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Mapping of a major paleodrainage system in eastern Libya using orbital imaging radar: The Kufrah River

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A B S T R A C T

Over the last few decades, remote sensing has revealed buried river channels in a number of regions worldwide, in many cases providing evidence of dramatic paleoenvironmental changes over Cenozoic time scales. Using orbital radar satellite imagery, we mapped a major paleodrainage system in eastern Libya, that could have linked the Kufrah Basin to the Mediterranean coast through the Sirt Basin, possibly as far back as the middle Miocene. Synthetic Aperture Radar images from the PALSAR sensor clearly reveal a 900 km-long river system, which starts with three main tributaries (north-eastern Tibesti, northern Uweinat and western Gilf Kebir/Abu Ras) that connect in the Kufrah oasis region. The river system then flows north through the Jebel Dalmah, and forms a large alluvial fan in the Sarir Dalmah. The sand dunes of the Calanscio Sand Sea prevent deep orbital radar penetration and preclude detailed reconstruction of any possible connection to the Mediterranean Sea, but a 300 km-long link to the Gulf of Sirt through the Wadi Sahabi paleochannel is likely. If this connection is confirmed, and its Miocene antiquity is established, then the Kufrah River, comparable in length to the Egyptian Nile, will have important implications for the understanding of the past environments and climates of northern Africa from the middle Miocene to the Holocene.

1. Introduction

Many of the major drainage basins in North Africa were influenced by the Messinian salinity crisis (late Miocene, 5–6 Ma), when desiccation of the Mediterranean Sea promoted deep landscape incision (Barr and Walker, 1973; Hsü et al., 1973; Goudie, 2005; Rubino et al., 2007). In central Sahara, extensive drainage systems originating in the Tibesti mountains were flowing northward to the Mediterranean Sea and southward to the Chad Basin. While this region is now hyper arid, remains of past river systems (both erosional and depositional features) have been detected using remote sensing imagery, leading some authors to propose paleodrainage pathways between south Libya and the Mediterranean Sea (Pachur, 1996; Griffin, 2002, 2006; Pachur and Altmann, 2006; Drake et al., 2008). Until now, however, detection and reconstruction of paleodrainage systems has been hampered by the widespread and thick aeolian deposits in the region.

In this paper, we used orbital imaging radar, which allows us to better detect paleodrainage systems when masked by Quaternary aeolian deposits (McCauley et al., 1982; Schaber et al., 1986). We thus precisely mapped a 900 km-long continuous paleodrainage system in eastern Libya, which could have linked the Kufrah Basin to the Mediterranean coast, through the Sirt Basin, possibly since the middle Miocene.

2. Use of orbital radar to map subsurface features

Low frequency orbital Synthetic Aperture Radar (SAR) has the capability to probe the subsurface down to several meters in arid areas. Previous studies have shown that L-band (25 cm or 1.2 GHz) SAR is able to penetrate meters of low electrical loss material such as sand (Elachi et al., 1984; Farr et al., 1986). Using the first Shuttle Imaging Radar (SIR-A), McCauley et al. (1982) obtained some of the first subsurface imaging results for a site located in the Bir Safsaf region, in southern Egypt: SIR-A L-band radar revealed buried and previously unknown paleodrainage channels, which afterwards were confirmed during field expeditions (Schaber et al., 1986, 1997; Paillou et al., 2003a). Subsequently, SIR-C data were used to map subsurface basement structures that control the Nile's course in northeastern Sudan (Abdelsalam and Stern, 1996; Stern and Abdelsalam, 1996): numerous hidden faults were detected, thus helping to better understand the Cenozoic uplift of the Nubian Swell (Thurmond

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et al., 2004). More recent studies have shown that combining SRTM — Shuttle Radar Topography Mission (Farr et al., 2007) — topographic data with SAR images better reveals subsurface features which still present a topographic signature. New paleodrainage flow directions have been mapped in the eastern Sahara (Drake et al., 2008), allowing better definition of drainage lines leading to oases and valleys, as well as a better understanding of the Nubian aquifer (Robinson et al., 2000, 2007; Ghoneim and El-Baz, 2007). In particular, RADARSAT-1 C-band (5.5 cm or 5.6 GHz) images revealed two large paleodrainage systems south of the Kufrah oasis in Libya (Robinson et al., 2006). Owing to the large flow volumes needed to sustain such paleodrainages, considerable groundwater recharge is likely to have occurred, and this could explain why continuous extraction of groundwater in the region is possible (El Ramly, 1980).

