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SANDY SOILS IN SILTY LOESS: THE LOESS SYSTEM OF MATMATA (TUNISIA)

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ABSTRACT

The purpose of this study is to better understand the system of Quaternary loess-palaeosol sequences (LPS) of the Matmata region in southern Tunisia. Results from a combination of predominantly classical methods (grain size and mineral analysis, $CaCO_3$-content estimation, environmental magnetism) indicate strong soil formation phases during which the conditions of sedimentation changed drastically. The heavy mineral analysis underlines northwest, west

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and southwest provenances of the loessic material. Furthermore, we discuss the process of soil formation in LPS and explain why these soils are very sandy in comparison to the loess units. During phases of soil formation, the northwestern sediment transport path was blocked while sandy material was blown dominantly from the southwestern Grand Erg. Thereto we present a conceptual model including a provenance analysis of the loessic material that support and improve earlier results of Coudé-Gaussen and collaborators.

RÉSUMÉ

DES SOLS SABLEUX DANS DU LOESS LIMONEUX : LE SYSTÈME LOESSIQUE DE MATMATA (TUNISIE)

Dans cette étude, nous présentons un modèle conceptuel pour une meilleure compréhension du système de séquences de loess paléosol (LPS) dans la région de Matmata situé dans le sud de la Tunisie. Les résultats d‘une combinaison de méthodes principalement classiques (analyse granulométrique, analyse minéralogique, détermination de la teneur en $CaCO_3$, magnétisme environnemental) indiquent des phases de formation importante de sols au cours desquelles les conditions de sédimentation ont fondamentalement changé. L‘analyse des minéraux lourds met en évidence une origine nord-ouest, ouest et sud-ouest du matériel loessique. En outre, nous discutons la nature de la formation des sols et expliquons pourquoi ces sols sont si sableux par rapport aux unités de loess. Pendant les phases de formation des sols, le trajet des sédiments en provenance du nord-ouest a été bloqué alors que les matériaux sableux pouvaient encore être soufflés à partir du Grand Erg au sud-ouest. Notre modèle conceptuel de la provenance du lœss à Matmata soutient et précise les conclusions de Coudé-Gaussen et collaborateurs.

Keywords: environmental changes, Quaternary, palaeosols, desert margins, Southern Tunisia

Mots-clés : changement environnementaux, Quaternaire, paléosols, marges désertiques, Tunisie du Sud

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1 - INTRODUCTION

Studies of geologic records of dust composition, sources and deposition rates are important for understanding the role of dust in the overall planetary radiation balance, fertilization of organisms in terrestrial and marine systems, nutrient additions to the terrestrial biosphere and soils, and also for palaeoclimate reconstructions (according to Muhs, 2013).

The loess region of Matmata in Southern Tunisia (fig. 1) was always a research area of great fascination because it bears one of the most well-known deposits of lower latitude loess (Zoeller & Faust, 2009). These loess deposits (up to 35 m thick) cover the western interfluves and valleys of the Matmata plateau (including the Techine sites) and contain various interbedded and reddened palaeosols (e.g., Dearing *et al.*, 2001). Previous studies of these loess-palaeosol sequences (LPS) (Coudé-Gaussen *et al.*, 1982; Coudé-Gaussen *et al.*, 1984; Coudé-Gaussen & Rognon, 1988) have used a comprehensive suite of analyses to discuss the provenance of the loess (Coudé-Gaussen, 1987). Several regions came into consideration as sources of the loess but until nowadays only a few studies tried to unravel its origin (e.g. Coudé-Gaussen, 1987, 1990; Coudé-Gaussen & Rognon, 1988). Coudé-Gaussen and Balescu (1987) published a study based on heavy mineral analyses and total mineral analyses pointing to prevailing western winds during the deposition of the Matmata Loess.

In this study we provide some indicative results that confirm their hypothesis of multiple westward source areas for loess particles but also highlight changes in their relative contribution through time. Additionally this study addresses different environmental aspects during loess deposition and soil formation that become evident using a multi-proxy approach and goes beyond the general idea of Coudé-Gaussen (1987). Beside the potential of reconstructing palaeowind directions, loess archives always provide the opportunity to differentiate periods of loess deposition and periods of soil formation. The switch from loess/sand deposition to soil formation is first of all a question of dust/sand availability (e.g. Kocurec & Havholm, 1993;

Roskin *et al.*, 2013; Faust *et al.*, 2015, Roettig *et al.*, 2017), which is not necessarily linked to climate change (Roettig *et al.*, 2019). Furthermore Roettig et al. (2019) reported about 'fake-soils' in dune-palaeosol-sequences of desert margins that have features of strong soil formation but were only red dust depositions.

The aim of our study is to present an explanatory approach of system behavior for the region around Matmata, which deals with paleogeographic conditions during soil formation phases and loess accumulation phases. For this purpose, it is necessary to work out and compare different features within the loess-palaeosol sequences (LPS). A fundamental prerequisite for the interpretation of the characteristics is knowledge on the genesis of the LPS and thus an understanding of the LPS system. For this reason, it is important for us to once again deal with the origin of the LPS material and to enrich the assumptions of Coudé-Gaussen and Balescu (1987) with new insights.

2 - GEOGRAPHICAL SETTINGS

The Matmata plateau in Southern Tunisia is a Middle Cretaceous limestone plateau called 'Dahar-Highlands' with elevations between 400-700 m (a.s.l.). Located at the extreme northern margin of the Sahara it is bordered by the Gulf of Gabes to the east and the Grand Erg Oriental to the west (fig. 1). The plateau contains several large basins filled in with sandy loess in the surroundings of the villages of Matmata and Techine (Coudé-Gaussen & Rognon, 1986). The region experiences 100-250 mm of rainfall per annum, mostly in form of winter cyclonic rains, with a contribution from summer convectional thunderstorms (Bousnina, 1986), which supports a poor desert scrub community (Wellens, 1997). The precipitation is slightly higher on the Matmata Plateau than on the surrounding lowlands due to orographic effects (Bousnina, 1986). The research area is situated on the northern edge of the Dahar-Highlands that underwent strong karstification that led to a dissection of the landscape with large basins filled up with loessic sediments. The LPS studied here are located in such basins and hereafter named Matmata-Basin

(MB) and Techine-Basin (TB). The dissection of the northern part of the plateau is still in progress. Our own geomorphological prospections and mapping point out that nowadays rivers at the northern edge of the plateau flow to the north-eastern Gulf of Gabes, whereas in former times the drainage was mostly to the north-west with rivers tapping the large salt lakes (e.g. Chott el Djerid). These rivers were later captured and the new drainage situation caused a deeper incision with strong gully erosion (Photo 1), today providing excellent access to the profiles with steep, but stable, slopes. On the contrary, the Techine Basin is situated more in the south and not yet captured, exposing a smooth loess landscape with gently rolling hills.

