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Shorelines in the Sahara: geomorphological evidence for an enhanced monsoon from palaeolake Megachad

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A HOLOCENE RESEARCH REPORT

Abstract: The Sahara Desert is the most extensive desert on Earth but during the Holocene it was home to some of the largest freshwater lakes on Earth; of these, palaeolake Megachad was the biggest. Landsat TM images and Shuttle Radar Topography Mission (SRTM) digital topographic data reveal numerous shorelines around palaeolake Megachad. At its peak sometime before 7000 years ago the lake was over 173 m deep with an area of at least 400 000 km^2, bigger than the Caspian Sea, the biggest lake on Earth today. The morphology of the shorelines indicates two dominant winds, one northeasterly that is consistent with the present-day winds in the region. The other originated from the southwest. We attribute it to an enhanced monsoon caused by a precessionally driven increase in Northern Hemisphere insolation. Subsequent desiccation of the palaeolake is recorded by numerous regressive shorelines in the Sahara Desert.

Key words: Lake, beach ridges, spits, remote sensing, DEM, Holocene, Chad.

Introduction

Lake shoreline landforms were discovered in the Chad Basin early last century when the existence of giant palaeolake Megachad was first postulated and described as an African Caspian Sea (Tilho, 1925). Initial estimates of the lake area by Tilho (1925) were 200 000 km^2 although this was later revised 320 000 km^2 (Schneider, 1967) with lake levels fluctuating because of climatic change during the Holocene (Maley, 1977; Servant and Servant-Vildary, 1980; Gasse, 2000). However, soon after the last of these studies the existence of a Holocene Lake Megachad was questioned and it was suggested that the lake shoreline beach ridges were in fact fault scarps (Durand, 1982). Further investigation of the archaeology and sedimentology of the ridges (Thiemeyer, 1992) led to the resurrection of the megalake theory, and these results were supported by interpretation of the topography of the Chad Basin using the TOPO 6 and GLOBE digital elevation models (DEMs) that allowed recognition of a very extensive wave-cut shelf interpreted as a lake shoreline feature (Ghienne *et al.*, 2002; Schuster *et al.*, 2003). Most recently, Schuster *et al.* (2005) interpret higher resolution (900 m) SRTM-30 DEM data and Landsat TM imagery to provide the first detailed overview of the sedimentary systems around palaeolake Megachad. They describe the palaeolake shoreline geomorphology at Goz Kerki, Kanem, Angamma and Chari palaeodeltas. From their analysis they place the palaeoshoreline at 325 m and describe a lake area of more than 350 000 km^2.

In this paper we interpret the high resolution (90 m) SRTM-3 DEM data, acquired by the Spaceborne Imaging Radar-C (SIR-C) radar interferometer (Rabus *et al.*, 2003), processed to remove artefacts in areas of low radar return (Jarvis *et al.*, 2004) and converted to Albers equal area projection. The DEM was used to locate and evaluate coastal landforms in combination with even higher resolution (30 m) Landsat TM imagery and field visits to the Bodele Depression, Angamma and Goz Kerki regions (Figure 1). We confirm the existence of Lake Megachad, show that there are numerous lake shorelines at different altitudes and thus many megalake phases. We estimate the areas of these lakes and interpret the changes in the wave and wind regime of the basin during this time. Based upon

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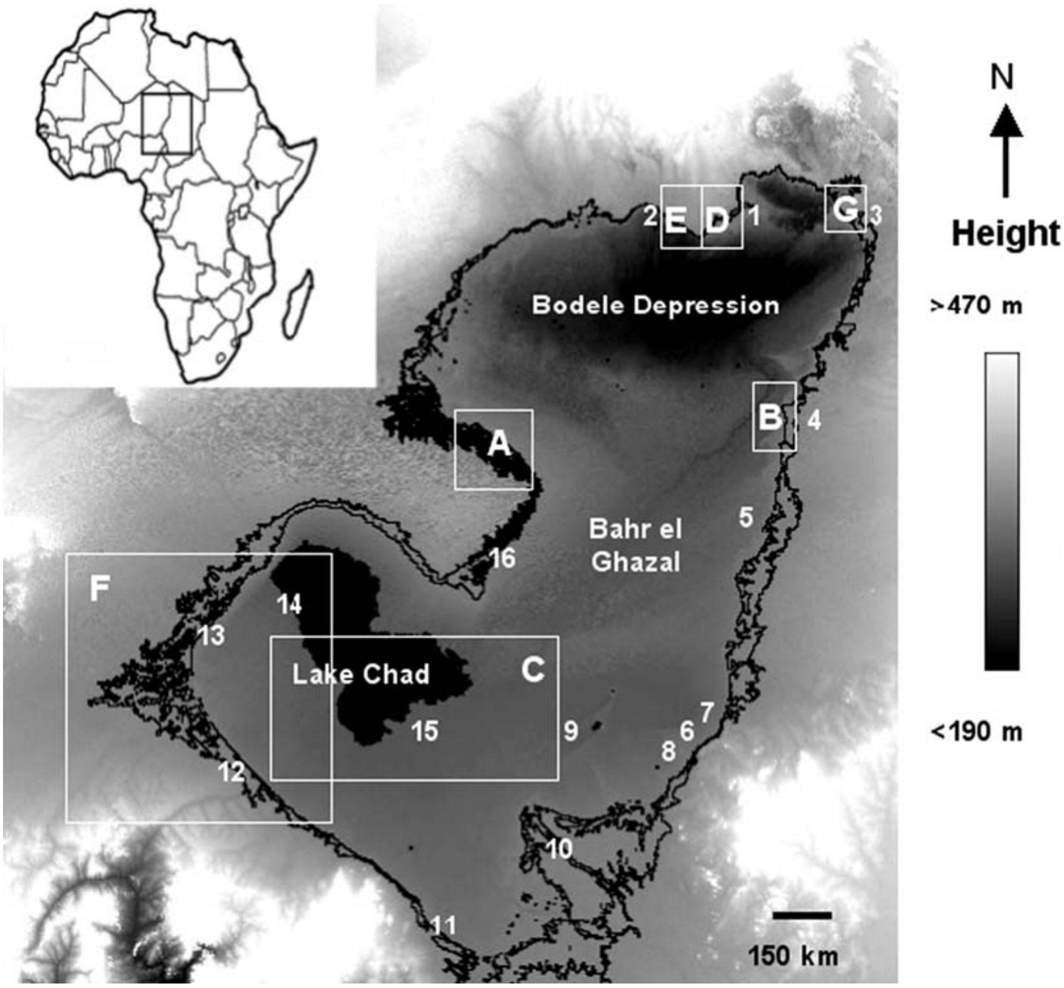

Figure 1 SRTM-3 90 m resolution DEM of Lake Megachad. As altitude increases the shades of grey change from black to white. The outline of two palaeolake shorelines of Megachad at 329 m and at 335 m are shown in black. The dark area in the north is the Bodele depression, the lowest point within the basin with an elevation of around 160 m. The black area in the southwest indicates the size and location of historical Lake Chad, the area of which is controlled an outflow channel at elevation around 286 m that flows into the Bodele depression via the Bahr el Ghazal. The numbered locations 1 to 13 correspond to shoreline locations in Table 1. The white boxes A, B, C, D, E, F and G show the location of the areas shown in greater detail in Figures 2–8

our interpretations of the palaeolake shoreline geomorphology and calculations of greater lake areas we suggest that an enhanced monsoon with southwesterly winds and increased precipitation are required.

