Master Thesis

“Slope stability and rock fall rates in a Mediterranean mountain range (Lefka Ori, Crete)”

Author: Despoina Krespi

Date: 17 May 2018

WAGENINGEN UNIVERSITY
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"Slope stability and rock fall rates in a Mediterranean mountain range (Lefka Ori, Crete)"

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Pictures front page:

Above: Part of the study area of Lefka Ori

Below: One of the slopes which was visited

Abstract

Lefka Ori is a mountainous chain in the southwestern part of Crete which has specific geomorphologic features of Alpine orogenesis and Mediterranean climate conditions. An experiment which was conducted in 2008 had as its main objective to provide some qualitative information about rock movement in the different slopes of these mountains. By establishing 13 transects in elevation of around 2000m and visiting them in the years 2011 and 2017, some conclusions were drawn. Meteorological conditions, tectonic processes and different lithology properties are the main parameters which this survey is focused on in order to explain these movements. All of these parameters are explained in the methodology part in order to specify the conditions under which the study area is influenced.

By analyzing the movements for each transect separately in the first part of the results, it was obvious that the high precipitation the period from September 2011 to August 2017 influenced the area, and as a result, more rock transportation was recorded in the most part of the transects compared to the period from August 2008 to September 2011. Furthermore, the earthquake density and the steepness of the slope have positive influence to the rock transportation. On the other hand, 50% of the transects include some points which had more movement in the year 2011 than in the year 2017. This also justifies the weakness of the experiment as neither the rocks were counted in the establish year, nor the transects were visited after long- term periods.

In addition, the total transported lengths in the second part of the results give a general view of mass movement in all transects. According to this, the lithologies which have not been dissolved have less rock transportation. The combination of steep slope, dissolved lithology and high precipitation is the worst scenario of movement as presented in transects 6 and 5.

Based on literature and remarks, all the data were analyzed in order to explain the natural process of slope instability. The aim is to enrich the knowledge of the Lefka Ori mountainous area by supporting the environmental heritage.

1. Introduction

Nowadays the changes in the environment have become the primary concern to the entire world due to a variety of consequences such as greenhouse effect, animal extinctions and all types of pollutions which have a vast array of negative effects on the quality of human life. Under high consideration globally, it is the soil which is called “the skin of the earth” and according to World Wildlife Federation (WWF, 2017) over the last 150 years our planet has lost half of its topsoil, a phenomenon which is probably related to human activities and natural processes of soil degradation. Field studies like the present thesis and works on modelling are the key to enrich the knowledge of soil erosion. Erosion is a process that soil, rocks or dissolved materials are moved from one location and they are transported to another. Mainly that process can have natural causes such as water and wind or by human actions like tillage (Figure 1). The need to understand natural processes of soil degradation is much more crucial than it was over the previous decades not only protecting the cultural and environmental heritage but also giving a new perspective in management by mentioning the hazards of each region.

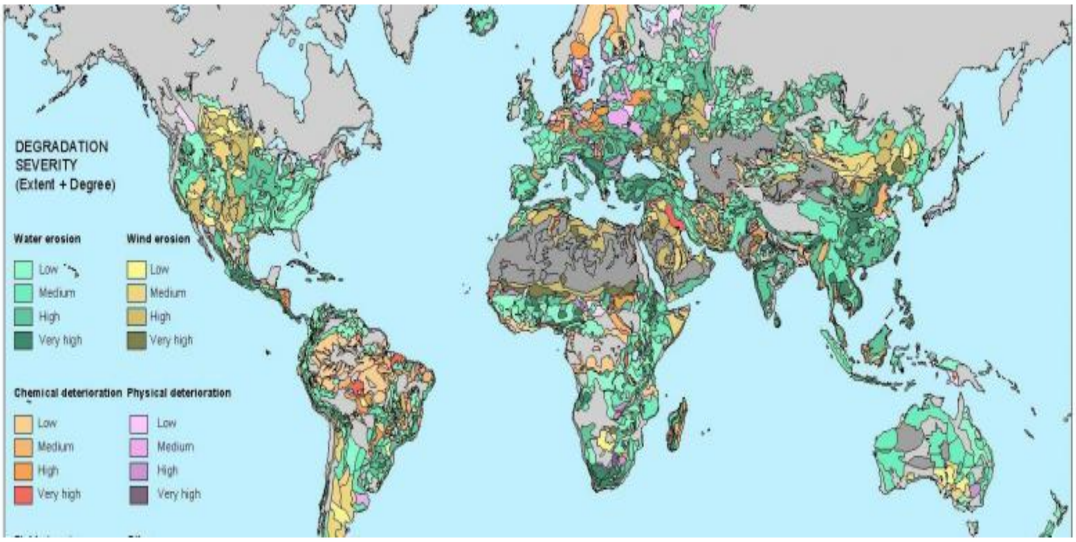


Figure 1: The map appears globally the type of erosion (1990 UNEP-funded GLASOD project available by ISRIC World Soil Information through website: http://www.isric.org/projects/global-assessment-human-induced-soil-degradation-glasod

By focusing on natural processes of soil degradation, mountainous areas are the most representative examples as impressive events have taken place exempted from human influence due to parent material, location and climate conditions. The process of landslide and slope movement is a specific part of soil erosion and sediment deposition studied by many scientists. A survey in northeastern British Columbia (Geertsema et al, 2009) describes some of these events by mentioning different types of movements like rotational slides, spreading and rock fall. Mountains have different shape, size, slopes, climate and lithology conditions; therefore, so biological diversity, complicated ecosystems and a variety of soil and rock movements are expected. One of these complicated but also unique ecosystems is the mountainous area of Lefka Ori in Crete which is also the study area of the present work.

Lefka Ori is a typical Mediterranean mountain chain which combines many geomorphologic structures with a variance in climate conditions such as high precipitation, snow but also sunny and dry days. The main lithology is limestone which has been influenced by the water giving as a result a karst landscape. Some surveys (Hartmann, 2014, 2015; Malago, 2016) have proved that karst regions can be more tolerant to climate changes like flooding and drought as the recharge of deep aquifer is more delicate when the precipitation is decreased rather than when it is increased (Malago, 2016). This is an advantage of western Crete which has a surplus of water resources compared to the eastern part which has low water availability and high demand (Rackham, 1996).

Despite the karst landscape and many surveys (Bakalowicz, 2015; Rackham, 1996) to study the local geological structure in order to interpret water resources, the natural processes of Lefka Ori tend to be unknown as there are not specific meteorological stations or monitors of slope movement in such elevation. Chaplot (2000) pointed out that the effect of the slope on rock and soil movements is positive when the gradient is increased by causing also more runoff velocity. By having materials in steep slopes the forces, including also gravity, are greater so that the transportation cannot be avoided due to Newton's laws of motion. In order to have slope stability the ratio of available shear strength to the shear stress should be larger or equal to 1 (Graham, 1984). David Varnes (1978) analyzed all the types of slope movement by dividing the materials in two classes, rock and engineering soils. He mentioned that the movement can vary from place to place or in different time scale. That is also supported by another survey (Katsaounis, 2010) which mentions that the western part of Crete where Lefka Ori is situated has the maximum hazard of landslide due to elevated mountainous areas.

Moreover, the hazard of landslide and rock movement can be enforced by referring that the area is under tectonic influence as Crete is the best example to describe the upper crustal creation of the outer Aegean domain by analyzing the geological data since the Upper Oligocene (Skourtsos, 2007). According to the paper of Tang (1994) an earthquake can cause debris flow, landslide, water and soil erosion or any other mountain disaster as the squeeze of tectonic plates can be transformed into kinetic energy of the materials.

Although the rock is a massive and hard material many examples have justified that different failures which can be caused due to tectonic or climate conditions, cut the rock in a variety of fractures which are parallel to the slope (Wyllie, 1980). Goodman and Bray stated that multi-block failures should follow the relationship $y/\Delta\chi>cota$-toppling occurs (where y=slab height, $\Delta\chi$=slab width, a=sip angle of base of slab).

In addition, vegetation of the area can influence rock and soil movement as plants can absorb part of the water and soil in their roots. The study of Francis, (1990) concluded that when the percentage of vegetation cover is increased the rock and soil movement is decreased. Despite the fact that semi-arid areas have less water capacity and as a result they produce less biomass, Mediterranean mountains are excepted from this assumption by giving satisfying results in the range of 170 t/ha to 350 t/ha (Kosmas, 1997). The combination of geological and climate conditions justifies the limited vegetation in Lefka Ori and therefore, more rock movement is expected.

By taking into consideration all the above and making an effort to understand the natural process of soil and rock movement, an experiment has been established in the year 2008 in Lefka Ori. As it was extremely difficult to observe soil movement due to the rocky landscape of the area, the survey was focused only on rock movement. The objective of the present work is to compare and analyze the slope movement by measuring rock transportation in specific transects in Lefka Ori for the time period 2008-2017. Transects were placed in different locations in a variety of slopes and aspects. Over the years 2011 and 2017 transects were visited and rocks measurements were taken in order to realize how natural parameters have influenced the slope movement. The analysis of comparing qualitative and quantitative information of transects by using the knowledge of the literature will contribute to the science by understanding the region and natural processes, improving the programs and giving a new perspective of management by mentioning the hazards.

The research question of the study is:

“How natural conditions, geology and weathering, of Lefka Ori can influence the rates of a slope movement?”

Also in order to have a better approach to the general research question some specific research questions were formulated:

SRQ1: “Which geomorphologic features can influence instability patterns?”

SRQ2:” How can the amount of precipitation affect and enforce slope movement?”

2. Materials and Methods

2.1 The study area

The investigated region is called Lefka Ori (White Mountains) and it is a mountainous area in the south west part of Crete (Figure 2). Crete is the fifth biggest island in the eastern Mediterranean and it is the most southern Greek island. It has four (4) prefectures but the study is focused on the prefecture of Chania which is the west part and covers a total surface of 2376 km^2.

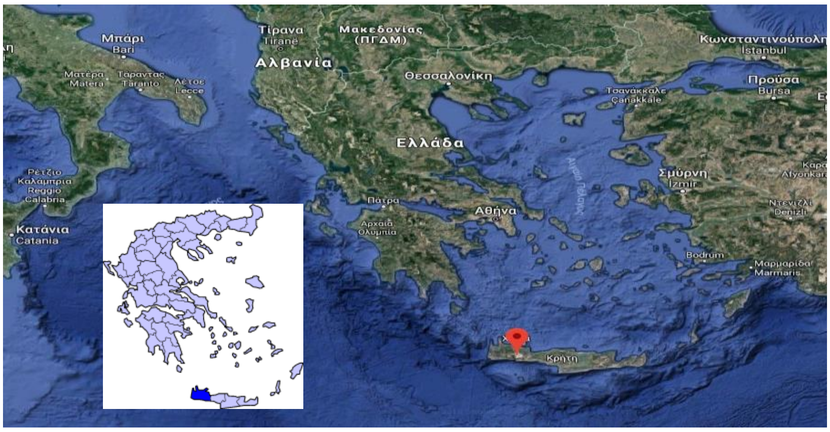


Figure 2: The bigger map indicates the location of Crete in the Mediterranean Sea. The red bullet is the location of Lefka Ori (image of Google maps 2018 Landsat /Copernicus,Data SIO, NOAA, U.S. Navy, NGA, GEBCO). The small map shows all the Greek prefectures. The darkest blue is the prefecture of Chania (Wikipedia 5 June 2005 file name: GreeceChania.png Available: https://el.wikipedia.org/wiki/Νομός_Χανίων)

Lefka Ori cover 40% of the prefecture of Chania, and the area is approximately 50 km (east to west) by 25 km (north to south). It is estimated that 510.28 km^2 is covered by mountainous area with elevation above 800 m whereas 591.4 km^2 is estimated orthographically (Nyktas, 2012). Lefka Ori have numerous peaks, around 50 with elevation above 2000 m, the highest is called Pachnes of 2453 m which is only 8 km far from the southern coast. The peaks are white during all the seasons of the year, justifying the name Lefka Ori (in Greek language Lefka means white and Ori means mountains) (see Figure 3-above). During the winter the peaks are covered by snow whereas in the summer the white color remains due to the lithology. The lithology is mainly composed of carbonate and fractured rocks including marbles, limestones, phyllites and dolomites in various sizes and structures (Pavlaki, 2013). The tectonic processes through the years and the high amounts of precipitation have caused a typical karstic landscape due to the interaction between the water and the components of each lithology.

