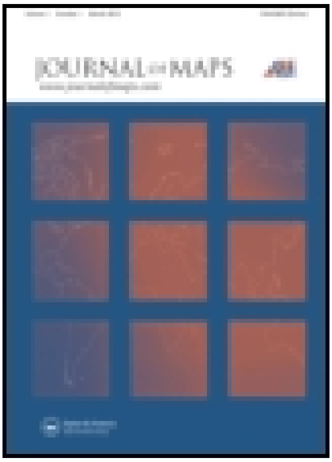

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SCIENCE

Geomorphological Map of the Tadrart Acacus Massif and the Erg Uan Kasa (Libyan Central Sahara)

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Here we present a geomorphological map of the Tadrart Acacus Massif and Erg Uan Kasa (SW Libya, central Sahara). The geomorphological mapping of the area was carried out by means of satellite imagery analysis followed by detailed control of units in the field. The Tadrart Acacus is a sandstone massif delimited to the West by a high scarp and cut by a dendritic fossil drainage network of W-E-oriented wadis. The massif has been shaped since the Tertiary by etchplanation and solutional processes; the latter is demonstrated by the ruiniform landscape and the high number of caves and rock shelters that dot the vertical cliffs of the wadis. To the East, the Tadrart Acacus merges below a complex system of sand ridges that form the Erg Uan Kasa. The large interdune corridors of the sand sea are dotted by lake sediments, which formed during the Pleistocene interglacials and the African Humid Period of the Holocene, when piezometric lakes were sustained by intense monsoonal rainfall. Geomorphological investigation demonstrates that the extant landscape originated thanks to the overlap of surface processes triggered by divergent (humid/arid) environmental conditions.

Keywords: arid zone geomorphology; remote sensing; sandstone massif; dunefield; climate changes; Sahara desert

1. Introduction and background

The Sahara occupies a wide part of North Africa, extending for more than 9.000.000 km^2 from the Atlantic Ocean to the Red Sea, from the southern shore of the Mediterranean Sea to the Sahel, where a transitional belt is at c. 15° latitude N. The Sahara is the largest warm desert on Earth and alternates a variety of landscapes, whose formation was controlled by two main factors: (i) the lithology of the bedrock outcropping in each region, and (ii) the different climatic settings that occurred since the Tertiary, with alternating pluvial to hyperarid environmental conditions. The region has been extensively investigated by scholars belonging to many branches of the Earth Sciences, mostly to interpret recent (e.g. late Quaternary) environmental changes (e.g. Hoelzmann et al., 2004; Nicoll, 2004; Zerboni, 2013 and references cited therein), and to understand the distribution of hydrocarbon resources (e.g. Arthur, Macgregor, & Cameron, 2003). Furthermore, extensive archaeological exploration has been devoted to understanding the human occupation of the region since the early Pleistocene.

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However, few medium-scale geomorphological maps are available for this vast region, allowing the interpretation of the processes driving the formation of the ancestral lineaments of the landscape and more recent geomorphological features. Regional geomorphological syntheses are available since the introduction of satellite imageries (e.g. AbuBakr, Ghoneim, El-Baz, Zeneldin, & Zeid, 2013; El-Baz, 2000; El-Baz & Warner, 1979; Ghoneim & El-Baz, 2007; McCauley et al., 1982; Perego, Zerboni, & Cremaschi, 2011; Pesce, 1969; Petit-Maire & Page, 1992; Robinson, El-Baz, Al-Saud, & Jeon, 2006; Symeonakis & Drake, 2004): they illustrate the main aspects of the landscape, but in many cases they were drawn without accurate field control. In contrast, detailed geomorphological maps of some localities are available, but with scarce reference to large-scale processes. Among the main aims concerning the geomorphological mapping of the Sahara, we recall here the need to (i) describe the main elements of the landscape at different scales of resolution, (ii) interpret the main geomorphological processes involved in their formation, (iii) infer the paleoclimatic factors that drove morphogenetic processes (Zerboni, 2011), and (iv) the necessity to provide an adequate geomorphological background to the archaeological evidence. A pilot study of such approach has recently been published in the Journal of Maps (Perego et al., 2011), illustrating the potential of geomorphological mapping for the central Sahara and introducing the main methodological aspects. The latter mostly rely on a remote-sensing approach to geomorphological mapping (image sources: Landsat, ASTER and Google Earth; altitude data: SRTM DEM and ASTER GDEM Version 2), integrated with field control, which represents an essential tool to solve ambiguities and avoid misunderstanding in the interpretation of remote-sensing data.

