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WP/CEAUP/#2021/4

Western Sahara Natural Heritage (Tifariti and Bir Lahlu)



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Part 1 - The environmental factors: climate, geology, soils, landscape, water resources.

Part 2 – Nomadic pastoral system.

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Part 1 - The environmental factors: climate, geology, soils, landscape, water resources.

This is the 1st part of a full scientific overlook on W. Sahara Ecology. The 2nd and 3rd part will be published separately.

Photographs not taken by the authors are marked with the source



Introduction

Western Sahara is located in the great Sahara Desert, a vast arid region in north Africa that stretches from the Atlantic Ocean to the Red Sea, between latitudes 18° and 30° N. Conditions of aridity extend even across the Middle East to deserts and steppes of Central Asia. The southern and northern margins of the desert receive more precipitation and their vegetation cover is denser. Along the Atlantic on the coasts of Morocco, Western Sahara and Mauritania air humidity and hidden precipitations in the form of fog or dew also allow for greater vegetation cover with high levels of endemism. The surface of the Western Sahara Desert presents areas covered by dunes, rocky hamada plateaus, wavy stony reg surfaces associated with inselbergs. Also, very flat areas (*gaa*), and temporary river beds (wadi) or temporary smaller streams (*dei*, *chelkas*, *fadra*, ...) cut the surface of reg, where some water flows, sometimes torrentially, during sporadic precipitations. Unlike volcanic mountains found in central Sahara, such as Hoggar, Air, Tassili or Tibesti, in Western Sahara only low hills can be found, sometimes extending for several kilometers.

In the Sahara Desert, rains that fell in previous wet periods constitute vast underground reserves of fossil waters which emerge in some places forming oases. In Western Sahara these outcrops are rare or small, like Lamsayad oasis, next to wad Saguia el Hamra (Haidar, 2016) and the majority of the Saharawi population depends on wells for water supply. Sahara is a desert of zonal origin where the high atmospheric pressures resulting from the subsidence of tropical air devoid of humidity prevent the formation of rain most of the year. Along the Atlantic coast desert is also caused by the cold Canary Islands current, giving rise to the misty coastal desert climate (Demangeot, 2000).

Tifariti and Bir Lahlou, the studied areas in our work, are located in the northeast of Western Sahara, within the liberated Western Sahara area controlled by the Saharawi Arab Democratic Republic (Figure1). They are located in the region of Western Zemmur, characterized by flat sand and gravel peneplains cut by wadi and where some hills emerge. In these valleys, vegetation adapted to aridity develops, with predominance of the ecosystem dominated by *Acacia tortilis radiana* which allows the traditional grazing of



camels, sheep and goats, the main economic activity and population food resource. The basis of the population's diet is milk, meat (camel, goat, sheep) and wild plants' fruits or seeds since the area does not have conditions for agriculture due to the scarcity of rain and poverty in groundwater. Ethnobotanical knowledge of the vegetation is very important for the survival of the population and food security. Pastoral nomadism has been practised here since ancient times, but for this system to be sustainable it needs to be managed rationally as deserts are ecosystems in delicate ecological balance and nowadays under the effect of climate change. Also, plants are often eliminated by uncontrolled use of livestock and for firewood and the population of the desert has increased considerably during the last century.

According to Volpato and Puri (2014), the science of desert pastoralism “requires in-depth knowledge of camel physiology and ethology, of the local vegetation (species, abundance, distribution, ...) and of climatic patterns, places, paths, and distances”. The scarcity of data regarding the ecology of Western Sahara as well as the grazing system carried out by the Sahrawis motivated this work to be carried out. After spending many years in refugee camps, the Sahrawis now seek to reactivate the activities of their ancestors by returning to the pastoralist exploitation in the interior of Western Sahara, in the Liberated Zone (Volpato and Puri, 2014). The return to this activity must be done in a sustainable way, without further aggravation of desertification, and this work aims to collect as much data as possible from the important pastoral area of Tifariti and Bir Lahlou where a reduction in aridity caused by particular atmospheric circumstances allows the development of good pastures and the production of meat and milk, which are indispensable for the self-sufficiency of Saharawi people. The authors participated in the mission of the Centre for African Studies of Porto University (CEAUP), having remained in the areas referred above during the first week of February 2020, and which aimed to make the archaeological and environmental recognition of the region of Western Sahara located between Tifariti and the border with Algeria (Figures 1 and 2).



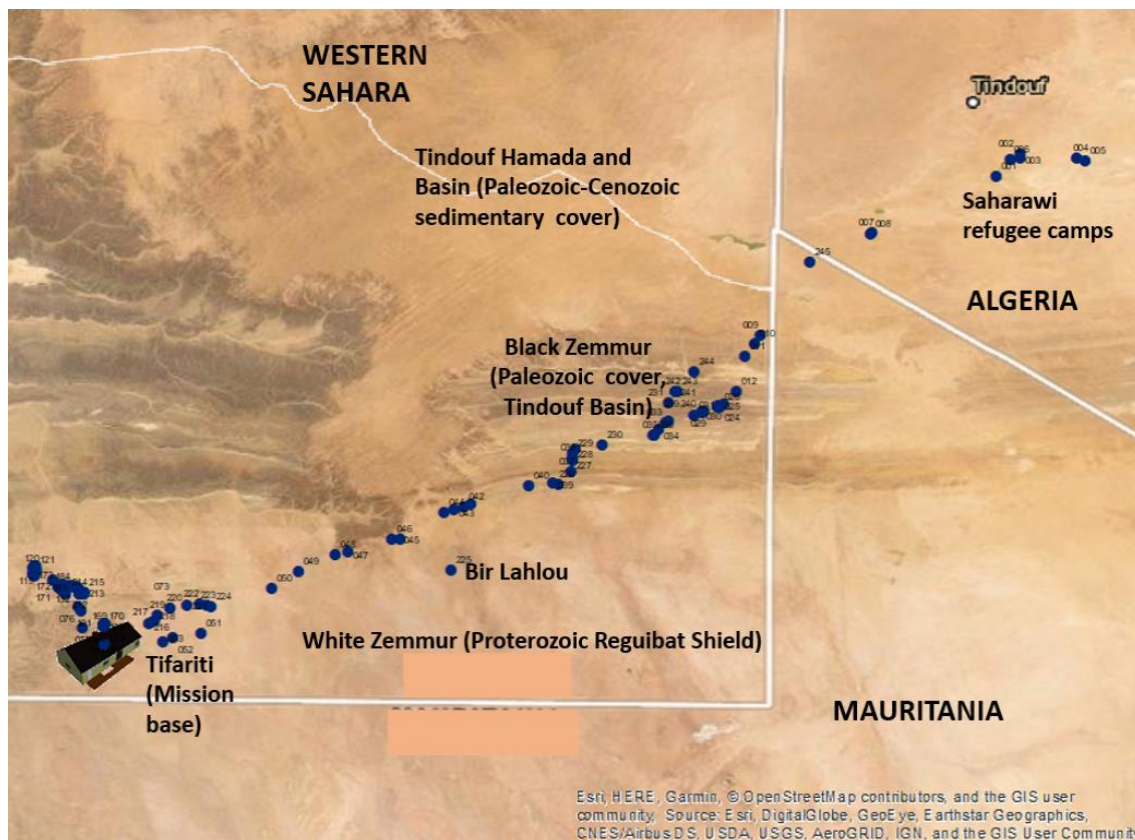


Figure 1. Route taken by the CEAUP mission (blue dots) and main geological zones of the studied territory.

