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Reconstruction of Megalake Chad using Shuttle Radar Topographic Mission data

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Abstract

In the 2,500,000 km^2 Lake Chad Basin in central Africa, the 2000 Shuttle Radar Topographic Mission (SRTM) data have been used to supplement the existing topographic data. SRTM data produce much sharper images of the region's topography and provide new insights into debates about the nature and extent of late Quaternary Lake Chad. This paper shows that the accuracy of SRTM30, the recently released 30 arc seconds topographic data from SRTM, largely surpasses that of previous global Digital Elevation Models (DEMs) available in the region. Using a GIS we identified from SRTM30 elevation data key features in the landscape topography providing further evidence for the existence of a Megalake Chad. The SRTM30 data corroborate the presence of two ancient shorelines associated with stillstands of the paleolake at the elevation of the Mayo Kebbi and Bahr el Ghazal spillovers. We found a general flattening of the topography in the region covered by Megalake Chad which is most likely the result of wave-cut action. The SRTM30 data show that the remains of the highest paleoshoreline have a constant elevation of 325±5 m amsl. At its maximum extent, Megalake Chad had an area of about 340 000 km^2 (only 8% less than the present-day world's largest lake, the Caspian Sea). The SRTM30 data also revealed ancient drainage networks in the Sahara that lead to Megalake Chad. We compiled available ^{14}C dates to constrain Holocene Megalake Chad events. The results presented in this paper have significant consequences for improving our knowledge of regional paleohydrology and continental climate change. This study is also the first step for a GIS-based reconstruction of late Quaternary paleohydrology in tropical Africa.

Keywords: Climate change; Paleohydrology; Lake Chad; SRTM; GIS; DEM; Africa; Paleolimnology; Hydrology; Terrain analysis

1. Introduction

The Lake Chad Basin occupies 2,500,000 km^2 in central Africa. It is the world's largest endorheic basin and most surface water drains into Lake Chad — a vast

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and shallow fresh water lake located in the central part of the basin. Presently, most of the northern portion of the basin lies in the Sahara desert and is dry. Most of the inflows to Lake Chad are provided by the Chari and the Logone rivers, which are flowing from the south. Lake Chad is located in a region of little relief and has currently no surface outlet. Its areal extent is very sensitive to climate fluctuations. For example, from 1960 to 1990 the level of the lake fluctuated approximately between 284 and 277 m amsl and its extent from 25,000 km^2 to less than 6000 km^2 (Olivry et al., 1996). The presence of a much larger lake during the late Quaternary, referred to as Megalake Chad, is debated. Some archeological, geomorphological, sedimentological and stratigraphical investigations have supported the existence of this large and deep Megalake Chad (Pias and Guichard, 1957; Schneider, 1967; Maley, 1981; Servant and Servant, 1983; Schneider, 1994; Schuster et al., 2003). However, it was strongly argued that the landforms which are considered to be the remains of the paleoshoreline for Megalake Chad were too discontinuous and too irregular in elevation to be of lacustrine origin, and were in fact neotectonic features following the directions of major structural faults (Durand, 1982; Durand et al., 1984; Durand, 1995).

Digital Elevation Models (DEMs) have proved to be of great assistance in the reconstruction of large paleolakes. For example, DeVogel et al. (2004) used a DEM to calculate areas and volumes for terminal lakes of the Lake Eyre Basin and identify flow directions across spillovers. In the Lake Chad Basin other DEMs, TOPO6 and GLOBE (which is similar to GTOPO30 in the region) have been used to calculate area and volume of Megalake Chad according to level fluctuations (Ghienne et al., 2002). These datasets have suggested the existence of a very large lacustrine shoreline terrace (Ghienne et al., 2002).

However doubt about the existence of Megalake Chad has in part resulted from a paucity of topographic and geomorphological observations due in part to the vast expanse of the Lake Chad Basin and difficulties in accessing some sites from the ground. The best topographic maps covering Lake Chad Basin are in two series (1/200,000 and 1/1,000,000) and are based on sparse topographic field measurements, if any in some regions to the north. The previous best global DEM available for the region, GTOPO30, was largely derived from these topographic maps. A new DEM derived by NASA from the February 2000 Shuttle Radar Topographic Mission data (SRTM30) has the potential to significantly improve our knowledge of the region's topography. In this paper we present a first accuracy assessment in the region for SRTM30. The result is encouraging enough for us to use the SRTM30 data to reconstruct the regional paleohydrology in a GIS.

We also compiled available ^{14}C dates in the region to better constrain Holocene Megalake Chad events.

2. Methods

2.1. Shuttle Radar Topographic Mission data

In February 2000, the space shuttle carried onboard, for the first time, a space-borne, single-pass interferometer. The mission was referred to as the Shuttle Radar Topographic Mission (SRTM). Two antennae operating in C- and X-bands simultaneously illuminated and recorded radar signals over the entire land mass between 60°N and 57°S. Global DEMs were processed by NASA-JPL from C-band radar using single-pass interferometry (Farr and Kobrick, 2000; Rosen et al., 2000). This method requires no ground control, and hence is very useful for inaccessible regions. The overall absolute horizontal and vertical accuracy of these 1 arc second data is estimated to be significantly better than the original mission requirements of 20 m and 16 m respectively (Rosen et al., 2001; Sun et al., 2003). For example, in southeastern Michigan, Sarabandi et al. (2002) found the 'Principal Investigator Processor' C-band data (not even the refined final data product) offered an average absolute height offset of 9 m with a standard deviation of 2 m.

SRTM3 and SRTM30 are the two DEMs at 3 and 30 arc seconds horizontal resolution respectively that have recently been released by NASA. They are both given with 1 m vertical precision and were generated by averaging SRTM elevation data first obtained at a 1 arc seconds resolution. In this paper, we propose a first analysis of SRTM elevation data in the whole of the Lake Chad Basin (2,500,000 km^2) using the most suited DEM at this scale considering computer limitations, SRTM30.

