Sedimentary and Geomorphic evidence of Saharan megalakes: a synthesis

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Abstract

It has long been recognised that the Sahara Desert contains sediment, landform and palaeoecological evidence for phases of increased humidity during the Quaternary period. Many authors have also suggested that during some of these humid periods very large lakes, termed megalakes, developed in several basins within the Sahara. Recent work has questioned their existence. In particular it has been argued that the lack of well-developed and spatially extensive shorelines in these basins suggests that discrete groundwater and spring deposits have been misinterpreted as evidence for megalakes. In this paper we re-evaluate the evidence used to identify megalakes. Firstly, we apply a comprehensive remote sensing and GIS analyses to the megalake shorelines, their catchments and the wider Sahara. This not only supports the previously proposed existence of numerous megalakes, but also indicates a previously unrecognised megalake in the Niger Inland Delta region, here named Megalake Timbuktu. Secondly, we review the geomorphic and sedimentary evidence for the megalakes, highlighting the importance of the sedimentary record in identifying lake highstands, particularly through the example of the Chotts Megalake in southern Tunisia where we provide new sedimentary information on lake shorelines. This analysis demonstrates that in much of the Sahara the dynamic aeolian systems preclude the preservation of well-developed shorelines, but the distribution of fragmented geomorphic features and localised lake deposits provide robust evidence for Quaternary megalake formation. The paper concludes by highlighting that although extensive evidence for Saharan megalake formation exists the current chronology of lake highstands indicates that the vast majority date to Marine Isotope Stage (MIS) 5 or earlier. Only megalakes Chad and Timbuktu, which derive much of their water from outside the desert, show evidence for Holocene (African Humid Period or AHP) shorelines. The AHP record of the other megalakes indicate the existence of much smaller water bodies than those that developed earlier in the Pleistocene indicating that it was significantly drier than these earlier humid phases.

Keywords

Sahara Desert; megalake; remote sensing and DEM analysis; sedimentology; shorelines.

1. Introduction

The Quaternary climate history of the low latitudes is dominated by cyclic changes in precipitation regime (Kutzbach and Street-Perrot, 1985; de Menocal et al., 2001; Prell and Kutzbach 1987). In multiple climate archives from these regions the timing of episodes of increased rainfall corresponds with precession modulated insolation maxima (Prell and Kutzbach 1987). This is seen most clearly in the $\delta^{18}O$ signal of speleothems and in the dust/mineralogical composition of marine sequences of these regions (de Menocal et al., 2001; Vaks et al., 2010; Helmke et al., 2008; Meckler et al., 2012; El-Shenawy et al., 2018). In arid regions, such as the Saharan and Arabian deserts, the poor-preservation of traditional biological proxies, e.g. pollen, and the restricted growth of speleothems means that an understanding of long-term changes in relative humidity/aridity is strongly reliant on geomorphic and sedimentary evidence (Drake and Bristow, 2006; Bristow and Armitage, 2016; Drake and Breeze, 2016). In areas that are currently arid/hyper-arid the presence of sediment/landform features such as spring mounds, travertine/tufa, lake shorelines, lacustrine sediments and fluvial deposits all provide evidence for hydrological processes being more active in the past (Grove and Warren, 1968; Kropelin et al., 2008). The dating of these features by ^{14}C, luminescence techniques and U/Th disequilibria, allows the timing of these humid phases to be reconstructed (Causse et al., 1989; Armitage et al., 2015).

In areas such as the Sahara the existence of such evidence, and the concomitant implications for the occurrence of Quaternary "humid" phases, has long been acknowledged (Grove and Warren,1968; Kuper and Kropelin, 2006; Kropelin et al., 2008; Drake et al., 2011). However, it is increasingly recognised that in some humid phases, the terrestrial record indicates that the landscape of the Sahara was not characterised by the existence of isolated and small-scale water bodies. Instead the record has been interpreted as indicating the existence of regional-scale integrated hydrological networks that occurred across the Sahara, terminating in a series of megalakes; megalakes Chad (Armitage et al., 2015; Drake and Bristow, 2006), Chotts (Causse et al., 1988; 1989; 2003; Zouari et al., 1998), Fezzan (Thiedig et al., 2000; Geyh and Thiedig 2008; Armitage et al., 2007; Drake et al., 2008), Darfur (Ghoneim and El-Baz, 2007); White Nile (Barrows et al., 2014; Williams et al., 2003), Tushka (Maxwell et al., 2010) and Ahnet-Mouydir (Conrad, 1970; Conrad and Lappartient 1991; Drake *et al.,* 2011). The proposed existence of these megalakes has wide-ranging implications for both palaeoclimate, as their formation requires large-scale increases in mean annual precipitation, and human dispersal, as it has been suggested that in concert they acted as humid corridors across the desert aiding human migration (Drake et al., 2011; Drake et al., 2008).

Although the formation of Saharan megalakes (here defined as lakes > 25,000 km^2 in area) has been widely accepted, the evidence that supports this theory is spread across large numbers of articles published over many decades. As such, no detailed synthesis and state of the art review of the evidence underlying the proposed occurrence of Saharan megalakes currently exists. Such ambiguity led Quade et al., (2018) to query the existence of these water bodies, arguing instead that humid phases in the Sahara were characterised by discrete, small-scale, isolated wetlands. Their study used two main lines of argument. Firstly, they question the quality of the geological data used to infer the existence of megalakes. Quade et al., (2018) have interpreted remote sensing imagery and reviewed some of the literature on selected megalakes to suggest that the evidence for megalake shorelines is limited and that many of the sediments and landforms previously defined as lacustrine were in fact spring and ground water features. Secondly, Quade et al., (2018) argue that rainfall within their mapped catchments of these megalakes was insufficient to generate surface water bodies of the extent that has been previously suggested. The re-interpretations by Quade et al., (2018) would have major implications for our understanding of both the Quaternary palaeoclimatic history of the region, and human dispersal pathways.

In this paper we re-evaluate Saharan megalakes in three different ways. Firstly, we investigate each of the proposed megalakes using a diverse array of remote sensing imagery compiled and viewed using Google Earth Engine (GEE) to allow seamless examination of the entirety of the Sahara. These data comprised PALSAR L band HH and HV radar, Landsat TM, Sentinel 2 and Google Earth imagery, Shuttle Radar Topography Mission (SRTM) and Advanced Land Observing Satellite (ALOS) 30 m Digital Elevation Model (DEM) data, in the form of global image mosaics which can be compared at the click of a button. Using these data we investigated all megalake basins, but also other large topographic basins in the Sahara where megalakes could have occurred. We first looked at known shorelines to evaluate the utility of the different types of imagery for lake shoreline identification. We then used this knowledge to survey all basins. This analysis identified previously unrecognised shorelines as well as evidence for a hitherto unacknowledged megalake in the Niger Inland Delta region of Mali, the evidence for which we present below. The interpretation of DEMs and satellite imagery can be subjective, leading to disagreements about the evidence for the existence of some megalakes. To provide greater clarity on the existence of megalakes we have developed a method that allows the interpreter to obtain different levels of confidence about the evidence for the presence of a lake in a basin during the past. We then apply this technique to all proposed megalakes to evaluate the veracity of the evidence for their presence.

Secondly, we comprehensively review the evidence for Saharan megalakes, using the criticisms from Quade et al., (2018) as a basis for discussion. This study focusses particularly on Megalakes Chad, Fezzan and Chotts, since these are the systems that the authors of this study have worked on directly. We also consider the newly discovered megalake Timbuktu as well as Megalakes White Nile, Tushka, Darfur and Ahnet-Mouydir, of which only the latter two were considered by Quade et al. (2018). Finally, when considering megalake Chotts we present new sedimentological information from shoreline sediments that provide evidence for the existence of a large water body.

The article begins by briefly summarising the history of research on Saharan megalakes and presents our current understanding of the major palaeo-water bodies in this region. The paper is then divided into two sections. Firstly, the geomorphic and sedimentary evidence for megalakes is reviewed and new results presented that not only confirms the existence of most megalakes, but also reveals a new one along the Niger River in Mali. Secondly, the mapping of megalake catchments and the modelling of water levels is summarised and discussed. The paper continues by arguing that robust evidence exists for the occurrence of megalakes in the Sahara, in contrast to prior assertions by Quade et al., (2018). This study concludes by emphasising that although the vast majority of basins contain abundant evidence for the occurrence of megalakes, their chronology is often poorly constrained. This has significant implications for interpreting the Quaternary history of the Saharan region and the associated archaeological record.

2. Mega-Lakes in The Sahara – Current Ideas and Understanding

Evidence for increased surface water in the Sahara during different periods within the Quaternary has been recorded by large numbers of studies utilising a diverse range of evidence (Goudie, 1992; Kutzbach and Street-Perrot, 1985; Kuper and Kropelin, 2006). Whilst much of this evidence could indicate the existence of localised and discrete wetland environments or spring systems, some of it has been used to suggest the existence of large lake systems, or megalakes, that if existing reconstructions are correct (Figure 1A), would range in extent from 27,000 km^2 (megalake Timbuktu) to 361,000 km^2 (megalake Chad; Drake and Bristow 2006).

2.1 Megalake Chad

Megalake Chad (Figure 1A) is the largest of the systems discussed here and has an extensive network of shoreline features, identifiable by a range of techniques (e.g. Drake and Bristow 2006; Schuster et al., 2005). These include evidence for palaeo-shorelines eroded into the landscape, littoral sediment accumulations (deltas, spits and berms, Drake and Bristow, 2006) and fine-grained deposits within the deeper parts of the basin that contain diatoms (Gasse, 2002), ostracoda and molluscs (Bristow *et al.,* 2018) indicative of freshwater conditions. Dating of numerous shorelines suggest megalake Chad existed between 5-11 ka (Armitage et al., 2015) and during MIS5, with two beach ridges dated to 114.2±14 and

125.4±11.6 ka (Drake et al., 2011). The evidence preserved in the Chad basin is, therefore, extensive and well-documented. Consequently, it is only megalake Chad, of all the proposed Saharan megalakes, that Quade et al., (2018) support the existence of.

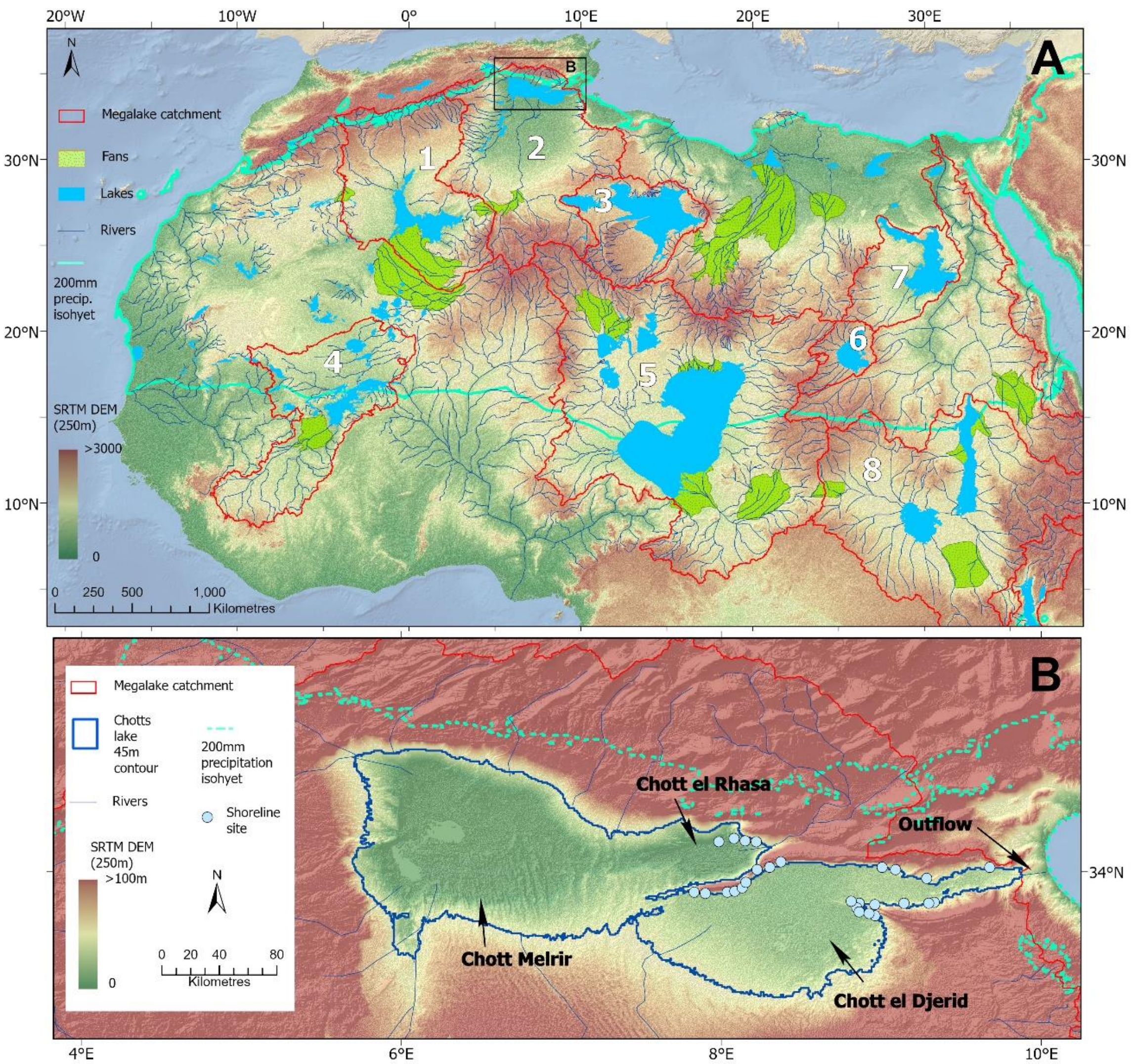

Figure 1. A) Map showing the topography (SRTM 1 km DEM) of North Africa overlain with the present-day 200 mm isohyet as defined by Worldclim (Fick and Hijmans, 2017), the location of the main rivers, fluvial fans, paleolakes, the catchments of the megalakes and their extent (from Drake et al., 2011 with new data added). 1 Ahnet-Mouydir, 2 Chotts, 3 Fezzan, 4 Timbuktu, 5 Chad, 6 Darfur, 7 Tushka, 8 White Nile. B) Megalake Chotts topography (SRTM 30 m DEM) overlain with rivers, megalake catchment boundary, present-day 200 mm isohyet and the 45 m contour, around which the location of the 27 shoreline sites (light blue dots) reported by Coque (1962) are clustered.