During the time spent in the desert, characteristics of the environment, pastoral system and vegetation were studied. Contact with local population has been privileged, while collecting as much data as possible on the use of plant resources in order to increase the ethnobotanical knowledge of this region. It was found that despite the scarcity of water and all the difficulties that life in the desert entails, the conditions for using the resources in order to make pastoral system in the Western Sahara sustainable can be improved. As Ozenda (2004) says in his work on the vegetation of the Sahara, it is possible to increase the vegetation cover of the desert by planting trees in areas where some water is available. During our field research we identified several species of plants that in other parts are already cultivated to improve livestock and people's nutrition as well as to fight desertification.



Figure 2. Political map of Western Sahara according to MINURSO (United Nations Mission for the Referendum in Western Sahara).

1. Western Sahara climate: where the Atlantic meets the Sahara

The climate of Western Sahara is of hot desert type Bw, according to the Köppen classification. As in the whole of the Sahara, tropical high pressure descending air prevents rain from occurring almost all year round and forms a zonal desert (Damageon, 2000). These downward currents result from the functioning of Hadley cells, contributing to the rise of equatorial hot and humid air in the Intertropical Convergence Zone. This air, after losing its water vapor in the form of rain in the equatorial forests and savannas, descends on both sides of the Equator, forming the belt of deserts that follows the lines of the tropics. This descending air, which is no longer moist, prevents the formation of rain and creates dry winds in the Sahara, which further prevent the entry of drafts laden with moisture (Rognon, 1994). Almost any desert is caused by one sole reason, and the desert in Western Sahara is not an exception. Near the Saharawi coast the cold Canary Islands Current dries the atmosphere and creates a coastal desert. Cold currents cool the air and cause it to descend, preventing the formation of rain. The same process can be seen in southern Angola (Benguela Current) and in the coasts of Peru (Humboldt Current). These cold currents also create the optimal conditions for large populations of fish. In the coastal desert, cold sea air mixes with hot desert air and causes the condensation of water vapor present in the mixture. As a result, fog forms (Demangeot, 2000) and spreads over the land which attenuates arid conditions, creating a unique kind of vegetation that lives from this source of water. This wet air can reach places in the desertic Saharawi hinterland reducing aridity and promoting plant development (Figure 3), what Monod (1989) calls an attenuated desert. For this reason, Haidar (2016) divides Western Sahara into two climatic zones: the less hot and more humid coastal Atlantic region and the desertic interior.



Figure 3. The dry Saharawi peneplain of Western Zemmur, as seen from the top of Kedie Rkeiz hills (Tifariti). In the distance a line of trees marks the valley of a temporary river (wad), the main places where life triumphs over dryness in Western Sahara. Near the hill a *fadra*, or sandy gorge, where rain water also flows during storms and trees can grow. Coordinates: 26,341505 N; 10,749561 W.

This desert is also of the tropical type, unlike those found in Central Asia, which are cold deserts. The proximity of the Equator is associated with strong solar radiation during most of the year and temperatures are high. As a result, heat joins the absence of rain and water evaporation is intense, which makes the existence of all living beings very difficult. In the Western Sahara almost sterile hyperarid areas of mineral landscapes can be found (Figure 4) but also areas of attenuated desert (Rognon, 1994) with trees and shrubs (Figure 3). As Rognon also writes, “Sahara's originality is to present the greatest diversity of situations where the incessant struggle between aridity and life remains”. It is a struggle that is not static: in the wetter years, surprisingly, the vegetation progresses at times. As



well as in the rainy periods that throughout the geological ages filled the Sahara with life (Monod, 1989; Rognon, 1994).



Figure 4. An almost sterile reg in the north-western tip of Western Sahara over the Tindouf Bassin, near the Algerian border. Coordinates: 26,818007 N; 8,833554 W. Elevation: 428 m.

The arid climate of the Sahara is limited to the north by the Mediterranean rain zone of the Atlantic cyclones and to the south by the Intertropical Convergence Zone that originates the African Monsoon rains. These sources of humidity penetrate sporadically the space occupied by the desert, the first from the north and the second from the south. On the north bank of the Western Sahara, Mediterranean-type rains fall during the autumn and winter months, while on the south bank they fall during the warm season. Between these two banks the climate is clearly Saharan and rains fall here in a very irregular way at any time of the year and there may be several consecutive years without rain (Guinea, 1945). In this central area, after months or years without rain there may be a sudden





thunderstorm accompanied by torrential precipitation (Ozenda, 2004) for one or more days. When this happens, the desert surface is covered with rainwater (Figures 5 and 6) and dry river valleys become dangerous places for people and animals due to strong currents (Figure 7). For example, unusually heavy rains fell in the Western Sahara hinterland during the second half of September 2008. Rains originated in two storms which came from the Atlantic Ocean during 16-19 and 25-27 September 2008. The heaviest rain fell from Awsard in the south to Mehaires and Tifariti in the north. Even strong rains fell in the Saharawi refugees' camps in Tindouf, Algeria. Ecological conditions after heavy rains become favorable to desert locust breeding during several months on. Large swarms form and invade many regions. After heavy rains in September 2008, locust swarms formed, invading Algeria and Morocco and only after two years and \$400 million was the plague controlled. Also, in 1987 heavy rains in the same area of Western Sahara caused a devastating locust plague across East Africa, the Near East and southwest Asia (FAO/ Desert Locust Information Service).





Figure 5. Rainwater covering the reg, filling the valley of a wad (left) and accumulating in small land depressions during a storm, between Smara and Tifariti (17 September 2008). Photo courtesy of FAO/DLIS.



Figure 6. Rainwater covering the reg between Tifariti and Bir Lahlou. With a flat relief and few deep depressions, water does not accumulate and is lost through evaporation due to high



temperatures and strong hot winds. Relief shape further aggravates dryness in Western Sahara (17 September 2008). Photo courtesy of FAO/DLIS.



Figure 7. Rainwater filling the valley of a wad during heavy rains near Tifariti (17 September 2008). In these valleys, rainwater seeps into the soil and allows the existence of many trees and shrubs – the desert savanna - that feed people and animals and are the main places for water supply in the form of wells. Photo courtesy of FAO/DLIS.

