Tunisian desert: a perfect place to simulate the landing on mars

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INTRODUCTION

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The face of Mars has been changed in the last few years. The data sent back by the Mars Global Surveyor (MGS) have shown a large number of details of the surface that a large number of new ideas, interpretations and guesses have been arisen by the scientific communities. This planet is now thought to be what just a small platoon of scientists was envisaging a few years ago. A large variety of

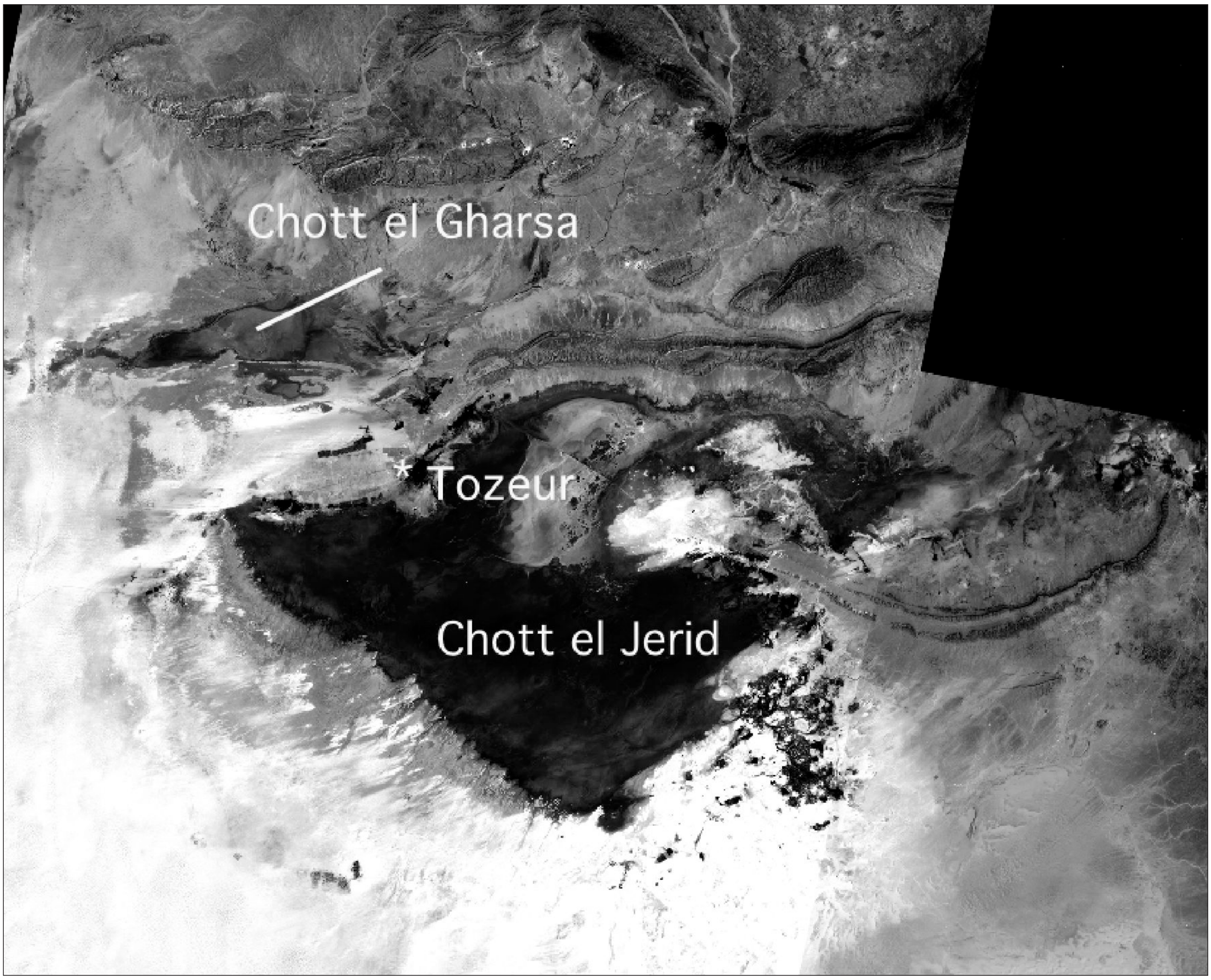

Fig. 1 - LANDSAT panchromatic mosaic of the Chott area.

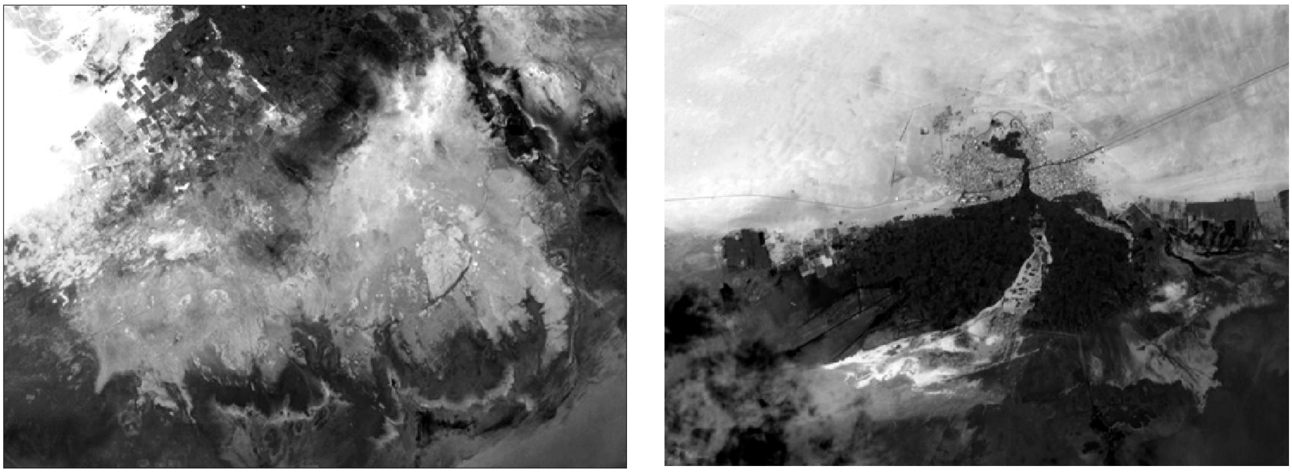

Fig. 2 - The town of Tozeur and the nearby town of Nefta on alluvial fan at the margin of Chott el Jerid Close up of ASTER image.

geological features and a complex planetary history are now of Mars characteristics and its relations to the entire planetary system is beginning to be understood. One of the most important contributions of MGS is a large data set with images at the scale of the geological observations that can be done on Earth.

The details observable in the MOC images are at a resolution that may start to allow detailed geological analysis. MOC will be followed by the High Resolution Stereo Camera on board Mars Express. This camera will send back medium- to high-resolution images covering a large part of the planet. A number of landers by NASA and ESA are planned to land on Mars and they will complement with their in-situ data the about 2 m/pixel orbital images.

High resolution is that we will move from large scale mapping-style to small-scale outcrop-like observations. A lot has been done in the past, but the details of the available data, now and in the future, will push geoscientists and other planetary scientists to look carefully to structures, processes, and models of our Earth, to be able to interpret the Martian environments. This major step will imply also that it will be possible to construct ideas on the Mars evolution based on detailed geological observations as it happens on Earth. These ideas although fuzzy are based on real data and they will be used for the

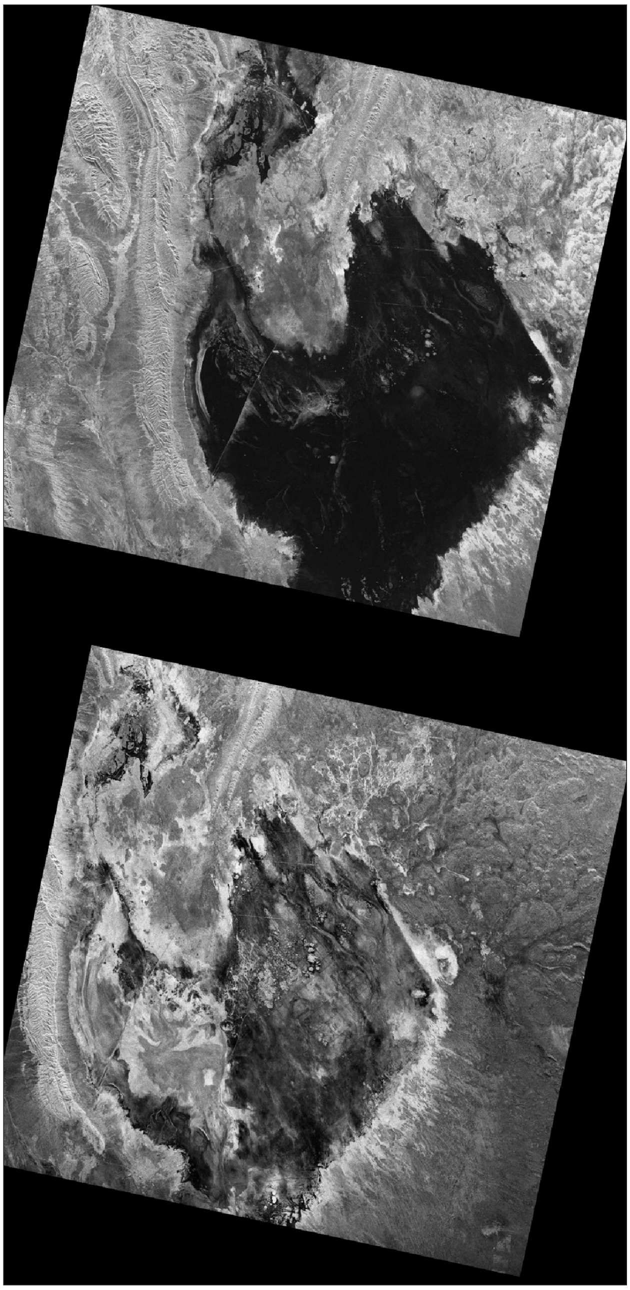

Fig. 3 - SAR (ERS 2) images of Chott el Jerid dry (below, summer 1995) and full of water (winter 1995, above). North is to the left. The base of each image is 100 km wide.

Fig. 4 - A: Chott el Jerid in Spring 2003 when the water covered the entire area od the dry lake; ***B****: the same area of Chott el Jjerid in Spring 2009 with only a few ponds of water present over an expesive dry lake bed*

validation of models. However, at the base of this effort there is the need to have a rigorous geological perspective.

It is necessary to understand that the Mars is a complicated planet with a large variety of processes acting along its history. It is likely that the outflow channels (or some of them) acted both as glacier valleys and as rivers in different time. This is very common on Earth and may be common on Mars as well. Even apparently simple features like Chott el Jerid and Chott el Gharsa are supported by a very complex history. Chott of Southern Tunisia, like many areas of our Earth are environments undergoing dramatic changes at different scales. They would be a major case to investigate analogies on Mars and Earth, and to understand how much and how many times the face of Mars has changed.