Geomorphological studies in the central Sahara have developed from extensive field experience gained since the 1990s through geoarchaeological research carried out by the University of Milan as part of the Italian-Libyan Archaeological Mission in the Acacus and Messak (Central Sahara) of Sapienza University of Rome and the Libyan Department of Archaeology. The Libyan central Sahara is well known for its archaeological treasures (e.g. Barich, 1987; Biagetti & di Lernia, 2013; Cremaschi & di Lernia, 1998; di Lernia, 1999; Garcea, 2001), together with exceptional artistic evidence (e.g. di Lernia & Gallinaro, 2011; di Lernia & Zampetti, 2008; Mori, 1965), which led UNESCO to insert the rock art sites of the Tadrart Acacus in the World Heritage list (http://whc.unesco.org/en/list/287). To complete a map of the Libyan central Sahara we decided to subdivide the region under license of the Mission into physiographically homogeneous areas and undertake geomorphological mapping of each quadrant. Due to the vastness of the area (more that 100.000 km^2), four maps at a medium scale (1:250,000) have been outlined: (i) the Messak plateau (Perego et al., 2011), (ii) the Tadrart Acacus Massif and Erg (in the Arabic dune field) Uan Kasa system, (iii) the Wadi Tanezzuft, and (iv) the Edeyen (in the Arabic wide dune field) of Murzuq. The first map has been published (Perego et al., 2011), the second is presented in this paper, with the maps of the Wadi Tanezzuft and the Edeyen of Murzuq currently in an advanced state of preparation.

The map covers two different physiographic elements of the landscape of the central Sahara: a massif and a dune field (Main Map). These two features appear rather different, but we decided to represent them together in the map because they belong to same (palaeo-)hydrological system. In fact, during the humid phases of the Tertiary and Quaternary, the massif and the lowlands occupied by the dune field were connected by a huge drainage system, whose existence is confirmed by extensive fluviatile deposits and palaeochannels. In the map, we highlight the importance of landforms and surface deposits typical of the extant arid environment, as well as features testifying to former humid periods.

2. Methods

Due to the size of the study area, we chose a 1:250,000 scale map, which required the use of remote-sensing data to identify and delimit the main geomorphological units. In addition, the geomorphological map was integrated with field surveys (Cremaschi, 1998; Perego, Cremaschi, & Zerboni, 2007; Zerboni, Trombino, & Cremaschi, 2011) carried out since the early 1990s. In arid regions, thanks to the almost complete absence of vegetation, a band ratio produced using satellite imagery is a good method for characterizing the properties of the ground surface and distinguishing different geomorphological units (e.g. Gad & Kusky, 2006; Gani & Abdelsalam, 2006). Several Landsat TM and ETM+ scenes acquired between 1987 and 2011 (in different periods of the year: March, May, July, August, September, October, November, December) with 30 m spatial resolution, and six ASTER scenes acquired in 2000, 2002, and 2003 (April, August, November), with 15 m spatial resolution in green, red and near infra-red bands have been analyzed. Small-scale geomorphological features and surface deposits limited in extension have been checked in the field and on higher-resolution Google Earth imagery. Morphological analyses are based on DEMs (digital elevation models); they allowed the evaluation of terrain altitudes, delimiting valleys cut into the plateau, and extracting contour lines at 100 m vertical intervals. The SRTM DEM (Shuttle Radar Topography Mission) acquired in 2000 with a spatial resolution of ca. 90 m was used in wide flat areas (glacis). The ASTER GDEM (Version 2) with 30 m spatial resolution (more detailed than the SRTM DEM, but with a greater vertical error) was used for mountainous and sand deposit areas, where SRTM data have gaps.

Bedrock lithology has been mapped with flat colors, while landforms and superficial deposits have been represented by means of colors and symbols providing information on their origin. The legend on the geomorphological map follows the guidelines of the Italian Environmental Agency (APAT, 1994).

3. Geography, geology, and climate

The Tadrart Acacus Massif is a sandstone massif located in south-western Libya, in the Fezzan region, well inside the hyperarid belt of the Sahara desert, between 26° and 24° latitude N. It covers an area of c. 5000 km^2 with a maximum elevation of c. 1300 m a.s.l. in the western part (Desio, 1937). The mountain system consists of a monocline, which is dissected by a fossil drainage network (Cremaschi, 1998), whose pattern is controlled by the tectonic structure (Galeĉiĉ, 1984; Jakovljeciĉ, 1984). A sharp scarp delimits the massif toward the West, while to the East it progressively passes through a pediment to the Erg Uan Kasa. The latter is a 4500 km^2-wide sand sea, mostly constituted by NW-SE-oriented alignments of complex dunes, located within the wide depression of Tin Merzuqa, between the Tadrart Acacus Massif and the Messak Plateau. The dune ridges are separated by wide and flat interdune corridors, whose bottom is occupied by thin sand covers becoming thicker toward the East.

