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Study of landslides in the molassic hills of Ait H'ssine between the Jurassic and Miocene of the El Ksiba Atlas, Morocco

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ABSTRACT

Landslides are a major problem in the Atlas Mountains and hills of Beni Mellal-Khenifra, Morocco. The main objective of this study is to examine the relationship between landslide movement and hydrogeological data from the Atlas hills in order to propose a model that characterizes slopes threatened by landslides appropriate. The field data collected was used to produce geological cross-sections and maps. The geology of these hills shows an abundance of marl-limestone and marl-clay formations and Permian basalt intrusions that are altered in places. The results also showed that these hills have areas of gravitational instability due to the behavior of the materials in the presence of water. The new techniques in structural geology and hydrogeology presented in this work support the hypothesis of an area at risk of naturally triggered slope movement. A map of 24 sources, including both dry and permanent sources upstream of the study site, shows that aquifers and groundwater levels determine the state of rupture and shear at slopes at risk of landslides. The depletion of the aquifer causes the appearance of desiccation cracks in the substrate at the level of the hills, making them highly vulnerable and susceptible to geological instability risks. The geological nature of the formations and the oscillation between dry and wet periods favor conditions conducive to rupture and downstream displacement of soil masses.

Keywords: Hydrogeology, Landslide, Molassic Hills, instability risks, Atlas, El Ksiba, Morocco

INTRODUCTION

Landslides are displacements (with or without rupture) downstream of rock masses, compact or disaggregated and/or loose ground under the effect of gravity (Benouis, et al, 2010). They can occur in the form of abrupt processes (falling rocks and blocks, landslide and collapse, sudden slide, mudslide and collapse) or slow and gradual (creep, permanent slow slide). The axis of the chain is often formed by Paleozoic and Precambrian terrain that overlaps the Mesozoic-Cenozoic cover through gently sloping reverse faults. Reverse Horst faults reflecting the overlap of the Paleozoic on the secondary, consequence of the opening of the Atlantic Ocean after filling of the Jurassic basin (Alaoui, et al 2022). In fact, normal faults during the Triassic extension reactivated as reverse faults during the Tertiary period. These structures served as drains for hydrothermal circulation, facilitating the deposition of zinc, lead, and barite mineralization. The High Central Atlas in Morocco is a segment of a vast intracontinental chain, which extends from the Atlantic Ocean in the region of Agadir in Morocco to the Gulf of Gabes in Tunisia (Alaoui, et al 2022).

In Morocco, the areas known by landslides are mainly the Rif, the Middle Atlas and the High Atlas thanks to the different reliefs, and friable geological formations (clays, flyschs, and marls), faced with local climatic conditions. Landslides can be caused by the effect of several factors, namely intense rains, floods, neotectonics, groundwater level variations, geology, vegetation cover, topography and anthropogenic action, therefore, these effects increase the shear stress or else decrease the cohesion of the sloped materials. The study of landslide risks is a key element in the management of political efforts in terms of disaster prevention, risk mitigation and management of their consequences (Yalcin, et al., 2008, Vakhshoori and Zare, et al., 2016). Although few studies have attempted to directly characterize the behavior of clay soils and muds in landslides (Coussot et al., 1998; Hungr and Picarelli, 2014; Malet et al., 2005). Landslide characterization could provide very useful clues to the nature of slope failure and subsequent debris movement, indicating where landslides could potentially occur (El Afi et al., 2023).

A series of studies based on the geological nature and mineralogy of soils provide useful information on the presence of clays in substrates that promote landslides (Daoudi et al., 2015; Diko et al., 2014; Ngole et al., 2007; Yalcin et al., 2007; Yalcin et al., 2008). Between the middle mountain and the area of molassic hills, there is a series of slopes which present landslides at different scales and magnitudes with respect to the nature of the geological formations and climatic conditions. This work can provide the information needed to locate areas susceptible to landslides, thereby protecting human lives and their property (houses, roads, agricultural fields, etc.). Knowledge of underground and surface water flows is one of the most effective ways to prevent, stabilize, or slow down a landslide. A study of groundwater and surface water supply is essential to provide an appropriate response. This demonstrates the importance of hydrogeological studies in understanding the evolution of landslides and controlling the associated risks.

Most of the aquifers in this area are fed by the snow slit from ridges between 1800 m and 2000 m, and fine rains in the presence of a porous calcareous-dolomite substratum (Alaoui et al., 2017). Measurements made for different aquifers upstream of the slope have shown that the arrival of water at the foot of the slope in dry periods has a direct impact on instability of the slide (Alaoui et al., 2017). Landslides caused by rainstorms are a widespread geomorphological hazard that can lead to major emergencies, causing serious damage to life and property. (Schilirò et al., 2016; Schilirò et al., 2022; Yin and Gao, 2024).

The main objective of this study is to determine the precursory causes of this landslide in a geological and hydrogeological context. This research focuses on the study of gravitational instabilities of landslides in the red hills of El Ksiba, in the central Middle Atlas Mountains of Morocco. The 3D model designed based on data collected at the site between the mid-mountain range and the plain aims to precise the location of the various aquifers that have a direct impact on the evolution of this landslide over time and space. This 3D model makes it possible to specify the geomorphology of the study area in order to detect all the thalwegs, streams and their paths towards the plain.