While the geographical coverage of the Shuttle Imaging Radar missions was limited, a more complete L-band radar coverage of the eastern Sahara by the Japanese JERS-1 satellite was used to realize the first regional-scale radar mosaic covering Egypt, northern Sudan, eastern Libya and northern Chad (Paillou et al., 2003b). This data set helped discover numerous unknown geological structures, particularly impact craters: a double impact crater was found in southern Libya, in a flat and hyper arid area covered by active aeolian deposits (Paillou et al., 2003c). More recently, more than 1300 small crater-like structures, distributed over an area of 40,000 km^2, were detected in the western Egyptian desert (Paillou et al., 2004, 2006; Heggy and Paillou, 2006). Continental-scale exploration is now being conducted using higher quality data from the new high-performance PALSAR L-band radar of the Japanese ALOS satellite (Rosenqvist et al., 2007). A new mosaic of the eastern Sahara made from PALSAR scenes shows excellent data quality, allowing a better detection of subsurface features, in particular paleodrainage networks (Paillou et al., 2007).

3. Mapping of the Kufrah River

PALSAR L-band data allowed for the first time an accurate mapping of a continuous 900 km-long paleodrainage system, herein termed the Kufrah River (Fig. 1). Its headwaters are mainly in southern Libya with observed tributaries arising in three main areas: (1) El Fayoud and El