2.2. SRTM30 quality assessment

We realised a preliminary assessment of the quality of SRTM30 and a comparison with GTOPO30 in the Lake Chad Basin using elevation data from surveys reported on topographic maps. SRTM30, GTOPO30 and survey points were referenced to the same horizontal datum: the World Geodetic System of 1984 (WGS84). However, the vertical reference for SRTM data is the EGM96 geoid (a modeled surface of the

Earth's gravity field, which globally best fits Mean Sea Level), while survey points are reference to tidal gauge benchmark. Surveyed measurements were obtained during a consistent leveling campaign (IGN, pers. communication). There is no global model for the conversion between the EGM96 geoid and the local vertical datum. However, in the case of our study area (central Lake Chad Basin), this discrepancy between heights referred to the geoid and the local vertical datum is limited by the very flat and low topography and should not exceed the 1 m precision of elevation data. In the Niger part of the study area, Delclaux (2004) found a consistent discrepancy between EGM96 and the local IGN datum of only 0.8 m.

Using a GIS, we captured the surveyed points from 12 topographic maps at 1/200,000 scale in Chad, Niger

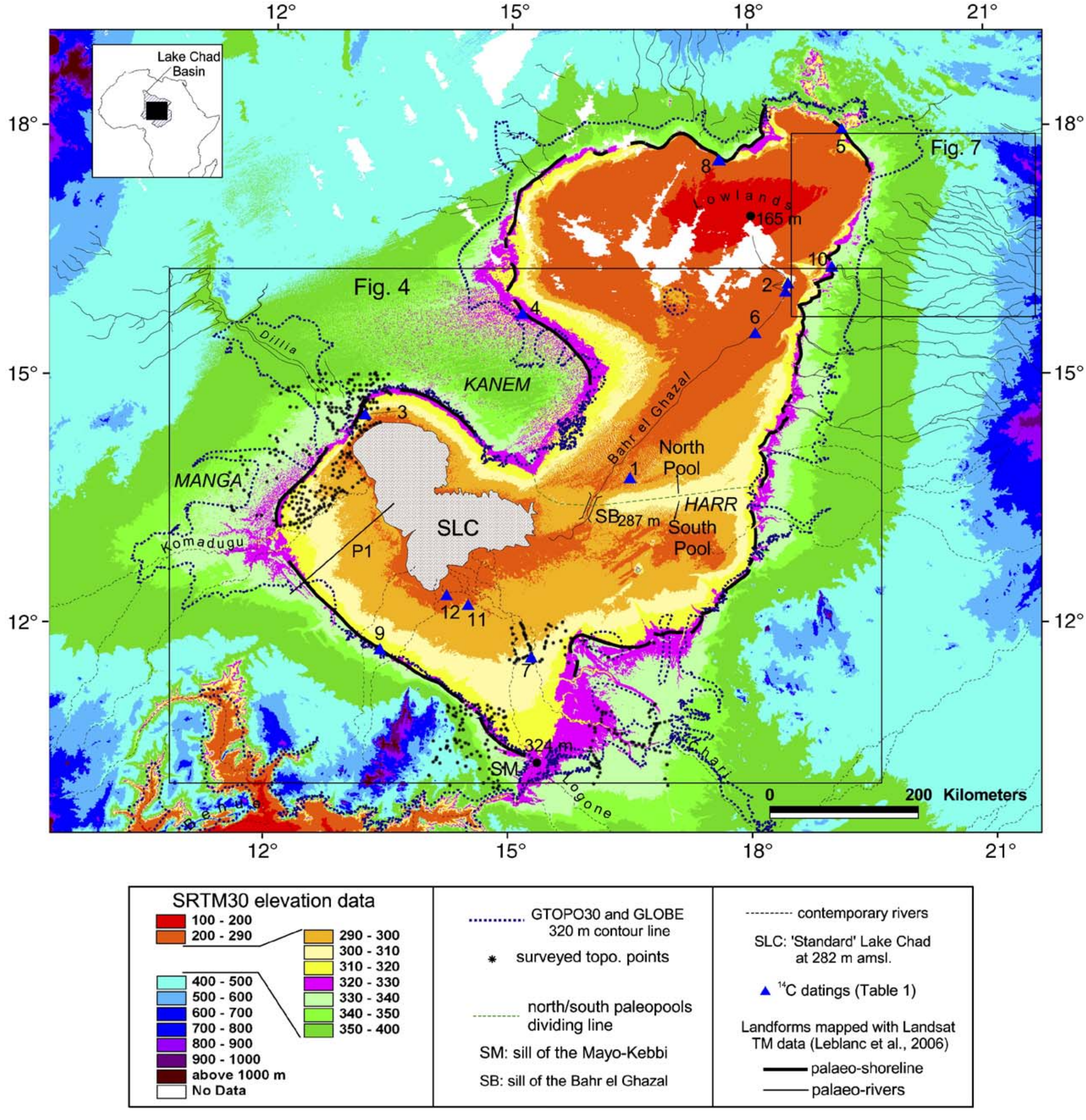

Fig. 1. SRTM30 elevation data in the Lake Chad Basin. Remains of Megalake Chad shoreline and Saharan rivers, that were mapped using satellite imagery (Leblanc et al., 2006), were overlaid on the SRTM30 data. Remains of Megalake Chad shoreline have a constant elevation of 325 ± 5 m amsl which corresponds to that of a major spillway to the Atlantic Ocean via the Mayo Kebbi valley (site SM).

and Cameroon, and the corresponding values of SRTM30 and GTOPO30 (see Fig. 1 for the location of the surveyed points). Each SRTM30 cell was accompanied with the standard deviation of the 1 arc sec SRTM data points used in the averaging of the cell height value. This standard deviation value is thus an indication of topographic roughness. Due to the fairly coarse resolution of both SRTM30 and GTOPO30 we only selected surveyed points in flat areas with an SRTM standard deviation below 2. This represents 469 points and 41% of all the surveyed points contained in the topographic maps. Fig. 2 shows the histograms of the elevation difference between the selected surveyed points and SRTM30 and GTOPO30 respectively. These histograms clearly indicate a smaller range in height offset from SRTM30 and a closer fit with the surveyed points. We found an average absolute height offset of 4.1 m with a standard deviation of 3.9 m between STRM30 and all the selected points from the topographic maps (Fig. 2). In comparison, an average absolute height offset of 13.6 m with a standard deviation of 12.2 m was found between GTOPO30 and the surveyed points from the topographic maps (Fig. 2). In particular, between 270 and 370 m, SRTM30 has a significantly better fit with the points from the topographic maps (Fig. 3). A shift in the histograms (Fig. 2A) shows that SRTM30 generally overestimates the surveyed elevation. The median of the differences between surveyed points and SRTM30 has a value of −3. This is, in part, due to the fact that surveyed points in the dunefields are generally taken at the bottom of the topographic depressions while the SRTM30 value represents average elevation in the ~1 km^2 cell.