Methods

Landsat TM false colour composites were visually interpreted in conjunction with the DEM. Both show clear evidence of coastal landforms of numerous types including cuspate forelands, tombolos, sand spits, deltas, beach terraces and ridges (Figures 1–7). The two data sets provide complementary information that is greater than the sum of their parts. Both show the outlines of the landform in question but the DEM provides precise altitudinal information while the Landsat TM imagery provides information on sedimentary features with limited topographic expression.

A prominent shoreline can be traced around most of the lake (Figure 1), though in places it has been eroded away by incision and lateral migration of rivers or locally covered by dunes. The shorelines transform into numerous different coastal landforms along their length. In places multiple stepped shorelines composed of beach ridges and sand spits are evident that must have been deposited by lakes with still-stands at different altitudes. Accurate calculation of the area of Lake Megachad from these coastal landforms is problematic because of their complexity and the uncertainty about exactly where the shoreline resides on some of these coastal features. Notwithstanding this we found that estimating lake area by applying a threshold to the DEM produced consistent shoreline heights from different coastal landforms across different parts of the lake basin (Table 1). The thresholding technique defines a shoreline by masking out all regions below a specified threshold altitude, with the threshold value representing the proposed lake level. For beach terraces and spits the threshold is incrementally adjusted until an optimum is reached, whereby as much of the land below the beach terrace or spit complex shoreline is submerged, but as much of the landward side as possible is above the threshold. Some of the beach ridges are interpreted as barrier beaches and thus the threshold in this case allows for lagoons on the landward side. We have applied this methodology to all shoreline landforms recognized by Schuster *et al*. (2005) and additional locations described here, in order to estimate the area of the lake during different still-stands and elucidate other aspects of the environment of palaeolake Megachad.

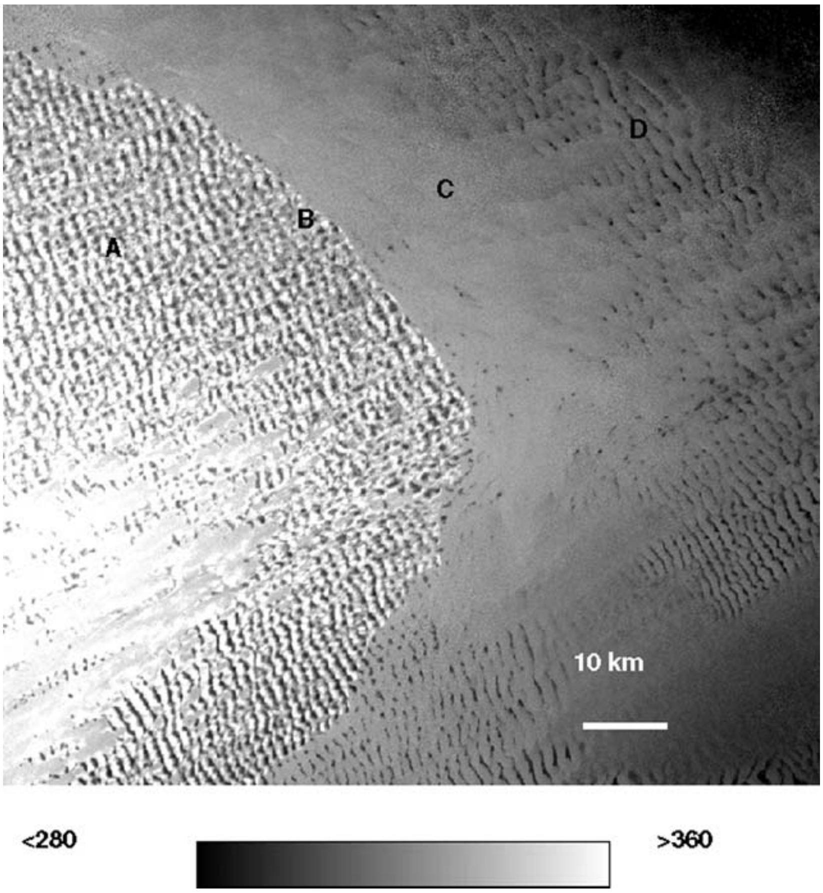

Figure 2 SRTM 90 m resolution DEM of the Eastern margin of the Kanem Erg showing a wave-eroded palaeolake shoreline truncating late Pleistocene transverse dunes. A, Late Pleistocene transverse dunes; B, erosional truncation of dunes; C, beach/wave cut platform where dunes have been reworked by wave action; D, partially reworked dunes

Results

Beach terraces

We tested the method on the prominent shoreline that can be found in most parts of the Chad Basin transforming into numerous different coastal landforms along its length. The best estimate of the shoreline elevation can be obtained from beach terraces as they exhibit a clearly defined junction between the terrace and the beach platform that closely relates to lake level. An extensive beach terrace is found in the Hebil region (Figure 1 site 6) with an altitude of 329 m. The terrace is clearly associated with a beach ridge in both north and south directions (Figure 1 sites 6 and 7) that produces a shoreline altitude estimate of 328 and 329 m. A further terrace is found in the northwest corner of the lake (Figure 1 site 12) with an altitude of 327 m while another is recognized by Schuster *et al.* (2005) etched into the eastern end of the Erg Kanem at 330 m (Figure 2). The Kanem shoreline is evident because above 330 m the transverse dunes have a well-preserved morphology. There is a clearly defined trim-line along the edge of the dunes where wave reworking has eroded into the dunes. Between the trim line and 320 m the dunes have been eroded by wave action into a beach/wave-cut platform, while below 320 m the dunes become progressively less eroded again and the dune topography is partly preserved as we move away from what would have been near the shore into a zone of deeper water with progressively less coastal erosion.

Spits and cuspate forelands

Spits are narrow and elongate coastal landforms that form as extensions of beaches with one end tied to the coast and the other, free end, extending into open water. They extend in the direction of predominant longshore drift (Komar, 1976) and are examples of drift-aligned morphology (Orford *et al.*, 1991). Because they are wave-formed features they are reliable indicators of water level, although their elevations can vary slightly because of wave run-up and overtopping. The orientation of spits in lakes has been used to interpret palaeowind directions (Krist and Schaetzl, 2001). Sand spits are found in both the Angamma (Figure 1 site 1) and Goz Kerki regions (Figure 1 site 4 and Figure 3) and produce shoreline height estimates of 332 and 330 m, respectively. These altitudes are in good agreement with the shoreline height estimates of the beach terraces and those derived from six other extensive shoreline exposures in other parts of the basin (Table 1). These height estimates produce an average of 329 m with a standard deviation of 1.7 m providing a lake area estimate of $361\,000 \pm 13\,000$ km^2 showing that the lake was larger than previous studies (Tilho, 1925, Schneider, 1967; Schuster *et al.*, 2005) have suggested.