2.2 Megalake Chotts

Megalake Chotts (Figure 1A) is one of the smallest of the proposed megalake systems (~30,000 km^2) and is comprised of three sub-basins (Figure 1B), Chott el Djerid, Chott Melrhir and Chott el Rhasa which span southern Tunisia and eastern Algeria (Coque, 1962; Richards and Vita-Finzi, 1982; Causse et al., 1989; Zouari et al., 1998). The identification of this megalake is heavily reliant on the occurrence of outcrops of shell rich sediments that have been interpreted as littoral lacustrine deposits (Figure 1B). These occur at an altitude of about 45 m over distances of 150 km around the margins of the Chotts el Djerid and el Rhasa, but are most abundant around the northern margin of Chott el Djerid near the Tunisian town of Touzeur (Coque, 1962; Causse et al., 1989; Zouari et al., 1998). The dominant shells within these sediments are of the species *Cerasteroderma glaucum*. Although classed as a brackish water species, *C. glaucum* is tolerant of a range of salinities and is found in lagoons on the coast of Tunisia today. Consequently, some early researchers ascribed the formation of these deposits, which are rich in brackish-water indicators, to a marine environment prior to a phase of uplift (Richards and Vita-Finzi, 1982). However, since it is now widely accepted that there has been no recent (since the Plio-Pleistocene) marine incursion, the *C. glaucum* deposits are today interpreted as lake shoreline sediments (Causse et al., 1988; 2003; Zouari et al., 1998). These deposits do not form a well-defined continuous shoreline (Causse et al., 1988; Zouari et al., 1998), but they are found at the same altitude (~45m), and this corresponds with that of the low point of the Chott el Djerid sub-basin watershed, through which a lake would overflow into the Mediterranean Sea near the town of Gabes (Figure 1B). At ~45 m the spillways separating Chott sub-basins would also be overtopped, generating a single extensive water body.

2.3 Lake Megafezzan

The Fezzan basin is located in western Libya and contains extensive evidence for large-scale lake development during the Neogene. This evidence consists of extensive limestone beds that are distributed throughout much of the basin. When their distribution is considered in relation to the topography of the basin it suggests a maximum lake area of 135,000 km^2 (Drake et al., 2008). There has been much debate about the timing of lake high-stands in the Fezzan. Thiedig et al., (2000) and Geyh and Thiedig (2008) argued that the lakes were Middle Pleistocene, probably MIS 7 and 11, based on U/Th dating of limestones. Brooks et al., (2003) proposed a lake highstand during the Holocene AHP based on identification of a shoreline, while Armitage et al., (2007) used luminescence dating of this shoreline along with sub-aqueous lake sediments to suggest high stands during the AHP and MIS 11. Drake et al., (2008) re-assessed the geomorphology of the proposed Holocene shoreline and concluded that it was in fact a springline, thus refuting a Holocene age for Lake Megafezzan. They investigated the sedimentology of the limestone bed reported in Geyh and Thiedig (2008) concluding that numerous thick sections (up to 30 m) of superimposed sand and limestone units indicated multiple, discrete lacustrine cycles. Hounslow et al., (2017) investigated similar sedimentary sections throughout much of the Fezzan Basin, and showed that their stratigraphy can be correlated over vast distances. Magnetostratigraphy of these sediments demonstrates that numerous high-stands occurred during the Miocene (Hounslow et al., 2017). Younger lake sediments in the basin yield MIS5 and Holocene ages (Drake et al., 2018), though in both cases these lakes were much smaller features (maximum surface area of ~1600km^2) than the megalake phases recorded in the Miocene limestone deposits. The evidence for these Late Pleistocene lake stands consists of birdsfoot deltas, coquinas and shell rich sands that contain sedimentary structures consistent with wave action and delta progradation at a lake margin (Drake et al., 2018). These deposits are interpreted by Quade et al., (2018) as spring deposits, however the presence of deltas and the evidence for wave action clearly precludes this possibility.

2.4 Megalake Darfur

In Darfur, Ghoneim and El-Baz (2008) record the presence of shoreline features, the most impressive of which comprises multiple beach ridges that are stacked against each other (Figure 2D). These beach ridges occur at the height of an overflow spillway (573±3 m), strongly implying that they were formed by an extensive water body within the Darfur basin. The beach ridges are neither extensive nor continuous, but their form and altitude is consistent with formation by a megalake. The altitude of the implied shoreline indicates that it had an area of 30,750 km^2. The age of this feature is currently poorly constrained, although Szabo et al. (1995) provided U-series estimates for a number of marl deposits in the region. Whilst some of these yielded early Holocene ages, implying the existence of water bodies during the AHP, the majority of ages relate to Pleistocene humid phases, including early and late MIS 5, MIS 7 and MIS 9. During the AHP there is evidence that a smaller lake (about 5330 km^2) existed in the Darfur basin (Hoelzmann et al., 2000). Since Hoelzmann et al. (2000) identified no shorelines related to this lake, the approximate area was determined using the elevation of archaeological settlements concentrated around the lake margin at an altitude of 555 m. Interestingly, this is precisely the elevation that we determine from the ALOS 30 m DEM for a shoreline beach ridge first identified by Parchur and Rottinger (1997) using radar imagery. Thus, two independent forms of evidence (remotely sensed and archaeological) suggest a lake shoreline at this altitude. Radiocarbon dating of the lake sediments suggests it existed between 9 and 4 ka, whilst highly depleted oxygen isotopes indicate intense summer rainfall, suggesting that the lake formed under an enhanced monsoon (Hoelzmann et al., 2001). These Holocene lake sediments preserve Nile Perch bones (Hoelzmann et al., 2001), a species that requires large (a minimum of several km^2), deep (several meters) and well oxygenated waterbodies (Van Neer 2012). The presence of Nile Perch in the Darfur sediments is inconsistent with them being spring deposits, as suggested by Quade et al., (2018).

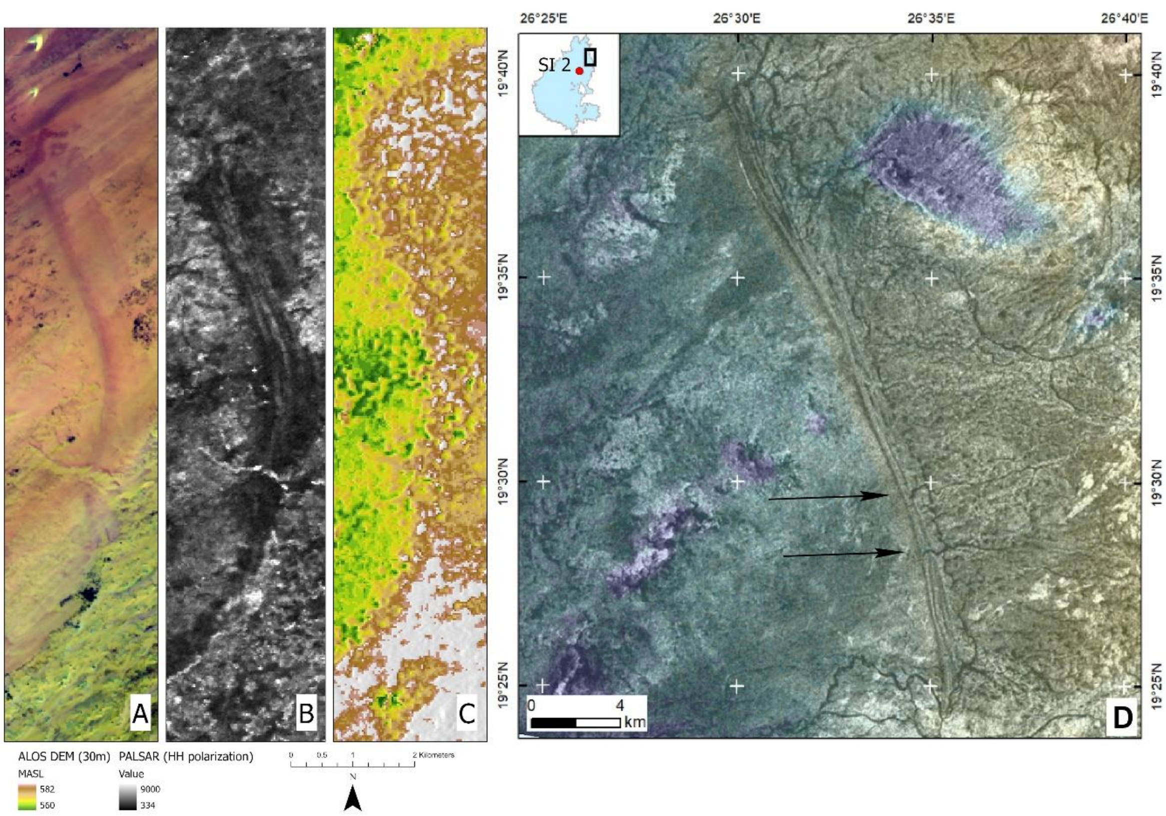

Figure 2. Paleolake shoreline of Megalake Darfur as revealed by (A) Sentinel 2 bands 12, 8, 2 (RGB) colour composite. The light north-south trending brown curvelinear feature is a beach ridge

shorelines. B) PALSAR HH polarisation radar image shows that the shoreline is composed of four ridges stacked against each other. C) the ALOS 30 m DEM showing the shoreline break of slope. D) Radarsat-1 image of the north-eastern part of the Megalake. In order to illustrate the topography, the SRTM 90 m DEM has been superimposed on the Radarsat-1 image with 85% transparency. A long palaeoshoreline showing beach ridges stacked against each other is evident. The two small wadis that are marked with arrows terminate exactly where they join the shoreline zone, as would be expected if they fed a paleolake and dried up at the same time it did (adapted from Ghoneim and El-Baz (2008)).

2.5 Megalake Ahnet-Mouydir

Conrad (1970) postulated the existence of a large lake in the Ahnet-Mouydir basin, based on extensive exposures of lake sediments. Causse et al., (1988) dated a substantial lake sediment outcrop using U/Th disequilibria to 92 + 20 -18 ka and Drake et al., (2011) used both the topography and altitude of the Causse et al., (1988) section to suggest that the Ahnet-Mouydir lake had a minimum surface area of ~50,000 km^2. Conrad and Lappartient (1991) summarise the geomorphology and sedimentology of the basin, reporting a number of locations with thick sections (up to 30 m) of lacustrine and deltaic sediments, characterised by a rich fauna of fresh and saline tolerant molluscs, ostracods, diatoms, foraminifera, and fish bones concentrated in several different levels. Such sediments could only have been deposited by an extensive lake.

2.6 Megalakes along the River Nile

Two megalake basins have been proposed along the course of the River Nile (Figure 1A). The first was identified on the basis of a shoreline adorned by cuspate headlands, spits and embayments located on the eastern margin of the Nile Valley (Figure 3A) south of Khartoum (Williams et al., 2003). This shoreline lies at an elevation of 386 m and was formed by a lake with an area of 45,000 km^2 (Williams et al., 2003). Like megalake Chad, this lake was fed by headwaters outside the Sahara, and extended southwards into the Sahel (Figure 1A). Burrows et al., (2014) report a ^{10}Be age of 109 ± 8 ka for the shoreline. Regional topography suggests that the lake was formed by an increase in White Nile discharge (Williams et al., 2003), implying higher effective rainfall both locally and in the headwaters around Lake Victoria.

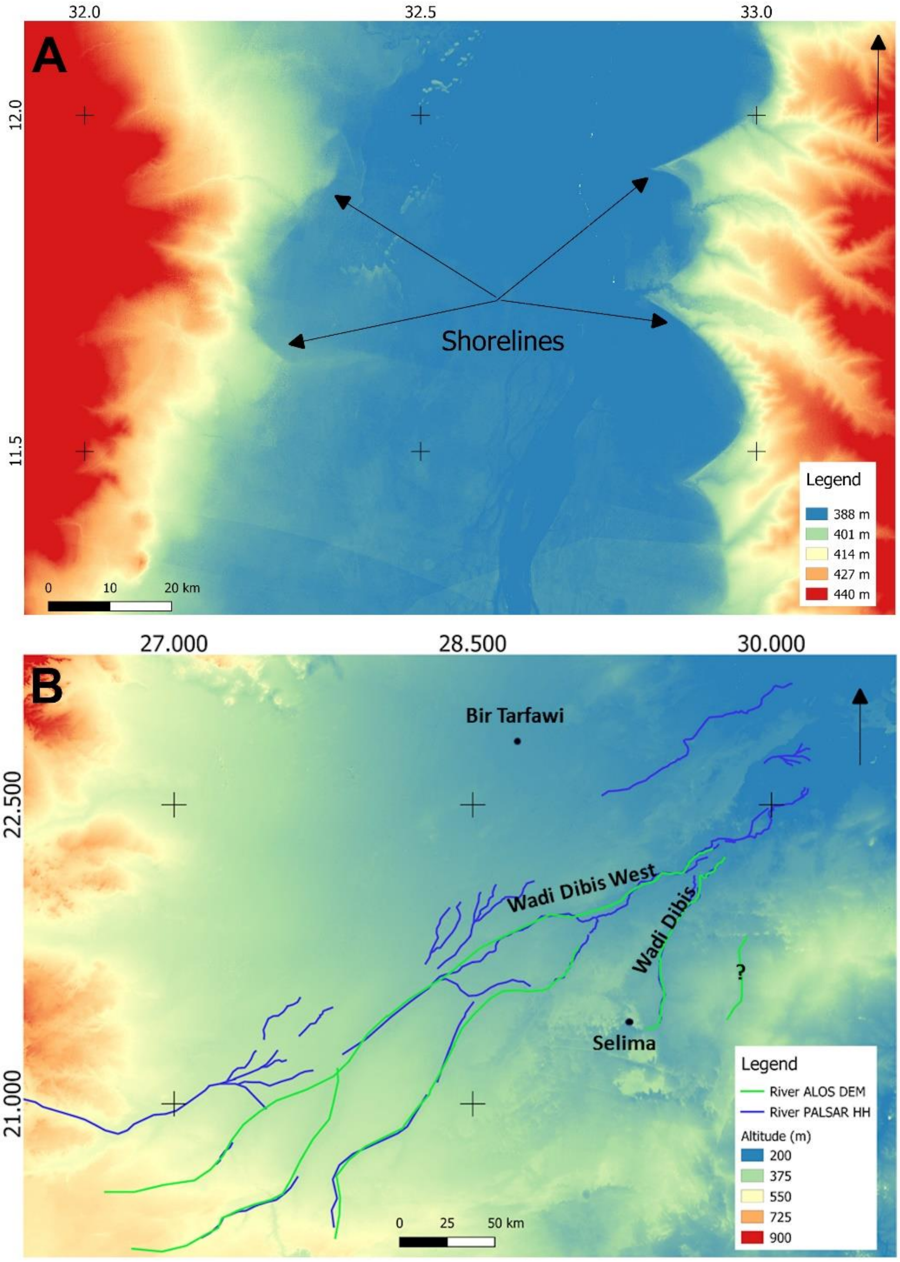

Figure 3. A) ALOS 30 DEM of the White Nile Megalake shorelines. The eastern shoreline is clearly evident in marked contrast to the western margin of the lake. The arrows indicate the only two fragments of the shoreline preserved on the western side of the lake and some of the most obvious shorelines on the eastern side, where similar features are preserved for much of its length (750 km). B) ALOS 30 m DEM of the Selima Sand Sheet. The rivers that were manually digitised from the DEM are shown in green whilst those digitized from the Palsar HH imagery are shown in blue.