Therefore, in the region, SRTM30 supplements the few elevation data from the topographic maps and largely exceeds the accuracy of previous global DEMs. In the most southern and densely forested part of the basin, the signal captured from the space shuttle represents the top of the canopy. However, the C-band wavelength (~5 cm) can penetrate small vegetation with dry, small leaves and branches. Alternatively the beam may also reach the ground where trees are far enough apart (Sun et al., 2003). Therefore, in the studied central part of the basin, the quality of SRTM elevation data is favoured by the very scarce to low vegetation cover – shrub savannah – and SRTM data are likely to represent the surface of the ground. SRTM30 covers approximately 98% of the Lake Chad Basin (Fig. 1).

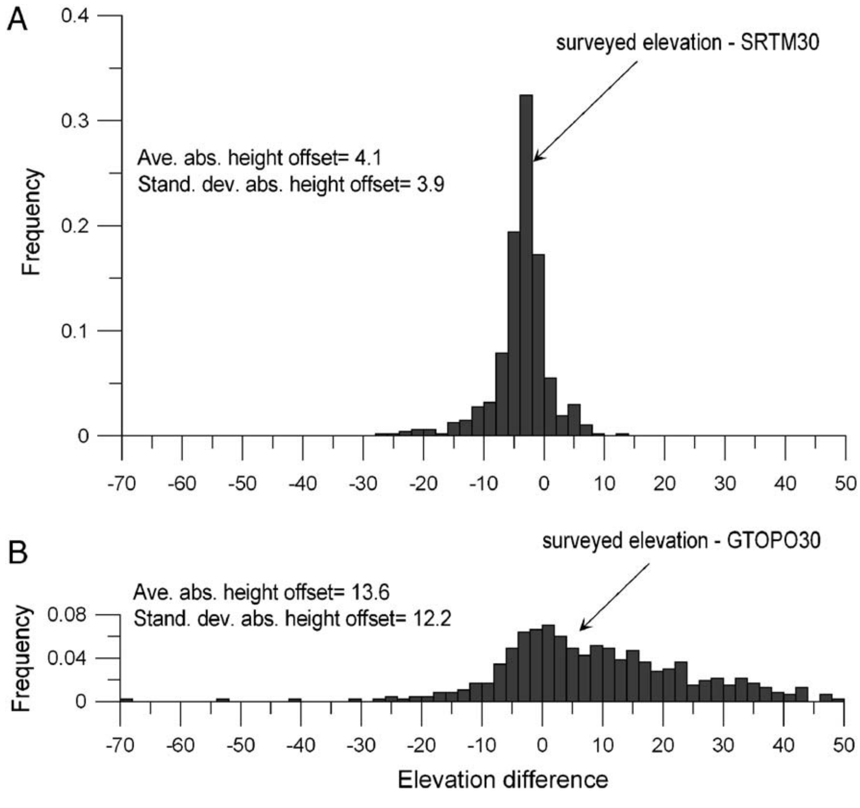

Fig. 2. Histograms of the elevation differences between the selected surveyed points and the DEMs. (A) Histogram of elevation difference between surveyed points and SRTM30. (B) Histogram of elevation difference between surveyed points and GTOPO30.

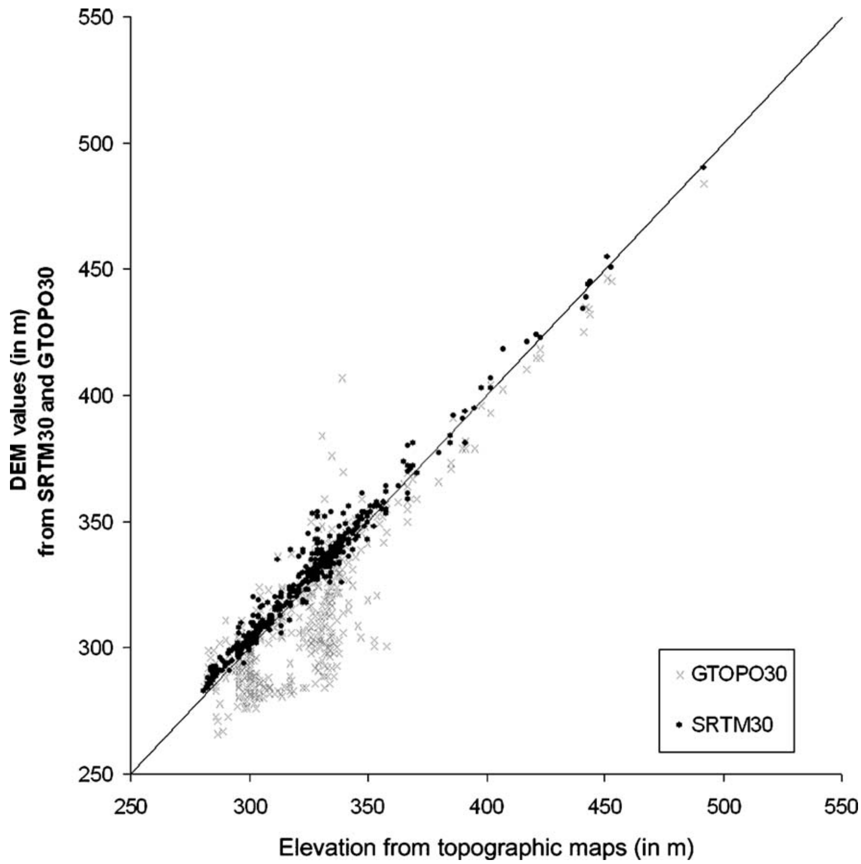

Fig. 3. Comparison between heights from SRTM30 and GTOPO30 for the selected surveyed points of the topographic maps.