MATERIALS AND METHODS

The study site is located along the NE-SW oriented red hills, which is part of the territorial commune of Dir El Ksiba, circle of El Ksiba, province of Beni Mellal, Kingdom of Morocco. This section at Lambert coordinates [430000E-45000E] and [210000N-225000N] is located between the Tadla plain with Quaternary terrains at an altitude of 600m and the mid-mountain at 1200m, from Permian, Jurassic to Miopleocene age. After selecting the site, the sources and aquifers were mapped, and the faults that govern groundwater flow were identified in the Jurassic and Cretaceous periods, targeting hills with a potential risk of landslides (Figure 1). The results obtained were interpreted as a hypothesis and an argument to deduce the appropriate methods to stabilize these red hills against external constraints (Figure 2). During field missions, 24 sources were mapped, including both dry and permanent sources, in order to gain an understanding of the main aquifers in the study area. Their flora environment has

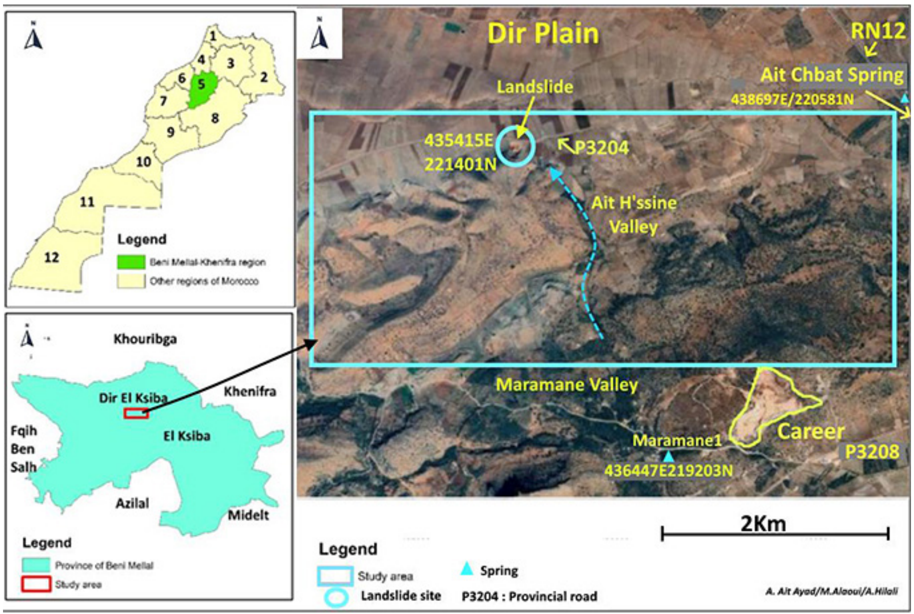

Figure 1. Geographical and regional location of the study area

been identified and the flow rate of permanent springs has been measured. Topogeological cross-sections were also made in the field to identify the dominant geological deposits. After targeting the study area, the intervention framework was extracted from the geological map of Qasbat Tadla at the scale of 1/100000, after its georeferencing using GIS, we digitized all the geological formations, streams, average elevations, slopes, (DTM excerpt) and inclinations encountered in the field, and the tectonic structures that have affected the region via Arc GIS (10.3) to revive and give the right rhythms of events geologic for better clarity of its paleogeographic context. A mathematical model has been developed using geological cross-sections of these sources, which is essential for determining the geological nature of the aquifers and their impact on gravitational instability in the molassic hills.

STUDY AREA

In El Ksiba, average monthly precipitation varied between 30 and 120 mm for the period 2003-2016. Average annual precipitation varies between 400 mm and 1,400 mm for the same period. These variations are sometimes accompanied by significant seasonal and interannual irregularities. Most precipitation occurs during the cool seasons. This precipitation rate is increased by the late summer and late spring showers each year (Alaoui, et al. 2017).The dry season, which extends from mid-May to mid-October, promotes decohesion and cracking of marl-clay soil (Alaoui et al. 2017). Beni Mellal-Khenifra is one of the most important regions of central Morocco, located between the pleated limestone the Beni Mellal High Atlas and the Tadla plain. It is one of the main agricultural areas of Morocco. This is due to good soil conditions, favorable climate and abundant underground and surface resources. Thus, agriculture is the main socio-economic activity in the region (Ennaji et al. 2018). The culture is based on cereals, fodder, orchards (olives and citrus fruits), sugar beet and cotton, and vegetables.

The altitude of the study area is varied from 550 m to 900 m (Table1). It is characterized by a Mediterranean climate with a dominance of semi-arid weather with a dry season from April to October and a rainy season from November to March with annual temperatures varying from 38°C to 40°C in summer and 3°C to 4°C in winter. The average rainfall received in this region is about 259 mm/year (Hilali et al., 2020).

Geological setting

During the Triassic period, the opening of the basin by conjugate normal faults caused a thinning of the continental crust, which led to the rise of the so-called "Upper Triassic" basalts. In the Lower Lias there were shallow carbonate deposits on platforms with reefs. At the end of