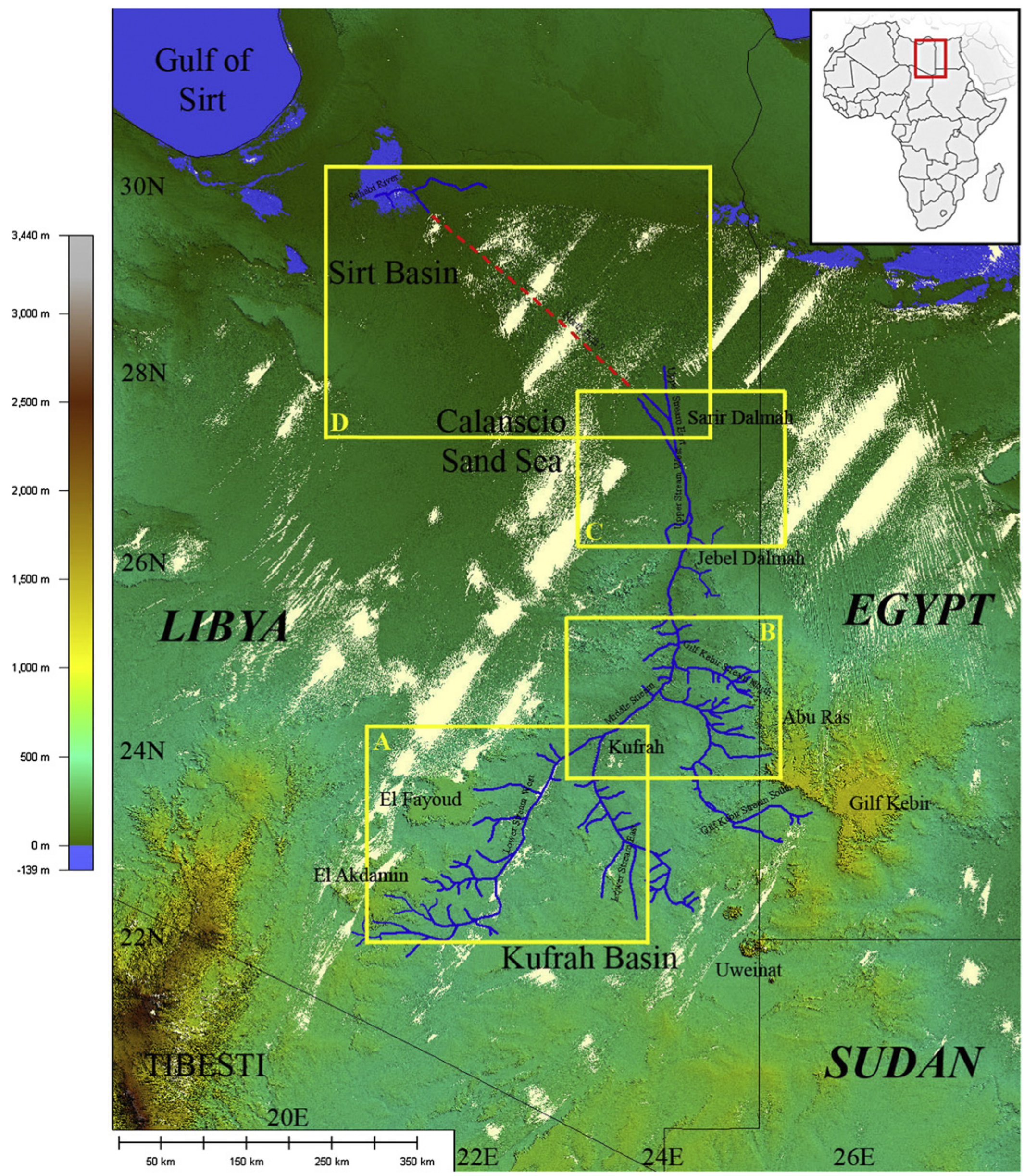

Fig. 1. The Kufrah River mapped onto SRTM topography (white areas are voids in the SRTM data). The red dotted line represents a possible path to the Mediterranean coast, through the Wadi Sahabi. Yellow boxes A, B, C, D correspond respectively to Figs. 2–5.

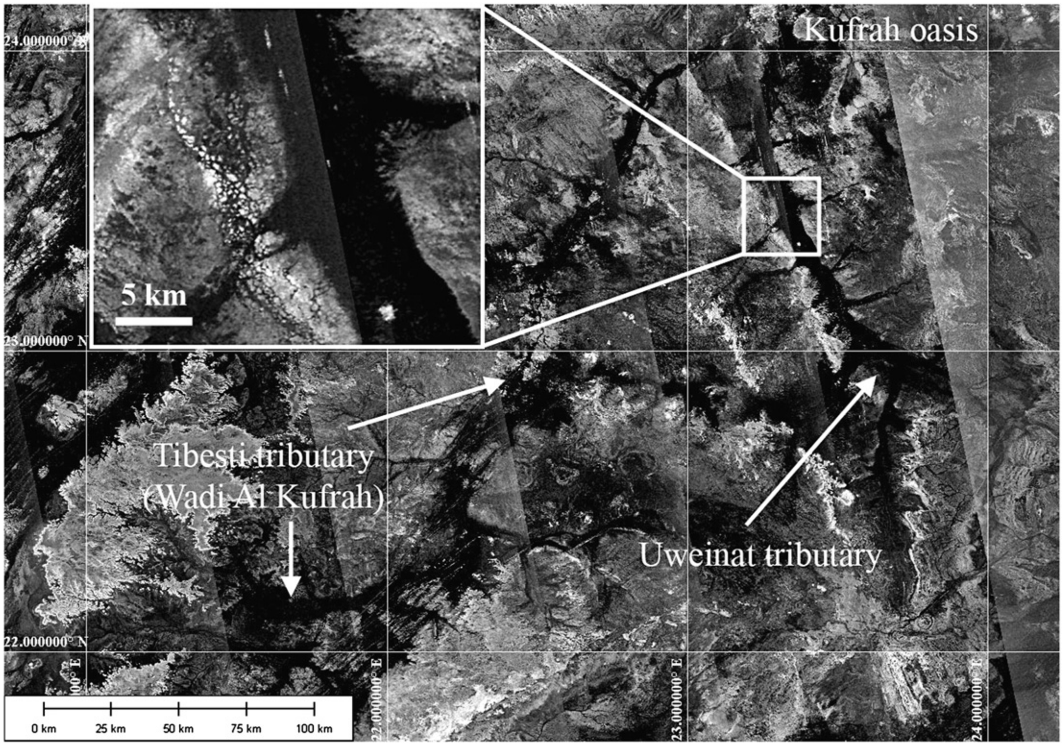

Fig. 2. PALSAR image of the southern part of the Kufrah River, showing the two main tributaries (dark valleys) from the Tibesti and Uweinat regions, which join at the Kufrah oasis. Zoom (inset) shows a secondary braided river pattern.