This good coverage with consistent source data and processing approach results in elevation data that significantly enhance currently available topographic data in the basin.

3. Results

3.1. Paleoshorelines

Recently, satellite imagery has enabled detailed mapping of the Megalake Chad shoreline remains (Leblanc, 2002; Leblanc et al., 2006). SRTM30 data cover the Megalake Chad shoreline and its surroundings with continuous and consistent topographic data. In this study, SRTM30 data show that these remains of the paleoshoreline have a constant elevation of 325 ± 5 m amsl (Fig. 1). We derived a map of the terrain slope from SRTM30 data in a GIS (Fig. 4). This map shows a ridge forming a rising pitch where the remains of the Megalake Chad shoreline have been identified (R in Fig. 4A).

The remains of another, lower paleoshoreline were identified to the north-west of today's Lake Chad (Leblanc et al., 2006). The map of the terrain slope derived from SRTM30 data also shows a topographic ridge in this location (RR in Fig. 4A). Fig. 5 is a topographic profile from SRTM30 data across the central part of the basin (profile location is reported in Fig. 1). The ridges of these two paleoshorelines are clearly visible in the topographic profile where they appear with a ramp-like shape (Fig. 5).

3.2. Megalake Chad level, area and volume relationship

The areas and volumes of the paleolake were calculated for lake levels ranging from 165 to 325 m by incrementally filling Megalake Chad meter by meter in the GIS (Fig. 6). The maximum elevation corresponds to that of the sill of the Mayo Kebbi and to that of the Megalake Chad shoreline.

Based on SRTM30 data, at its maximum level Megalake Chad had a shoreline length of approximately 3150 km, an area of about 340,400 km^2 (only 8% less than the present world's largest lake, the

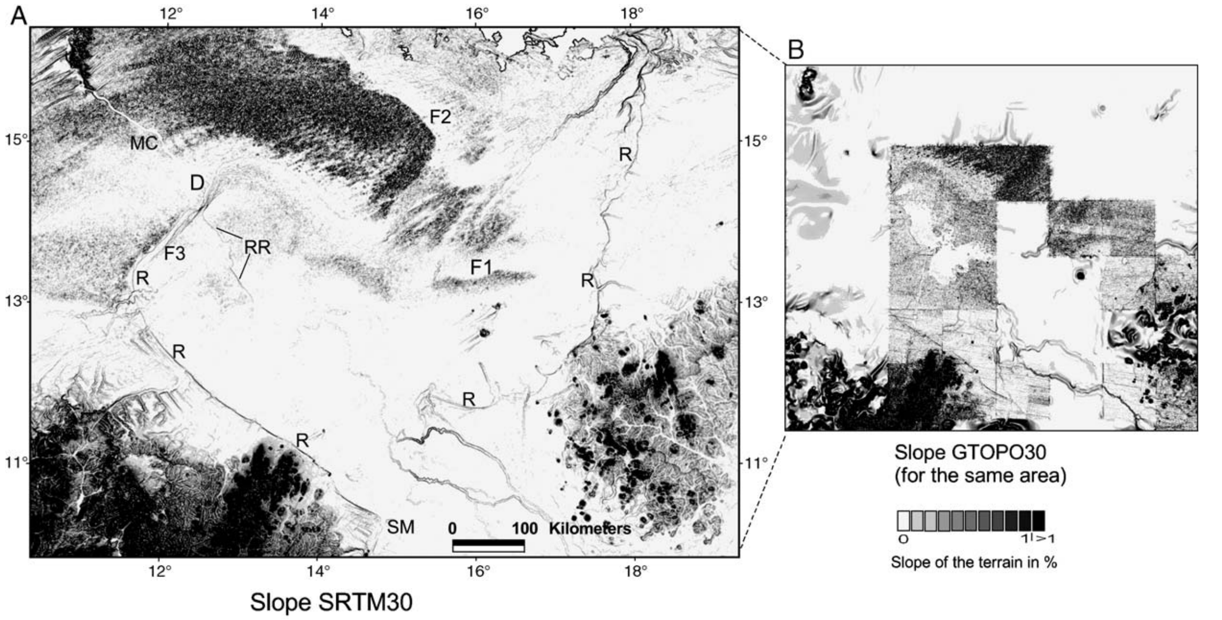

Fig. 4. Map of the slope of the terrain derived from SRTM30 (A) and GTOPO30 (B) data. SM: sill of the Mayo Kebbi; R: topographic ramp marking the paleoridge of Megalake Chad shoreline; F1, F2 and F3: flattenings of major dunefields; MC: main channel of the ancient Dillia river; D: paleodelta of the Dillia river bordering Megalake Chad shoreline. Note the much greater details from SRTM30 than GTOPO30 data, which also contain large noisy blocks. The location of this figure is reported in Fig. 1.

Caspian sea) and a volume of about 13,500 km^3. Its maximum depth was about 160 m. For comparison, present-day maximum depth is less than 10 m for a maximum storage of about 80 km^3 (Olivry et al., 1996).

3.3. Sills and stillstands

In the southern part of the study area, Fig. 1 (site SM) shows the paleoridge ceasing abruptly at the border of the Lake Chad Basin just before the Mayo Kebbi river, a tributary of the Benue (see also site SM in Fig. 4A). The SRTM30 data indicate that the elevation of the sill of the Mayo Kebbi is the same as the base of the paleoridge (Fig. 1). Therefore, it is confirmed that in this region, a discontinuity of Megalake Chad shoreline coincides with a substantial spillway, a former outlet to the Gulf of Guinea, via the Benue and Niger rivers. This observation confirms earlier report that, at its high level around 325 m, Megalake was no longer a close lake (Pias and Guichard, 1957).