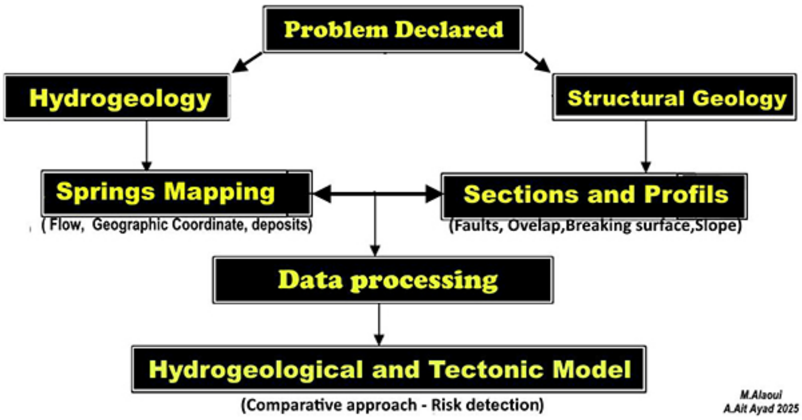

Figure 2. Methodology adopted in this study

Table 1: Lambert and geographical coordinate of Landslide study area

Sample E2	X	Y	Z (m)
Lambert (GPS)	435415	221401	673
Geographic Coordinates (Google Earth 3D)	32°35'12''N	06°05'10''W	682

the Middle Jurassic the filling of the basin was generalized with red layers (Laville et al., 1984). During the Cretaceous, when a tectonic phase had begun that has lasted until today, a transgression in the Upper Cretaceous is related to the opening of the South Atlantic, with also the rapprochement of Africa and Europe. The erosion of the overlapped mountains favored the formation of the Molasse hills which take the same direction of the thrust line which is NE-SW in general. Geological factors and slope play a key role in triggering these active hazards in relation to regional seismicity, which ranges from 3.2 to 4.4 on the Richter scale (Figure 3).

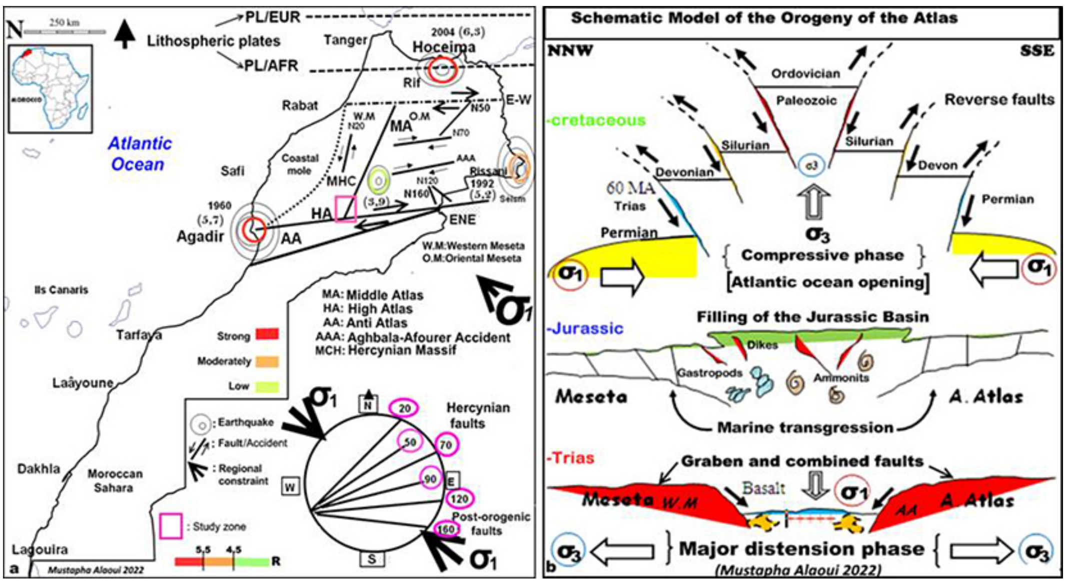

Figure 3. Schematic Structural and Sismic Map and Model of Orogenesis;
(a) Simplified tectonic and principal Sismic Mapping of Morocco;
(b) Synthetic Model of the Central Atlas orogeny: (σ1), regional stress of the final Tertiary basin; (σ3), regional distension of the Triassic basin; NF, Triassic normal fault; RF, Tertiary reverse fault (Alaoui et al. 2022)

RESULTS AND DISCUSSION

Structural study

The study site is characterized by two fault networks. The first network is oriented NE-SW, which corresponds to Triassic normal faults that reactivated as reverse faults during the Cretaceous, leading to the overlapping of Jurassic formations over those of the Miocene to the NW. At the level of the valleys, the formations become vertical as they move downstream in relation to the nature and difference of rheological competence. The overlapping faults have affected the karst pockets and aquifers, leading to the emergence of most of the springs in the region. The second NW-SE oriented fault network is younger and causes the formation of the main valleys that drain water towards the Dir plain. The NW-SE oriented geological section [DD'] crosses most of the Atlas field between the high Jurassic mountains and the Pliocene-Quaternary plain, passing through the zone of external and internal scales. This cross-section shows us the overlap of the ancient field over the recent fields, which is in principle linked to the geodynamics of the Atlas orogeny. The Jurassic marl-limestone and dolomitic series constitute the allochthonous scales of El Ksiba on the autochthonous Cretaceous and Pliocene-Quaternary series. This area, which is the subject of several mining exploration permits aimed at exploiting new mines and old abandoned galleries and spoil heaps, is exposed to risks of instability. The old abandoned lead mine of "Boulmâadane," nestled in the travertines of El Ksiba, is a typical example of a risk area (Figure 4; Figure 5; Figure 6).

The geological nature and the type of sediment are two critical and primordial triggers. These hills form low structures oriented NE-SW, of friable land formed by marine deposits of limestone and marl, phosphate sands, conglomerates and pink sandstones, going up to El Ksiba constituting a chain bordering the Atlas and which are part of the outer series superimposed to the South and East showing a landslide phenomenon in places, and are limited by outcrops of altered basalt from the Permian-Trias volcanic, and schists and quartzites on the metamorphic limits on either side, and on the other side of the Ait Chabat valley to the northeast.