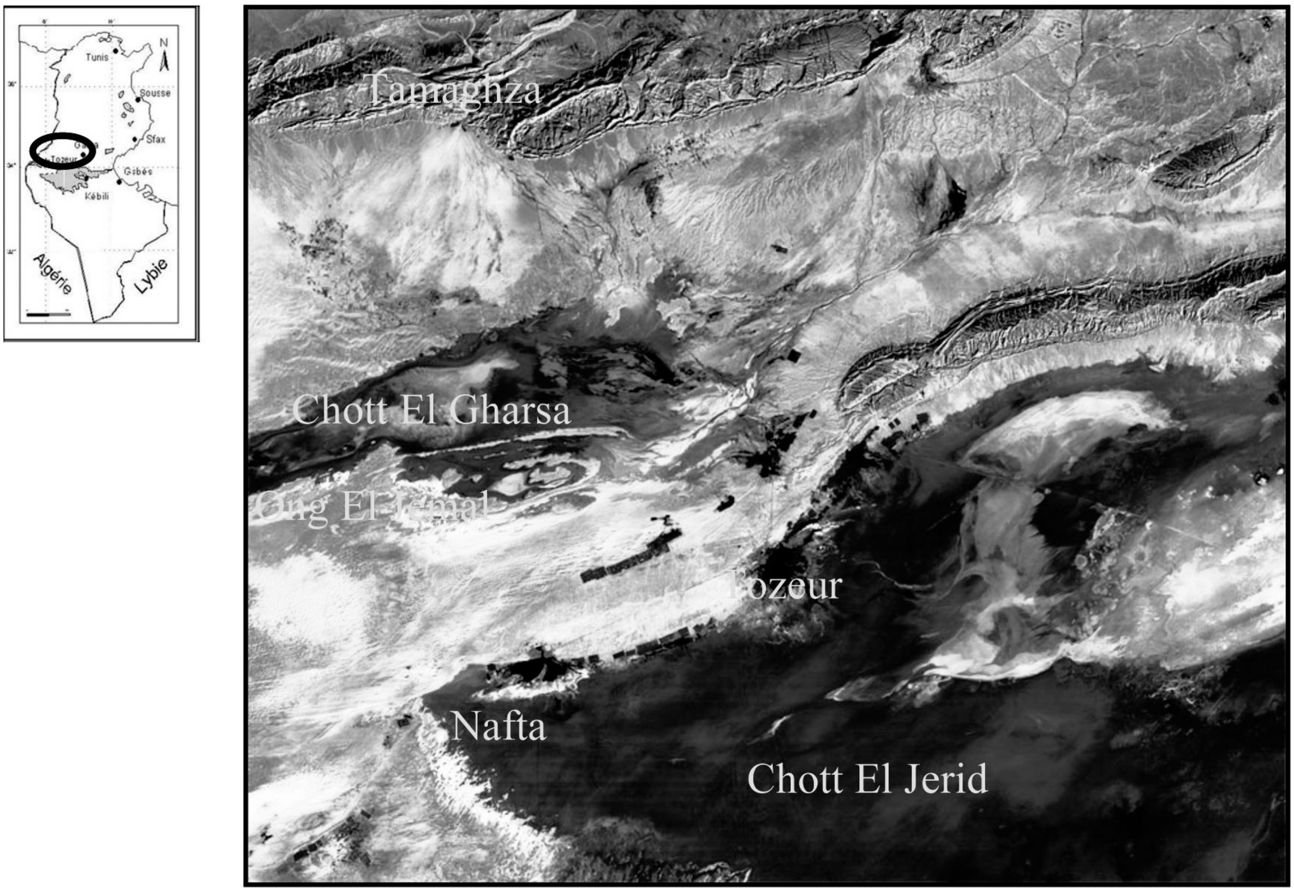

Fig. 5 - Satellite image of the field trip area. In the upper square Tunisia.

GENERAL PRESENTATION OF THE TOZER REGION

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Located at the northern margin of *the Great Eastern Erg*, the area is defined as a hyper arid space with few and irregular precipitations and strong dry winds. The natural environment has a very fragile equilibrium mainly due to:

- skeletal and little extended soils,
- a rare and very degraded natural vegetation in places totally absent,
- very poor quality water resources with main risk of exhaustion.

Two major depressions characterise the area: *Chott El Jerid* in the South and *Chott El Gharsa* in the North (Fig. 5)

The area of *Jerid* is the southern passage to the Sahara, and the oasis of *Tozeur*, has always constituted the inevitable passage of routes connecting these two chotts. Moreover, the presence of several fresh water springs in such a hostile environment, allowed the concentration and settling of local populations since the ancient times.

The blooming of civilizations of *Jerid* area was marked by the development several water use systems that rose this area to a strategic place able to offer food and goods to caravaneers mainly trading salt .

The name Jerid indicates the entire oases located close to the town of Tozeur. However, today it is used also to indicate the natural south-west part of Tunisia located between Nefzaoua, Gherib and the lower southernmost plains (Fig. 6).

The strategic position of the Jerid oasis led the Romans, since the time of Traiano (reign between 98 -

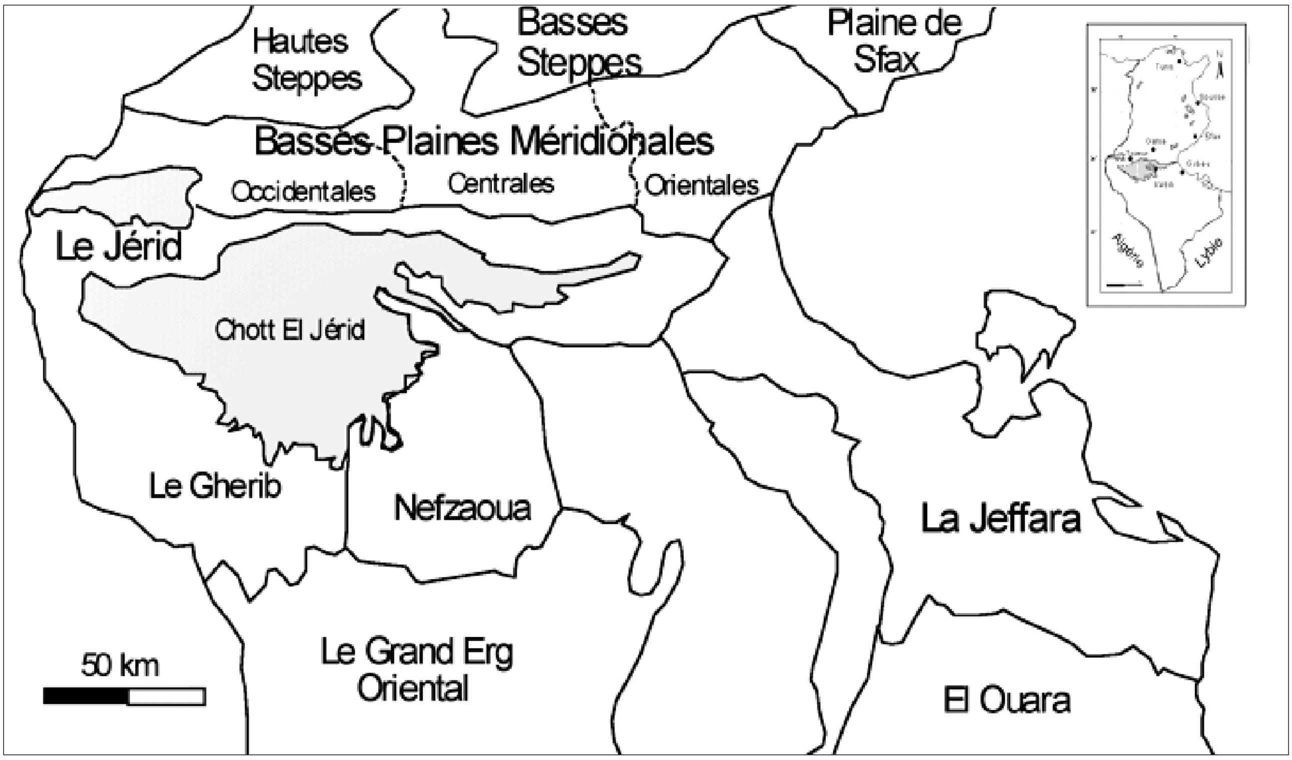

Fig. 6 - Tunisia provinces.

117), to have a permanent a military station. Later, during the Muslim time, the area of Tozeur maintained, if not reinforced, its position of privileged passage for pilgrims “er Rakb”, moving from “Sakiat el Hamra”, on the Atlantic, towards their final destination, to La Mecque.

Climatic characteristics

According to the index of Emberger, the area of Tozeur belongs on the *higher Saharan bioclimatic level*. Its climate is mainly controlled by three factors:

- the continentality of the zone and its distance from any the maritime influence, this implies very high diurnal and annual thermal variations;
- the position on the Northern edge of the Sahara desert, opened to the influence of subtropical high pressures;
- the Southern Atlas mountain chain constituting a frontal barrier to any northern climatic influence.

The Temperatures

The very marked continentality of the area of Tozeur is expressed by a very contrasted thermal mode with very marked annual and diurnal amplitudes. The average temperature is about 22°C. Two extreme seasons mark it climate. The *hot season,* starts in May with temperatures higher than 22°C and lasts 4 to 5 months (May-September). The average temperature during the hot season is close to 30,5° C, and the highest may easily exceed 50°C. The *fresh season*, is characterized by soft winter, with monthly average temperatures always higher than 10°C with the coldest month with temperature minor than 4°C, and a considerable temperatures drop down during the night with occasional frost (Fig. 7).

Rain periods

The area of *Tozeur* is located in the lower part of the isohyets 100 mm per year and often lower than 50 mm. Precipitations are rare and irregular. The average of rainy days is of 20d/y, with a minimum of 6d/y and maximum of 28d/y (Fig. 8). March and November (or sometimes September) are the most rainy.

The water balance:

High temperatures long insolation determine an enormous evaporation capability (ETP). This high

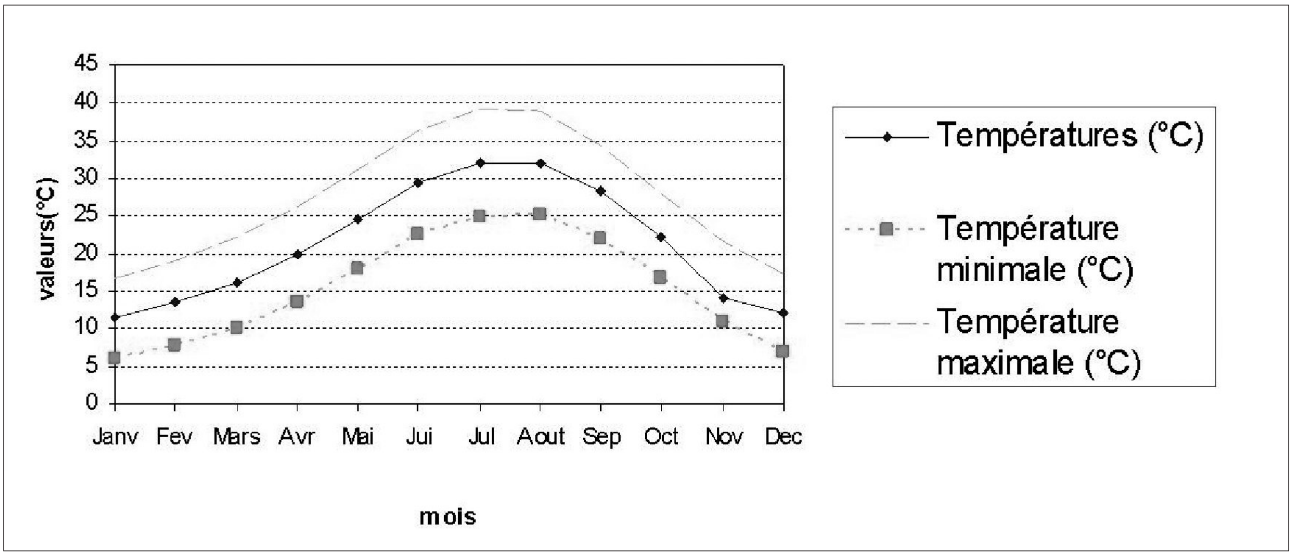

Fig. 7 - Temperatures measured at Tozeur (1989-1999)

evaporation, combined with scarce rain, determines a strong negative annual balance. The permanent deficit is from about 1400 to 1800mm/y and increases toward the *Eastern Erg*. Thus, the received rain covers only 10 to 15% of the ETP (Fig. 9).