Akdamin hamadas in northeastern Tibesti (Wadi Al Kufrah), (2) northern Uweinat close to the Sudanese border (Uweinat tributary), and (3) the western Gilf Kebir and Abu Ras plateaux on the Egyptian border. El Fayoud and El Akdamin headwaters are more likely to actually lie on the eastern side of the Tibesti, but small dendritic drainage could not be clearly discerned in radar images.

The Tibesti and Uweinat tributaries flow in wide (up to 10 km) paleovalleys that were initially mapped by Robinson et al. (2006) using

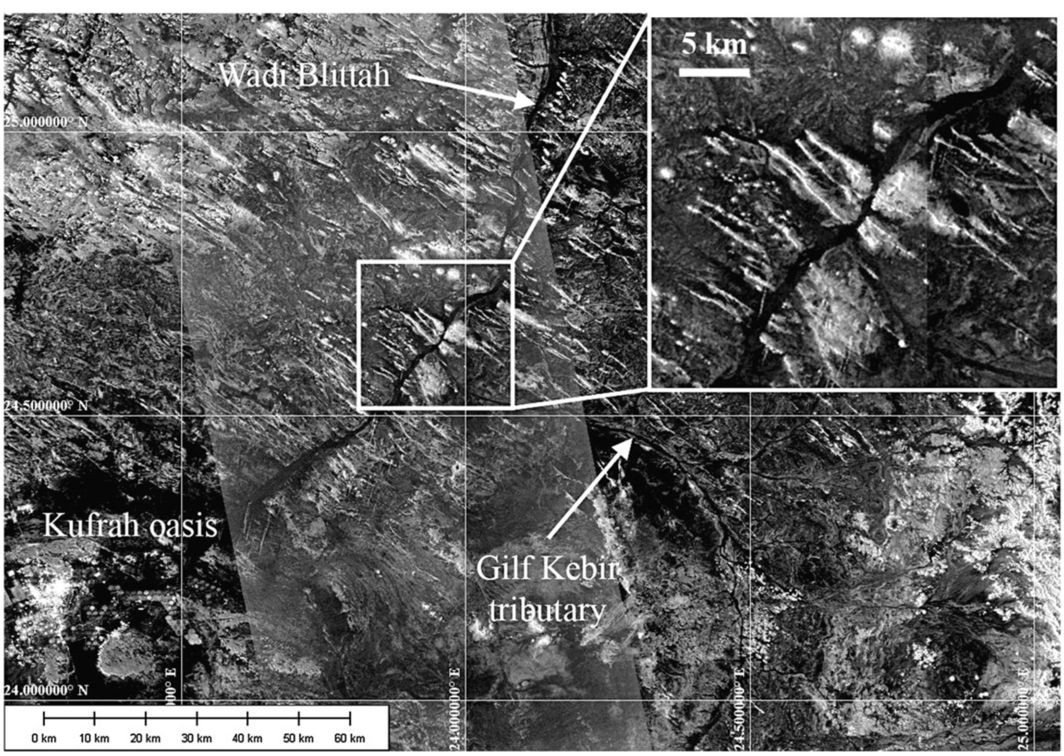

Fig. 3. PALSAR image of the central part of the Kufrah River. Tributaries from Gilf Kebir and Abu Ras plateaux join the main river channel about 80 km northeast of the Kufrah oasis. Zoom (inset) shows the narrow incised river bed, less than 1 km in width.

