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# EFFECT OF LITHOLOGICAL AND GEOTECHNICAL CHARACTERISTICS ON THE GENERATION OF DEBRIS FLOWS IN MATMATA, SOUTHEASTERN TUNISIA

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**Abstract:**

The Matmata region, located in the south of Gabès (Tunisia), experienced significant damage during the floods of the Beni zelten wadi on November 11, 2017. These floods, exacerbated by the steep slopes and underlying soil conditions, led to the occurrence of debris flows, posing a threat to road infrastructure. The generation of debris flows is closely linked to intense rainfall events that surpass the soil capacity to retain water. To gain insights into the behaviour of the soil samples, various characteristics were analysed, including texture, clay mineralogy, grain size distribution, and Atterberg limits. The results showed that the mean liquid limit values ranged from 38% to 62%, while the mean plasticity index of the materials in the landslide-prone areas varied from 18% to 27.9%. These findings indicate presence of clay formations and highlight a significance of the increased soil clay content as contributing factors to landslide development. The X-ray Diffraction analysis revealed that gypsum, quartz, phyllosilicate and calcite minerals were the most abundant minerals identified in the soil samples. This work shows the importance of clay mineral and geotechnical parameters of the soils in the occurrence of landslides and predicting debris flows occurrences in the Matmata region.

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**Key words:** Beni zelten wadi, Atterberg limits, XRD analysis, grain size distribution, debris flows.

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## INTRODUCTION

Landslides can result from various interacting factors, including intense rainfall, seismic activity, water level changes, storm waves, rapid stream erosion, geology, land cover, slope geometry, groundwater saturation, vegetation cover and human activity (Hong *et al*., 2007; Guzzetti *et al*., 2012). These factors can either increase a susceptibility of slope material to shear stress or reduce its resistance to failure (Tanyas and Topal, 2015). In mountainous areas, the assessment of debris flows and rockfalls has become a significant concern for disaster management and risk reduction efforts (Hungr *et al*., 2014).

The geotechnical properties of weathered units play a crucial role in determining the mechanical behaviour of slopes (Yalcin *et al*., 2011; Dufresne and Davies, 2019). To understand the landslide behaviour, it is important to examine factors such as water content, consistency limits, grain size distribution and the characteristics of fine-grained lithological units. Evaluating the geotechnical characteristics of these units is essential for predicting landslides and debris flows (Petley *et al*., 2005; Carrière *et al*., 2018). While few studies have directly assessed the rheological behaviour of clayey soils and muds resulting from landslides (Malet *et al*., 2005; Meisina and Scarabelli, 2007), classifying of landslides can provide valuable insights into the type of

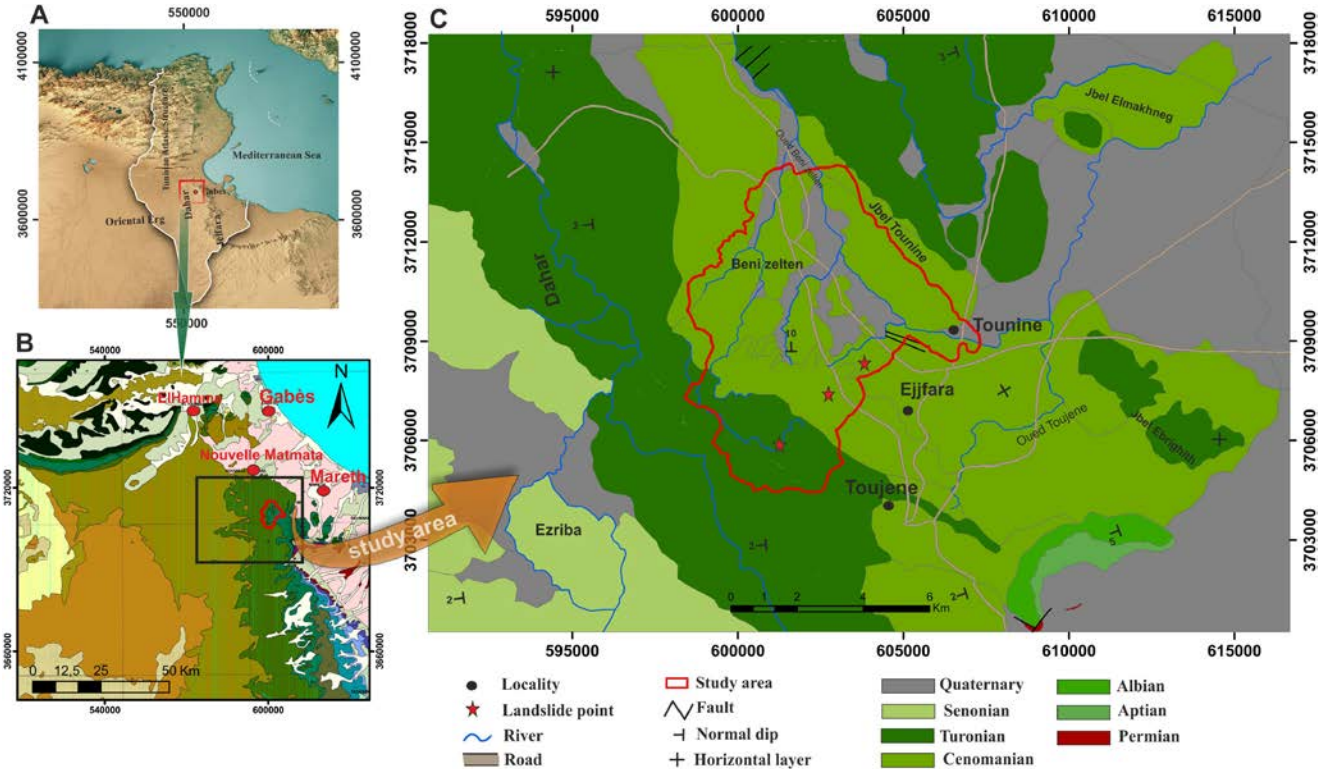


**Fig. 1.** Location of the studied area: A – Tunisia in the Mediterranean and the eastern limit of the North African chains. B – The delimitation of Gabès governorate in the south of Tunisia. C – Geological map of the study area.

slope failure and subsequent debris transport, helping to identify potential landslide-prone areas (Basharat *et al.*, 2016; El Jazouli *et al.*, 2022).

A type of rock, especially clay, which undergoes alteration processes along with the amount of water in the soil during rainfall, significantly affects the geotechnical properties of rocks. These factors lead to reduce shear strength, decrease soil cohesion and increase pore pressure (Mitchell and Soga, 1993; Yalcin, 2007). A occurrence of landslides has been linked to the presence of clay in soils, as indicated by several studies to examine the physicochemical, mineralogical and geotechnical characteristics of clayey soils (Daoudi *et al.*, 2015; Diko *et al.*, 2014; El Jazouli *et al.*, 2022; Ekosse *et al.*, 2005; Fall and Sarr, 2007; Ngole *et al.*, 2007; Yalcin, 2007).

Tunisia exhibits diverse climatic zones extending from its northern to southern regions. This variation is shaped by the combined influence of a Mediterranean Sea-derived humid climate and an arid climate resulting from its location along the eastern boundary of the North African chains and the Saharan platform (Fig. 1A). Despite this, the study of landslides in Tunisia is limited, although several instances have been observed, particularly in the northwestern region. In February 2012, heavy rainfall led to numerous landslides in the Jendouba province, resulting in a complete isolation of the Ain-drahem village for three days (Anis *et al.*, 2019). The landslides caused significant damage to properties, infrastructure (amounting to 18 mln dollars) and unfortunately, resulted in multiple fatalities (Anis *et al.*, 2019).