The second proposed Nile megalake is located downstream of the first in northern Egypt. Maxwell et al., (2010) used SRTM 90 m DEM data to show that river channels flowing into a depression west of the Nile Valley terminate at an altitude of ~247 m. This altitude matches the elevation of Middle Pleistocene fish fossils at Bir Tarfawi, which is located in the same basin, suggesting that the channels terminated in a megalake of 68,200 km^2 in the basin (Maxwell et al., 2010). A lower lake level (190 m) is also postulated based on the elevation of Wadi Tushka, a river valley that links the River Nile to the basin. The elevation of this channel is consistent with Palaeolithic sites at Bir Kiseiba and Maxwell et al., (2010) use this evidence to suggest a further lake at this time. It is proposed that the source waters for both these lakes was local rainfall and the overflow of the Nile through Wadi Tushka during periods of strengthened monsoons.

3. Saharan Megalakes – Myth or Reality?

The existence of the Saharan Megalakes discussed above has recently been challenged by Quade et al., (2018) who examined remotely sensed data from the proposed megalake basins and suggest that no reliable evidence exists for well-developed and spatially extensive shorelines in these regions. They use their extensive experience of working on large lake systems from elsewhere in the world to suggest that any major lacustrine system would, on the basis of water depth and surface area, be affected by wave processes. These wave dominated shores should be characterised by the erosion of sediments and the deposition of shorelines composed of wave mobilised bodies of sediment. Such shorelines would also include deltaic landforms that represent sediment accumulation at the interface between the lake and major tributaries. Furthermore, they suggest that shorelines produced by these wave processes should be characterised by sedimentary evidence for wave activity (cross-bedding and rounded-clasts for example). The absence of such shoreline features has led Quade et al., (2018) to suggest that these megalakes cannot have existed, and that any lake deposits (e.g. marls, mudstones and gypsum) relate to much smaller, discrete wetland systems, whilst any “shoreline” deposits are likely to be spring or groundwater related features that have been misinterpreted as indicative of a more extensive lake system. To aid future researchers, Quade et al., (2018) propose a series of objective criteria for identifying ancient megalakes. However, despite their extensive field experience in other regions of the world, the authors of this study do not appear to have visited any of the Saharan sites which they discuss. Instead, Quade et al., (2018) dismiss geomorphic evidence for the existence of Saharan megalakes based solely on interpretation of satellite imagery and their reinterpretation of published data. The second argument made by Quade et al., (2018) is that the volume of water required to generate the proposed megalakes is too great to be feasible given: 1) The extent of their reconstructed catchment of each system; 2) The modern annual rainfall regime at the location of each megalake (typically <<100 mma^{-1}) and 3) the modelled increase in mean annual rainfall in "wet" phases during the Holocene humid period, relative to present day rainfall.

The review by Quade et al., (2018) is important for two reason. Firstly, it provides objective criteria for identifying ancient megalake systems. Secondly, it attempts to synthesise geomorphic data from a range of lake basins across the Sahara. This is the first exercise of its kind as most studies focus on reconstructions that are specific to individual basins. Because the findings of this work have major implications for both the palaeoclimate and human history of the Sahara, we discuss the ideas and issues raised by Quade et al. (2018) in the following sections. In the next section we consider the presence/absence of shoreline features in the landscape of the megalake basins and discuss the evidence for such features along with the possible causes for their absence. In the subsequent section we discuss the modelling of the catchments of these basins and the implications that this has for the viability of megalake formation.

4. Geomorphological and Sedimentary Evidence for Saharan Megalakes

4.1 Geomorphic evidence for shoreline features

A major tenet of the Quade et al., (2018) argument is that in the majority of the large lake systems that they have worked on, well-developed and spatially extensive shoreline features exist. They provide a number of examples, including Lake Bonneville (North America), Lake Lisan (Middle East), Ngangla Ring Tso (Asia), Lake Uyuni and Cardiel (both South America) which have mappable and readily identifiable shoreline landforms. A key difference between the large lake systems described by Quade et al., (2018) and the Saharan lake systems is the far greater importance of aeolian processes in the latter

(Sweezey, 2003). In much of the Sahara, and in particular in the proposed megalake basins, aeolian erosion and deposition is a major geomorphic process, and active sand sheets and dune systems cover a significant proportion of all of these basins. For example, ~55% of the megalake Darfur catchment is covered by sand (Hoelzmann et al., 2000), with the majority of these deposits being found in the centre of the basin where they largely obscure lake sediment and shoreline exposures. Dune fields are particularly common in these low lying areas because rivers transport sands and other fine grained sediments to these regions during humid periods and they are subsequently reworked during arid episodes.

Aeolian processes have the ability both to erode and to bury shoreline features. The effectiveness of such processes is amplified by the fact that the Saharan shoreline deposits are, in our experience, comprised primarily of sand and are therefore highly susceptible to aeolian erosion. In contrast, the examples cited by Quade et al., (2018) occur in regions where dune fields are negligible. It is likely that aeolian processes are key to the sediment dynamics of these Saharan megalake systems. Aeolian sands mobilised during arid phases and stabilised at the transition into more humid phases may subsequently be remobilised by lake processes and redeposited as shoreline features. These features are then eroded and reworked by the wind during the following arid phase. This process is clearly shown in Figure 4A, where the main shoreline of megalake Chad can be seen to terminate as it enters a sand transport corridor where wind is funnelled between the Ennedi and Tibetsi Mountains (Washington et al., 2006). Strong winds have eroded any trace of the shoreline for the next 100 km to the north and west.

Those shorelines that are not subject to aeolian erosion may instead be buried by transported sand. For example, as 55% of the Darfur basin is covered by sand, it would be expected to obscure substantial portions of any shoreline features which are present. Similarly, within the proposed Chotts megalake system, deflation of the Chott el Djerid saline mudflats produces a considerable amount of gypsum sand which is transported in a south-westerly direction and deposited on the south-western margin of the depression (Drake, 1997). This gypsum dunefield covers approximately one quarter of the proposed Chotts Megalake shoreline. Whilst Quade et al., (2018) propose that contiguous shoreline preservation is a pre-requisite for the identification of megalake highstands, we argue that aeolian sediment dynamics make this criterion unsuitable for application in the Sahara.

Instead we propose that the intermittent preservation or indeed complete absence of shoreline features is likely to be characteristic of regions such as the Sahara.

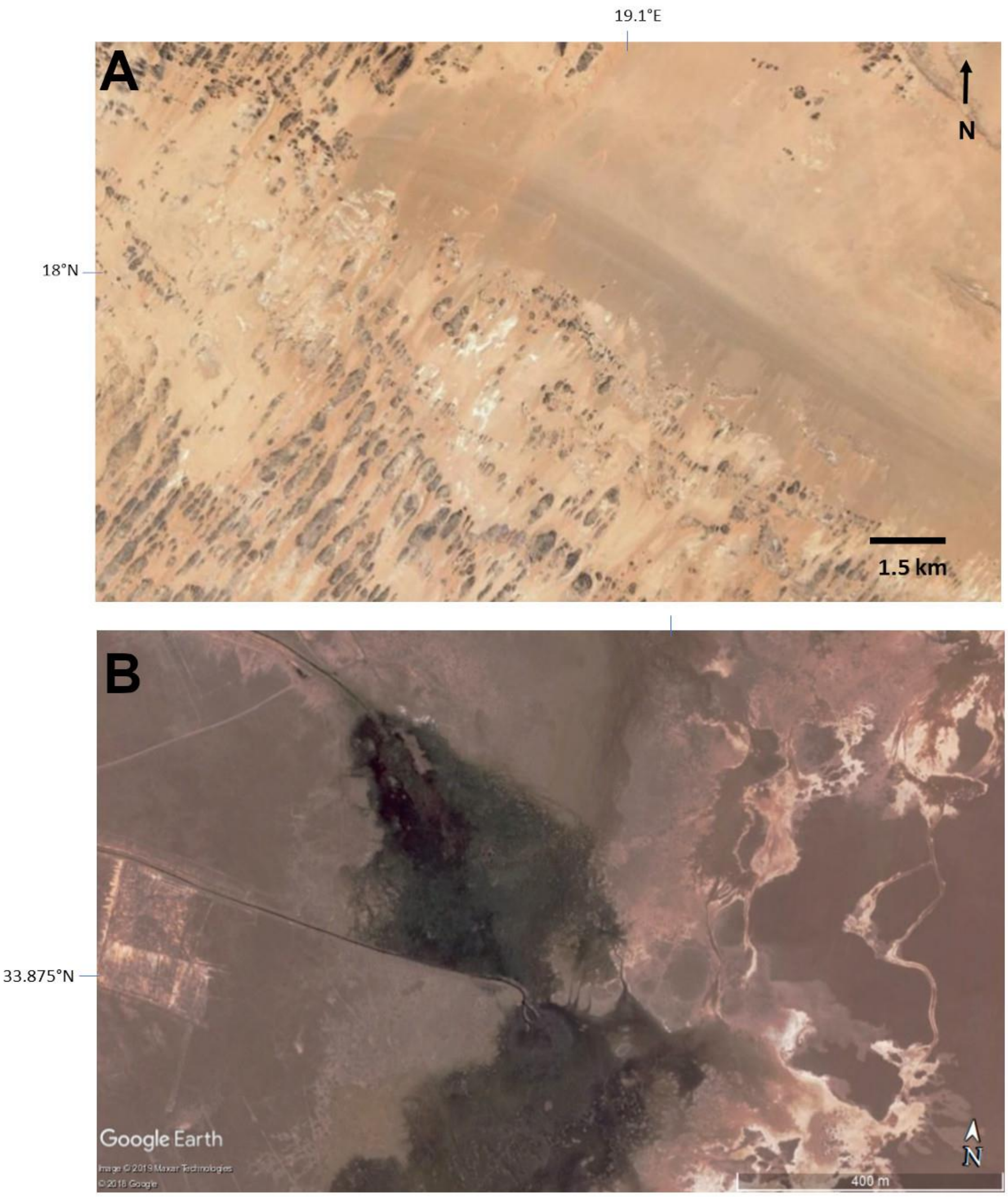

Figure 4. A) Bing Maps image of the termination of a megalake Chad AHP beach ridge (Microsoft product screen shot reprinted with permission from Microsoft Corporation). B) Google Earth image of the region between the Tozeur Oasis and the Chott el Djerid, showing wastewater drainage channels and plumes of water dispersing across the mudflat where they terminate. The straight dark lines feeding the water plumes are channels dug into the saline mudflats of the Chott el Dejrid in order to dispose of excess irrigation water from Tozeur oasis. These plumes were identified as springs by Quade et al., (2018). However, these are anthropogenic features (Imagery, Google, Maxar Technologies 2019).

Regardless of the role aeolian processes play in shoreline preservation, the assertation by Quade et al., (2018) that all lakes produce well-developed shorelines does not appear to hold. For example, in Ethiopia and Kenya at the southern end of the Main Ethiopian Rift there are three large endorheic basins containing Lake Abaya (surface area 1,081 km^2), Lake Chamo (310 km^2) and paleo-lake Chew Bahir. The latter is now a 210 km^2 saline mudflat (Fischer et al., 2020), but in the middle of last century it was a lake with an area of 2,200 km^2 (Figure 5). During the AHP these lakes were much larger and deeper than they are today, as evidenced by paleochannels linking Lake Abaya to Chamo (18 m above its present lake level), Chamo to Chew Bahir (14 m above the modern lake) and Chew Bahir to Lake Turkana (45 m above the now dry basin floor; Fischer et al., 2020). Analysis of cores from Chew Bahir indicates that a lake high-stand lasted throughout much of the AHP (Foerster et al., 2012). When this was the case the Abaya-Chamo-Chew Bahir-Turkana lake cascade system was functioning and all these lake were full. Given their large surface area, volume, and the duration of the high stand, one would expect to find palaeoshorelines in the basin, particularly at the altitude of the outflow channels. However, investigation of satellite imagery (PALSAR, Landsat TM, Sentinal 2 and Google Earth) and the ALOS 30 m DEM shows none are evident (Figure 5 A and B). Indeed, the only reported evidence for lake high stands that have been found found at Chew Bahir, are scattered shell beds found at the same elevation as the overflow sill (Fischer et al., 2020). This analysis demonstrates that not all large lakes produce shorelines that are clearly visible in satellite imagery or DEMs, and sometimes they only leave behind a small amount of scattered sedimentological evidence.

The absence of well-defined shorelines, even in areas where aeolian processes do not dominate, could reflect a number of factors. Firstly, to produce a well-developed shoreline feature, wave energy must be focussed at a tightly defined location for a substantial period of time. However, if the lake level and therefore the location of the shoreline routinely fluctuated, the result would be that any associated erosion/deposition would have been "smeared" across a broad area. This is likely to be particularly true in regions where the landscape surrounding the lake is subdued with a low gradient. In such settings, small changes in the altitude of the lake water will shift the focus of shoreline erosion/deposition to a different location, again resulting in sediments and landforms being spread over wide areas. Modern Lake Chad provides an example of such a lake and has not produced well-developed shoreline geomorphology during the last 3 ka. Secondly, if the underlying bedrock is soft and mechanically unresistant, as is the case in many of the Saharan megalake basins discussed here, then any geomorphic features cut into it are easily erodible. This means that even where erosive shoreline features are formed, they can subsequently be readily erased from the landscape and have limited preservation potential. These factors, combined with the impact of aeolian processes, may mean that many large lake systems leave patchy evidence for shoreline features in the landscape, even after prolonged high stands.