Photo 1: Loess is deposited in intramountain basins forming badlands due to erosion phenomena.
Photo 1 : Le loess est déposé dans des bassins intra-montagneux et forme des terrains ravinés par l'érosion.

3 - METHODS

Our work spans over several fieldtrips. After a first, long lasting prospection phase during which we opened as much profiles as possible, we selected some characteristic LPS for detailed geochemical and granulometric analyses. We established our first stratigraphical framework in the field by comparing the thickness of loess units and intercalated soils (counting). As these soils were sometimes present in the form of soil complexes, they developed special features (such as sandwich structures) that were easily differentiable. Furthermore, $CaCO_3$-crusts provided suitable marker-horizons. Most important for our compilation of stratigraphical profiles were changes in $CaCO_3$ concentration within each profile as well as grain size fluctuations. Particle size distributions have been measured by wet sieve technique and pipette analyses (Schlichting *et al.*, 1995) and $CaCO_3$ content was determined by Scheibler-apparatus (Schlichting *et al.*, 1995) in the geo-lab of Dresden University.

Magnetic susceptibility and frequency dependent magnetic susceptibility were measured and calculated in order to detect and evaluate soil formation intensity. For rock magnetic investigations measurements were taken at the Laboratory for Palaeo- and Environmental Magnetism at University of Bayreuth. Therefore, the magnetic susceptibility, anhysteretic remanence (ARM) and isothermal remanence (IRM) were measured and frequency dependent susceptibility, S-ratio, etc. calculated. Initially the samples were dried, carefully homogenized and put into 6.4 cm^3 plastic boxes. The susceptibility was measured at two frequencies with a Magnon VSFM susceptibility bridge at 3 kHz and 0.3 kHz with a field strength of 320 A/m. The ARM is induced by using a Magnon AF Demagnetiser 300 and was measured with a JR-6A Agico dual spinner magnetometer. The IRM is induced in a two-stage process using a Pulse Magnetizer II for applying a 2 T DC field and a 0.3 T field in the opposite direction. The measurement itself is taken by a JR-6A Agico dual spinner magnetometer.

Clay mineral (XRD) analysis was conducted at the University of Córdoba in the Faculty of Science (Physical Geography laboratory) for the purpose to discuss the degree of soil formation and the possibility of inherited clay minerals versus neoformation. After the saturation of the clay fraction in magnesium and ethylene glycol, X-ray diffraction analyses (XRD) were realized using a Siemens D5000 diffractometer with CoKα-radiation and a Fe-filter (methodology according to Brown & Brindley, 1980). The semi-quantitative analysis determination of clays was calculated by Montealegre (1976), depending on the peak area and reflection power of the different clay peaks.

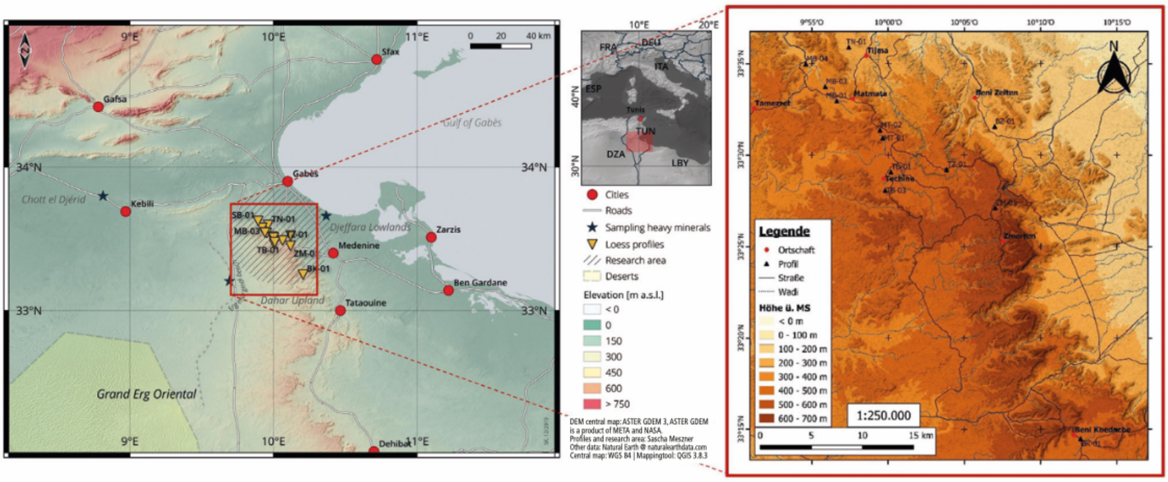

Fig. 1: Study area in Southern Tunisia.
Brown triangles: studied loess-palaeosol sequences in the frame of the project. Black stars: sampling locations for heavy mineral analysis in the possible source areas of loess material.
Fig. 1 : Zone d'étude dans le sud de la Tunisie. Triangles bruns : séquences de loess-paléosol étudiées dans le cadre du projet. Etoiles noires : lieux de prélèvements pour l'analyse des minéraux dans les zones sources possibles du matériel loessique.

In order to be able to make further statements on the origin of the loess in the Matmata region, samples from potential source areas (see black stars in figure 1) were compared and evaluated with those from the loess-palaeosol sequences (LPS) with regard to their heavy mineralogical composition. A total of 19 samples from the LPS in Matmata and 4 samples from the potential source areas were measured by means of heavy mineral analyses. From the LPS in Matmata 9 soils and 10 loess layers were analyzed. In order to dissolve calcareous particles, the samples had been pretreated with 30% acetic acid (CH_3COOH). In contrast, a treatment with hydrochloric acid was refrained sustaining minerals important for this region like apatite and barite (Mange & Maurer, 1991). Heavy mineral separation was carried out by gravity separation with a mixture of sodium polyoxotungstate ($H_2Na_6O_{40}W_{12}$) and deionized water until the density of 2.9 g/cm³ was reached. For a first differentiation, the ferromagnetic fraction was isolated with a magnet. To preserve paramagnetic minerals like tourmaline, which is essential to determine the mineralogical maturity, the magnet was led circa two centimeters above the sample (Boenigk, 1983). Afterwards, the heavy minerals were prepared for use under a polarization microscope. The method of partial embedding with liquid immersion was used applying 1-Chlor-onaphthalene as a refractive index liquid with n = 1.622, because a permanent embedding was not needed. Finally, a minimum of 200 transparent grains per sample, excluding micas, were examined and counted with the ribbon counting technique, both to reach a representative statistical value (Mange & Maurer, 1991).