Early efforts in the Sebou basin by Avenard (1965) involved the census, description and mapping of mass movement events, laying the foundation for studying erosion and landslides in the region. We are concentrating the study on the Matmata region, located in the southwestern part of the Gabès governorate, experienced torrential rains on November 11 and 12, 2017, following an extremely hot and dry summer. The resulting floods had detrimental impacts on both human life and material possessions, leading to the evacuation of 117 individuals and the loss of five lives, as reported by the National database of disasters losses. Additionally, these floods triggered debris flows and rockfalls in the region (Fig. 2), further exacerbating the damage caused by the natural disaster. It is evident that the unique climatic conditions and lithological formations in Tunisia contribute to the occurrence of debris flows.

The aim of this study is to enhance our understanding of the geotechnical properties of the studied samples. These findings will contribute to a better understanding of the complex interactions between lithology, slope, elevation and the occurrence of rockfalls, as well as the behaviour of soils during debris flows in the Matmata region. This holistic approach will provide valuable insights into the mechanisms and triggers of landslides, ultimately aiding in a development of effective mitigation strategies and measures to reduce the risks associated with debris flows in similar geological and environmental settings (Sangchini *et al.*, 2016).

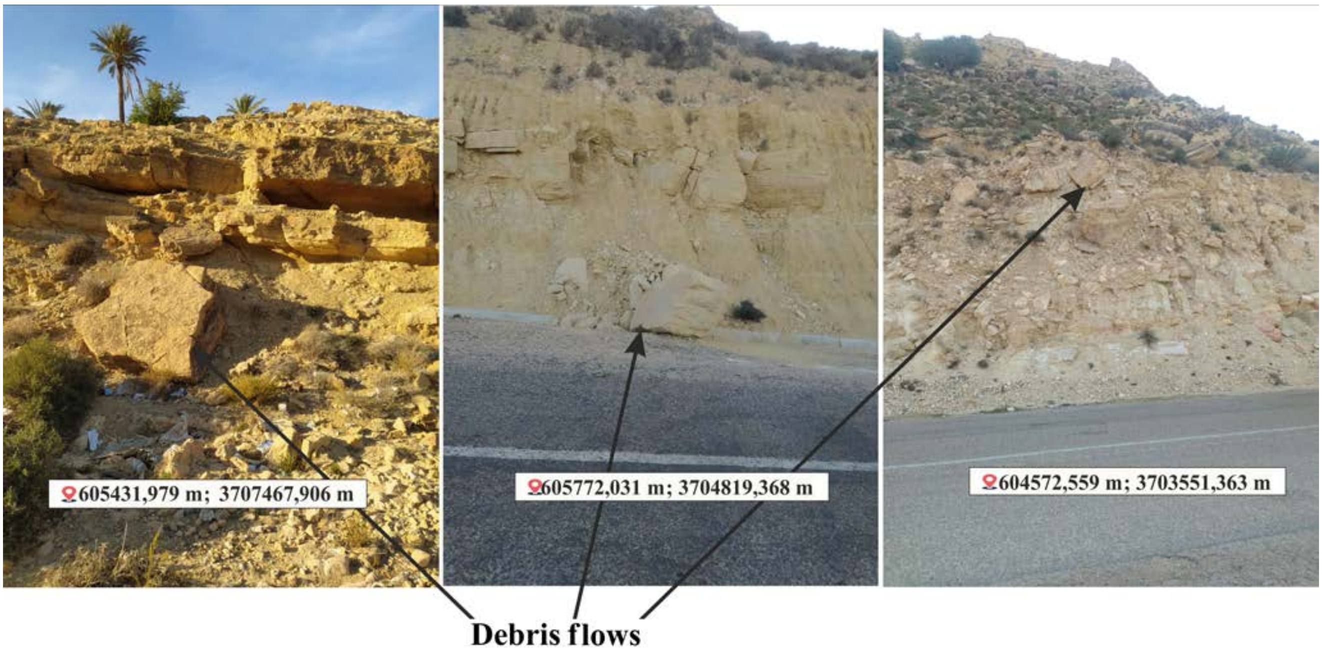


**Fig. 2.** Location of debris flows in the study area.

## MATERIALS AND METHODS

### Soil sampling

In November 2020, under wet weather conditions, an extensive soil sampling campaign was conducted in the Matmata region to investigate the impact of clay characteristics on landslides. A total of 18 soil samples were collected from three specific areas prone to landslides following the guidelines outlined in the AFNOR XP P94-202 standard (AFNOR 1995), as identified in Fig. 1C. The sampling, conducted from the topsoil to a depth of approximately 20 cm, employed the Global Positioning System (GPS) for precise spatial documentation (Fig. 3). Samples were immediately labelled, preserving their integrity and transported to the laboratory for analysis. To ensure accuracy, the samples underwent air drying to remove excess moisture before being sealed in polyethylene bags, preventing contamination. This meticulous process ensures the reliability of the collected soil samples, laying a strong foundation for subsequent laboratory testing and analysis.

### Atterberg limits

The presence and characteristics of clay minerals significantly impact the physicochemical properties of soils. Atterberg limits, which include the shrinkage limit (Ls), plastic limit (Lp) and liquid limit ($W_L$), are indicators of soil plasticity influenced by changes in moisture content (Howie *et al.*, 1992; Nesse, 2012; Boggs and Krinsley, 2006; El Jazouli *et al.*, 2022). Clayey soils exhibit different states, ranging from solid to semi-solid, flexible, or semi-liquid, depending on their moisture concentration (Carrière *et al.*, 2018; El Jazouli *et al.*, 2022). The Atterberg limits play a crucial role in determining these transition points.

The swell potential of soil samples was assessed through the Atterberg limits whereas the liquidity (IL) and plasticity (Ip) indices were calculated using the NF P 94-051 standard (NFP94-051 1993). The IL measures the relative consistency of plastic soils, while the Ip indicates the range of water content at which soils exhibit plastic behaviour. Soil samples were categorized based on their Ip, allowing classification into non-plastic, slightly plastic, low, medium, high, and very high plastic categories (Thomas *et al.*, 2000; Meisina, 2004; El Jazouli *et al.*, 2022).

In the context of debris flows, the Atterberg limits provide vital information about soil moisture characteristics and plasticity (Costet *et al.*, 1969). Soils with high plasticity, characterized by a higher Ip, may be more susceptible to moisture-induced volume changes and potential instability (Thomas *et al.*, 2000). Understanding the Atterberg limits helps to assess the potential for debris flows in areas with specific soil characteristics, enabling informed mitigation strategies to reduce associated risks. The relationship between clay minerals, Atterberg limits, and debris flows underscores the importance of considering soil properties in landslide susceptibility assessments.