The landslide in question is of the gravitational type according to Varnes model (1978). This hazard case mobilizes a very large volume of materials downstream. The area affected by this movement exceeds 11,000 m^2 (Figure 7). The simplified geological cross-section conducted on-site shows the main formations of the studied site from the Quaternary to the Paleozoic. The part exposed to the landslide is located on the post-orogenic molasses resulting from the erosion of the overlapping terrains (Figure 8).

Slope is a key factor in landslides. In this study, the average slope is between 10% and 30%, which promotes instability of the material after particle cohesion breaks down, particularly after heavy rainfall. As a result, mudflow develops due to the excess weight of the particles caused by the water content (w), which reduces pore resistance or pore pressure. The Ait H'ssine valley, where the slope tends towards 30% at an altitude ranging between 850 m and 900 m, has promoted the migration of part of the slope towards the P3204 road. The areas located in the foothills of the Atlas Mountains have altitudes between 600 m and 900 m, which increase the risk of actual landslides. Between the three sites

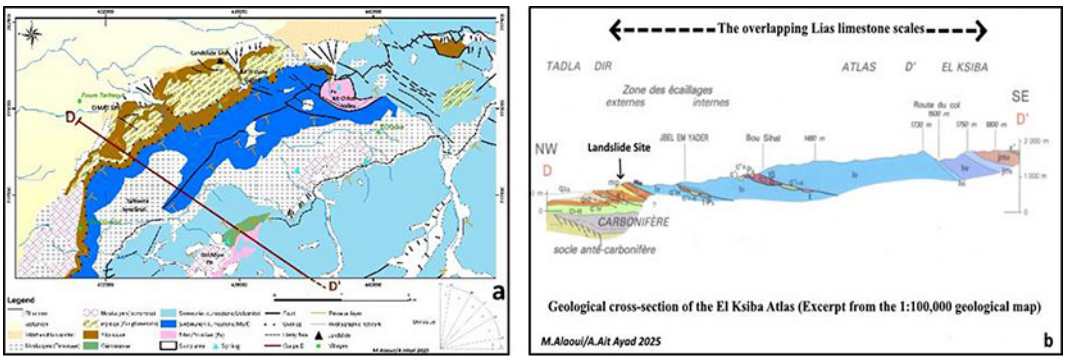

Figure 4. General context of local geology between mid-mountain and molassic hills of El Ksiba (a) Geological map of the part designed by GIS (Modified from El Afi et al., 2023); (b) Kilometric section between the high mountain and the area of the Molasse hills towards the North-West

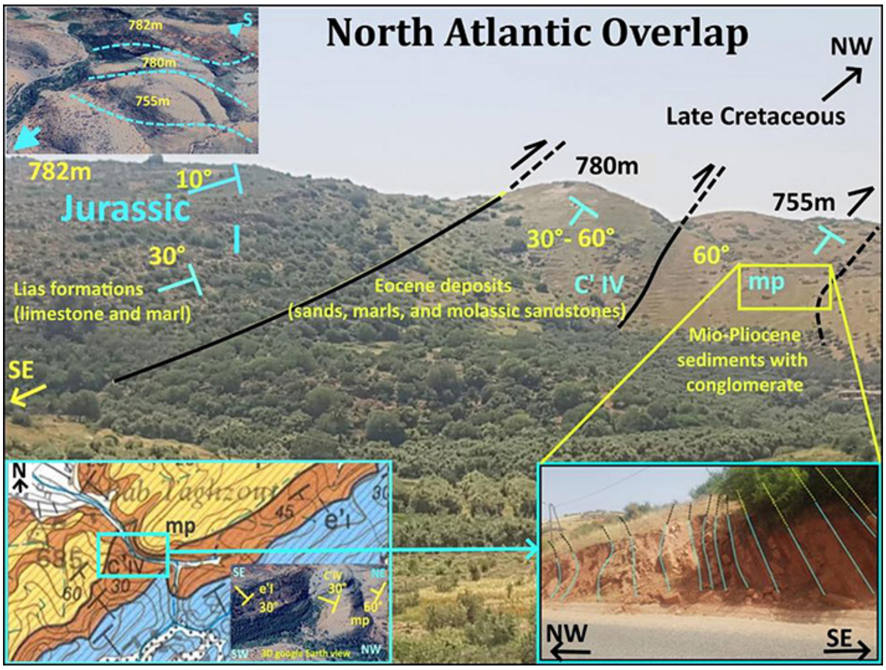

Figure 5. Field mapping and 3D Google Earth view of the overlap between the Lias and the late Cretaceous (Part of the geological map of Qasbat Tadla 1:100,000) where the roadside shows the formations overlapping the Miocene with a vertical fault