4 - RESULTS

Among all studied profiles, our selection was constrained by the location of heavy mineral and clay samples, the most relevant for our study. These data were completed by the most representative records for environmental magnetism, grain size and $CaCO_3$ content, which are however not always located on the same profiles. Moreover, the absence of radiometric ages (in progress) is here not that critical as the present study focuses on the binary opposition between loess units and soil horizons whatever their types, and not on the reconstruction of the fully detailed palaeoenvironmental history of the area.

4.1 - GRANULOMETRY AND $CACO_3$ CONTENT

All investigated profiles show very similar features in terms of grain size composition and $CaCO_3$ content. Profile TB1 will thus serve as an example to depict the main changes observed in both $CaCO_3$ content and grain size distributions in locally studied profiles (see fig. 2).

First, the soils identified by their characteristic reddening during fieldwork tend to be almost decalcified whereas underlying horizons show a strong increase in $CaCO_3$ content. This is a clear feature of soil formation and pedogenetic redistribution of $CaCO_3$ with a nearly decalcified B-horizon and an underlying $CaCO_3$-enriched horizon (Cca-horizon with up to 40 % of $CaCO_3$, and named Bk-horizon on figures). The $CaCO_3$ content of the loessic material is generally lower than 20 %.

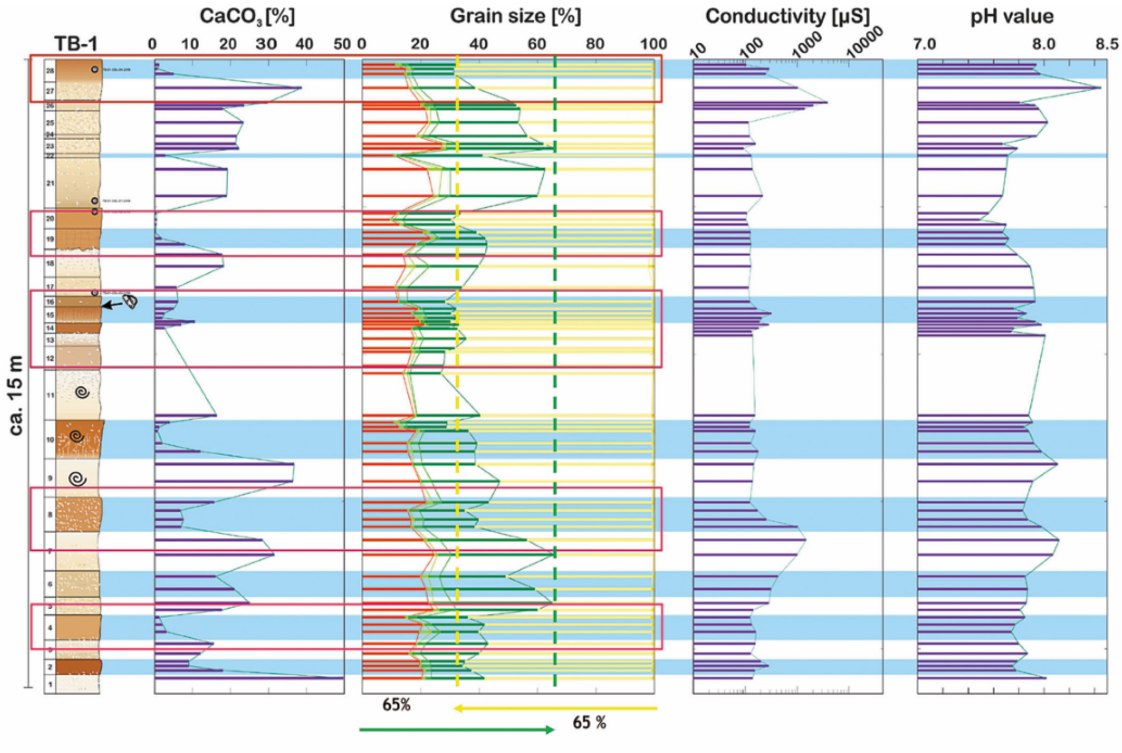

Fig. 2: TB-1 profile and associated analytical data.
Red rectangles enclose sandy soils; green dashed line marks 65 % of clay (in red) and silt (in green); yellow dashed line marks 65 % of sand. Data of the TB-1 profile are characteristic and representative for other loess-palaeosol sequences of Matmata region. At a depth of about 7 m the shard symbol indicates the presence of stone tools (see also figure 7).

Fig 2: Profil TB-1 et données analytiques associées. Les rectangles entourent les sols sableux ; la ligne pointillée verte indique la limite de 65 % d'argile (en rouge) et de limon (en vert) ; la ligne pointillée jaune indique la limite de 65 % de sable (en jaune). Les données du profil TB-1 sont caractéristiques et représentatives de celles des autres séquences de loess-paléosols de la région de Matmata. Le symbole d'éclat lithique indique la présence d'outils en pierre à environ 7 m de profondeur (voir aussi la figure 7).

Second, grain size distributions show strong shifts between soil formation and loess deposits. Surprisingly the grain-size distribution revealed that the reddish soils always have a very high sand content between 60 % and 65 % (fig. 2; see units 4, 8, 12, 14-16, 19-20 and 28 in red boxes). In contrast, the loess layers have a sand content that varies by 40%. The question why the soils are much sandier than the loess layers from which they were formed has never been asked before (e.g. Coudé-Gaussen & Rognon 1986, 1988; Dearing et al. 2001).

Although Coudé-Gaussen & Rognon (1988) published grain size diagrams from some LPS in Matmata, which show that the soils are much sandier, however, these findings were never addressed.