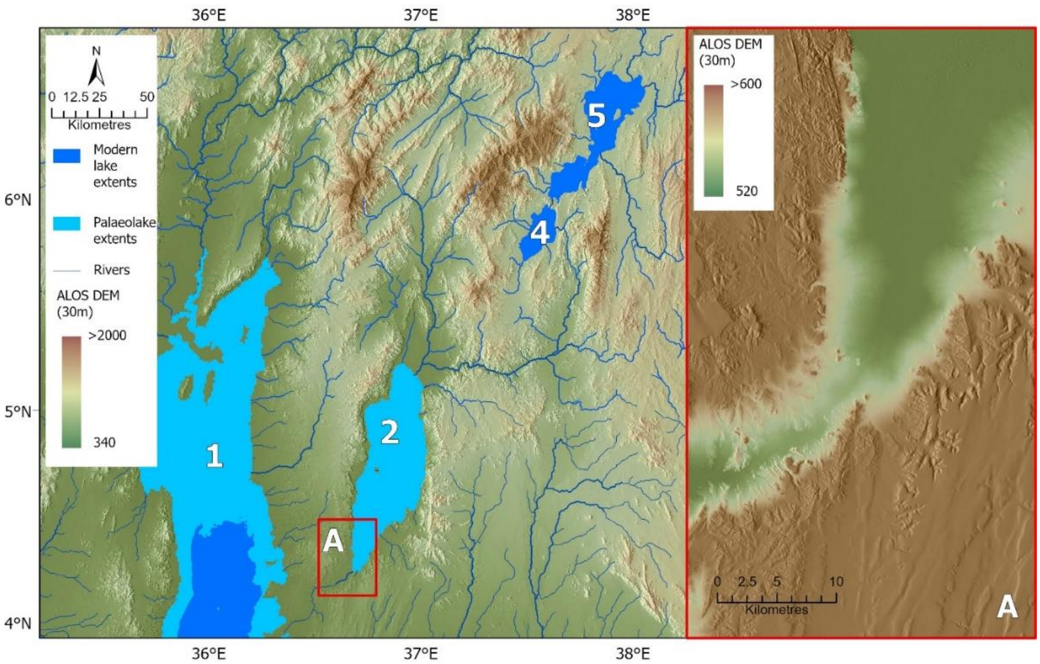

Figure 5. Topography of the Chew Bahir catchment and the northern part of the Lake Turkana as revealed by the ALOS 30 m DEM. Rivers are derived from HydroSHEDS and calculated using >100 km^2 in upstream accumulation area (Lehner et al., 2008). Current lake extent was obtained from the Global Water Occurrence dataset (Pekel et al., 2016, thresholded to areas with water > 90% of the time between 1984 and 2015), and paleolake extents from Drake et al., (2011). 1) Lake Turkana, 2) Paleolake Chew Bahir, 3) Lake Chamo and 4) Lake Abaya. The red box (A) outlines the outflow channel of Paleolake Chew Bahir that is shown in more detail on the right.

4.2 Remote sensing and DEM analysis of shoreline features

Many Saharan megalakes have been identified through detection of shorelines (e.g. megalake Chad and Timbuktu) or shoreline fragments (e.g. megalake Darfur and White Nile) using DEMs (e.g. Drake and Bristow 2006) or different types of remote sensing imagery including radar (Ghoneim and El-Baz 2008) and visible and infrared (Barrows et al., 2014). However, it is unclear what types of imagery or DEMs are best employed to implement a systematic analysis of megalake shorelines. In order to answer this question we investigated known shoreline using all the different types of satellite imagery and DEMs outlined in section 1. We found that the ALOS 30 m DEM identified all shorelines while the SRTM 30 m DEM identified fewer because it exhibited more noise and contained many areas with no data, since strong absorption of the radar energy precluded altitude estimation. PALSAR HH radar imagery identified many shorelines and, in some cases, added extra detail (e.g. Figure 2A, B and C). In contrast PALSAR HV imagery was extremely poor for shoreline detection. Visible and infrared imagery was approximately as effective as PALSAR HH imagery, and commonly provided detail not evident in the ALOS 30 m DEM or the radar imagery. Typically visible and infrared imagery was most useful where shoreline topography caused vegetation patterning and became more effective with higher spatial resolution (i.e. Google Earth imagery was more effective than Sentinel 2, which in turn was more effective than Landsat TM). Given these findings, our systematic mapping of shorelines started with ALOS. Once an interesting feature was detected the other types of imagery were studied to see if they provided further information to confirm or refute shoreline identification. The findings of this image interpretation are outlined below, where they are integrated with the wider literature on megalake geomorphology.

4.3 Evaluation of Megalake Geomorphology

4.3.1 Megalake Chad and Darfur

Quade et al., (2018) accept that the Chad basin contains a number of megalake shorelines, but dismiss the identification of shorelines in the Darfur basin on the basis that they are insufficiently extensive and have not been validated by field observations. However, Quade et al., (2018) do not discuss the most obvious shorelines in the Darfur basin, despite Ghoneim and El-Baz (2008) identifying multiple beach ridges stacked against each other

(Figure 2D). Furthermore, Ghoneim and El-Baz (2008) present compelling circumstantial evidence that the Darfur shorelines delimit a large lake. Firstly, multiple shorelines are preserved at the same elevation as the lowest point in the catchment perimeter, suggesting that the altitude of highstands was controlled by the elevation of a lake overflow. Secondly, two small wadis that flow into the Darfur basin have cut distinct channels into the surrounding landscape, but both channels terminate at the elevation of the proposed shorelines (Figure 2D). This landform arrangement is typical of rivers flowing into an extensive lake basin and grading to that regional base-level. Our analysis of the megalake using the Sentinel-2 20 m imagery, the ALOS 30 m DEM and the 25 m resolution PALSAR HH radar imagery has identified further shorelines landforms at the same altitude, including a series of beach ridges (Figure 2A, B and C) that are preserved at the same elevation as the shorelines shown in Figure 2D. These landforms could not have been formed by anything other than a lake. The fact that the shorelines associated with megalake Darfur are sparse and poorly preserved is consistent with the impact of aeolian processes described above.

4.3.2 Megalakes along the River Nile

The proposed White Nile megalake shoreline is poorly preserved. The ALOS DEM reveals a 370 km long stretch of well-developed shoreline on the eastern shore, but only two fragments on the western shore (Figure 3A) and nothing at the northern and southern margins. Shorelines are not evident on alluvial fans, where sand dunes are present, or when the shoreline is close to the active channel of the River Nile. These observations imply that most of the shoreline has been obliterated by a combination of aeolian and fluvial activity. Fluvial activity is particularly important in erasing geomorphic evidence for the White Nile megalake, since it extends outside the Sahara into the more humid Sahel.

We have reanalysed portions of the White Nile megalake shoreline using the ALOS 30 m DEM in a geographical information system (GIS) and find it to be about 10 m higher than reported by Williams et al., (2003) and Burrows et al., (2014). The preserved shoreline is no longer flat, being 9 m higher in the south than it is in the north, making lake area estimation difficult. Based on the mean shoreline height we calculate the lake area to have been 70,660 km^2, substantially larger than previous estimates. Below the main shoreline there is a bench, 5 m above the present-day river level at an elevation of 382 m, which has been interpreted as a further lake shoreline (Williams et al 2003). This shoreline has been dated to the late

Pleistocene and early Holocene, when White Nile flooding formed a lake with an area of 4690 km^2 (Williams et al., 2006).

The Tushka megalake is unique amongst proposed Saharan megalakes, since it was identified on the basis of fluvial rather than lacustrine landforms, and no shorelines have been reported. Maxwell et al., (2010) used the SRTM 90 m DEM to show that three wadis in the Tushka basin all terminate at the same elevation as lake sediments at Bir Tarfawi. However, few other outcrops of lake sediment are found in the basin that can be directly attributed to this lake, whilst the Bir Tarfawi sediments have since been shown to have been formed by a much smaller lake (Hill and Schild 2017). Furthermore, our analysis of the ALOS DEM shows that the three wadis studied by Maxwell et al., (2010) cease to be visible in the DEM at different altitudes (241 m (Wadi Dibis), 224 m (Wadi Dibis West) and 299 m (the wadi marked with a question mark in Figure 2 of Maxwell et al., 2010 and in Figure 3B), rather than 247 m as Maxwell et al. (2010) proposed. Thus, the new topographic information provided by the ALOS DEM does not support the existence of a megalake in this basin. This conclusion is endorsed by interpretation of the PALSAR HH imagery, which shows even more detail of the rivers, allowing the three wadis to be traced continuously from their sources to an altitude of about 200 m where they appear to have fed small lakes in localised depressions (Figure 3B).

4.3.3 Megalake Timbuktu

Using our GEE global image mosaics of the datasets discussed above, we discovered a new Saharan megalake in the vicinity of the Niger Inland Delta of Mali (Figure 6). It has long been recognised that during the last glacial maximum the delta was dry, with active dunes that blocked the Niger River valley at the Taoussa Gorge (Beaudet et al., 1977; Figure 6A). Upon the reactivation of the river during the AHP, the dunes damming the gorge are thought to have diverted a rejuvenated River Niger into the Araoune region (Beaudet et al., 1977), a large flat plain to the north of Timbuktu (Figure 6A and B). However, as the AHP progressed the River Niger cut through the dunes and its current course was established (Beaudet et al., 1977).

Petit-Mare and Riser (1983) investigated the Araoune region and confirmed the findings of Beaudet et al., (1977), recognising an interior delta containing a network of paleochannels and abundant lake sediment outcrops. We investigated this area using satellite imagery and DEMs and find that the paleolake sediments and river channels recognised by Petit-Mare and Riser (1983) are clearly visible. However, the ALOS 30 m DEM also reveals an abundance of lake shorelines, both in the Araoune and in the Niger Inland Delta, expressed as rhythmic shoreline features (RSF), that indicate the presence of a large lake. RSF's are undulations in a shoreline that are roughly periodic in space along the shore (Walton 1999, Pruszak et al., 2008; Figure 6D). In the inland Niger Delta they are found in various shapes, sizes and wavelengths. In many cases they form sand spit like features (Figure 6D), but in other cases the protrusions of sand are at or near 90˚ from the shoreline (Figure 6C). They also vary significantly in size (here defined by their width) and wavelength, with the smallest RSFs discernible in the ALOS DEM exhibiting an average width of 130 m and wavelength of 288 m (Figure 6C), while the largest ones found in the Niger River valley are 6 km wide with a wavelength of 8 km (Figure 6D). RSFs are usually rare shoreline landforms, but are common in this region of Mali, being found adorning the majority of paleolakes in the region (e.g. see figure 8A and B).

RSFs at an altitude of 264 m are found along the northern margin of the Niger River valley whilst a shoreline at the same altitude occurs on the southern margin but in this case it is composed of beach ridges and barrier islands (Figure 6D). Thus, a large lake must have existed here in the past. Shorelines adorned largely with RSFs, but also sometimes exhibiting beach ridge complexes and barrier islands (Figure 6C and D), are found at the same altitude in the southern Araoune, in the large deep lakes basins to the west of Timbuktu and along the edges of the numerous lakes to the south of the River Niger (Figure 6C). All these lakes are connected to the main lake in the Niger River valley by channels that, when the water level was at 264 m, would have transferred water from the latter to the former, producing one large interconnected water body. DEM analysis shows that this lake has an area of 27,352 km^2 and a maximum depth of 92 m, but was predominantly shallow, with a median depth of just 2 m. We have called this large expanse of water Megalake Timbuktu.

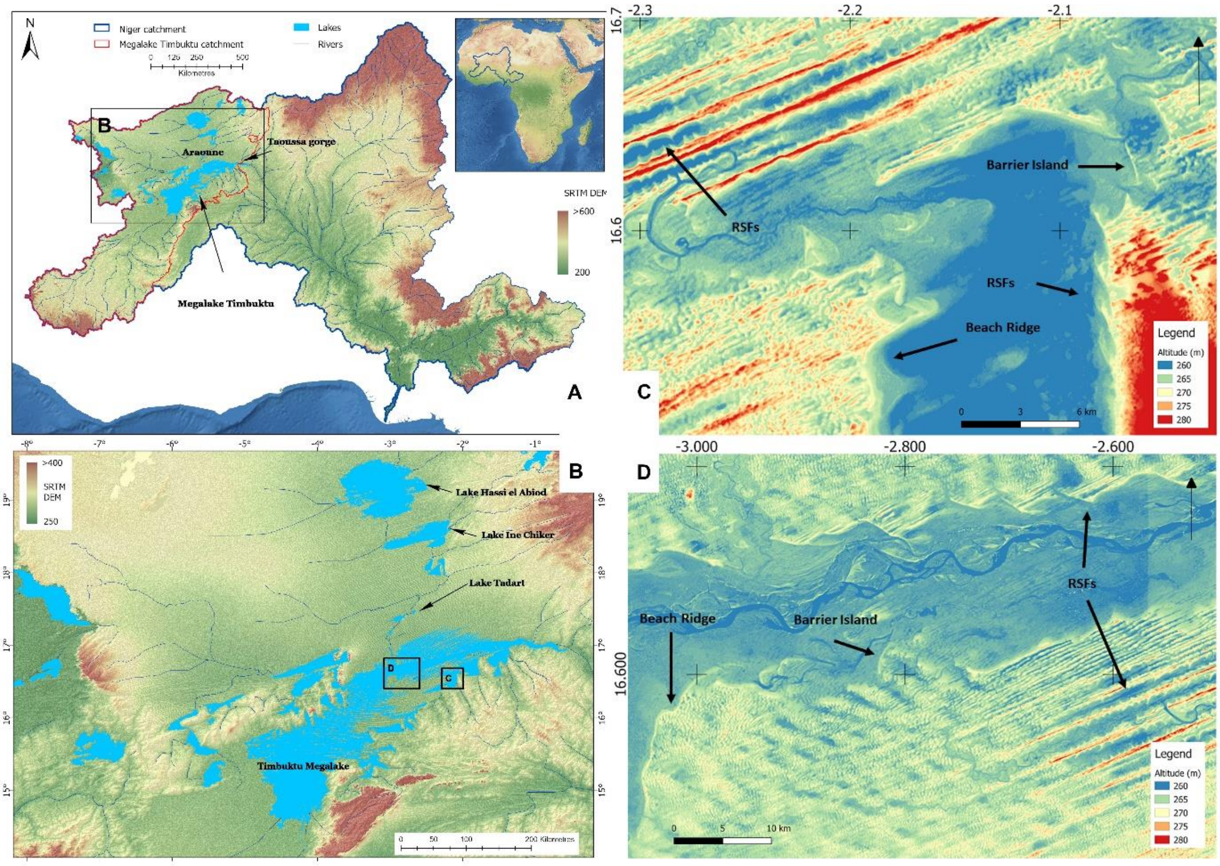

Figure 6. A) The topography of the Niger River Catchment derived from the SRTM 90 m DEM showing the Niger River, Magalake Timbuktu, its catchment and the other large lakes within it (rivers and lakes derived from Drake et al., 2011 apart from Megalake Timbuktu that was mapped in this study). B) A more detailed view of the paleohydrology of Megalake Timbuktu and the Saharan portion of its catchment. The topography is derived from the SRTM 90 m DEM and the lakes, rivers and catchments outlined in A. C) The shoreline landforms of the Lake Aougoundoupart part of Megalake Timbuktu as revealed by the ALOS 30 m DEM. D) ALOS 30 m DEM showing the shoreline landforms of Megalake Timbuktu along the Niger River valley. The northern margin of the River Niger valley is comprised of a series of large RSFs whilst smaller ones are found in the interdune depressions to the south. Similar small RSFs can be seen in more detail in C.