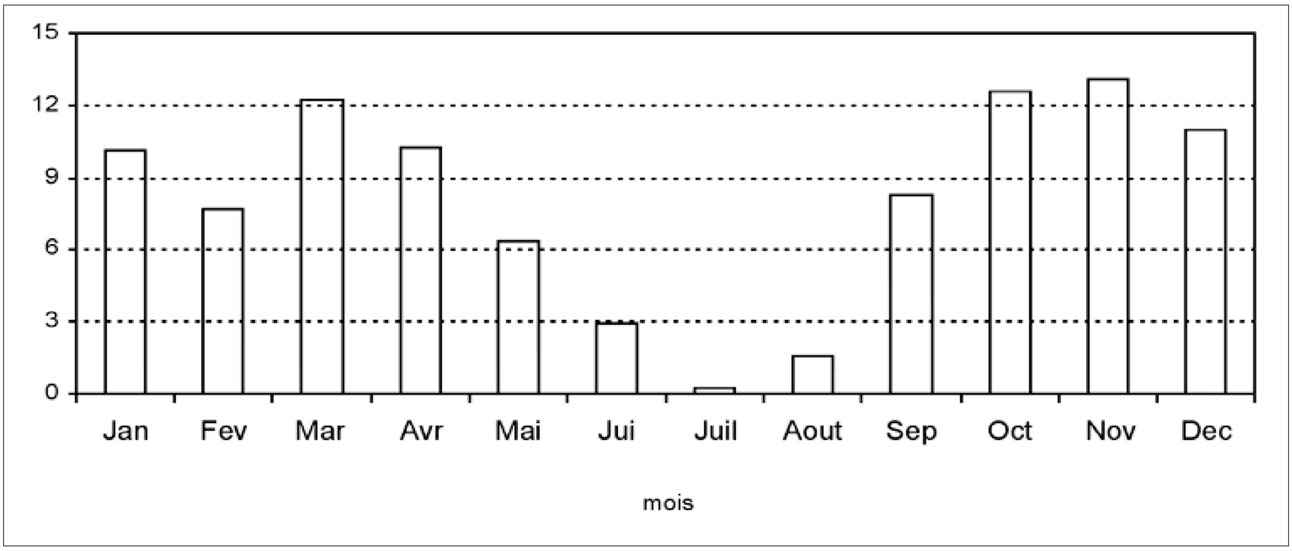

Fig. 8 - Rain measured at Tozeur in mm (1900-1995)

The Winds

Winds play a central role in the morphological dynamics of the Jerid arid region. It is blown by several E-W winds using natural corridors (depression between chains) connecting the chotts with the eastern Erg (chain of *Jbel Negueda-Jbel Enneflet*, chain of *jbel Sidi Bouhlel, Jbel Tebaga and Fatnassa,…* Tozeur has recorded 120d/y strong wind, with a clear predominance of NE coming winds mainly in autumn and in spring. While in the summer from SE. Tozeur is also characterized by high frequency sand winds (74d/y), 45,9% of which during summer. This sandy wind has fatal consequences on the cultivation, in particular during summer, considering that it coincides with hot and dry winds (Sirocco) and an abrupt increase of temperature (10 with 15°C in one or two hours).

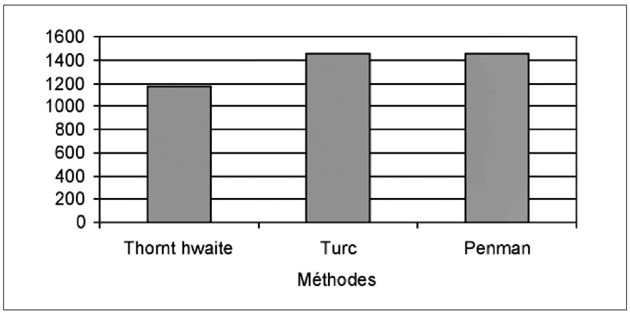

Fig. 9 - Evapotranspiration in Tozeur (mm/year)

The Vegetations :

The Jerid is dominated by a pseudo steppe with psammophile and gypsophile species reaching a maximum high of 200cm for a single pant. This steppe covers a maximum of 20% of the total ground. The pasture offered is poor and only used during summer as integrated food supply for camels.

Tamarix is the primitive vegetation normally distinguished three groupins depending on the kind of ground:

- on salt: *Haloconemum Strobiloceum, Arthrocnemum indicum, Salsola Siberico, Salsola tetrandra, Sueda mollis*;
- on sand: *Aristida pungens* (*Stipagrostis pungens*), *Retama raetam*, *Calligomum* ;
- on gypsum: *Astragalus armatus, Zygophyllum album, Erodium glaucophyllum*.

MORPHOLOGY

In terms of morphology, the most representative units are:

The low hill «Draa El Jérid»:

Located between two chotts el Gharsa and el Jérid it represents the Western prolongation of the Northern chain of Chotts. It is East-West oriented and extended for approximately 30 km with an average altitude of about 150 m.

The closed depression «Chott El Gharsa» :

Located in the Western part of the area, Chott el Gharsa, it has a triangular shape and corresponds to a vast closed depression (600 km ?)extending toward the west for more than 50 km. It is for most part 20 to 30 m below the sea leavel.

Two are the main aspects Chott el Gharsa:

- The first is the perfect flat surface of the depression. This feature is connected with the seasonality of the chott itself. During the winter important volumes of water occupy the depression forming a thin sheet. This water blade evaporates very quickly leaving space to this plane surfaces typical of “Sebkha”.
- The second are the aureoles characterizing the Sebkha surface for the most part colonized by a very dense halophilous vegetation resembling true grass. This the typical “Hmadha” landscape.

The plain of «EL Oudia»

The El Oudia plain has triangular form and constitutes the Western prolongation of Essegui El Guebli Village. Its altitude varies from 40 m in the East to -19 m in the Western sector and, therefore, it acts as a low-land area.

The plain of «Chamsa»

It is a very wide surface extending N-S from the southernmost edge of Chott El Gharsa to the borders of Draa el jérid. To the West it is bordered respectively by the mouth of wadi Gouifla el Melah and the algéro-Tunisian border. Average altitude is approximately 35 m with a gentle slope toward the North.

SOUTHERN TUNISIAN CHOTTS: A GEOMICROBIOLOGICAL APPROCH

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INTRODUCTION

In recent years there has been a dramatic increase in the knowledge of microbial diversity of hypersaline environments since the time when they were thought to represent virtual sterile environmental settings. However, much has still to be discovered, as confirmerd by the ongoing research on hypersaline (especially continental) settings and their geobiology. Microbial populations have been described from stratified multicolored intervals in natural and artificial (salterns) evaporation ponds throughout the world. High saline waters of arid regions, in particular, are sites inhabited by extremely halophilic groups, including halophilic archaea (halobacteria), halophilic cyanobacteria, and green algae (Grant et al., 2008). Recent investigation has showed that the establishment of microbial ecosystems in saline ephemeral lakes of arid regions (sabkha) depend on a number of factors, including dryness, daily thermic excursion, oxidative processes, and salty conditions. In particular, microbial species living in sabkha lakes develop specific adaptations for high osmolarity that typify hypersalinity (Oren, 1999) In such critical conditions, in which a combinations of limiting factors may interact in a fairly complex (and still largely unknown) way, also the relationship between the physical nature and mineral composition of sediments and microbial populations play an important role. This is documented, as a paradigmatic example, by the establishment of endolithic communities in hypersaline settings from different arid areas (recent examples in Wierzchos et al., 2007; Stivaletta and Barbieri, 2008, 2009). The most important interaction between endolithic microbes and physical environment is that sediments and minerals may provide protection for the communities. Evaporitic minerals, as gypsum or halite, can preserve microorganisms from exposure to UV radiation, strong temperature fluctuation, desiccation and, in the meantime, they have a sufficient degree of traslucence to allow photynthesis (Friedman, 1982).

The dectetion of water-soluble salts (sulfates and chlorides) with a potential origin through evaporitic processes on Mars (Gendrin et al., 2005; Osterloo et al., 2008) is the reason why halophiles are today considered a reliable potential target in the search for extraterrestrial life.

Microbial comunities (and their remains) in the saline environments of the southern Tunisian chotts

The area of the southern Tunisian chotts includes a belt of shallow salt lakes (chotts) extending from southern Tunisia to the Atlas Range (Algeria). As in other continental sabkhas, the chotts turn to dry salt flats during the dry season. This occurs in the Chott el Jerid, where precipitated salt (halite) crusts, due to the lowering of the water table, cover most of this area. Differently, on winter the area may be largely flooded (Fig. 10). The only sites of the Chott el Jerid where water is persistently present are artificial saltern channels and ponds that are located along the straight road crossing the chott. Environmental measurements performed in Spring 2005 in the Chott el Jerid waters provided salinity values between 29 and 37 % NaCl, and pH values between 7.4 and 7.8 (Stivaletta et al., 2009). In these waters (and in the precipitated salt crystals and crusts) halophiles and hyperhalophiles belonging to archaea, cyanobacteria, or green algae (*Dunaliella*) grow in large numbers. The cosmopolite eukaryotic alga *Dunaliella*, in particular, is particularly abundant and provides intense red-orange coloration to the water (Fig. 4). This is due to the carotenoid pigments that abound in these *Dunaliella* populations. As observed by Stivaletta et al. (2009) overproduction of carotenoids, as in *Dunaliella* of the Chott el Jerid waters, is a likely indicator of light stress, since carotenoids are thought to give photo-protection. Other microbial communities are abundant at the sediment-water interface and are dominated by unicellular and filamentous cyanobacteria (Stivaletta et al., 2009).

In both Chott el Jerid and Chott el Gharsa sulfate precipitates of evaporitic origin are largely present.

At the margins of the Chott el Jerid mounds produced by artesian springs consist of sand accumulation cemented by salt (gypsum) precipitates (Roberts and Mitchell, 1087). They developed until the last decades, when the overexploitation of the aquifer has dried the springs. At the top of the mounds, gypsum crusts (Fig. 3A) with stratified multicolored intervals of variable thickness are colonized by modern endolithic communities described and interpreted by Stivaletta and Barbieri (2009). These microbial ecosystems colonize layers immediately beneath the gypsum crust surfaces, where green-colored (cyanobacteria) communities are placed between and around gypsum crystals (Fig. 3D-F in Stivaletta and Barbieri, 2009). Other halophile components include the chlorophycean green alga *Dunaliella*, which has been recognized in orange colored horizons a few mm beneath the surface of the gypsum crusts. Deposits making up most of the body of the spring mounds consist of gypsum and sand that mimic a travertine-like organization (Fig. 3B) in which signatures of microbial origin have not been detected.

In the eastern side of the Chott el Gharsa depression gypsum of evaporitic origin (Fig. 4) makes up the top of terraces produced by erosional processes. This fossil (upper Pleistocene, Swezey, 2003) gypsum represents most of the evaporite deposits of the Chott el Gharsa and its geomicrobiology has been described and interpreted by Barbieri et al. (2006). In spite of the negligible organic contents still preserved (C_{org} contents <0.1%, Barbieri et al., 2006), in the laminated gypsum deposits of the Chott el Gharsa unambiguous preserved (fossil) evidences indicate fingerprints of microbiological activity. They include i) mineralized morphologies similar to those described by bacteria in modern counterparts (mucilage, rods, microfibers); ii) dumbbell morphologies, pyrite framboids, and changes in gypsum kinetics suggested by gypsum crystal shapes.

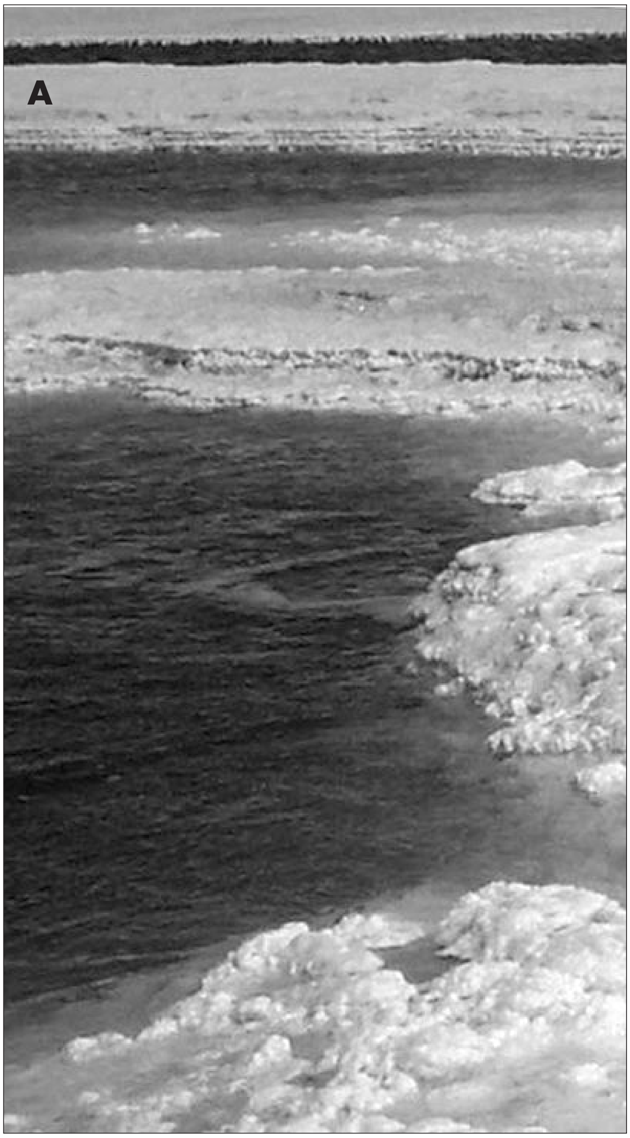

Fig. 10 - Salt (halite) accumulation in artificial saltern and ponds of the Chott el Jerid. The red/pinkish coloration of water (Fig. 10A) and salt (Fig. 10B) is caused by the high concentration of the chlorophycean green alga Dunaliella

Chotts microbial life: relevance to astrobiology

The main reasons making sulfates a primary target in the search for Martian present and fossil life include: i) the unambiguous detection that liquid water (and consequently a past wet) characterized the geological history of Mars, and this also includes ii) the detection of a number of sulfate (including gypsum) minerals on the Martian surface, which also are hydrated minerals; .iii) sulfates (and generally speaking evaporites) may easily trap remains/traces of microbial activity. Terrestrial evaporite environments (especially from continental settings) can therefore be regarded as reliable analogues of Martian environments in which landing sites for near future astrobiology missions can be planned. Furthermore, the analysis of terrestrial analog materials can provide the necessary experience and the analytical skill for the interpretation of remotely sensed data derived from orbital and rover missions to Mars. Also they can provide new information on specific microbial taxa, such as *Chroococcidiopsis*, a partially unknown, extremely resistant halophilic cyanobacterium, proposed as as a pioneer microorganism for the terraforming of Mars (Friedmann and Ocampo-Friedmann, 1995).