4.2 - ENVIRONMENTAL MAGNETISM

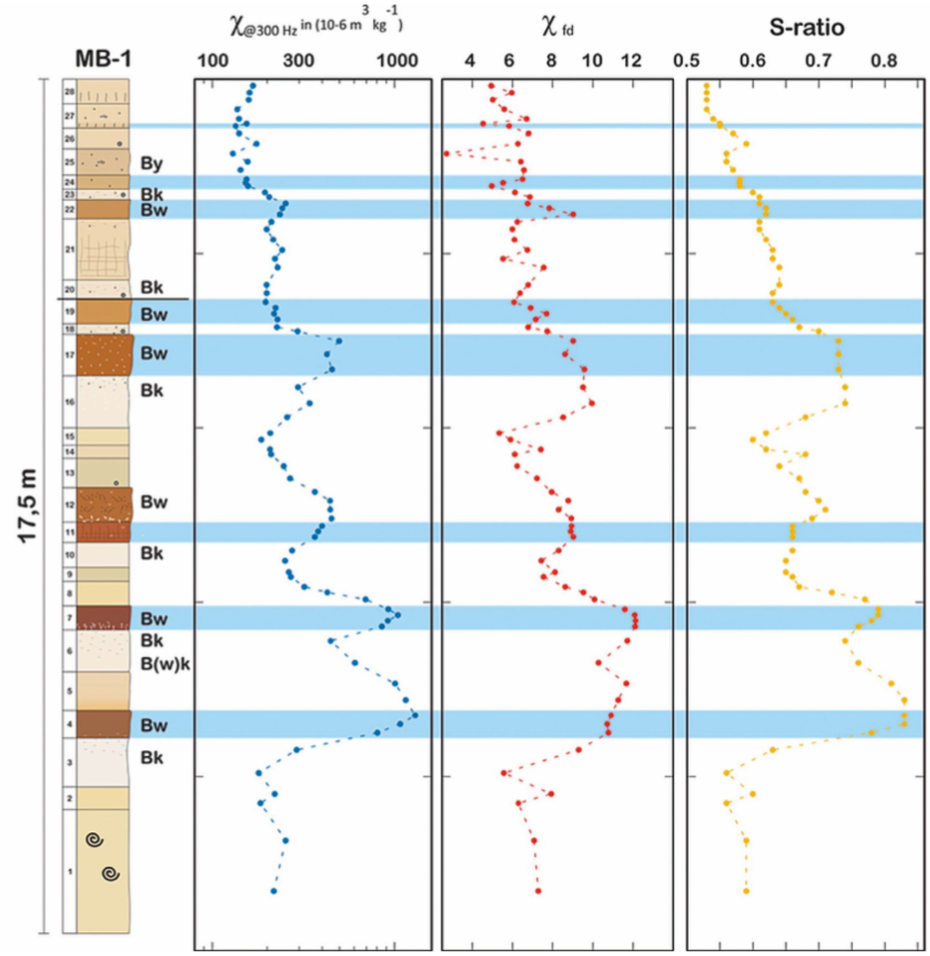

Fig. 3: Environmental magnetism data of MB-1 profile.
These data are representative for other loess-palaeosol sequences of Matmata region.
Fig. 3: Données de magnétisme environnemental du profil MB-1. Ces données sont représentatives de celles des autres séquences de loess-paléosols de la région de Matmata.

Changes in magnetic parameters have been studied throughout the MB-01 profile (fig. 3). MB-01 profile was chosen because it shows very similar patterns concerning grain size distribution and $CaCO_3$-content compared to the sections TB-01 and others, however their magnetic characteristics seem to be most explicit. This profile can be regarded as a representative example of the behavior of magnetic parameters in the Matmata Loess Region. Layers with relatively high values of XFD indicate a relative increase of pedogenetic formed superparamagnetic ferrimagnetic minerals. Hence, low values of XFD indicate very few pedogenetic features of the layer material. Increasing values of both magnetic and frequency-dependent susceptibility are known and described as “magnetic enhancement” (e.g. Evans & Heller, 2003). If one compares the magnetic susceptibility of all measured samples in a cross plot with the frequency-dependent susceptibility, the values follow the trend of high magnetic susceptibility correlating to high frequency-dependent susceptibility (fig. 4). This is typical for loess sediments and confirms the assumption that the environmental magnetic parameters have been modified mainly by soil formation.

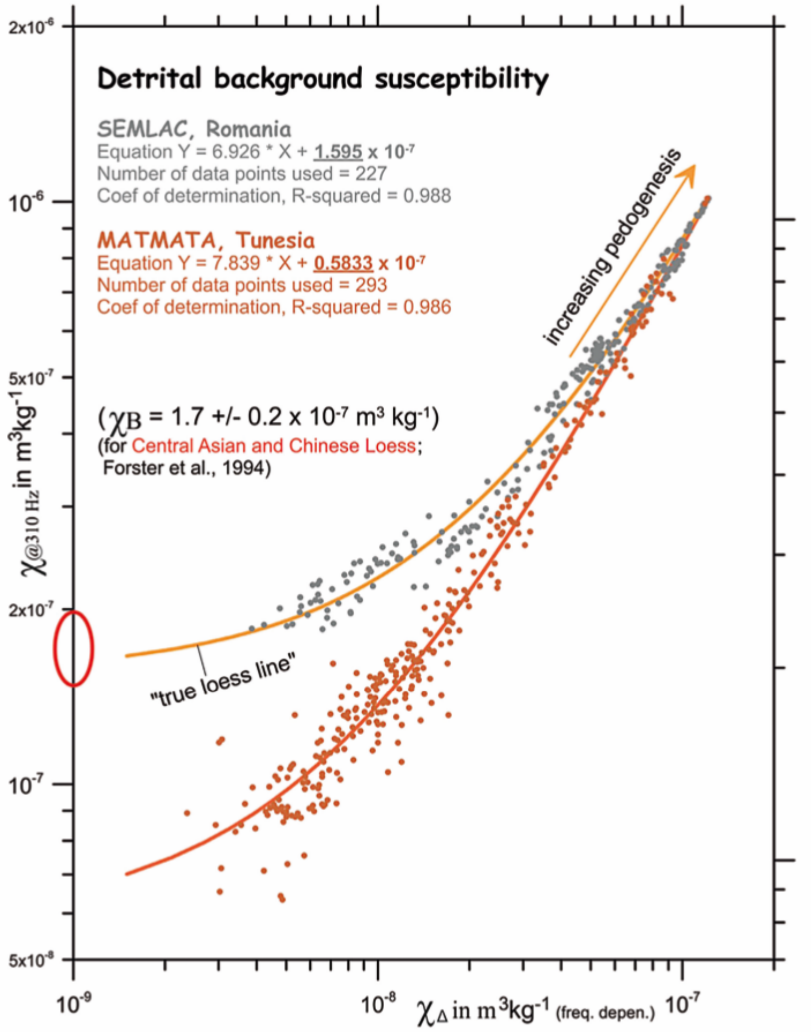

Fig. 4: Comparison of Matmata magnetic susceptibility results with the values of the "true loess line".