In northern Western Sahara, mainly Mediterranean autumn and winter rains, coming from the North, fall mainly from September to December, as in Tifariti and Bir Lahlou (Figures 5 and 6). However, the Zemmur region has more developed vegetation due to higher humidity and to rains coming from the ocean, featuring a less extreme climate regime (Guinea, 1945). According to local information this is due to the geographic features of the Saguia el Hamra river valley and the gulf located on the coast north of Tarfaya, which leads to the entry of masses of moist air from the ocean. Upon encountering the high plateau of Tindouf Hamada, the Ergaiwa hills range and hills of Tifariti, humid air is



trapped and provides further development of vegetation, which allows for greater development of livestock. Haidar (2016) also considers that the higher areas of Western Sahara such as Zemmur are more humid and therefore provide more food for livestock. As can be seen from the meteorological stations closest to the studied area, Smara, in the area presently occupied by Morocco (Figure 8), the amount of average yearly precipitation is less than 100 mm which is a typical value of desert Bw climate. In this climate the amount of precipitation also varies a lot in different years, which worsens aridity and its effects on vegetation. Rain is often light and does not seep into the soil and many times high temperatures cause the rain to evaporate before reaching the plants. Only heavy rains are effective and these are the ones that accompany storms, sometimes falling violently and quickly a few times a year, but in total rarely exceeding 50 mm rainwater. The Sahrawis call this rain *bal*, a rain that soaks and wets the soil (Haidar, 2016). After heavy rains, Zemmur displays a savannah-like environment dominated by acacia-panicum vegetation, while flowering prairies may appear on reg flat gravel areas (Volpato *et al.*, 2017).

In winter, temperatures during the day can vary between 25 and 30 °C and at night drop below 0 °C. In summer they can reach 40-45 °C in the daytime in the shade and at night go down to 20 °C. Daily thermal amplitudes are high due to the scarcity of atmospheric humidity and there may be temperature differences between day and night that exceed 20 °C, especially in summer (Mulay, 2014). Close to the sea, the cold Canary Islands current causes a drop in temperatures which rarely exceed 25 °C in the coast. According to Guinea (1945) there is a coastal band, wider in the north and narrower in the south, subject to the influence of ocean humidity, and a transition band more or less parallel to this, towards the interior, where conditions are clearly arid. The valley of the Saguia el Hamra river (Figure 2) also marks a boundary between a desert area to the south and a steppe-type area to the north, where wells are surrounded by a vegetation of small oases (Guinea, 1945).

Predominance of flat or undulating terrains associated with the occurrence of permanent desert-centred high pressure have the effect of causing high intensity winds. These winds of hot and dry air - sirocco and harmattan - are loaded with particles of sand, silt, clay and





salt, further aggravating the effects of aridity on vegetation and leading to the formation of sandstorms.

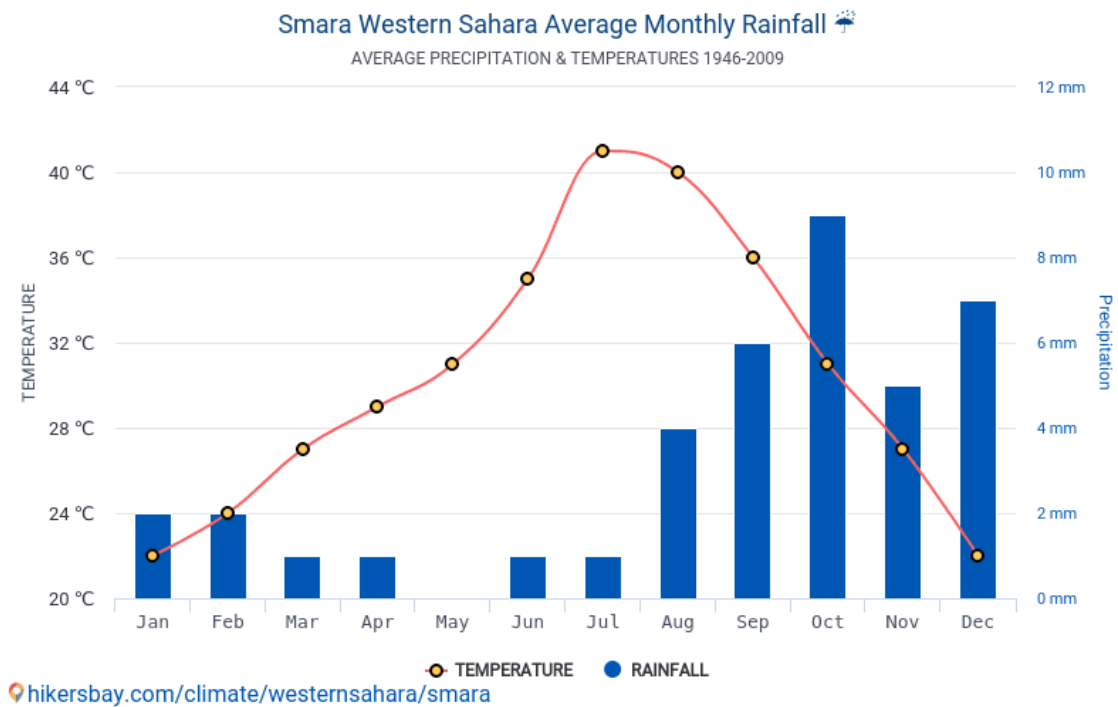


Figure 8. Climate graphic of Smara, Western Sahara. Average yearly precipitation: 39 mm.
Average yearly temperature: 30 °C.

2. Geology of Western Sahara: the sedimentary cover and the Reguibat Shield

In the Sahara Desert two basic geological units are distinguished: the Precambrian shields and the more recent sedimentary cover (Julivert, 2003). In the northeast Western Sahara, the Precambrian Reguibat Shield corresponds to the terrains of White Zemmur, and the sedimentary cover to the Black Zemmur and the Tindouf Basin and Hamada (Figure 1). In the rest of Western Sahara sedimentary cover constitutes mainly the El Aioun Basin. To the interior east, across the Mauritania border, the outcrop of the Archaic and Proterozoic granites of the Reguibat Shield extends from the south to the north-eastern of the Saharawi territory, from Tiris to Tifariti and Bir Lahlou (Mulay, 2014) (Figure 9). The Zemmur mountains would have been formed by the Hercynian wrinkle, during the upper Paleozoic era according to Haidar (2016). He also considers Zemmur to be the highlands of Western Sahara, along with Aulad Dleim and Erguibat. The highest point in Western Sahara is at Zemmur on Mount Agalmin Mallas, near Guelta Zemmur (688 m). Geologically Zemmur can be divided into two sub-areas: White Zemmur (*Zemour el-Abiodh*) and Black Zemmur (*Zemour el-Akhdhar*) (Julivert, 2003). Tifariti and Bir Lahlou zones are located in White Zemmur according to Mulay (2014) maps. Further north are Black Zemmur and the Tindouf Basin on the border with Morocco and Algeria. Geologically the Tindouf Basin is considered to belong to the northern region of Western Sahara, where it forms the Hamada (Haidar, 2016) (Figure 1).

The Reguibat Shield (also referred as Tiris Shield) limits two sedimentary basins, that of Taoudeeni to the south in Mauritania, and that of Tindouf, to the north (Figure 9). It is characterized by a monotonous and wavy plain relief, worn by erosion for millions of years, cut by wadi and punctuated by the presence of island hills or inselbergs, known in Arabic by the term *guelb* and also in the Western Sahara language, hassania Arabic, as *uteit*. On the surface sand dunes accumulate in some places. However, large areas of reg predominate, which results from the wind erosion of land surface (Figure 4).