Because of the flat regional topography, at intermediate lake levels, small changes in the paleolake height would have resulted in large fluctuations of the paleolake areal extent. However, the maximum paleolake level was stabilized through the Mayo Kebbi sill, which transferred overflows to the Gulf of Guinea. The presence of the well defined shoreline at 325 m can be

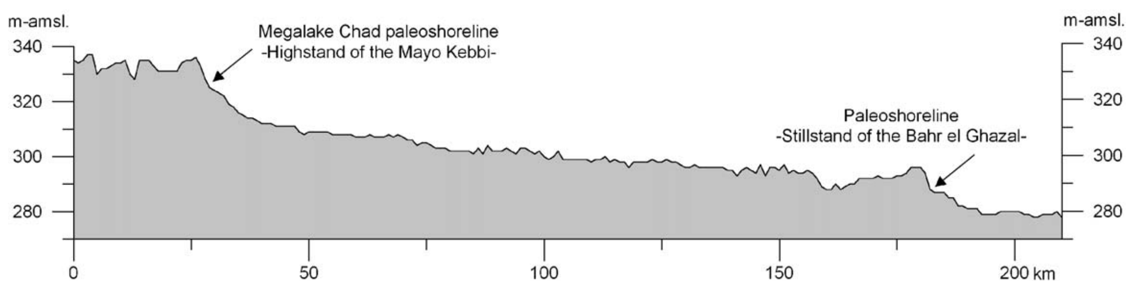

Fig. 5. Topographic profile from SRTM30 data across Megalake Chad shorelines. The profile shows topographic ramps marking an accumulation of deposits along the paleoridges of Megalake Chad shorelines. The location of the profile is reported in Fig. 1 as P1.

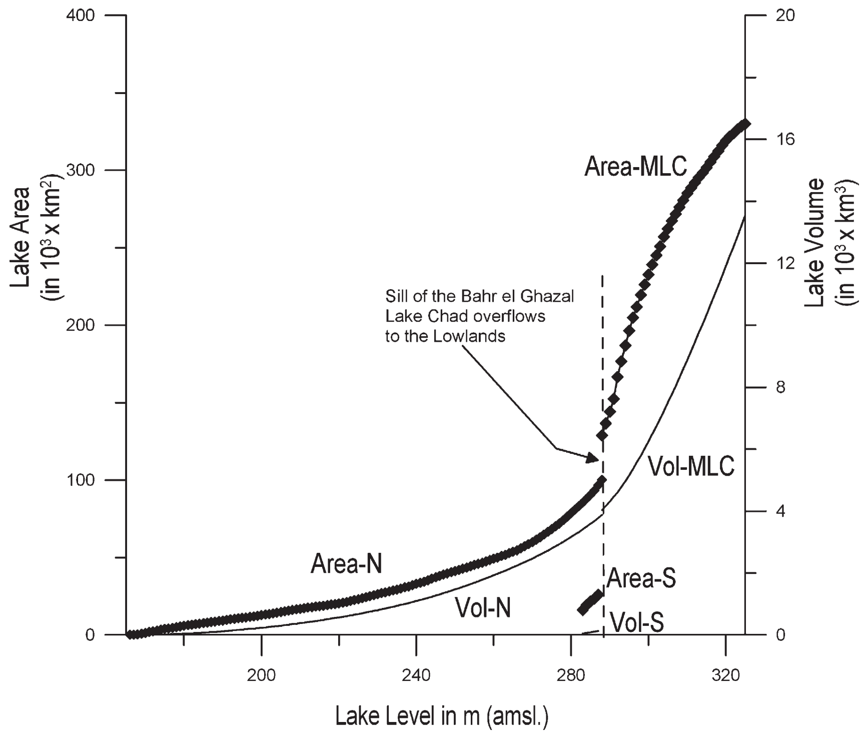

Fig. 6. Hypsographic curve of Megalake Chad reconstructed using SRTM30 data. Area-N, area for northern pool; Vol-N, volume for northern pool; Area-S, area for southern pool; Vol-S, volume for southern pool; Area-MLC, area for Megalake Chad — water level exceeds the sill of the Bahr el Ghazal, southern and northern pools are connected; Vol-MLC, volume for Megalake Chad — water level exceeds the sill of the Bahr el Ghazal, southern and northern pools are connected. The dividing line between the southern and northern pools is reported in Fig. 1.

explained by prolonged stillstands of terminal Megalake Chad related to the topographic threshold of the Mayo Kebbi at this elevation.

SRTM30 data also confirm that the sill level of the Bahr el Ghazal, a currently dry river that has only run for very short periods during the last millennium (Maley, 1981; Maley, 1993), controls the overflow from Lake Chad to the Lowlands region (Fig. 1). When the lake level rises between 287 and 288 m amsl, the area and volume plot show a very significant increase in both area and volume by ~98,900 km^2 and 3800 km^3 respectively (Fig. 6). This major increase in area and volume occurs just after the elevation threshold of the Bahr el Ghazal has been breached, and corresponds to the filling of the Lowlands depression. SRTM30 elevation data indicate that the second, lower paleoshoreline identified to north-west of today's Lake Chad corresponds to the stillstand of the Lake around 287 m amsl, at the elevation of the Bahr el Ghazal spillover (Fig. 1).

3.4. Paleorivers

SRTM30 data substantiate the presence of Saharan paleorivers leading to the shoreline of Megalake Chad. Despite the relatively coarse resolution of SRTM30, it is possible to observe in northern Chad many v-shape patterns that mark the location of paleorivers (Fig. 7). These ancient valleys become less pronounced and cease before reaching the Megalake Chad shoreline. In the western part of the basin, the map of the terrain slope shows a part of the Dillia drainage system with its main channel leading to the Megalake Chad (MC in Fig. 4A).