Fig. 4 : Comparaison des résultats de susceptibilité magnétique de Matmata avec les valeurs de la "vraie ligne des loess".

It is noteworthy that the magnetic susceptibility of some units is very low compared to loess from Asia or Pannonian Basin (fig. 4). This result might be linked to the comparatively higher sand content, according to which the magnetic susceptibility increases with decreasing grain size. Coarse-grained sandy sediments therefore generally have less magnetic susceptibility than finer silty sediments.

4.3 - CLAY MINERAL ANALYSES

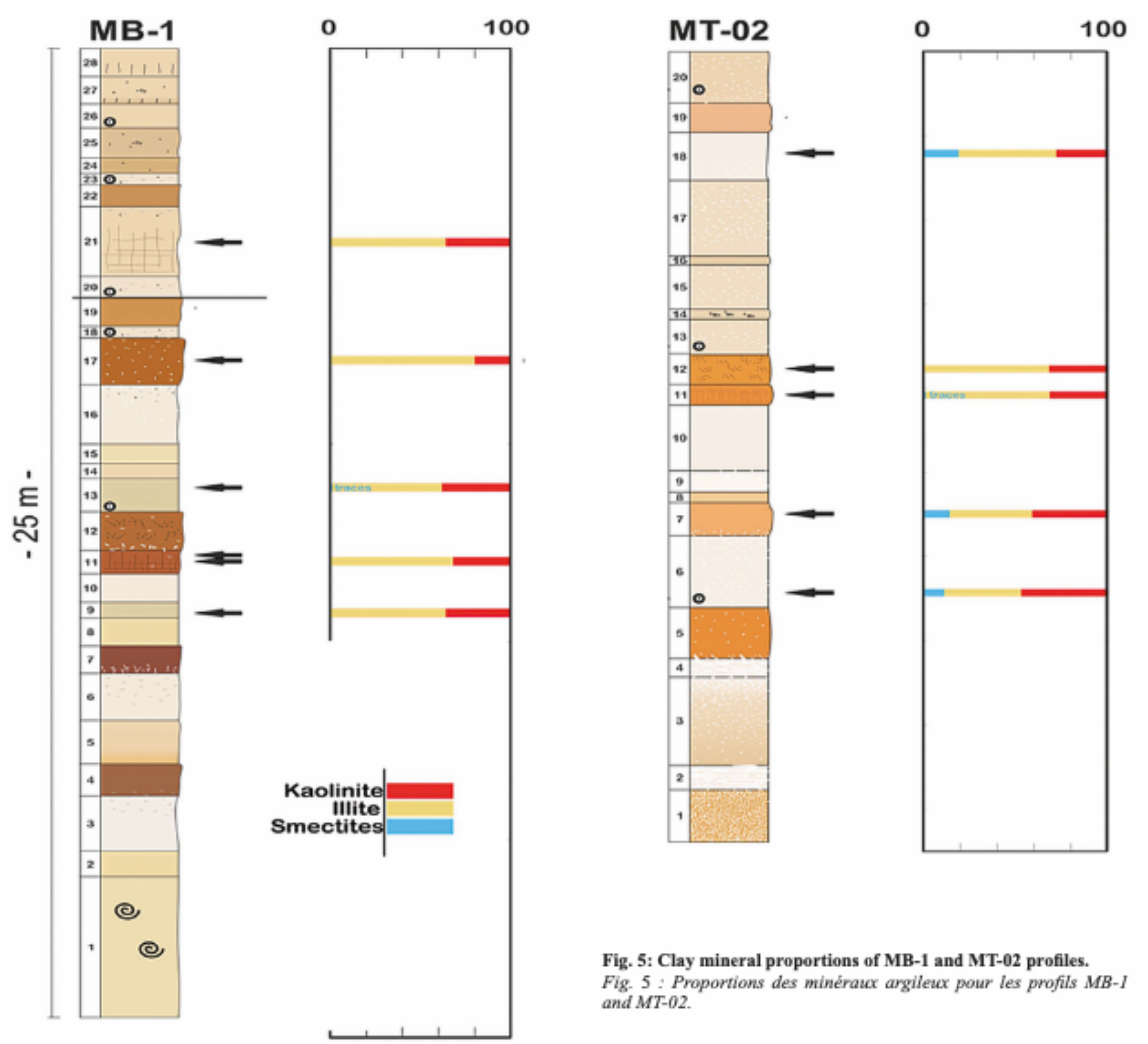

Fig. 5: Clay mineral proportions of MB-1 and MT-02 profiles.
Fig. 5 : Proportions des minéraux argileux pour les profils MB-1 and MT-02.

The determination of clay minerals in soils enable conclusions to be drawn about the duration of both soil formation and edaphic conditions on-site. Clay mineral analyses provides a percentage distribution of the three clay minerals: smectite, illite and kaolinite (fig. 5). In both MB-1 and MT-02 profiles, we observed that smectite is underrepresented and sometimes only present in traces. Illite is the dominant clay mineral in all profiles. The clay mineral spectra (fig. 5) hardly differ between loess units and soil horizons, which raises the question whether neoformation of clay minerals occurred during soil formation phases. The smectite would then be the first possible neoformed clay mineral, although it does not occur in the most pedogenetically transformed horizons. In the MT-02 profile, smectite occurs both in the loess and in the slightly pedogenic horizon of unit 7. In the profile MB-01 there is almost no smectite, apart from the loess unit 13, where traces could be detected. Hence, we assume that the clay minerals in our LPS were not formed *in situ*, which leaves the question of their origin open.