### Grain size distribution

Particle size distribution significantly influences landslide frequency and speed (Dai *et al.*, 2001; Yalcin, 2007). In this study, laser particle size analysis, following the ISO 13320 (2009) standard, was employed to determine soil grain

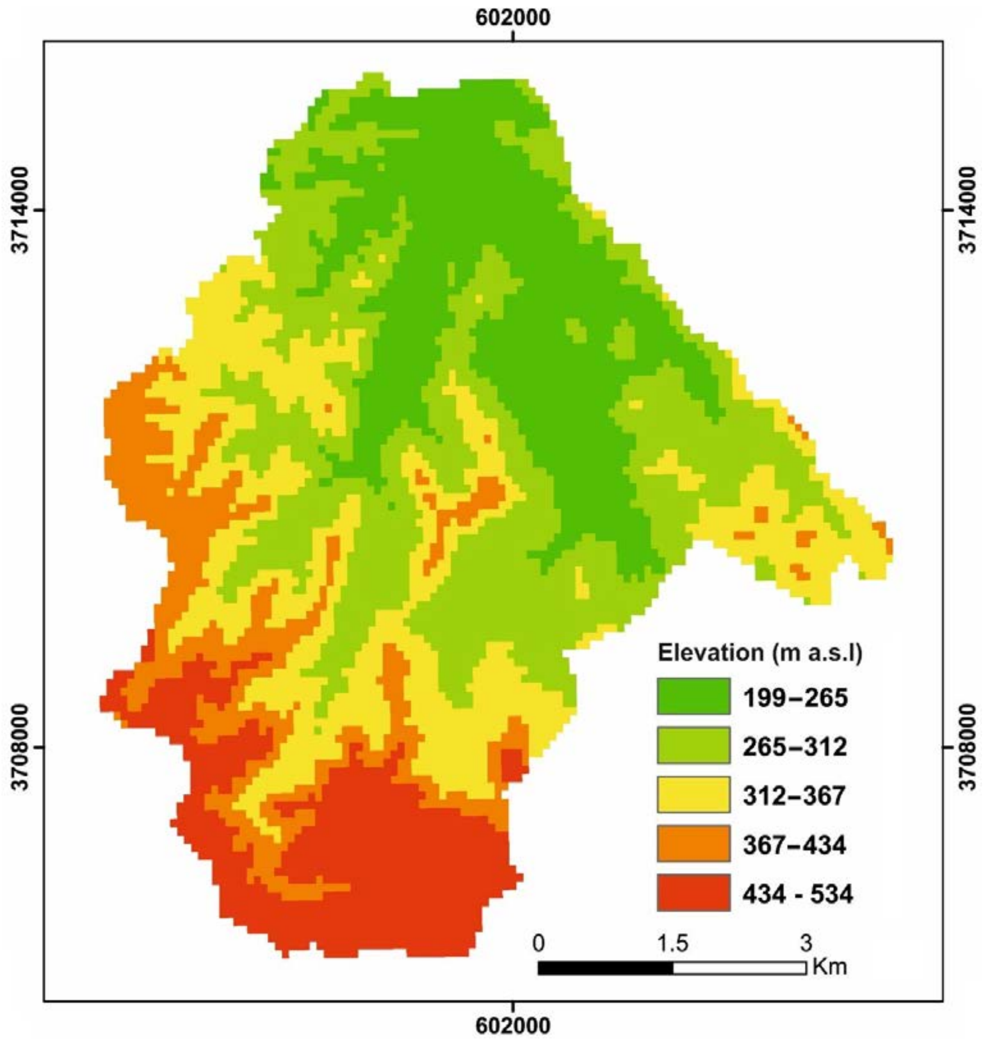


**Fig. 3.** Delimitation map of the Beni zelten-basin and sampling points.

size in landslide-prone areas. This standard provides guidelines for particle size analysis using laser diffraction methods. The results, presented in Table 1, reveal the distribution of clay, silt, and sand fractions, crucial for understanding debris flow processes, characterized by rapid downhill movements of saturated soil, rock fragments and water. Fine-grained particles, such as clay and silt, identified through ISO 13320-compliant laser analysis, contribute to increased water-holding capacity, rendering the soil more susceptible to saturation during intense rainfall. The particle size distribution plays a pivotal role in determining debris flow characteristics, where fine particles contribute to viscous flow, and coarser particles provide strength and resistance to erosion. The comprehensive understanding of soil composition, particle sizes, and water content, facilitated enhances the assessment and mitigation of landslide hazards in vulnerable areas.

Table 1. Particle size distribution (in %) of samples.

| | Sand fraction (>62.5 µm) | Silt fraction (4–62.5 µm) | Clay fraction (<4 µm) |
|---|---|---|---|
| MT0 | 2.04 | 69.89 | 28.07 |
| Mt1 | 1.88 | 85.59 | 12.53 |
| Mt2 | 0.13 | 63.22 | 36.65 |
| MT3 | 3.92 | 82.36 | 13.72 |
| MT7 | 1.30 | 85.89 | 12.81 |
| MT10 | 9.70 | 83.12 | 7.18 |
| MT11 | 10.71 | 77.34 | 11.95 |
| MT14 | 8.19 | 71.05 | 20.76 |
| MT16 | 3.03 | 69.19 | 27.78 |
| mt18 | 1.92 | 83.63 | 14.45 |

## X-ray diffraction (XRD) analysis for mineral identification

In the study aimed at determining the mineralogy of clay samples, the X-ray diffraction (XRD) technique was employed. Sample preparation adhered to the guidelines outlined in ISO 13779-1, defining the method for preparing powder samples specifically for XRD analysis. To ensure optimal analysis conditions, particles smaller than 75 µm underwent wet grinding, aiming for a preferred size fraction of

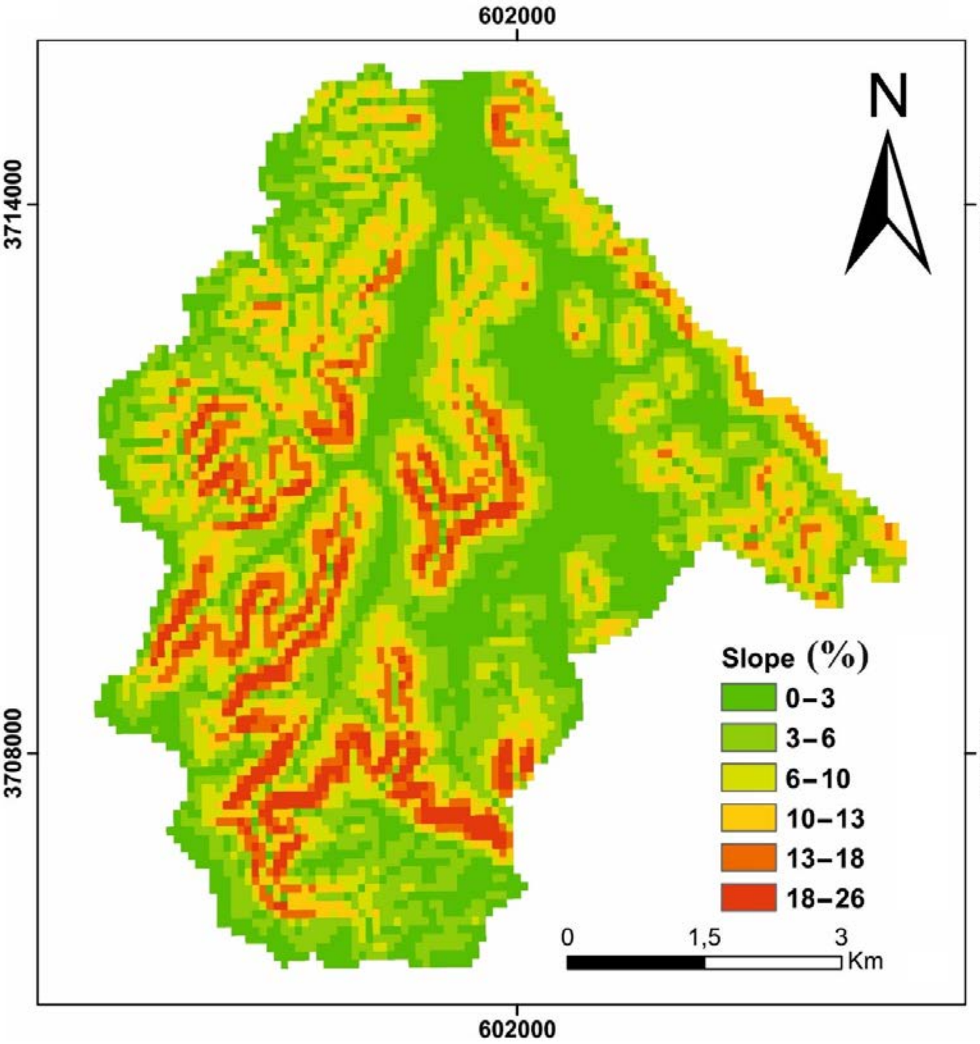


**Fig. 4.** The elevation topography of the Beni zelten area.

less than 10 μm, a crucial step inspired by practices detailed in ISO 13779-1. This meticulous preparation was undertaken to minimize background noise during subsequent XRD analysis (Loubser and Verryn, 2008; El Jazouli *et al.*, 2022).