In Tifariti and Bir Lahlou, the Reguibat Shield is composed of rocks from the Paleoproterozoic era, while in the southeast of Western Sahara the dorsal is made up of even older rocks, from the Archaic period (Figure 9). In this shield granitic rocks predominate, weathered over time and then removed during the Paleozoic, Mesozoic and wet periods of the Plio-Quaternary (Fabre, 2005). This very old rock emerges in vast areas and through the fractures that existed in it occurred at different times, and right in the Archaic period, eruptive emissions that originated the intrusions and outcrops of volcanic rocks that occur in several points of the shield. Its formation corresponds to the initial periods of the Earth's crust when the first land masses emerged over the primitive seas. One of these masses resulted in the West African Craton, of which the Reguibat Shield is a part. The successive erosive processes that have undergone transformed the surface of these rock masses into the peneplain we can observe today (Mulay, 2014) (Figures 3, 4 and 15).

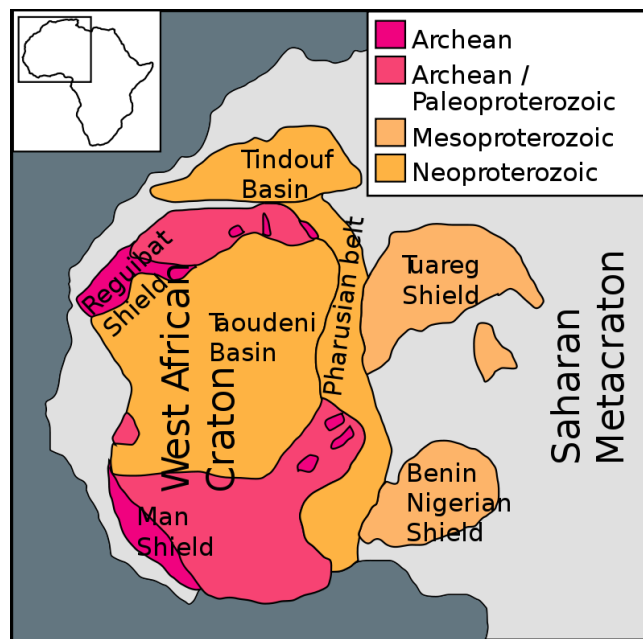


Figure 9. The Reguibat Shield and the Tindouf Basin (Source: Wikipedia)

Most of Western Sahara is occupied by the sedimentary cover, which constitutes most of the land that is now in the area occupied by Morocco. Also, the northeast of Western



Sahara is a continuity of the sedimentary cover of the Tindouf Basin in its southernmost part (Mulay, 2014) and this occupies part of the studied region, extending from the border with Algeria to the Saguia el Hamra valley (Figures 1, 10 and 11). The basin results from a depression formed in the North African shield by tectonic movements that led to a subsidence of the terrains. In the Ordovician period (Paleozoic era) it formed a gulf of the Sea of Tethys and later it became an inland sea in the Carbonic period. It is filled with a layer of marine sediments deposited from the Cambrian to the Carbonic, 8 km thick. This layer is in turn covered by continental sediments from Cretaceous and Pliocene that also form the Tindouf Hamada. The Paleozoic layers of the Tindouf Basin emerge north of Bir Lehlou forming the Black Zemmour (Figures 1, 11, 12 and 13) and contain a lot of iron, as for example in the region of Wad Slugiat (Julivert, 2004; Fabre, 2005).



Figure 10. Tindouf Basin in the northeast of Western Sahara is covered by very dry reg. However, in some thin valleys where water accumulates few acacias trees vegetate. The removal of small particles of sand and clay by the wind leaves small stones forming the reg. Coordinates: 26,818007 N; 8,833554 W. Elevation: 428 m.



Figure 11. The Saharawi sedimentary marine Paleozoic cover seen from the top of Mount Jerleixa, in the Black Zemmur (*Zemour el-Akhdhar*). Several Paleozoic marine fossils of coral reefs can be found at this point. At that times most of Sahara area was submerged and situated in the southern hemisphere. Coordinates 26,731479 N; 9,027239 W.



Figure 12. Rugose coral fossils from a Devonian period (419,2 to 358,9 million years ago, in Paleozoic Era) coral reef, found in Mount Jerleixa.



Figure 13. Tabulate coral fossils from a Devonian coral reef found in Mount Jerleixa. During middle Devonian, Zemmur was situated at the northern margin of Gondwana.



Figure 14. The Reguibat Shield outcrops around Tifariti, in wad Anannia, giving origin to granitic reg. In some depressions and riverbeds rainwater accumulates and vegetation develops. Coordinates: 26,288892 N; 10,659581W. Elevation: 420 m.



At the bottom of the Tindouf Basin the marine sediment strata of the Silurian period, 438 million years old (MA), accumulate on the oldest Proterozoic and Archeozoic crystalline rocks that continue on the Reguibat Shield, which limits the basin to south and outcrop in Tifariti and Bir Lahlou. Devonian (410 MA) and finally Carboniferous-Permian material were deposited on the Silurian sediments, which today occupy most of the Tindouf Basin and which end up burying themselves under the hamada, already in Saharawi territory (Figure 1). These sediments have abundant traces of marine animals from the Paleozoic period, such as algae, trilobites, foraminifera and brachiopods, as well as deposits of sandstone, limestone and iron that occurred in a marine environment (Fabre, 2005).

In Black Zemmur, on the southern edge of the Tindouf Basin and in Saharawi territory, there are sediments with fossils of coral from the Devonian period (Figures 1, 12 and 13). A second sedimentary cover of continental origin later accumulated on these sediments from the Mesozoic - when much of North Africa was again submerged - until today, which outcrops at the center of the basin and forms the Tindouf Hamada (Figure 1). No sedimentary traces of the Triassic and Jurassic are found either in the Tindouf Basin or throughout Western Sahara. But in Cretaceous (135 MA) the sea spreads again over large areas of Western Sahara and will only leave these regions at the beginning of the Tertiary (65 MA). The Reguibat Shield appears to have remained emerged (Fabre, 2005).

In the lower Mesozoic, namely in the Jurassic period, the separation of Africa from America caused intense volcanic activity in Western Sahara with a rise of basaltic magma (Fabre, 2005) likely to be the source of the rhyolite rock that covers much of the region in north eastern Saharawi region in Bir Lahlu and Tifariti (Mulay, 2014). In the Cenozoic a great differentiation between Western Sahara and Central Sahara occurred. The sea level rises 200 m, but penetrates little into Western Sahara. Siliceous, ferruginous and limestone continental crusts are formed in both Paleogene and Neogene. These are the large limestone slabs that cover the top of hamadas in northwest Africa.