The DEM and satellite images show a series of cuspate forelands with spits and beach ridges along the eastern shore of the lake in the Goz Kerki region (Figure 3). Cuspate forelands such as Dungeness on the south coast of England are associated with convergent longshore drift with waves approaching from two directions (Bird, 2000), they can also evolve from spits, eg, Cape Henlopen (Kraft *et al.*, 1978). The way in which a cuspate foreland evolved is often recorded by beach ridges that can be used to reconstruct the evolution of coastal morphology (Taylor and Stone, 1996; Otvos, 2000). Beach ridges at Goz Kerki are visible on the TM image (Figure 3) forming a gentle fan from a

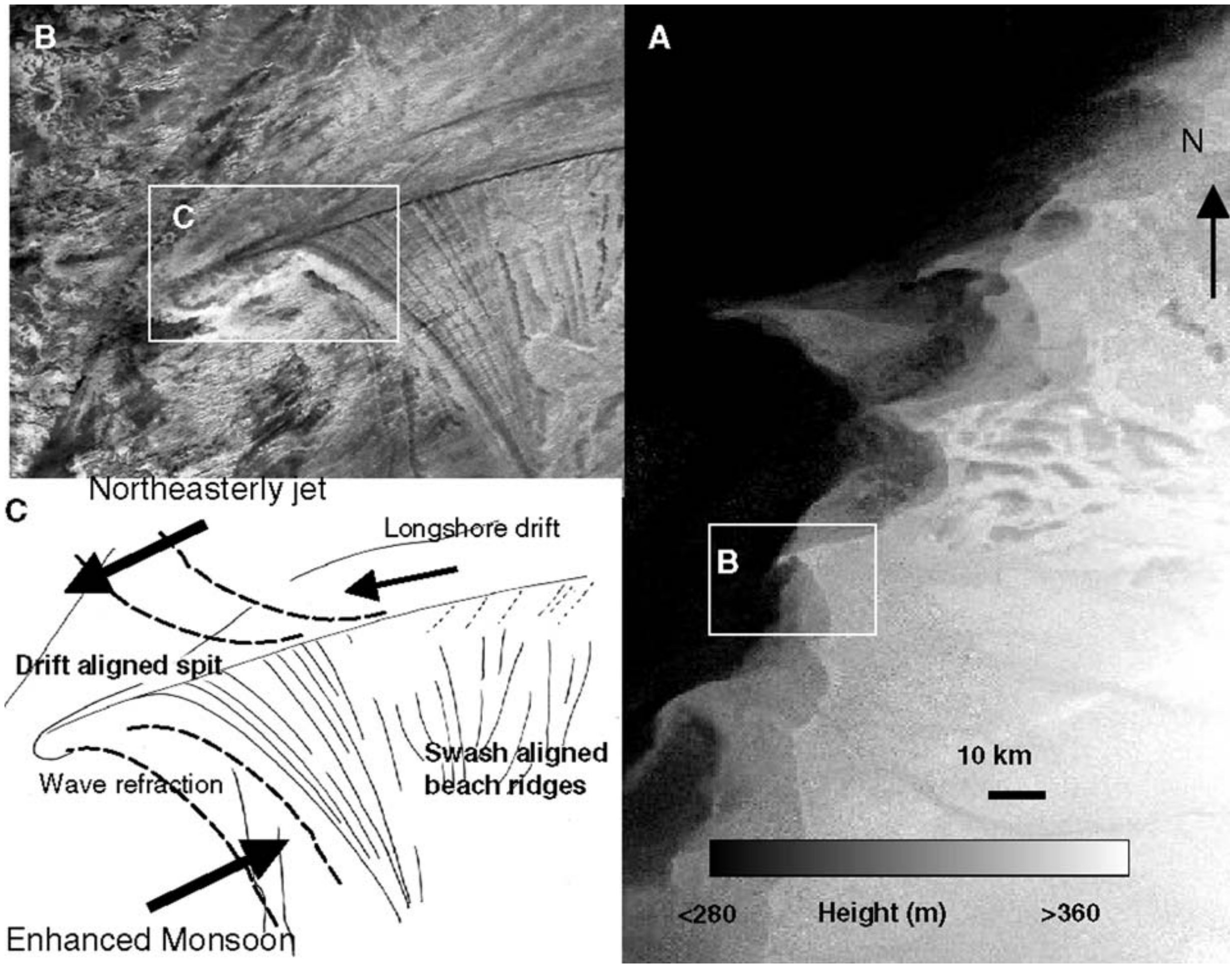

Figure 3 Goz Kerki sand spit and beach ridges, area B on Figure 1. (A) SRTM-3 DEM of Goz Kerki sand spits. (B) LANDSAT TM band 4 image of a single sand spit and associated beach ridges. The beach ridges consist of very coarse sand and are interpreted as swash-aligned beach ridges perpendicular to waves driven by southwesterly monsoon winds (C). The spit extends towards the southwest and this extension is interpreted as a drift-aligned feature formed by longshore drift with waves from the northeast. The northeasterly winds are dominant in the Bodele depression at the present day. The other spits show similar shoreline orientations and are interpreted to have formed under a similar wind and wave regime with probable seasonal alternations between summer southwesterly monsoon winds and winter northeasterly winds. Shoreline elevations are shown in Table 1, with the higher shore at 329 m, the intermediate shoreline at 320 m and the lower at 304 m

north–south alignment to a northwesterly trend. They are truncated at their northern end with a spit projecting towards the southwest on the apex of the cuspate foreland. The morphology of the cuspate forelands indicates the interaction of two sets of waves with wave approach from the southwest and from the northeast. The southwesterly waves formed swash-aligned beach ridges while the northeasterly waves truncated the northern end of the beach ridges and created the drift-aligned spits at the apex of each cuspate foreland by longshore drift. The DEM (Figure 3A) shows spit and cuspate foreland development at three different elevations: 304 m, 320 m and 330 m (Table 1), suggesting three lake still-stands.

Palaeodeltas

The palaeodeltas of the Chad Basin exhibit shoreline landforms cut into, or incorporated within, deltaic sediments. The Chari River delta (Figure 1 site 10) has prograded into the lake incorporating two beach ridges within it at elevations of 372 and 329 m. The delta front itself forms a barrier beach with a shoreline at 328 m and a lower, less prominent shoreline at 315 m. The Chari River has avulsed towards the south, subsequently incised into the palaeodelta (Schuster *et al.*, 2005) and continues to flow into Lake Chad where a modern delta has developed on the abandoned bed of Lake Megachad. Two terraces are etched into this delta near the current margin of Lake Chad at an altitude of 288 and 285 m (Figure 4). A beach ridge, known as the Ngeiewa Ridge, is found at an altitude of 290 m running along the western margins of Lake Chad. Presumably this belongs to the same shoreline as the higher terrace (288 m). Both terraces converge on an outflow channel known as the Bahr el Ghazal that flows over a sill with an elevation of 285 m into the Bodele depression, the lowest point within the Chad Basin. Discharge down the Bahr el Ghazal fed a lake in the Bodele Depression, the shorelines of which are found in the Taimanga area and on the Eastern side of the Angamma Delta (Table 1).

