The Geologic Contribution to the Mountain Slopes Instability and its effect on Rockfall Hazards. A Case Study to the Zintan Road, Jabal Nafusah, Libya

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ABSTRACT

The paper is intended to address geological characteristics for risk evaluation of rockfall hazards attributable to the high cut in weathered rock that sometimes obstruct the passage of vehicles in the Zintan mountain road case study region and recommend mitigation steps to reduce these threats. The geological structure of the area, the composition of the rocks, the hydrologic conditions, and the steepness of the slopes all affect these materials' strength and susceptibility to failure. The areas at the source of the falling rock have been identified. The evaluation of geological formation and its structures as rocky units of slopes determined in this present study demonstrates that it is mostly comprised of friable rocks interbedded within hard rock such as dolomitic limestone. In addition, it contains a group of fractures and joints, which take different directions, with a slight dipping for the rock layers. Based on field investigation and a detailed study, the weathering and erosion effects of rocks have also been examined in all stratigraphic sequences that contribute to rockfalls. Sidi as Sid Formation which is composed of dolomitic limestone of Ain Tobe Member intrebedded with Yafran Marl Member is identified as the typical source areas of rockfalls. The results of this study indicate that the study area is at risk of rockfall and requires adequate preventive measures to reduce these risks. Finally suggestions and recommendations are made to predict rockfall and help provide optimal solutions.

Keywords: rock, mountain road, mass movements.

1 Introduction

Rockfall is a widespread phenomenon in mountain ranges, coastal slopes, volcanoes, river banks and on the edge of slopes due to gravity [1; 2; and 3] and these collapses can occur in any terrain if and only if it has ideal conditions, such as soil, moisture, and inclination angle. In this study, rockfalls are classified according to [4] as a type of landslide that consists of the detachment of a rock block (or several individual rocks) from a vertical or sub-vertical cliff followed by rapid down-slope motion which is characterized by free-falling, bouncing, rolling and sliding phases. Landslides redistribute soil and sediments in a way that can be in the form of sudden landslides [5] or slow gradual slides along with mudflows, rock debris flows, and landslides, which can be among the most important causes of their occurrence: rain, floods, earthquakes, and factors Other Naturals [6]. Some factors are due to humans, such as land levelling, terrain cutting and filling, and others. Landslides are studied to reduce their risks which may cause more disasters than any other geological hazard combined, and can also cause damage to facilities, transport, and any other type of infrastructures. Geological structure and rock formation are an important factor in the formation of slopes and in the stability of rock masses that are at risk of collapse [7], as they can accelerate or slow down the process of slipping, as the elements of instability represented by fractures and application contribute to the occurrence of such slides. It increases when the inclination and direction of these elements correspond to the inclination and direction of the slope of the rock threatened with collapse, while the delay or non-slip gets delayed when there is incompatibility with the inclination and direction. When there is a variation in the nature of the rocks and the extent of their hardness, the erosion of soft internal rocks due to different erosion factors takes place quickly, leading to an imbalance of the upper layers, and thus to the occurrence of processes of falling and slipping rocks [8], and increases that if these rocks are porous and permeable to water and affected by fractures and joints, all of these factors facilitate the process of reaching water to other rocks, and this leads to saturation of the lower layers with water, and then falls and sliding. In contrast, the presence of fractures, faults, and joints in areas of landslides of steep slopes makes them geologically unstable, and the ancient and recent erosion factors in those areas lead to the breakdown and decomposition of some parts of the rocks that lead to their alteration into clay rocks that play an important role in the occurrence the landslides because it is swollen, and then become liquid, which leads to the collapse of rocks containing fractures and faults. Most of the stratigraphy of the study area is composed of sedimentary rocks, most of which consist of layers of limestone, sandy, clay, mudstones of varying rigidity, as the variability in their hardness and the degree of ductility of their rocky formations leads to heterogeneity between successive rocky layers, and this difference leads to an increase in the activity of its weathering and erosion forming different terrain. Through the properties of successive rock layers and the different mineral components, their texture, porosity, permeability, and geological structure are represented by folds, faults, fractures, and joints that can explain the different types of geomorphological phenomena that are formed by exogenous processes.

2 Location and Case Study area description

The target area of the study of rockfall is located in the Nafusah Mountain in the western region of Libya, between the longitude of 12° 11′ 45″ to 12° 14′ 30″ east, and latitudes 31° 56′ 50″ to 31° 58′ 00″ north (Fig. 1).

Figure 1 *Location map of the study area*

The study area (the Zintan mountain road) is considered one of the regions with a dry and semi-arid climate and the rainfall rates are variable, and this descent is in a limited period between October and April and is often due to the gust of western or northwestern winds, in limited quantities and the amount of rain varies from region to another, which is about 150-300 mm, and this amount decreases as one head south. The temperature ranges in January between 3-15 °C and rises in August to reach between 20-40 °C, which is often subjected to a cycle of drought that increases the loss of moisture levels that high porous surface rock formations can store and maintain, especially during periods of the hot south wind.

