et al. 2009 p.96) but note that they found no interruption in sedimentation caused by a phase of fluvial erosion or formation of palaeosol in the sections they examined.

3.5 Mali

We are only aware of one luminescence dune dating study in Mali by Stokes et al. (2004), who conducted a reconnaissance survey of dunes in southern Mali close to Tombouctou. Their aim was to investigate the environmental archive of drought conditions from dune reactivation, and towards this end they collected 7 samples from 5 linear dunes and 9 samples from 5 transverse dunes to the south of Tombouctou (AFNL00077-92). Possibly as a result of the studies of the Lantewa dunefield in Nigeria, where Stokes and Horrocks (1998) found linear dunes to be older than barchanoid dunes (Holmes et al. 1999), the authors make a distinction between samples from linear dunes and transverse dunes in Mali and found a similar trend with older linear dunes and younger transverse dunes (Stokes et al. 2004). The ages reported by Stokes et al. (2004) for the linear dunes range between the Younger Dryas (12.7 ± 0.5 ka AFNL00080) and late Holocene (0.025 ± 0.004 ka AFNL00083) including ages in the mid-Holocene (Fig. 2E). The ages of the transverse dunes are more tightly clustered in the late Holocene between 3.4 ± 0.2 ka (AFNL00085) and 0.025 ± 0.003 ka (AFNL00089) (Fig. 2E). The youngest ages can be attributed to late Holocene aridity and recent (20th century) drought induced reactivation (Stokes et al 2004). However, the mid-Holocene ages (8.53 ± 1.32, 6.44 ± 0.35, 5.97 ± 0.33 and 5.21 ± 0.64 ka, AFNL00078, 82, 81 and 79) are unexpected because they fall within the African Humid Period. Stokes et al. (2004) argue that the dunes experienced multiple, short-term reactivation because the dune system “lay close to a threshold of field wide remobilisation via-climate based fluctuations” (Stokes et al. 2004, p.290).

3.6 Mauritania

Lancaster et al. (2002) report 19 luminescence ages from linear dunes with three distinct trends in the Azeffal, Agneitir and Akchar sandseas (AFNL00129-149). The ages range from 24 ± 3 to 0.16 ± 0.04 ka with two clusters of ages at 24 and 12 ka (Figure 2F). The cluster of ages at 24 ka falls within the LGM and is taken to indicate the emplacement of large linear dunes which trend NE-SW at that time. All of the ages between 24 and 15 ka are associated with the NE-SW dune trend (Lancaster et al. 2002). The second cluster at 12 ka falls within the Younger Dryas (YD) and are associated with linear dunes that trend NNE-SSW. The youngest ages are attributed to recent dune activity reworking these older linear dunes. There is one additional late Holocene age from Mauritania 3.7 ± 0.3 ka (AFNL00051) reported by Felix-Henningsen et al. (2009) from a sand ramp. This age indicates some Mid to Late Holocene dune activity although Felix-Henningsen et al. (2009) report soil development and stabilisation of the dune since that time. At the present day the dunes are reported to be reactivated due to grazing (Felix-Henningsen et al. 2009).

4.0 Latitudinal trends

Plotting the dune ages against latitude using all 124 luminescence ages from the southern Sahara shows no obvious relationship between age and latitude (Fig. 5). This is surprising given the established model for southward expansion of the Sahara during the LGM (Grove and Warren 1968, Sarnthein 1978). The established model suggests that dunes which were active during the LGM became fixed by vegetation due to an enhanced West African Monsoon (WAM) and northward migration of the intertropical convergence zone (ITCZ) culminating in the African Humid Period. Given this scenario of southward desert expansion followed by northward retreat it was expected that there should be a fringe of older dune ages preserved along the southern margins of the Sahara within the Sahel which includes most of the dune dates reviewed in this study as mapped by earlier workers (eg. Grove 1958, Grove and Warren 1968). We also expected to see progressively younger ages spreading from north to south due to dune reactivation during the late Holocene as the ITCZ moved south (Haug et al. 2001), wetlands dried out progressively from north to south (Lézine et al 2011) and the desert expanded southwards again. However, this model does not appear to be supported by the data. Indeed, if the two outliers of pre-LGM age (37.7 ka sand ramp at Naga, and 29.3 ka soil in Niger) are ignored, visual inspection of figure 5 suggests that there are older dune ages at higher latitudes; the opposite to the model prediction. On the other hand, there might be a slight trend for younger ages to increase southwards from 5 ka, which would fit the model, although this was anticipated to be the weaker trend since higher latitude dunes would continue to be reworked after the reactivation progressed south. It would appear that the most likely explanation for the later trend is a lack of sampling of younger dunes at higher latitudes. The lack of older dune ages in the south might be attributed to more widespread reactivation and reworking since the LGM, for example during the Younger Dryas and late Holocene.