Geologically, this region belongs to the western fringe of the Murzuq Basin (Desio, 1937; El-Ghali, 2005), whose base, mainly composed of Palaeozoic shales, sandstone, marls, and, less frequently, limestone, lies upon the intrusive formation of the Tassili. The Tadrart Acacus Massif consists of Lower to Middle Silurian shales (Tanezzuft Fm.), apparently conformably overlying Upper Silurian and Lower Devonian sandstones (Acacus and Tadrart Fms.; McDougall & Martin, 2000; Traut, Boote, & Clark-Lowes, 1998). In the Tin Merzuqa depression some NS-oriented cuestas outcrop cut into Carboniferous limestone (Rossi Ronchetti, 1939). The Late Quaternary deposits consist of fluviatile sand and silt and loamy-clay formed in lacustrine to shallow water environments (swamp) during wet phases; further, during arid environmental conditions sand sheets and dunes were formed thanks to enhanced wind activity.

The present climate of the SW Fezzan is hyperarid; the climate and palaeoclimate are governed by the seasonal migration of the ITCZ (Intertropical Convergence Zone) in response to changes in the location of maximum solar heating, resulting in belts of monsoonal climate with summer rains and winter drought (e.g. Nicholson, 2011). The meteorological stations closest to the study area indicate that the mean annual temperature is between 22° and 25°C, and the mean annual rainfall is between 0 and 10 mm (Walter & Lieth, 1960). During the Pleistocene interglacials and interstadials, the region was wetter than today (Drake et al., 2008; Geyh & Thiedig, 2008; Petit-Maire, 1982; Zerboni et al., 2011), and higher water availability is also recorded for the Early and Middle Holocene (Cremaschi & Zerboni, 2009; Cremaschi, Zerboni, Spötl, & Felletti, 2010).

4. Geomorphological units

4.1. *Structural and residual forms*

The main structural pattern of the Tadrart Acacus and adjoining areas consists of monocline relief, interleaved with flat areas. The cuestas are composed of Palaeozoic sedimentary rocks (Desio, 1937; El-ghali, 2005; Goudarzi, 1971; Marcolongo, 1987) that in the Tadrart Acacus areas are cut by a dendritic fluvial network. Satellite imagery and published geological maps (Galeĉiĉ, 1984; Jakovljeciĉ, 1984) highlight the occurrence of a major inactive fault cutting the Tadrart Acacus Massive from north-to-south, while a system of parallel inactive faults oriented SW-NE, roughly correspond to the main direction of the fluvial network.

The present-day shape of the massif was determined by the onset of etchplanation processes, which are presumably dated to the Paleogene under humid and warm climatic conditions (Busche, 2010). A thick lateritic soil developed in this phase but was then almost completely removed during subsequent erosional events with only a few paleosol strips currently still evident in the Tadrart Acacus (Zerboni et al., 2011). Due to moderate tectonic uplift and climate oscillation since the Neogene, erosion shaped the massif in a series of structural terraces corresponding to sub-horizontal strata. The desert pavement of the terraces and of the most elevated, flat, parts of the massif correspond to a hamada surface, whose clast (and most of the exposed rock surfaces of the region) are coated by a continuous layer of dark Mn-rich rock varnish (Zerboni, 2008).

Toward the East, the massif grades through a pediment to the dunes of the Erg Uan Kasa; the pediment was created by planation processes and is discontinuously covered by alluvial gravel and sand. Several N-S to NW-SE cuestas are present in the eastern part of the pediment, partially covered by sand dunes.

4.2. *Slope forms and deposits*

Toward the West, the Tadrart Acacus Massif is delimited by an uninterrupted escarpment up to 400 m high, which consists of a series of hanging valleys (Figure 1). At the base of the scarp a talus ramp (Oberlander, 1997) is present, where sandstone blocks have accumulated; at the foot of the slope deposits are covered by Holocene alluvial sediments of the Wadi Tanezzuft (Cremaschi & Zerboni, 2011). The eastern margin of the map is marked by an almost continuous complex escarpment, whose properties are discussed in the geomorphological map published by Perego et al. (2011).

Along the wadis of the Tadrart Acacus, several mass-wasting deposits, consisting of angular sandstone blocks, are present. They are interpreted as large landslides affecting the cliffs of the wadis and triggered by thermoclastic processes under arid environmental conditions (Cremaschi, 1998).

Figure 1. The hanging valleys at the western fringe of the Tadrart Acacus Massif.