The targeted road is a part of the main road which connects the coast cities, through the Zintan Village, to other cities and villages on the mountain plateau (Fig. 2). The starting point of the road under this study is the mountain foot at an altitude not exceeding 360 meters above sea level, which is characterized by frequent zigzagging, where many twists (5 turns) are observed when penetrating the road to the mountain front (Fig. 2), then upward towards the Zintan Village from after that, the road gradually returns to semi-flatness in the regions of the mountain plateau. The Nafusah mountains region elevations in the western region of Libya ranges between 71 meters in the Jafarah Plain and 900 meters in the mountainous area above the sea surface with a gradual decrease whenever we head south. Zintan Village is about 136 km to the southwest of Tripoli city, located on one of the hills in the middle of this mountain. The targeted road is a part of the main road which connects the coast cities, through the Zintan Village, to other cities and villages on the mountain plateau (Fig. 2).

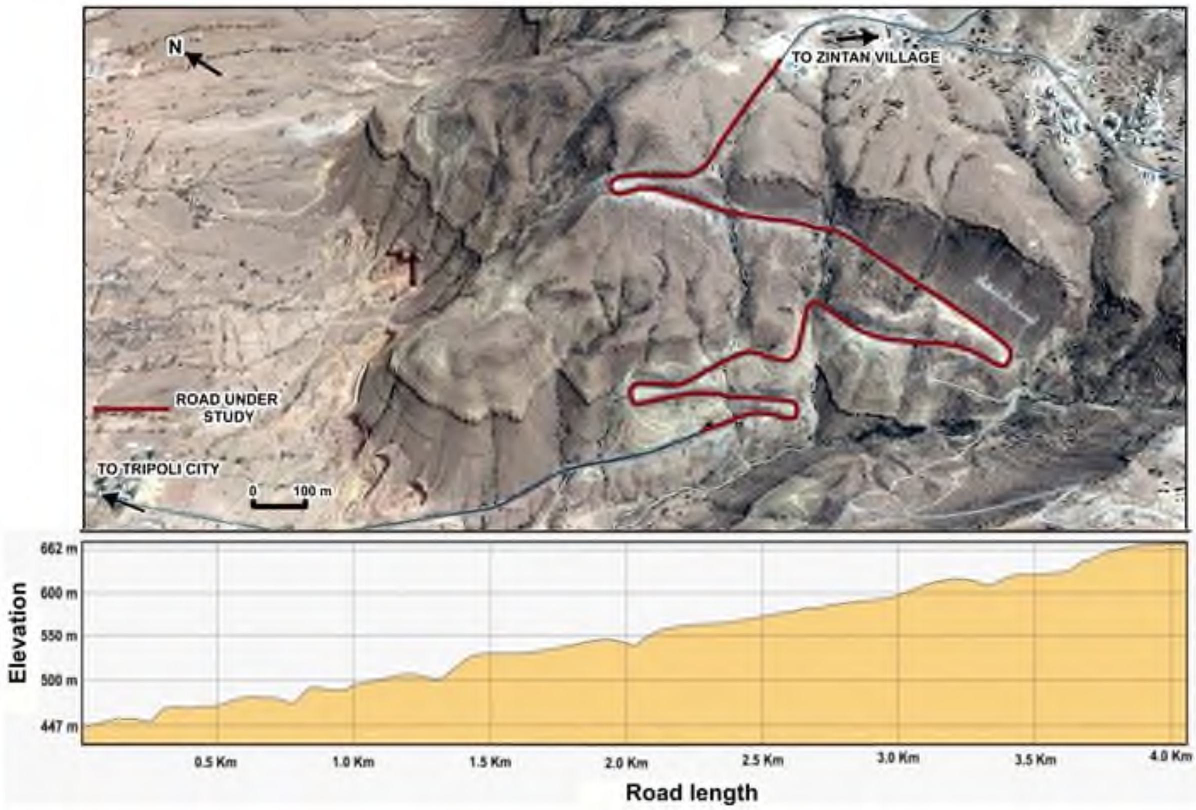


Figure 2 *A Google earth 3D satellite image and its profile showing elevation points along the Zintan mountain road*

Mostly there are friable rocks (sand, sandstone, marl, mud, and limestone), and erosion factors in the area of the rocks that make up this facade led to the formation of scattered hills around the road path and gave them the current geomorphological shape. It is characterized by the abundance of deep valleys that cut across north-south directions as one of the main reasons that cause rockfall in this region.

3 The aims and objectives of the case study .

The aims and objectives of this study are to identify the main source areas of rockfalls based on the comprehensive field investigation and geological analysis of the mountain slopes adjacent to the Zintan road with a focus on:

1. Study the current status of the area and determine the main reasons for the possibility of landslide or rockfalls in the study areas.