For data acquisition, the study followed ISO 22262-1, which describes XRD data acquisition methods for the qualitative analysis of crystalline phases. Additionally, ASTM D5322, a standard by ASTM International, was consulted for specific procedures related to XRD data acquisition for clay materials. Ten soil samples were then subjected to oriented-sample preparation methods on a Bruker D8 Advance diffractometer.

Data analysis incorporated practices from ISO 22262-2, detailing XRD data analysis methods for identifying crystalline phases. The processed diffractograms were analysed using X'Pert HighScore software. Moreover, the study referred to the Joint Committee on Powder Diffraction Standards-International Centre for Diffraction Data (JCPDS-ICDD), a reference database for X-ray diffraction patterns, enhancing the accuracy and reliability of the obtained insights into types and proportions of clay minerals present in the soil composition. This comprehensive approach, integrating sample preparation, data acquisition and analysis standards, provided valuable preliminary insights crucial for understanding the mineralogical composition of the clay samples.

## GEOLOGICAL SETTING

The studied area is mainly covered by a sedimentary series of the Cretaceous, with different facies and thickness variability, these series are often tabular with a small dip of 5 degrees, usually to the west, but occasionally also to the north and northeast (Bouaziz, 1995; Aydi *et al.*, 2022). The Mesozoic series of the tabular structure rests in angular unconformity on the Upper Permian – the Lower–Middle Triassic strata which form an N80 striking alignment known as Jebel Tebega of Medenine. The alternations of competent levels (dolomites and limestones) and tender levels (clay, marl and sandstone) with a slight dip to the west, are subject to differential erosion which has made it possible to identify stepped plateaus limited by escarpments and witness mounds (Busson,1970; Bouaziz,1995) (Fig. 1C)

The choice of the study area was not arbitrary as Tunisia is defined by the eastern limit of the North African chain known as the Atlassic belts structure (Fig. 1A). Specifically, the Gabès governorate, located in the eastern part of pre-Saharan Tunisia, exhibits extensive outcroppings of the Cretaceous series (Fig. 1B). The region which is open to the Mediterranean through the Gulf of Gabès, boasts a diverse morphology resulting from a long history of geological and geomorphological evolution (Masrouhi *et al.*, 2019).

Within the Gabès plain, the dominant feature is the Matmata Mountains, which form the northern portion of the Dahar range. These folded Mesozoic mountains, commonly known as the Matmata Mountains, comprise diverse basins, valleys and corridors situated at varying elevations. Importantly, these depressed landforms are characterized by deep accumulations of loess silt, which is 10–20 m thick (Masrouhi *et al.*, 2019).

The studied sector is delimited by many domains. To the south, the Jeffara domain or Jeffara plain, located in the extreme south of Tunisia, is a vast lowland region., bounded to the west by the Mesozoic series of the Dahar plateau and to the east by the marine coast of the Mediterranean. To the west and south there is the Dahar, corresponding to a morphological and structural entity which forms a large part of the Tunisian Saharan platform, covered by the sand dunes of the great "Oriental Erg ".

Around the region of Matmata, the Beni zelten watershed covers the northern part of the great cuesta of Dahar and the Jeffara plain, which extends from 10°02'E to 10°09'E and from 33°24'N to 33°39'N. It occupies 49.025 km$^2$ at 199–534 m above sea level (Fig. 4). The study area's topography sharply ascends from the coast, characterized by variations in slope across hills, mountains, and valleys stretching from west to east. This rugged terrain increases the susceptibility to debris flows, with the risk being closely tied to the slope angles.

## Stratigraphy

A lithology or a type of rock and soil composition play a significant role in triggering debris flows, indeed different lithological formations have varying erodibility characteristics. Some lithologies, such as loose unconsolidated sediments, highly weathered rocks or weakly cemented materials, are more prone to erosion and detachment during intense rainfall or other triggering events. These erodible lithologies are more likely to contribute to debris flow initiation.

The outcropped series in the study area are spread from the Permian to the Quaternary age, distinguished by facies and thickness variations of series (Fig. 5). They are defined from the oldest as:

The Permian (Oum Alafia clay): it is a red clay outcrop in the of Oum Elafia wadi. They contain intercalations of sandstone and carbonates with fusulines, attributes to the Upper Permian age. The base of this set is covered by the Albian–Cenomanian unconformity, which makes determination of thickness impossible (Bouaziz, 1995).

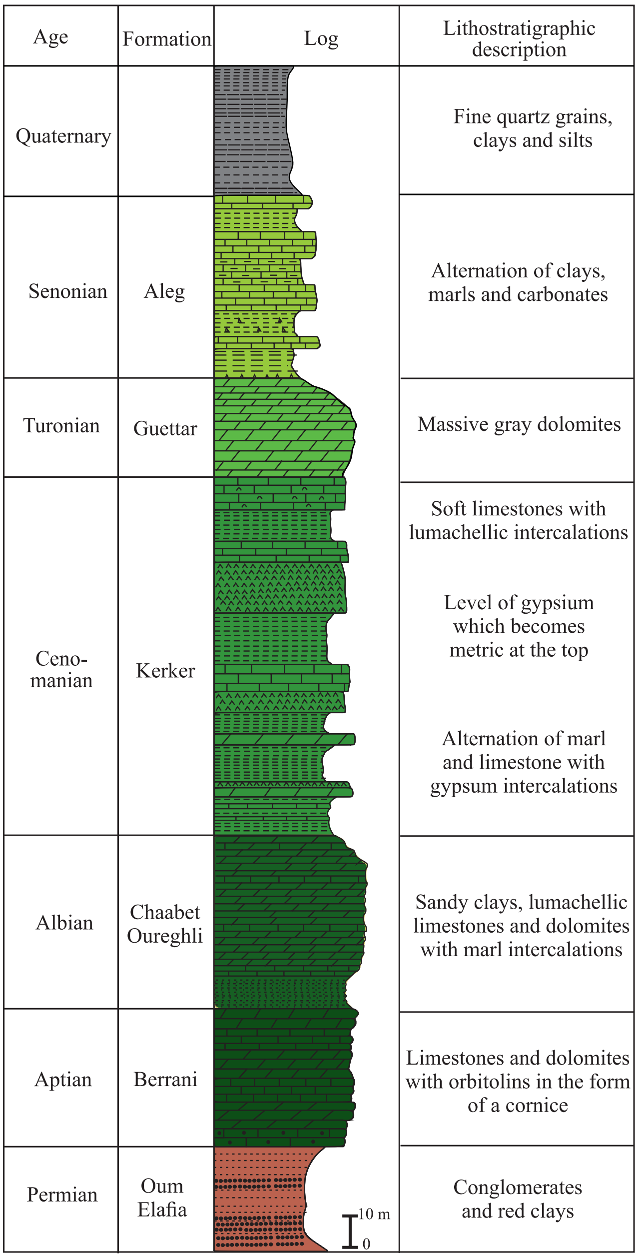


**Fig. 5.** Lithostratigraphic log of outcropped series made in the studied sector.

The Aptian (Berrani Formation) is constituted of limestones and dolomites with orbitolins which outcrop as a cornice form (Bouaziz, 1995; Aydi *et al.* 2022).