4.1 Latitudinal trends in SAR data

Restricting the data to dune ages measured using the SAR protocol reduces the database from 124 to 58 ages. A plot of luminescence ages against latitude for the SAR data shows no obvious correlation between dune age and latitude, but a tighter grouping of latitudes and ages with two groups of ages around latitudes 13°N and 17°N that are attributed to sampling bias (Figure 6). Around each of these latitudes there is a spread of ages. The greatest difference between the SAR data shown in figure 6 and all OSL age data shown in figure 5 is the lack of ages from higher latitudes above 18° in figure 6 which can be attributed to a lack of sampling.

5.0 Longitudinal trends

In addition to the latitudinal changes the monsoon system is also believed to have strengthened with the enhanced monsoon spreading further inland and palaeohydrological records suggest that humidity associated with the African Humid period started and ended several millennia earlier to the east than to the west of the Sahara (Lézine et al. 2011). Thus changes in dune activity from west to east across the continent might indicate differences in the intensity of the respective monsoons, the WAM in the west and the East African Monsoon (EAM) in the east, as well as the timing of the onset and end of the AHP. A cross-plot of dune age and longitude (Figure 7) shows slightly older ages in the east and in the west with the exception of one outlier in the central Sahara. If the two pre-LGM ages (27.7 and 29.3 ka) are ignored there is a slight trend for dune ages to decrease from east to west across the continent apart from the Mauritanian dunes in the west which show even older ages (Figure 7).

5.1 Longitudinal trends in SAR data

A plot of dune age (SAR) against longitude (Figure 8) appears to show an apparent trend for the maximum dune age to increase from east to West across the southern Sahara and Sahel. This trend is enhanced by the locations of two pre-LGM ages (29.3 ± 4.9ka AFNL0054) is from a sandsheet in Niger, and (37.7 5.3 ka AFNL00121) is from what appears to be a sand ramp near Naga in Sudan. This pattern is probably an artefact of sampling. The lack of older ages in other areas is attributed to a lack of data rather than a lack of late-glacial dunes, as can be seen when comparing figures 7 and 8. There are older dunes in Mauritania (Fig. 7) but those dunes have been dated using a different technique and therefore do not appear in figure 8. Another feature that is apparent in Figure 7, and more so in figure 8, is the large gaps in the latitudinal sampling especially between 0 and 15° W with only a single data point in an area 1,500 km wide that includes several large ergs.

6.0 Age distributions

The cumulative age distribution plot for all 124 dune ages in the southern Sahara (Fig. 7) shows a gradual decrease with age up until the LGM with a minor break during the Bølling Allerød (BA) followed by almost continuous ages through the African Humid Period (AHP) and into the late Holocene. An exponential decay in ages like this has been interpreted to indicate extensive dune reworking (Nanson et al. 1992). Surprisingly there is little evidence in the south Saharan dataset to support Sarnthein's contention that sand dunes were generally dormant 6000 years ago. However, the middle Holocene age distribution is in part biased by the unusual preservation of the artefact covered parabolic dunes in Sudan (Bubenzer et al. 2007) which include 14 ages from the early to middle Holocene, a time that is generally considered to be relatively humid in north Africa and when dunes are supposed to have been less active. On the other hand, studies of African lake levels indicate that regionally synchronous dry periods occurred during the AHP around 4.0, 6.6, 8.2 ka (Gasse 2000), and given the precision of the luminescence ages, it is possible that there has been repeated dune reactivation for short periods during the Holocene, especially if the dunes lay close to some threshold of dune reactivation e.g. Stokes et al. (2004).