Since minerals that precipitate in evaporite environments are tightly related to biotic components (halophiles), different microbial products (cells, pigments, bio-induced morphologies) can be incorporated and preserved in fossilized salt even for an extended geological time span (see example in Satterfield et al., 2005). In spite of their limited possibility of long lasting preservation (especially in areas with active surface hydrology), evaporites can therefore be regarded as a good repository for microbial fossils. This is a further aspect that makes evaporites reliable in an astrobiological perspective. For further discussion on the astrobiological potential of the chotts environments see Barbieri et al. (2006) and Stivaletta et al. (2009).

GEOLOGY AND PALEOHYDROLOGY OF THE CHOTTS AREA IN SOUTHERN TUNISIA

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Regional geology

The chott area (Trough) in southern Tunisia is located on the southern front of the Atlas thrust and fold belt, in a region between 33.5??N and 34.5??N and 8.5??E and 9.5??E (Figure 1). This area corresponds to the eastern segment of the Tunisian Atlas foreland basin. The Tunisian Atlas is part of the Alpine-Himalayan Tertiary-Quaternary orogen, caused by the collision of the Eurasian and African Plates.

Sedimentary history of the chott began with the opening of the Thethys Ocean during the late Paleozoic to early Mesozoic. It started as passive margin deposition. During the Jurassic and early Cretaceous more than 4000 m of sediments were deposited in the Chotts Trough (Ben Fejani et al.,1990) because of the accommodation produced by the E-W trending fault system bordering the chott (Hlaiem, 1999).

Salt tectonics might have been of some importance in the tectono-stratigraphic evolution of chott, both during the Jurassic-Cretaceous extensional phases and the late Tertiary and Quaternary compression due to the Alpine orogeny (Fig. 11, modified from Hlaiem, 1999). Since the Mio-Pliocene a separation of depocenters has continued in the Chotts Trough. Both Chott el Gharsa and Chott el Jerid occupy synclines (Swezey, 1996). During the Quaternary sedimentation in the Chotts Trough is mainly linked with strike-slip tectonics.

The subsidence rates in the Chotts Trough varied with time: for the Miocene and Pliocene an average value of ~0.01 mm/y has been estimated,n while for the Quaternary the range of calculated subsidence rate varies from 0.01 to 0.27 mm/y (Swezey, 1996), depending on the location. The most subsiding areas during the Quaternary are Chott el Jerid and Chott el Gharsa (sedimentation strongly affected by local subsidence linked with strike-slip faulting, and water table height variations at shorter timescales).

The geological evolution of chott appears complex: from the Mesozoic extension related to the Thethys opening, to the Tertiary compression due to continental collision and foredeep formation up to the Quaternary subsidence produced mostly by local effects of strike-slip faulting. Since the Tertiary the depocenters remained spatially discrete (Swezey, 1996), leading to the present physiographical separation between different chott.

Quaternary hydrology and sedimentation of Chott el Jerid

There has been a major controversy about age and nature of hydrologically wet periods of Chott el Jerid in the Quaternary. Some early studies found that there was a major lacustrine phase coinciding with the late Pleistocene glaciation. Richards and Vita-Finzi (1982) claimed that high-water stands were caused actually by a marine invasion at about 25-35 ka. In order to explain the marine invasion at that time, the area must have been uplifted at least 80 meters since 25 ka. This hypothesis has been argued against by Cause et al. (1989) who examined U-Th data and concluded that major flooding episodes occurred at around 150 and 90 ka. They contend that earlier estimates of the carbonate ages around 17-40 ka based on radiocarbon analyses are not reliable. They also insist that the area has been subsiding rather than uplifting. This controversy has not been solved to this date.

Chott el Jerid is underlain by a think accumulation of Cretaceous and Tertiary (Mio-Pliocene) sediments that contain gypsum-rich ancient marine evaporites. A thin Quaternary deposit lies on top of the accumulation. The Quaternary deposit consists of a wide variety of evaporites and eolian materials. The most common evaporitic minerals are gypsum, halite, and also carnallite ($KMgCl3·6H2O$). The evaporite formation is an ongoing process in Chott el Jerid. The present mean annual precipitation in the chott is about 80 to 140 mm. But the evaporation rate is about 1,500 mm, far exceeding the precipitation.

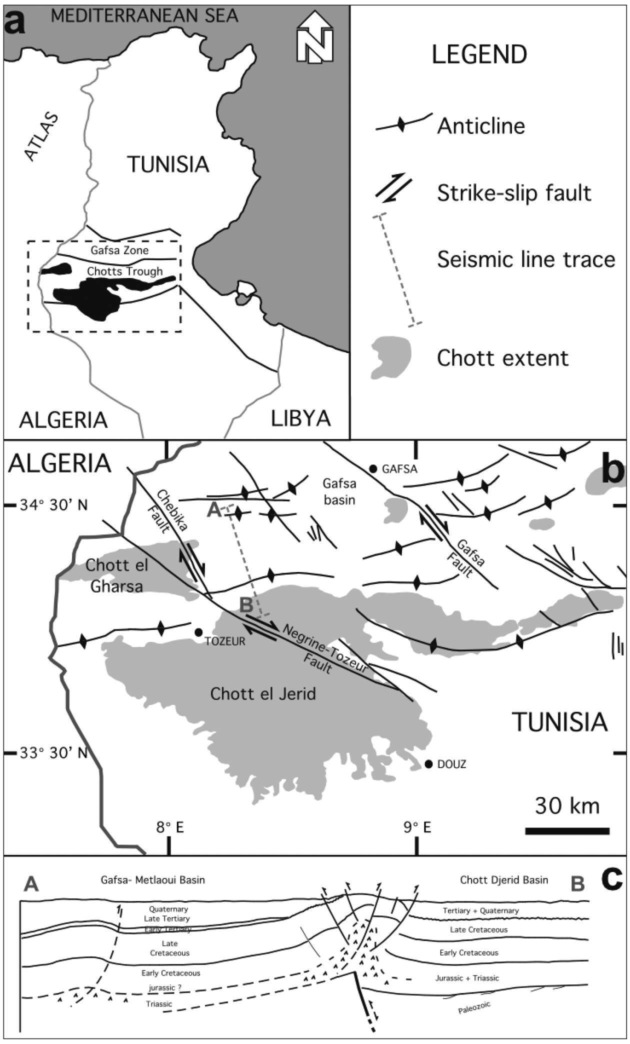


Fig. 11 - Main geological features of the chott area a) Location map with major structural features (modified from Swezey, 1996). b) Geological sketch map of the Chotts Trough (modified from Swezey, 1996). c) Line drawing of a reflection seismic line (modified from Hlaiem, 1999) along the north side of Chott el Jerid. A fault induced salt diapir is interpreted in this seismic line (Hlaiem, 1999).

It is of course extremely difficult, if not even impossible, to date the evaporitic and eolian deposits in the Chott area. However, in the shake of simplicity and rigour, we will identify the sediment object of this field trip as generically late Neogene and Quaternary. This broad envelope include all the deposits that have been deposited in the area influenced by lacustrine and eolian processes.

A large quantity of new evaporite minerals is formed after major flooding events. An example of such events is the 1990 flood which inundated the whole basin (Bryant, 1999). As the evaporation of water proceeds, sequential crystallization of different types of minerals occurs, a process that is controlled normally by the chemistry change in the brine. This process results in zonation of evaporite minerals and such zonation can be observed by remote sensing techniques (Drake et al., 1994). The zonation of evaporites is a dynamic process in space and time due to repeated crust destruction and re-formation (Bryant et al., 1994). The waters entering the basin generally have the same bulk chemistry and it reflects that the waters underwent the same general chemical evolution. In this case, the waters flowed through the ancient marine evaporite deposits of the region (Bryant et al., 1994). Therefore, the evaporite mineral assemblage of Chott el Jerid is generally consistent with that derived from the evaporation of seawater.

Spring mounds are abundant in the southeastern part of Chott el Jerid (Roberts and Mitchell, 1987).

They are in the form of ridges, towers, pinnacles and conical hills with or without central cones.

Their heights reach from less than 1 meter up to over 30 meters and diameter can be up to 500 meters. Most consist of sand and slit size particles cemented by varying amounts of tufa, travertine and gypsum. They are fed by spring water from the main aquifer the Complex Terminal, the most important bed being the Upper Senonian (late Cretaceous) limestones. Radiocarbon analyses gave dates for Terminal water ranging from 30,000 to 3500 years, implying that the recharging of the aquifers happened during pluvial periods of the Quaternary and current recharge from sporadic rainfall must be relatively small.

Stratigraphic outline

Rocks present in the Jerid area record a 1330 m thick succession of various paleoenvironments that alternated from Creatceous to the Neogene. (Fakhraoui et al. 1994, Abdallah 1987), although during this last time mainly fluvio-deltaic environment (Beglia formation and Segui formation) developed (Biely et al., 1972).

THE CRETACEOUS:

Late Albian

Late Albian rocks crop out in the middle part of jebel Zitouna and jebel El Askar. They consist of metric dolomitic beds up to 40 m thick.

Cenomanian

Cenomanian deposits crop out in the intramontane depressions of jebel Ksar El Asker, jebel Sefra and jebel Taferma. They are made of alternates of massive gypsum and marly beds. Their thickness is approximately 195 m.

Turonian

Turonian deposits crop out in the middle part of jebel El Kébriti and in the Northern side of jebel Zitouna. They are composed of dolomite beds alternated with clay and marly-limestone. Their thickness can reach 70 m.

Coniacian

Coniacian deposits crop out in the North of jebal Taferma and jebel Ksar el Asker. They are the best exposed rocks of the area, in particular toward the West of the area, such as close to jebel Tarfaoui, Morra and Cherb. They are composed of white limestone alternate with decimeter greenish to yellow clay beds. The thickness is of about 100 m.

Santonian

Santonian deposits are present in limited outcrops in Northern Chotts chain where they reach a maximum thickness of 55 m. In the middle part jebal El Atra they, however, reach a thickness of 150 m. These rocks are composed of alternation of marly-limestones, marls and greenish clays.

Campanian

Campanian deposits crop out in the northern part of jebal Taferma, jebal Zitouna, jebal Torriche and jebal El Morra and in Western termination of the jebel El Berda anticline. They are composed of:

- alternation of yellowish marly limestones and sandy clays with some limestone beds interlayered (20m);
- decimetre beds of sandstone with gypsum clay interlayered (15 m);
- a thick calcareous layer with slightly gypsum clay interlayered (25 m).