The Albian (Chaabet el Ouargli Formation) is an alternation of dolomitized fossiliferous and lumachellic limestones with intercalations of clayey-sandstone layers at the base (Bouaziz, 1995).

The Cenomanian (Kerker member) is typically consisted of dolomitic limestone banks and marl at the base, associated to alternations of marl, gypsum and marl in the middle, and a few limestone banks at the top (Bouaziz, 1995; Ben Ouezdou *et al.*, 1999; Aydi *et al.*, 2022).

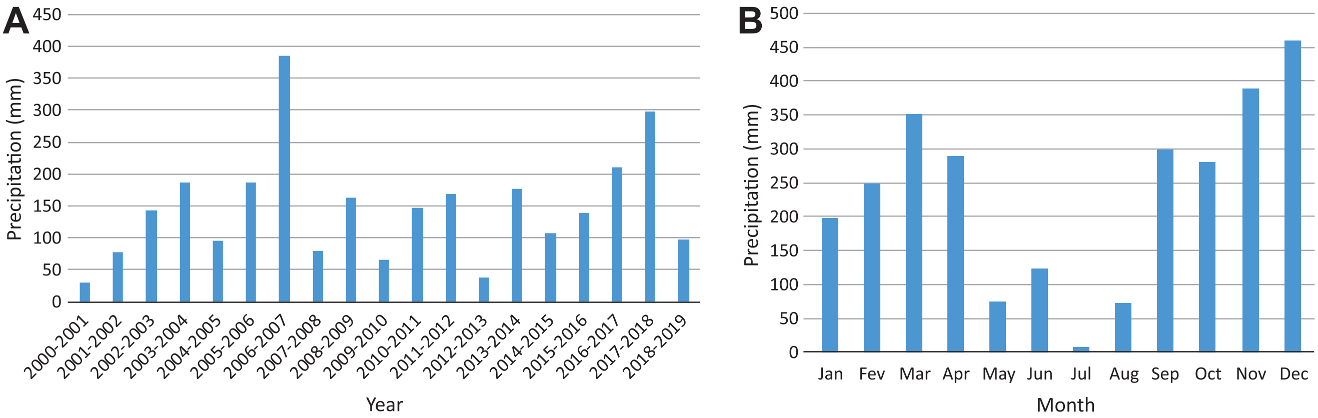


**Fig. 6.** Average precipitation in the Matmata: A – annual average precipitation (2000–2019), B – monthly average precipitation between 2000 and 2019.

The Turonian (Guettar bar) is composed of thick sandstone dolomites, 50–80 m thick (Ben Ouezdou *et al.*, 1999; Aydi *et al.*, 2022).

The Senonian (Aleg Formation) is composed of alternating clay, marl and carbonates (Bouaziz, 1995).

The Quaternary (Loess Matmata) is composed of a variety of geological formations. Dominating the scene are the Matmata silt, characterized by their reddish tint and featuring fine quartz grains, clay and diverse inclusions. These silt fill the valleys and perched depressions, taking the shape of channels and discontinuous lenses with limestone pebbles and gravel.

Overall, the bedrock is characterized by a great lithological heterogeneity, due to the frequent vertical and lateral alternation of different lithological sequences; the lithostratigraphic series are characterized by an abundance of clay as shown in Fig. 3 which controls a debris flows evolution in studied sector.

## Climate

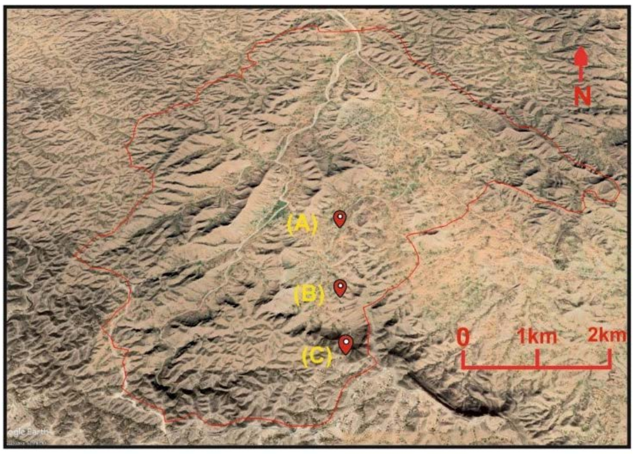
The climate plays a significant role in the initiation of debris flows. Intense or prolonged rainfall is a primary triggers which saturates a ground, increases pore water pressure and weakens the shear strength of a soil or a rock mass. Additionally, the temporal distribution of rainfall, such as concentrated or localized patterns during convective storms, can rapidly saturate specific areas, destabilizing slopes and leading to mass movements. Seasonal variations also influence debris flow occurrence, with wet seasons being more prone to such events. Antecedent moisture conditions, including soil saturation from previous rainfall or snowmelt, further contribute to the likelihood of debris flow initiation. Climate change, with its potential alterations to precipitation patterns and intensity, may also impact the frequency and magnitude of debris flows. Understanding the interplay between climatic factors and other variables, such as slope characteristics, lithology, vegetation cover, and human activities is crucial for assessing and mitigating the risks associated with debris flows.

The Matmata province has a hot Mediterranean climate with an arid bioclimatic and a dry summer. Low and erratic annual precipitation is between 100 and 300 mm (Fig. 6A), the monthly average precipitation for 19 years reveals that the rainiest months are December (with an average of 460.2 mm) and November (with an average of 388 mm), and the driest month is July with an average of 7.5 mm (Fig. 6B). While annual temperatures is 18–20°C, the annual evaporation varies between 1500 and 2000 mm. (Aydi *et al.*, 2022).

In conclusion, the Matmata province in Tunisia is characterized by a hot Mediterranean climate with arid conditions and dry summers. The region experiences low and erratic annual precipitation, with varying monthly averages. December and November are the rainiest months, while July is the driest. The annual temperatures remain relatively consistent and evaporation rates are high. These climatic factors have implications for the availability of water and the moisture content of the soil, which can contribute to the triggering of debris flows in the area. Understanding a climate pattern and its influence on debris flow initiation is crucial for effective risk assessment and mitigation strategies in the Matmata region. Further research and monitoring of climatic variables are necessary to improve our understanding of the complex interactions between climate and debris flow dynamics in this region.

## Hydrogeology

With a westward dip, the Dahar cuesta forms the eastern boundary of a large synclinal structure, namely the basin of the Grand Erg Oriental, where the lowest part is the Chotts depression. The eastern rim of this structure, known as the Matmata monocline, serves as the hydrogeological recharge zone for aquifer structures situated further west towards the centre of the Grand Erg Oriental basin. Moving eastward from the Matmata Cuesta, there is an area where the dip of the Cretaceous beds either faces north or is nearly negligible. This zone hosts several aquifer structures, predominantly free-flowing and phreatic (Bouaziz, 1995).