The outlet of palaeolake Megachad is located at the southern end of the Chad Basin where the lake waters overflowed into the Mayo Kébi River (Figure 1 site 11) and ultimately flowed into the Atlantic Ocean via the Benue River (Servant and Servant-Vildary, 1980). The outflow lies at an elevation of 325 m, slightly lower than the main highstand shoreline at about 329 m. To the west of the outflow channel there are a series of NW–SE trending beach ridges with ridges rising 354 m, well above the 329 m shoreline suggesting that the palaeolake level was higher before the 329 m still-stand and the Mayo Kébi outflow channel has subsequently incised.

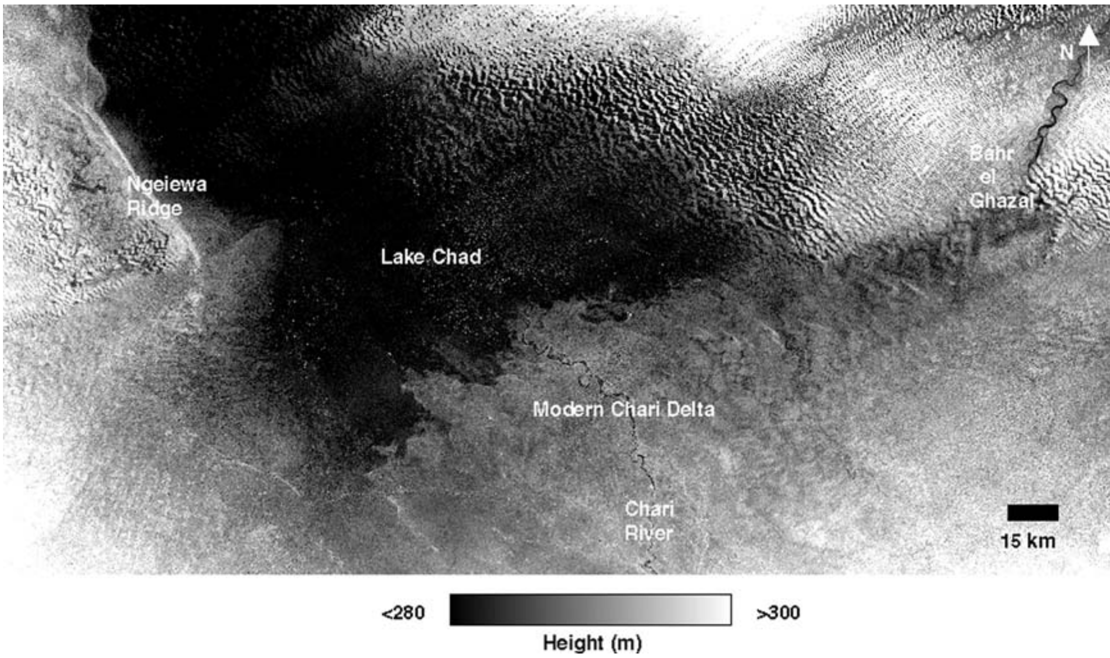

Figure 4 SRTM-3 90 m resolution DEM showing Lake Chad, the modern Chari Delta and the lake shorelines on the southern margins of Lake Chad. Shoreline elevations are shown in Table 1. The river known as Bahr el Ghazal that connects Lake Chad and Lake Fitri to Lake Bodele during high stands is evident in the northeast corner of the figure

The northern shoreline of palaeolake Megachad is dominated by the Angamma palaeodelta (Ergenzinger, 1978; Schuster *et al.*, 2005). The delta has prograded beyond a beach ridge with shoreline elevations of 345 m and in doing so, has also incorporated cuspate forelands on the eastern side of the delta at 343 m (Figure 5B site 1), 340 (Figure 5B site 2) and 335 m (Figure 5B site 3). The orientation of the preserved beach ridges and the morphology of this cuspate foreland indicates wave approach from the southwest and from the northeast, indicating palaeowinds blowing from both directions (Figure 5B). Construction of the cuspate forelands is attributed to convergent longshore transport with sediment derived in part from the Angamma Delta to the west and also brought along the coast by longshore drift from the northeast.

The Angamma delta has a cuspate morphology (Figure 6) typical of wave-modified deltas (Elliott, 1986). The prominent palaeoshoreline is clearly defined by a beach ridge at 333 m that forms part of the prominent shoreline found throughout the basin. Braided river channels on the delta top and the delta-front shoreline are remarkably well preserved with no falling-stage or low-stand incision cutting down through the relatively steep delta front, known as the Falaise de Angamma. The preservation of the beach ridge and lack of incision on the Angamma palaeodelta indicates that fluvial discharge ceased before the lake level fell. There is, however, local gullying and wadi formation at the base of the Angamma delta on its western side. It is notable that the gullies on the delta front do not connect to channels preserved on the delta top. We attribute the gully formation to groundwater sapping and suggest that although surface water discharge had ceased there was still some flow of groundwater into the lake basin with subsurface flow emerging at the base of the delta deposits. Below the delta front on its eastern side the DEM reveals additional shorelines at 323, 305 and 286 m. These beach ridges appear to have been formed by waves reworking delta sediments as the lake level fell from the cordon litoral because they are uncut by either groundwater sapping or fluvial activity from the delta that would be expected were they from older still-stands.

Bama Ridge

The westernmost shore of palaeolake Megachad consists of an extensive beach ridge, known in Nigeria as the Bama Ridge (Thiemeyer, 1992), that extends around the western shores of the palaeolake with a relatively straight shoreline at 328 m (Figure 1 site 12; Figure 7) with other parallel ridges further west, one of which has a well-developed shoreline at 336 m. The lack of spits or cuspate forelands in this region suggests little longshore drift. We interpret this as the weather shore at the downwind end of palaeolake Megachad where the northeasterly low-level jet blew onshore, as it does today. This shoreline would have been the highest energy shoreline along the coast of the lake. The beach ridge complex terminates at the Komadugu River, which appears to have eroded away much of the complex through channel migration. To the north of the river a well-developed shoreline terrace sequence is evident (Figure 7) with two distinct levels suggesting two still-stands.