6.1 Cumulative distribution SAR ages

The plot of cumulative age distribution for SAR luminescence ages from the southern Sahara (Fig. 10) differs slightly from the pattern seen in figure 9. There are two ages from the pre-LGM (37.7 ± 5.3ka AFNL00121, and 29.3 ± 4.9ka AFNL00054). A single age within the LGM (21.0 ± 3.6ka AFNL00120) but a cluster of late-glacial ages within the Older Dryas (OD), one age within the Younger Dryas (YD) and a cluster of ages in the early Holocene and through the African Humid Period (AHP). There is also a short but notable gap in the late Holocene between 2 and 3 ka, before a cluster of recent ages due to late Holocene dune activity. The two ages from pre-LGM are not from mobile dunes within sand seas but come instead from a sand ramp in Sudan (AFNL00121) and a sandsheet in Niger (AFNL0054). The single central age during the LGM, when dunes are supposed to be most active, suggests that dune activity should not be conflated with preservation. At times of maximum aridity and windiness when dunes are most active, they are freely migrating and overturning so that there is little preservation. It is when the climate changes to more become more humid that dune strata can be preserved as the water-table rises and vegetation becomes established. Thus the lack of dune ages from the LGM and YD is not unexpected. Indeed, the ages that we have from the Older Dryas are in locations where dunes within endorehic basins have been flooded by lacustrine transgressions in Lake Chad and the Bodélé Depression. Small offsets within the Holocene data might correspond with a weaker monsoon, but given the precision of the dune ages, this is speculative. A more noticeable gap between 3ka and 2ka might be more significant although it could also result from under-sampling. Circumstantial evidence supports the possibility that the gap is climatically driven, since it corresponds with a short but clearly defined humid phase between 3.5 and 2.5 ka, identified in the western Sahel by Lézine et al. (2011) and overflow from Lake Chad into the Bodélé Depression through the Bahr el Ghazal (Armitage et al. submitted), as well as soil development in transverse dunes beside the Bahr el Ghazal (Mauz and Felix-Henningsen 2005).

Discussion

The results from the compilation of dune dates for the INQUA Quaternary Dune Atlas show that much progress has been made using luminescence dating to constrain the age of sand dunes in the Sahara since the review of Swezey (2001). However, optical dating of sand dunes in the southern Sahara dune systems can be described as patchy, or more probably spotty, and in many areas there are no data whatsoever, leaving large gaps in the coverage. We provide a map of the distribution of dune ages (Fig. 1) showing where these gaps are located, and these appear to include the majority of the large ergs in the southern Sahara identified by Wilson (1973), including: Ouarane, Aouker, Aklé, El Mréyé, Erg Tombouctou, Erg Azouad, Erg Azouak, Erg Bilma-Ténéré, Erg Foch, Erg Kanem and the Sudanese Qoz. It will take considerable resources to design and implement sampling strategies to fill the gaps.