Sampling points:

| | | |
|---|---|---|
| (A): MT10,MT11,<br>MT12,MT13,<br>MT14,MT15,<br>MT16,MT17 | 605441,976 m E | 3707468,584 m N |
| (B):MT5,MT6,<br>MT7,MT8,MT9 | 605772,031 m E | 3704819,368 m N |
| (C):MT0,MT1,<br>MT2,MT3,MT4 | 604572,559 m E | 3703551,383 m N |

**Fig. 7.** Slope card indicates abrupt rises of topography with extension of mountains and rivers from west to east.

The Permian outcrops of the Tebaga mountain chain, oriented from west to east, contribute to hydrogeological compartmentalization. South of Tebaga, this leads to the presence of an extensive plain (Sahel el Ababsa), hosting a bi-layered aquifer centred on the Metameur Wadi. Further north, the predominantly Aptian–Cenomanian carbonate formations prove to be aquifers in the Zeuss-Koutine region. The relatively dense hydrographic network at the foothills of the Matmatas has facilitated the formation of phreatic aquifers, primarily "underflow" aquifers associated with the sub-flow of wadis. As a result, the aquifer structures in the Matmata sheet can be classified into two types of aquifers:

- Phreatic aquifers, with a prevalence of underflow aquifers associated with specific wadis and located within alluvial deposits.
- Deep aquifers housed within the of the Cretaceous, Jurassic and Triassic formations.

## RESULTS

### A role of slope angle in triggering and accelerating hazardous events

Because a slope of the terrain plays a significant role in triggering debris flows, in fact steeper slopes result in increased gravitational forces acting on the materials leading to higher shear stress. As the slope angle becomes steeper, the weight of the overlying material can exceed the strength of the underlying layers causing them to fail and initiate a debris flow. Moreover, steeper slopes provide a greater potential for downslope movement of materials. The gravitational force acting on the debris becomes more significant on steeper slopes, promoting the acceleration of the flow, this can lead to faster and more destructive debris flows. It is important to note that the slope angle is not the only factor triggering debris flows. Other factors, such as type and properties of materials involved, presence of water or excess pore pressures, vegetation cover which is absent in our case and antecedent conditions, also interact with slope angle to influence debris flow initiation. Therefore, a comprehensive understanding of local conditions and terrain characteristics is necessary to asses and mitigate the risks associated with debris flow. From the DEM, the slope layer was extracted and the study area slope map was divided into 6 categories: 0–3, 3–6, 6–10, 10–13, 13–18 and 18–26% (Fig. 7). These steep slopes facilitate erosion and the transport of loose materials downslope. When heavy rainfall or other triggering factors occur on steep slopes, the increased flow velocity can detach and mobilize sediment resulting in debris flows. The erosive power of the flowing debris can further increase with steeper slopes, causing more extensive damage.

### Arranging soils according to Atterberg limits

The plasticity of clay rocks plays a significant role due to their ability to undergo irreversible deformation without cracking or crumbling (Meisina, 2004). Changes in water content led to corresponding volume expansion or contraction in clay, making it susceptible to irreversible deformation (Yalcin, 2007; Yalcin *et al.*, 2011; El Jazouli *et al.*, 2022). The evaluation of plasticity is commonly done through Atterberg limits, including the liquid limit ($W_L$) and the plastic limit (Lp). Additionally, the plasticity index (Ip), calculated using equation (2), is used in the Casagrande plasticity chart (Casagrande, 1936).

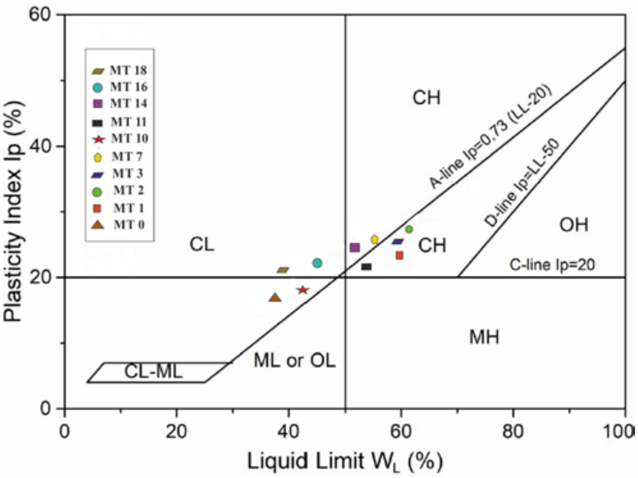


**Fig. 8.** Distributions of samples on the plasticity chart (CL: clay, silty clay, sandy clay of low plasticity, ML: silt, silty or clayey fine sand with slight plasticity, OL: silt and silty clay of intermediate plasticity, CH: clay of high plasticity, MH: silt of high plasticity).

The results of the analysis revealed that the liquid limits ranged from 38% (MT3) to 62% (MT2), with an average value of 51.9%. The plastic limits ranged from 18% (MT3) to 34.1% (MT2), with an average value of 25%. The plasticity index varied from 19% in MT10 to 27.9% in MT2, with a mean of 22.9%. Based on the Casagrande plasticity chart, seven samples (MT0, MT1, MT2, MT3, MT7, MT11 and MT14) belonged to the CH group, indicating high plasticity inorganic clay soils. The remaining samples were categorized as CL group soils, representing medium to low plasticity inorganic clay soils (Fig. 8).

These findings demonstrate the variability in plasticity characteristics among the analysed clay samples, with some exhibiting higher plasticity and others showing lower plasticity. Understanding the plasticity of clay minerals is essential for assessing their behaviour in response to changes in water content, which can have significant implications for slope stability and the triggering of debris flows.

## XRD characterisation of soils samples

The analysis of the examined samples provided semi-quantitative estimations of the mineral abundances in terms of weight percentages of the entire rock analysis. The study area revealed the presence of clay minerals from families such as smectite, illite and kaolinite. These clay minerals were identified along with their parent substances, including silica and quartz. Among the minerals found, quartz was the dominant mineral, while illite minerals constituted the majority of the clay minerals present. Additionally, there were other minerals observed in moderate proportions, such as gypsum, calcite and dolomite (Fig. 9).

The lithology of the Cenomanian formations in the study area is characterized by a high percentage of clay and marl. These formations, in combination with leaching and erosion processes, are susceptible to reduced consolidation and increased permeability during floods. As a result, they