3.5. Ancient shoreline terrace and dunefield flattening

It is evident from SRTM30 data that the topography inside the limit of Megalake Chad highstand (below 325 m) is significantly flatter than outside (above 325 m). Both the slope data derived from SRTM30 and the standard deviation data from the averaging process (Section 2.1) show significantly smaller values and a sharp break below 325 m (Fig. 8). In particular, this is well expressed along the Kanem and Manga dunefields where the Megalake Chad shoreline is marked by pronounced flattenings of these dunefields (see F2 and F3 in Fig. 4A). Because of their large distribution and their correlation with Megalake Chad

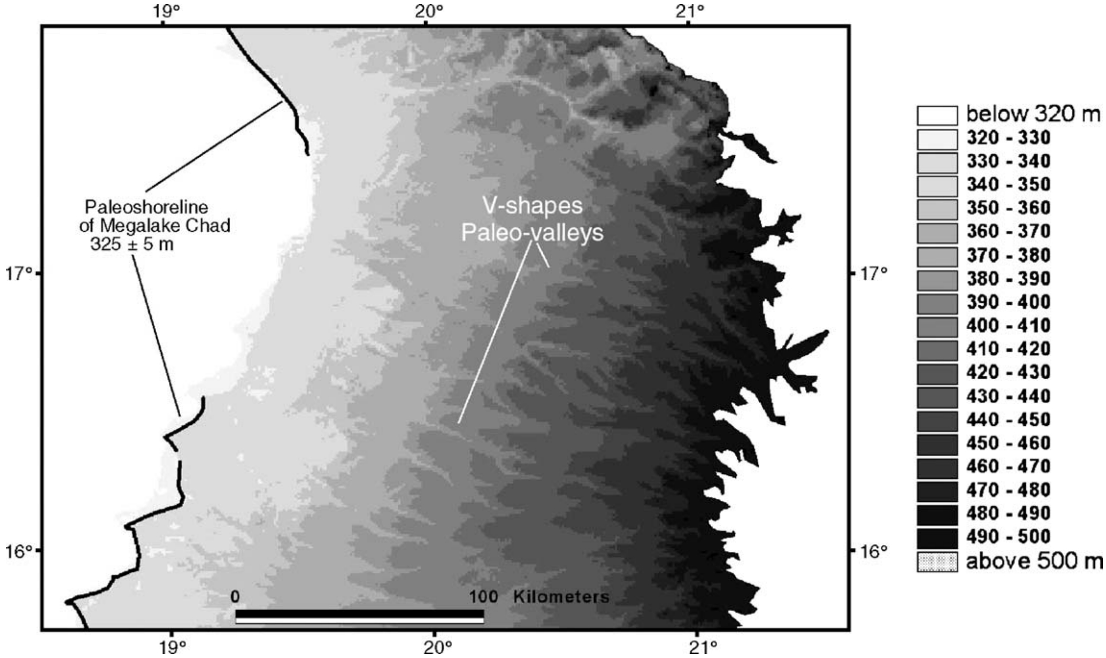

Fig. 7. SRTM30 elevation data showing ancient drainage systems in the Sahara leading to Megalake Chad shoreline (325 ± 5 m amsl). The location of this area is reported in Fig. 1.

extent, these general flattenings most likely resulted from wave-cut action.

4. Discussion

Elevation models produced from the SRTM data offer the most comprehensive, accurate and consistently processed topographic dataset ever produced for the Lake Chad Basin. In this study, the accuracy assessment of SRTM30 was essentially confined to the central part of the basin. In the north, where surveyed measurements are extremely sparse, SRTM30 should provide an even greater improvement compared with other available DEMs.

A major argument used to refute the existence of Megalake Chad was that the suspected remains of the paleoshoreline were found too irregular in elevation to be of lacustrine origin (Durand, 1982; Durand et al., 1984; Durand, 1995). This dismissal was largely based on sparse measurements contained in the topographic maps. SRTM30 data unambiguously confirm the presence of a well developed shoreline associated with the Megalake Chad highstand at 325 ± 5 m, which corresponds to the elevation of a spillover to the Atlantic Ocean through the Mayo Kebbi valley. This altitude is in good agreement with initial estimates of about 320 m for the Megalake Chad shoreline (Pias, 1967; Schneider, 1967), and confirms more recent geomorphological evidence of near 325 m for the Megalake Chad water level (Schuster et al., 2003). Our results show that steep slopes occur on both sides of the paleoridge (Figs. 4 and 5). The Megalake Chad ridge can reach tens of meters in height and can be few kilometers in width. In accordance with previous descriptions (Pias and Guichard, 1957; Schneider, 1967), we interpret this topographic ramp as an old beach ridge where aeolian and perhaps lacustrine sediments were deposited around the Megalake Chad shoreline. Further studies are however needed to better describe the morphology and sedimentology of the mega-ridge. In semiarid areas, as in other environments, (paleo-)shoreline ridges can be of aeolian and/or of lacustrine origin, and may slightly differ from the water level elevation (e.g., Magee and Miller, 1998; Otvos, 2000).

Using GLOBE elevation data, Ghienne et al. (2002) identified in the northern part of Megalake Chad a large lacustrine shoreline terrace between 300 and 310 m amsl which was attributed to an intermediate level of Megalake Chad. In the GLOBE data, this terrace, marked by a very small slope (i.e. increased flatness), is up to 100 km wide and can be followed at constant elevation over hundreds of kilometers (Ghienne et al., 2002). We did not find this northern terrace in the SRTM30 data. The wider areas found between 300 and 310 m in the GLOBE data in the northern parts of the paleolake are not present in SRTM30 data (Fig. 1). Fig.