In the Western Sahara territory the Hamada extends from Aidar to Zemmur and it is part of the Tindouf Basin. Its soils are very dry and permeable, poor in vegetation,





and rain is rare due to tropical high pressures and great distance from the sea (Figure 10). Despite its stony soil, and unlike the reg, the hamada has a rocky and elevated base (Haidar, 2016).



3. Saharawi landscape: a masterpiece of heat, wind and ancient rivers

The west of the Sahara Desert is an immense peneplain with altitudes less than 500 m diminishing smoothly until the Atlantic Ocean, although this does not happen in a regular way. In this peneplain there are only reliefs of small hills and *mesas* in contrast to the Central Sahara, where the mountainous elevations exceed 3000 m as in Tibesti. Great river valleys are practically non-existent and few reach the Atlantic Ocean, remaining dry most of the years. The hydrographic network is poorly developed due to the desert climate and the flat relief. It is formed by small and short valleys unable to join in larger ones and reach the sea (Rognon, 2004). Many of these valleys have no way out to sea and end up in inland lakes or disappear into sandy dunes, which also explains the high soils salts content. In the territory of Western Sahara, the valley of Wad Saguia el Hamra is the largest one, but remaining dry most of the years (Guinea, 1945). Its hydrographic basin begins north of Tifariti, in the northeast of the territory. These wide valleys, where water rarely flows, are a testament to the moist periods of the Sahara, which have been occurring for 20,000 years periods during the last 3 million years (Rognon, 1989). As a consequence of high atmospheric pressure centers that dominate the Sahara, everywhere the constant work of heat, wind and sand particles dragged along draw the landscape, originating the wind morphology largely dominant in the desert (Le Houérou, 1995). The landscape at Zemmur is characterized by gravel planes with occasional surface of sandstone and granite in its eastern and central parts and by higher relief and hilly terrain in the western part (Volpato et al, 2017).

The wind is of great importance in shaping the landscape of Western Sahara, carrying with it sand and clay of the regs, where big and small stones remain. The height reached by the abrasive action of the sand particles blown by the wind does not generally exceed 50 cm (Julivert, 2003), so the erosive attack is mainly done at the base of the rocks, which gives rise to mushroom-rocks (Figure 15).





Figure 15. Granitic mushroom-rock near Uteit Annania, Tifariti. Hard rocks in the middle of the reg resist erosion and create these mushroom forms. Here in Uteit Annania the hard granitic rock of the Reguibat Shield rises to surface creating these natural sculptures. Coordinates: 26,307858 N; 10, 679216 W.

Most of the territory in the north-eastern of Western Sahara is covered by reg (Figure 16), which the Sahrawis also call *aftut* or *salb* (Haidar, 2016). They are rocky areas, almost flat, between sand river valleys or at the top of the hills, formed by wind and torrential waters. Water but mainly wind drag the fine particles of sand, silt and clay, leaving a carpet of stones, slabs and rocks. Fine sediments under this layer are protected from erosion. In some areas of the reg, depressions called *graras* are formed, where good quality and impermeable soil are concentrated and used by people as agricultural land during rainy periods, as it is very fertile (Haidar, 2016). *Daias* or small freshwater lakes form at the center of them. However, in the places we visited, it was not possible to observe any *grara*, which are more common in the north of occupied area.



Rainwater has difficulty in infiltrating reg soil due to the stony cover, lack of depressions, as well as the clayey impermeable nature of the soil (Figures 20 and 21). The material of the reg is constituted of several rocks that originate the different colors and gauges and in Tifariti these rocks are mainly granite and rhyolite (Mulay, 2014). The depth of the reg soil varies between 20-40 cm and the layer of stones rests on top. There is some sand mixed with red clay enriched with iron oxides, sometimes consolidated in a crust and which includes debris in contact with the underlying rock.

According to information collected locally, when the reg occupies a rugged area and with chaos of larger stone blocks, these places are given in hassania the name of *karba* (Figure 16) and when the stones form mounds in the middle of flat areas of the reg these formations are called *arikim*.



Figure 16. Reg covering a rugged area (*karba*) next to Tifariti. Dark colours are also originated in Fe and Mn oxides that accumulate on the surface of stones. On the horizon line the acacia trees of wad Tifariti. Coordinates: 26,204612 N; 10,553265 W. Elevation: 477 m.



Reg surface is cut by water lines, some larger (*dei*), others smaller (*chelka*), through which the rainwater that does not seep into the reg flows into wadi (Figure 17). It presents a rigid and resistant constitution where cars move easily (Figure 45), in contrast to the beds of the wadi in which sands cars easily bog down (figure 24). In reg, water is at great depth and therefore constitutes areas with very little vegetation (Guinea, 1945) or animals (Figure 22), where even the acacias have difficulty in developing (Figure 27). Vegetation is sparse and mainly concentrated in reg depressions (Ozenda, 2004).

Regs are covered in many areas of Tifariti by dark stones of very different sizes which, according to Dresh (1961) and Mulay (2014), are rhyolite (Figures 18 and 19), a testimony of ancient volcanic eruptions that occurred in the territory of Western Sahara. Elsewhere in this region the reg emerges from the granite of the Reguibat Shield (Figure 20). The disaggregation of these granitic massifs operates from the diclases and fissures that have been installed in them since their formation from magma. In these fissures there is a clay alteration that ends up separating the blocks that disintegrate into loose stone. Continuously, the desert high temperatures peel these granite pebbles in the reg, in a process of thermoclastic desquamation that finally disintegrates them (Fabre, 2005) (Figure 19). Then, wind erosion drags the finer elements with it - which will be used as abrasion elements - leaving the gravel and pebbles of smaller or larger size that constitute the reg. Many of these finer particles made up of fragments of quartz, micas, clays and other crystals are blown away by the wind and will enrich the soils of savannas and tropical forests located further south (Coudé-Gaussen, 1988 cit. by Fabre, 2005). Dust from the desert can even fall on fields and cities in Europe and America.





Figure 17. A wad cuts the reg (on the left) near Bir Legacia. In the deep sandy soil of the wadi the desert savannah of *Acacia tortilis radiana* and *Panicum turgidum* develops. Rare but intense rainfalls allows the accumulation of water and the development of vegetation in these small valleys. A high concentration of acacia trees indicates a good place to dig a well and get water for camels. Coordinates: 26,351354 N; 10, 012912 W. Elevation: 492 m.

Stones rest on a clay surface consolidated with manganese and precipitated iron. Stones and rocks are covered with a lacquer formed by manganese and iron or even with clay minerals. The dark, almost black color comes from manganese and the red from the presence of iron (Julivert, 2003). The formation of this lacquer only occurs in desert climates and explains the dark color of large surfaces covered by reg stones. This lacquer is produced by the action of microorganisms and biochemical reactions that lead to the fixation of manganese and iron (Julivert, 2003) (Figure 19). Granitic regs in Tifariti, however, do not show this type of dark colors due to its origin in pink granite rock (Figure 20).





Figure 18. The reg in Tifariti. “Les regs monotones et plats ont jusqu’ici attiré beaucoup moins l’attention que les ergs qui frappent l’imagination” (Dresh, 1961). Coordinates: 26,163916 N; 10,565007 W. Elevation: 506 m.