Late Campanian/ Early Maastrichtian

The deposits of this age are present in limited outcrops in the northern part the Northern Chotts chain. They, instead have a considerable extension in the jebal Sehib where they reach a maximum thickness of 60m. They are made of alternate of marls and limestones.

THE PALEOCENE-EOCENE

Paleocene-Eocene rocks are well exposed in the southernmost part of Jebal Sehib anticline of and in the plate of Mzenda Jellabia, whereas they occur in limited outcrops in the north Chotts chains.

Paleocene strata are made clays and marls interlayered beds capped by nodular limestones. Their have a maximum thickness of 30 m.

THE NEOGENE:

The Neogene and Quaternary deposits (visited during field trip) are well exposed throughout the Jerid area. They progressively increase in thickness toward the western termination of the Northern Chotts chain and the southernmost side of Chott El Gharsa. They are grouped in the Beglia and Ségui formations (Biely. A et al. 1972; Sghari. With, 1991, Hull 1962). However, these two Formations are not clearly defined and both in term of age and physical stratigraphy. We will ragere to this deposits as simply Late Neogene and Quaternary.

Paleohydrology of Western Sahara

The western Sahara has been affected by strong and dramatic environmental changes. Pluvial periods alternated with arid periods deeply shaping the Sahara geomorphology and sedimentology. The evidence of for these changes is overwhelming and extensively published. However, the setting of the river systems in the Sahara is still debated. The present day river systems in the Sahara are basically ephemeral (Fig. 12). Many of them are contained in large paleovalleys, which have been formed during pluvial periods. These paleovalleys have been the product of perennial rivers. Therefore the fluvial landforms in the Sahara are produced by the complex interactions of perennial rivers, which flew during pluvial periods, and ephemeral stream which flew during dry periods.

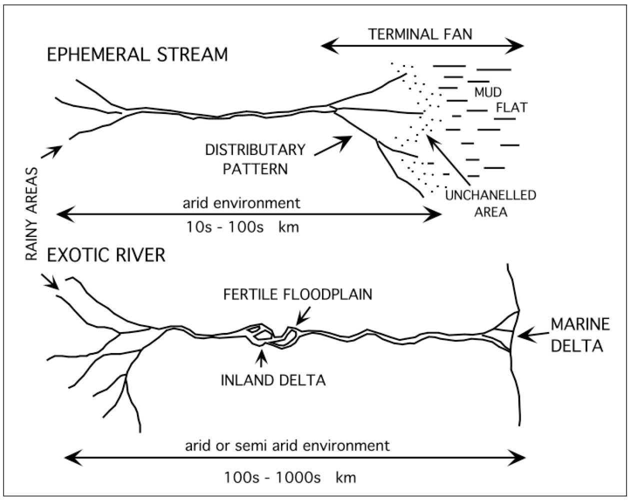


Fig. 12 - Characteristics of exotic and ephemeral river channels.

Sedimentology of the desert rivers

The sedimentology of the rivers flowing in arid and semi-.arid environments does not have attracted much attention in the past (Miall, 200; Tooth, 2000). Basically the sole model of "desert" rivers is the ephemeral one. Actually, the rivers in this climatic setting display a remarkable complexity, and show strong variability in facies and channel patterns (Tooth, 2000) (Fig. 13). In term of complexity they can be compared even with the pluvial-tropical rivers (Sioli, 1984; Ori, 1987). Among the large variety of river systems we can recognize the following basic types: (i) the ephemeral streams which undergo episodic flooding and long inactive dry periods; and (ii) the exotic rivers, which are perennial even if affected by large discharge fluctuations.

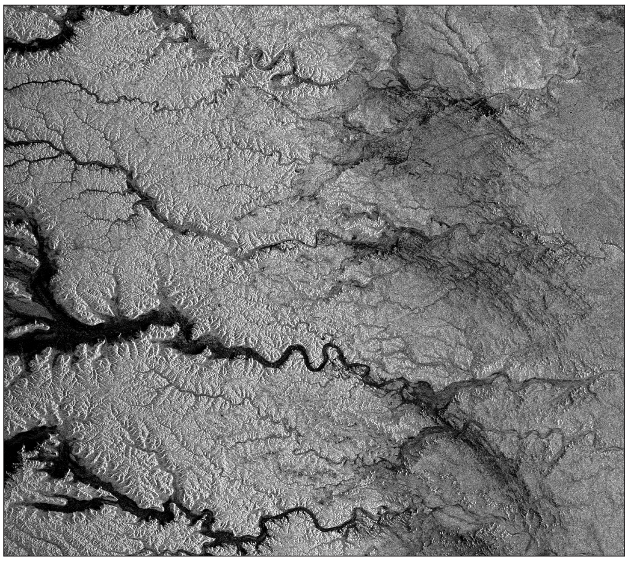


Fig. 13 - Meandering paleovalleys in the M'zab region. One of these meanders is shown in Figure 3.

The base of the ERS (radar SAR) image is 80 km. North is up. The ephemeral streams are usually short and with relatively small drainage basins. The major characteristic of the ephemeral streams is that they are affected by rare floods with high peak discharges.

Fig. 14 - A meander of paleovalleys in the M'zab (see Figure 2).

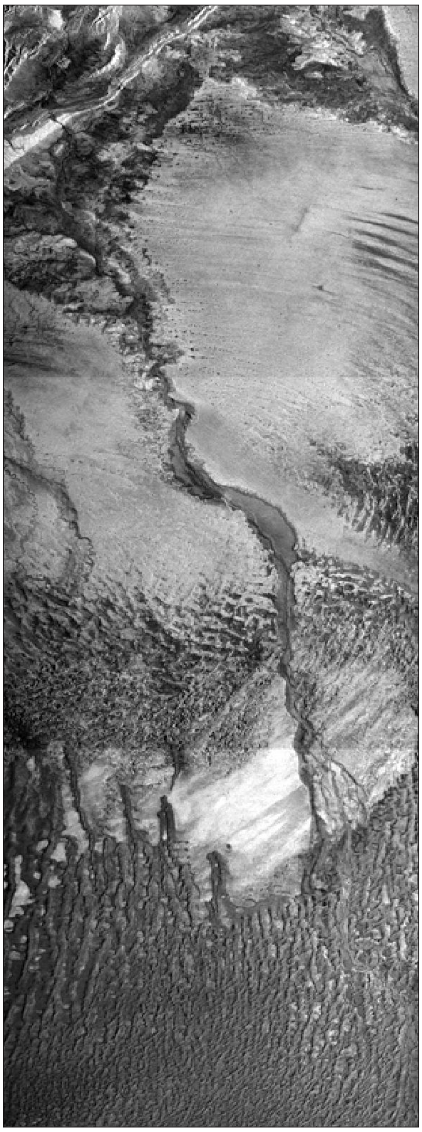


Fig. 15 - Oued Namous paleovalleys. This valley is located in the northern (Atlasic) margin of the large endoreic sahara basin. The width of the ERS mosaic is 100 km. North is up.

Currents are usually in the upper flow regimes due to both the high velocity and the shallow depth. Eolian sands accumulate in the river beds in between floods (Figs 14, 15). These rivers occur in arid areas, even in the innermost part of the Sahara. Evaporation and infiltration play a major role in decreasing the river discharge by producing a remarkable loss of water. Consequently, the rivers lose capacity of transport and the channel become less defined, shallow and broad in cross section up to form, in the downstream end, a distributaries pattern of channels. The channels fade out spreading their waters over large unchanneled areas (mud flat). These distributary systems have been named terminal fan (Mukerij, 1976, Friend, 1978) and pass downstream in sebkha environments. Exotic perennial rivers (Czaya, 1981) flow from rainy areas across arid zones: typical examples are the Nile, Niger and Senegal rivers. Their common characteristic is to lose water along their courses without vanishing entirely. When these rivers are present in areic basins they reach the sea and form marine deltas. If they occur in endoreic basin they debouch in lakes. Along their courses, exotic rivers undergo hydrological crisis that produce tremendous loss of water. The decrease in discharge is matched by a decrease in capacity of transport and erosional power: channels become shallower and form an intricate anastomosed patterns. In these zones the floodplain extensively consists of swamps and marshes forming the so called inland delta. Very well known examples of inland deltas occur along the Niger River and the Nile (Sudd). In

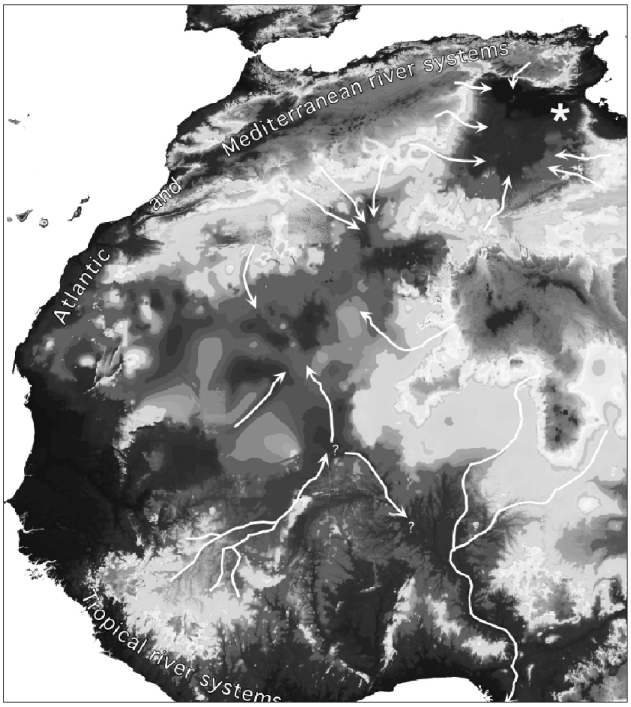


Fig. 16 - Paleohydrological sketch of the River systems during the Holocene pluvial period (9000 – 5000 years BP). The white lines schematically show rivers courses and flow directions.

these cases the rivers survive the hydrological crisis (the Niger River looses 70% of its water), but in other cases the rivers fade out into the delta (see, for example, the Okavango River in Botswana).

The inland deltas share some features with the terminal fan, because both are distributary systems due to loss of water. The distribution of the flowing water in several channels is the direct product of the decrease in erosional capability and in the increase of accumulation of sediment. However, the exotic rivers form anastomosed patterns because they are able to built around the channels fine-grained floodplain deposits. Instead the distributary channels in the terminal fans rest simply at the top of pre-existing surfaces.

Arid rivers and climatic changes The two types of rivers are subject to the change in climate and environmental conditions.

The exotic rivers are linked to source areas with long strong rainy seasons and occur in both deserts and savannas. During the pluvial periods the Sahara desert has been crossed by several of these type of rivers as it is testified by the large number of paleovalleys preserved in the highlands; whereas lacustrine deposits had been observed extensively in the lowlands, which are currently covered by ergor sand sheets. The perennial and exotic rivers during the pluvial periods affected both areic and endoreic basins. Mediterranean and Atlantic rivers of the northern segment of the coastline were short headed, whereas the rivers flowing in two the Atlantic south of the Senegal River were long and with high discharge. However, these rivers are out of the Saharian domain. Those that flew in the present day Sahara were mostly connected with endoreic basins. The Chott el Jerid stay at the margin of an endoreic basin that covered the area where the Grand Erg Oriental is currently located. Paleovalleys have been identified all around the marginal highlands. Some of the best examples of Saharian paleovalleys occur in the western margin of the basin in M'zab. Lacustrine deposits are buried below Holocene deposits in the centre of the basin.