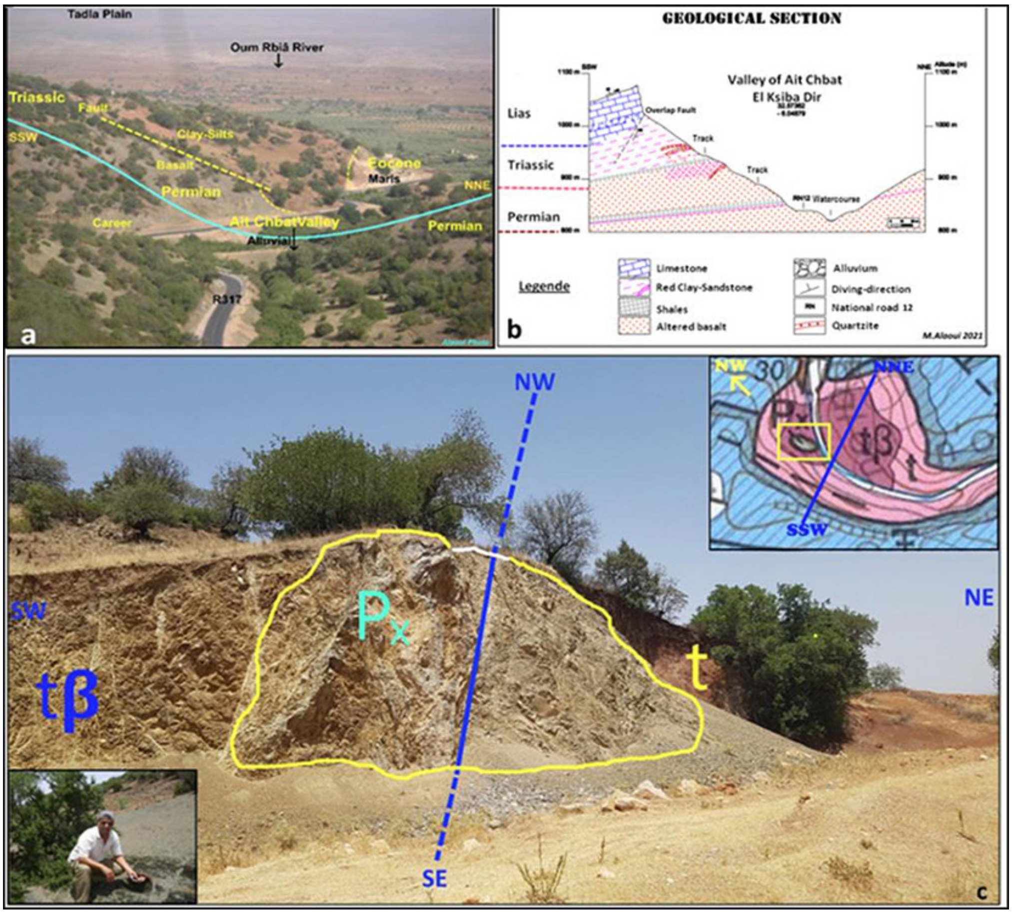

Figure 6. The Ait Chebat Valley between the Permian and Triassic periods: (a) Panoramic view of the valley from the ESE, (b) Synthetic cross-section of the Permian basaltic part of the valley; (c). A Crochon-Fault within the Permian surrounded by Permian-Triassic basalt

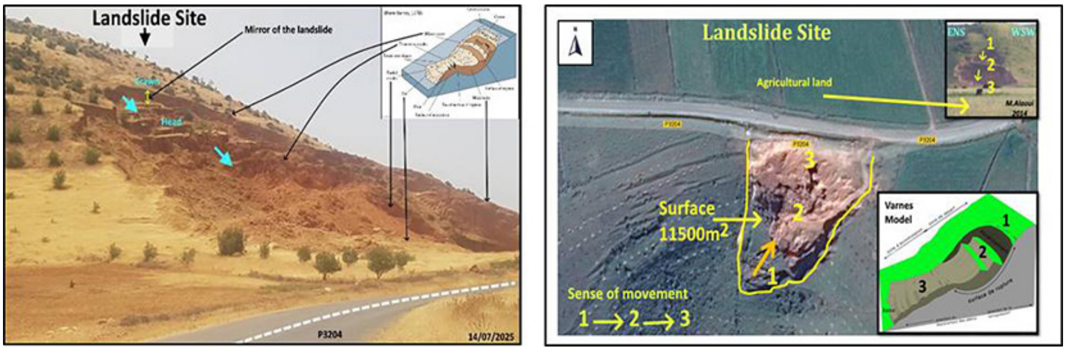

Figure 7. 3D satellite image showing the surface area in (m^2) of displaced soil and photo of the landslide site: case of a mobile embankment according to the Varnes model (1978)

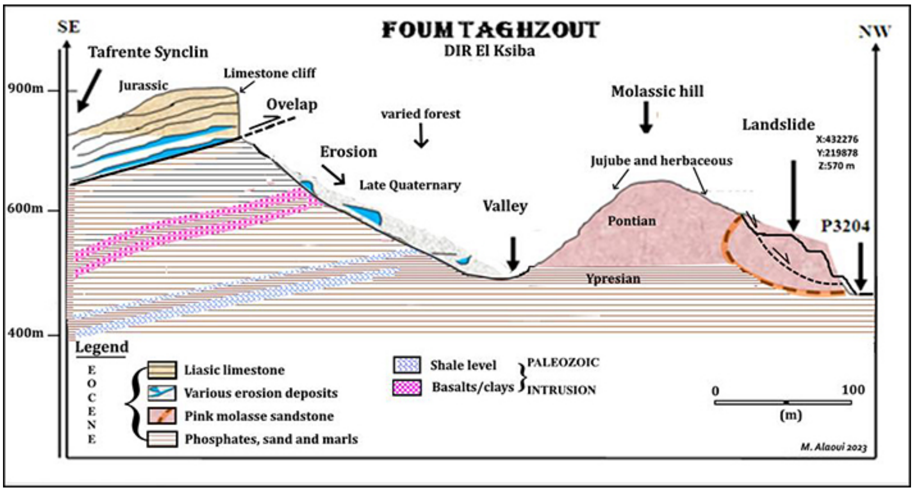

Figure 8. Simplified schematic model of the genesis of molassic hills after overlap followed by erosion of the Lias ridges and model of instability of the newly formed layers downstream

of gravitational instability, there is a risk of landslides that increases with the slope, ranging from 20% to 30% for the landslide site (Figure 9).