The southward expansion of the Sahara during the LGM, followed by dune stabilisation after the LGM and during the early to middle Holocene, might be expected to have left a fringe of relic vegetated dunes across the southern margin of the Sahara and the Sahel, which corresponds with the latitudinal extent of the dunes ages reviewed in this paper. This model predicts older dunes preserved in the south and younger, Late Holocene, reactivation of post-AHP dunes to the north. However, the cumulative age distribution of SAR ages (Fig. 10) shows some intriguing patterns with an absence of ages in the LGM and a single age in the Younger Dryas, when dunes are believed to have been most active (Grove and Warren 1968, Sarnthein 1978). The most likely explanation is that dune activity does not equate to preservation, leaving gaps in the stratigraphic and chronologic record. Thus, interpreting the chronological record of dune stratigraphy is difficult because it is not possible to state with certainty whether gaps represent a cessation of dune activity or an increase in aeolian activity with increased transport but a lack of accumulation and preservation (Chase 2009). There are also questions regarding the significance and interpretation of the dune record due to the patchy coverage within the southern Sahara, so that we can only speculate upon the significance of the age distributions. A hypothesis that explains the observed dune ages is that Holocene reworking has completely reset earlier dune ages within much of the central southern Sahara. However, this hypothesis raises a conundrum; if Holocene reworking is so widespread, then Holocene dune activity must have been at least as widespread as the Quaternary dune activity during the LGM in order for such extensive reworking to have occurred. If Holocene reworking was less extensive we would have predicted a fringe of older LGM ages to have been preserved along the southern margins of the Sahara, for which there is no evidence here. It is possible that the proposed LGM fringe has not been sampled but we should also consider that reworking during the Younger Dryas might have extended further south, reworking LGM dunes. Additional research including stratigraphic sampling of

Sahelian dunes preferably constrained by GPR imaging of dune stratigraphy be undertaken in order to determine the extent of Holocene reworking.

In addition to reactivation and reworking of pre-existing dune fields we should also consider other sediment sources. At least two of the sites where dunes have been dated are likely to have sand supplied from local ephemeral or seasonal rivers - Wadi Howar (Bubenzer et al. 2007) and the terraces of the Niger River (Rendell et al. 2003). In such locations source-bordering dunes are a common feature of semi-arid river banks. The Inland delta of the Niger and ephemeral river systems across the Sahara are likely sources of sand for dune construction. In addition, lake basins such as Lake Chad and the Bodélé Depression have associated dune fields that extend downwind away from the lake shores. The lake basins probably act as temporary sediment sinks during humid periods and then release sediment as the lakes dry out. At the present day, dry lake beds in the Sahara appear to be major sources of atmospheric mineral dust (Prospero et al. 2002, Engelstaedter et al. 2006) and in the case of the Bodélé Depression in Chad, which is the single largest source of atmospheric mineral dust on Earth (Washington et al. 2003), wind erosion appears to have scoured out a deep basin (Washington et al. 2006) providing a source of sand as well as dust.

There are four examples of dated dune sands preserved beneath lacustrine sediments; Gobero in Niger (Sereno et al. 2008), Lake Chad in Nigeria (Armitage et al., submitted), the Bodélé depression in Chad (Armitage et al., submitted), and the intervening Erg du Djourab (Mauz and Felix-Henningsen 2005). Field observations from other parts of the Sahara suggests that this is a widespread and relatively common occurrence where dunes that migrated into endorehic basins in dry periods became flooded during succeeding humid periods (Callot 1991, Swezey, 2001; Armitage et al. 2007). The ages of the dunes preserved beneath lake deposits in the southern Sahara range between 19 ± 2 and 4.7 ± 0.3 ka, and appear to represent at least three distinct lake transgressions. At the end of the LGM the waters of Lake Chad rose and flooded over a dune field that is now preserved as islands in the lake, the lake waters rose until the water spilled north through the Bhar el Ghazal to flood the Bodélé Depression preserving transverse and barchan dunes. A second transgression associated with the African Humid period in the early Holocene preserved barchan dunes at Gobero in Niger (Sereno et al. 2008), while a third transgression around 4.7 ka preserved dunes in the Erg du Djourab in Chad (Mauz and Felix Henningsen 2005).

In their review, Lézine et al. (2011) omitted dates from sand dunes because they were deemed too scarce to provide a sub-continental record of dry events and too imprecise to be fitted into their mapping intervals. Our results show that, despite the incomplete coverage, it is possible to derive some value from the aeolian record using the limited SAR data available, but that the dune dates do not necessarily correspond with dry events. In fact they may well indicate the onset of humid events which lead to a cessation of dune activity but results in dune preservation, and this is best expressed within endorehic basins such as Lake Chad and the Bodélé depression which became desiccated during the LGM but flooded during the Older Dryas and the AHP.