2. Preparing a detailed geological study to identify the stratification of the rocks along the path of the study area.

3. Conducting laboratory analysis for samples collected from the affected areas and many matching columns are drawn for the rock units that appear along the slopes,

4 Geological Characterization of the Study Area

The Jabal Nafusah escarpment extending from southeaster Tunisia to north-western Libya encompasses over a distance of 400 km as distinctive topographic strikes in a WSW-ENE orientation as a gently south westward dipping (1-2°) monocline, which represents the northern border of the Ghadames Basin. Consists of a succession of Mesozoic sediments, with the early to mid-Cretaceous part. This part of Libya (Fig. 1) is considered geologically from a region rich in abundance of information, and a large number of studies [9; 10; 11; and 12] that have been carried out by geologists, in addition to the fact that the Nafusah mountain region is an ideal place to study the sediments of the Mesozoic era, where the rock sequences appear clearly, also cut many mountain roads led to increasing recognition of the geology of the region. The presence of various sediments of the terrain forming this mountain extends within the Libyan borders for a distance of more than 150 km, which is a plateau, and volcanic cones, the maximum height of which sometimes reaches about 900 meters above sea level.

The study area as a part of this escarpment consists of a number of 6 rock units (Fig. 3 and 4).

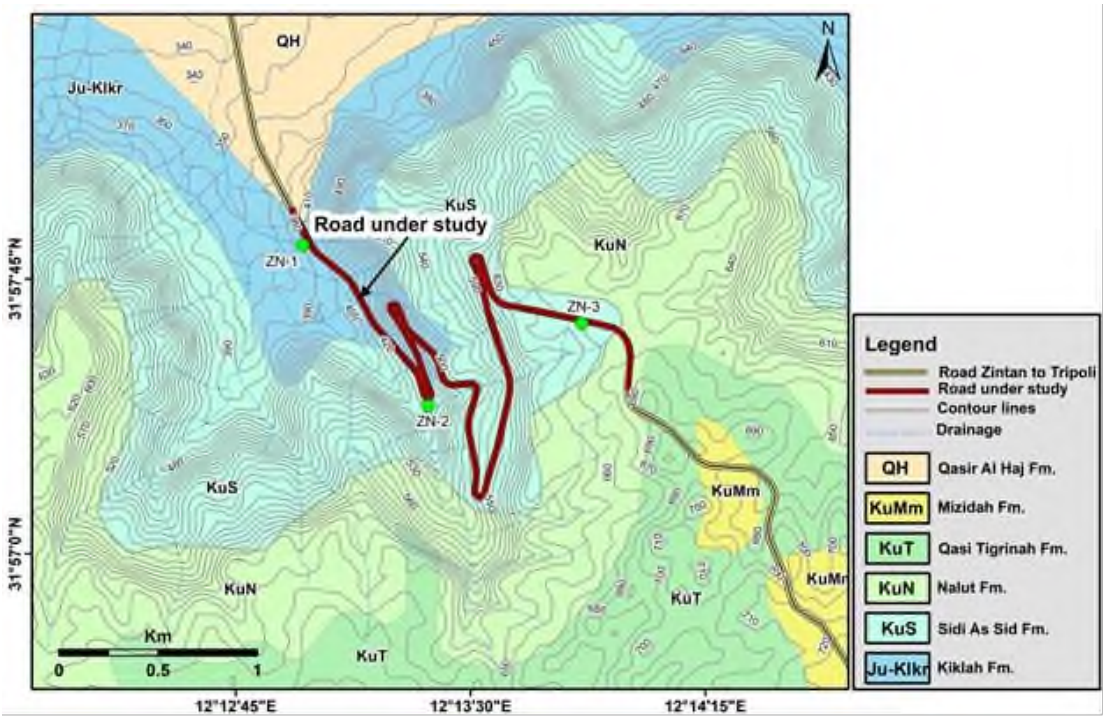


Figure 3 ***Geological map of study area as a part of Nafusah mountain region***

From the oldest to the recent are sandstone and clay deposits of kiklah Fm., limestone and marl deposits of Sidi as Sid Fm., and limestone and dolomitic limestone of Nalut Fm., the marl deposits and marly limestone of the Qasi Tigrinah Fm., and deposits of marl, marly limestone, and limestone of Mizidah Fm. In addition to the deposits of proluvial cemented and non-cemented gravels, sand and sandstones with calcareous crust interbed with the Qasir Al Haj Fm.