4.4 - HEAVY MINERAL ANALYSES

In the present study, heavy mineral analysis is of particular importance, since the analysis of the origin of loess sediments is an essential prerequisite for understanding the loess-palaeosol system. Heavy mineral analyses were carried out to obtain information on the origin of the loess, with samples being taken from the loess units and palaeosol horizons and compared with samples from possible source areas. Possible dust sources include the Grand Erg and the depression of Chott el Djérid in the west and the Djeffara depression in the east (see black stars in figure 1). Coudé-Gaussen and Balescu (1987) conducted a heavy mineral study for the loess region around Matmata. We can confirm their findings and considerably expand them with our own investigations. Our analyses showed that the percentage of dominant heavy minerals in all samples exhibited a similar pattern. However, the detailed examination of the mineral spectra revealed marker minerals, although they were clearly underrepresented in percentage terms. The three minerals zoisite, hypersthene and a mineral of the olivine group could be identified as marker minerals from a broad spectrum of heavy minerals found in our samples. The regional distribution (source areas and LPS) of these three minerals is shown in figure 6 with an occurrence of the mineral hypersthene in the Grand Erg and in the Chott el Djérid depression. This heavy mineral was also found in both loess and palaeosols. In the possible eastern source areas hypersthene is only detectable in traces from a sample of the coastal plain.

The heavy mineral from the olivine group showed only one occurrence in the eastern areas of the beach region and the coastal plain. This mineral did not occur in the LPS. The situation becomes very clear when one considers the mineral zoisite. Zoisite occurred only in the Grand Erg and in traces in the Chott el Djérid depression. The distribution of the marker minerals of the LPS is taken from the reference profile BK-01 situated in the southern Matmata region (see fig. 1). Astonishing is the comparative increase of the zoisite content in the soils of the LPS. Other rare minerals such as scheelite, allanite from the epidot group and xenotime (phosphate) do strongly confirm this general trend.

5 - INTERPRETATION AND DISCUSSION

The above presented data and figures allow a new interpretation of the loess system in the region of Matmata. Owing to the methods used and on the basis of the results obtained, a reasonable scenario can be derived for the accumulation of loess.

5.1 - GRANULOMETRY AND $CACO_3$ CONTENT

The grain size distribution showed a pattern that holds in all profiles. The loess layers were characterized by a sand content of about 35 %. In the soils, however, the sand content rose up to 65 %. With intensive weathering and soil formation, one might assume that the fine sandy loess will weather into even finer material. This is obviously not the case and raises the question of whether we are finally dealing with soil formation. Recent studies (Roskin *et al.*, 2013; Faust *et al.*, 2015; Roettig *et al.*, 2019) pointed out that soil formation intensities can be largely overestimated in desert margin areas. Roettig *et al.* (2019) reported from Fuerteventura that dune sequences were separated by fine-grained silty reddish layers simulating soils but merely made up of red dust layers, which were consequently named ‘fake soils’.

The question of ‘true’ or ‘fake’ soil formation in our profiles is relatively easy to answer. Looking at the $CaCO_3$ content in the profile (fig. 2), it becomes evident that the brown horizons were almost completely decalcified. The immediate horizons below showed the highest $CaCO_3$ contents, indicating intensive soil formation associated with *in situ* decalcification and formation of a calcic horizon (Cca-horizon/Bk-horizon). We therefore assume that soil formation took place in corresponding phases.

In order to decalcify and redden the material, relatively favorable precipitation conditions were required. The reddening indicates that this soil formation phase was characterized by hematite formation due to more arid conditions. We assume an alternating humid climate with contrasting seasons (analogous to the current climate situation in the Mediterranean region) allowing the soil to dry in summer. The particle-size distribution showed that all soils are associated with high sand contents.

At the moment we cannot classify the soil formation phases in terms of time. Dating is not yet complete, but is in progress. Therefore, a chronologic estimation and a supra-regional comparison is not yet possible. However, we have strong evidence (Faust *et al.*, 2020) that the stone tools found at the surface of palaeosols in the LPS (fig. 2 & 7) are older than marine isotope stage (MIS) 6, which makes them the oldest stone tools ever found on Tunisian territory. Studies on Central European loess sections (e.g., Antoine *et al.*, 2013; Meszner *et al.*, 2013) and even from Armenian loess sequences (Wolf *et al.*, 2016) assumed that soil formation took place during cessation periods of sedimentation and impacted the last deposited material. In the LPS of Matmata, however, more humid phases are characterized by both deposition of predominantly sandy material and soil formation. It is still a matter of debate whether soil formation took place after the deposition of the sandy material in a rather short humid time span or if soil formation happened during the deposition of the sandy material (aggrading soil). The strong sandy component in the soils however provides a first indication of changing sediment sources during loess-palaeosol alternations.

5.2 - ENVIRONMENTAL MAGNETISM

The magnetic signals also underlined the trend, which can already be deduced from the particle size spectrum. All magnetic parameters indicated soil formation in the corresponding horizons (figs. 3 & 4). Figure 4 compares the magnetic parameters measured for this study with those from Eastern European LPS (Zeeden *et al.*, 2018). It is noticeable that the susceptibility values in the loess from Matmata are significantly lower than those from Eastern Europe and China. In our opinion, this is due to the higher sand contents in the loess of the Matmata region. The increase of the susceptibility values in the Matmata loess (brown dots in figure 4) is indicating soil formation and coincides with the susceptibility values of soils from Eastern European loess. The detrital background susceptibility is assumed to be 0.5833 x 10^{-7} $m^3.kg^{-1}$ which is very low compared to Central Chinese loess (1.7 ± 0.2 x $10^{-7}.m^3.kg^{-1}$) and eastern European loess (1.595 x $10^{-7}.m^3.kg^{-1}$). The magnetic signals confirmed a soil formation phase, which was marked by the brown-red horizons in our profiles.

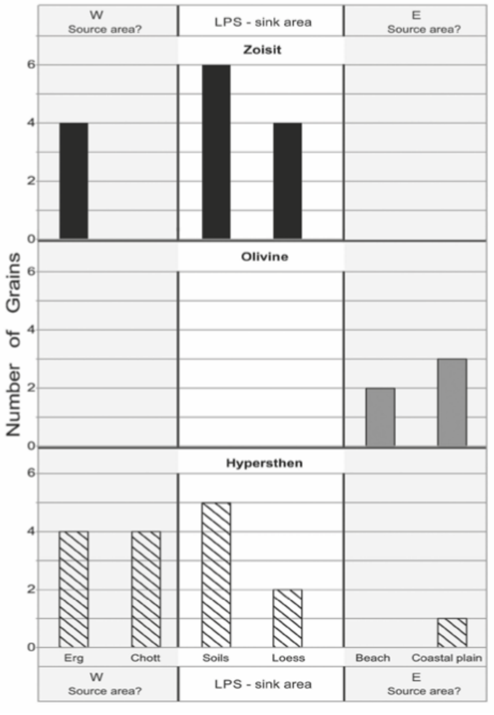

Fig. 6: Contents in zoisite, mineral of the olivine group and hypersthene in the loess-palaeosol sequence of Matmata (profile BK-01) and in the potential source areas of eolian particles (Chott and Grand Erg in the west and beach and coastal plain in the east; see fig. 1) obtained by heavy mineral analyses.