Specifically, northern air masses meet the upwind side of the orogenes and finally they are lifted abruptly by causing their condensation. One portion of the rain and the water of the snow react with the carbon dioxide (CO_2) by producing H_2CO_3. The product of this reaction (H_2CO_3) destroys the carbonate geological forms by the equation $CaCO_3 + H_2CO_3 \rightarrow Ca(HCO_3)_2$ (EDU ARCTIC, 2018)(Figure 3-right).

Figure 3: Above: The blue line indicates the border of the whole area of Lefka Ori and the red one indicates study area (Nyktas, 2012). Right: A highly karstic landscape in Lefka Ori (photo by Baxevani P. for the European program LIFE 13/INF/GR/000188 available: http://www.ecovalue-crete.eu/el/sites/gr4340008)

The result of this karstification is an amazing diversity of geo-structures like caves, gorges, plateaus, dolines and many aquifers (Figure 4). The rest of the water percolates to the groundwater aquifers by providing water recourses to the whole island.

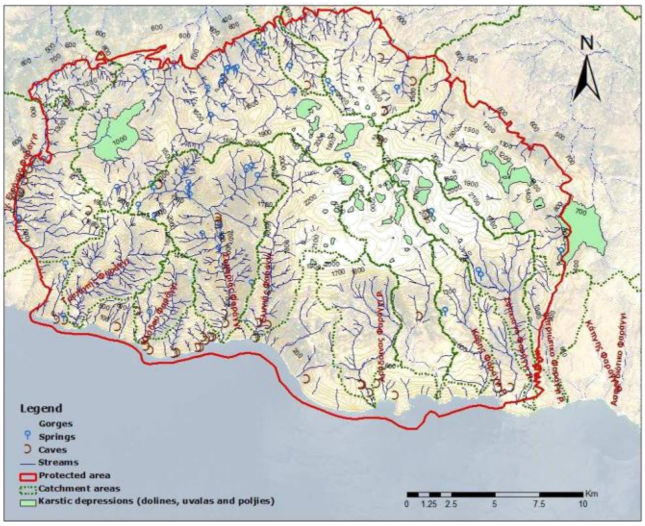


Figure 4: Map of Lefka Ori shows the location of geo-structures like gorges, caves, springs, dolines and karstic depressions (Nyktas, 2012)

The impressive geo-environment and the climatic conditions of Lefka Ori is the home to many valuable endemic species of animals and plants. Due to this fact, Lefka Ori has been a National Park since the year 1962 while since 1995 many efforts have been made in order to have the region become a member of European protected programs by specifying in detail the flora and the fauna of the region. Finally, in the year 2011 the region of Lefka Ori entered in the European Network of Protected Areas NATURA2000 in both Special Protected Area (SPA) and in the Site of Community Interest (SCI) with the code GR4340008 and corresponding law 3937/29-03-2011 (Greek Ministry of Environment and Energy). Despite the strict regime of the area, adverse effects have happened such as soil degradation and failure events.

2.2 Genesis of Crete

The geological history of Crete is related to the imense geodynamic processes and the ongoing Alpine orogeny, old basins' evolution and the convergence of the Eurasian and African plates. In the middle Mesozoicum (225-140 million years ago), Crete as well as the biggest part of Greece were part of the Tethys sea floor (Figure 5). The organisms which lived in that sea created a type of sediment in the depth of the sea after their death. This sedimentary lithology was uplifted forming the Greek islands such as Cyclades and Crete. The limestones and dolomites in the Lefka Ori mountain chain are due to this sediment as it was formed by a transformation of siliceous shell (Kalogeraki, 2015). Moreover, 160 million years ago the ocean deepened rapidly due to the divergence of Eurasian and African plates. All the above contributed to the uplifted evolution which is also part of Alpine orogenesis and it is estimated in the time scale between late Cretaceous (70 million years ago) and Miocene (25-10 million years ago). The gradual appearance of uplifted masses and their east western movement to lower areas (nappes) was the reason that Greece was created. That moment until some more millions of years afterwards, Greece was an undivided land and its name was "Aigaiida" (Αιγηίδα).

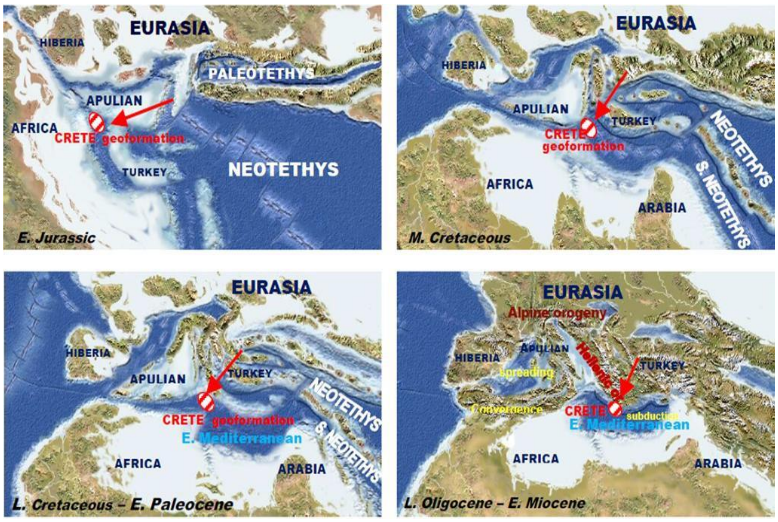


Figure 5: The formation of the Mediterranean basin and the location of Crete through time from the Jurassic to the Miocene (Pavlaki, 2013)

At the end of the Miocene until the middle of Pliocene (3-5 million years ago), this continuous Greek land broke up and some parts were sunk so the distinction between the main land of Greece and the islands was created. Crete was one of these islands which due to the high mountains, was not submerged completely. Neogene geological formations like marls, sands and clays were deposited in coastal areas. On the other hand, salty and gypsum formations in mountainous areas and mainly in south-west Crete were due to Messenian Salinity Crisis (5 million years ago). In that period the Mediterranean Sea dried up and the mountainous areas in Crete seemed to be like Himalayan landscape (Rackham et al, 1996). Between the end of Pliocene and the beginning of Pleistocene (2 million years ago) more mass movements of earth's crust which are called grabens (Figure 6) were formed. In Crete there were three main graben systems with a maximum depth of 800 m. According to several studies (Roberts, 2013) the vertical movements of the Lefka Ori mountains over the last 2 million years are estimated around 2 km and the average rate of uplift is 1.2 mm per year (Pavlaki, 2015).

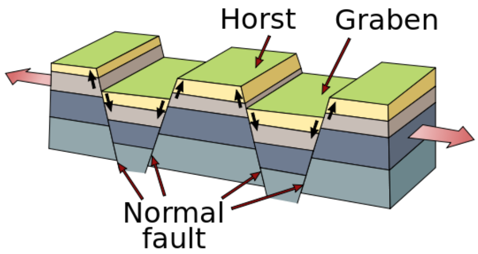


Figure 6: Cartoon of graben system which is a compressed mass into normal faults. Mainly it seems like a valley close to escarpment (U.S.Geological Survey derivative work: Gregors (talk) 11:17, 7 June 2011 (UTC) - Horst_graben.jpg available: https://en.wikipedia.org/wiki/Graben)

From the middle Pleistocene to the Middle Holocene (600.000-5000 years ago) there was no vast tectonic influence but there was the glacial period which influenced the world's sea level to increase and fall consecutively. Under this condition Crete and Greek mainland came closer (almost like present situation) and Cretan mountains acquired glacial features like moraines and cirques.

Furthermore, the following centuries from middle Holocene until nowadays many earthquakes have occurred in the region and some of them were extremely disastrous. The location of Crete is very crucial as it is in the border of the African Plate which goes under the Aegean micro plate with estimated velocity of 4.5 cm/year by causing important earthquakes (Figure 7). The definition of seismic Benioff zone by studying 109 earthquakes in a range of 60 km to 180 km depth in Hellenic Arc was very helpful in order to recognize that the area mainly in the shape of Hellenic Trench and 150 km under the Volcanic Arc, is very sensitive to produce earthquakes. The earthquakes have depths of around 40-50 km, specific direction which follows the length of the Hellenic Trench and the size is up to M=8.3 (Papaioannou, 2008). The biggest historical earthquake was in the year 365 AD which happened in the north western area of Chania in the scale of 8.3M (Pavlaki, 2015). Moreover, the Mediterranean Ridge supports the earthquake sensitivity of the region as its rate of outward growing wedge is up to 17.7 Km/Ma, the largest on earth (Kopf, 2003). According to Papazahos (2002) an earthquake in the size of 7.0 can cause fault's length 52 km while in the size of 8 the length is around 170 km. Nowadays, by using technology and satellites, it is found that every year Crete moves approximately 3 cm towards the south while Africa moves to the north side almost 1 cm (Fasoulas, 2008). There is no information about the update vertical movement of Crete but in global scale the mountains around the valley of San Joaquin have vertical movement 3 mm per year (Georgiadis, 2014) whereas Nepalese mountains have almost 1 cm per year (Gkanetsou, 2015)

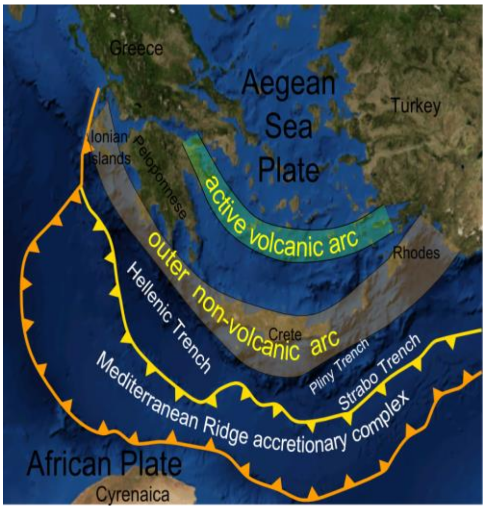


Figure 7: Tectonic map of Greece by showing all the parts of the Hellenic Arc. Hellenic Trench is a bathymetric escarpment of 2-5 km depth which starts from Ionian Islands until south west Crete and Rhodes. It includes Pliny and Strabo Trench and it seems to be a catcher of the accretionary complex. (Shaw, 2012). The *Mediterranean Ridge is a tectonic prism which is increased according to different Earth's transformation. (It is created 28 July 2010, based on screenshot from NASA WorldWind software and various sources such as Charmot-Rooke et al.2005. It is available https://en.wikipedia.org/wiki/Hellenic_arc)*

All the tectonic and weather conditions which happened through the time scale influenced the geological formations to be created (Figure 8). The geological structure of Greece is divided into many zones which have an orientation from north western to south eastern (Figure 9).