Hydrogeology study

The region of El Ksiba enjoys a set of moderately dense forests with a variety of species of trees and shrubs among other herbaceous. The altitude and the calcareous nature of the soil favors the existence of some endemic types relating to this region such as Laurel sauce, Zen Oak. The intense demand for construction materials has prompted contractors to exploit quarries in order to target thick series with friable calco-dolomitic formations as well as the hills and foothills with karstic limestone of Dir El Ksiba. These trees retain the majority of the rainwater that infiltrates by intercepting or recharging the water table. Forests have a significant effect on the water cycle, especially with evapotranspiration. Vegetation cover is of considerable importance in stabilizing slopes, as roots reinforce and fix the soil layers. This is why trees and shrubs with deep, dense roots are more effective in reducing soil movement. The karsts sheltered mineralization at the level of the middle Lias by the establishment of zinc and lead mines as "Calamina" or Calamine in the Atlas Béni Mellal-Khenifra.

After the years of drought between 2019 and 2024, the aquifers in this region have seen a change in the flow of springs. A map of around twenty-four (24) dry and permanent springs between the mid-mountain (1350m) and the molassic hills (650m) showed that the majority of springs located downstream are less affected by the lack of rainfall. Most of the upstream aquifers are virtually depleted as a result of drainage by the slope and the deficit in snowfall and rainfall over the last four years.

The bedrock of these aquifers is generally carbonate, as shown in the 3 sections (Figure 10).

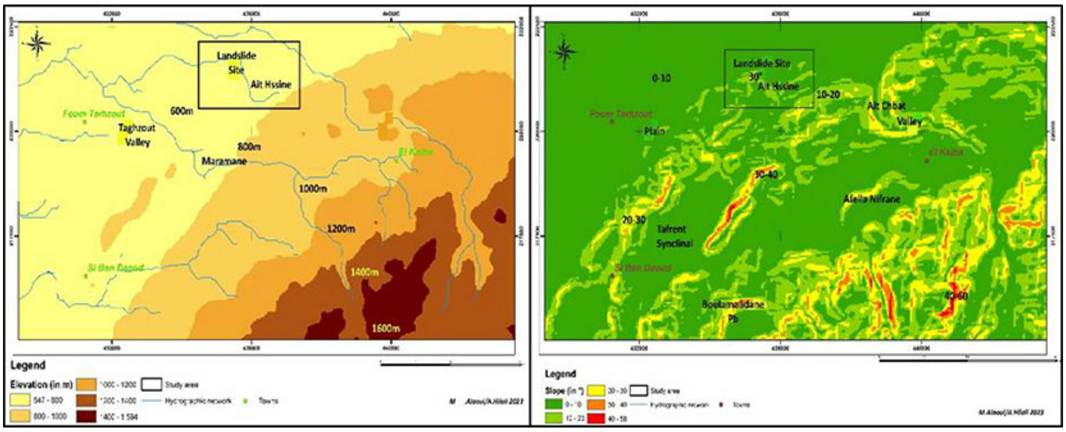

Figure 9. Elevation and Slope maps with location of the study area (Modified from El Afi et al., 2023)

Clay levels are found between the Permian basalt and the Liassic limestone, which shows that the aquifer wall is impermeable. This is explained by the permanence of some springs throughout the year, despite the very high summer temperatures. This water downstream from this area may be a real precursor of the gravity instabilities encountered on the way to the red Tertiary hills known as the Molassic Hills.

Between 2016 and 2024, the region recorded high temperatures from April to September, and the deficit in annual precipitation has influenced water resources. This impact has affected the state of spring flows, leading to the desiccation and disappearance of most springs, especially those arising from the aquifers of the medium mountains and molassic hills. Consequently, 9 out of 24 springs listed in the Dir of El Ksiba remained permanent, while 15 out of 24 dried up due to the weather changes in the region and throughout Morocco. 68% of the mapped springs are confined within the limestones. 32% of the springs are located in the travertines, basalts, schists, silts/clays, and marls with comparable percentages of 8%. The flow rate of the continuously flowing springs varies between 55.6 l/s and 0.1 l/s, mainly those from limestone and karst formations; while the depletion of springs is frequent in enclosed aquifers in the basalts and schists as they are altered and permeable. The environment of the mapped sources is characterized by the dominance of plants that require a significant water supply. Despite these years of drought, the resilience of a few trees (oleander, poplar, and fig) has been observed at this site. It can be seen that the upstream springs have a low flow rate compared to the downstream springs, to the point of becoming zero, as in the case of Afellanifrane1 and Taghbalout1, which have completely dried up. In this regard, it can be deduced that the shallow aquifers located upstream are being depleted due to their small surface area and low recharge rate. As for the deeper downstream aquifers, they are more extensive and are fed by drainage water from the melting snow on the dolomitic limestone ridges (Table 2).

The analysis and interpretation of the data collected in the field shows the abundance of limestones, dolomites, clays, and marls, the latter always forming groundwater reservoirs and springs. After modeling, the 3 sections below show the dominance of carbonates and the outcropping of Permian basalts and alluvium (Figure 10).