Lezine et al. (2011) also chose to omit radiocarbon ages from archaeological sites to avoid bias due to trade practices (of shells) from distant places and all kinds of interpolation between dated samples. In this paper we have included OSL ages from archaeological sites at Gobero (Sereno et al. 2008), Nagga (Berking and Schütt 2011), and Wadi Howar (Bubenzer et al. 2007), because the dune ages were collected to gain information on the palaeoenvironmental context and landscape evolution around the sites rather than direct dating of artefacts, hearths or occupation horizons. Having said that it is notable that the majority of the ages from Gobero and Wadi Howar fall within the early Holocene AHP when the Sahara was wet and green and best suited to human occupation (Kuper and Kröpellin 2006). However, the concentration of ages from a limited number of locations could introduce a spatial as well as a temporal bias to the data, especially when the data is sparse, as is the case in the southern Sahara and Sahel.

Conclusions

Armitage et al. (submitted) present new dune ages from dune islands in Lake Chad and barchans dunes in the Bodélé depression which indicate that the onset of post LGM humid conditions in the Sahel occurred between 19 ± 1.9 and 15.6 ± 1.6 ka. At the moment the database of dune ages for the southern Sahara is not sufficient to address contentious issues such as the timing and rate of the desiccation of the Sahara and Sahel at the end of the African Humid period. It lacks the temporal and spatial resolution to test whether the changes were abrupt, gradual or intermittent. This might in-part be attributed to systematic problems associated with the interpretation of dune ages (Chase 2009) but can also be attributed to very limited sampling, some of which has been undertaken for archaeological studies and hence not aimed at solving geomorphological or palaeoclimatic questions. The studies by Lancaster et al. (2002), Stokes et al. (1999), and Holmes et al. (1998) show distinct relationships between dune pattern and dune age. This may in part be attributed to a well-planned sampling strategy, specifically targeting dunes with different orientations. Such targeted sampling appears to be lacking in most of the other studies of dune fields in the southern Sahara. Four examples of dated dune sands overlain by lacustrine sediments in Lake Chad, the Bodélé Depression, Gobero in Niger and the Erg du Djourab in Chad, provide unequivocal evidence for an increase in lake levels and climate change as the primary driver for some dune preservation. In other localities soil development on-top of dune sands is most likely due to stabilisation by vegetation as a precursor to soil formation in response to an increase in humidity. This is supported by analysis of the SAR dune ages which include no records for the LGM or YD when dunes are believed to have been most active, but indicates preservation in the succeeding humid intervals. On the other hand, some sites may be subject to local controls, for example Rendell et al. (2003) suggest that sand supply from the Niger River played a role in dune accumulation which appears to correspond with wetter rather than dryer periods. In conclusion, there is still much to be learned about the dune activity and sand seas of the southern Sahara. Vast areas of the southern Sahara remain to be investigated including many of the most extensive sand seas such as the Erg du Bilma in the Ténéré, as well as the Ouarane, Aouker, Aklé, Azouad and Azouak ergs. Additional sampling of major sand seas is required to achieve a more detailed understanding of the ages of the dune fields and sand seas of the southern Sahara. In particular sampling needs to be targeted at dunes with different trends, and constrained by studies of the dune stratigraphy.

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List of Figures

Figure 1. Map of North Africa showing the location of samples, dune type and place names mentioned in the text. Note that symbols are indicative and some sites have multiple samples within a small area that cannot be represented at this scale.

Figure 2. Histograms showing sand dune luminescenece age distributions by country across the Sahara from Sudan to Maritania, (A-F), with the data source. Note that this includes three loess ages in northern Nigeria from Stokes and Horrocks (1989).

Figure 3. Photograph of cross-stratified yellow dune sand from a barchan dune preserved beneath freshwater diatomite exposed on the floor of the Bodélé depression. The luminescence age for the sand at this location CH22 is 15 ± 1.5 ka (Armitage et al., submitted). The contact between the dune sand and diatomite is sharp with no evidence for soil formation, which is interpreted to indicate a rapid lake transgression flooding over the dune.