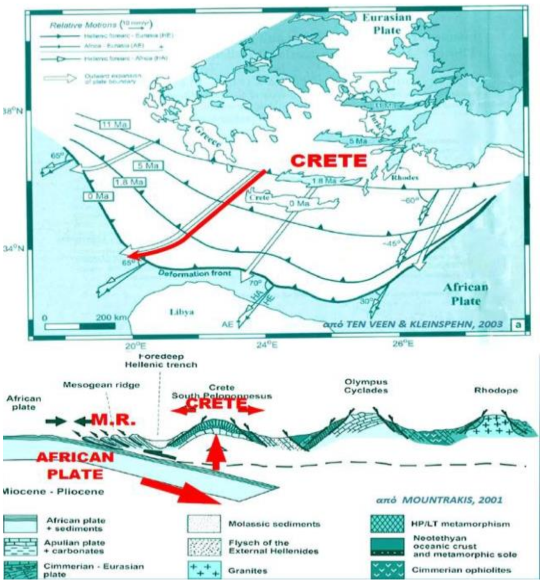


Figure 8: Tectonic activities in the Greek area after the convergence of the African and Eurasian plate. The graph below the map shows how some geological types were created by the movement of the African Plate below the Eurasian plate (Pavlaki, 2015)

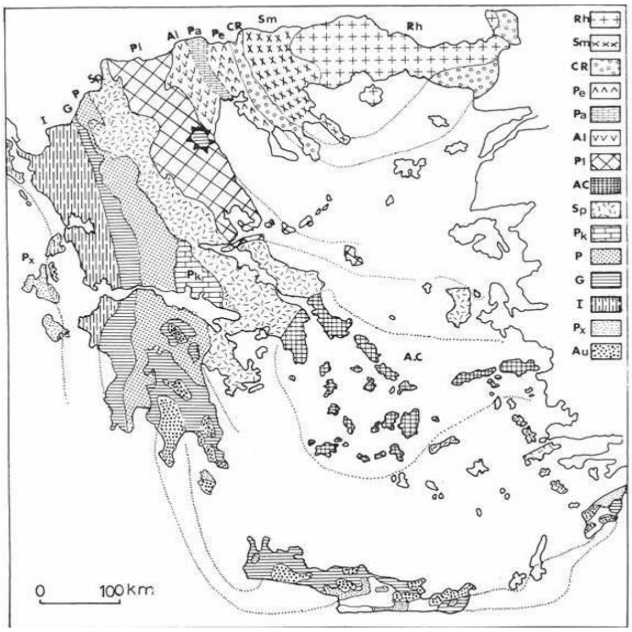


Figure 9: Map with the geological structures in Greece (Mountrakis, 1985)

It is obvious from Figure 9 that Crete has a complicated geological structure compared to its size due to its location and the variety of tectonic activities that have happened. During the Alpine orogenisis strong pressure forces expanded Earth's crust so that some geological forms were beneath others (Fasoulas, 1994). That justifies the division into two groups of geological forms which are the lowest layer and the upper layer. The lowest layer includes formations which were created in the middle of Oligocene to late Miocene when tectonic plates were converged in depth more than 30 km under specific conditions like high pressure and low temperature. Platy limestones, Trypali Unit and Phyllite-Quartize Group are included in this layer. On the other hand, the upper layer contains formations like Tripolis Group, Pindou Group and Orhiolites which are presented in a light metamorphic situation due to detachment faults (Figure 10).

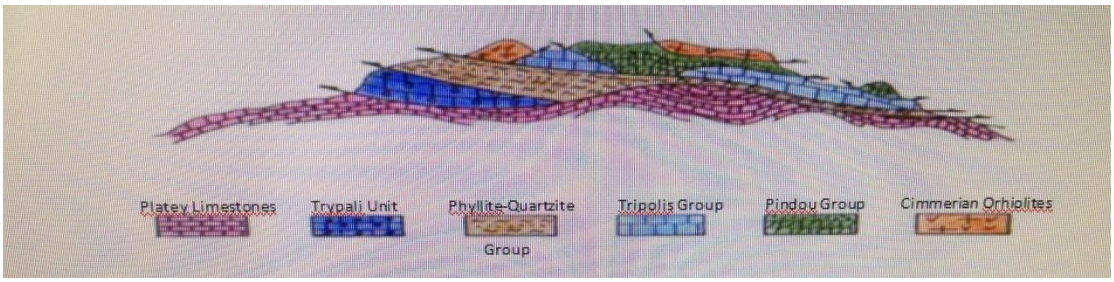


Figure 10: A typical transect of geological structure in Crete (Pavlaki, 2015)

2.3 Geological Structure of the Study Area

The study area has a variety of geological forms (Figure 11) with different properties which will be presented in hierarchical bathymetric way from lower to upper levels. In that way Figure 10 will be helpful in order to understand how each nappe reclines to the others.

Platy limestone (Plattenkalk): This lithology is estimated 345 to 55 million years ago (from Carboniferous to Eocene) but it was mainly transformed by high pressure and low temperature conditions during Oligocene (Rackham, 1996). It is the deepest geology form which has been pressed by many tectonic events, and as a consequence, a variety of creases in different size and faults has been created. Marbles and meta-cherts with parts of siliciclastic rocks and meta-pelites on the bottom and on the top respectively are the main component of Plattenkalk (Manutsoglou, 2003). Its color is mainly green, purple and grey with white chert whereas the soil in that area is very compact with less red color due to the oxidation of the iron. It has physical and chemical weathering which is more obvious as the altitude is increased. It is found in layers that also justify its name Platy and its water holding capacity in the fissures between the layers can support some vegetation.

Crystalline limestone: Its age is dated back to the Mesozoic period (250 to 65 million years ago) and fossils can be found due to transition from Permian to early Tertiary age. The usual color is light grey to black variant which presents to have holey lava as a texture. This lithology is not layered so it is more sensitive to weathering, water infiltration and soil erosion. The most part of the area has this lithology which under a specific chemical process can be changed to dolomites or strong re-crystalline marbles. Dolomite is mainly black and it is formed when the calcium of the calcium carbonate and limestone is replaced by magnesium. Long-term dissolution reinforces the creation of karst structures. Moreover, in some cases the switching of white layer and ash-black layer into the dolomite can demonstrate its Norian age (Manutsoglou, 2003). It is usual to meet whitish unstructured re-crystalline marbles above the black dolomite.

Phyllite-Quartzite Group: It is estimated at least 300 million years ago and it is a metamorphic rock including silicate minerals and portion of clay (Rackham, 1996). The structure has important role as there is a distinction between the blocky structure which is called quartzite and the plate which is called phyllite. A variety of colors can be occurred with the most often brown and green but also black, yellow and red is possible. In the year 1990 a specific horizontal zone was discovered which is a combination of greenish phyllite and crystalline limestones(Pavlaki, 2015). That is the zone of flysch which is mainly is a slight transformation of calcitic and chloritic phyllite. Its depth is shallow only from few centimeters to some meters due to its low sedimentation and it can be eroded easily.

Tripali Unit: This lithology is above the Platy limestone and it is composed by carbonate sediments of Triassic and Jurassic time period. Basically it includes Plattenkalks some parts of which were uplifted to their original lithology under high pressure by the convergence of tectonic plates (Kalogeraki, 2015). Due to the uplifting, the rocks were separated and important cracks were created. The water could be transferred easily resulting in higher degree of karstification to be more powerful to this unit. Despite the way it was generated, two different horizons were formed. The lower horizon includes well-bedded white-grey marbles without cherts whereas the other horizon consists of unbedded and micro-medium crystalline's carbonate rocks like white limestones, black dolomites, carbonated conglomerates and the pebbles (Pavlaki, 2013).

Tripolis Unit: This unit is mainly based on Phyllite-Quartzite Group and its age is estimated late of Triassic and later. It includes carbon deposit comprising alterations of schists and sandstones with small layers of grey calcareous turbidities.

Ophiolites: It is estimated that their age is between 148 to 156 million years ago. The uplifting conditions and the tectonic "Melange" of the rocks in the Pindos unit and submarine volcanic eruptions in the depth of Tethys were the reasons of their formation. Serpentinite, peridotite and basalt are included in that lithology (Chalkiadak et ali, 2010).

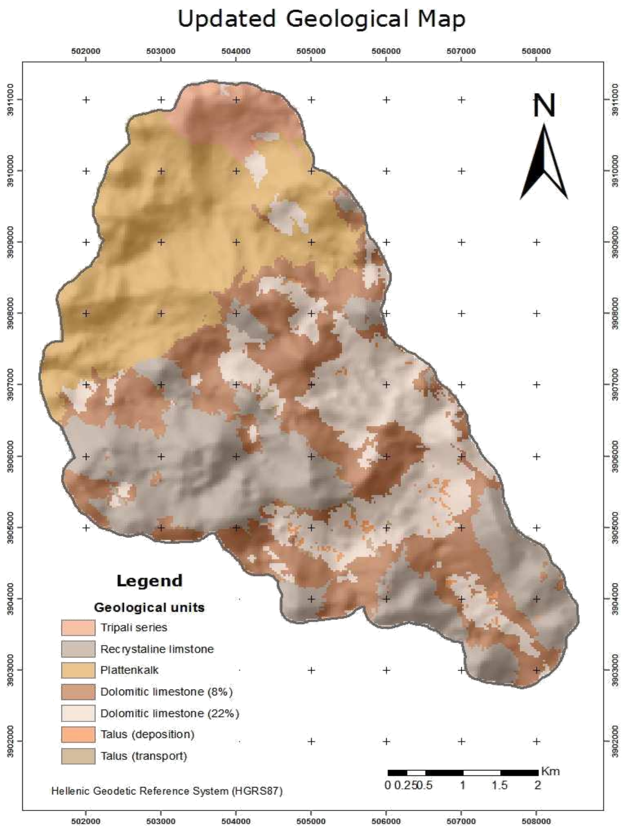


Figure 11: The most recent geological unit in the study area (Nyktas, 2012)

2.4 Meteorological Conditions

2.4.1 General weather features

Crete is in the north part of horse latitudes which means that there are mainly two seasons due to the high distribution of subtropical air pressure during the summer and westerly airstreams during the winter (Alexandraki, 2012). It is distinguished between warm and cold season according to the temperature or wet and dry season depending on the rainfall. The location of Crete in the middle of Mediterranean Sea also indicates that there are slight variations in the climate with main characteristic to be mild in winter and have high temperatures with very little or no rainfall in the summer. This typical Mediterranean climate justifies a strong relation between temperature and rainfall. Consequently, there is an interrelation between cold and wet season which is mainly the period between October and April. A relation also exists between warm and dry season which is the months from May to September. The coldest months are January and February with average minimum temperature -2 °C whereas August is the warmest month with mean maximum temperature 35 °C. The temperature in mountainous areas is decreased by 6°C for every 1000m (Rackham et al, 1996) whereas the temperature in the south coast is around 1°C higher than in the north coast.

There are 31 meteorological stations in Crete some of which are very recent like the station of Samaria Gorge at the elevation of 349 m which has only been in operation since 2013. On the other hand, there are no records for the mountains above 1300 m. All these stations have provided enough data through the years so as to have an overall view of the main climate characteristic of the island. One of these properties is the high percentage of sunny days. One indicative month is October 2016 when the maximum total sunshine was around 345 hours whereas the precipitation ranged from 41.7 mm in the south coastal area of Sfakia, 75.1 mm in the north coastal area of Hrakleio to 126.5 mm in the central mountainous area of Omalos (elevation 1250 m). Rainfall increases regularly with altitude whereas the orientation seems also to influence the rainfall. Reporting the data, it is obvious that rainfall is increasing from south to north whereas it is decreasing from west to east (Rackham, 1996). As a result, the lowest annual precipitation appears in the southern parts and it is around 500 mm or less while in the mountainous areas the maximum annual precipitation is around 1100-1200 mm (Matzarakis, 2005). The peak of annual precipitation is recorded in Lefka Ori between 1800-2000 mm. In such high elevation areas above 1400 m there is also snow. The snow melts in May or later in some sunless locations and the water runs off through the pores of the limestone. According to literature, in Lefka Ori the percentage of the areas which are covered with snow at an elevation of 2287 m ranges from 40% to 55%.

Moreover, Crete is a windy island. The seasonal winds have specific directions mainly from north to north-west and they interact with the complicated mountains by creating a microclimate which is appropriate for plant communities. During the summer, the north-westerly wind which is called Meltemi can cause a dry and less visible atmosphere. On the other hand, during spring and autumn the wind which is called Sirocco has a south-eastern direction and it transfers huge masses of warm air and red dust.