Most of the permanent flow sources in the Béni Mellal-Khenifra region come from aquifers formed in the Jurassic limestone karsts. The depletion of aquifers during dry periods leads to the formation of desiccation fractures. The return of humid and rainy periods causes the recharge of the aquifers and the reactivation of fractures. The increase in water content in the rock intensifies interstitial pressure, subsequently causing landslides in certain areas.

According to monitoring carried out during August 2025, it was found that the dried-up springs located at the foot of the overlapping limestone scales (Tarkast, Aazawa1, Aazawa2, Boutout2) are fed by karst pockets located between 1,400 m and 2,035 m above sea level. Given the succession of drought years from 2019 to 2025, these small reservoirs have been depleted, which has automatically affected the water status of these springs. As for the Ali-O-Brahim and Maramane springs, the exploitation of the aquifer by

Table 2. Mapping of dry and permanent springs between the Jurassic and Permian periods in the overlap zone (1, Upstream Spring; 2, Downstream Spring, 2004 to 2025 Dry Years)

Name Source	X (m)	Y (m)	Z (m)	Q (l/s)	Substrates	State	Vegetation
Afellanifrane1	439069E	217836N	1080	20,7	Limestone/Karst	Permanent	Oleander
Afellanifrane2	439045E	217784N	1075	1,5	Limestone/Karst	Permanent	Oleander
Ali O Brahim1	437964E	218430N	962	0	Travertine	Dry(2020)	Fig tree
Ali O Brahim2	437968E	218464N	946	0	Travertine	Dry(2025)	Fig tree
Aghbalou	440528E	218511N	1053	55 ,6	Limestone/Karst	Permanent	Carob tree
Tarkast	440657E	218604N	1068	0	Marl/Silt/Clay	Dry(2021)	Mastic tree
Taghbalout1	442330E	217631N	1153	0	Dolomite/Limon	Dry(2020)	Poplar
Taghbalout2	442221E	218006N	1138	18,4	Dolomite/Limon	Permanent	Poplar
Ali Ou Jdid	439500E	218954N	961	0	Silt/Clay	Dry(2019)	Olive tree
Ait Chbat1	-	-	-	0	Basalt/Schist	Dry(2016)	Carob tree
Ait Chbat2	438697E	220581N	853	0	Basalt/Schist	Dry(2021)	Carob tree
Maramane1	436447E	219203N	893	0	Limestone/Sandstone	Dry(2021)	Olive tree
Maramane2	434355E	219234N	720	0	Limestone/Sandstone	Dry(2022)	Olive tree
Ousfrou1	433753E	216903N	819	10,8	Limestone/Karst	Permanent	Olive tree
Ousfrou2	433727E	216934N	816	12,3	Limestone/Karst	Permanent	Olive tree
Boutout1	436178E	216420N	1039	0	Marl/Silt	Dry(2022)	Fig tree
Boutout2	436115E	216571N	1029	0	Marl/Silt	Dry(2025)	Mulberry
Awdim1	435435E	215138N	1150	0	Limestone/Dolomite	Dry(2020)	Oleander
Awdim2	435617E	215642N	1134	0	Limestone/Dolomite	Dry(2021)	Dwarfpalm
Aazawa1	435748E	216070N	1048	0	Marl/Limestone	Dry(2025)	Poplar
Aazawa2	435681E	216317N	1026	0	Marl/Limestone	Dry(2025)	Olive tree
Taqi1	440231E	222370N	759	0	Limestone/Karst	Dry(2004)	Carob tree
Taqi2	440246E	222384N	747	0	Limestone/Karst	Dry(2021)	Carob tree
SidiBendaoud	431440E	215684N	712	0	Limestone /Marl	Dry(2020)	Spurge

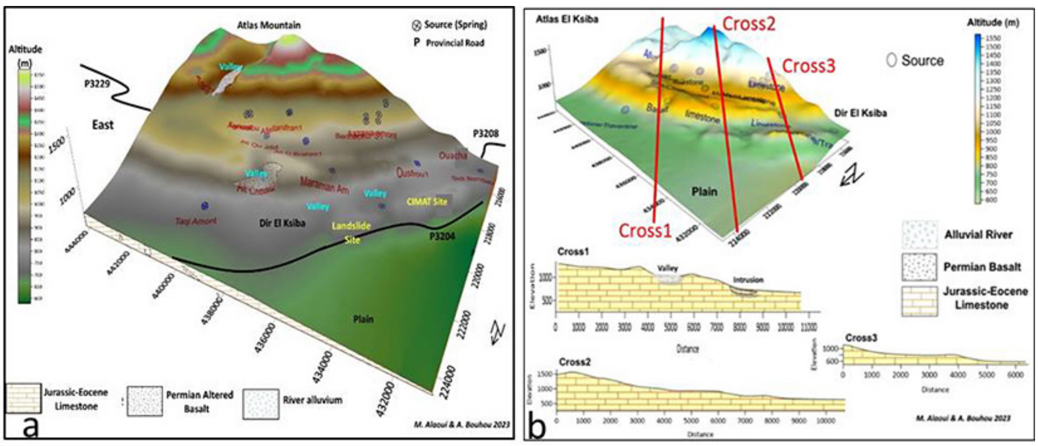

Figure 10. Mathematical model between the base and the aquifers in the landslide area in the molassic hills: (a) 3D map showing the locations of springs and the geomorphology of the study area; (b) simplified cross-sections between the mid-mountain area and the hill area

pumping wells at depths of between 130 m and 110 m at the Tafrent syncline has led to their total depletion (Figure 11). Consequently, the depletion of the aquifer causes the appearance of desiccation cracks (Alaoui et al 2017) in the substrate at the level of the hills, making them highly vulnerable and susceptible to geological instability risks. Deforestation and the arrival of autumn rains triggers