Fig. 6 : Contenu en zoïsite, minéral du groupe de l'olivine et hypersthène dans la sequence de loess-paléosols (profile BK-01) et des zones sources possibles du matériel loessique (Chott et Grand Erg à l'ouest et plage et plaine côtière à l'est ; voir fig. 1) obtenu par analyses des minéraux lourds.

5.3 - CLAY MINERALS

The determination and distribution of clay minerals in soil horizons allows conclusions to be drawn about the duration of soil formation phases and the pedological conditions on site in the Matmata loess area.

First of all, it became apparent that illite and kaolinite dominate the clay mineral spectrum, with low proportions of smectite. The similar distribution of kaolinite and illite in both palaeosols and loess indicates that the clay minerals were not formed *in situ*, but in their respective source areas.

In addition, the clay content in the grain size spectra exhibits a characteristic pattern. Increases in the clay content occur in loess, especially in units 21 and 7 (fig. 2). This feature is even more pronounced in other profiles (e.g., profile MB-1, not shown). We thus assume that clay was mainly windblown in the form of aggregates (e.g. Mason *et al.*, 2003). The Chott el Djérid and neighboring depressions constitute a potential deflation area, as the smectites, which were transported along with the other clay minerals, form predominantly in poorly drained soils. The clays can also be transported enclosed in salt crystals, whereby after deposition the salt dissolves due to percolating water following occasional rainfalls, leaving only the clays behind (see Bourgou and Oueslati (1994) for the formation of clay dunes).

We assume that the conditions of clay formation in the loess region of Matmata never enabled kaolinite formation because pH-values never drop down to initiate strong desilification. To turn primary minerals into kaolinite a very long alteration period is required, much longer than the timespan assumed for soil formation in Matmata. Thus, irrespective of the clay proportion, the kaolinite content constitutes an evident indicator that all clay minerals were inherited and have not been developed *in situ*.

5.4 - HEAVY MINERALS

The interpretation of the results from the heavy mineral analyses show that the main stock of minerals of all provenance samples hardly differs between samples and is therefore not very meaningful. Only detailed heavy mineral analyses deciphers important marker minerals, which were, however, very poorly represented in the spectrum. We identified rare heavy minerals such as zoisit, hypersthene, a mineral of the olivine group as well as scheelite, allanite and xenotime as marker minerals. Except the mineral of the olivine group all the others were exclusively found in the western possible source areas (Chott and Erg) and thus support the trend of prevailing western winds. Figure 6 shows proportions in grains of three identified marker minerals (Z, H, O) from samples of the LPS and from possible regions of origin: in the west the margin of the Grand Erg and the Chott area and in the east the Djeffara Lowlands, where we took samples at the beach and in the coastal plain (see black stars on figure 1). In figure 6a, a marker mineral from the olivine group could only be identified in the samples from the eastern Djeffara depression. However, this mineral did not occur in the investigated LPS, which suggests dominating western winds during sedimentation phases. This hypothesis appears to be confirmed by the proportions of hypersthene grains that originate mainly from the western Chott el Djérid together with gypsum and from the Grand Erg. The proportions of zoisite can be interpreted even more straight forward. Zoisite is only found in the Grand Erg. In the profile BK-01 zoisite is subordinate in the silty loess layers, whereas zoisite has higher proportions in the soils. These results, in turn, suggest that during soil formation material deposition from the south western Grand Erg dominated, making the soils so sandy.

This assumption was also confirmed by the extended XRD analysis (fig. 7) showing that during periods of soil formation the sediments in which soil developed were characterized by an increased quartz content. The quartz source here is also above all the Grand Erg. In addition, the heavy mineral analyses of all profiles show a tendency for profiles in the southern sector of the Matmata highlands (Techine, Zmerten and BK-01) to have an Erg signature and for profiles in the northern sector to have a Schott signature, which can be explained by the respective distances to the source areas.