2.4.2 Weather conditions in the study area

In paragraph 2.4.1 some general climate conditions are mentioned but for the study area meteorological data should be specified in order to analyze the observed data. Due to the high elevation, there are no stations in the study area so the station of Samaria (Omalos-Xyloskalo), in elevation of 1250 m in the western side of the region, which is the highest and closest station, seems to be more helpful to provide data for the study years 2008-2017 (Figure 12). On the other hand, as the precipitation is decreased by moving from west to east (Rackham, 1996), the stations Plateau of Askyfou in elevation of 715 m and Vrysses in elevation of 58 m in the eastern side of the region were chosen in order to strengthen the assumptions of predicted conditions in the study area. It is mentioned that the station Plateau of Askyfou has been used since January 2014 whereas the station Vrysses since October 2007. That means that Plateau of Askyfou cannot provide enough data for all the study years by itself while the north-eastern and closest station of Vrysses was chosen as the precipitation is increased from south to north. It was estimated that these three (3) stations can be representative for justifying the measurements as they surround the study area (Figure 13).

Figure 12: The 31 meteorological stations in Crete. The white tag shows the station of Samaria (Omalos-Xyloskalo) where the data is taken from. (Image 2018 TerraMetrics Google. Available in website www.meteocrete.gr)

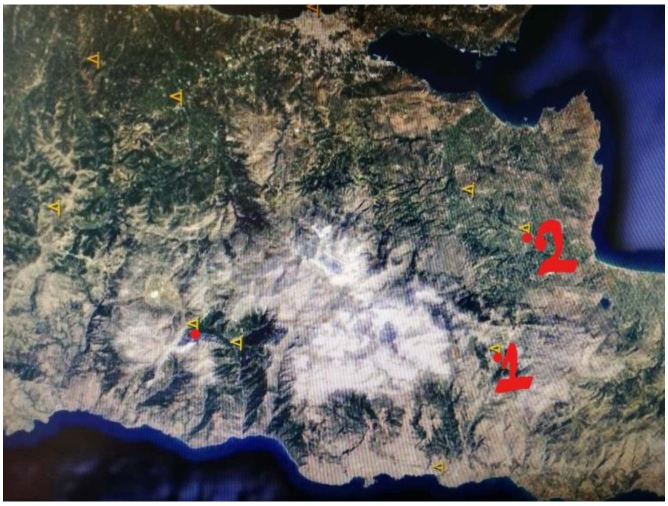


Figure 13: The three red bullets show the meteorological stations which are located around the study white study area. The bullet without number in the west part is the station of Samaria (Omalos-Xyloskalo) whereas the bullet in number 1 is the station Plateau of Askyfou and the number 2 is the station of Vrysses (Image 2018 TerraMetrics Google. Available in website www.meteocrete.gr).

The annual precipitation (Table 1) shows that Samaria station each year has between 23% to 37% difference from the previous year except the year 2011 which has a total precipitation of 2450.4 mm and 64% more than the year 2012. Comparing the data of Samaria station and Vrysses station, Samaria values are higher in the range of 45% to 55%. The year 2011 was the wettest year for both of them and mainly in the month of February by giving 728.2 mm for Samaria and 284.7 mm for Vrysses station. Besides the low elevation of Vrysses station (58 m), the precipitation is totally high due to its northern location. By noticing the values of stations Samaria and Plateau of Askyfou many questions have been raised. Theoretically, both of them are almost in the same latitude (Samaria has 35° 18′ N and Plateau Askyfou 35° 12′N) so it was expected Plateau of Askyfou to have less total precipitation due to the lowest elevation. Also, according to the literature rainfall is decreased from west to east which is true by comparing other stations in remote eastern sides like the Anogeia Rethymnon station in elevation of 801 m. The annual precipitation in Plateau of Askyfou presents an increase in the level of 23% compared to the Samaria station. As the study region is in the middle of these stations it is difficult to conclude clear assumptions. Taking into consideration the direction of the wind just over the indicative year 2017 (Table 2) of north/northwest orientation (Rackham, 1996), probably the precipitation in Lefka Ori tends to be between the two annual values of the stations (Samaria and Plateau of Askyfou). The air masses due to the wind can be transferred to the west side which is the direction of the study area so more rainfall is expected compared to the station of Samaria.

On the other hand, as the elevation in the study area is almost two and three times more than the western and eastern station respectively, it will be appropriate to use a linear regression model from all the stations in order to find out the relationship between precipitation and elevation. This has already been done in many studies (Nyktas, 2012; Roseman, 1967; Naoum, 2003) and different formulas have been created. It seems to be logical as all of them worked on a regression model in different time periods. In that case the formula of Roseman (1967) will be mentioned which is for west Crete and areas above 2000 m like the study area.

Formula: **P=550+1.1*H** (whereas **P**= mean annual precipitation in mm, **H**=elevation in m).

Table 1 Annual Precipitation (mm)			
Year	**Samaria Station (Omalos)**	**Vrysses Station**	**Plateau of Askyfou**
2008	**610,8**	**315.6**	
2009	**1880,2**	**876,4**	
2010	**1525,5**	**700,4**	
2011	**2450,4**	**1122,7**	
2012	**1493,6**	**982,2**	
2013	**1104,2**	**844,1**	
2014	**1483,3**	**819,3**	**1481,0**
2015	**1742,7**	**992,4**	**2212,0**
2017	**1377,9**	**936,4**	**1792,8**

Table 2 Wind Speed (km/h)											
Plateau of Askyfou station						**Samaria station (Omalos-Xyloskalo)**					
YR	MO	AVG.	HI	DATE	DIR	YR	MO	AVG.	HI	DATE	DIR
17	01	10.2	70.8	05	N	17	1	6.7	88.5	23	NW
17	02	12.2	74.0	16	N	17	2	5.2	72.4	16	WNW
17	03	7.1	75.6	08	N	17	3	5.4	70.8	12	NW
17	04	7.5	53.1	13	N	17	4	4.5	53.1	4	NW
17	05	6.5	59.5	19	N	17	5	5.1	57.9	6	NW
17	06	4.9	45.1	20	N	17	6	3.2	46.7	7	NW
17	07	11.8	67.6	08	N	17	7	6.9	69.2	8	WNW
17	08	13.4	64.4	15	N	17	8	9.1	66.0	17	WNW
17	09	5.2	45.1	06	N	17	9	4.1	49.9	22	NW
17	10	7.4	62.8	15	N	17	10	4.1	72.4	15	NW
17	11	7.3	64.4	13	N	17	11	5.1	90.1	13	WNW
17	12	10.3	70.8	24	N	17	12	6.1	74.0	17	WNW

Moreover, it will be useful to present the graphs of total precipitation for each month and for each station in order to have a whole image about the conditions (see Figures 14, 15 and 16). As the transects were visited during August in the years 2011 and 2017 the previous months' conditions are important for interpreting the results. There is no data for the year 2016 in any location according to the historical reports of the stations.

It is obvious from the graphs (see Figures 14, 15 and 16) that the months December, January and February have the biggest amount of rainfall whereas from June until September is null. However, the year 2015 was rainy almost every month for all the stations by giving the second highest precipitation after the year 2011. The months September and October have the same precipitation around 250mm whereas months April and May have double precipitation in the mountainous areas.

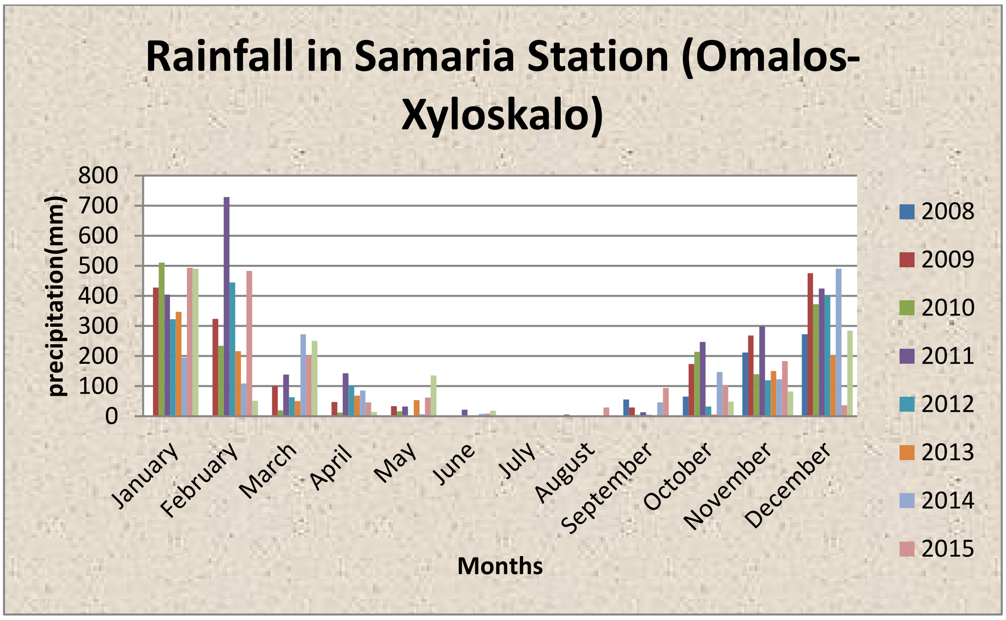


Figure 14: Monthly Precipitation (mm) over the years 2008-2017 according to the meteorological station Samaria (Omalos-Xyloskalo elevation 1250 m) Available in website www.meteocrete.gr

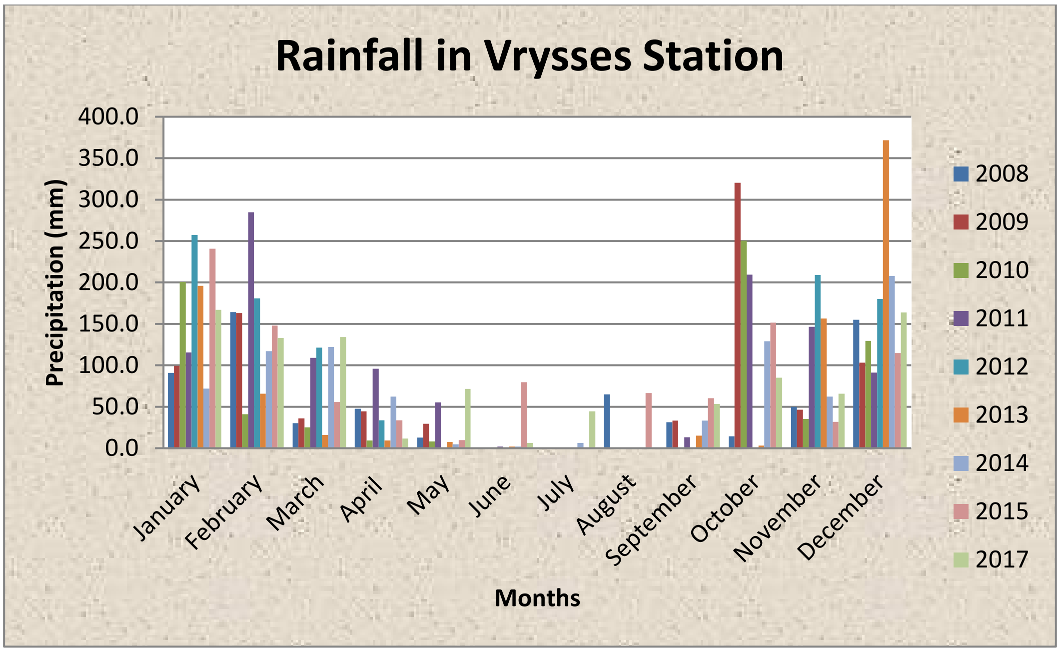


Figure 15: Monthly Precipitation (mm) over the years 2008-2017 according to the meteorological station Vrysses (elevation 58 m) Available in website www.meteocrete.gr