Another large endoreic basin can be identified by the in the central part of the Western Sahara. This basin is probably composed of several sub-basins. Remarkable paleovalley examples occur in the northern margin of the basins. The rivers have their sources in the Algerian Atlas and crossed a plateau before reach the lowlands and, probably, the lacustrine systems. The dissected plateaus show a number of paleovalleys and, as in Oued Namous (Fig. 15) form a delta-like feature at the margin of the basin. Probably these exotic perennial rivers have been active several times during the Quaternary and, possibly, the Pliocene. Dating may be possible only by a detailed stratigraphy of the lacustrine sediments. Unfortunately, the area where these deposits crop out are currently largely unsafe

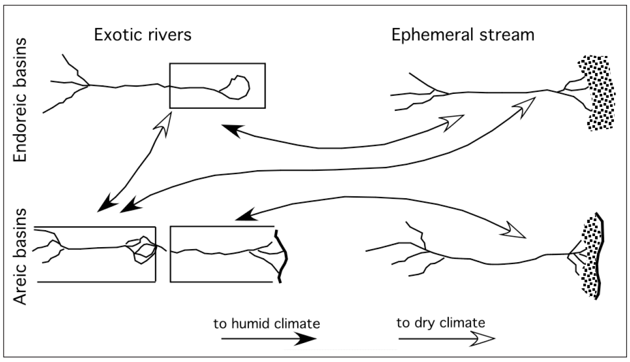
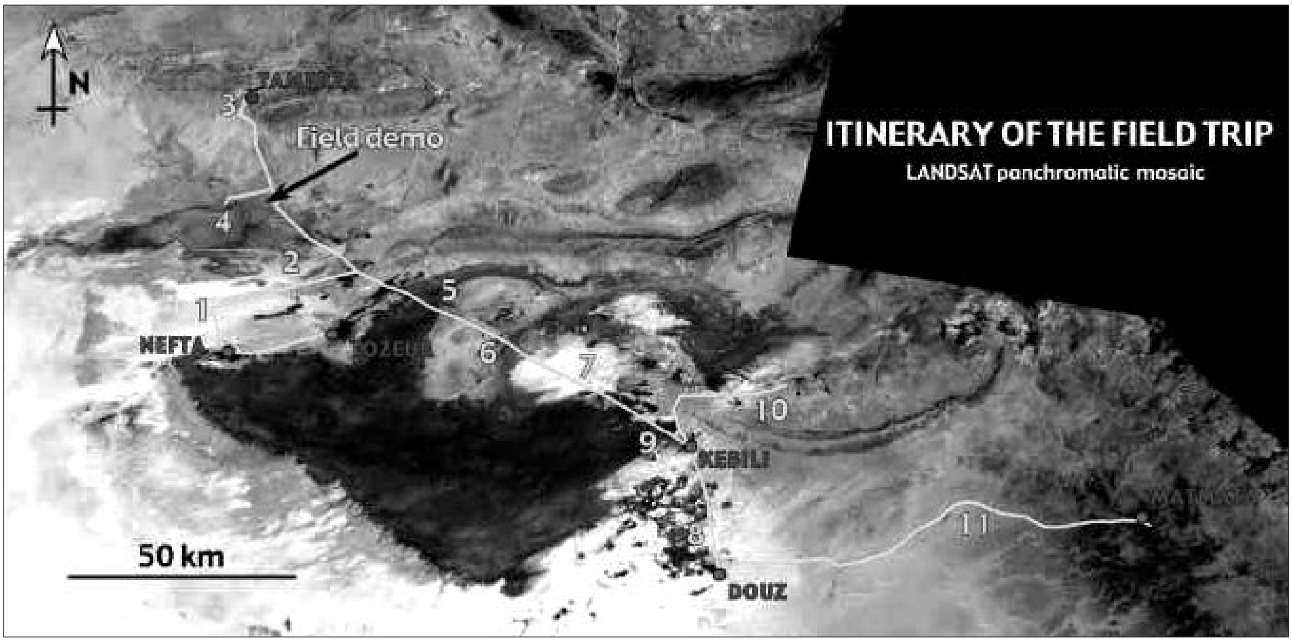


Fig. 17 - River type modifications according to climatic changes. The dark lines at the rivers termini show sea shorelines.

(Algeria and Northern Mali) and the fieldwork is impossible. It is clear, however, that these rivers were active during the Holocene pluvial period. The most updated date for this event in the area of study is from 9,000 to 5,000 years BP (Fig. 17).

Climatic changes toward drier climate will tend to form endoreic basins, splitting exotic rivers in two or more ephemeral streams. The paleovalleys are currently the floor of small ephemeral streams. Passage after 4,000 years BP to dryer conditions produced the change from exotic to ephemeral stream. The climatic changes play an important role in the rivers system type and in their changes along with the type of basins. In figure 17 it is shown several possible changes of river types in areic and endoreic drainage basins.



STOPS DESCRIPTION

The itinerary of the field trip will depend on the conditions of the tracks, the amount of water in the soil and sebkha surfaces, and the presence of wind carrying sand and dust (vent sable). Therefore the numbering of the stop does not represent the sequence of the stop and the itinerary. Some of them can be cancelled and other can be expanded according to the constrain of climate and environments. Even if we are staying in comfortable hotel and we will drive on air conditioned 4WD, we are still in the desert.

STOP 1

This stop will deals with the relathionships between sebkha and dune fields. We will stop in present days and ancient (Late Neogene and Quaternary) aeolian and sebkha deposits.

Locality: *Star Wars stage*
Subject: *Fossil and active eolian dunes, super bounding surfaces, eolian cross-bedding*
Discussion: *Eolian deposits on Mars, how to recognise old eolian deposits*

Eolian dunes form thick sequences of crossbedded sand and sandstones. At this stop it is possible to observe fossil dunes associated with modern active dunes (Fig.18). The fossil dunes rest as pinnacles of moderately cemented sand on a deflation surface that represents also the base of the active dunes (Figs 18, 19). The association of fossil and active dunes means that a change in climatic conditions de-activated the eolian deposition and the pore water started an early cementation of the sand. Then the climate setting returned favorable for the eolian sedimentation and the dune systems reactivated on top of the fossilised one. The boundary between the fossil dune deposits and the currently active dunes can be traced over a long distance and can be represented as a 3-dimensional surface bounding the two units. (Fig. 20) This type of surface is called "super bounding surface" and reflect changes chiefly in climate, wind regime, and humidity. Super bounding surfaces have been observed extensively in desert erg (sand seas) and are probably present on Mars. It is quite probable that the large part (if not all) of the eolian dunes is inactive at the present day. Therefore, it seems that now on Mars it is time for the formation of a superbounding surface. Probably deflation is prevailing. In the recent past,

Fig. 18 - Remnants of fossil dunes partially covered (to the right) by modern dunes. The pinnacles are not deformed and the inclination of the less dipping side reflects the dipping of the forests of the cross-stratification.

Fig. 19 - The pinnacles in the foreground are the fossilised dunes, whereas the active modern dunes can be seen in the background.

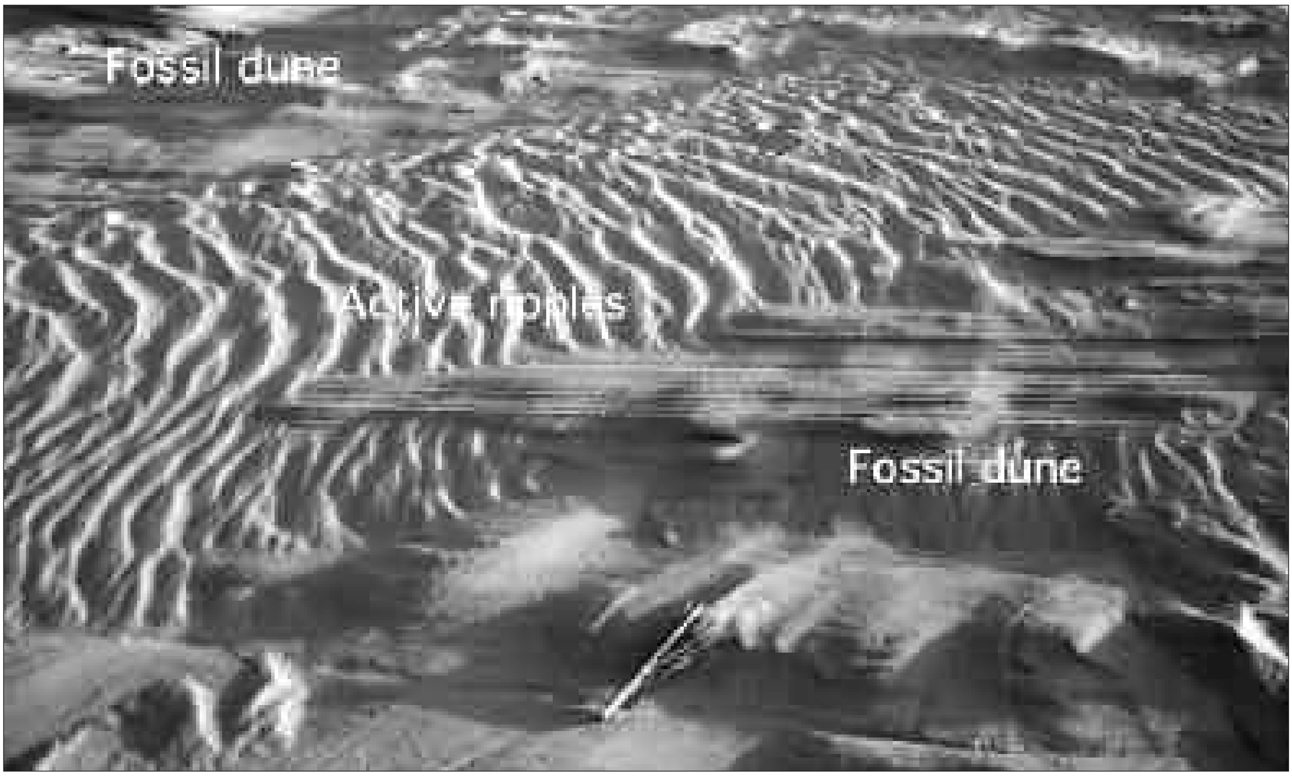


Fig. 20 - Details of the super-bounding surface between the fossil dune and the active eolian sand.

however, eolian sedimentation has been remarkably active accumulating dunes and sand seas. It is probable that this change in climatic conditions (or simply wind regime) occurred several times in the Martian environments, leaving fossilised dunes and super bounding surfaces exposed.

STOP 2

In this location we will investigate some fluvial patterns of a terminal fan.

Locality: *Oued el Melah terminal fan*
Subject: *Facies, surface and channels of the distal terminal fan*
Discussion: *Are terminal fans present on Mars? Comparison with alluvial fans, superficial deposits and facies*

Note: The visit to this stop will depend strongly on the condition of the surface that change frequently even within a week. No clear locations can be given because the itinerary on the surface of the chott will depend on the capacity of 4WD to run on the surface.
Terminal fans form when an ephemeral stream starts to loose water and tend to vanish downstream (Fig. 21). The loss of water is mainly due to the strong evaporation. Infiltration may play a secondary role. The stream channel with the decrease in discharge becomes subdivided in several distributary channels that become poorly defined downstream (Figs 22-24).

Fig. 21 - A small channel in the middle part of a terminal fan. The surface is covered by extensive patches of halite.

Oued el Melah is a good example of this kind of river terminus. This ephemeral stream is also used by a local mining company to collect the dump water from a phosphate mine. The channels gradually loose their shape and the flows in the distal part become unchanneled and spreading over a large portion of Chott el Gharsa (Fig. 24).

Fig. 22 - The terminal fan of Oued el Melah. Note the ephemeral stream (blue in this ASTER image) that diverges southward in several shallow water channels, then with an unchanneled surface into the chott (black). White indicates sand.

Fig. 23 - Distal area of the terminal fan, where channels almost disappeared. Note the broad and poorly defined swell, and the change in soil moisture and mud cracks shape. Geological hammer for scale.

Fig. 24 - At the margin of the chott the channels are entirely vanished and only sheet floods occur. The Land Rover track for scale.

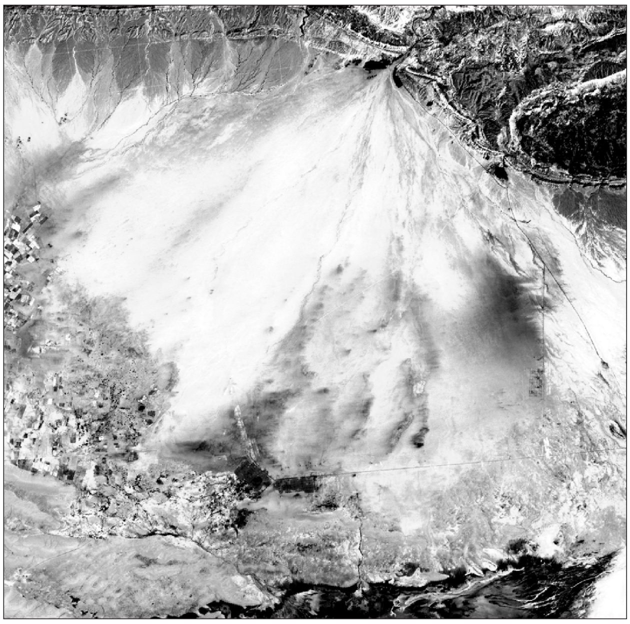


Fig. 25 - The alluvial fan of Oued Sendess remaining perched above the chott margin. A small alluvial fan (at a topographically lower position) rests at the margin of the chott. ASTER image. The base is 14 km wide; North is up.