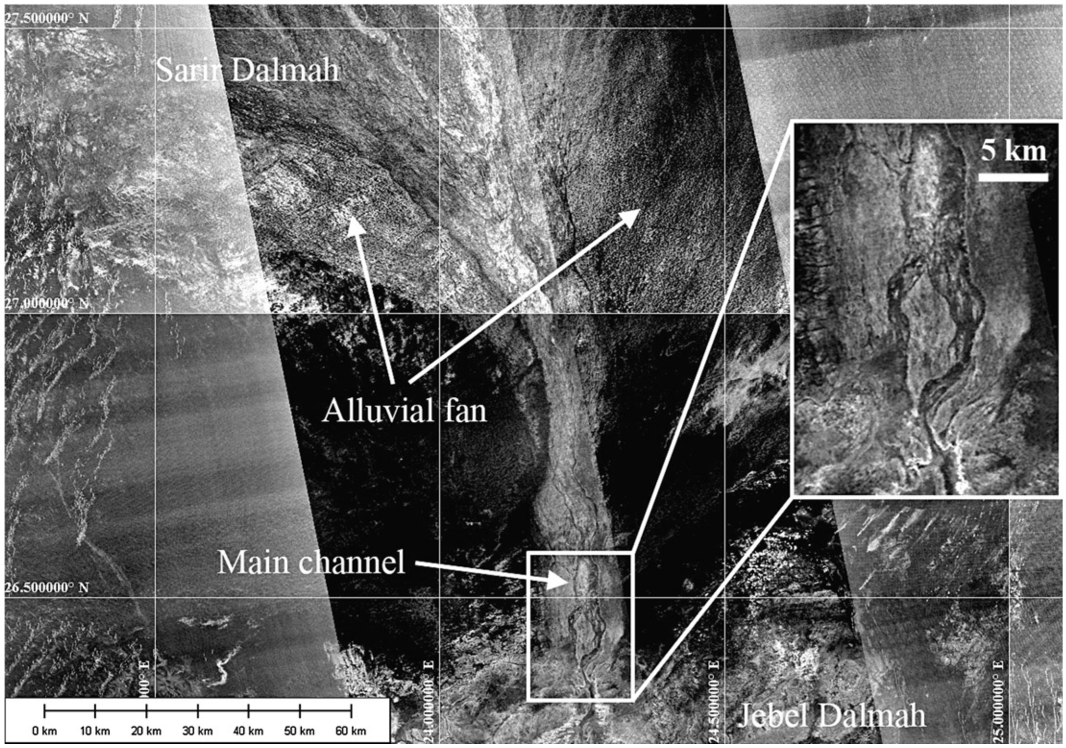

Fig. 4. PALSAR image of the northern part of the Kufrah River. North of the Jebel Dalmah, it forms a large alluvial fan in the Sarir Dalmah. Zoom (inset) shows the main channel south of the alluvial fan.

RADARSAT-1 data. Fig. 2 shows the PALSAR image of these 350 km-long features, which join in the Kufrah oasis. A secondary braided river pattern can be detected along the Uweinat tributary (Fig. 2 zoom, inset), which by analogy with modern river channels is suggestive of a high channel gradient and abundant sediment supply. Both tributaries lie in the Kufrah Basin, mainly composed of continental sandstones of Cambro-Ordovician to Early Cretaceous age. Lower Cretaceous sedimentary rocks are 1000 to 1500 m thick and constitute the surface of