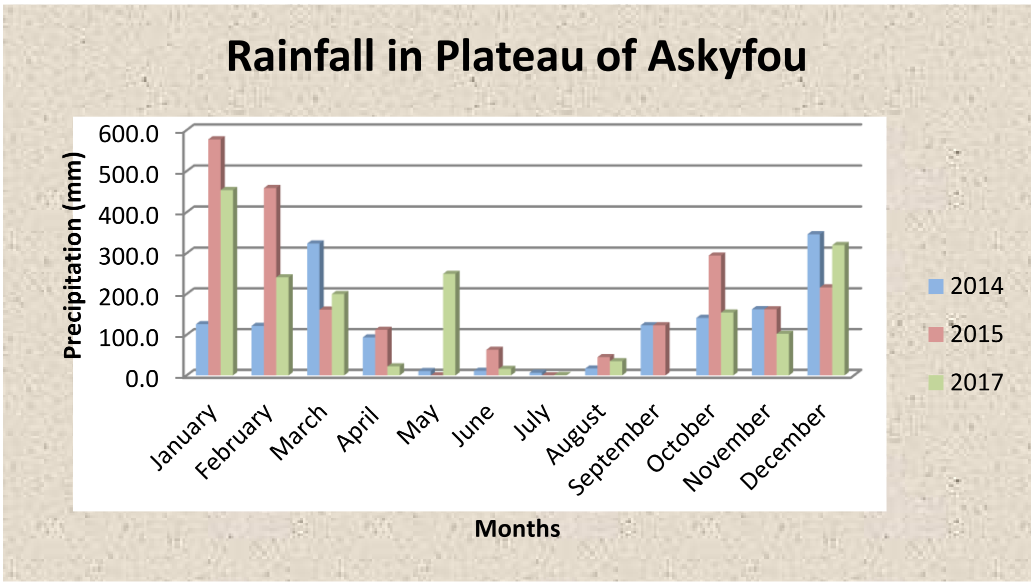


Figure 16: Monthly Precipitation (mm) over the years 2014-2017 according to the meteorological station Plateau of Askyfou (elevation 750 m) Available in website www.meteocrete.gr

The temperature as it has already been mentioned is decreased with the increase of elevation so it is expected that Samaria station is close to the real temperature of our study area. That is the reason why only the graph (Figure 17) of Samaria station's data is presented. The minimum average is in the months January and February, -4 °C and -3.5°C respectively, whereas the maximum average is in the months July and August 29.5°C (Figure 17). In the end, for the research the data of Samaria station were selected due the high elevation.

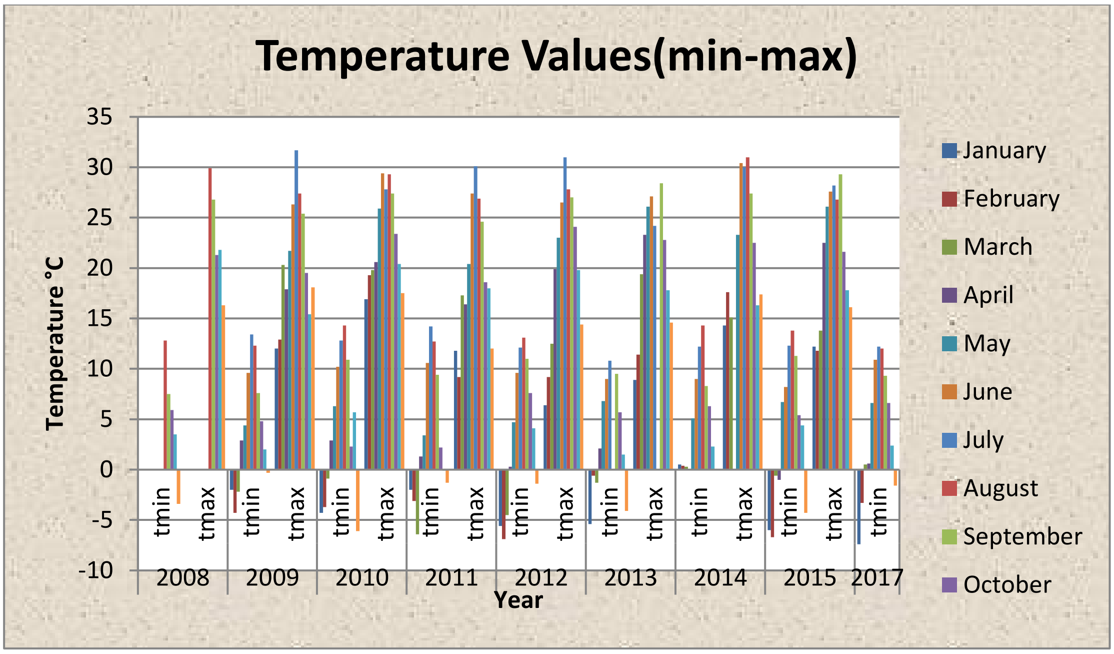


Figure 17: Minimum and Maximum Temperature (°C) over the years 2008-2017 according to the meteorological station Samaria (Omalos-Xyloskalo elevation 1250 m) Available in website www.meteocrete.gr

2.5 Earthquake density in the study region

By passing through the years from Jurassic to Miocene, the layers which had been created under high pressure and overlapping was the main reason to have a tectonic process in tense in Crete. Mainly the west-southern part of Crete is very crucial to have earthquakes as it is close to the Mediterranean Ridge which is extremely active. Many scientists (Papaioannou, 2008) tried to represent the tenses which are caused by earthquakes in that part of Crete in order to understand or predict the tectonic process of the region (Figure 18).

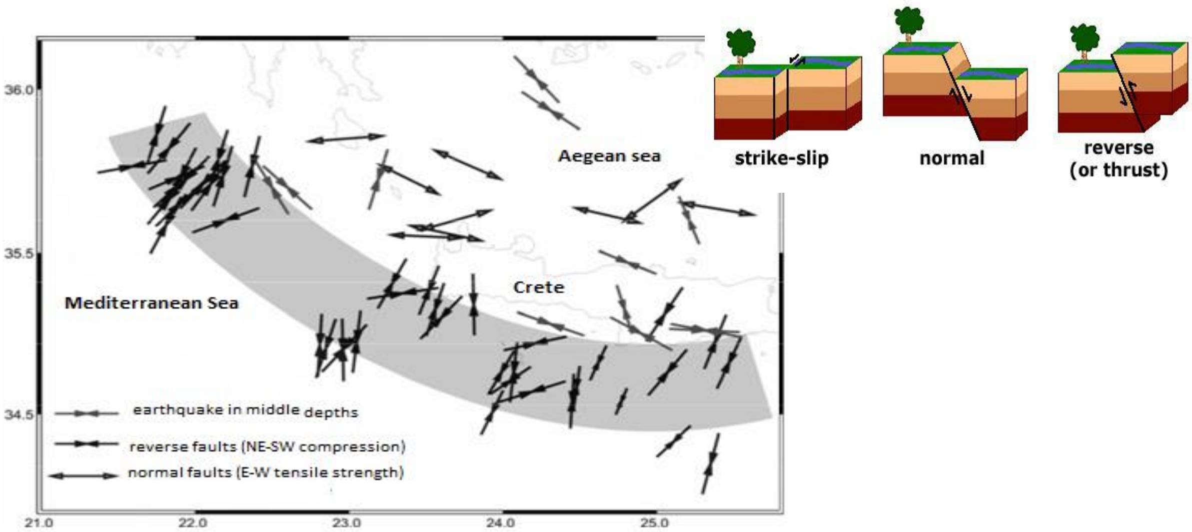


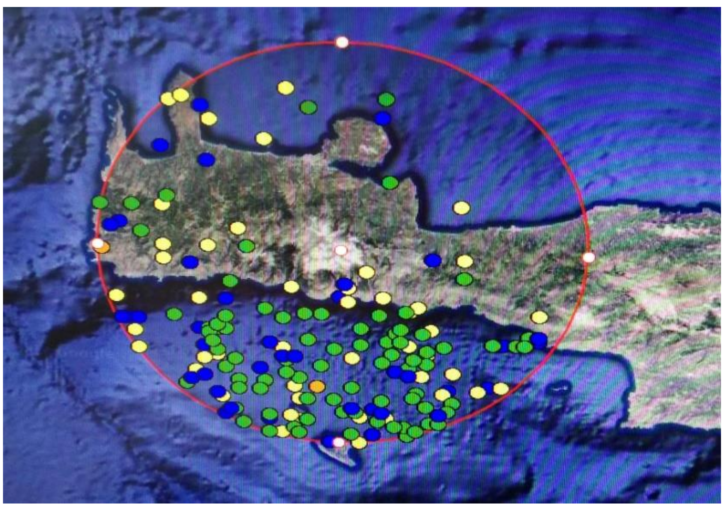
Figure 18: Left: The picture shows three different types of tenses depending on mechanisms of earthquake generation in the level M≥4 in the south part of Crete(Papaioannou, 2008). Right: Normal faults happen when the upper level of the responsible tectonic surface is moved downwards so two collapsed areas are distanced. The opposite effect happens in the reverse faults (Spyrakos, 2012)

By definition, earthquake is the physical phenomenon of the ground shaking which is caused by sudden release of energy in the Earth's lithosphere. This type of energy can be provoked by compression, tension or shear of the Earth's crust by causing a fault in that point. Seismic waves start from the focus or hypocenter which is the exact location of the fault and they can be transferred in long distance depending on the depth and the size of the earthquake. The seismic waves can be divided into two basic categories the body waves which travel inside the Earth and the surface waves which can be transferred along the Earth's surface. Body waves which are more important include P waves (Primary or Compressional) and S waves (Secondary or Shear). Both of them travel in estimated velocities but P waves are faster by approaching almost the velocity of 6 km/sec while S waves only up to 3.5 Km/sec (Udias, 2015). On the other hand, S waves travel only through solids in transverse directions and they are extremely disastrous whereas P waves travel in solids and liquids in longitudinal directions.

Moreover, there is a variety of scales in order to estimate the size of the earthquake which is symbolized by the letter M which means Magnitude. The properties of seismic waves like amplitude, time period and duration of the earthquake are essential in order to estimate the size. The most common scale is Richter which is based on the movement and the produced energy of the fault. It is mentioned that a possible increase in Richter scale from 4.6 to 5.6 corresponds to 25 times more produced energy. So an earthquake M=6.7 includes 700 times more energy than the earthquake M=4.7 (Gerasimos, 2015). A survey of Choy and Boatwright (1995) showed that the produced energy in an earthquake M=4 is around 1010 tn, for M=5 is around 31800 tn while M=6 produces 1.010.000 tn. In Greece the produced energy is estimated by the formula 1 of Papazahos (1997)

Formula 1: **logE = 12.24+1.40*Ms** (whereas E= produced energy and Ms=the size of the earthquake in the surface)

In order to give explanations about the slope movement of the study area, tectonic process should be analyzed. The data were taken from the Institute of Geodynamics (National Observatory of Athens) for the time period 2008-2017. These data were mainly divided into two sub-periods according to the time that the locations were visited. So the first period is 2008-2011 and the second is 2011-2017 while both of them start in the month of August. The first effort was to draw a circle with a center in Lefka Ori and a radius of 50 km in order to produce maps with all the earthquakes that happened during the two periods and they may have influenced our results (Figures 19 and 20).



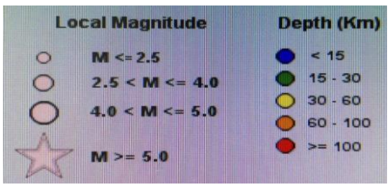
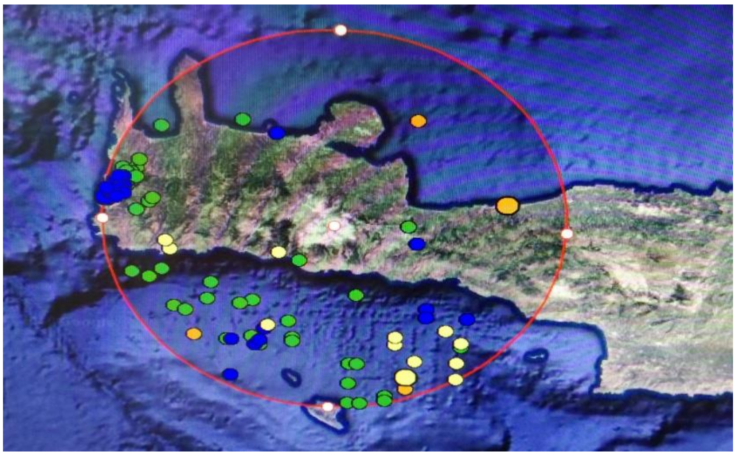


Figure 19: Map shows all the earthquakes that happened in the period 2008-2011. The center is the study area and the radius is 50 km.