4.3. *Fluvial forms and deposits*

Busche (2010) suggests that the onset of linear erosion in the central Sahara is dated to the Plio/Pleistocene transition, when a major change in the climate regime occurred. In the Tadrart Acacus area a moderately continuous tectonic uplift allowed linear erosion to dissect the dense dendritic net of wadis; this is evident in satellite imagery. The wadi banks are deeply incised in to the sandstone bedrock, becoming narrow and meandering canyons with vertical cliffs further upstream (Figure 2). In the lower part of their course, the wadi bottom is generally flat and filled by fluvial sediments, covered by aeolian sand. The excavation of deep valleys was triggered by the occurrence of major inactive faults and fractures cutting the bedrock, while the original width of the valleys has been enlarged by the backwasting of scarps (Cremaschi & Zerboni, 2011). During wetter phases, turbulent water carved along the wadis a complex systems of longitudinal grooves, pools and deep potholes throughout the upper part of canyons. The largest of these potholes, which occasionally are in part excavated in the sandy bed of a wadi, are locally called *gueltas* or *agelma* in the Tuareg language (Davies & Gasse, 1988; di Lernia, Massamba N'Siala, & Zerboni, 2012). They consist of small water reservoirs recharged by occasional rainfall and persisting for several months (Figure 3). The most important gueltas (in terms of availability and durability of water) have been identified in collaboration with local people (di Lernia et al., 2012; Zerboni, Massamba N'Siala, Biagetti, & di Lernia, 2013).

The glacis between the Tadrart Acacus and the Messak plateau displays more evidence of fluvial activity. The area is marked by ephemeral streams descending into the Tin Merzuqa depression; further, some scarps produced by fluvial erosion are occasionally evident on the satellite imagery. At several locations, the palaeochannels cut the glacis and the main cuestas and are generally W-E oriented, while in the central part of the Tin Merzuqa depression a discontinuous N-S-oriented cut emerges between the dunes (Figure 4). Palaeochannels are the evidence of an ancient drainage system that dissected the glacis from north-to-south well before the formation of the sand sea. Moreover, transversal E-W cuts may be related to several tributaries flowing from the Tadrart Acacus and Messak massifs into the depression of Tin Merzuqa. The formation

Figure 2. Panoramic view of a meandering canyon in the upper reaches of the Wadi Teshuinat (central Tadrart Acacus Massif).

Figure 3. Different types of *gueltas* (people for scale): (A) excavated in the sandstone bedrock at Intriki (southern Tadrart Acacus Massif); (B) excavated in the sand along Wadi Teshuinat (central Tadrart Acacus Massif); (C) along the narrow canyon of Wadi Agmir (central Tadrart Acacus Massif).

of these palaeochannels, whose existence was reported by Drake et al. (2008), required large water availability and were possibly cut in the Tertiary or Early Pleistocene and largely buried by dunes during the Pleistocene. For that reason, the hypothesis of Drake et al. (2008) suggesting

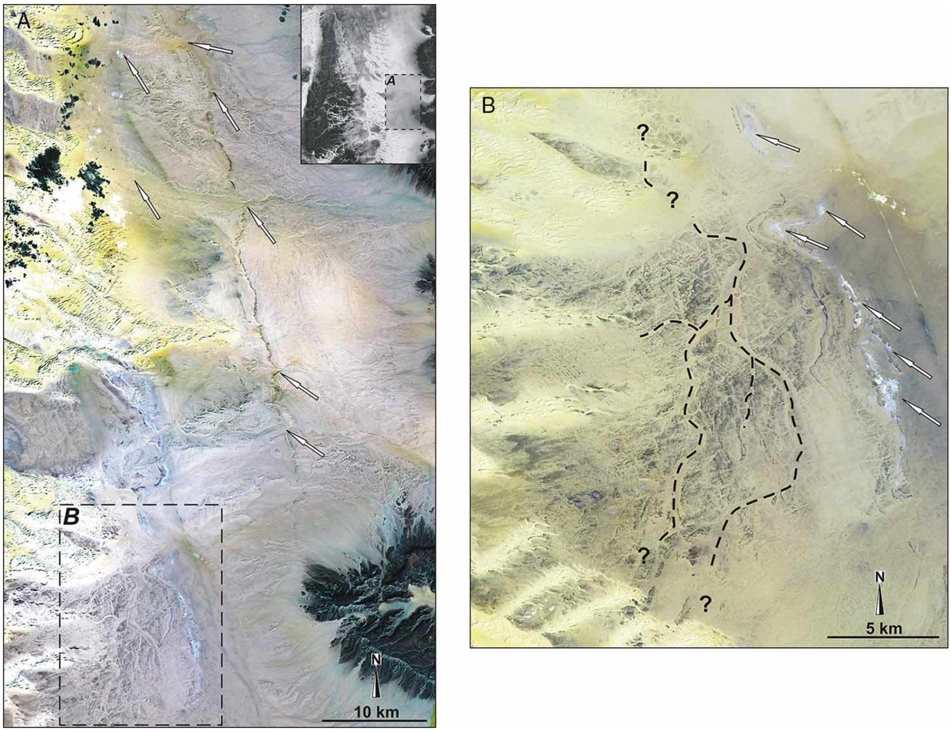

Figure 4. Satellite images (Landsat) illustrating the ancestral fluvial network cutting the Tin Merzuqa depression; the insert in (A) indicates the position of the area considered. (A) A series of E-W-oriented palaeochannels cutting the cuestas (indicated by the arrows); the rectangle indicates the area where a N-S-oriented palaeochannel is located. The latter is shown in (B); note the presence of a bright blue strip, corresponding to a limestone outcrop (indicated by the arrows).