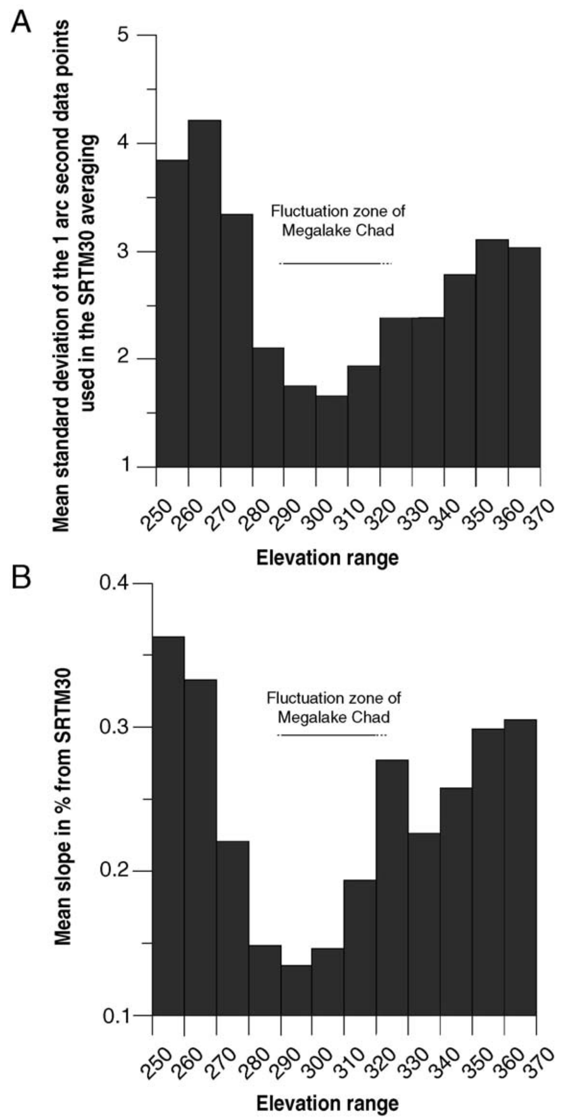

Fig. 8. Indicators of the terrain slope and roughness by elevation range. (A) Mean standard deviation in 30×30 kernels of the 1 arc sec SRTM data used in the averaging of SRTM30. (B) Mean terrain slope from SRTM30 data.

6 shows that there is no significant upsurge in the area of the lake when water levels rise between 300 and 310 m.

A selection of available ^{14}C dates constraining Holocene Megalake Chad events is proposed in Table 1. Sampled and analysed sediments are well distributed around the Megalake region, in different geomorphological positions (Fig. 1) and concern various remains including:

– dates from charcoal found at the top of the paleoridge (site 9, cf. Table 1 and Fig. 1);
– dates from shells found on the inner flank of the paleoridge (sites 3 and 10);
– a Holocene sedimentary sequence in the central part of Megalake Chad with 3 dates, diatoms and pollens analysis (site 1);
– a deltaic sequence from early to middle Holocene in with 3 dates (site 8);
– isolated logs inside the Megalake Chad area (sites 5, 4, 2, 6 and 7);
– dates from the base of 2 archaeological tells (sites 11 and 12) indicating that no Megalake Chad event occured since 3000 yrs. cal. BP (Table 1).

One of the difficulties in obtaining accurate dates relates to the application of ^{14}C analyses (Reimer et al., 2004). The use of ^{14}C dating for constraining Megalake Chad events is mainly limited by the nature of the old beach ridge, which is composed of siliceous sand. However, charcoals that related to Neolithic settlements were found in the top of the ridge, indicating that the beach ridge was already well developed around 7100 cal. BP (Thiemeyer, 1992).

Additional dates from the Megalake Chad region include analysis of shell deposits found at Mitimi on a paleobeach at the bottom of the paleoridge. These shell deposits give another date for a possible Megalake Chad event ca. 7790 cal. BP (Durand, 1995). During Megalake Chad events, storms and waves washed out contemporary deposits and accumulated them in local topographic depressions. A similar process is still occurring in today's Lake Chad. The sediments of the Tjeri's log, near Moussoro in the central part of the Megalake Chad, were deposited under these conditions. This log provides a continuous recording with a relatively well established chronology — in particular 3 dates were obtained for the Holocene from an 8 m thick series (Maley, 2004). The analysis of diatoms and pollens from Tjeri's log allowed the reconstruction of fluctuations in water levels and the relative importance of fluvial inflows and variations in regional vegetation (Maley, 2004). Tjeri's data show that the Holocene Megalake Chad occurred only during the middle Holocene from ca. 8500 to 6300 cal. BP (ca. 7700–5500 ^{14}C BP) with 3 sub-phases interrupted by brief regressions. Some characteristic points of these sub-phases can also be found in logs and datings from other areas. Further south, clayey sediments from the Mailao log include carbonate nodules which provided a date of ca. 9135 cal. BP (Table 1). These deposits characterize the late Pleistocene/early Holocene formation (Bouteyre et al., 1964) on which was laid the very large paleodelta of the Chari and Logone rivers (Pias, 1967). The