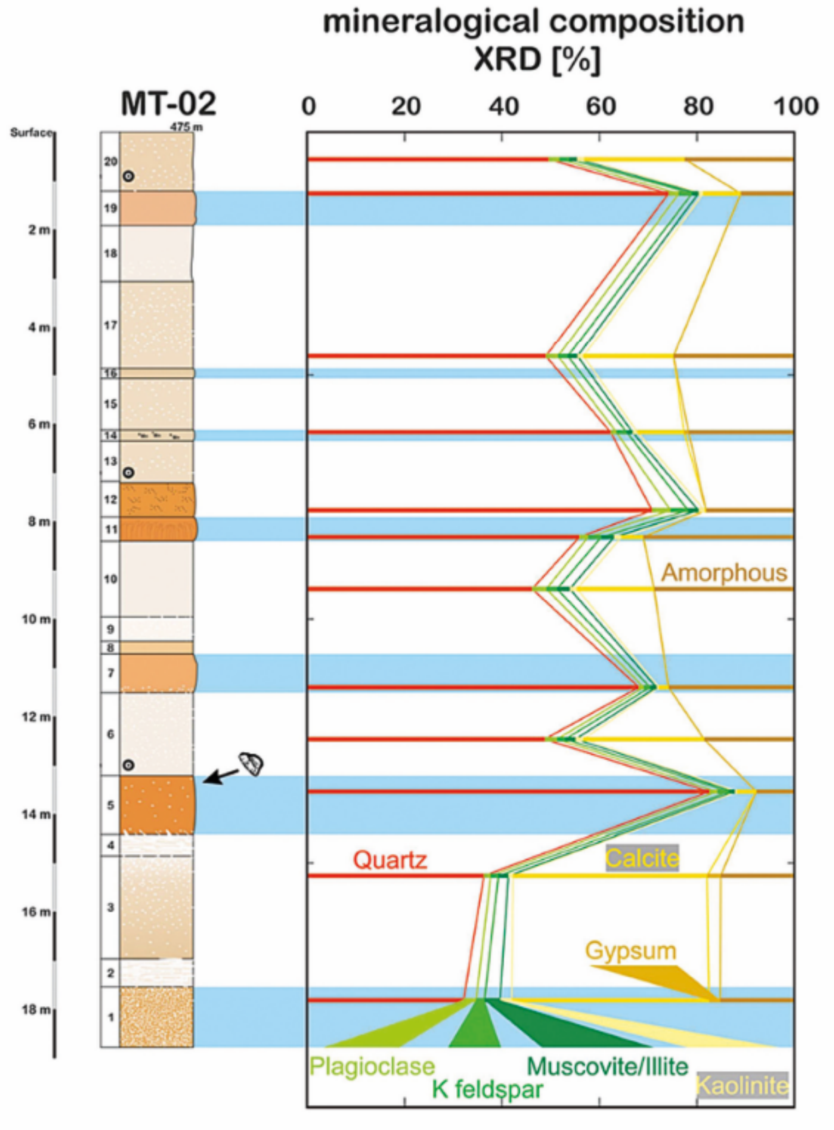

Fig. 7: Mineralogical composition of sediments of MT-02 profile.
Note the quartz enrichment in the soils. At a depth of about 13.2 m the shard symbol indicates the presence of stone tools (see also figure 2).
Fig. 7 : Composition minéralogique des sédiments du profil MT-02. Notez l'enrichissement en quartz dans les sols. Le symbole d'éclat lithique indique la présence d'outils en pierre à environ 13,2 m de profondeur (voir aussi la figure 2)

6 - ENVIRONMENTAL CONDITIONS

Since the Middle Pleistocene the formation of LPS in Matmata is constrained by oscillations between two distinct types of environmental conditions with transitional phases in between:

- phases of loess deposition including approximately 30 % of sand;
- phases of soil formation closely associated with eolian deposition dominated by sand.

Intermediate phases are characterized by lower loess accumulation and synchronous weak soil formation. Here, again, it can be seen that the sand content increase in the material deposited during these phases. Intermediate phases should be regarded as an independent type of phase, which does however not always lead from a loess unit to a soil horizon (transitional phase), but can also occur between two loess phases or two soil horizons according to the prevailing climatic shifts (fig. 8).

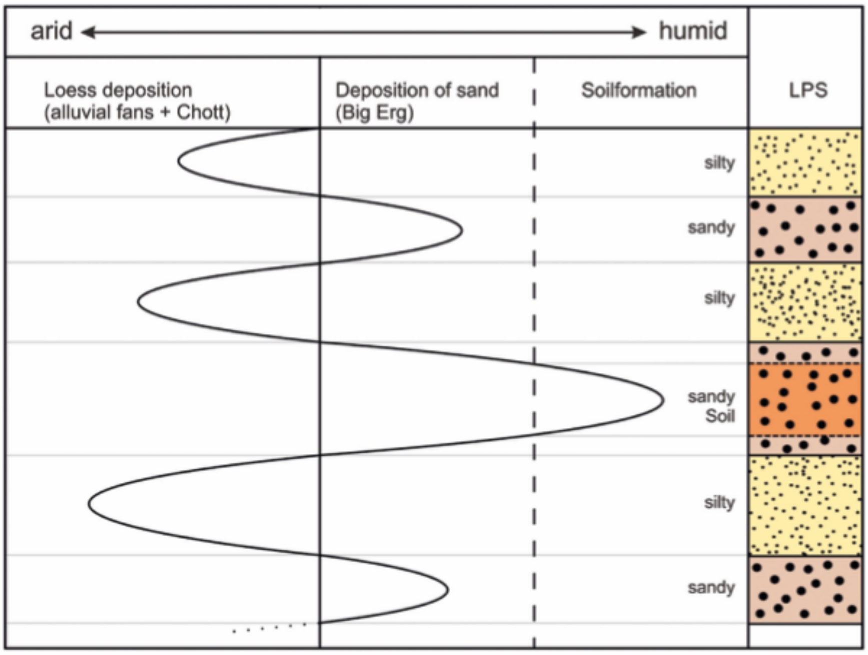

Fig. 8: Conceptual model of moisture dependent processes.
Fig. 8 : Modèle conceptuel des processus dépendant de l'humidité.

In summary, we assume that loess accumulation phases in the Matmata region were characterized by aridity. Prevailing western winds blown the sandy loess into the Matmata region. The loess was generated from the sediments of the southern Atlas slopes, from material of the sebkhas (Chott el Djérid) and from the sands of the Grand Erg. This mixture does not produce a typical loess with a clear peak in the coarse silt, but it is characterized by relatively high sand contents (about 40 %) and relatively high clay contents (up to 20 %). Due to the high aridity in the source areas, free of vegetation, deflation processes were facilitated. The rivers flowing from the South Atlas formed alluvial fans in the forelands during occasional flooding phases. The dried out *chotts* served as a source for the relatively high clay content. During the aridity phases, the Grand Erg served as the main sand source and was free of vegetation anyway. In contrast, during phases of soil formation, completely different environmental conditions prevailed. These phases were characterized by a significantly higher humidity. The precipitation was able to dissolve $CaCO_3$ and leached it into the lower soil horizon forming typical Bk-horizons. As already mentioned, during the soil formation phase we assume a deposition of sandy material in which pedogenesis took place and probably led to an aggrading soil. Evidently, the transport of clay and silt was somehow blocked. We assume that during these humid phases the southern slopes of the Atlas Mountains were protected by vegetation and the depressions were completely filled in with water that formed a mega-lake (e.g. Quade *et al.*, 2018) and prevented the deflation of fine material from these source areas. In contrast the Grand Erg desert margin in the further south received less precipitation during this time span. In addition, mostly made of sand the Erg strongly favors edaphic aridity. With prevailing westerly winds, the Grand Erg was thus the only sediment source able to deliver sand. The capture of the sandy material in the LPS of Matmata may have been favoured by a predominant vegetation cover developed during humid conditions and soil formation as proposed for sandy loess sequences of the Rhône Valley in south-eastern France (Bosq *et al.*, 2018).

7 - OUTLOOK

In a next step we intend to complete the system presented here with its changing phases in an overall view presenting all investigated profiles in the Matmata region. In addition, on-going luminescence dating will allow us to build up a chronostratigraphical model in order to place phases of soil formation in a Quaternary time frame. We intend to chronologically better resolve the Middle and Late Pleistocene with respect to past environmental changes (soil formation vs loess deposition). Finally, the results will be placed in a supra-regional Mediterranean context in order to test their transferability.

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