STOP 3

Locality: *Road to Tamerza*

Subject: *Panorama of the alluvial fan of Oued Sendess*

Discussion: *paleovalleys and their significance for Mars*

The Oued passing across Tamerza debouches into the plain of the Chott el Gharsa with an impressive alluvial fan (Figs 25, 26). The valley is a possible example of a paleovalley formed during pluvial periods. The present day river is underfit and active only a few times per decade.

The best examples of these paleovalleys are in the western part (see Ori this guidebook) and in the south. The alluvial fan formed probably during a pluvial period and its toe remains at a higher elevation than the present surface of the chott.

The alluvial fan probably acted as a fan-delta (a fan debouching directly in a standing body of water) during pluvial periods and it is now underfit and rarely active. Smaller alluvial fans occur at the basin margins of the chott. Their streams dissect the older and larger "pluvial" fans. This is a situation that can be seen in other part of Chott el Gharsa and Chott el Jerid.

We will also investigate in the gorges the Cretaceous deposits of the southern border of the Atlasic Mountain Chain and then, visit the town of Tamerza.

Fig. 26 - Panorama from the stop 3. The channels of the alluvial fan (light strips in the foreground) radiate from the fan apex.

STOP 4

Sedimentary facies of the evaporitic deposits Late Neogene in age. They are probably similar to several sulphate deposits on Mars.

MGS and MRO have recognized several putative evaporitic lakes. They consist of basins (craters) containing layered deposits (Fig. 28). Several layers are made up of high albedo material that strongly resembles evaporitic sediments (Fig. 29).

Moreover, as we will see in the field trip, sebkha have a strong exobiological potential (see Barbieri, this guidebook).

Fig. 27 - Panoramic view of the test site. The upper part of the cliff of the mesas consists of evaporitic deposits. Can the rover cope with harsh environmental conditions? Can we really get data from these instruments? What about the quality of the observations compared with the one done by a geologist in the field?

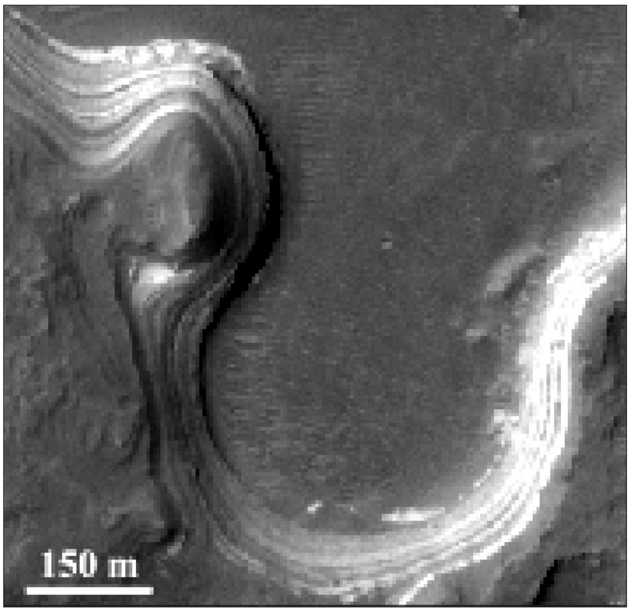


Fig. 28 - Putative evaporitc deposits in the Holden Crater on Mars (MOC image)
The sequence that drillers will hit selenitic gypsum interbedded with thin and rare limestone and clay. These deposits are exposed along the road cut and can be investigated before the drilling operations.

The rovers that will have the evaporitic deposits as targets will drive on a desertic surface that is formed by a mixture of the product of the weathering and mechanical fragmentation of the underlying deposits and wind blown sediments. This surface is not entirely similar to the surface of the Mars Pathfinder, but is the kind of terrain that may be encountered in several sedimentary environments including interior layered terrains, peri-glacial and glacial polar areas, and lacustrine basin.

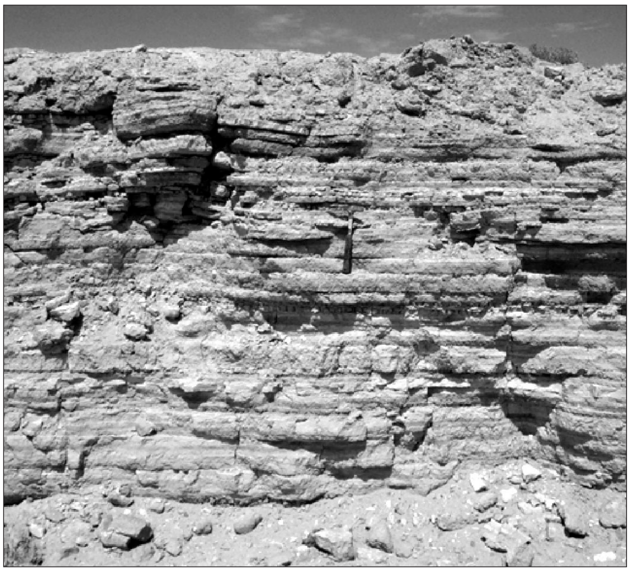


Fig. 29 - Road cut of the lacustrine sebkha deposits that will be tested by the drillers. Hammer for scale.

STOP 5

This stop is within the city of Toszeur and it is an optional if we cannot visit STOP 8. In this stop we will investigate shoreline deposits with bivalves (*Cerastoderma*) deposited during wetter period when the lake was permanent and deep.

Locality: *Tozeur*
Subject: *Shoreline deposits*
Discussion: *wet period*

STOP 6

We will stop several times along the road crossing Chott el Jerid from Tozeur to Kebili.

Locality: *Chott el Jerid floor*
Subject: *Polygonal surface and halite crust, salt deposits, microbial activity*
Discussion: *Salt formation and Mars analogues*

Warning: We will visit only the canal next to the road. Caution must be paid walking on the evaporitic crust: it rests on a fine-grained detrital unit that, if saturated by water, may collapse under your weight. Check the resistance of the crust before you walk on the crust. There is not personal danger, but shoes and clothes may sustain permanently damage.

Polygonal surfaces are the typical expression of dissection of mud flats in the evaporitic basins. These structures are associated with laminites consisting basically of clay and organic matter. The polygons are formed in a superficial layer of halite that has been deposited when the chott is full of water (Figs. 30, 31). The contribution of these superficial sedimentation to the evaporitic basin is smaller compared with the minerals concentration produced by interstitial water.

This mud flat facies includes extensive microbial mats (stromatolites). The bacterial colonies spread over the surface forming an organic lamina, whereas sediment is entrapped into the mat. Unfortunately, the very dry climatic conditions of the recent years have inhibited the formation and preservation of these mats (Fig. 32).

Fig. 30 - Polygons in the halitic superficial crust.

Fig. 31 - Close up of the surface. Note the crystals of halite producing the small scale roughness. Incipient cracking indicates the start of a polygon. The brownish colour is due to a veneer of dust. The base of the picture is 1 m wide.

Fig. 32 - A microbial mat recovered from the mud flat of Chott el Jerid during wet conditions in 1985. The mat is a mixture of organic material and detrital sediment.

Due to the dryness of the last few years the chott surface has been inactive and it is not possible to see salt crusts in formation. However, some artificial salina occur next the road that cross Chott el Jerid. Here it is possible to see the newly formed halite and, possible some microbial content (Fig. 33). The halite crusts have been formed directly at the surface from brine. If artificial ponds are preserved, it will be possible to see the halite crystal in formation. Evidence of microbial activity in the artificial pond is given by the reddish and green colour of some part of the crust. However, bacteria and bacterial remains have been observed in both the halite crust and the underlying organic-rich sediments.

The margin of the Chotts consists of extensive areas with a thin layer of wind-blown sand. Dunes do not form in these areas due to the little sand available. The sand cover displays small bed forms such as wind ripples, obstacle marks and incipient dome-shaped dunes. Similar environments (called sand sheets) occur extensively in desertic areas where the sand supply is too poor to form larger dune fields. They are also characteristic of the margins of the erg.

STOPS 7, 9 and 10

Locality: *Guettaia*
Subject: *Spring mounds*
Discussion: *Mounds on the surface of Mars*

The southestern margin of Chott el Jerid shows a large number of mounds produced by spring waters. These mounds may be several 10s meter high and a few 100s m wide. They consist of limestone and gypsum accumulated by the gushing waters and eolian sands. These features are rather prominent on the flat surface of chott (Fig. 34). Palm trees (alive and dead) usually rest on the tops and on the sides of the mounds (Fig. 35). Currently, all the mounds are dry due to the recent overexploitation of the aquifer and climatic conditions. Most of them are old features: some radiocarbon analyses date them back to more than 20,000 years BP. In this stop we will visit a mound

Fig. 33 - Pond next the road. It is possible to observe different stages in the halite formation. Crystals form on the water surface (the bright spot on the water). The reddish colour is due to microbial activity.

where the morphology is well preserved, whereas in the next stop the mound will be suitable for lithologic observations.

The mound is covered by a thick layer of eolian deposits (Fig. 36). They crop out near the top and show the typical stratification. In the higher part of the mound there are the walls of the houses of an abandoned village (Fig. 36). The village was probably abandoned about 700 years ago giving a minimum age for the mound. A depression in the mound indicates the location of the spring pool. From the pool departs a couple of channels that funnelled the overspilling water. Several mounds and mound-like features have been observed on Mars and some of them could be similar to the mounds of Chott el Jerid (Fig. 38). There are many possible causes of water releases from the subsurface (hydrothermal active, gas hydrate dissociation, liquefaction, etc), but the geomorphological results may be similar.

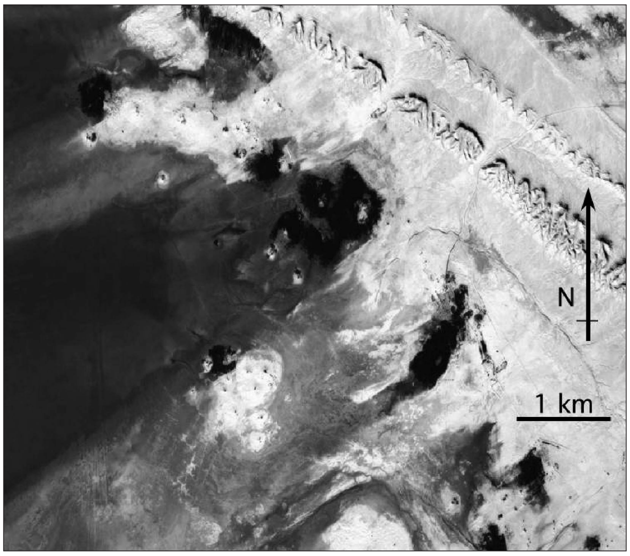


Fig. 34 - Spring mounds in the southeastern margin of Chott el Jerid. They occur isolated or in clusters

Fig. 36 - Eolian accumulation on the mound.

Fig. 35 - A mound profile in the sand sheet at the margin of the chott.

Fig. 37 - Ruins of the village abandoned about 700 years ago.

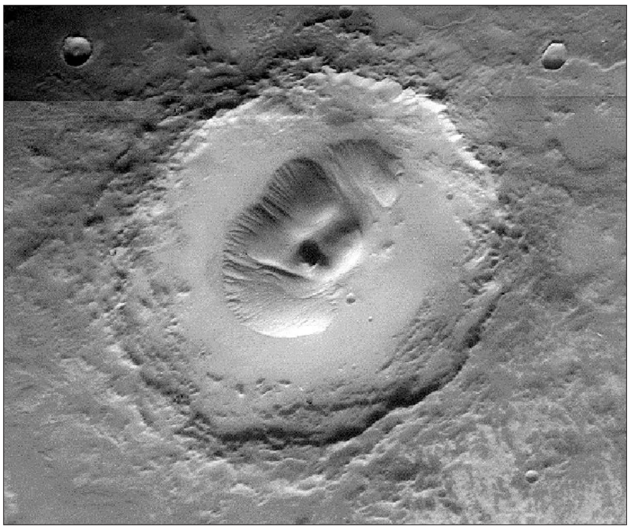


Fig. 38 - The central part of the Nicholson Crater (Mars) consists of an outsize bulge that may be produced by release of water and sediment from the subsurface.