Figure 19 Degradation of reg stones trough thermoclastic effect and showing the Fe and Mg patine (top left).



Figure 20. Granitic reg in Uteit Annania, Tifariti, made directly from granite of Proterozoic Reguibat Shield. Coordinates: 26.307239 N; 10.67952 W.



Figure 21. Below the reg surface clay may accumulate in large quantities. This soil has good quality but also blocks water infiltration from torrential rains preventing vegetation growth. Desert soils also show high salt concentrations. Salts are dragged by intense evaporation to the soil surface and by the absence of runoff of rainwater to sea. Coordinates: 26.310314 N, 10.682485 W.



Figure 22. Dhobb lizard (*Uromastix acanthinura*) has its habitat in the Western Sahara reg where it lives in burrows it builds. Coordinates: 27.214641 N; 8.592019 W.

In Western Sahara the soil of wadi valleys is formed by accumulation of sand and clay dragged from the reg (Figures 23 and 24) and where rainwater is concentrated. They are dry most of the years but during episodes of torrential rain a lot of water can run (Figure 7). The alluviums concentrated at the bottom of the valleys, being dry on the surface, store water in depth and allow the development of more dense vegetation and are the places in Western Sahara where animals and people find more food (Figures 25 and 26). Also next to the wadi or in their bed there are numerous wells with water, which also favors cattle raising in these places. The amount of water accumulated in the alluviums depends on its depth and extent, the feeding capacity of the wadi as well as the intersection by the wadi of aquifers of the sedimentary cover that supply it with water (Julivert, 2003).



Figure 23. Deep sandy soil in a wad near Sluguiat, the best soil for plants in Western Sahara., due to its ability to store water coming from the reg, in the deeper layers.



Figure 24. Deep sandy soil of a wad near Tifariti allows *Acacia tortilis* and other trees and shrubs to develop their long roots and provide a lot of food for livestock and wild animals. Coordinates: 26.356764 N; 10.748636 W.



Most of these dry valleys are occupied by desert savanna, a vegetation formation dominated by the association of the legume tree *Acacia tortilis radiana* with the perennial grass *Panicum turgidum*, which benefit here from the waters that flow from the reg and that are concentrated in its soil, what Ozenda (2004) classifies as “concentrated vegetation” (“végétation contractée”). In this process rainwater flows from the reg surface to the wadi valleys, consequently causing a high dryness in those and greater humidity in these ones.

In wadi beds, sand carried by wind and water accumulates in obstacles like trees and shrubs trunks, where vegetable debris are also trapped. These debris accumulation gives rise to mounds around trees or shrubs, called *fersig* (Fabre, 2005) or *ziras* (Haidar, 2016) (Figure 25). The great width of several wadi valleys, even in areas far within the territory of Western Sahara, bear witness to the rainy periods that have existed throughout its geological history (Rognon, 2005; Mulay, 2014; Haidar, 2016)) (Figures 26 and 28).



Figure 25. A *fersig* formed in the bed of a wadi with *fersig* trees (*Tamarix amplexicalis*). These mounds take their names from the *fersig* trees, one of the biggest trees that can be found in Western Sahara’s wadi. “I believe that the tree, in the process of burying itself and suffocating under the ever-growing mound, always grows upwards to keep the crown out of the sediment. If



there are mounds close to each other and of the same size, it is because they are made up of *Tamarix* of the same age” (Theodore Monod, 1964 cit. by Fabre, 1995). Ifersig trees are salt loving plants (halofitic) very well adapted to dryness and could be planted in river beds and banks allowing more food for cattle and wood for fire. Coordinates: 26.353996 N, 10.743366 W.



Figure 26. In wadi beds, like this one near Tifariti, talha trees (*Acacia tortilis*), atil (*Maerua crassifolia*) or Ifersig (*Tamarix amplexicalis*) trees can develop very well and give shelter to livestock, several species of birds and other small animals.



Figure 27. During rains, small streams (*chelka* or *shalja*) like this one drain water with sediments from the *reg* to *dei* which join wadi (in the horizon line). Sediments and water also accumulate in these water lines and some vegetation develops. However, trees like *talha* (*Acacia tortilis*) (in the photo) remain small due to the lack of enough water. Coordinates: 26.310314 N, 10.682485 W.



Figure 28. The large valley of wad Tifariti. A testimony of the great rivers that flowed in the Sahara thousands of years ago. Coordinates: 26.292192 N; 10.617876 W. Elevation: 427 m.

Western Sahara, and particularly Tifariti, is a region of *inselbergs* (*uteit* in Arabic hassania). Here in Tifariti they are formed of pink granite and surrounded by chaos of blocks that come off them (Figures 29 and 30). Apparently, it is the Aftout or Traourit granite referred to by Fabre (2005) for Western Sahara (Figure 31). They are Proterozoic rocks with more than 1.6 billion years covering this area and being part of the Reguibat Shield. *Inselbergs* are isolated hills, with rugged walls, which appear as an island in the middle of the Saharawi peneplains. They represent relics of hard rocks saved from wind and water erosion during thousands of years and modelled by the tropical desert climate. Diaclasses are formed, with flaking and granular disintegration, producing large loose crystals that spread throughout the reg (Figure 20) (Dresh, 1961). Despite successive applanations, these Precambrian reliefs still appear well preserved today (Fabre, 2005).



Figure 29. Granitic *inselberg* near Tifariti (Uteit Annania) surrounded by granitic reg with water lines where sediments accumulate and some plants grow. Coordinates: 26.307239 N, 10.67952 W. Elevation: 429 m.



Figure 30. Inselbergs near the wad Tifariti. On the horizon line there is a *dehar*, a low-lying sandstone plateau. Coordinates: 26.289657 N, 10.610439 W. Elevation: 430 m.



Figure 31. Beautiful pink granite forming an *Inselberg* in Uteit Annania, Tifariti.

Garas are mounds formed by compact layers of limestone or sandstone and others of looser sediments such as clays. Wind and rainwater drag sediments from the top and leave a layer of limestone or sandstone uncovered. This compact layer stops the erosion of the underlying and a “table” is formed (Fabre, 2005). They are very common in the Tifariti landscape (Figure 32). In contrast to *gara* type mounds, in which the wind and water dragged the ridges made of loose materials, or the *uteit* which are inselbergs, *dehar* are hills prolonged for several kilometers (Figure 30).



Figure 32. *Gara* (plural, *gour*) landscape as seen from Uteit Annania. This is a typical landscape of Zemmur and all Western Sahara. Coordinates: 26.307239 N,10.67952 W. Elevation: 429 m.

Fadra (plural, *afdar*) are found at the base of the hills around Tifariti and are discharge areas where infiltration of rainwater in depth and deposition of debris, mainly sand, dragged by the running water from the top and the hillsides occur (Figures 34 and 35). These are gorges where torrential rain also forms temporary streams. In Sahara these sites allow vegetation to develop similarly to what occurs in the wadi (Rognon, 1994) and acacias can reach a large size, more than 7 m high according to our measurements. Also, atil trees (*Maerua crassifolia*) develop well in this environment. For this reason, they are places sought by the herds of camels that find good pastures here, provided with more biodiversity (Figure 33). Soils are similar to the wadi ones, sandy and with some clay in depth (Figure 36).