Table 1
Review of ^{14}C datings constraining Holocene Megalake Chad events

Site name (no., Fig. 1)	Lon °E Lat °N	Alt. (Ref.) m-amsl	Site description	Material	Depth (cm)	Age ^{14}C (years BP)	Calendar age (years BP), extreme values and (mean)	Lab. code	Ref.
Inner Megalake Chad deposits									
TJERI (1)	16°30′ 13°44′	267	Lacustrine deposits interdunal depression	Organic clay	775	9000±200	10300 to 9790 (10200)	GIF 1226	i, e
TJERI (1)	16°30′ 13°44′	268	Lacustrine deposits interdunal depression	Organic clay	700	8750±200	10175 to 9535 (9700)	GIF 1227	i, e
TJERI (1)	16°30′ 13°44′	272	Lacustrine deposits interdunal depression	Organic clay	250	4280±60	4870 to 4830 (4850)	Beta 93999	f
KORO-TORO (2)	18°29′ 16°07′	266	Base of a diatomite sequence	Shells of *Melania*	–	9470±220	11170 to 10480 (10710)	GIF 1095	i, j
KORO-TORO (2)	18°29′ 16°05′	267	Base of a diatomite sequence	Shells of *Corbicula*	–	3160±105	3470 to 3320 (3380)	I 2165	i, h
KORO-TORO (2)	18°27′ 15°59′	259	Terrace 17 m above Bahr El Ghazal	Fluviatile oysters in living position	–	3000±110	3355 to 3000 (3210)	GIF 1606	i
MITIMI (3)	13°12′ 14°30′	304	Lumachelle on a sandy plateau	Shells of *Corbicula*	0–100	6950±240	8000 to 7580 (7790)	LHGI 2413	d
DIK (4)	15°09′ 15°43′	294	Lacustrine deposits	Shells	–	4260±360	5320 to 4410 (4840)	Ny 67	g, h
FAYA-LARGEAU (5)	19°11′ 17°57′	270	Base of a diatomite sequence	Shells, diatomite limestone	–	7000±170	7975 to 7670 (7840)	GIF 1231	i, f
BEURKIA (6)	18°04′ 15°29′	260	Base of a diatomite sequence	Shells, diatomite limestone	–	6990±140	7960 to 7675 (7835)	T 642	i, f
MAILAO (7)	15°17′ 11°34′	293	Laminated lacustrine clay	Vegetal remains	334–342	8220±190	8995 to 9465 (9135)	GIF 1028	c, i
Megalake Chad deltaic formations									
ANGAMMA (8)	17°38′ 17°34′	250	Base of a deltaic formation	Loamy limestone with ostracods	–	10160±160	12090 to 11400 (11820)	T 732	i, j
ANGAMMA (8)	17°37′ 17°34′	250	Base of a deltaic formation	Shells of *Valvata* and *Pisidium*	–	9260±140	10650 to 10245 (10490)	T 731	i, e
ANGAMMA (8)	17°38′ 17°34′	305	Upper part of a deltaic formation	Limestone with vegetal remains	–	6050±150	7160 to 6730 (6895)	GIF 1264	i, e
Megalake Chad sand ridge									
KONDUGA (9)	13°25′ 11°40′	320	Top of the ridge	Charcoal	100–150	6340±250	7480 to 6950 (7265)	KN 4300	k
KONDUGA (9)	13°25′ 11°40′	320	Top of the ridge	Charcoal	100–150	6180±60	7167 to 6990 (7105)	Utc 2248	a
KOULINGA (10)	19°14′ 16°17′	315	Inner flank of the ridge	Lacustrine shells	–	5260±410	6445 to 5590 (5995)	Ny 68	g, h
Human settlements after MegaLake Chad retreat									
DAIMA (11)	14°30′ 12°12′	290	Base of archaeological tell	Charcoal	1050	2520±110	2825 to 2360 (2710)	I 2945	b, f
KURSAKATA (12)	14°14′ 12°19′	288	Base of archaeological tell	Charcoal	580	2880±140	3240 to 2840 (3000)	N 480	b, f

(a) Breunig et al. (1996).
(b) Connah (1976).
(c) Dupont and Delaune (1970).
(d) Durand (1995).
(e) Maley (1981).
(f) Maley (2004).
(g) Schneider (1967).
(h) Schneider and Wolff (1992).
(i) Servant (1973).
(j) Servant et al. (1969).
(k) Thiemeyer (1992).

Angamma delta in the northern part of Megalake Chad was fed with inflows from the Tibesti region. Its 30 m thick deposits gave 2 dates at the base of the formation indicating that the delta started functioning in the late Pleistocene (ca. 11,800 cal. BP), during which time the paleodelta was probably associated with lakes limited to the Bodelé Lowlands depression. Another date from Koro-Toro (Table 1) is also probably related to these Lowlands lakes. A carbonate nodule obtained in the top of the Angamma deposits, indicates deltaic depositions ceased approximately ca. 6895 cal. BP. It also gives a possible date for the last Megalake Chad event. The base of two diatomite sequences at Beurkia and Faya-Largeau allowed the dating of the beginning of a transgressive phase of Megalake Chad around ca. 7840 cal. BP. In Koro-Toro area, two datings probably relate to a last transgression of Lake Chad, of smaller extent than Megalake Chad, ca. 4000–3200 cal. BP (Maley, 2004). The date obtained on oysters found in living position indicates that the Bahr el Ghazal river was active ca. 3200 cal. BP and probably supplying a lake in the Bodelé Lowlands region.

Therefore, ^{14}C analyses of carbonate or organic sediments consistently point to the early to middle Holocene for the last main Megalake Chad filling event (Maley, 1981; Servant and Servant, 1983; Schneider, 1994; Thiemeyer, 1992). Maley (2004) identified Holocene Megalake Chad filling between ca. 8500 and 6300 cal. year BP (7700 and 5500 ^{14}C year BP), with three major sub-phases: 8500–8200 cal., 7900–7400 cal. and 6900–6300 cal. year BP (7700–7400, 7100–6600 and 6000–5500 ^{14}C year BP). This is consistent with high flows and water levels in other basins across the region during early to middle Holocene (Pachur and Kröpelin, 1987; Gasse, 2000; Hoelzmann et al., 2000).

Our results both confirm the existence of a Megalake Chad during the late Quaternary and provide an accurate surface water delimitation that could be useful to improve past climate simulations over tropical north Africa. The existence of a Megalake Chad during the late Quaternary has significant implications for climatology. The area and volume relationships to lake level provide useful data for constraining of climate and precipitation change at the regional scale. Compared to present levels, such a large hydrological change implies that Megalake Chad represents climatic conditions very different from modern day (Kutzbach, 1980; Hoelzmann et al., 2000). Coe and Bonan (1997) have shown that surface waters had an important positive feedback influence on the climate of northern Africa during the middle and early Holocene and that these must now be included in global climate models for accurate simulations. Our data support the view of Gasse (2000) that hydrological fluctuations in tropical Africa in late Pleistocene and Holocene period appear to have been a series of events of significant magnitude. By quantifying the area and volume to level relationships, this research sets the scene for modelling the regional hydrological response to what was probably a series of large-scale Holocene shifts of the tropical rain-belt in the southern Saharan Africa (Gasse and Roberts, 2004).

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