an activation during the Late Quaternary humid phases (upper Pleistocene and Holocene) of a N-S fluvial system located between the Erg Uan Kasa and the Messak (connecting this region to the lake systems in the Fezzan Basin) is unlikely. On the contrary, the fluvial sediments present between the dunes in the southern part of the Erg Uan Kasa testify to recent (Late Pleistocene and Early-Middle Holocene) endorheic fluvial activity in the region. In fact, in the southern part of the sand sea the interdune corridors correspond to the downstream direction of the main valleys cutting the Tadrart Acacus Massif, with their bedrock covered by pink silty sediments up to several meters thick (Cremaschi & Zerboni, 2009). Sediments are poorly laminated to massive and sometimes cut into yardangs.

4.4. *Aeolian forms and deposits*

The Erg Uan Kasa is the most evident aeolian landform on the map. It formed along the Tin Merzuqa depression, which is a flat glacis developed between the cuestas cut into the Carboniferous limestone and sandstone strata. The dunes of the erg are organized as parallel ridges, generally NW-SE oriented and separated by wide flat basins, sometimes crossed by transverse sand crests (Figure 5). The morphology of the dune ridges is complex and they cannot be interpreted simply as a series of multiple or dendritic linear dunes (Hesse, 2011). They represent complex sand structures formed from networks of linear dunes connecting star domes (Lancaster, 1995). Complex sand ridges are separated by flat interdune basins, up to several km wide; the most depressed

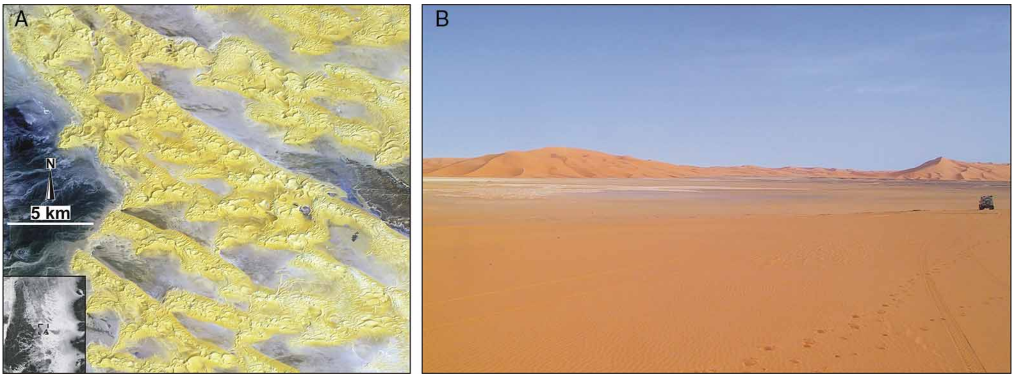

Figure 5. (A) Part of a complex alignment of dunes of the Erg Uan Kasa shown on satellite imagery (the inset indicates the position of the area considered); note the presence of a wide interdune basin between two parallel sand ridges. (B) Field picture of an interdune basin closed by complex dunes.

part of the basins are generally poorly covered by sand and fine-textured serir outcrops. The sandy cover on the basins' bottoms increases toward the East, and at the eastern margin of the dunefield a discontinuous sand sheet dotted by single or grouped barchans is present. Most of the aeolian dunes and sand sheets appear active due to the winds that characterize the hyperarid climate of the region. Large accumulations of sand, strongly weathered and partly dismantled sometimes emerge from the active dunes these represent dunes accumulated in the Pleistocene and weathered under interglacial wet and warm conditions (Figure 6).

Along the main wadis of the Tadrart Acacus Massif, and at its margins, some minor aeolian forms are present; most of them are very small and thus difficult to represent at the chosen scale. They mostly consist of sand sheets formed on the flat bed of some wadis, discontinuous fields of small barchans, climbing dunes accumulated against the wadi banks, and nebkhas developed around shrubs in the most vegetated parts of the valleys. Only at the southern margin of the massif, in the Takarkori region, is a larger aeolian feature present. A wide depression at the border between Libya and Algeria holds a significant accumulation of sand (a sand sheet dotted by small barchans), and is slowly covering the remains of a palaeolake (Cremaschi et al., 2014). At the northern margin of the Takarkori depression a large and complex dune, possibly resulting from the coalescence of several star dunes, is present.