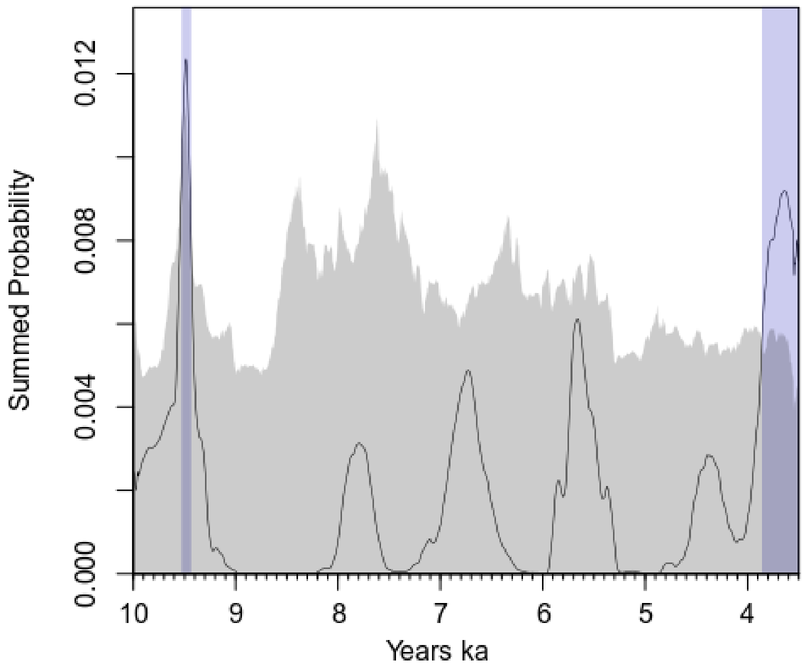

Figure 7. Monte-Carlo Summed Probability Distribution plot (Shennan et al., 2013) of the 15 radiocarbon dates tested against a null hypothesis of uniform hydrological activity between 10 and 3.5 ka employing 1000 simulations. The black line shows the probability distribution for the observed dates, the shaded grey area shows the 95% confidence interval from the simulated summed probability distributions and the blue bars indicate areas of the probability distribution that exceed the 95% confidence interval upper limit.

4.3.3.1 The age of Megalake Timbuktu

Megalake Timbuktu must have developed soon after the onset of the AHP and would have existed until the time the dune dam in Taoussa Gorge was breached. Though no direct dates on the shorelines of Megalake Timbuktu exist, there are 15 ^{14}C dates on aquatic fossil remains from other lakes in its catchment that shed some light on when the region was humid, and thus provide the best data currently available for its likely age (Table 1). If we plot the ^{14}C dates, there appears to be considerable fluctuations in the evidence for wetness from 10 to 3.5 ka (Figure 7). However, as there are only 15 dates the plot is dominated by the sporadic nature of the small sample size and the inevitable gaps between individual calibrated dates cannot be interpreted as a decline in hydrological activity (Bleicher 2013, Surovell et al. 2009).

SiteName	Latitude	Longitude	Labcode	C14 Age	C14 Error	Material	Reference
Arawan (1)	18.9000	-3.4667	UQ1021	8800	200	Mollusc	Petit-Maire and Riser 1987
Arawan (2)	19.0000	-3.5833	UQ1043	4800	100	Mollusc	Petit-Maire and Riser 1987
Azawad (1)	17.5167	-3.1000	GIF6460	3530	90	Mollusc	Petit-Maire and Riser 1987
Azawad (2)	18.0000	-3.0000	UQ1051	9250	100	Mollusc	Vernet 1998
Bou Jbeha	18.4667	-2.5667	GIF6459	3460	90	Mollusc	Petit-Maire and Riser 1987
Hassi El Abiod AR8	19.1000	-3.9167	UQ368	8450	60	Mollusc	Riser et al., 1984
Ine Chiker	18.6667	-2.5667	GIF6463	3940	90	Mollusc	Petit-Maire and Riser 1987
Jebel Tadart	17.4167	-3.0333	GIF6461	8500	120	Mollusc	Petit-Maire and Riser 1987
Kobadi hydrology	15.3500	-5.4833	PARISVI2	3335	100	Bone	Raimbault 1986
Tin guettai AR6	19.2700	-3.5400	UQ1019	8700	200	Mollusc	Petit-Maire and Riser 1987
Tin guettai AR6	19.2700	-3.5400	UQ1078	5900	200	Mollusc	Petit-Maire and Riser 1987
Tin guettai AR6	19.2700	-3.5400	UQ370	4970	60	Mollusc	Petit-Maire and Riser 1987
Hassi el Abiod AR7	18.7300	-3.4900	GIF5495	6970	130	Bone	Petit-Maire et al., 1983.
Hassi el-Abiod	19.1167	-3.9167	GIF6462	5920	100	Mollusc	Petit-Maire et al., 1983.
Kobadi	15.3580	-5.4870	PA221	3335	100	Bone	Jousse et al., 2008.

Table 1. Radiocarbon dates from paleolakes within the Megalake Timbuktu catchment. Dates are from fossil aquatic organisms found in paleolake sediments and archaeological sites on lake margins.

To test the significance of these fluctuations, we therefore use the Monte-Carlo Summed Probability Distribution (MCSPD) method of Shennan et al., (2013), which assesses the combined probability distribution of our 15 radiocarbon dates against a null hypothesis of uniform hydrological activity between 10 and 3.5 ka employing 1000 simulations (Figure 7). Our results reveal a departure from the uniform model, with two periods of increased hydrological activity at 9.5 and 3.9-3.5 ka (p-value=0.012). Between 9.5 and 3.5 ka the observed data does not fall outside the 95% confidence limit of the simulated data, suggesting there is insufficient data to reject uniform hydrological activity over this period.

These results therefore indicate that Megalake Timbuktu became active around 9.5 ka, when we see a peak in hydrological activity and the catchment remained relatively wet until 3.9 ka, at which point there was another peak in hydrological activity, which ceased at about 3.3 ka. However, the demise of Megalake Timbuktu was not caused by a return to aridity, but the breaching of the dune dam in Taoussa Gorge, and this could have occurred any time between 9.5 and 3.3 ka. Given the high erodibility of dune sands and the considerable discharge of the Niger River, thus its high erosivity, the failure of the dune dam is likely to have occurred sooner rather than later and thus probably happened in the early to middle Holocene.

4.3.3.2 Erosion of shorelines in the catchment of Megalake Timbuktu

There is an apparent contradiction between the excellent preservation of the Megalake Timbuktu shorelines and our argument that only fragments are preserved in deserts due to aeolian erosion and deposition. This can be explained by the fact that Megalake Timbuktu is situated on the 200 mm isohyet (Figure 1A), straddling the boundary between the Sahara and the Sahel. Here dunes were stabilised after the end of the Last Glacial, and aeolian processes are not particularly active, meaning that they retain their LGM dune form and evidence for subsequent modification by fluvial and lacustrine processes during the AHP. Moving north of the Megalake aridity increases, the dunes become more active, and the lake shorelines become less distinct as they are increasingly eroded and covered in sand. For example, 27 km north of the megalake, the shoreline of Lake Tadart (Figure 6B and Figure 8A) is completely intact, clearly showing both RSFs, embayments and beach ridges. A further 125 km north lies Lake Ine Chiker, with about one third of the shoreline remaining (Figure 6B and Figure 8B), though it still displays well developed RSFs. Another 110 km north lies Lake Hassi el Abiod (Figure 6B and Figure 8C) where about a fifth of the shoreline is evident and this is simply a highly eroded ridge with no other diagnostic features (Figure 8C). This north-south transect supports our argument that aeolian erosion and deposition severely affect shoreline preservation in the Sahara. It clearly shows that in the sand sea of northern Mali just 262 km north of the Sahara/Sahel boundary the vast majority of the paleolake shorelines are no longer visible in remote sensing imagery or DEMs, with only fragments remaining.

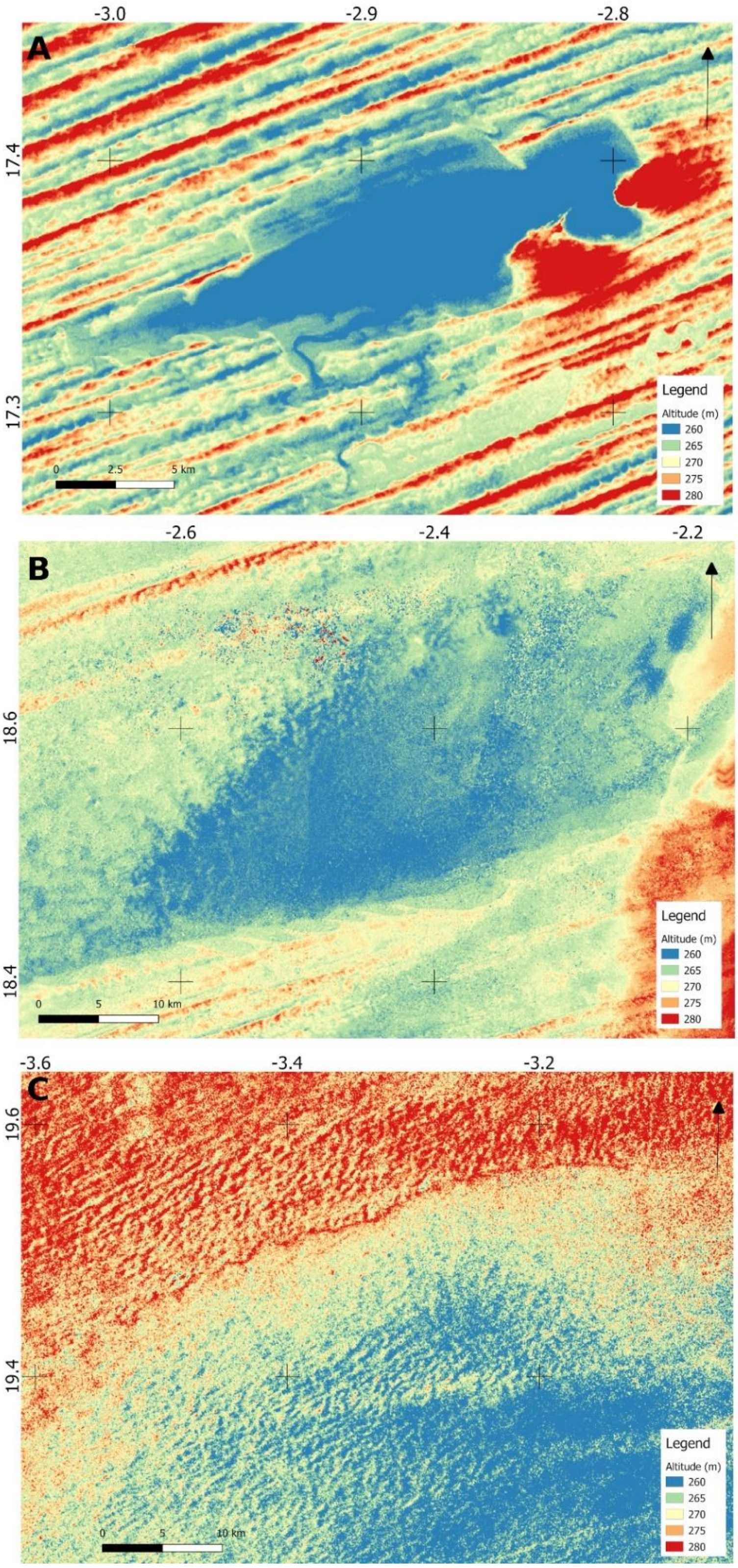

Figure 8. Timbuktu catchment lakes. A) ALOS 30 m DEM of paleolake Tadart, B) paleolake Ine Chiker and C) paleolake Hassi el Abiod. See figure 6B for their location.

4.3.4 Confidence Estimation for Remote Sensing and DEM analysis of Megalake Geomorphology

Three of the megalakes discussed above have been identified solely by interpretation of shoreline features in satellite imagery and DEMs (i.e. Darfur and Timbuktu, Tushka), and have not been verified with field evidence. Furthermore, the existence of two of these lakes has been questioned by others interpreting similar satellite imagery and DEMs (e.g. Megalake Darfur by Quade et al. (2018) and Megalake Tushka in this study). These disagreements occur because there are no formally recognised criteria using imagery and DEMs to identify palaeolakes. To overcome this problem we have developed a method that allows the interpreter to obtain different levels of confidence about the evidence for the presence of a lake in a basin during the past. We have then applied the method to all the megalakes discussed above in order to evaluate systematically the veracity of the lake shoreline evidence.

Our method recognises that not all shoreline landforms are equal; some are more diagnostic than others. The least diagnostic shorelines are single beach ridges or wave ravinement surfaces. This is because similar shaped landforms can be formed in other ways, thus there is an uncertainty associated with their attribution as a shoreline. Figure 9A illustrates this point, showing a break of slope overlain by sand dunes, which could be a lake ravinement shoreline or simply a reflection of variation in the topography underlying the dunes. In contrast, many costal landforms have more diagnostic shapes, such as spits (Figure 9B), cuspate headlands (Figure 9C), barrier islands (Figure 9D), beach ridge complexes (Figure 9E), tombolos (Figure 9E), deltas (Figure 10A), and RSFs (Figure 9F). Thus, their identification in a closed basin provides strong evidence for the presence of a lake.

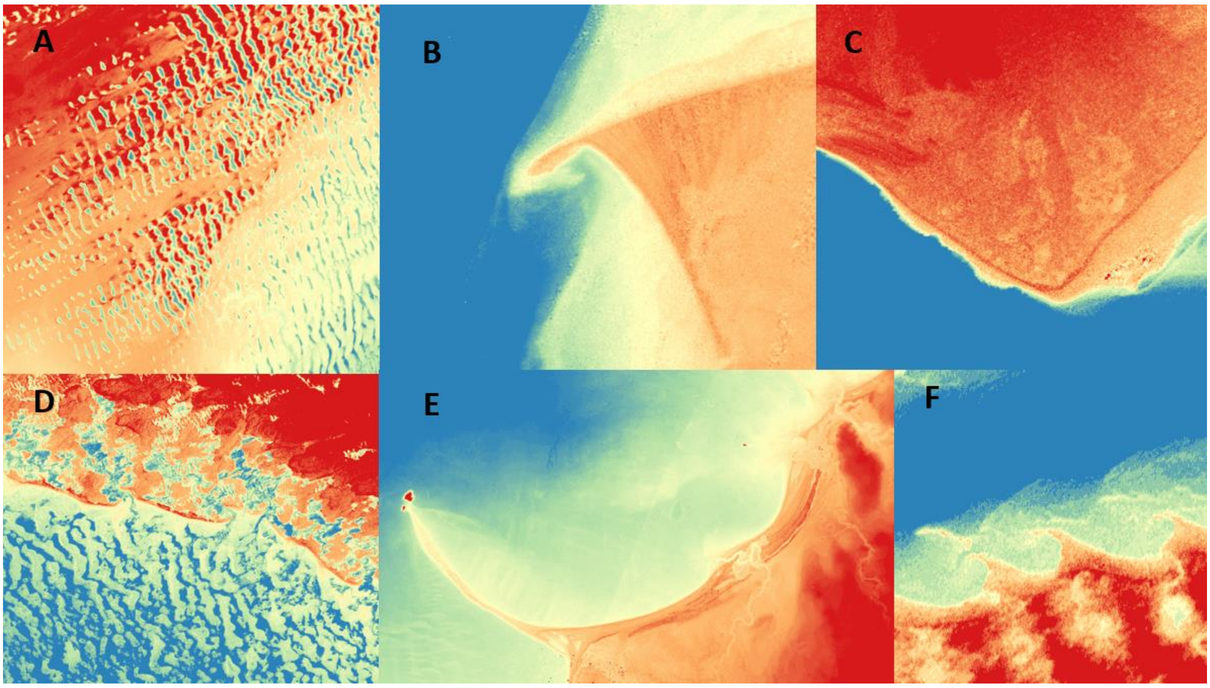

Figure 9. Shoreline landforms of Megalake Chad (a,b,c,d,e) and Timbuktu (f) as revealed by the ALOS 30 m DEM. A) Lake ravinement shoreline at E15.454, N13.156. B) Sand spit at E18.6446, N15.8075. C) Angamma Delta Cuspate headland at E17.7320, N17.5631. D) Barrier islands at E13.5848, N14.4087. E) Beach ridge complexes and Tombolo at E17.5328, N12.1363. F) RSFs at W4.3918, N16.5749. Low elevations are displayed in blue, intermediate yellow and high red.