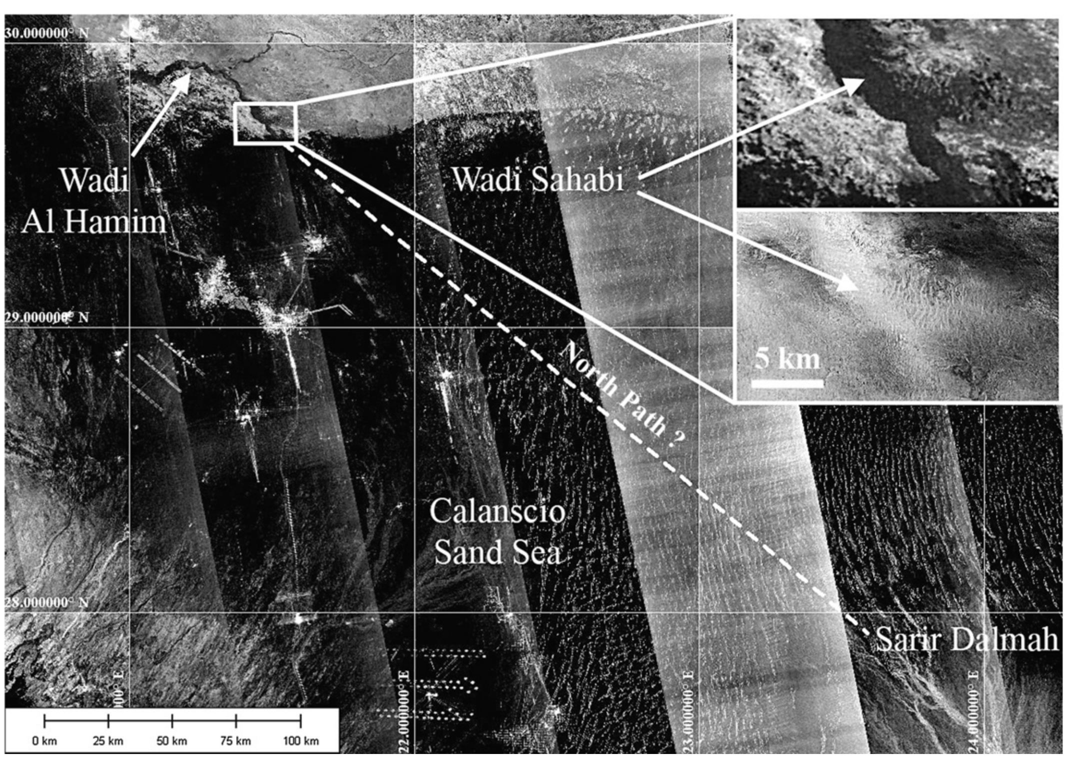

Fig. 5. PALSAR image of the Calanscio Sand Sea. The white dotted line indicates a possible path between the alluvial fan in the Sarir Dalmah and the Wadi Sahabi paleochannel. Zoom shows the Wadi Sahabi paleochannel as seen by the radar of PALSAR (top) and by the optical sensor of LANDSAT-TM (bottom, source Google Earth).

most of the basin (Salem and Busrewil, 1980). About 80 km northeast of the Kufrah oasis, a shorter tributary, about 200 km in length, comes from the Gilf Kebir and Abu Ras plateaux (Fig. 3), which are composed of late Jurassic to Cretaceous clastic sediments (Said, 1990).

From the Kufrah oasis, the main river system becomes narrower (less than 1 km) and clearly incises the sandstone bedrock (Fig. 3). The low sinuosity and narrow character of the channel suggests strong structural control. While this channel is hard to see using optical remote sensing because of the widespread aeolian sand cover, radar shows a sharp contrast between the river bed and the sandstone banks (Paillou et al., 2003a). The channel follows the present-day Wadi Blittah to the northern Jebel Dalmah over a distance of about 230 km. Farther north, in the Sarir Dalmah, the Kufrah River then disperses as a network of small shallow channels across the surface of a broad alluvial fan that covers more than 15,000 km^2 (Fig. 4), indicating that the flow competence has declined markedly downstream. It is possibly an inland delta (Di Cesare et al., 1963), its morphology and size reminding the fluvial fan of the modern Okavango River in Botswana (Stanistreet and McCarthy, 1993). Coarse alluvial sand and gravel constituting the fan sediments increase the surface roughness and volume scattering effects, so that it appears as a bright feature in the radar images.

The Sarir Dalmah fan is surrounded by the large linear sand dunes of the Great Sand Sea to the east, and the Calanscio Sand Sea to the west, and is likely to have been a sediment source for these sand seas (El Baz et al., 2000). The PALSAR orbital radar is not able to penetrate these thick sand deposits, so it is not possible to follow the paleodrainage course to the north. However, the shallow channels on the alluvial fan surface indicate a dominant drainage trend to the northwest. About 300 km away in this direction, a major alluvium-filled paleochannel with sharp valley sides, 2 to 3 km in width, named Eosahabi channel or Wadi Sahabi (Barr and Walker, 1973), appears in the PALSAR images. Again, while classical optical remote sensing fails to detect this feature, the PALSAR sensor clearly shows this wide paleochannel, probably incised into bedrock, emerging from beneath the Calanscio Sand Sea (see Fig. 5 zoom, inset). As such, it is possible that the sand sea is hiding a pathway between the Dalmah alluvial fan and the Wadi Sahabi in the Sirt Basin (dotted line in Fig. 5). The Sirt Basin reflects significant rifting in the Early Cretaceous and syn-rift sedimentary filling during Cretaceous through Eocene time. It extends offshore into the Mediterranean Sea, with a northern boundary drawn at a depth of 2000 m. Late Cretaceous rifting formed a series of large northwest-trending horsts and grabens that step progressively downward to the east (Ahlbrandt, 2001). In this latter region, seismic data have revealed spectacular bedrock incisions that are many kilometers in width and several hundreds of meters deep (Barr and Walker, 1973; Benfield and Wright, 1980; Rubino et al., 2007).