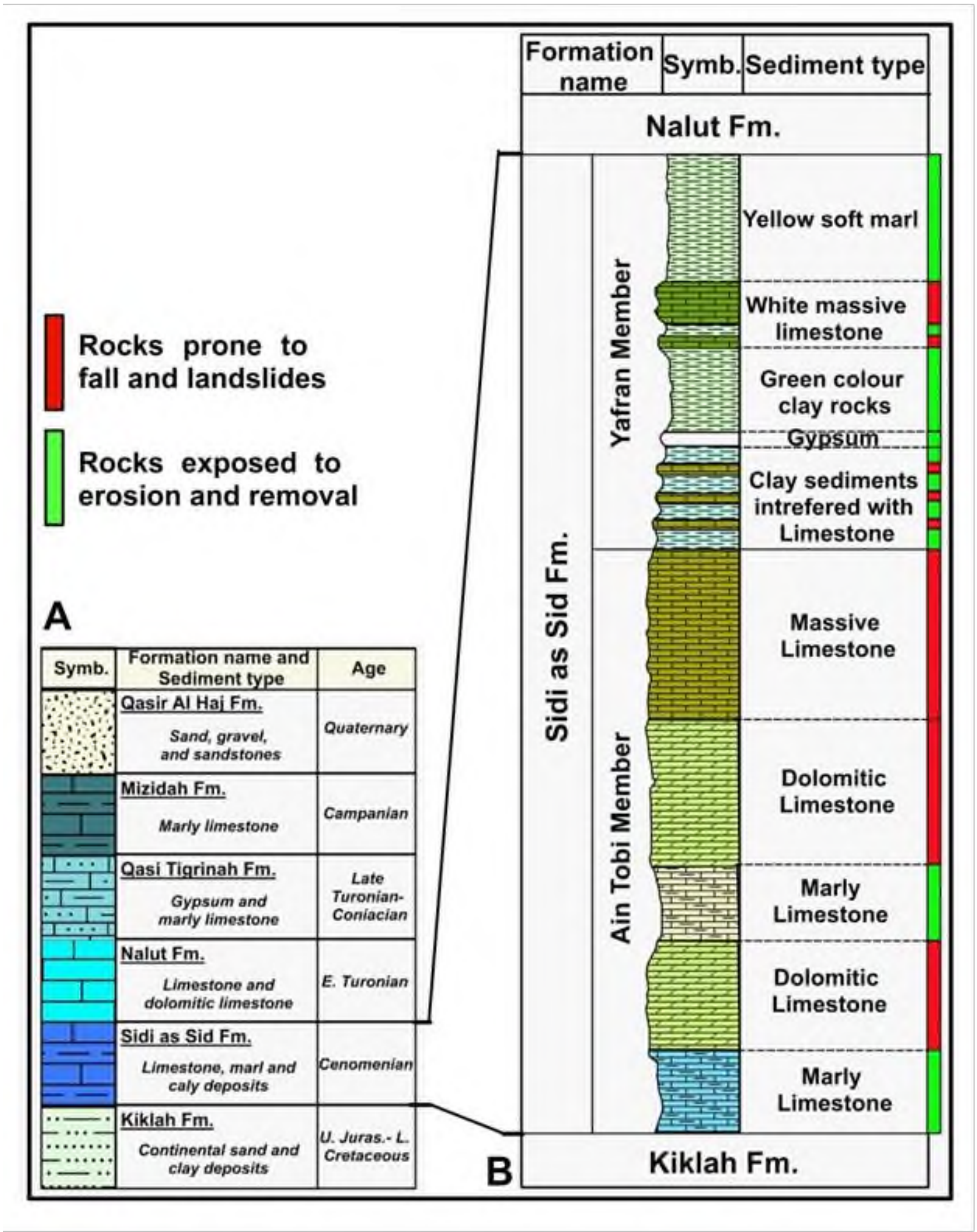


Figure 4 *Stratigraphical columnar section (A) for whole area (B) Along the road under this study.*

Tectonically, it is believed that the northern Ghadames Basin is mostly influenced by the Hercynian and Alpine unconformities and other movements in the Jurassic and Cretaceous and the Tertiary time, and these movements are the cause of the emergence of most geological structures in the mountain such as faults, fractures, small folds, domes and unconformity surfaces. During the Hercynian orogeny, this part of the basin treated as inverted, culminated in late Carboniferous, and formed a broad arch trending in an eastern-western direction called the Jeffara–Nefusa Arch [13] which eroded during the Permian time [12]. Then during the Mesozoic until Palaeocene times, sedimentation has been resumed again. Moreover, the Alpine phase reactivated and uplifted the Nafusah escarpment during the time of the dextral strike-slip movement on the basement-rooted Sabratah-Cyrenaica fault system [11].