Aeolian landforms are comprised almost exclusively of quartz grains, whose yellow to bright red color results from coatings of Fe-oxides. Quartz grains were accumulated during arid phases (glacial periods) by wind that eroded former soils rich in clay minerals and Fe-oxides, which had developed under pluvial conditions in the Tertiary and during Quaternary interglacials (Zerboni et al., 2011).

4.5. *Forms and deposits related to the high groundwater stand*

Notwithstanding the strong wind erosion that affected the region over the last five millennia (Swezey, 2001), the dunes of the Erg Uan Kasa still preserves many freshwater sediments, which formed under wetter environmental conditions (Cremaschi & Zerboni, 2011). Lacustrine sediments can be identified on the basis of visual interpretation (Hoelzmann, Kruse, & Rottinger, 2000) of satellite imagery (Figure 7): they are represented by areas with high reflectance, grayish to light bluish in color, and brighter than sand. The distribution and morphology of lake sediments was also checked in the field as the outcrops of Mesozoic limestone display almost the same reflectance and colors.

Figure 6. A Pleistocene sand dune emerging from the extant dunes of the Erg Uan Kasa; note the deeply weathered paleosol at its top (a person for scale).

Lake deposits are made of calcium carbonate-rich mud and are mainly located close to the largest dunes systems (Figure 7); they cover the bottom of corridors or were cut by wind erosion forming terraces and yardangs. Sediments were dated (on the basis of a robust ^{14}C chronology and their relationship with archaeological indicators) to the Pleistocene and Holocene (Cremaschi & Zerboni, 2011; Zerboni, 2006). The latter are in many cases unconsolidated and cover the most depressed parts of the basins; in several cases Holocene carbonates occur as aerodynamically shaped yardangs (Zerboni & Cremaschi, 2012). In contrast, Pleistocene lacustrine deposits are represented by massive carbonate terraces and iron crusts, possibly related to bog iron deposits (Hoelzmann, Keding, Berke, Kroepelin, & Kruse, 2001). Lacustrine sediments can be attributed to piezometric lakes (Cremaschi, 2001; Cremaschi & Zerboni, 2011), whose formation was triggered by the outcrop of surface water reservoirs recharged by intense monsoonal rainfall during Pleistocene interglacials and in the African Humid Period (Zerboni & Cremaschi, 2012).

A third kind of feature represented on the map, hydromorphic forms, are related to former phases of high stands of the water table (Figure 7). At the bottom of the dunes and within the interdune corridors a thick hydromorphic horizon consisting of slightly laminated bleached and mottled aeolian sand (etiolated sand, *sensu* Pachur & Hoelzmann, 2000), and occasionally of friable weathered sandstone (saprolite), is present (Cremaschi & Zerboni, 2009). Hydromorphic features indicate that in the area of the Erg Uan Kasa the ground was water logged for long periods. On the satellite images, etiolated sands have a high reflectance and appear light in color; in order to distinguish between hydromorphic horizons and lacustrine sediments a detailed field survey was required.