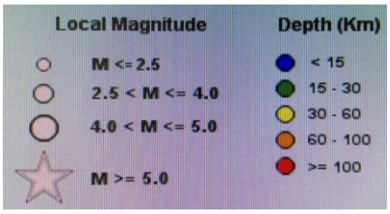


Figure 20: Maps shows all the earthquakes that happened in the period 2011-2017. The center is the study area and radius is 50 km

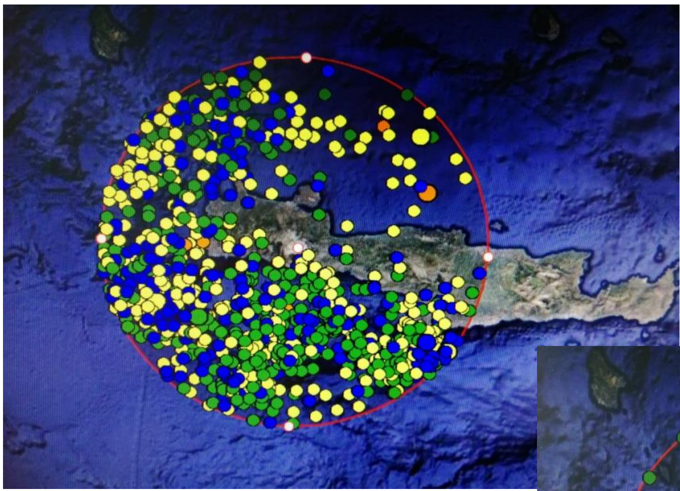
By observing the maps in Figures 19 and 20 and the results of the measurements, it is estimated that bigger radius should have been chosen. This decision is also supported with the formulas 2, 3 which express the lapse of earthquake intensities in shallow depths and middle depths respectively. The distinction between the depths is that up to 30 km are the shallow depths, 30 to 70 km the middle depths while above the 70 km are the biggest depths. The deeper the focus of the earthquake is, the less disastrous can be due to the dispersion of seismic waves which finally reach to the surface with less power.

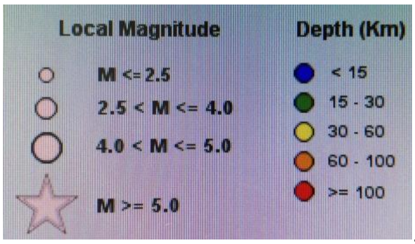
Formula 2: $I=2.94+1.438M_w-3.59*\log(D+6)$ (Papazachos and Papaioannou, 1997)

Formula 3: $I=0.78+1.69M_w-3.34*\log(D+30)$ (Papaioannou, 1984)

(whereas I= lapse of earthquake intensities, M_w= magnitude of the seismic moment is estimated by the formula $M_w= \mu*A*u$ (μ=stiffness of the material in the fault, A=surface of the fault, u=mean movement of the fault) D=distance from the fault)

It is obvious that an important earthquake in a longer distance can also influence the results in the study area. This assumption is also supported by many scientists (Jeffreys and Bullen, 1948) who had created tables by giving specific times of waves transferring based on the depth of the earthquake. Into this consideration, a radius of 100 km was used in both time periods (Figure 21). Mainly the radius of 100 km was chosen by lack not only to increase the number of earthquakes but also to keep a short and satisfying scale. Comparing the maps but also noticing the sizes over the period 2008-2011, more earthquakes have occurred with a mean size 3.4 whereas the peaks are 4.4 in the depth of 63km and 4.2 in the depth of 39 km (the orange and yellow bigger bullets in the north-east side of the map Figure 21-Above). On the other hand, over the period 2011-2017 less earthquakes have occurred but a bit larger. The mean size is estimated at 3.8 whereas the peaks are at 6.2 in depth 65 km which is the yellow star in west side, 5.1 in depth 24 km and 5.5 in depth 26 km which are the green stars in the map (Figure 21-Right). Also, at the same period more than 15 earthquakes are estimated in the range of size 4 to 5 in shallow depths.





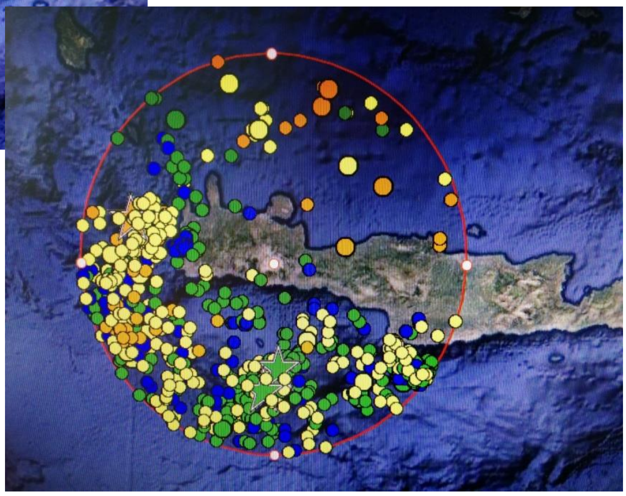


Figure 21: Above: The map shows the earthquakes in the period 2008-2011. Right: Earthquakes happened in the period 2011-2017. For both of them, the center is the study area and the radius is 100 km

2.6 Vegetation in the field

The combination of geomorphology and weather conditions of Crete has contributed many rare and unique ecosystems to be created. Some of them are totally endemic species which indicates the high value of the region to be protected as cultural and environmental heritage. It is estimated that Crete has around 1800 taxa which means species and subspecies in total by categorizing them 1655 to be indigenous and 14 possibly indigenous (Nyktas, 2012). Out of these, 23 species are found only in Lefka Ori, 96 are endemic species in Crete while 15 have been mentioned as “endangered” and 17 as “rare”.

In the study region due to high altitude and the geological structure the vegetation is extremely rare. According to a survey (Nyktas, 2012) the most common endemic species in the area are Anchusa cespitosa and Alyssum fragillimum (Figure 22). Both of them are short only 2-5 cm above the ground and can survive in rocky areas.

Figure 22: Left: Anchusa cespitosa Right: Alyssum fragillimum (Nyktas, 2012)

2.7 Data Collection

As the main research question is to analyze and compare the observed values of slope movement in Lefka Ori, an experiment was conducted. This experiment was to estimate the slope movement in the area by selecting 13 transects in different slopes (Figures 23 and 24). Transects were chosen according to the slope gradient, aspect and geology (Table 3) in order to record the influence of these parameters in mass movement and present representative results for the area. The experiment was carried out in August 2008 by Nyktas (2012) and the measurements were taken in the years 2011 and 2017 in the course of the present study. Each transect had a different slope length and it was divided in points every one or two meters by painting the stones in each point (Figure 25). Therefore, in the following years 2011 and 2017, the movement of the painted stones was measured vertically. It is mentioned that the number of the stones hadn't been counted in the established year 2008 but in the following years of measurements only the individual moved rocks have been counted. Finally, the starting and end point of each transect are huge stones which are almost steady so there were no monements in those points.

Figure 23: Transects 3, 4, 8, 9, 10, 11, 13 over satellite image

Figure 24: Transects 5,6,7,8 over satellite image

Figure 25: Left: One transect with the division of painted points. Right: Painted rocks in one point. During the years part of the rocks has been moving (Nyktas, 2012)

Table 3						
Transect	**Altitude**	**X cordinate**	**Y cordinate**	**Slope %**	**Aspect**	**Lithology**
1	1953	24,034183	35,316524	32	200	Platy Limestone
2	1938	24,031489	35,315382	38	390	Platy Limestone
3	2059	24,040586	35,30568	50	335	White Recrystalline Limestone
4	2034	24,04044	35,306207	26	332	White Recrystalline Limestone
5	2054	24,061722	35,293689	63	146	Mixed light & dark Gravel
6	2036	24,06214	35,293489	59	158	Mixed light & dark Gravel
7	2001	24,062633	35,293165	51	144	Mixed light & dark Gravel
8	2147	24,050196	35,295172	65	102	White Recrystalline Limestone
9	2100	24,048091	35,298276	55	57	White Recrystalline Limestone
10	2083	24,048513	35,298616	32-53	31	White Recrystalline Limestone
11	2050	24,048181	35,29943	32-45	340	White Recrystalline Limestone
12	2127	24,052196	35,298057	28	302	Platy Limestone
13	2115	24,053012	35,299035	35	255	Platy Limestone

3. Results and Discussion

3.1 Introduction of landslide and slope movement

The triggering factor which in most of the cases is a combination between the external forces like tectonic and weather conditions and geomorphologic features of the slope like the gradient, aspect and lithology, causes the separating and the slide of geological material. Lithology is one of the most important factors with percentage of frequency 91.48% as the landslide and the slope movement are based on the material failure in order to maintain its consistency and its properties. According to a survey (Mpantis, 2001) display frequency of other factors is flow accumulation 66.21%, water retention capacity 44.17%, tectonic forces 20.4%, rainfall 92.83% and due to decomposition of rock and soil materials 72.49%. Rainfall has the second highest percentage due to the water which percolates through the materials of the slopes; their pores are saturated increasing the weight so under the gravity forces parts of the materials to slide down.

Moreover, the velocity of landslide is extremely difficult to be determined as sometimes is not obvious or it happens in a variety of stages each of which one has its own velocity (Katsaounis, 2010). Despite the difficulties, engineering theoretical part includes many formulas in order to predict and manage the landslide but also build safe constructions. For example, tectonic forces are simulated in two directions (vertical and horizontal) by having formulas based on Newton Second Law of Motion F=m*a (whereas m= mass in kg, a= acceleration in m/s^2). According to the Greek laws Greece has divided in three (3) risky zones of earthquake and Crete is in the second (II) risky zone which means that acceleration is equal to 0.24*g (g=gravity acceleration equal to 9.81 m/s^2) (Gerasimos, 2015). By using this formula and static analysis, mass movement can be predicted. In spite of the engineering progress other scientists (Kouli, 2010; Pandley, 2007; Saha, 2002) have calculated a formula by inserting the most common factors which can influence the slope movement. Each factor is related to two indexes which are the weight of the factor (Wi in percentage) and the rate of its influence (Xi) so the formula is LHI= Σ (Wi*Xi) (Formula 4). All the indexes are given by tables (Katsaounis, 2010)

3.2 Results of the transects

In order to answer the research question, it is time to analyze each transect separately by using all the provided information above. The results of 13 transects will be divided in some cases according to the lithology while for all of them there will be a complete justification for the differences that may exist between the two time periods of measurements.

3.2.1 Platy limestone (Plattenkalk)

Platy limestone is found in four (4) transects 1, 2, 12 and 13 each of which has its own movements but not vast differences in the two measurement years. Analytically transect 1 (Figure 26) is 7 m long and it is divided into 6 equal segments every 1 m. In the year 2011 only one rock was moved 90 cm in the first point whereas in the year 2017 the first point had the same movement and the rest had a movement from 1 to 6 rocks in the range of 10 cm to 175 cm. The photo of transect 1 (Figure 26-Right) shows that its location is in a gully position. Gully is a steep-sided channel mainly in a slope or in active erodible materials which is formed due to water flow and it contributes to sediment transportation (Poesen, 1996). Gully erosion is very noticeable in Plattenkalk formations as due to its morphology which is layered, thin plates roll on the surface (Jurney, 1948). A dense gully system exists in high mountain environments due to intense rainfall and snow melting process. A study which was established in Upper Gallengo River valley, Central Spanish Pyrenees, the year 1987 in elevation between 2060 m and 2280 m and with many gully networks, shows how snow accumulation and melt process influence positively sediment transportation and hydrological sensitivity to global changes in temperature and rainfall (Lana Renault, 2011). As transects are almost in the same elevation with Lana Renault's study and under the Mediterranean climate conditions, it is estimated that snow factor has also affected the movement of the transects. This hypothesis is also supported by many surveys all of which are mentioned in Lopez Moreno's (2005) document by insisting that snow depth in Spanish Pyrenees influence the precipitation and has the same trend as in the southern Mediterranean areas. By observing the photo (Figure 26-Right), transect also appears to be in a debris-flow channel as a variety of rocks exists. The debris-flow channels are a very common phenomenon in glaciated landscapes as the rocks in the slopes under snow pressure are broken, lose the connectivity and due to gravity a channel is formed (Brardinoni, 2006).