5 Discussion and Results

5.1. The Zintan mountain road

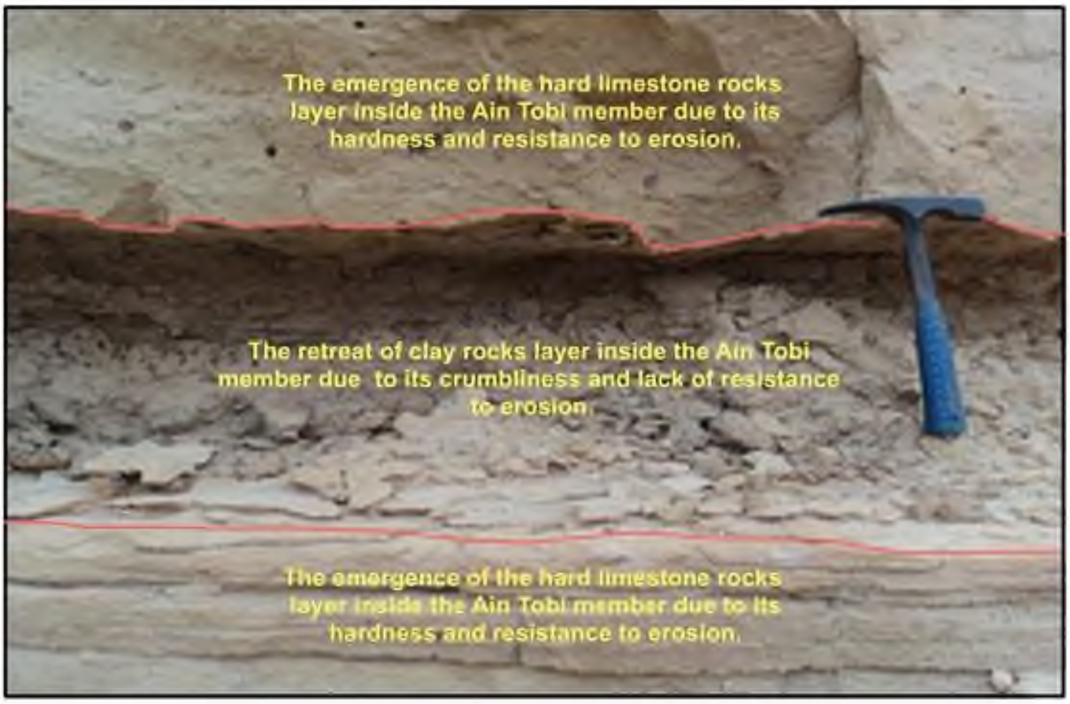
The road under study is about 4.04 km long, starts from the valley of Zart, at the mountain foot at an altitude of 500 meters above sea level, characterized by frequent zigzags of steep and winding clumb up the face of the mountain to Zintan village which rises about 600 meters. Along this one-lane road, there are 5 hairpin turns and blind corners with an average northward inclination of 4.1% according to measurements taken from (Google Earth). It crosses the path of the mountainous façade (Fig. 2) up towards the Zintan village, after which the path gradually returns to the semi-levelling in the mountainous plateau areas, with a slightly smooth slope towards the south. This road passes through many exposed areas of natural and abnormal earth material on the surface, as their shape was varied geologically and geometrically, and the heights of cuttings and slopes facing the road range from several meters to 160 meters above the road level.

Usually, this road is showing some rock falling and slipping, particularly during and after the rains, which causes this road to be closed during these periods. For this, it is very necessary to determine the field evidence and laboratory work of the geotechnical properties of the soil and rocks required in the process of assessing the stability and instability of these materials on slopes. Likely, the main causes of the occurrence of falling and rolling rocks in the study area are due to the nature and rigidity of the rock structure, stratigraphy, the presence of joints and fractures, heights, and the degree of slope of the earth where the action of gravity increases as the angle of slope exceeds 35 degrees. In addition, the presence of interruptions in rock layers is related to separations during the rock slopes and mainly to differential weathering during weak and non-resistant rocky ranges such as soft material (clay, mud, or marl) with massive limestone and sandstones. Through fieldwork it was found that the exposed rock types that deposited along the two sides of this road to the end belong to two geological rock units (formations) (Figure 4), arranged according to the geological age from the oldest to the recent as follows:

- Kiklah Formation, which ages back to the Cretaceous period (Albian).
- The formation of Sidi as Sid Formation, which ages back to the Cenomanian era.

5.1.1 Kiklah Formation (Albian).

The geologist (Christe 1955) first described this formation as belonging to the geologic rocks of the Wealden epoch. Kiklah Formation exposed on the Jabal Nafusah escarpment from the Tunisian border to the east of Gharyan, which characterized by a significant lateral trend with three main facies variations, in the western part, central and in the easternmost of the region [10]. It overlies with marked unconformity the Early Cretaceous, Jurassic and Triassic sediments of Jabal Nafusah. In contrast, this formation is overlain by the Sidi as Sid Formation with overlying angular unconformity units as it is evident only in the central Gharyan area. In the study area which is located in the central part of the Jabal Nafusah escarpment, Kiklah formation rocks in the study area (Figure 3, and 4) are exposed on both sides of the road at the beginning of the turned road, which is dominated by sandstone with rare occurrences of red silty clay intervals with medium to very coarse grain sizes (poorly sorting). It is also spread with a few conglomeratic facies interbedded with clay-rich mudstone and grains of quartz, which is a well-cemented sometimes (due to the presence of cemented material of silica and hematite) and when these rocks corrode, they collapse due to weathering factors down and as a result of their proximity to the road footnote leading to the use of the construction of concrete walls to reduce from the rockfall (photo 1).