Taimanga Ridge

At the northern end of palaeolake Megachad there is a prominent NW–SE oriented beach ridge complex, Taimanga, close to the town of Faya Largeau (Figure 1 site 3; Figure 8). The Taimanga ridge has a similar orientation to the Bama Ridge but is at the opposite end of the palaeolake and was formed as a swash-aligned beach ridge by waves from the southwest. The waves were driven by southwesterly winds blowing along the full length of the palaeolake, providing clear evidence of southwesterly monsoon winds at the northern end of the palaeolake. Thus the lake appears to have experienced seasonal alternations between summer southwesterly monsoon winds and winter northeasterly winds. In places along the Taimanga ridge six different shorelines are visible in the DEM at 328, 320, 316, 302, 297 and 284 m, with many other shorelines at lower elevations evident in the Landsat TM imagery but too small to be seen in the coarser resolution

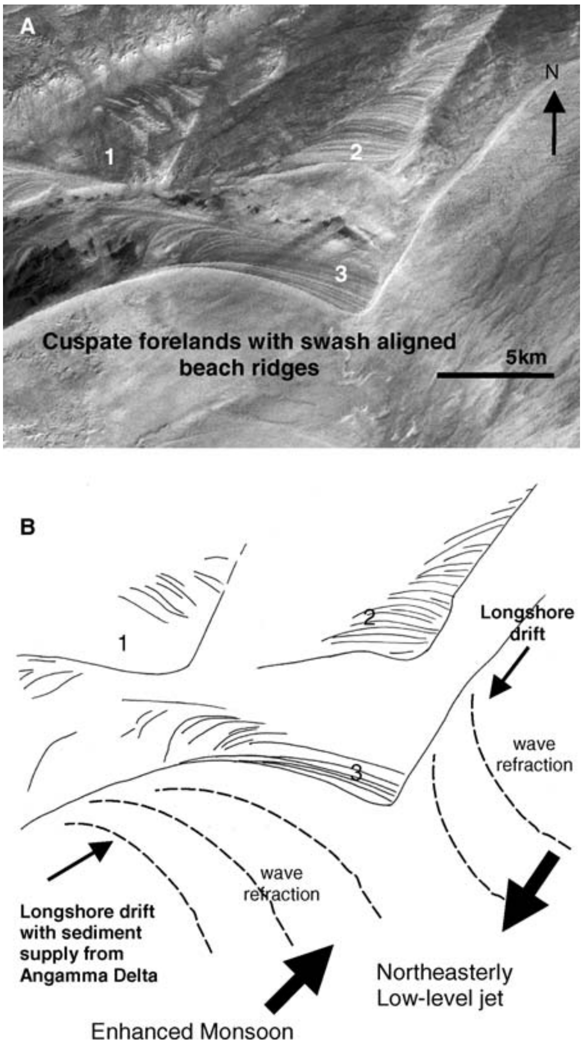

Figure 5 Cuspate forelands to the east of the Angamma delta. (A) Landsat Band 4 image of the cuspate forelands. (B) Line drawing interpretation of the Landsat image showing reconstruction of waves driven by southwesterly (Monsoon) and northeasterly (Harmatan) winds (see text for details). Three cuspate forelands are evident on the eastern side of the delta at 343 m (site 1), 340 m (site 2) and 335 m (site 3)

DEM. These landforms presumably track the final demise of the lake that formed in the Bodele Depression once Lake Megachad had contracted and split into separate lakes.

Discussion

While previous studies have identified one shoreline around palaeolake Megachad (Thiemeyer, 1992) and in some cases two (Schuster *et al.*, 2005), we have identified many new shorelines at numerous different elevations (Table 1). Of these, our method produces similar shoreline altitude estimates from different coastal landforms along the same shoreline in numerous regions. In each of these regions shorelines are found at many different elevations with shorelines clustering at 285 ± 1.4, 289 ± 1.4, 305 ± 1.2, 316 ± 1.7, 322 ± 2.1, 329 ± 1.8 and 335 ± 0.8 m. These shorelines are attributed to lake still-stands, allowing time for wave-formed shorelines to develop. Of these, there is a prominent shoreline at around 329 m (Figure 9) where shoreline geomorphology is preserved around the vast majority of the palaeolake that has been radiocarbon dated to 6340 ± 250 ^{14}C yr BP (Thiemeyer, 1992) that calibrates with a two sigma range to 7500–6940 BP. The majority of the beach ridges below this elevation are interpreted as being younger as they appear to be unaffected by fluvial activity (eg, the shorelines below the Angamma Delta), having formed as falling stage beach ridges during the lake regression from the prominent shoreline. However, some of the lower shorelines at Goz Kerki could be older because their morphology is less well preserved than the 329 m shoreline (Schuster *et al.*, 2005).

The beach ridges found at higher elevations than the prominent shoreline appear to have been formed by a larger and older lake. Four ridges are found at 335 ± 0.8 m providing a lake area estimate $413\,000 \pm 9000$ km^2 (Figure 9). If this lake existed today it would be the biggest lake in the world. We have located five places where even higher shorelines are found (Table 1). Presumably these isolated shoreline outcrops represent vestiges of an even larger and earlier lake, the highest beach ridges at 372 m gives an area of 837 000 km^2. As none of these shorelines can be traced right around the lake basin, or correlated between sites, the reconstructions of palaeolake levels from them are less certain. Furthermore, many of the ridges have been heavily eroded and are now dissected by well-developed drainage networks that are indicative of their antiquity but further complicate accurate lake area estimation. Notwithstanding these problems it is interesting to note that the smallest lake area estimate produced by these palaeoshorelines is 455 740 km^2 while the largest is 837 000 km^2. Thus, at its peak, palaeolake Megachad could have covered an area equivalent to around 8% of the Sahara.

Palaeolake Megachad is not the only giant lake to have once existed in the Sahara (Figure 10). Indeed the Sahara contains four megalakes in adjacent catchments that link to straddle the desert. Immediately north of Lake Megachad is Lake Megafezzan (Drake *et al.*, 2006; Armitage *et al.*, 2006), further north still there was a large lake in the Basin of the Chotts in southern Tunisia and Algeria (Causse *et al.*, 2003), while east of these lakes is the catchment of Ahnet-Moyer Megalake in central Algeria (Conrad and Lapparient, 1991). As lake-generated precipitation forms a significant portion of the hydrological budget of large lakes (Coe and Bonan, 1997), the Saharan megalakes could be responsible for increased precipitation in their vicinity. To investigate the effect of surface water on Saharan climate, Coe and Bonan (1997) modelled the feedbacks between climate and surface water in northern Africa during the middle Holocene. They found that increasing the surface water by 6% produces changes in climate variables that are similar in size to changes produced by orbital forcing. As the Saharan megalakes outlined above could have covered an area equivalent to about 10% of the Sahara they could be expected to have a similar, or somewhat larger effect. Thus it appears that the existence of Saharan megalakes could, at times, have led to a more humid climate in their vicinity than would have existed had the topography of the central Sahara not been conducive to their formation. Together these water bodies and associated wetlands could have provided a corridor for animals, including humans, to migrate north across what is now the Sahara Desert.