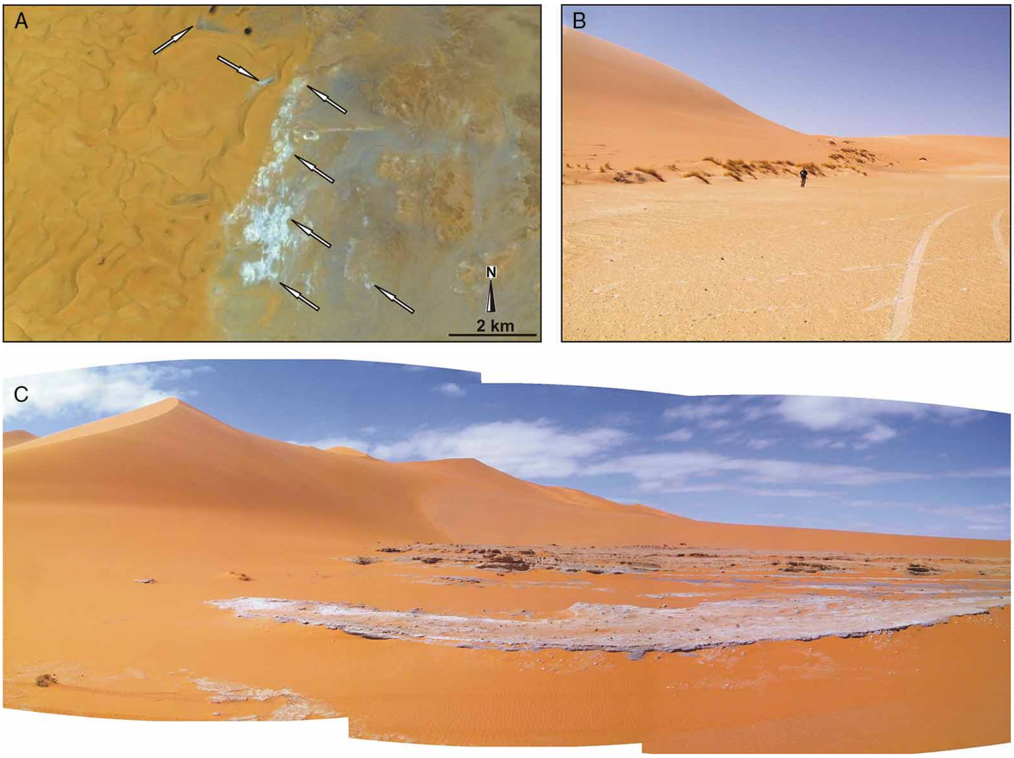

Figure 7. (A) Satellite imagery (Copyright Google Earth) of the dunes of the Erg Uan Kasa displaying lake deposits (indicated by the arrows). (B) Whitish hydromorphic sand at the foot of the dune of the Erg Uan Kasa (a person for scale). (C) Composite picture of Holocene lacustrine carbonatic (whitish) and organic (dark grayish) sediments between the dunes.

Outside the limits of the Erg Uan Kasa several large marsh deposits are present; they consist of tens of centimeters thick organic matter-rich sands, occasionally covered by carbonatic mud or gypsum pans. This kind of sediment is common in the northern part of the study area, between the upper reach of the Tadrart Acacus Massif and the northernmost dunes of the Erg Uan Kasa; marshes were generally active at the base of the vertical escarpment of the cuestas. The sedimentological properties of deposits and their position suggest that they are related to the occurrence of former springs dated, according to several radiocarbon dates, to the Early and Middle Holocene (Cremaschi & Zerboni, 2011). Satellite imagery also highlights the occurrence, between the Tadrart Acacus Massif and the Erg Uan Kasa, of some bright bluish spots, which in the field correspond to thick silty to clay, inorganic crusts, displaying a fining upward sedimentary trend. These surfaces do not represent marsh deposits, but can be interpreted as desiccation crusts: the small depressions were occasionally/seasonally flooded by ephemeral streams and the desiccation led to the deposition of fine-grained sediments (Goudie, 2013). Desiccation crusts are also present along the largest wadis that cut the Tadrart Acacus Massif, but their extent is too limited to be represented on the map; their occurrence and significance is discussed in di Lernia et al. (2012).

4.6. *Spring tufa in the Tadrart Acacus*

Along the wadi banks on the inner parts of the Tadrart Acacus Massif, at an elevation ranging from 900 to 1000 m a.s.l., calcareous tufa were identified (Cremaschi et al., 2010; Zerboni &

Figure 8. An alignment of calcareous tufa on a vertical cliff along the upper reach of wadi Imha (southern Tadrart Acacus Massif); note that the longest flowstones are c. 2 m long.

Cremaschi, 2012). Outcrops of this kind of rock were found within rock shelters, along vertical fractures inside relict solutional tunnels, and on vertical cliffs; they are related to the horizontal boundary between sandstone and thin, impermeable beds of shale or fine-grained sandstone beneath (Cremaschi et al., 2010). In the central part of the Tadrart Acacus, tufa deposits occur as thin laminated crusts on the floors of rockshelters and belong to the pool and barrage types; in the upper reaches of the wadis, up to several tens of meter long alignments of massive flowstone line vertical walls (Figure 8). In the latter case stalactites may be 2 m long. The microscopic properties of tufa are discussed by Carrara, Cremaschi, and Quinif (1998) and Cremaschi et al. (2010), with several U/Th and radiocarbon dates placing their deposition to the Early Holocene (Cremaschi et al., 2010). Due to the topographic and geologic position of tufa and their sedimentological characteristics, we define them as spring tufa and their occurrence indicates the position of ancient springs that were active during humid phases.

4.7. *Solutional features*

During the Late Tertiary and at the beginning of the Pleistocene the central Sahara was characterized by tropical/pluvial environmental conditions; under such settings, solutional processes on sandstone (Young, Wray, & Young, 2009) occurred and the resulting forms are still visible in the Tadrart Acacus as they were subsequently exhumed by wind erosion and aeolian corrasion (Zerboni, 2011). Solutional processes are common in sandstone massifs and are also known as silica-karst or pseudokarst (Wray, 1997). Underground solutional processes, reaching several hundreds of meters in depth, are well exposed in the Tadrart Acacus area, but could not be represented on the map. They consist of vertical and horizontal tubes, tunnels, weathering pits, large caves, pits etching bedding planes on steep slopes (caverned cliffs, Young et al., 2009), rock arches, towers, and pillars. The ruiniform landscape at the eastern entrance of the massif, which consists of a wide assemblage of towers and pillars, clearly demonstrates the effects of solutional processes on sandstone (Figure 9). Cavernous weathering is particularly