Photograph 1. *Shows the hard rocks (hard limestone) emergence and the retreat of soft, friable (marl) rocks within Ain Tobi member as one of the main causes of rock falling. Alternating hard and soft rock is favourable for the occurrence of landslides.*

5.1.2. Sidi as Sid Formation (Cenomanian).

The geologist [14] divided the later Cretaceous formations into two main formations, the Sidi as Sid Formation (the oldest) and the Nalut Formation of (the latest). The composition of Nalut dates back to the late Cretaceous and contains recrystallized dolomitic limestone and dolomite, irregular, or cross-bedded, and marly in some parts. Cherty nodules and concretions are common in the upper part of the sequence which is sometimes red. The term Sidi as Sid Formation has been introduced by [15] as one of the most widely distributed rock units of Jabal Nafusah occurring from the Tunisian border to the Mediterranean coast near Al Khums (see Fig. 3).It is divided into two members: Ain Tobi and Yifran Mbs [16; 12]. The lower part of the Sidi as Sid Formation is known as Ain Tobi Member. It consists mostly of Limestone deposits of yellow and grey dolomite limestone with various spherical, tubular, and nodal interferences of Cherts (Fig. 3 and 4). The rocks of this member are distinguished by the abundance of pores and the high rock strength due to its rock composition known as (DOLOSTONE) [17], and this helped to increase the action of mechanical weathering, especially the thermal effect and the weak activity and impact of chemical weathering [18].

The upper part of the Sidi as Sid Formation is known as a Yifran Marl Member (Fig. 3 and 4), and it consists of limestone partially changed to dolomite, with overlays of Marly limestone and yellowish-grey silt [15]. The rocks of Sidi as Sid Formation are exposed on both sides of the turned road in the Zintan region, first with the rocks of the Ain Tobi Member characterized by the occurrence of siliciclastic deposits (silt to very coarse sandstone, with a carbonate matrix) interbedded with the dolomitic sediments. Is mainly consisting of limestone classified as (wackestone-mudstone) grey yellow, containing an average percentage of clay, and solid with many pores scattered from mold porosity, and irregular pores (dissolving pores) are filled with some adhesives.

These beds of interlocking layers of friable mudstone are intertwined with weathering due to the influence of water and wind. Most of the mountainous round (turned) road was cut through the rocks of Ain Tobi Member of Sidi as Sid Formation so that it was discovered almost at right angles to the edge of the road.

5.2. The distance between the bottom of the exposed rock and the road footnote:

The distance varies between the bottom of the exposed rocks of Kiklah and Ain Tobi Mb. Of Sidi as Sid formations along with the twisted road range from less than one to two meters, and part of these distances are covered with rockfall while the other part remains free of rocks (photograph 2).

Photograph 2. *Shows the distance between the exposed rocks units and the road footnote.*

This road which is in the form of a zigzag starting from the Zart Valley is characterized by the presence of concrete walls, lamellar metal walls (photograph 3A-B,) and metal grids created to reduce the fall of those rocks that were created on the edge of the road to prevent the rockfall. The rocks of these formations are highly affected by weathering factors such as wind and rain, which contribute greatly to the closure of the road as a result of the rockfall of this formation, which led to the creation of laminar metal walls to reduce the risk of rockfall and landslide.

5.3. Physical, chemical, and biological weathering factors

As a result of the formation of the rocks outcropping, this led to exposure to many physical, chemical, and biological weathering factors that contributed to their fragmentation and fracturing. Physical factors (such as earthquakes and vibrational movements caused by the vehicle passage and heavy machinery, in addition to the vibrations caused by explosives that were used during the road construction) led to many fractures and fractures in the formation rocks.

The difference in temperature (day and night - summer and winter) also led to the expansion and contraction of rocks, which in turn caused the external parts to become loose and fragmented over time. The lower temperatures in the freezing of water trapped between the pores of the rock contributed to the increase in the size of fractures due to the freezing and increase of water volume. Laboratory results of Kiklah Formation showed that these rocks have very little ability to absorb water by 0.09% (Figure 5) whereas for Ain Tobi Mb. of Sidi as Sid Formation was 1.67% (Figure 6) and Yafram Marl was 1.98% (Figure 7).

Photograph 3 (A - B). *Showing the use of metal nets fences and concrete walls to prevent the rockfalls of Ain Tobi Member.*

As for the chemical factors, due to the interaction of freshwater (rain) with the formation rocks, which led to dissolving and removing friable rocks (clay layers), which removed the supporting clay of the rocks that are above them.

Also, the mountainous facades and their slope affected by the wet season rains, despite their scarcity, resulted in weakness and loosening of the clay rocks, thus removing them, which caused the rocks to slip. As for the biological factors, their effect is very clear, as the nature of this type of rock and its contents include clay and sand helped the growth of some small and large herbal trees, especially inside fractures and fissures (Photo 4).

Geotechnical properties and rock unit description

Formation name: Kiklah
Rockfall factor: Physical weathering

Rock Description:
Sandstone: fine-grained, solid, very hard,
(the cemented material is silica), has no pores.
Natural color: very light gray (N8).
Weathering color: gray orange-pink (5YR 7/2).

Point Load Index

Sample No	Test Type (Axi/Dia)	A mm²	D²	D' (mm)	Failure Load (kN)	Point Load Index (I_s) (Mpa)	Size Correction Factor (F)	Point Load Index (I_{s50})
ZN-1	Block	900	1146	39	5	4.35	0.89	3.90

Absorption & Bulk Specific Gravity

Sample No	Depth (m)	Dry wt (gm)	Immersion wt (gm)	Wet Wt (gm)	Bulk specific gravity	Absorption (%)
ZN-1		2717	1673	2720	2.60	0.09

Figure 5 *Geotechnical properties and rock unit description of the rock sample (ZN-1) of Kiklah Formation*

Regarding Yafran Marl Member of Sid as Sid Formation rocks which lie on top of Ain Tobi Mb., they are relatively far from both sides of the road and appear in one of the quarries, as they do not contribute in any way to the closure of the road due to the rockfall. Laboratory results showed that these rocks have the ability to absorb water at a very small rate of 1.98% (Figure 7).