Schuster *et al.*, (2005) have radiocarbon dated shells from a regressive shorelines just below the prominent shoreline to somewhere between 4410 and 5280 cal. BP, suggesting that the lake started to contract at around this time. Other regressive shorelines can be dated using our knowledge of the archaeology found on the plains that were exposed by the final demise of Lake Megachad and they appear to be much younger. The oldest archaeological sites found in the vicinity of Lake Chad are thought to have been first occupied soon after the

Figure 6 Landsat Band 4 image of the Angamma delta showing braided river channels on the delta top. The delta has a cuspate morphology typical of wave-modified deltas and a well-defined beach ridge or beach ridge along the top of the delta front. The pristine preservation of the delta top and lack of incision through the beach ridge along the top of the delta front indicate that there was no low-stand or falling stage incision and that fluvial discharge ceased before the lake level fell. However, the base of the delta front is cut by gullies on its western side. This gully formation is attributed to groundwater sapping. We suggest that although surface water discharge on the delta top had ceased there was still some flow of groundwaters into the lake basin with subsurface flow emerging at the base of the delta deposits

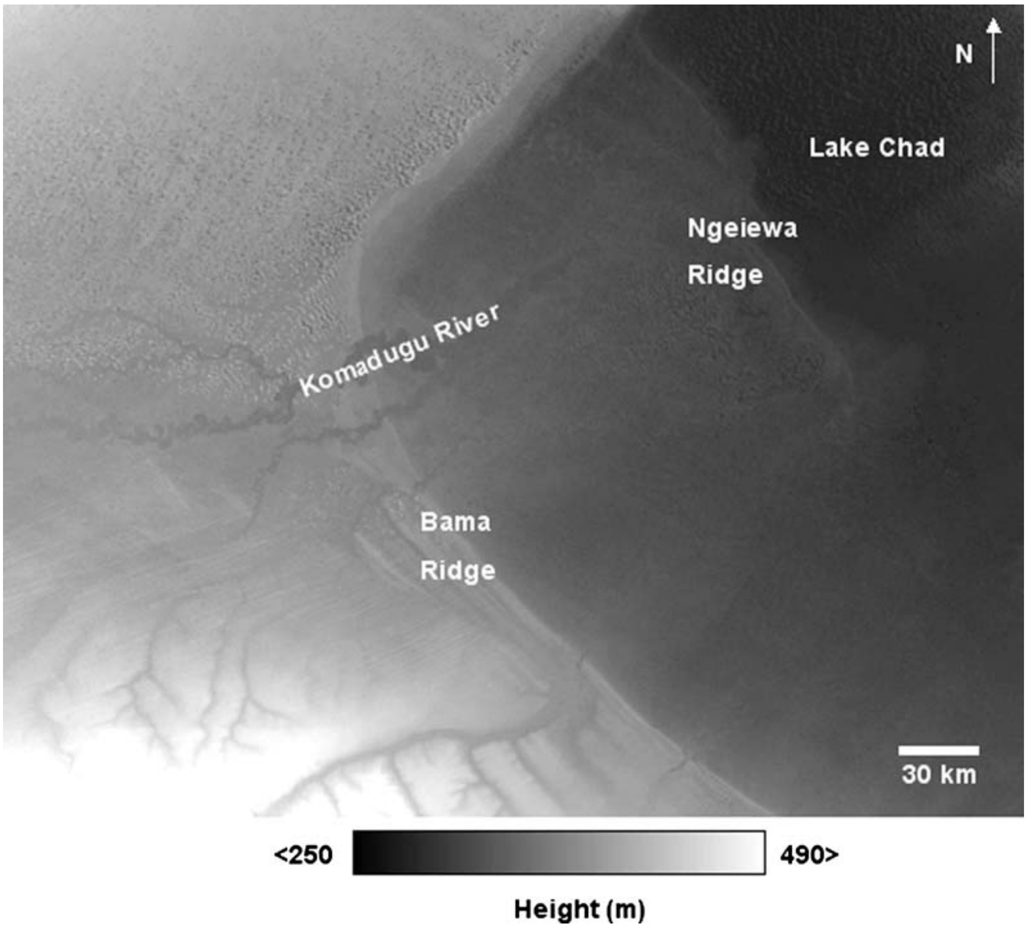

Figure 7 The Bama Ridge on the southwest shoreline of Lake Chad. A well-developed beach ridge complex is evident to the south of the Komadougu River known as the Bama Ridge in Nigeria. To the north of the river is a set of well-developed lake terraces. The elevations of all these shoreline landforms are shown in Table 1

Table 1 Shoreline elevations extracted from the DEM, the locations are indicated by the numbers on Figure 1

Shoreline locations	Shoreline height (m)											
1 East of Angamma	286			305		323	333		340	345		
2 West of Angamma				305	318		332					
3 Taimanga Ridge	284		297	302	316	320	328					
4 Goz Kerki Spits				304		320	330					
5 South of Goz Kerki					314		327					
6 The Hebil Terrace							329					
7 North of the Hebil							329	334				
8 South of the Hebil							328	335				
9 Moyto Island				304			328					
10 Chari Delta					315		328					372
11 Mayo Kébi Ridges							330	335			354	
12 Bama Ridge							328	336				
13 Terraces North of Barma					316		327					
14 Ngeiewa Ridge		290										
15 Historical Lake Chad Terraces	285	288										
16 Kanem							330					
Mean (m)	285	289		305	316	322	329	335				
Standard deviation (m)	1.4	1.4		1.2	1.7	2.1	1.8	0.8				
Mean lake area (1000 km^2)	114[a]	141	218	266	310	333	361	413	456	497	573	837
Error (1000 km^2)	5	7		5	8	7	13	9				

The lake area values and associated errors have been rounded to the nearest 1000 km^2. Errors were calculated by rounding the standard deviation to the nearest metre, adding and subtracting this value from the lake area, determining the lake area, differencing it from the mean and averaging the two differences.

[a]The area reported for the 285 m shoreline is the combined area of Lake Chad (22 000 km^2) and a lake in the Bodele depression (91 000 km^2).

desiccation of Lake Megachad and date to about 4000 BP. These settlement sites are found at an altitude of 298 m along the margin of a once larger Lake Chad (Breunig *et al*., 1996) suggesting the retreat of Lake Megachad from the 305 m shoreline before 4000 BP (Figure 9). As the lake level continued to fall the lake became divided into three separate water bodies with Lake Chad and Lake Fitri in the southern basin and another lake in the Bodele depression to the north. Lake Chad initially had a shoreline altitude of 289 ± 1.4 m and an area of 22 000 km^2 controlled by a sill with overflow to the north along the Bahr el Ghazal, which fed into the Bodele depression (Figure 9). The lake in the Bodele depression was larger, with a shoreline at 285 m producing an area estimate of 91 000 km^2. Falling water levels and intermittent recharge from Lake Chad created multiple regressive shorelines around the Bodele depression. These shorelines, which are well preserved near Taimanga at the northern end of the basin, have potential for a detailed chronology of palaeolake desiccation at the end of the African humid period, which must have occurred soon after 4000 BP.

Palaeoshorelines are found at similar altitudes even when separated by thousands of kilometres, providing further evidence that they are not the tectonic features that Durand (1982) thought they were. Notwithstanding this, the elevations of the prominent Holocene high-stand shoreline appear to be slightly higher at the northern end of the lake than they are at the southern end. For example, in the north, the beach ridge on the Angamma palaeodelta is at 333 m while the beach ridges on the Chari palaeodelta are at 328 and 329 m. The change in elevation may indicate slight regional tectonic tilting with uplift of a few metres at the northern end of the lake.