Unfortunately, diagnostic landforms are rare in comparison to their undiagnostic counterparts, and are sometimes absent. In the latter case, altitudinal relationships between the different undiagnostic shoreline landform fragments in a basin can provide evidence for the presence of a paleolake, because all coastal landforms formed in a single phase of lacustrine activity will be found at the same altitude. Furthermore, if the lake has filled to the level of an outflow, the shorelines will have the same altitude as the lowest point on the catchment rim, where a lake outflow channel may also be found.

Given these characteristics of shorelines it is possible to use them to assign different levels of confidence to the identification of a paleolake in a basin. We express this confidence using a scale of 0 (uncertain) to 5 (certain). If there is only a single small exposure of an undiagnostic shoreline in a catchment it is not possible to demonstrate that there was a lake in the basin (Level 0). However, extensive preservation of an undiagnostic shoreline at the same altitude or smaller exposures at multiple locations are suggestive of the presence of a lake in the basin in the past (Level 1). If these landform altitudes coincide with that of the lowest point on the catchment rim, where lake outflow would be expected to occur, it adds further evidence (Level 2), as does the presence of a lake outflow channel at this location (Level 3). If a diagnostic landform is found then it is highly likely that a palaeolake existed in the basin (Level 4), and the presence of more than one diagnostic landforms in a basin constitutes unequivocal evidence for the presence of a palaeolake (Level 5).

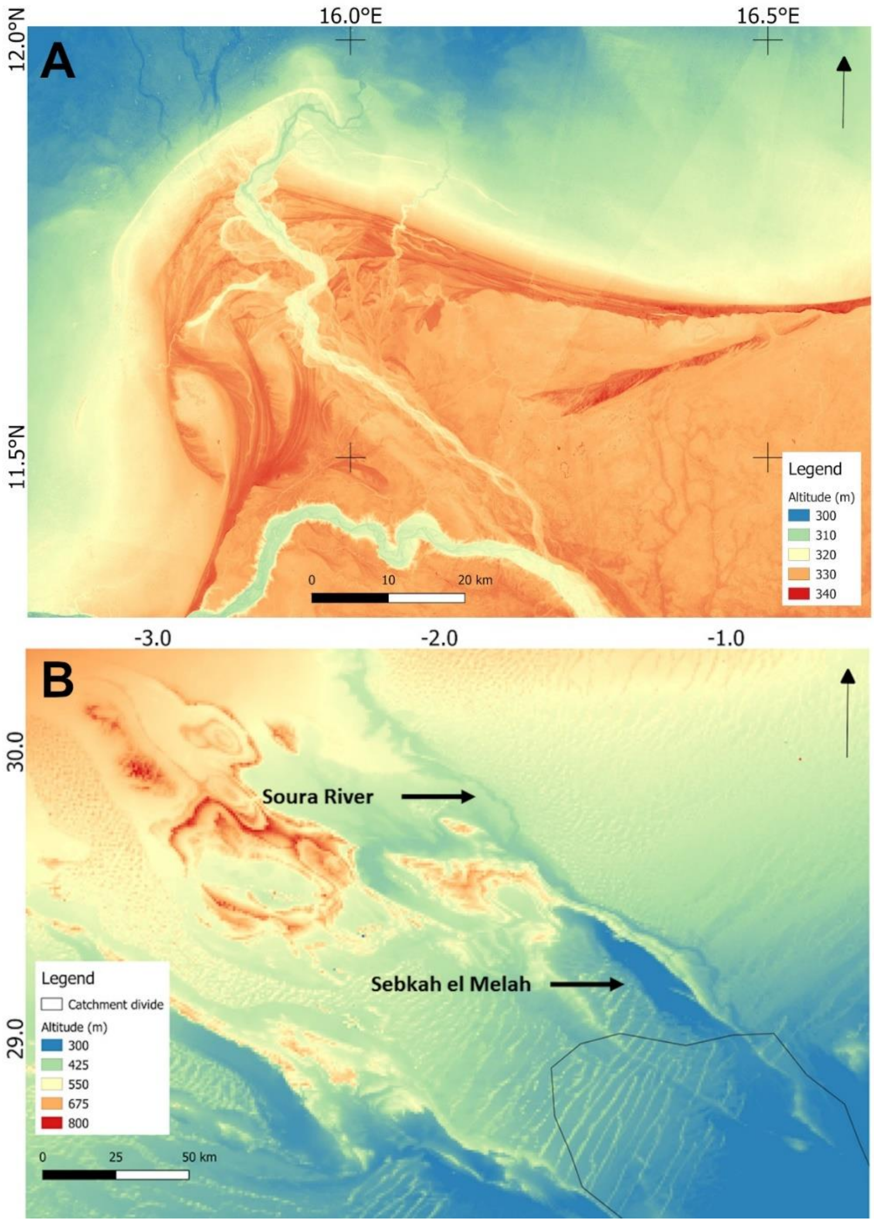

Figure 10. A) ALOS 30m DEM of Lake Megachad's Chari Delta. The delta front is composed of numerous different beach ridge complexes that have been incorporated into the delta as it prograded into the megalake. B) Topography (SRTM 1 km DEM) of the Soura River region. The black line shows the catchment boundary as mapped by Quade et al., (2018).

Applying this classification scheme to the Saharan basins where controversy exists, we find that the Darfur Megalake scores a 5 because of two diagnostic landform exposures, both at the same altitude as the lowest point on the catchment rim. Tushka Megalake scores 0 because no shorelines are identified. The less controversial Megalakes Chad, White Nile and Timbuktu all score 5 due to the presence of diagnostic shoreline landforms. In contrast Megalake Fezzan, Ahnet-Mouydir and Chotts all score 0 because no shorelines have been identified by remote sensing and DEM analysis in these basins. However, the absence of shoreline features evident in images of DEMs in some basins is not unexpected given the impact of aeolian processes, though it does preclude the identification of palaeolakes using remote sensing alone. In these areas it may still be possible to identify shorelines, and therefore megalakes, on the basis of sedimentary evidence.

4.4 Sedimentary evidence for Saharan Megalakes

In some of the Saharan basins it is sedimentary rather than geomorphic evidence that has been used to infer the presence of lacustrine systems. Many authors report the occurrence of shell-rich deposits and have used the altitude of these to infer the height of palaeo-lake levels. Quade et al., (2018) have suggested that many of these deposits were spring and groundwater deposits that have been mis-interpreted as lake shorelines. It is important to highlight that this suggestion is based on a study of satellite imagery and not field observations.

The sedimentology of the Fezzan basin has been investigated in detail. Evidence supporting the existence of Lake Megafezzan consists of outcrops of interbedded lacustrine limestones and sandstones that are protected from erosion by a layer of heavily indurated limestone. These outcrops are found throughout much the Fezzan Basin, their stratigraphy can be correlated over vast distances and dating shows that they are similar in age (Hounslow et al., (2017), thus providing conclusive evidence for a large lake. For example, the eastern margin of Lake Megafezzan is defined by a 200 km long outcrop of shallow freshwater limestone that could not have been deposited by anything but a large contiguous body of water.

The sedimentary evidence for the Ahnet-Mouydir megalake is comprised of numerous outcrops composed of thick sequences of lacustrine and deltaic sediments, with some sections recording the transition between these two facies indicating the progradation of the delta over the lake sediments as the water level fell. The sediments are extremely rich in organic remains, with numerous layers composed exclusively of either shells or diatoms (Conrad and Lappartient 1991). The shell layers consist primarily of *C. glaucum,* which is indicative of brackish conditions, but species such as Hydrobiidae sp. that can live in freshwater or brackish waters are also present. In some layers these species are absent and *Bithynia thomasi* and *gaudryi*, *Melanoides taberculata* and Planorbis sp. dominate, suggesting a different lacustrine environment. The diatomites include 45 different species (names not reported by Conrad and Lappartient 1991) found associated with ostracods (Potamocypris sp., *Cyprideis cf. torosa* Jones, and *Cyprinotus cf. salinus* Brady) and foraminifera (*Ammonia beccarii* (Linnne) var.tepida Cushman, Protelphidium sp., and Elphidium sp.). Fish bones are also present belonging to Percidae and Siluridae families (Conrad and Lappartient 1991). The sedimentology, large spatial distribution of the lake sediment outcrops and biological diversity can only be explained by their formation by a large lake. However, at present there is a lack of information on the exact location of many of the deposits and their altitudinal relationships. Furthermore, little work has been done on the facies relationships between them. Thus there are still large gaps in our understanding of this megalake.

In the Chott basins much of the evidence for megalake shorelines has been described from the area around the town of Tozeur at an altitude of about 45 m (Figure 1B; Zouari et al., 1998). Tozeur is famous as an oasis resort and is surrounded by extensive date palm plantations. On studying images of the Tozeur region Quade et al., (2018) observed no shoreline features but identified at least two active springs and large patches of white sediments that they interpreted as fossil spring deposits. From this they inferred that previous authors (Causse et al., 2003; Zouari et al., 1998) had mistaken these springs for shell rich lacustrine deposits. In fact the spring features that Quade et al., (2018) identify are the termination of channels dug into the saline mudflats of the Chott el Dejrid in order to dispose of excess irrigation water from Tozeur oasis. These channels can be clearly seen in Google Earth (Figure 4B). Furthermore, fieldwork shows that the patches of white sediments are the drier parts of the Chott mudflats, where efflorescent gypsum and halite crusts have started to develop on the playa surface. Nothing that Quade et al., (2018) discuss in reference to their interpretation of satellite imagery of the Chott basin relates to the features we have seen in the field, or those used to identify shorelines by Zouari et al., (1998).

The shell rich deposits described by Zouari et al., (1998) are found within Tozeur oasis and are not visible on satellite imagery because of the extensive palm tree canopy. Quartz-rich sand and shell deposits are found in the Touzer region (Figure 11), stretching westwards to the town of Nefta, whilst small outcrops of similar deposits have been reported in the Chott el Djerid basin across a distance of 150 km (Figure 1B; Coque 1962). Whilst Quade et al., (2018) have argued that these sediments should be interpreted as spring deposits, they are overwhelmingly dominated by a single species, the bivalve *C. glaucum* (Richards and Vita-Finzi, 1982; Causse et al., 1989; Zouari et al., 1998) indicating brackish conditions (Figure 11 (right) A). Modern springs in the Tozeur region contain no *C. glaucum* because they produce potable water, and are instead dominated by *Melanoides tuburculata*, implying that the two species are indicative of different depositional environments (Roberts and Mitchell, 1987). The *C. glaucum* shells within the proposed shoreline deposits are rarely in life position or articulated. Instead, they show evidence for current transport and occur within sandy deposits characterised by well-rounded pebble clasts (Figure 11 (right) B) and well-developed cross-bedding (Figure 11 (right) C and D). Disarticulated shells in cross-bedded sands and gravels are typical of shells that have been hydrodynamically sorted by traction currents and are common in beach shoreface environments (Reineck and Singh, 1980). Conversely, springs in the region typically produce spring mounds which are formed when gypsiferous aeolian dune sands are trapped by vegetation growing around the spring. These mounds typically display a complex stratigraphy with organic layers, root casts/traces and wash deposits dipping away from the water source and a molluscan fauna that is dominated by *Melanoides tuburculata* (Roberts and Mitchell, 1987). A final notable difference between springs and beach deposits is their altitude. Beach deposits are found clustered around 45 m because, in this basin this is the maximum altitude that lake waters could reach before overtopping a col that allows outflow into the Mediterranean Sea (Figure 1A). In contrast, spring deposits are found at a wide variety of altitudes, reflecting local variations in the position of the water table and the nature of the underlying rock strata. Consequently, spring and beach deposits are readily differentiated in the field, and we concur with Zouari et al., (1998) in their identification of shell rich shorelines in the Chott el Djerid region of Tunisia.