Taking into consideration these assumptions, in the year 2011, it was expected that some rocks should have been moved from all the points. Especially in 2011 which is presented to be the wettest year, even more in the month of February with the highest precipitation the rock transportation should have been apparent in August 2011. It is mentioned that the calendar year starts every August because of the fact that it is the month in which the experiment was conducted and the locations were visited in the years 2011 and 2017. As a result, the year 2011 is related to the months before August whereas the rest of the months are related to the next measurement which took place in the year 2017. According to the Samaria station (Omalos-Xyloskalo) the total precipitation in the 2011 was 1466 mm whereas for the rest of the months the total precipitation was 984.4 mm. Most of the total precipitation in 2011, which was before the measurement, should have contributed to the rock movement but this did not happen. By having one rock in 90 cm both years 2011 and 2017, in which is unknown if it is the same rock, is an objective of concern as the area was under the influence of tectonic and weather conditions. Probably the explanation was hidden in the other transects.

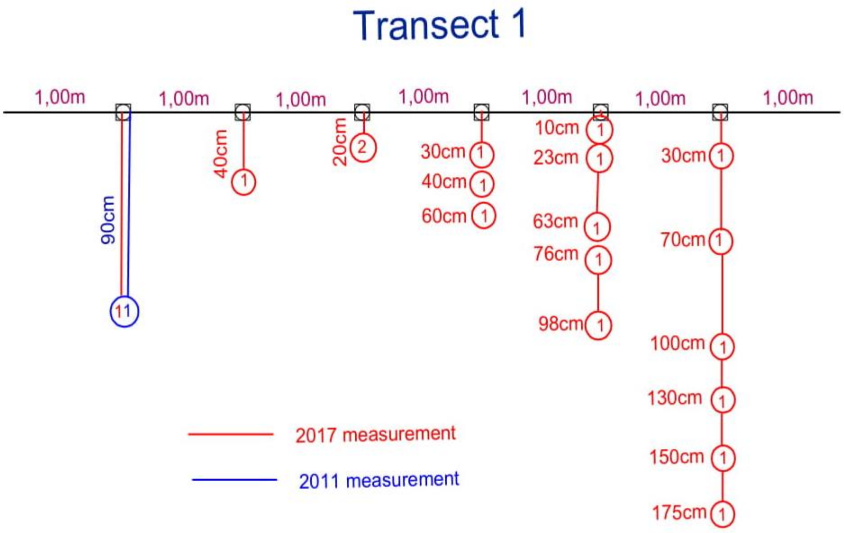


Figure 26: Above: Graph shows the movement of each point. The circle represents transferred rocks while the number inside is the amount of rocks which were found in that distance. Right: a photo of transect 1 in 2017

By observing transect 2 (Figure 27) along with the other two (2) (see Appendix) a significant remark was raised. Some points had more movement in the year 2011 rather than in the year 2017. Transect 2 which is 11 m long has two points with scattered rocks 0-50 cm and 0-150 cm whereas in the year 2017 only individual rocks were found in 40 cm and 50 cm respectively. That means that the scattered rocks in both points were lost in the slope by moving in the bottom or they may be buried by the upper layers of the slope. As the rocks had not been counted in the established year, it is extremely difficult to know the accurate number of what is lost. Maybe the same event happened in transect 1 by also having movement in the year 2011 which was not found. It is supposed that if this happened in transect 1 then the movement would be only independent rocks otherwise if it was scattered then the possibilities to find transported rocks in the measurement years would be higher.

On the other hand, as it has already been mentioned, water reacts with limestone and carbonate acid is formed which creates a karstic landscape. Karstic rocks prevent water from running off on the surface since it is all inserted into the Earth by creating subterranean rivers (Fasoulas, 2007). A survey which took place in Mount Lykaion in Peloponnese (elevation 1421 m) which also has karst limestone (the same type view Figure 9) showed that the water percolates through the pores and the limestone blocks support the other materials against their movement (Davis, 2017). This knowledge may cause the assumption that no movement is expected to karst landscape until taking into consideration the tectonic process. By observing the earthquakes, in the years between 2011-2017, there is a special seismicity with strong earthquakes. Definitely the earthquakes which happened during the time 04/2013 (size ML=5.1), 09/2012 (size ML=5.5) and 10/2013 (size ML=6.2) and the knowledge that Crete moves 3cm south every year is the key to justify the movements.

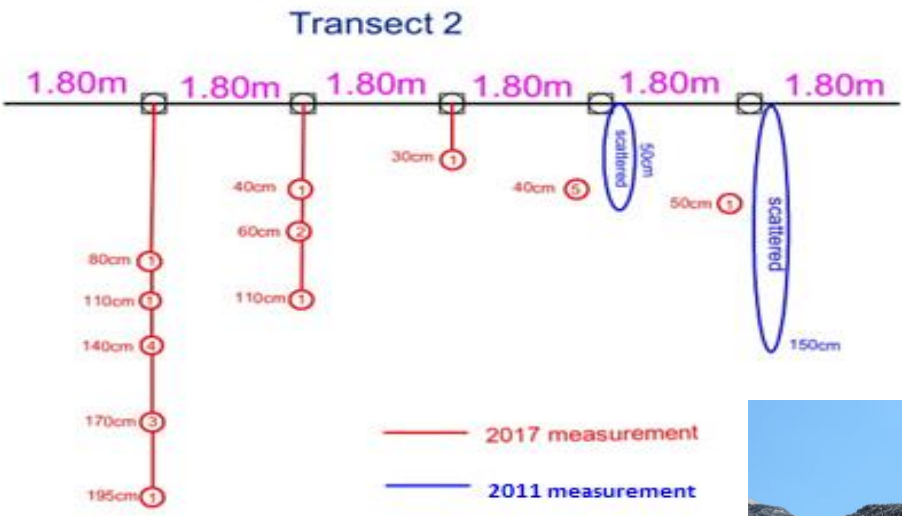


Figure 27: Above: Graph which shows the movement of each point. The circle represents transferred rocks while the number inside is the amount of rocks which were found in that distance. Right: a photo of transect 2 in 2017

Moreover, in order to have an overview of Plattenkalk formation it is essential to mention the differences of movement per each transect by using statistical analysis and graphs. As the rocks had not been counted accurately and the interest focuses on the lithology the maximum movement per transect is selected as the worst scenario. Figure 28 presents the maximum movement by using the total precipitation of two different periods based on the time that the locations were checked. The first period includes the months from September 2008 to August 2011 while the second period includes the months from September 2011 to August 2017. The precipitation increased 42% based on the first period, causing more maximum rock movement than in the year 2011 and giving percentages of 94%, 30%, 50% and 5% to the transects 1, 2, 12 and 13 respectively.

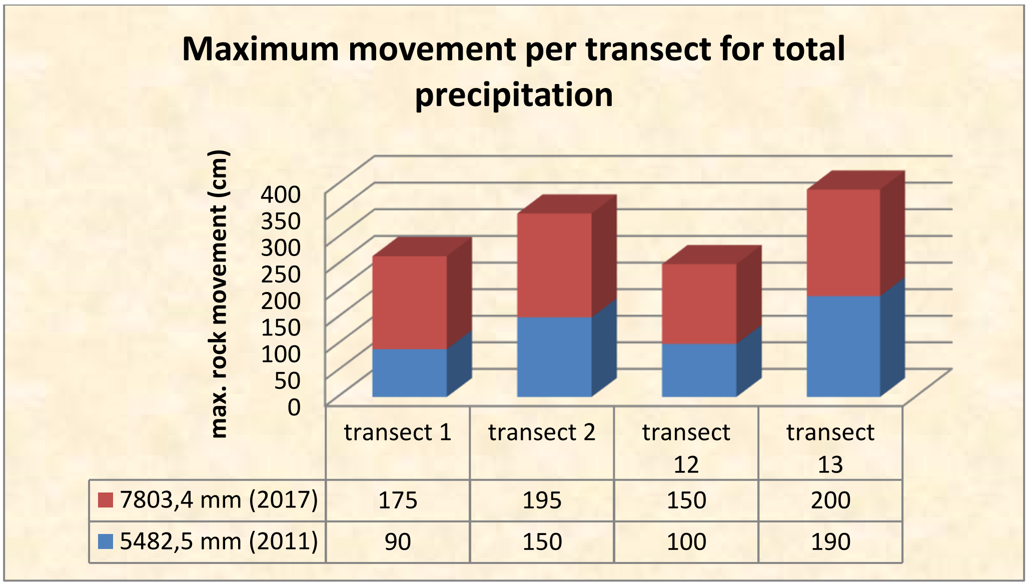


Figure 28: Maximum movement for each transect according to total precipitation. The amount 5482.5 mm is from September 2008 to August 2011 while the amount 7803.4 mm is from September 2011 to August 2017

By observing the Figure 28 and also the previous Figures 26 and 27 of the transects respectively it will be interesting to use statistical analysis and mainly R-studio program in order to estimate the possible relation among the measurement years. Transects 2 and 13 are used since almost all their points have moved by using the maximum value of transportation for each point. The residuals between the values which were measured and the values which were predicted by the constructed (empirical) relation through the model appeared in the plots of regression lines (Figures 29 and 30).