5.4. Influence of Lithology and geological structures factors

The landscape of the study area includes ridges and valleys with an N-S trend corresponding to the strike of the main structures. The ridge crests and upper parts of the valley slopes develop over the most resistant lithologies such as hard limestone. It became clear from this study that on most slopes that evolved over the resisting rocks, the rocks are exposed to weathering and erosion with the little cover of discontinuous soil or recent deposits.

Geotechnical properties and rock unit description

Formation name: Sidi As Sid
Member: Ain Tobi

Rockfall factor: Physical weathering

Rock Description:

Limestone: Crystallized limestone to clay stone, containing a high percentage of clay, tight, hard, and locally showing pale thin layer.
Natural color: gray yellow (5Y 8/4).
Weathering color: Mild yellow (5Y 7/6)

Point Load Index

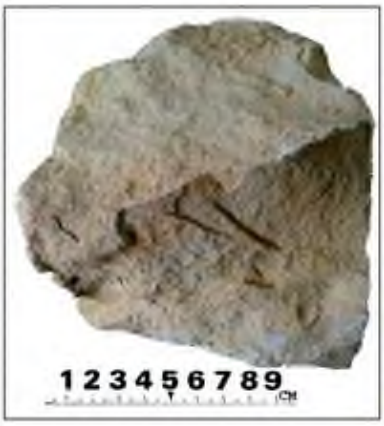
Sample No	Test Type (Axi/Dia)	A mm²	D²	D' (mm)	Failure Load (kN)	Point Load Index (I_s) (Mpa)	Size Correction Factor (F)	Point Load Index ($I_{s(50)}$)
ZN-2	Block	900	1146	33	14	12.21	0.83	10.13

Absorption & Bulk Specific Gravity

Sample No	Depth (m)	Dry wt (gm)	Immersion wt (gm)	Wet Wt (gm)	Bulk specific gravity	Absorption (%)
ZN-2		2288	1456	2326	2.67	1.67

Figure 6 *Geotechnical properties and rock unit description of the rock sample (ZN-2) of the Ain Tobi Mb. of the Sidi as Sid Formation.*

Geotechnical properties and rock unit description



Formation name: Sidi As Sid
Member: Yafran Marl

Rockfall factor: Physical weathering

Rock Description:

Limestone: Filled limestone, clay stone, to marley stone containing an average proportion of clay, hardened, textured, and locally showing weak thinning.
Natural color: dark yellow to medium gray (5Y 8/5).
Weathering color: Mild yellow (5Y 7/6)

Point Load Index

Sample No	Test Type (Axi/Dia)	A mm²	D²	D' (mm)	Failure Load (kN)	Point Load Index (I_s) (Mpa)	Size Correction Factor (F)	Point Load Index ($I_{s(50)}$)
ZN-3	Block	4226	5383	40	5	0.93	0.90	0.84

Absorption & Bulk Specific Gravity

Sample No	Depth (m)	Dry wt (gm)	Immersion wt (gm)	Wet Wt (gm)	Bulk specific gravity	Absorption (%)
ZN-3		1857	1136	1884	2.50	1.58

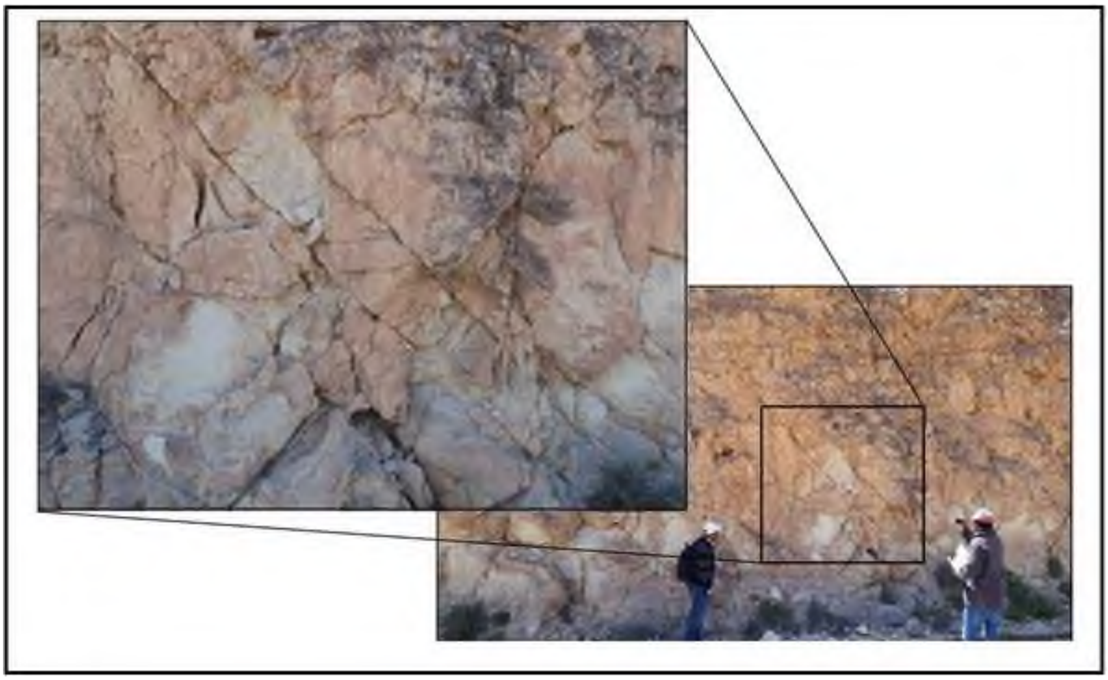
Figure 7 *Geotechnical properties and rock unit description of the rock sample (ZN-3) of the Yafran Marl Mb. of the Sidi as Sid Formation.*