4. Discussion

Several previous studies have proposed paleodrainage systems that could have linked the Tibesti mountains to the Mediterranean Sea. Indirect evidence for a major north-flowing river is also provided by the enormous aeolian sand accumulation in the Great Sand Sea and the Calanscio Sand Sea in northern Egypt and Libya (Breed et al., 1987; Issawi and McCauley, 1992), as these must have been at least partially sourced from fluvially-transported sediments. Griffin (2002) proposed a vast river system, the Eosahabi River, that would have flowed from the Messinian Lake Chad, eroding the east Tibesti valley, and ending in a well preserved channel near the coast of the Gulf of Sirt. The proposed path for the Eosahabi River, however, is based on fragments of river channels observed in LANDSAT-TM images, and on the analysis of low resolution topographic data. Its proposed starting point is in the Erdi region, north of the Neogene Lake Chad, and it then traverses the east Tibesti valley and finally joins the Eosahabi channel in the Sirt Basin through the Calanscio Sand Sea (Griffin, 2006). Pachur and colleagues have conducted extensive geological studies and explorations in the eastern Sahara (Pachur and Altmann, 2006). They proposed that an extensive paleodrainage system could have connected the Tibesti mountains to the Sirt Basin during the Holocene (Pachur, 1996; Pachur and Hoelzmann, 2000). This paleodrainage system is divided into two main parts: one fed by the northern Tibesti mountains and then flowing to the north through the Behar Belema paleochannel, and one originating in the eastern Tibesti mountains and flowing into the Kufrah Basin, then following Wadi Blittah and ending in the Sarir Dalmah. Pachur (1996) proposed that this channel was active during the early Holocene.

We could not observe evidence of the river path proposed by Griffin (2002) on PALSAR radar images, and SRTM topographic data suggest that the Erdi region is too elevated to allow any connection between the Kufrah Basin and Lake Chad. Instead, this area from Ennedi to Tibesti looks more like a watershed separating the Libyan and Chadian basins. This is consistent with Ar/Ar dating results: the relatively elevated Erdi region is related mainly to the uplift of the Tibesti mountains which began as early as ca. 17 Ma during the middle Miocene (Maley, 2004), which could then be the time when the Kufrah River system originated. Fig. 1 shows the observed path for the Kufrah River, which does not connect to the Chad Basin in the south and instead flows north through the Kufrah oasis, east of the proposed path by Griffin (2006). On the contrary, the Kufrah River that we mapped using PALSAR data fully agrees with the one proposed by Pachur and Altmann (2006). However, the continuous path we observed in radar images, together with the size and apparent maturity of observed paleochannels, and the clear channel incision into the sandstone of the Kufrah Basin (Fig. 3) leads us to propose that the whole 900 km-long system was contemporaneously and repeatedly active and is probably much older in origin, possibly already being in place at the end of the Miocene when a significant part of the Sirt Basin was flooded (Hsü et al., 1977). Also, the mapped Kufrah River, although fed by the western sides of Gilf Kebir and Abu Ras plateaux in Egypt, does not seem to be related to the Nile Basin: we could not observe any connection between the Kufrah system and the “radar rivers” east of Gilf Kebir plateau (McCauley et al., 1982; Burke and Wells, 1989). Issawi and McCauley (1992) proposed that a “Gilf River” could have existed in western Egypt from the Oligocene to the end of the Miocene, linking the Gilf Kebir region to the Mediterranean Sea through the Siwa oasis. Unfortunately, as the Great Sand Sea in northwest Egypt does not allow the PALSAR sensor to probe the subsurface, a possible connection between the alluvial fan in the Sarir Dalmah and the Siwa oasis to the east could not be observed. However, this should be investigated in the future.