Figure 4. Satellite image of Lake Chad with NW-SE trending pale grey stripes that are transverse dunes preserved as islands surrounded by darker lake water and vegetation. The dunes were flooded as the lake waters rose soon after the Last Glacial Maximum (LGM) preserving dunes with ages from 19 ± 1.9 ka to 15.6 ± 1.6 ka (Armitage et al., submitted).

Figure 5. A plot of dune age against latitude using all 124 ages from the southern Sahara. There is no obvious relationships between age and latitude. If the two outliers at 37.7 and 29.3 ka are ignored there are slightly older ages >20 ka in the north at higher latitudes which is the opposite to model predictions.

Figure 6. A Plot of luminescence ages against latitude for the SAR data. There is no obvious correlation between dune age and latitude but a tighter grouping of latitudes and ages.

Figure 7. A plot of dune age against longitude for all 124 ages shows no consistent pattern. One older age from the sand ramp at Naga gives the impression of an older age in the east, but is not considered to be significant.

Figure 8. A plot of dune age (SAR) against longitude. There is an apparent trend for the maxium dune age to increase from East to West across the southern Sahara but this is an artefact of the sampling

and dating and Slightly older dunes are apparent in the central southern Sahara, though in practice this corresponds with the Chad Basin where Palaeolake Mega-Chad flooded over dunes in Lake Chad and the Bodélé Depression soon after the last glacial maximum. tThe lack of older ages in the East other areas is attributed to a lack of data rather than a lack of older sand late glacial dunes.

Figure 9. A cumulative age distribution for all 124 dune ages in the southern Sahara. There is a gradual decrease with age until the Last Glacial Maximum (LGM), with a minor break during the Bølling Allerød (BA), followed by almost continuous ages through the African Humid Period (AHP) and into the late Holocene.

Figure 10. A cumulative age distribution for SAR luminescence ages from the southern Sahara. Overall there are less ages, notable decreases are a single central age during the last glacial maximum (LGM) and a single central age in the Younger Dryas (YD) times when dunes are believed to have been most active. The lack of dune ages from these times is attributed to a lack of preservation. In contrast a cluster of ages in the early Holocene and through the African Humid Period (AHP) are attributed to preservation of dunes, especially when lakes within endorehic basins rise and flood across dune fields in the Chad basin. There is also a short but notable gap in the late Holocene between 3 and 2 ka, that might be attributed to increased humidity, before a cluster of recent ages due to late Holocene dune activity.

Tables

Table 1.

Sample number	Latitude	Longitude	Dune type	Depth (m)	Age (ka)
CH16	N 16° 52’ 48.5”	E 18 32’ 38.2”	Barchan	0.6m	14.8 ± 1.5
CH22	N 16° 46’ 45.6”	E 18° 17’57.5”	Barchan	1.5m	15.0 ± 1.5
CH51	N 16° 42’ 17.5”	E 17° 42’ 57.1”	Barchan	0.5m	17.0 ± 1.7
NG33 Phulkime	N 13° 17” 14.7’	E 13° 52’ 57.46”	Transverse	1.6m	15.6 ± 1.6
NG34 Madayi	N 13° 24” 21.4’	E 13° 48’ 43.3”	Transverse	2.3m	18.7 ± 1.9
NG35 Madeyi	N 13° 24” 21.4’	E 13° 48’ 43.3”	Transverse	3.25m	19.9 ± 1.9
NG36 Zango II	N 13° 22’ 05.9”	E 13° 50’ 08.5”	Transverse	2m	16.4 ± 1.6

OSL sample locations within the Bodélé depression in Chad (CH16, CH22, CH51), and Lake Chad in Nigeria (NG33, NG34, NG35, NG36). Details of the dating methodology, does rates and corrections can be found in Armitage et al. (submitted) and the supplementary information accompanying that paper.