In Tifariti sandstone hills, vegetation finds water in crevices where plant roots grow. Rainwater and dew infiltrates rock crevices contributing also to their chemical degradation.

This vegetation may reach good development despite the lack of water on rock surface and lack of soil (Figures 37 and 38).



Figure 33. At Fadra Erkeiz an *Oenanthe monacha* bird (*bubucher* in hassania) is attracted by humans. According to WWF this bird is regarded as endemic to the Sahara ecoregion. Coordinates: 26.356764 N; 10.748636 W.



Figure 34. Despite being a few hundred meters high, rainwater and sediments that fall from the Erkeiez hills get in the valleys and allow the development of vegetation in these *fadra*. Protected from camel grazing, plant species can be found in these hills that are not seen in reg or wadi. Coordinates: 26.364716 N, 10.748645 W. Elevation: 426 m.



Figure 35. The Erkeiez Hills seen from the *fadra* (Fadrat el Erkeiez) where desert savannah of *Acacia tortilis*, *Maerua crassifolia* trees, and *Panicum turgidum* perennial grass develops providing good pastures for camels.



Figure 36. Deep sandy soil in a *fadra* or dejection cone at the base of Erkeiez Hills allows trees to reach large dimensions and good pasture production.



Figure 37. In the Erkeiez Hills rare species of plants can be found in the small caves and crevices formed in the sedimentary rock. Some of these caves also served as a shelter for human beings for many thousands of years and wall paintings can be found there. Apparently, sedimentary rock found in these hills is arkose (Dorsch ,1961), a type of sandstone. Coordinates: 26.343509 N; 10.749449 W.



Figure 38. Zmar (*Barleria schmittii* Benoist) (left) and eydari (*Rhus tripartita* (Ucria) Grande) (right) growing in the crevices of Erkeiez Hills. Camels can eat their leaves but here they are protected by the hill slope and become larger than in the planes.

4. Water Resources in Tifariti and Bir Lahlou: how to live with few salty water

As elsewhere in the Sahara Desert there are no normal hydrographic networks in the great peneplains of Western Sahara as they are found in other climatic areas. The region is mainly endoreic and rainwater accumulates at the bottom of valleys or in small lakes because the annual amount of rain does not allow the formation of rivers. High temperatures also cause intense evaporation and prevent the formation of rivers (Rougnon, 1989, Julivert, 2003). However, even in late Pleistocene (2,5 million to 11,000 years ago) there were rivers in Western Sahara that carried water into the sea while others drained into the interior of the continent forming large lakes. Although this hydrographic network remains presently dry most of the years, the Saharawi oral tradition still divides the hills of Zemmur into Zemmur At-tallas and Zemmur Alhabas (Haidar, 2016) (Figure 39). The first leads the water over the sea to the Saguia el Hamra wad basin (exorreic) while the second drains inland (endorreic). Tifariti is located between these two areas. However, near Tifariti wadi are born that feed the Saguia el Hamra wad basin during periods of torrential rain. According to Haidar, (2016) Aluad Labiadh and Udéi Attarshán originate near Tifariti and flow into the Erni wad, a tributary of the Saguia el Hamra wad. But to the south of Tifariti, many small watercourses run southwards towards the interior. Next to Bir Lahlou is wad Remz and wad El Mendaab, which are also endoreic wadi whose water flows into the Mauritania hinterland.

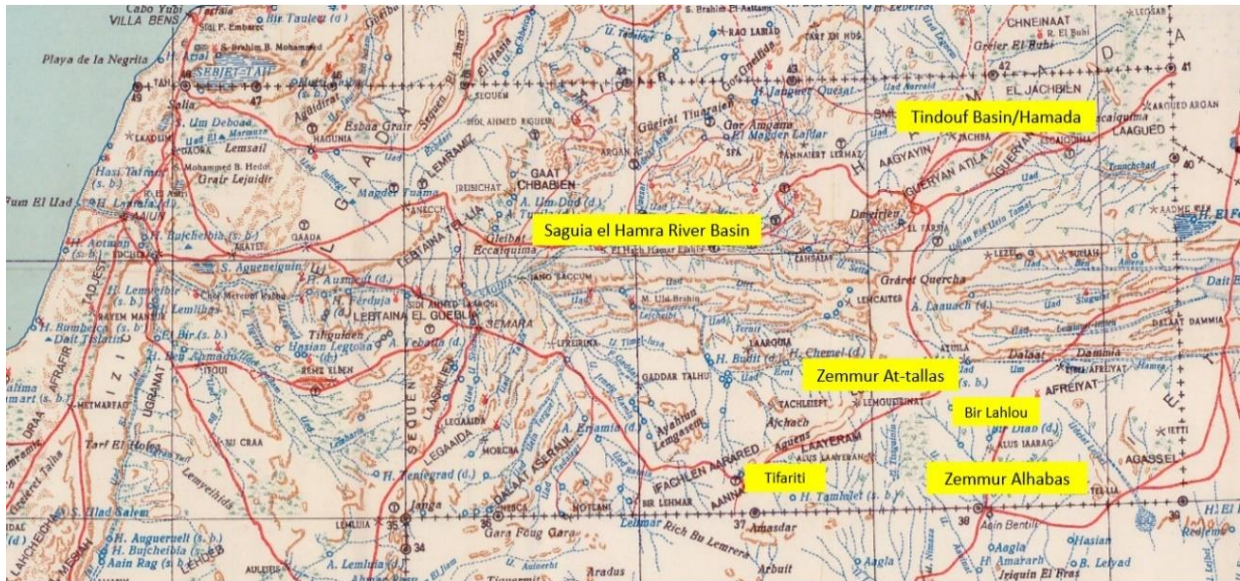


Figure 39. Saguia el Hamra wad basin and the situation of Tifariti and Bir Lahlou. Source: Mapa de las Provincias de Ifni y Sahara y Archipiélago de Canarias.

Western Zemmur, where Tifariti and Bir Lahlou are located, is drained by occasionally active water channels that flow north and west into the Saguia el-Hamra valley basin (Volpato *et al.*, 2017). This is the most important river in Western Sahara which however can remain dry for several years. When it rains torrentially in the Hamada and Zemmur the Saguia el Hamra wad can contain a lot of water (Haidar, 2016).

In all of this area, groundwater is of paramount importance to the population and can be found at the bottom of wadi and in aquifers installed under sedimentary cover. However, many wells and springs have salt water that is not drinkable by people due to the high salt content, but livestock can drink (Haidar, 2016). Western Zemmur is located on the granitic Precambrian outcrops of the Reguibat Shield, on which rest more recent thin sedimentary layers where little water is found. This shield is formed by shales, gneisses, quartzites and mainly granites (Fabre, 1995). These rocks occupy large areas here, often only covered by a weak layer of sand or reg and are not conducive to the accumulation of water. When it rains some water infiltrates the granite diaclasses but it is not easy to find aquifers with water in significant quantities. In Western Sahara there are also many seismic faults where water also infiltrates, which draws water from the streams that are



formed during storms. Another factor that prevents infiltration is the very flat relief and clay soil of reg, which causes the formation of *gaa*, superficial flat ponds of rainwater accumulation and where the loss of water through evaporation is intense (Mulay, 2014) (Figure 40).