The lithology on both sides of the road is mainly dolomitic limestone, and marl, of Ain Tobi Member, which is cut by several sets of joints to form blocks, wedges, and other geometric forms that are likely to move downward from the parent rocks in the form of rockfall.

Therefore, the rockfall sources in the study area are concentrated on the dolomitic limestone and mudstone areas and the risk of rockfall and landslides is increased by the presence of some orthogonal fractures, especially in the Free Faces.

Photograph 4. ***Illustrates grow of some trees especially inside the fractures and fissures.***

In this regard, soft rock such as mudstone and clay in the study area can be considered weak interlayers within the hard rock of dolomitic limestone, potentially cutting the hard rock into discontinuous segments and more easily inducing landslides and rockfalls. It is evident that lithologic variation coincides with differential weathering and a greater number of joint sets increase the probabilities of rockfall. The number of joints or fractures sets (Photo 5) is significant predictors of rockfall and landslides. In addition to the aforementioned geological factors, likely, the rock blasting techniques for the purpose of making the road that was used at that time have caused significant damage to the fragmentation and fracturing of the rocks mass. Moreover, the conditions of stability are likely to be degraded due to weathering of the rocks, the loosening of the surficial blocks by water and wind, as well as due to the growth of tree roots. All of these effects can lead to persistent instability that may require extensive studies and treatment programs.



Photograph 5. *Illustrates the abundance of fracture and joints in Ain Tobi Member that helped break rocks and fall (People for scale).*

6 Conclusions

Based on the comprehensive analysis it is found that the presence of the path of the case study road in a mountainous area is characterized by the deep slopes, which leads to the falling of the rock masses that get detached from the layers of the mother rock (rocks of Ain Tobi Member in the Sidi as sid Formation). The lithology on both sides of the road is mainly dolomitic limestone, and marl, of Ain Tobi Member, which is cut by several sets of joints to form blocks, wedges, and other geometric forms that are likely to move downward from the parent rocks in the form of rockfall. The occurrence of the clay and mudstones between the layers of hard limestone rocks of Ain Tobi Member that are subjected to the differential weathering of rocks and erosion. This type of rock when it is saturated with water has a potential of liquefaction process due to chemical weathering operations.

When this phenomenon occurs, the clay and mudstones would behave like a liquid and as a result of a layer of solid limestone rocks above these layers, an imbalance will occur and this leads to occurrences of falling and slipping rocks. Since these rocks are porous and permeable to water due to their impact by fractures and joints, which facilitates the process of reaching water to other rocks of the lower layers and this also leads to their saturation with water and then causes falls and slipping. It is noted that there are some trees and shrubs with large roots that are located along the edge of the path slopes that played a large role in the sliding process. Its roots grow inside the fractures and fractures in the rocks, which led to its expansion. It also helps to preserve an amount of water when it freezes, causing the rocks to be broken and converted into debris over time. The current study reveals indicates that the study area is at risk of rockfall and preventive measures must be taken to reduce these risks. The results of this study have the potential for being considered as a reference for predicting rockfall areas under similar conditions.

7 Suggestions and Recommendations:

Following guidelines, if adopted has potential for prevention of rockfalls

1. Clean, dry and remove dirt from rainwater drainage channels.
2. Designing and constructing new rainwater drainage channels to prevent it from penetrating and reaching the rocky masses that fall.
3. Building concrete walls and barriers that work to prevent the falling blocks of rock from falling and fill the rock fractures with cement materials in order to prevent rainwater from penetrating the rocks.
4. Use metal screws to fix parts of the rock that are expected to collapse.
5. Reduce the slope angle and minimize the stresses which affect the slope.
6. Working on graduating the slopes of large or high slopes as agricultural terraces.
7. Carry out tectonic and seismic geological studies in addition to studying the soil and rock mechanics of the sites to be used when implementing any new construction projects.
8. During the rainy season, it is necessary to monitor the existing fractures and joints and to know their wideness.
9. Preparing geological maps that determine the locations of landslides and their severity.

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