The morphology of the lake shorelines indicate two dominant winds, one northeasterly, which is consistent with the present-day northeasterly winds in Chad, and another from the southwest that is consistent with an enhanced monsoon moving further north into the Sahara than it does today. The northeasterly winds drove waves from the northeast, forming the swash-aligned beaches of the Bama Ridge along the megalake's southwestern shore, and formed spits by longshore drift at Goz Kerki and recurves at the mouth of the Chari palaeodelta. The southwesterly winds formed swash-aligned beach ridges at Goz Kerki and in the vicinity of Taimanga. Both sets of waves contributed to the cuspate morphology of the wave-dominated Angamma delta and associated cuspate forelands when the lake was last full around 7000 BP. Subsequently the lake has dried out and its desiccated lake bed is now the biggest single source of atmospheric dust on Earth (Mainguet and Chemin, 1990; Washington *et al*., 2003) because of deflation by a powerful northeasterly low-level jet (Washington and Todd, 2005). These northeasterly winds also appear to have been important in the arid period associated with the last glacial maximum as they seem to have controlled the formation of transverse dunes in the Erg Kanem prior to the Holocene lake highstand (Figure 2).

Schuster *et al*. (2005) argue that continental trade winds (Harmatan) controlled the longshore drift in the northern part of palaeolake Megachad with no major shift in ITCZ. We suggest that the geomorphological evidence of swash-and drift-aligned palaeoshorelines require the presence of a southwesterly (Monsoon) wind extending to the northern end of palaeolake Megachad. The southwesterly wind was associated with an enhanced monsoon extending from the Gulf of Guinea, which contributed increased rainfall within palaeolake Megachad and was driven by increased convection in response to precessionally driven increase in Northern Hemisphere insolation and associated vegetation–albedo positive feedback effects (Claussen *et al*., 1999, DeMenocal *et al*., 2000) with accompanied northward shift in the ITCZ. The morphology of the spits and beach ridges at Goz Kerki and formation of cuspate forelands indicate that the winds and waves were contemporary. We suggest that they were most likely to have been seasonal, with southwesterly winds associated with an enhanced monsoon in the summer months and northeasterly winds during the winter months.

The contrasting forms of the Chari and Angamma deltas provide evidence that enhanced monsoon rainfall contributed

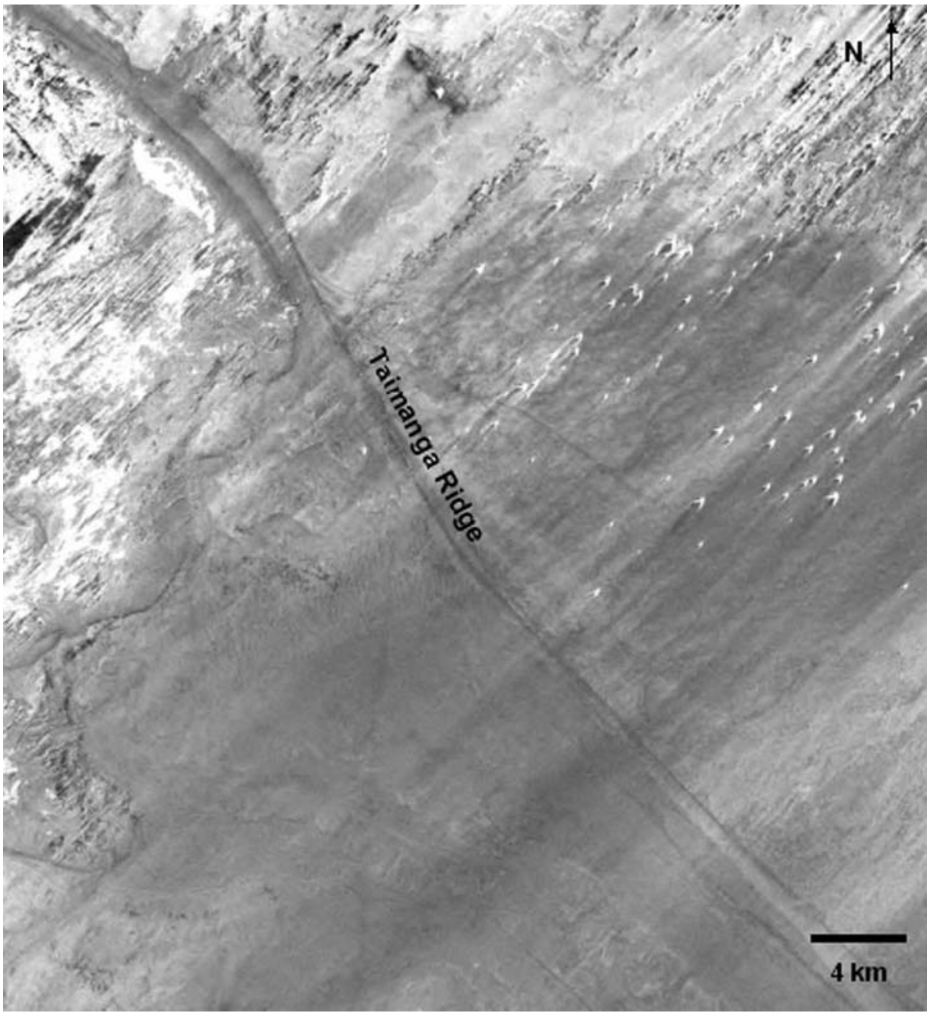

Figure 8 Landsat TM band 7 image of the northern end of the Taimanga beach ridge, which is trending northwest to southeast and is interpreted as a swash-aligned beach ridge formed by waves form the southwest. The bright patches on the top left of the image are exposed diatomaceous lake sediments. Light grey barchan dunes can be seen in the top right portion of the image. The barchan dunes are formed by the modern northeasterly Harmatan wind

to the flooding of palaeolake Megachad. At the southern end of palaeolake Megachad the Chari River has incised through older and higher palaeodelta deposits (Schuster *et al*. 2005) as the lake level fell and continues to flow into Lake Chad via this new channel. In contrast, the Angamma palaeodelta shows a well-preserved delta front and shoreline, with no evidence of incision, indicating that the river that fed the Angamma palaeodelta dried up before the lake level fell. This is consistent with a pattern of regional desiccation from north to south caused by the weakening of the monsoon. In effect, fluvial discharge on the Angamma delta ceased while the water level in the palaeolake was maintained by fluvial discharge from rivers in the southern half of the catchment including the Chari and Yobe. The Chari River has continued to flow, incising into the palaeodelta as the lake level fell and preserving a succession of regressive delta fronts that record the falling lake levels.

Conclusions

Interpretation of Landsat TM imagery and DEMs clearly reveals a wide array of coastal landforms in the Chad Basin including beach ridges, spits, cuspate forelands and deltas that were formed around palaeolake Megachad. The evidence of wave action preserved in the coastal landforms is attributed to a combination of northeasterly and southwesterly winds. The winds appear to have been seasonal with northeasterly winds in the winter and southwesterly winds due to an enhanced monsoon in the summer. Enhancement of the southwesterly monsoon is important because it contributed to increased rainfall in the Chad basin and to the filling of palaeolake Megachad. Geomorphological evidence from the Angamma and Chari paleaodeltas indicates subsequent drying from the north, with the Angamma delta in the north abandoned during the lake highstand before the lake level fell, while the Chari River in the south continues to flow into Lake Chad and has incised into its palaeodelta leaving successive delta fronts that record the falling lake levels. Palaeoshorelines have been traced around the lake and found at similar altitudes even when separated by thousands of kilometres. At its maximum extent Lake Megachad was larger than any lake that exists on Earth today. At around 7500–6950 BP it was $361\,000 \pm 13\,000$ km^2; by 4000 BP it had shrunk even further and split into three separate lakes, Lake Chad, Lake Fitri and Lake Bodele. As the catchment of Lake Megachad adjoins that of other large lakes to the north it is possible that these lakes provided a humid corridor across the Sahara that would not have existed had the Sahara not been dominated by large closed basins. Such a corridor may have implications for palaeoanthropology and biogeography as the Sahara is thought to provide a barrier to the movement of hominids and animals out of Africa.