Fig. 39 - The top of the mound near Fatnassa with the stratification dipping according to the slope.

Fig. 40 - Gypsum travertine encrusting biological (vegetal) remains

Locality: *Road to Fatnassa*
Subject: *Lithologies of the spring mounds*
Discussion: *Exobiology potential*

In this stop we will investigate the lithologies that form in the mounds (Fig. 39). The stratification follows the external shape dipping according to the slope. Two main lithologies are present in this mound (that are representative also for other deposits): microcrystalline gypsum, sulfate and carbonate travertine. In this mound gypsum is prevailing, but other mounds may be rich in calcareous deposits (Fig. 40).

The exobiological potential of spring mounds on Mars is great. Moreover, some of spring-like features on Earth include gas-induced seepage such as methane in cold vents. In this case chemosynthetic microbial life may flourish even in harsh conditions and atmosphere not suitable for life.

At the base of the mounds it is possible to find fossil shells of *Cardium* s.p. These marine or brackish water bivalve fossils have been observed in terraces around the chott (see next stop). Probably the age of this mound dates back to more than 20,000 years BP, and it is in agreement with the isotopic analysis of the water.

We will dissuss also some aeolian cross bedding and yardangs.

STOP 8

Locality: *Near Limaguess (Chott el Fejaj)*
Subject: *Terraces, shoreline deposits, calcrete*
Discussion*: Martian terraces, water on Mars, exobiological calcrete*

Terraces are present at places on the margin of the chott. They are prominent in the southeastern part of Chott el Jerid and in Chott el Fejaj (Fig. 41) and present on Mars (Fig. 42). The age of these terraces is still debated and various analyses range roughly between 100,000 to 9,000 years BP. Also the interpretation of these terraces is debated. Some authors believe they are due to a marine transgression that flooded basin of the chotts.

Other think they are due to brackish (lacustrine) water high level. We cannot provide any solution at this time. However, the terraces are a good analogue of similar features found in crater on Mars.

The terraces rest unconformambly on Cretaceous clay and older carbonate deposits and show a very flat surface at the top. The lithologies are mainly moderately sorted gravel and sand (Fig. 43). Gravels are well stratified and laterally continuous. Erosional surfaces are very rare. The stratification and lithology suggest that the terraces were the product of wave reworking in a beach environment. Brackish water fauna can be found. Alluvial conglomerates are

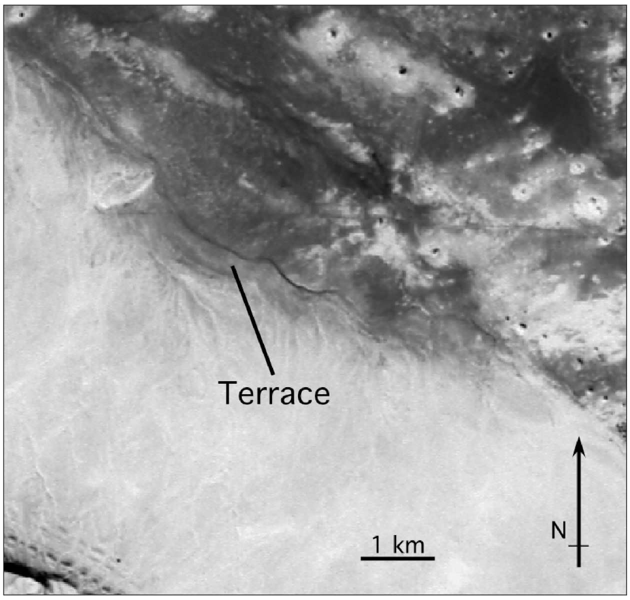


Fig. 41 - Corona image of the southern margin of Chott el Fejaj. A prominent terrace borders the plain of the chott, where a spring mound is extensively present (upper right corner).

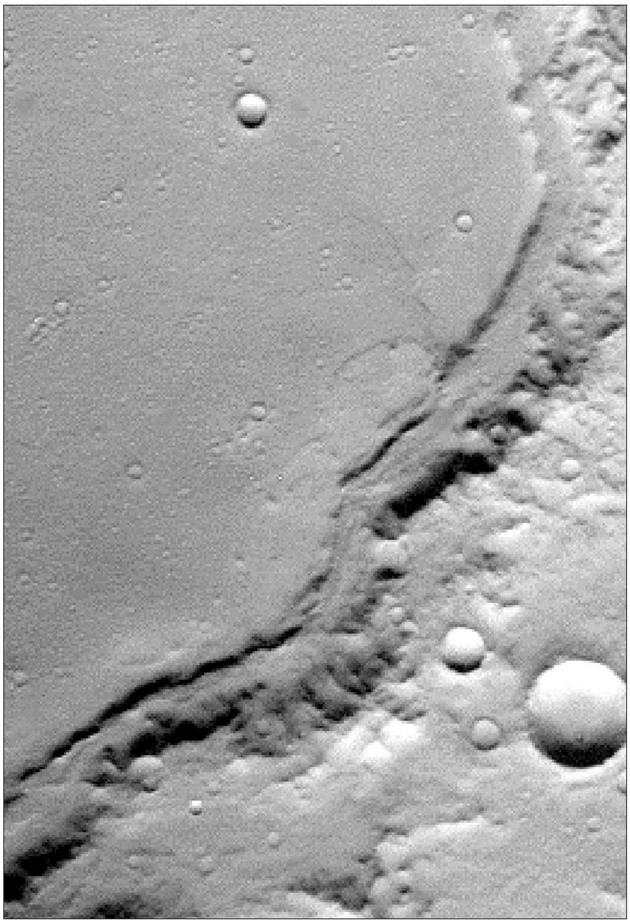


Fig. 42 - A terrace in a crater in Memnonia (Mars). Compare with the terrace in Figure 41. The deposits of this terrace, if produced by wave-reworking in a shoreline must not be much different from the terrestrial deposits.

extremely different. They are usually poorly sorted and stratification is very discontinuous. Moreover they are rich in erosional surfaces.

These terraces seem to be the analogue in term of morphology and lithology, of the putative lacustrine terraces observed on Mars. The top of the terraces shows a thick limestone unit. These limestone are calcrete: hard horizon mainly of calcium carbonate formed by the weathering in desert environments (even if poorly developed calcrete and caliche may be found in all climatic conditions). Calcrete have some exobiological potential because microbial activity may play some roles in their formation

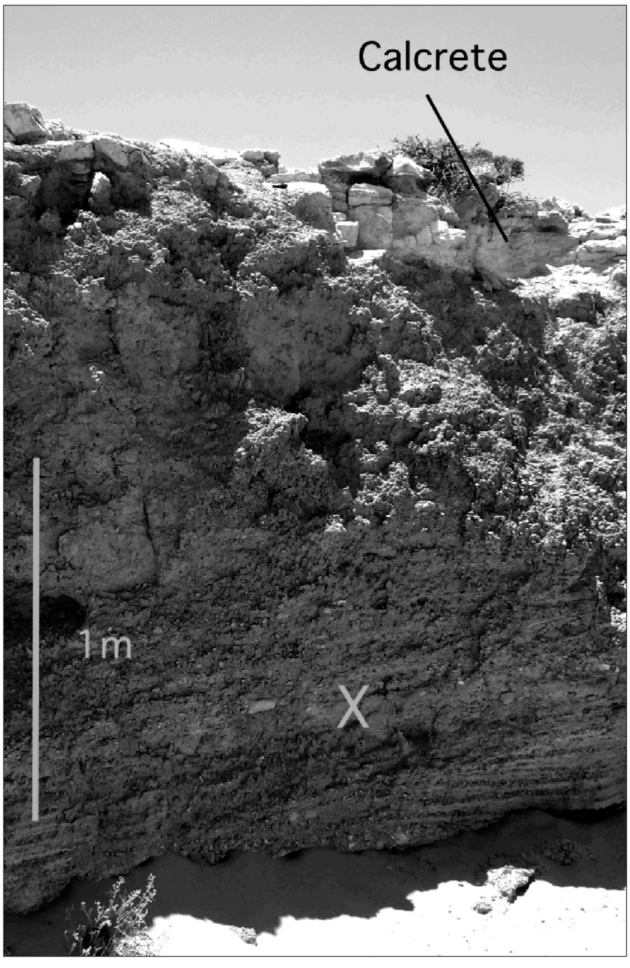


Fig. 43 - Well-stratified and moderately sorted gravels (X), indication of the wave action in the accumulation of these deposits

STOP 10

In the area of Zafrane sand sheets and ergs border the Chott forming an inhospitable environment. It is interesting to contrast the northern side of the Chott tectonically dominate and the south side. To the north, the Chott terminate abruptly against the rising foothills of the Atlas. To the south the boundary between the Chott and the Grand Erg Orientale consist of lowlands with sand sheets and a seasonally waterlogged area.

Locality: *Chott and Gran Erg Orientale*
Subject: *Different environments in the chott*
Discussion*: chott seasonality*

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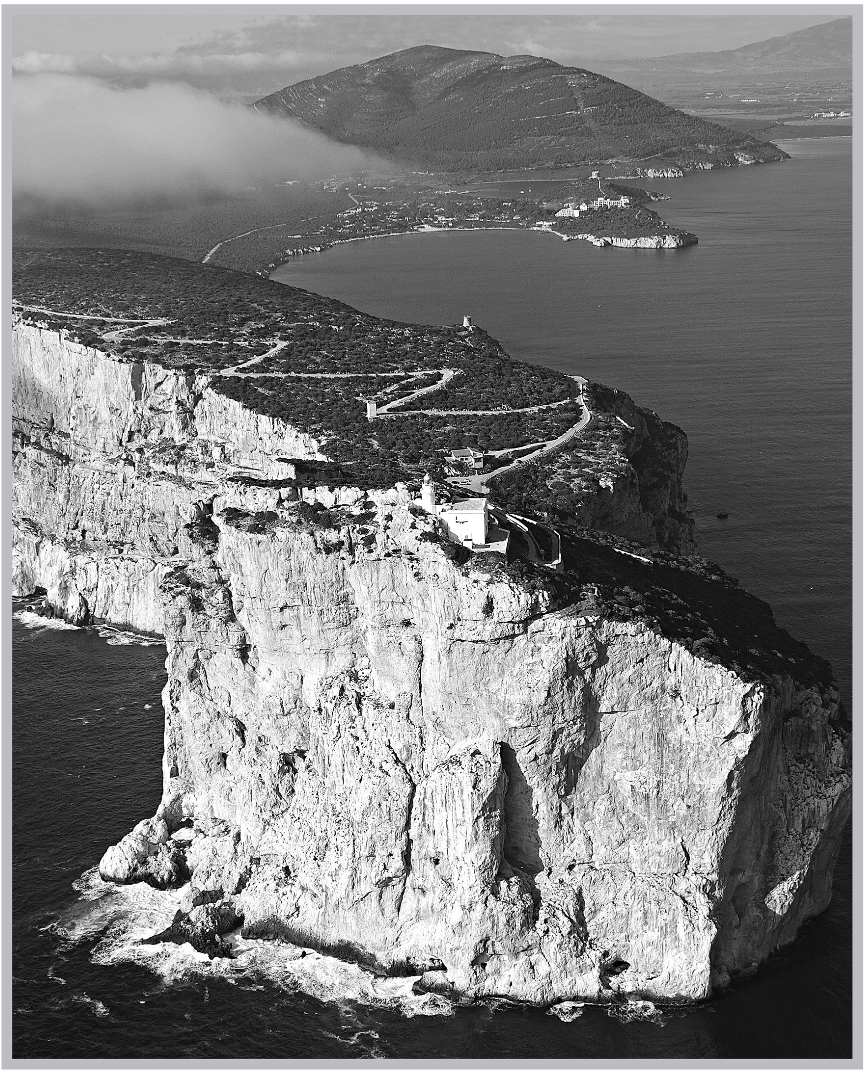

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