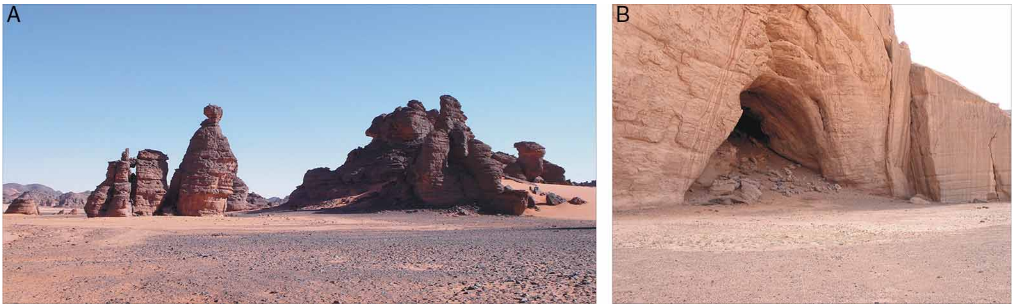

Figure 9. (A) The ruiniform landscape at the entrance of the Tadrart Acacus Massif. (B) The Uan Afuda Cave was excavated by deep solutional processes into the sandstone of the Acacus Fm. (central Tadrart Acacus Massif).

Figure 10. A massive banded iron speleothem within a cave along Wadi Agmir, central Tadrart Acacus Massif, (A) in the field and (B) in thin section under a petrographic microscope. (C) A gravel body (indicated by the arrows) cemented by an iron-rich cement close to the entrance of a cave along a narrow canyon in the southern Tadrart Acacus Massif.

well-developed along the banks of the main wadis, that are dotted by rock shelters, alcoves and caves formed in massive sandstone units by undersapping along bedding planes at the contact between the sandstones beds and the shales (Figure 9). Finally, solutional micro-features are also present, mostly represented by clustered potholes and shallow depressions on flat horizontal surfaces.

In the Tadrart Acacus, peculiar Fe-bearing mineral deposits, whose formation is related to the occurrence of a deep underground network of cavities, are worthy of note. Under a tropical climate solutional processes were able to reach the ferruginous sandstone beds of the Tadrart and Acacus Fms., and contributed to the chemical mobilization and leaching of iron. Due to large water availability (possibly reaching water saturation for the whole mountain), Fe-rich solutions migrated within discontinuities of the bedrock, precipitating as iron minerals within caves and fractures (Zerboni & Verrecchia, 2013). Iron mineralization consists of banded iron speleothems inside large caves, mammilate stromatolite-like crusts along fractures, and as Fe-cements within gravel bodies at the mouth of the underground drainage network (Figure 10).

5. Conclusions

As evident from this overview on the geomorphology of the Tadrart Acacus sandstone massif and Erg Uan Kasa, the main traits of the landscape of this part of the central Sahara originated from processes acting under contrasting climatic settings: some of them were triggered in the Tertiary and Early Pleistocene by wet and warm environmental conditions (tropical pedoclimate), while the arid climate promoted the development of aeolian features and the formation of a Mn-rich rock varnish on exposed rock surfaces. The chosen approach, combining desk photo-interpretation and the study of satellite data with field validation of physiographic units (Perego et al., 2011), allowed interpretation of the geomorphological complexity of the region.

The geomorphological map includes two different units of the landscape (mountain and dunes), but they belong to the same ancient drainage system, occasionally reactivated in the Late Quaternary. The map highlights the importance of geomorphological processes driven by climate, which also affected the trajectories of human groups that lived in the region. Thus, the map represents a useful tool for interpreting the distribution of archaeological sites in the region from a geoarchaeological perspective, tracing the different types of landscape exploitation related to human occupation during the Middle and Late Pleistocene and the Holocene (e.g. Barich, 1987; Biagetti & di Lernia, 2013; di Lernia, 2002; di Lernia et al., 2012; Garcea, 2001; Mori, 1965).

Finally, we hope that this map may also be used as a tool to supplement tourist itineraries including cultural and natural features, as well as major geosites and geomorphosites of the region. The increase in tourist activities in the Tadrart Acacus and Erg Uan Kasa may favor the economic development of the whole region, dramatically interrupted by the Libyan civil war.

Software

The following software was used to produce the geomorphological map of the Tadrart Acacus Massif and Erg Uan Kasa: OSSIM Image Linker 1.8. (processing of satellite imagery); SAGA GIS 2.0.6 (Digital Elevation Model data analysis); QuantumGIS 1.8.0 and GRASS 6.4.0 (digitisation of geomorphological units); Esri ArcGIS 9.2 (map layout).

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