While Pachur and Altmann (2006) did not map paleodrainage systems north of the Sarir Dalmah, PALSAR images reveal a major paleochannel in the Sirt Basin, the Wadi Sahabi (Fig. 5 zoom, inset), that could represent part of the final 300 km-long section of the Kufrah River before the Mediterranean Sea. Both the alluvial infill of the Wadi Sahabi and the Quaternary gravels and sands found in shallow drill holes in the south of the Sirt Basin indicate fluvial transport from the central Saharan mountains (Barr and Walker, 1973; Pachur, 1996; Pachur and Altmann, 2006). The Wadi Sahabi feature was also observed in SRTM topographic data by Drake et al. (2008), who proposed that the Gulf of Sirt was fed by large river systems, originating in northern and eastern Tibesti, through deep canyons that drained much of Libya during the late Miocene. Although it was not mapped precisely, Drake et al. (2008) proposed a “Sahabi River System” that connected southeast Libya to the Mediterranean Sea during humid periods in the Messinian. They propose the hypothesis that this system was later captured by an eastern one, the Al Kufrah River, which was activated by tectonic subsidence in the Kufrah Basin at the end of the Pliocene, and linked to the Mediterranean Sea through the Sirt Basin. Similar to Griffin (2002, 2006) and Drake et al. (2008), we then propose a possible link to the Mediterranean coast through a large paleochannel, the Wadi Sahabi. However, the connection of the alluvial fan in the Sarir Dalmah to the Wadi Sahabi through the Calanscio Sand Sea still has to be demonstrated. In particular, the formation of the alluvial fan has to be explained if such a connection to the Mediterranean Sea has existed. Many large alluvial fans form where rivers exit relatively confined valley settings and enter broader topographic depressions that commonly are fault controlled. In such settings, flow competence declines markedly down valley so that sediment accumulates in a fan-shaped form, in some cases locally on-lapping bounding faults at the distal margin of the depression, such as occurs on the modern Okavango fan in Botswana (Stanistreet and McCarthy, 1993). As such, formation of the alluvial fan of the Kufrah River might have been promoted by faulting in the Sirt Basin, possibly in combination with climate change, at a time when the river was connected to the Mediterranean Sea through the Wadi Sahabi. Under this scenario, the Wadi Sahabi would represent the reduced outflow of the Kufrah River across the faulted distal margin of a depression. Alternatively, the alluvial fan of the Kufrah River could have formed prior to its connection to the Mediterranean Sea through the Wadi Sahabi. The alluvial fan initially would have then represented the terminus of the Kufrah River (i.e. an inland delta), only later becoming connected to the Mediterranean Sea owing to bedrock incision and headward retreat of the Wadi Sahabi, which in turn may have been promoted by climatic change or the Messinian salinity crisis for instance. Clearly, evaluating such alternative explanations will require further remote sensing and field investigations. In particular, there is a critical need to constrain the timing of the initiation of the alluvial fan formation, estimated from the lower Pliocene by Drake et al. (2008) to the early Pleistocene by Pachur (1996), as well as the history of the Wadi Sahabi incision in relation to the tectonic, climatic, and sea level changes that have affected this part of North Africa during the late Cenozoic.

Despite the fact we have no direct indication about the age of initiation and history of the Kufrah River, it is very likely to be have been active during in recent (Holocene) times as proposed by Pachur (1996) and Pachur and Altmann (2006): even though L-band radar does not allow us to see deeper than 1–2 m, the paleochannels are clearly visible in PALSAR images, suggesting that they are only at shallow depths. Earlier (Pleistocene) phases of activity are also likely: recent work by Osborne et al. (2008) proposes a “humid corridor” that was connecting the Kufrah Basin to the Mediterranean coast within Marine Isotope Stage 5e (130–117 ka). From the analysis of SIR-C radar images of the Kufrah region, showing the same paleodrainage channels as in Fig. 2, and Nd isotopic characterization of Quaternary sediments sampled in these channels, Osborne et al. (2008) propose a continuous humid connection between the southern Sahara and the Mediterranean Sea at around 120 ka. This hypothesis is consistent with the geographic gradient in the oxygen isotope anomaly observed by Rohling et al. (2002), suggesting that extra freshwater was delivered into the Gulf of Sirt during the Eemian interglacial maximum, 125 k.y. ago.

If the connection between southeastern Libya and the Mediterranean Sea through the Kufrah and Sirt basins is confirmed, the whole Kufrah River system that we have mapped using orbital radar would be more than 1200 km-long, comparable in size to the Egyptian Nile. If the Miocene antiquity of this paleodrainage system can be confirmed, it will have important implications for the understanding of the past environments and climates of northern Africa from the middle Miocene to the Holocene, with consequences for faunal, floral, hominid and human dispersal.

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