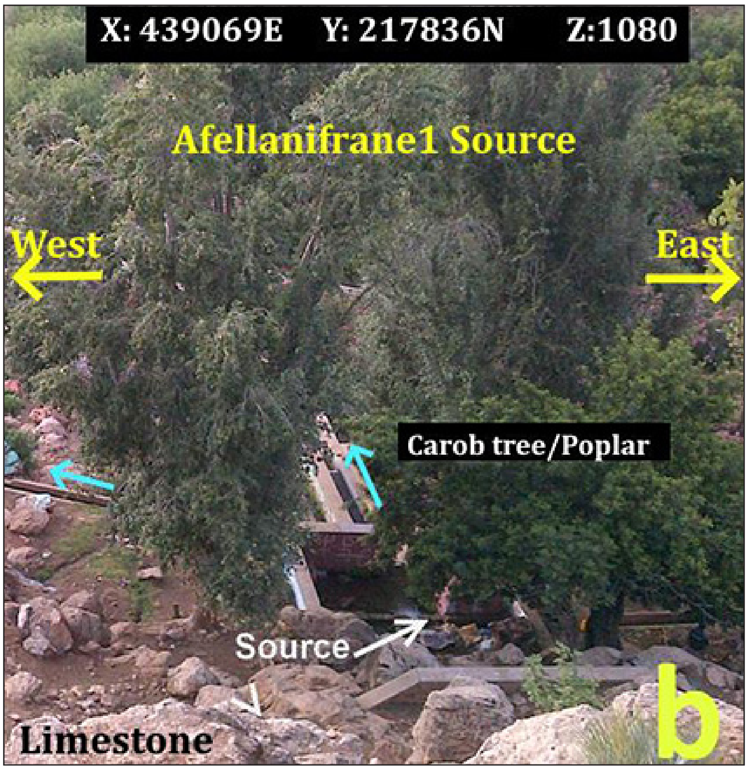

Figure 11. Cases of mapped springs. (a): Dry spring (SidiBendaoud); (b): Permanent spring (Afellanifrane1), located upstream of the landslide

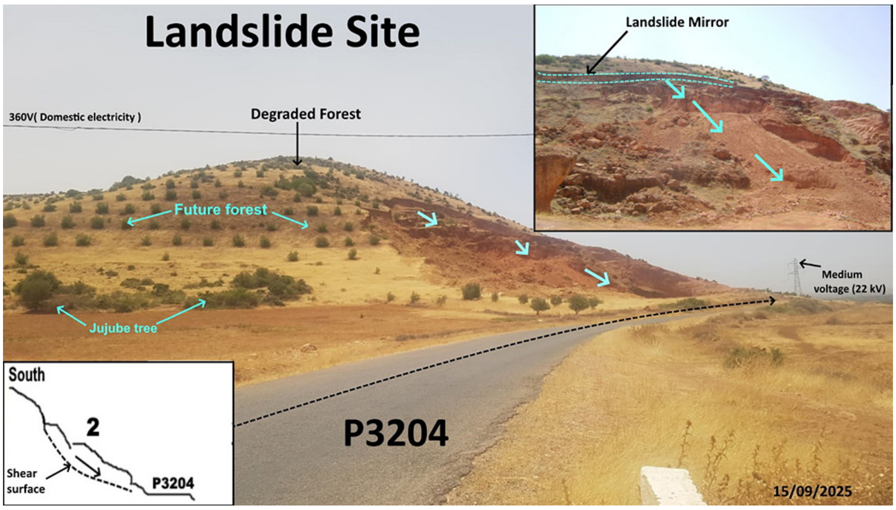

Figure 12. Panoramic view of the molassic hill with potential for landslides, mobilizing a large mass of soil toward provincial road P3204

breaks and shearing in geological formations by reducing particle cohesion (Figure 12).

CONCLUSIONS

The main factors of gravitational instability vary from one region to another depending on climate changes between rainy periods and dry ones. In the case of this landslide, the triggers manifest in two major categories, namely:

- Geological nature, the mechanical state of the soil, and regional seismicity are indirect factors that govern the mechanism of failure of slopes and geologically unstable slopes;
- Hydrogeology, hydrology, precipitation, and slope are the main direct natural factors of this type of landslide; however, human activities

related to infrastructure works and the exploitation of quarry materials can be one of the indirect factors.

In general, the study area is a marly-limestone and clayey domain. It is worth noting that this area is crossed by temporary watercourses that follow the NW-SE faults. The overlapping NE-SW faults have affected the karst pockets and aquifers, leading to the emergence of most of the region's springs in carbonate formations. The recharge of desiccation fractures by rainwater promotes the mechanical action of water on the failure state of certain slopes, exacerbated by slopes ranging from 20% to 40% in these geologically unstable formations.

The study area and its extensions to the northeast and southwest are exposed to slope movements, and over time, these risks will increase due to population growth, increasing urbanization and development in steep areas, deforestation of slopes, and increased regional precipitation caused by climate change. Forest degradation reduces slope stability after the deterioration of the tree root system, which facilitates the mechanical action of rainwater.

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