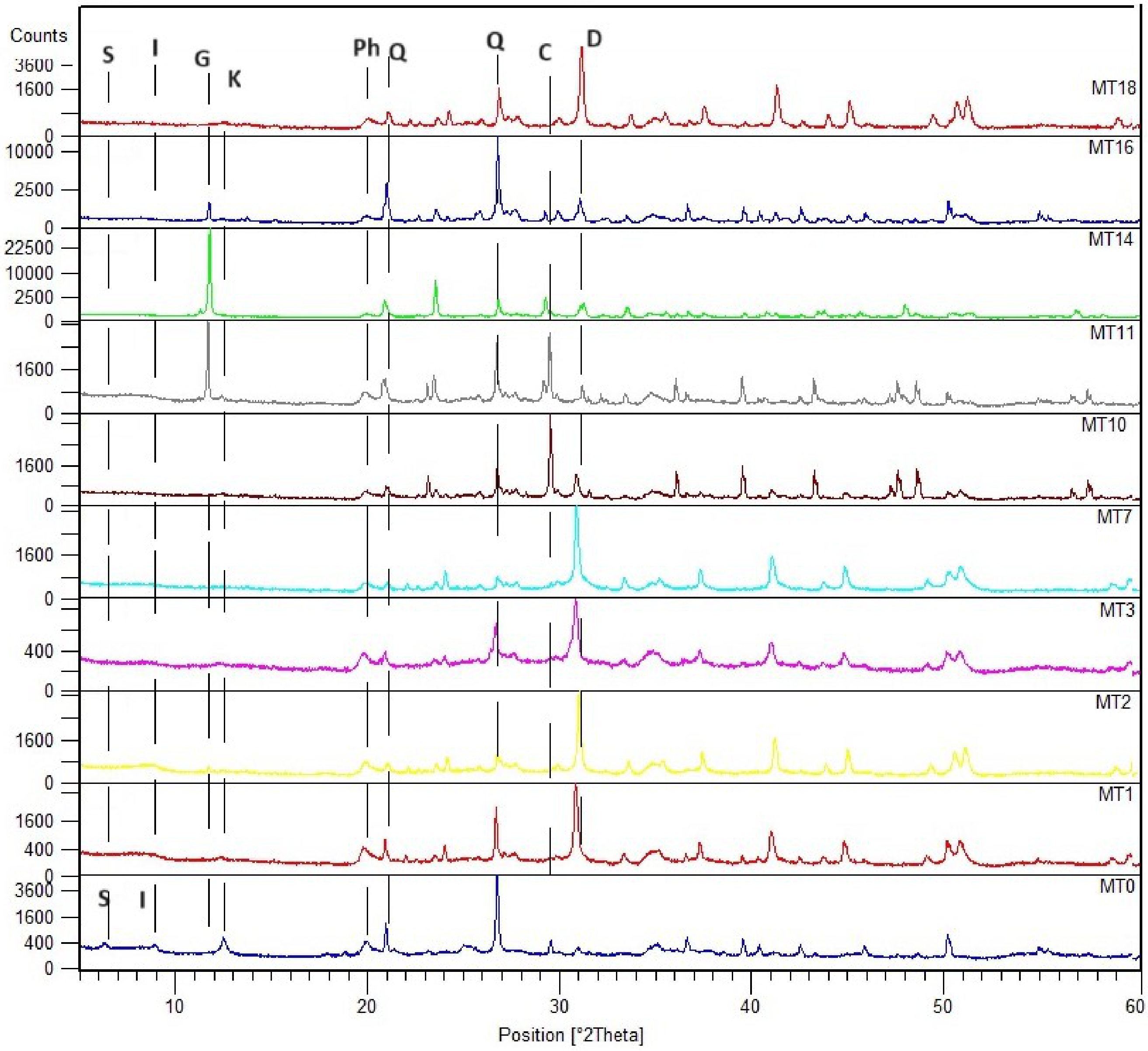


**Fig. 9.** X-ray diffractogram of the studied samples. S: smectite, I: illite, K: kaolinite, G: gypsum, Ph: phyllosilicate, Q: quartz, C: calcite, D: dolomite.

become more vulnerable to landslides. The presence of clay and marl in the lithology, combined with their altered properties due to flooding, contributes to the increased potential for landslide occurrence in the area.

The presence of clay minerals such as smectite, illite and kaolinite in the study area can have a significant influence on debris flows. Clay minerals have unique properties, including their ability to absorb water and undergo irreversible deformation without cracking or crumbling. When clay-rich formations, such as those with high percentages of clay and marl, are exposed to water during heavy rainfall or floods, they can become less consolidated and more permeable.

In wet conditions, clay minerals in the lithology absorb water, leading to an increase in their volume. This volume expansion, combined with the reduced cohesion and increased permeability of the clay-rich formations, can contribute to a destabilization of slopes and trigger debris flows. The excess water absorbed by clay minerals increases a pore pressure within a soil, reducing its shear strength and making it more prone to failure.

Furthermore, a presence of clay minerals affects behaviour of a soil during debris flows. The high plasticity and low strength of clay minerals can lead to increased flow velocities and higher mobility of a debris. The ability of clay minerals to deform under the influence of water further contributes to the fluid-like behaviour of debris flows, allowing them to travel significant distances and cause extensive damage.

Therefore, the combination of clay-rich lithology with a presence of gypsum and interaction with water during wet conditions creates favourable conditions for debris flows to occur. Understanding the influence of clay minerals on debris flows is crucial for assessing landslide susceptibility, implementing effective mitigation measures and reducing potential risks, associated with these hazardous events.

## DISCUSSIONS

The combination of intense rainfall, the clayey and marly nature of the outcropping rocks, and the presence of valleys connected to steep slopes has resulted in numerous landslides, including debris flows, in the studied area. Debris flows, a specific type of landslide phenomenon, occur when a mass of soil, rock fragments and water rapidly move down a slope. In the context of the Matmata region, the specific lithology, such as the Kerker formation composed of clay, silt and marl, plays a significant role in the occurrence of debris flows.

The distribution of grain size analysis reveals that the predominance of fine-grained particles, particularly silt and clay, greatly influences the triggering of debris flows. The high percentage of silt (ranging from 63% to 85%) and clay (ranging from 7% to 36%) in the slope materials contributes to their susceptibility to liquefaction during intense rainfall events. When the water content exceeds the bound water content in clay, the material transition