Figure 40. In the flat relief of northern Western Sahara, here next wad Sluguiat and the Mauritania border, rainwater accumulates in basins of clay reg – the *gaa* - where due to high temperatures it evaporates quickly, aggravating dryness. *Acacia tortilis* trees may live with this scarce water and they could be planted in these basins in order to increase water infiltration into the soil. Coordinates: 26.811046 N, 8.847996 W. Elevation: 424 m.

That is why in this region in the Western Sahara hinterland located on the Reguibat Shield (Figure 45) water is scarce and wadi alluvial valleys constitute the main reservoirs of water available to the inhabitants, where most wells are dug (Figure 42). Locations with good acacia development are often chosen, a good sign of groundwater accumulation





(Rougnon, 1989). In some places, the bed of wadi cut aquifers installed in the sedimentary cover and can provide water in a more permanent way (Julivert, 2003). In depressions torrential rainwater also accumulates during storms and in these places population also digs wells that remain with water for a long time (Haidar, 2016).

Large Saharan sedimentary basins where fossil water accumulates and outcrops in some places, allowing water pumping for irrigation in agriculture, are non-existent here, unlike the coastal zone of Western Sahara where sedimentary cover predominates. At the northeast end of the Sahrawi territory, located north of Tifariti and Bir Lehlou, which covers the south of the Tindouf Basin, the chances of finding water are greater. However, contrary to what happens in central Tindouf Basin (Figure 41), these lands are made up of Paleozoic sedimentary layers in which the exploitation of aquifers is more difficult (Julivert, 2003).



Figure 41. Hortus of Saharawi refugee camp of Smara (Tindouf, Algeria). In this area of Tindouf Basin underground water pumped from a well allows several crops like broad beans and carrots



and greater growth of talha trees (*Acacia tortilis*). Acacias are legumes that fix nitrogen and their leaves and fruits improve soil fertility above canopy. The underground of the Tindouf Basin accumulates water and this basin forms also part of northern Western Sahara. But farming can be affected by high salt concentrations in soil, like here in the refugee camp of Smara, where farmers had to bring less salty soil by truck from another place.

In some places, structures called *motfia* are found. They are water deposits dug in the rock and covered up, at the base of a rocky slope that fills it with rainwater, serving for the watering of camels (Figure 43). Greenhouses can be found in Tifariti at the bottom of the valleys where water can be pumped for irrigation. Greenhouses in this part of the desert allow the production of vegetables protected from frost, sandstorms and swarms of locusts. In these cases, the use of drip irrigation is an efficient way to use the little water available (Figure 44). Nomadic animal production is the main agricultural activity in the Western Sahara hinterland and water is the main limiting factor for the development of livestock production. Groundwater is pumped for the animals (Figure 46), although in many places its concentration in salts exceeds the internationally recommended maximum limits (Mullay, 2004).

Soil surface when protected with vegetation cover, particularly trees, causes an increase of water infiltration reducing water loss by evaporation. Due to political, sociological and cultural reasons tree plantations in desertic areas are rare although possible (Ozenda, 2004). In arid zones of industrialized or developing countries desertification has increased during the last century due to overgrazing and the cut of trees for fuel, and Western Sahara is not an exception (Figure 47). Large areas in Tifariti and Bir Lahlou covered by *Acacia tortilis* and other trees (*Tamarix* spp., *Maerua crassifolia*, *Acacia ehrenbergiana*) could be improved planting more trees, in order to increase its surface and so increase underground water. As in other parts of the Sahara, water resources in Tifariti can hardly now support large population. But we can also be more optimistic and hope that an increase in vegetation cover around water points and villages (Ozenda, 2004) will lead to better living conditions for the populations.





Figure 42. A well in Bir Legacia. Bir is the hassanya word for deep well. Water was at this moment at 30 m deep. Nearby a wad can be found with dense *Acacia tortilis* trees cover. Coordinates: 26,691212 N; 9,243167 W. Elevation: 429 m.



Figure 43. A *motfia* near Tifariti, excavated directly in the granite of the Reguibat Shield, where camels were waiting for some water. This is a runoff water collection point. During rains a water stream is formed from the top of the hill and the *motfia* is filled. Coordinates: 26.241427 N, 10.617414 W. Elevation: 456 m.



Figure 44. In some places, like here in Tifariti, water is pumped from subsoil of dry river bed to irrigate tomatoes and other crops in greenhouses. Greenhouses protect crops from the harsh sandy hot winds from the desert, the cold nights and also from crickets' invasion.



Figure 45. In many places around Tifariti soil is absent and the granitic stone of the Reguibat Shield rises to surface. In these areas subsoil is practically devoid of water. Coordinates: 26.241427 N, 10.617414 W. Elevation: 456 m.



Figure 46. Water for camels is pumped from underground in wells situated on dry river beds, like here in Wad Tifariti. Despite high concentration of salts in the water these wells are absolutely essential to the existence of livestock and human beings in this part of the desert where oases do not exist. Coordinates: 26.286473 N, 10.611036 W. Elevation: 423 m.



Figure 47. Cutting talha (*Acacia tortilis*) wood for the fuel of our lunch near wad Annania (Tifariti). Weren't we supposed to plant a few more acacias?

5. Conclusions

For thousands of years the people of Western Sahara have adapted to life in a hostile environment marked by an arid climate of light and irregular rains and where high temperatures and wind during most of the year cause intense evapotranspiration. That is why agriculture is almost impossible in this region and the populations depend on pastoral nomadism. We studied the area of Tifariti and Bir Lahlou, in Western Zemmur, where geological conditions are particularly unfavorable to the accumulation of water in the subsoil or to the outcrop of aquifers with the formation of oases, as it is located on the granite Reguibat Shield. Land topography also does not promote the accumulation of surface water due to the absence of large deep depressions or valleys where rainwater accumulates. Endorreic conditions may also lead to salt accumulation in water, making it unsuitable for human consumption. The studied region is covered mainly by reg, which is formed by soils that do not lead to the accumulation of torrential rainwater which is typical of the Saharan climate. It is the wadi that cross the reg that capture the waters and concentrate them in their subsoil, allowing the existence of ecosystems of greater productivity and biodiversity based on the desert savannah constituted by association of *Acacia tortilis* trees with the perennial grass *Panicum turgidum*. For this reason, wells are excavated in wadi and allow people to have water to keep the cattle, but this is always in little quantity and constitutes the main limiting ecological factor to the development of this region. In Tifariti and Bir Lahlou, there is no substitution of trees that are cut for firewood or eliminated in the feeding of cattle. Like in other arid areas of the world, human beings have also worsened the conditions of aridity here for centuries.

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