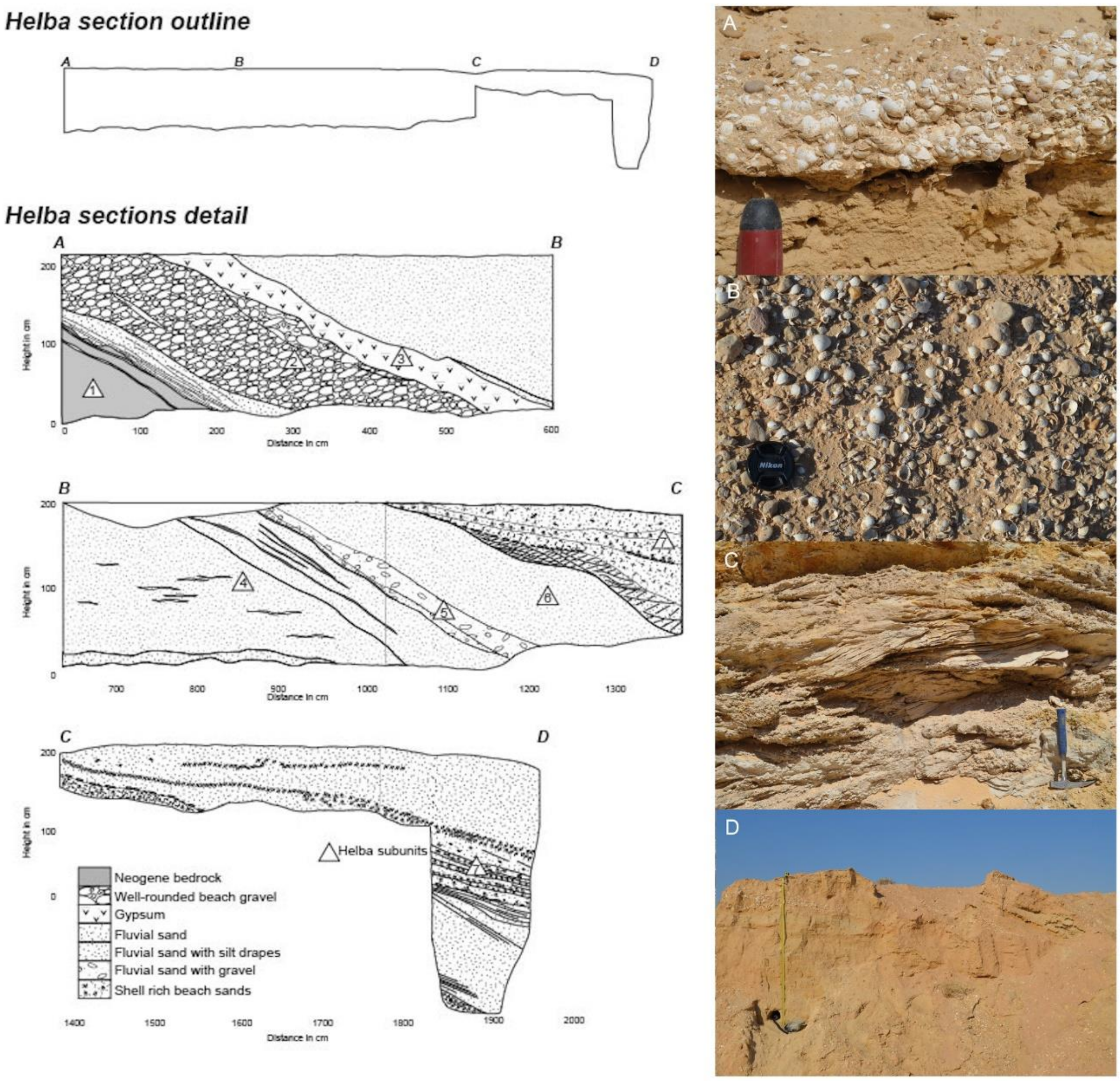

Figure 11. The figure on the right shows the sedimentary section of the lake shoreline outcrop at Helba Oasis. The full section is outlined at the top but has been split into three to allow the full detail to be presented. The seven subunits that make up the sequence consist of; 1) Neogene bedrock, 2) well-rounded clast rich deposits (shoreface), 3) gypsum (desiccating lake basin), 4,5,6) red fine-grained terrigenous sands (fluvial/sheetwash during low stand), 7) cross-bedded sands rich in unarticulated *C. glaucum* (shoreface). The photos on the left show the Characteristic sedimentary features of the palaeo-shoreline deposits in the locality of Tozeur. A) Comminuted shell beds showing disarticulated valves of *C. glaucum*. Such beds are typical of shells transported and

deposited by strong current flow processes. B) Palaeo-shoreline surface showing *C. glaucum* shells and well-rounded quartz clasts, the latter being the typical product of tractional shoreline currents. C) and D) cross-bedding within the palaeo-shoreline deposits at a range of scales, representing small-scale bedforms (C) and shoreface deposition (D).

The nature of shoreline deposits in this region can be illustrated using the site of Helba, located near the town of Tozeur. The deposit consists of medium/coarse sands with occasional fine pebbles and accumulations of disarticulated and reworked *C. glaucom* shells. The sands are typically cross-bedded. This sequence is shown in Figure 11 (left) and consists of 7 main stratigraphic units (listed from the base up): Subunit 1 consists of Neogene bedrock composed of gypsum and clays, subunit 2 is a deposit consisting of rounded gravel clasts and sand lenses, subunit 3 is a gypsum unit, subunits 4, 5, 6 are reddened fine sands and silts with clay drapes reflecting deposition of terrigenous deposits by fluvial processes and surface wash, subunit 7 consist of quartz-rich sands with beds of *C. glaucum* shells. This sequence is interpreted as containing two discrete shoreline deposits (subunits 2 and 7), coincident with high lake levels, separated by low stand deposits (subunits 3-6). These low stand deposits consist of an initial unit of gypsum accumulation (evaporite concentration and precipitation during lake desiccation, subunit 3) followed by the erosion and deposition of sediments by sheetwash and fluvial activity (subunits 4-6) during a period of low lake level.

The facies relationships between the high and low-stand deposits reflect lake rather than spring deposits. Furthermore, neither of the two shoreline deposits (subunit 2 and 7) can be interpreted as spring-line or groundwater deposits. Subunit 2 meets the criteria of a shoreline deposit as laid out by Quade et al. (2018), since it consists of well-rounded clasts. These sediments are typical of the accumulation of clastic material that has been rolled by wave processes along a littoral, shoreline environment. Whilst subunit 7 is not clast rich, the cross-bedding within the sands and the well-sorted nature of the sediments indicates that they are the result of current flow processes, whilst the abundance of *C. glaucum* shells supports the idea that this was current flow in association with brackish water. The deposition of sand by coastal processes associated with a large brackish water body can only be explained by shoreline processes operating in association with a lake system. As the formation of a lake shoreline at the altitude of Helba (40m) requires most of the Chotts to be flooded, the occurrence of these sediments requires the existence of a megalake.

The Helba sequences highlights the disadvantages inherent in trying to identify lake shorelines in the Sahara using remote sensing alone, since the shoreline deposit is buried by younger terrigenous sediments, obscuring it from view. This phenomenon is common in the Chott basin, and deposits rich in *C. glaucum* shells are often overlain by several meters of terrigenous sediments. Combined with the preferential location of oasis agriculture on these deposits, owing to their good drainage and low salinity, this makes the identification of continuous shorelines in the Chott basin via remote sensing problematic. In conclusion, the Chott el Djerid basin contains well-preserved shoreline sedimentary sections that contain clear evidence for an extensive lake system. The absence of shoreline landforms can be explained by erosion, burial or human activity.

From the above review of megalake sedimentology it can be concluded that in order for there to be strong sedimentary evidence for a megalake, the deposits must satisfy two criteria. Firstly, they must show evidence that the sediments are lacustrine not palustrine; all the megalakes discussed above meet this criterion. Secondly, they must exhibit sedimentary characteristics that can only be formed by a large lake. Here the strength of evidence varies. For Megalake Fezzan the evidence is strong with lacustrine sediments distributed over large areas. Evidence is also strong for the Chotts Megalake, with a multitude of shoreline sediment exposures exhibiting similar sedimentology found at a similar altitude around the basin. For the Ahnet-Mouydir Megalake the evidence is less strong. Although there are a number of lake sediment outcrops, their exact location and the altitudinal and facies relationships between them are as yet unclear.

5. Catchment Mapping and Rainfall Estimation

Quade et al., (2018) use the catchment size and past/present rainfall regimes of the Saharan megalakes in a modelling exercise, concluding that it was not feasible for megalakes to have existed during the Holocene AHP. However, in most cases the catchment areas used by Quade et al., (2018) were significantly smaller than those used in this paper (Drake et al., 2011; Figure 12 (top) and Table 2) and previously published estimates (e.g. Servant and

Servant, 1983; Schuster et al., 2005 for Lake Megachad). As a result, Quade et al., (2018) exclude a number of major tributary systems from their analysis that would have been important sources of runoff for Saharan megalakes. Furthermore, in most cases the catchments proposed by Quade et al. (2018) do not include mountains which form one of the main moisture sources for several Saharan megalakes, particularly in their function as 'water towers' (Lezine et al., 2011; Figure 12 (top)).

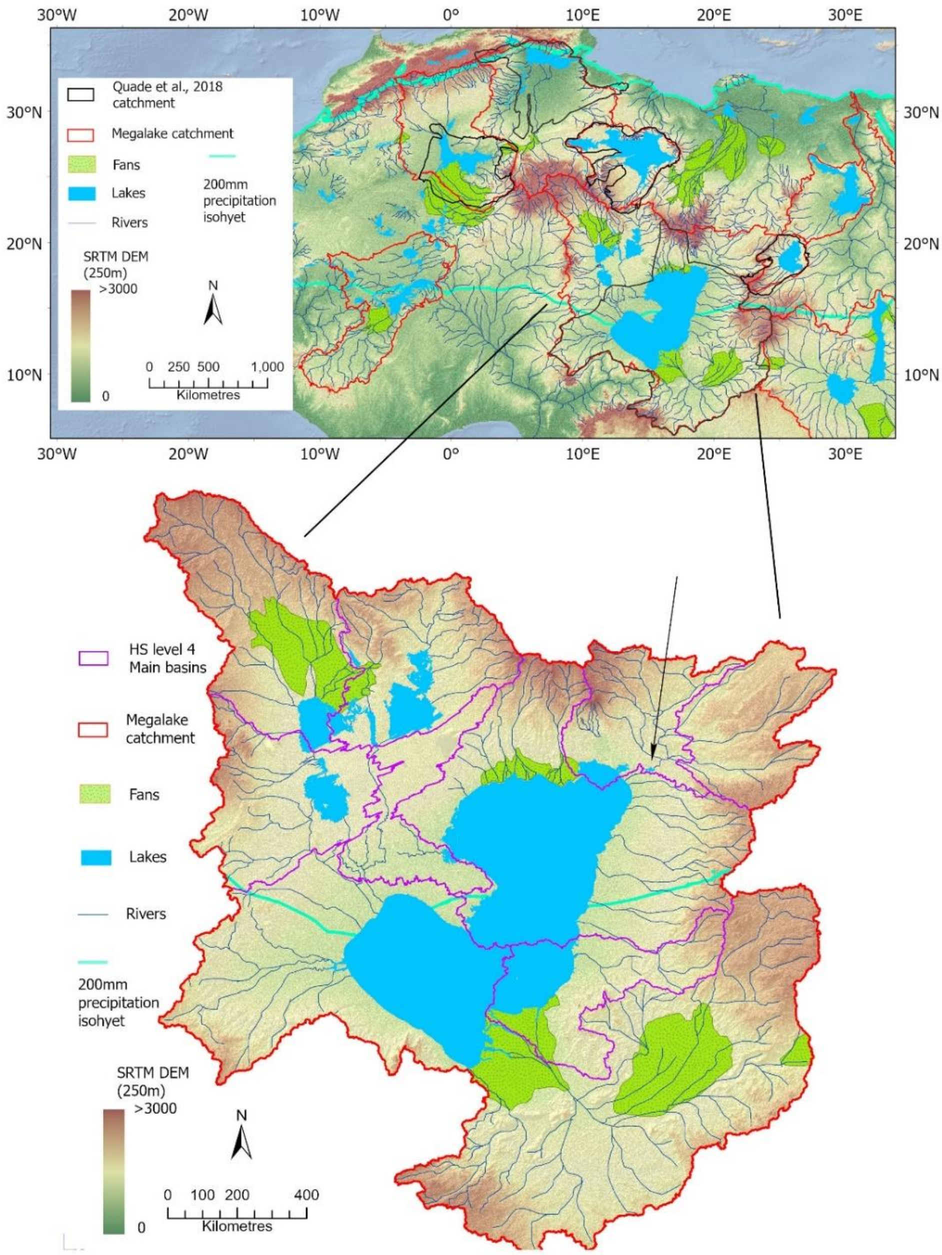

Figure 12. Top: Map showing the topography (SRTM 1 km DEM) and paleohydrology of North Africa with a comparison of the Quade et al. (2018) and Drake et al. (2011) megalake catchments. Bottom: Megalake Chad catchment topography (SRTM 90 m DEM) showing the lakes mapped by Drake et al.,

(2011) and their sub-catchments as defined by the HydroSHEDS level 4 catchments. The arrow highlights a small lake not readily evident to the eye.

In our analysis the megalake catchments of Drake et al., (2011) were used. These were produced by manual digitisation from the SRTM 1 km DEM. Firstly, the rivers that fed the megalake were digitised from their mouth to source, including the main tributary channels encountered along the way. The catchment boundary, located at the source of these channels, was then digitised by tracing along the catchment divide defined by the channel headwaters. Furthermore, it was assumed that when the megalake existed, the entire catchment would be humid in order to sustain such large volumes of water in the lake. Under these conditions the sub-basins within the megalake catchment would contain paleolakes and it would be wet enough for these lakes to fill to overflow and feed their excess waters into the megalake in question, just as lakes do in more temperate regions today. Thus, all lake sub-basins were included within the megalake catchments. This is illustrated well by the Megalake Chad catchment that contains many substantial lakes in the north, which form in numerous different sub-catchments (Figure 12 bottom).

Quade et al., (2018) provide insufficient detail to precisely replicate their catchment area estimates. However, in many cases their catchments terminate where there are paleolake sub-catchments. This suggests standard GIS catchment mapping techniques (e.g. ArcGIS) have been used to define catchments, as they treat each lake basin as a separate catchment. For example, Quade et al., (2018) exclude all the sub-catchments of Megalake Chad that contain lakes (Figure 12 top and bottom). However, perhaps the best example of the problems caused by this approach occurs when defining the catchment of Megalake Ahnet-Mouydir. The northernmost margin of this catchment is defined by the headwaters of the Soura River (Conrad, 1970), the largest of a number of rivers that flow from the Atlas Mountains, feeding moisture into the Sahara (Figures 1A and 12 (top)). Quade et al., (2018) exclude much of this river from their catchment, instead placing the boundary 460 km south of the Soura River headwaters, at the point where the river feeds into Sebkah el Melah, a small lake that exists along the river's course (Figure 10B). Since the ALOS 30 m DEM clearly shows the Soura River flowing into and out of the lake and onwards into the Sahara, there is no justification for terminating the megalake catchment boundary here. Thus, it would appear that standard GIS based catchment mapping methods have been employed by Quade et al (2018) and this has resulted in sub-catchments being defined as separate entities, such as that of the Sebkah el Melah and the lakes in the north of the Megalake Chad catchment.

Megalake Catchment	Drake et al (km^2)	Quade et al (km^2)
White Nile	2,188,386	n/a
Chad	2,458,720	1,611,234
Timbuktu	736,989	n/a
Darfur	126,556	142,394
Tushka	316,256	n/a
Fezzan	378,429	330,221
Chotts	829,370	377,765
Ahnet-Mouydir	740,447	329,180
Total	7,775,153	2,790,794

Table 2. Catchment areas of Saharan megalakes as estimated by Quade et al., (2018) and in this paper.

As noted above, Drake et al., (2011) assumed that the entire catchment is humid in order to be able to sustain a megalake, and that all lake sub-basins are full to overflow. In contrast the catchments of Quade et al., (2018) are much smaller because they terminate as soon as they reach a lake sub-basin. Thus in terms of catchment size, the two approaches are endmembers in a continuum, one representing wet conditions, the other dry. It is possible that a megalake could be sustained somewhere between these extremes, with lakes in small parts of the catchment not overflowing into the megalake. However, the method of Quade et al., (2018) implicitly assumes a relatively dry climate in all sub-catchments, with insufficient rainfall to allow any of them to fill to overflow. It is very unlikely that a megalake could be sustained under these conditions and this assumption has resulted in underestimation of the extent of most of the megalake catchments (Table 2).