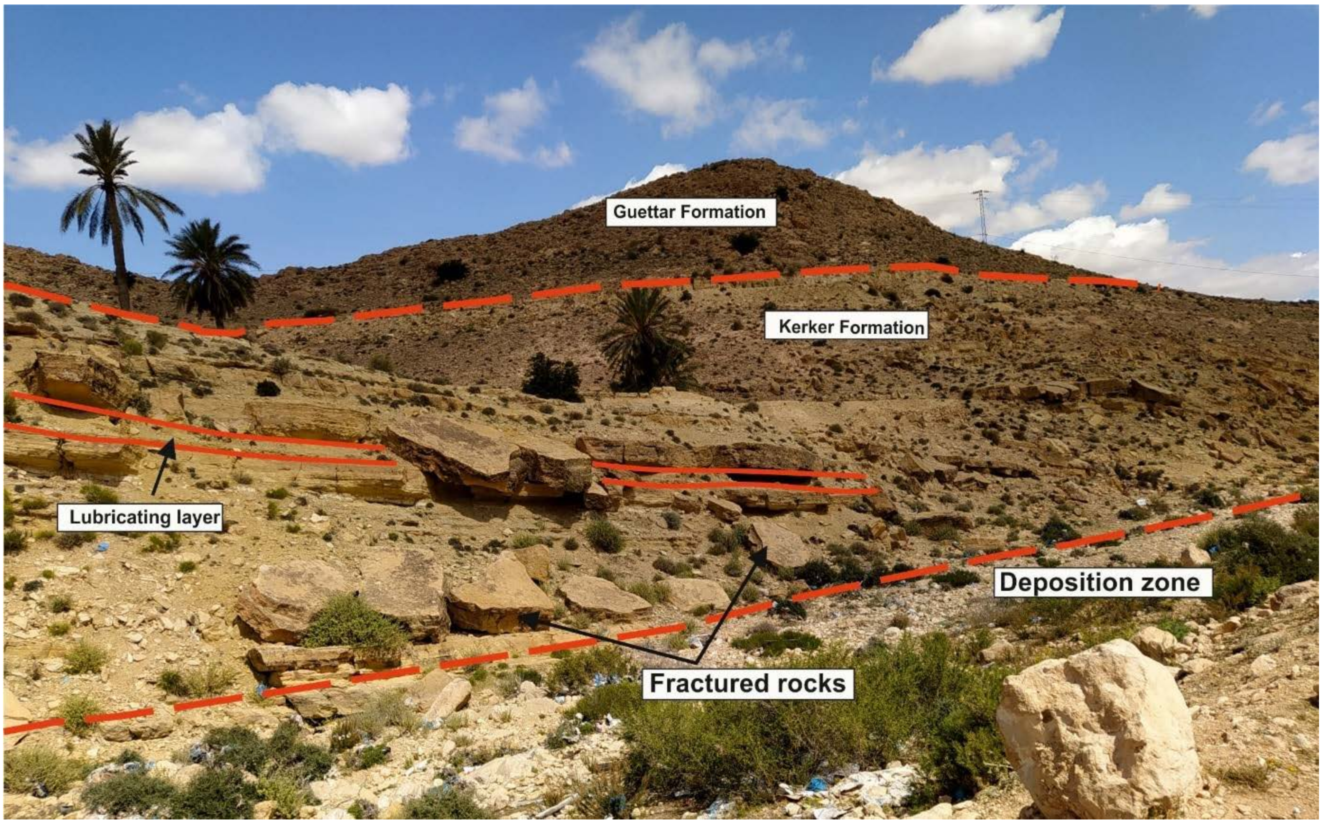


**Fig. 10.** Effect of lubricating layer on debris flows.

from a solid to a plastic and eventually to a liquid state, what increases their mobility and facilitates occurrence of debris flows.

Furthermore, a saturation of soils beyond the Atterberg limits (Wp and Wl) due to heavy precipitation further decreases the stability of the land and contributes to the rapid and instantaneous displacement of a large quantity of materials, characteristic of debris flows. The combination of clayey lithology, fine grain size distribution and saturation conditions creates an environment conducive to the initiation and propagation of debris flows in the Matmata region.

Additionally, external factors such as tectonic movements and the degradation of the rock mass further contribute to the occurrence of debris flows. These events exert strong stresses on the rocks, reaching their rigidity limit and deformation capacity, leading to rupture. The resulting alteration and opening of fractures enhance the detachment and fall of blocks, which are then mobilized as debris flows under the influence of gravity.

In summary, the specific lithology, fine grain size distribution dominated by silt and clay, saturation conditions and external factors collectively contribute to the occurrence of debris flows, a particular type of landslide phenomenon, in the Matmata region. Understanding these relationships is crucial for assessing the susceptibility to debris flows, implementing appropriate mitigation measures and ensuring a safety of the affected areas.

The Matmata area experiences the occurrence of debris flows, which are a result of specific geological and hydrological processes. The Guettar formation, characterized by carbonate and dolomite rocks known for their high mechanical resistance, significantly contributes to the initiation of debris flows in the Matmata area. These rocks create conditions conducive to the formation of clay materials, which act as a lubricating layer, facilitating the downward movement of large blocks with volumes exceeding 1 m$^3$. A presence of such block falls is a clear indication of the destructive nature of debris flows in this region (Fig. 10). The mechanical properties and composition of the Guettar formation, combined with the influence of gravity, play a crucial role in triggering these hazardous events.

The process of debris flows in the area is further influenced by hydraulic action, particularly the seasonal increase in hydrodynamic pressure associated with heavy rainfall events and fluctuations in the water table. The combination of intense precipitation and the rise in water levels exerts substantial forces on the already susceptible clay materials, destabilizing them and leading to the mobilization of debris flows. The erosion caused by the high-speed flow of water through wadis exacerbates the risk of landslides, including debris flows.

To mitigate the impact of debris flows and reduce the risk of landslides, practical measures such as the construction of storage dams have been implemented. The debris flows transported materials that filled the retaining dams or energy dissipating walls. By managing and controlling the speed of water flow, the risk of destabilizing the clay materials and triggering debris flows can be mitigated.

**Fig. 11.** . Location of sediment storage dams.

Overall, the process of debris flows in the Matmata area is influenced by the geological composition of the Guettar formation, the presence of clay materials acting as a slippery layer, and the hydraulic action of heavy rainfall and water table fluctuations. Implementing measures like breakwaters to manage water flow can effectively reduce a risk of debris flows and enhance the stability of the area. The susceptibility of the clay materials to act as a soap layer is further exacerbated by hydraulic action. The seasonal increase in hydrodynamic pressure, triggered by heavy rainfall and fluctuations in the water table, significantly impacts the stability of materials. The combination of intense precipitation and water level oscillations exerts substantial forces on a clay, making it more prone to instability and mobilization as debris flows.

To address the risk of debris flows and mitigate their impact, practical measures have been employed in the Matmata region. One such approach is a construction of storage dams (Fig. 11), which serve to slow down a water flow through wadis. By reducing a speed of water flow, storage dams help to decrease erosion and minimize a risk of debris flows. These measures aim to manage and control the hydraulic forces acting on the clay materials, enhancing overall stability and reducing the likelihood of debris flow occurrences.

In conclusion, the occurrence of debris flows in the Matmata area is influenced by a geological composition of the Guettar formation, a presence of clay materials acting as a lubricating layer and a hydraulic action associated with heavy rainfall and water table fluctuations. Implementing measures like storage dams can effectively mitigate a risk of debris flows and enhance an overall stability of the region.

## CONCLUSIONS

Understanding the factors that contribute to debris flows phenomenon, including lithology, slope, aspect, elevation and vegetation cover is crucial in managing a risk of debris flows. Our study focused on establishing a relationship between geotechnical characteristics and clay mineralization, utilizing XRD testing and Atterberg limits to classify soils. The results demonstrated a clear correlation between the properties of clayey soils and the occurrence of shallow landslides, particularly during periods of heavy rainfall. To mitigate the impact of flooding-related landslides, implementing advanced monitoring systems such as riverbank sensors can provide timely warnings and help prevent further damage. Additionally, utilizing the natural properties of clayey lithological formations, such as creating impermeable layers for mini-dams, can effectively manage runoff water and reduce the risk of debris flows. By considering these measures, we can enhance our understanding of the debris flow process and to develop effective strategies to mitigate their impact, ensuring a safety of communities and infrastructure in susceptible areas.

Overall, gaining a nuanced understanding of the multifaceted factors contributing to the phenomenon of debris flows, encompassing lithology, slope, aspect, elevation and vegetation cover, is paramount for effective risk management. Future research endeavors could focus on delving deeper into the geotechnical aspects of debris flows, exploring additional factors or refining relationships between key variables such as lithology, slope, elevation and vegetation cover. Integration of advanced remote sensing technologies, like satellite imagery and LiDAR data, could provide a more comprehensive and detailed perspective on terrain characteristics, enriching risk assessment models and capturing changes in landscape features over time.

Moreover, considering the potential impacts of climate change on rainfall patterns and intensity is crucial for anticipating future scenarios. Investigating how changing climatic conditions may influence the frequency and magnitude of rainfall-triggered landslides, can enhance our adaptive strategies. In parallel, community engagement initiatives should be prioritized, involving local populations in risk reduction programs, implementing community-based early warning systems and fostering collaboration with local authorities to build resilience and awareness.

Furthermore, future studies could adopt a multi-disciplinary approach by collaborating with experts from diverse fields such as hydrology, climatology and ecology. This holistic understanding of the interconnected nature of natural processes can lead to more effective mitigation strategies. Finally, bridging the gap between research findings and policy implementation is crucial. Advocating for policies that incorporate insights from such studies can contribute to proactive land-use planning and infrastructure development in vulnerable areas, ensuring the safety of communities and infrastructure.

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