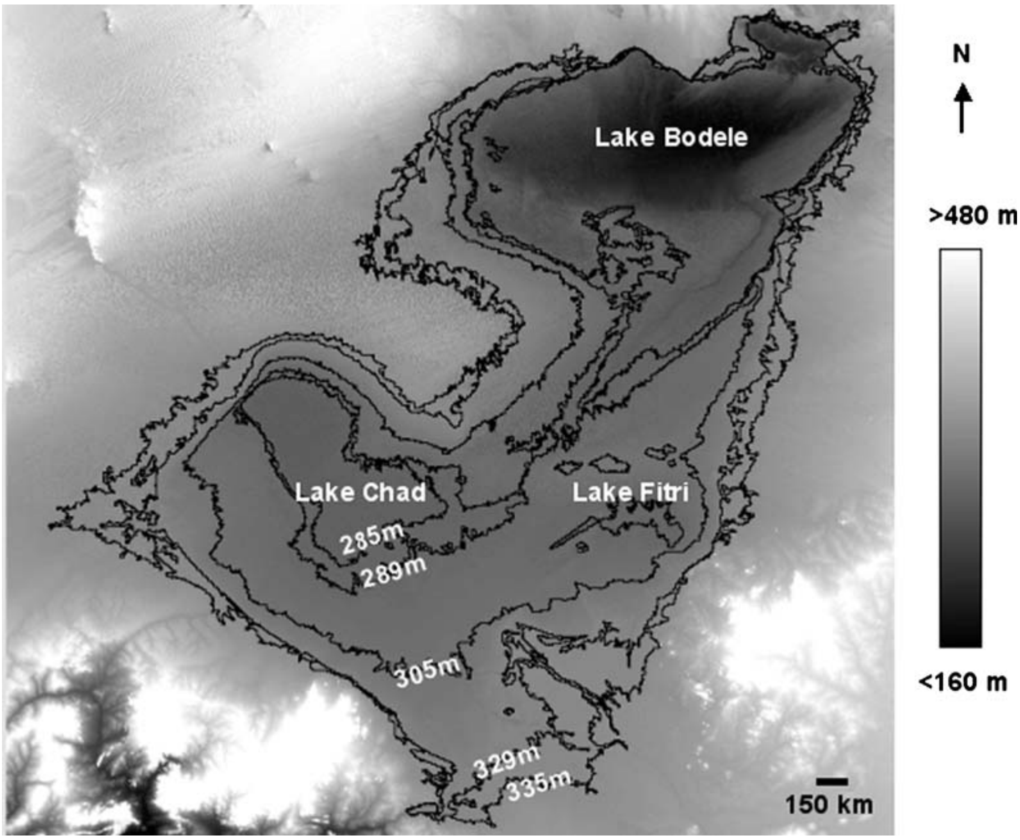

Figure 9 SRTM-3 90 m DEM of Lake Chad with the contours of many of the shorelines mentioned in the discussion overlaid. The lake defined by the 335 m contour would be the largest lake in the world if it existed today

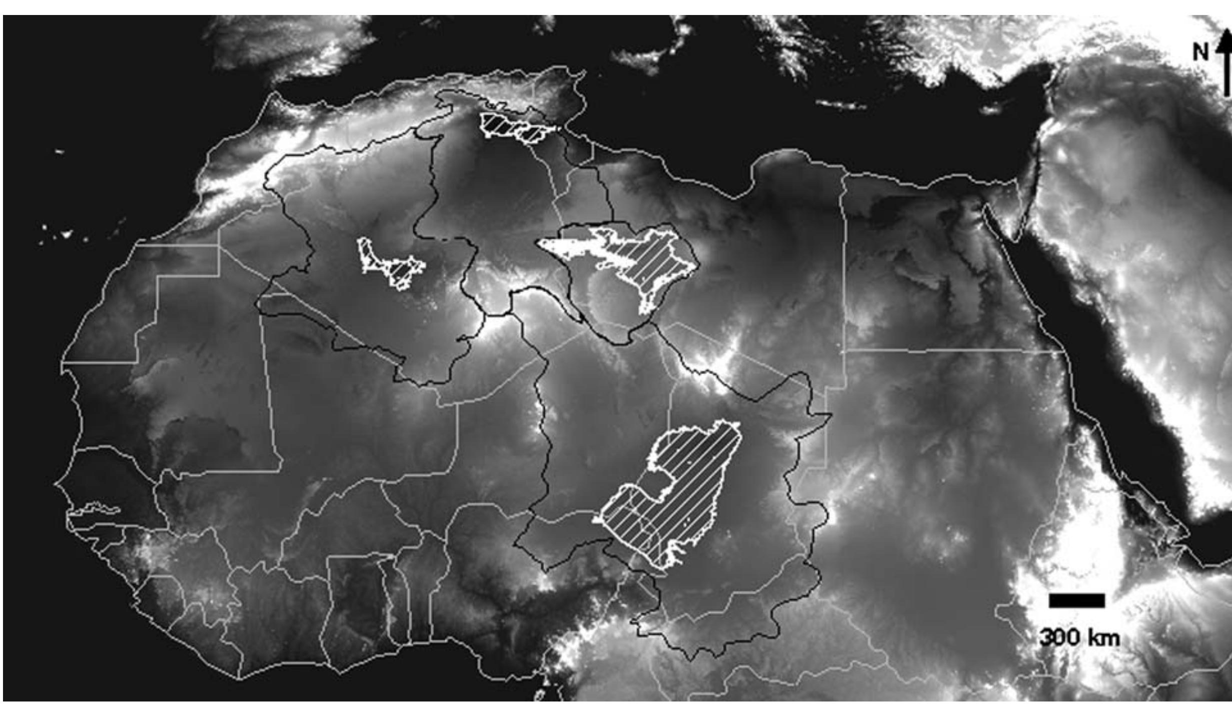

Figure 10 Megalakes of the Sahara. Lakes overlaid on the SRTM 1 km DEM of northern Africa. As altitude increases the shades of grey change from black to white. Lakes are marked with a diagonal white line pattern with the lake catchment areas marked in a black line. The area of the lakes was calculated from the heights of lake outflow channels (ie, the Chott el Djerid), lake shorelines (ie, Lake Megachad and Megafezzan) and, in the case of the Algerian Lake where no shorelines or outflow channels are evident, the maximum height of lake sediment outcrops reported by Conrad and Lapparient (1991)

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