In some cases there is clear evidence for sub-catchment lakes filling and outflowing into a megalake basin. For example, the role of the Soura River as a significant water source to megalake Ahnet-Mouydir is well known, having been discussed in detail by Conrad (1970). Furthermore, Dumont (1987) reports that the Soura was perennial as far south as Reggane in the centre of the Ahnet-Mouydir basin during historical times, and that it was still periodically active recently, reportedly flowing 800 km into the Sahara at least once during the 20th century (Dumont 1987). Investigation of MODIS satellite imagery of the river shows that as recently as 2014, severe flooding in the Atlas Mountains activated the river and brought floodwater 550 km into the desert, filling Sebkah el Melah and then flowing onwards towards Reganne. Importantly, the Soura River is only one of three large rivers draining the Atlas Mountains that would have fed megalake Ahnet-Mouydir during past humid periods (Figure 1A; Drake et al., 2011), with the lake thus receiving a considerable amount of runoff from this region. However, none of these rivers are included in the Ahnet-Mouydir catchment of Quade et al., (2018), producing a severe underestimation of the moisture received by this megalake.

An important problem with such underestimations of catchment area is that they tend to exclude mountainous regions, those parts of the catchment with the highest rainfall, and which play an important role in regional hydrological responses during humid episodes (Lezine et al., 2011). In the example above, by excluding the Atlas Mountains from the reconstruction of the Ahnet-Mouydir catchment, an area of significantly higher annual rainfall from outside the Sahara is excluded from the modelling of the lake budget. However, even in cases where the catchment mapping of Quade et al., (2018) matches that of previous studies, the authors tend to underestimate rainfall. Quade et al., (2018) state that, with the exception of megalake Chad, the other proposed Saharan megalakes occur "where the contributing watersheds are confined between 15^{o}N an 35^{o}N in areas that receive <<100mm/yr (rainfall) today". Yet according to the WorldClim global annual average rainfall maps (Fick and Hijmans, 2017), the headwaters of the Soura River in the Ahnet-Mouydir basin receives 356 mm/a rainfall, whilst one of the rivers draining into the Chotts receives 700 mm/a (Fick and Hijmans, 2017), much higher than the <<100 mm/yr proposed by Quade et al., (2018). Furthermore, during humid periods rainfall in the Atlas Mountains was much higher than at present (Zielhofer et al., 2017), exacerbating the underestimation caused by any exclusion of contributions from the Atlas Mountains.

In summary, the catchment mapping of Quade et al., (2018) underestimates the size of many of the proposed megalake catchments, and consequently underestimates the precipitation falling within them. In addition, Quade et al., (2018) justify their modelling results by comparing them to global paleoclimate modelling studies which are known to fail to produce a green Sahara during the AHP (Claussen et al., 2017), despite a well-documented tendency for such models to underestimate rainfall in the region at this time (Hopcroft et al., 2017). Consequently, we question the accuracy and completeness of the mass balance hydrologic modelling presented in Quade et al., (2018) and resultant assertions that the megalakes in question are hydrologically implausible.

6. Chronological evidence for the timing of megalake development

The evidence presented above shows that there is robust evidence for the existence of Quaternary megalakes in the Nile, Niger, Chad, Chott, Ahnet-Mouydir and Darfur basins. However, it is clear from the literature that the timing of the development of many of these megalakes is poorly constrained. There are two reasons for this. Firstly, many megalake sediments frequently contain little dateable material. Organic material suitable for ^{14}C dating is poorly preserved in arid regions and often researchers have relied on dating fossil shells. Both ^{14}C or U/Th disequilibria techniques yield notoriously unreliable ages for fossil shells due to reservoir effects, dead carbon, diagenesis and the porous nature of freshwater mollusc shells (Walker, 2005). Whilst luminescence techniques have the potential to reliably date the quartz-rich sand shorelines found in many of these basins, this technique has only been applied to the White Nile, Chad and Fezzan basins (Williams et al., 2003; Barrows et al., 2014; Armitage et al., 2007, Armitage et al., 2015; Drake et al., 2011; Drake et al., 2018).

For Megalake Timbuktu there are currently no direct dates. However, our analysis of dates from other paleolakes in its catchment suggest that it developed at about 9.5 ka and its geomorphology indicates it had reached its demise by the middle Holocene. In the Darfur basin no dates are available for the high stand shoreline, though the smaller AHP lake is well dated (Hoelzmann et al., 2000; 2001). In the Ahnet-Mouydir and Chotts Megalake basins, the only chronological information for the lake is U/Th dating of shells, a notoriously unreliable method. Thus, of the megalakes where dating has been attempted, the Ahnet-Mouydir and Chotts Megalakes are the least securely dated. Despite these limitations, the dating evidence that is available can be used to make some observations about the timing of megalake formation in the Sahara. Firstly, megalake Chad and Timbuktu provide a very large area of surface water in the southern Sahara and Sahel during the AHP. However, only in the Chad basin does a reliable chronology for a Holocene megalake exist (Armitage et al., 2015). Combined luminescence and ^{14}C dating shows that the main megalake phase occurred from ~11 to ~5 ka (Armitage et al., 2015). Pre-Holocene shorelines are much rarer in the Chad basin and only two have currently been dated, providing luminescence ages of 114.2±14 and 125.4±11.6 ka (Drake et al., 2011).

In none of the other basins does the existing chronology indicate the establishment of megalakes during the AHP, though substantial lakes are found within them at this time; White Nile (4690 km^2), Darfur (5330 km^2) and Fezzan (210 km^2). The White Nile Megalake shoreline has been dated using ^{10}Be to 109±8 ka (Barrows et al., 2014). In contrast the Fezzan megalake development is a phenomenon of the Miocene (Hounslow et al., 2018). Whilst there is clear evidence for lake formation during humid phases associated with MIS 5 (Armitage et al., 2007; Drake et al., 2018) and the early-mid Holocene (Drake et al., 2018), these are much smaller water bodies with a maximum surface area of ~1600 km^2 (Drake et al 2018).

In the Chott basin, Richards and Vita-Finzi (1982) presented ^{14}C ages for *C. glaucum* shells between 35 and 25 ka, close to the age limit of radiocarbon techniques at that time. Causse et al., (2003) used U/Th disequilibrium techniques to date shells from similar deposits and identified high stands at 30.2±1.7, 96.4±5.2, 145±16 and 184±19 ka. Currently no dating evidence exists to indicate that a megalake developed in the Chott basins during the AHP. A similar pattern is seen in the Ahnet-Mouydir basin where U/Th disequilibrium work on shells from nearshore sediments yields an age estimate of 92 + 20 -18 ka (Causse et al., 1988). Though luminescence dating of these deposits is required to generate a more secure chronology, the U/Th ages do imply megalake formation during MIS 5 rather than the AHP.

In summary, apart from at the southern margin of the Sahara (the Chad basin and Niger Inland Delta) there is negligible evidence for megalake development during the AHP. Whilst all basins apart from Tushka, contain reliable evidence for megalake formation, these lakes mostly formed during earlier interglacial or “warm” marine isotopic stages, and predominantly date to MIS 5. Furthermore, for those basins that exhibit both AHP and earlier lake records, the AHP lakes are always considerably smaller. This implies that across most of Saharan Africa, the AHP was significantly drier than MIS 5. However, even in a period like MIS 5 there is no consistent pattern of megalake development. Whilst the Chad, White Nile, Ahnet-Mouydir and the Chott basins experienced megalake development, lakes in the Fezzan basin during this time interval are relatively localised.

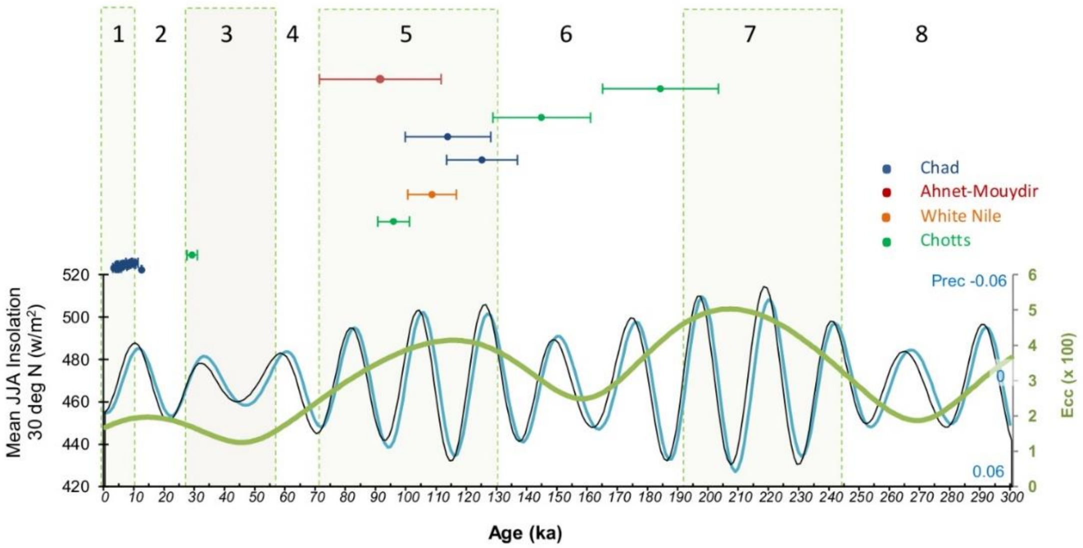

Figure 13. Dates of Saharan Megalakes compared to precession, eccentricity and total insolation for the central Sahara (30 degree north) from to present 250 ka.

In the literature it has been widely proposed that humid phases in the northern hemisphere low latitudes correspond to peaks in insolation, when the inter-tropical conversion zone (ITCZ) is situated further north and the monsoon increases in strength (deMenocal et al., 2000; Prell and Kutzbach 1987). The limited and relatively imprecise dating of mega-lake shorelines discussed above, means that definitively correlating relic shoreline features with specific insolation peaks is problematic (Figure 13). For example, whilst it is clear that MIS 5 is a period when megalake formation is recorded in a number of Saharan basins, rarely are the uncertainties associated with the age estimates derived from shoreline sediments precise enough to allow a robust correlation to individual insolation peaks or substages within MIS 5. Nonetheless, there is nothing in the dataset presented here that refutes the idea that insolation peaks drive the occurrence of humid phases. There is extensive evidence for the formation of megalakes during MIS5, and this period is characterised by three pronounced insolation peaks (Figure 13).

If insolation peaks are the driver of mega-lake development in the Sahara, it is noticeable that the insolation peak associated with the Holocene (Figure 13) is less intense than all of the peaks associated with MIS 5 (5e, 5c, 5a) and MIS 7 (7e, 7c, 7a), and is only marginally stronger than that associated with MIS 3 (Prell and Kutzbach 1987). Consequently, the apparent dryness of the AHP relative to previous humid periods is explainable by contemporary orbital parameters. If it is assumed that the intensity of the insolation maximum controls the degree to which the ITCZ shifts northwards, then it is unsurprising that the AHP was drier than previous humid periods, particularly in the northern basins of the region most distal from the starting point for a monsoon incursion (i.e. the Chott and Ahnet-Mouydir basins). In this context it is unremarkable that Quade et al., (2018) argue that the AHP was not wet enough to generate megalakes. With the exception of megalake Chad and Timbuktu, which both source water from outside the desert, our review highlights that no researchers currently propose the existence of AHP megalakes in the Sahara.

7. Summary and Conclusions

Geomorphic and sedimentary evidence for the formation of megalakes can be found in the Chad, Niger, Chotts, Fezzan, Ahnet-Mouydir, White Nile and Darfur basins of the Sahara. However, no single criterion can be used as a means of identifying a former megalake. This is primarily because the aeolian systems of the Sahara are so dynamic that landform and sedimentary evidence for megalakes can be easily removed or obscured, resulting in a sparsely preserved record. Sweezy (2003) estimated that because erosion predominates in this landscape, none of the palaeolake deposits of the Chott megalake would ultimately be preserved in the geological record. Consequently, a strict criterion requiring well-defined and spatially extensive shorelines for the reliable identification of a megalake is not usefully applicable in the Sahara. Rather, a holistic approach must be taken. This must consider geomorphic, sedimentary and fossil evidence, and evaluate the environmental significance of that evidence, rather than relying solely on the identification of extensive shorelines using remote sensing. Although imagery and DEM analysis alone has been used to identify some Saharan palaeolakes, the use of different criteria has produced contradictory results. To overcome this problem we have developed a method to evaluate systematically all the shoreline evidence in a basin. This method yields a categorical assessment of the strength of evidence supporting recognition of a paleolake. Applying this method to the Sahara demonstrates that strong evidence exists for two of the megalakes that have been identified using remote sensing and DEM analysis alone (Darfur and Timbuktu), but not for the third (Tushka).

Our production of linked global mosaics of key remote sensing datasets in GEE has allowed rapid interpretation of a wide variety of satellite imagery and DEMs. This proved to be very effective, allowing intercomparison of the utility of these different types of remote sensing imagery and DEMs for shoreline identification and mapping. Our analyses found the ALOS 30 m DEM to be the most useful data source, but both radar and visible and infrared imagery provided important ancillary detail in many cases. These data allowed the recognition of a megalake in the Niger Inland Delta region of Mali for the first time, that we christened Megalake Timbuktu. Furthermore, interpretation of this imagery provided new evidence to support the existence of some of the previously postulated megalakes.

The understanding of the hydrology of humid phases, and the robust modelling of lake mass balance, requires an accurate reconstruction of lake catchments. The presence of megalakes in the Sahara was questioned by Quade et al., (2018) on the basis of a mass balance model and a perceived absence of shoreline features. Critically, our analyses contradict this interpretation, demonstrating that shorelines are not a diagnostic criteria for lake presence in the Sahara due to the geomorphological dynamics of the region, and that key parts of the fluvial networks that feed Saharan megalake basins were omitted from the mass balance calculation, leading to substantial underestimates the runoff available to these systems. This is particularly true in the case of the Ahnet-Mouydir basins, where the Atlas Mountains, the wettest part of the catchment in the present day, was omitted by Quade et al., (2018).

Finally this review draws two key conclusions which are in concord with the work of Quade et al., (2018):

1) The chronology of Saharan megalake deposits is currently poor. Consequently, the climatic history that these deposits and landforms hold is under-developed and efforts should be made to rectify this. With an improved chronology of these regions it will be possible to produce robust histories for megalake development in individual basins and, consequently, understand regional synchronicity/asynchronicity in the timing of megalake highstands.
2) Megalake formation is not a feature of the AHP, with the exception of megalakes Timbuktu and Chad. As a consequence, the Holocene of the Sahara would appear less 'wet' than Pleistocene humid phases such as those in MIS 5. Although the AHP was characterised by a humid and green Sahara, the landscape and geomorphic systems operating within this region during the Holocene were very different from those of Pleistocene interglacials. This has implications for human dispersal across, and occupation within, this region during the Holocene relative to MIS 5. It is likely that the "drier" conditions which prevailed during the AHP relative to earlier humid periods are a consequence of the relatively weak summer insolation peak which occurs during the Holocene.

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