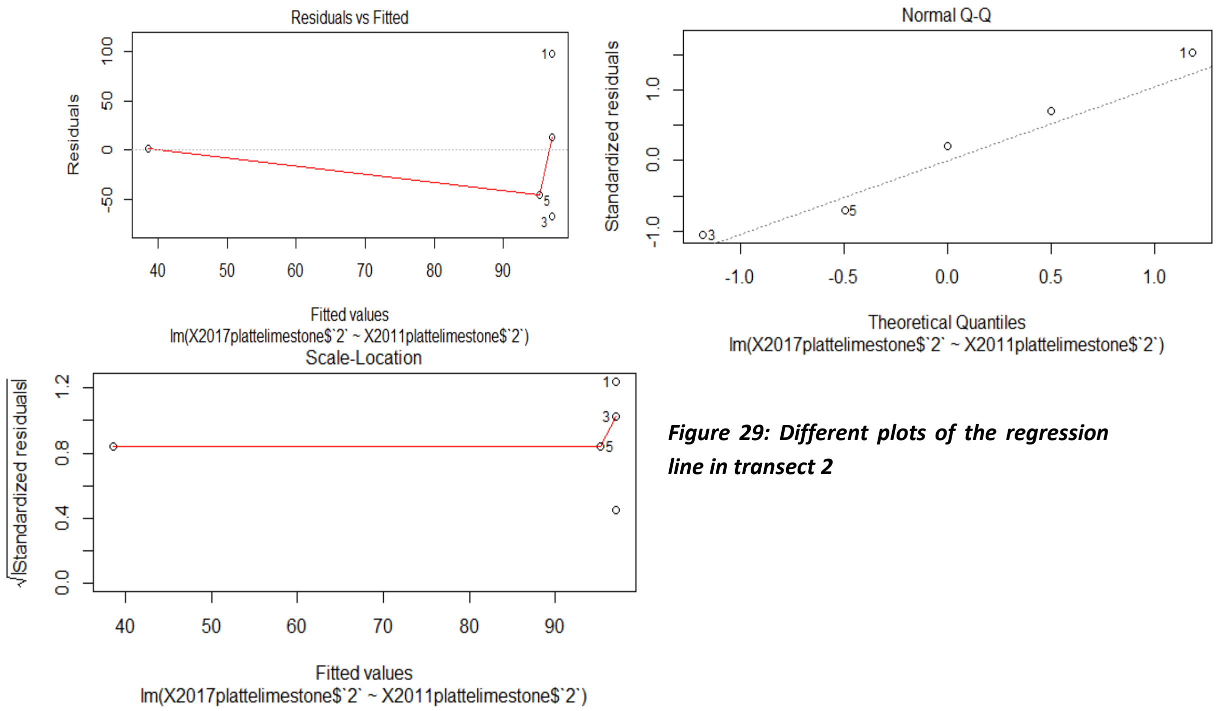


Figure 29: Different plots of the regression line in transect 2

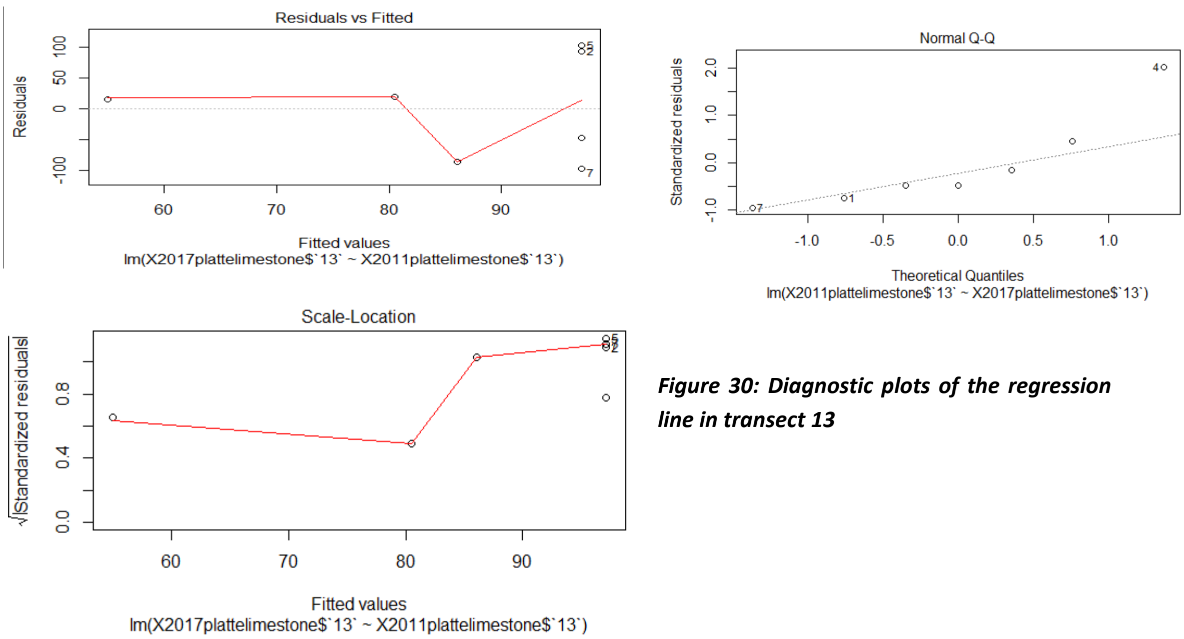


Figure 30: Diagnostic plots of the regression line in transect 13

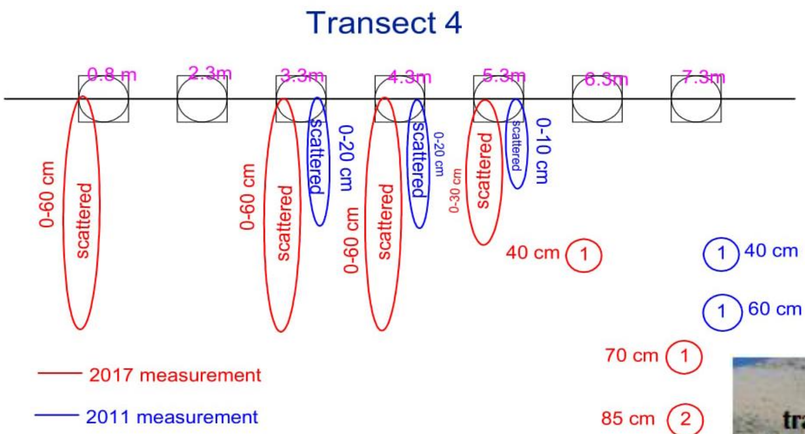
The predicted model for transect 2 and transect 13 has a small statistical significance for the intercept whereas the negative value of the gradient is no significant. The empirical model for transect 2 has R^2 = - 0.1447 and standard deviation is 73.74 while transect 13 has R^2 = - 0.1562 and standard deviation 88.17. That means that the values of 2017 do not have any relation to the values of 2011.

3.2.2 White Re-Crystalline Limestone

This lithology was found in six (6) transects which are 3, 4, 8, 9, 10, and 11. The white color indicates huge amount of pure carbonates whereas re-crystalline means that limestone has been metamorphosed intensively. Due to tectonic processes through the years (as mentioned in paragraph 2.2) and extremely weather conditions this type of limestone is dissolved so the layered structure is not apparent. A heterogeneous structure is formed consisting of variety crystals of calcite (calcium carbonate) and dolomite (calcium-magnesium carbonate) which create platy parts of this lithology. In most transects coarse platy mantle of debris were found due to the disintegration of the original lithology. This event is very usual to this lithology as it is also justified by a survey in the central Namib dessert where due to the disintegration of the limestone, wind erosion is present (Sweeting, 1982).

Transects in that lithology are located in two different slopes and one isolated transect which is number 8. The two slopes consist by the slope with transects 3, 4 and the slope with transects 9, 10, 11 (Figure 23). All of them have an important movement as the re-crystalline limestone is very sensitive to erosion despite the karst landscape which is present but in a lower percentage.

Specifically, the transect 4 (Figure 31-Above) is 8 m long and transportation was obvious in some points whereas others were with any none of the years. Compared to the year 2011 the year 2017 has 66% more transportation for rocks which seemed to have a normal distribution in the range of 0-60 cm while individual rocks were moved 50% more. It is unknown if they are the same rocks in both measurements but just by observing the location of the transect (Figure 31-Right) which is in the bottom of the slope with gradient 26% it is estimated that some of them should be the same.



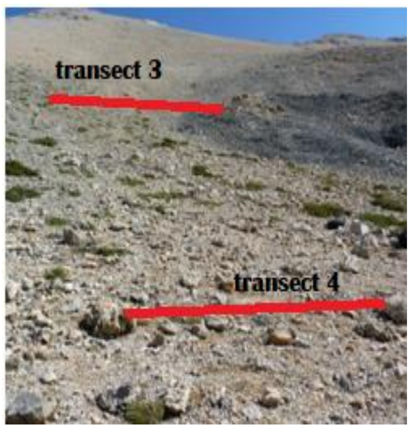


Figure 31: Above: graph shows the movement of each point. The circle represents transferred rocks while the number inside is the amount of rocks which were found in that distance. Right: photo of transects 3 and 4 in 2017

On the other hand, transect 3 (see Appendix) which is 20 m long and in 50% slope is presented to have more compelling results. In the year 2011, the movement is almost null whereas in the year 2017, in three (3) points none of the rocks were in their primary location by being in a scale of 30 cm to 50 cm downwards. The other points have only isolated rocks from 40 cm to 240 cm but it is doubted that others did not move without being found. As it is known under tectonic pressure through the rocks cracks are created in the same direction as the earthquake's waves. The axe of these cracks is parallel with the maximum compression whereas their size is increased in the direction of the minimum compression (Garyfallidis, 2012). Cracks also enlarge their size under temperature differences. Probably in the case of transect 3 some cracks were formed until the year 2011 due to earthquakes' density in the region whereas the big earthquakes over the following years, which means more pressure, influenced the final movement's results. Also the extreme weather conditions of rainfall and snow increase the possibilities of transportation as cracks are fulfilled with water so the materials lose part of their durability as a consequence to be eroded easily. Despite that many surveys (Gunn, 2013) have shown that limestone solution concentrations in natural conditions are unpredictable, the colder climates due to the presence of snow have more solute amount, and as a result, bigger erosion rates.

Moreover, the transect 9, 10 and 11 are in the same slope but with different gradient. Transect 9 has 11 m length and is cited in the upper part whereas transect 11 is 28 m long and it is in the bottom of the slope. The conbination of high gradient (55%) of transect 9 and the lithology which is vulnerable in weathering, justifies the important movement in both years (Figure 32). The year 2011 which was the wettest year and mainly the month of February seems to have affected the rock transportation, as in August's measurement in some points the rocks were found until 6,80 m downwards. When rainfall hits the surface of the ground has a specific energy which can be transformed to kinetic energy of the materials which exist there (López Vicente, 2010). The weight of the materials can be a reason to resist this transportation. However, the background of Figure 27 proves that this transect is in a steep slope and also consists of small sized rocks which can easily be relocated.

Despite the results of the year 2011, the six-year period until the last measurement had enough precipitation and snow so the values were expected to be higher. It was found that almost the most part of the rocks was scattered in vast segments like 0-150 cm or 55-240 cm which indicates that the landslide in that slope is impressive. Probably the lanslide is facilised due to the morthology of the materials which are debris of the limestone.

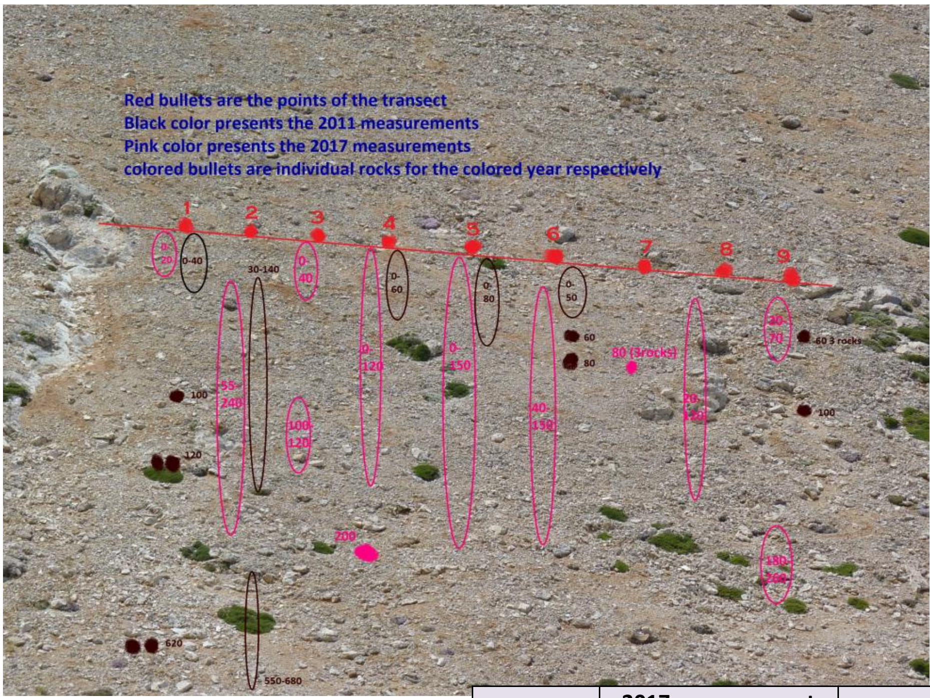


Figure 32: Photo of transect 9 in 2017 where movements were placed in the points respectively. The table in the left helps to recognize the values as in the photo due to the colors are not so obvious.

Points	2017 measurement (cm)	2011 measurement (cm)
1	0-20	0-40,100(1),120(2),620(2)
2	55-240	30-140,550-680
3	0-40 και 100-120	0
4	0-120,200(1)	0-60
5	0-150	0-80
6	40-150	0-50,60(1),80(1)
7	80(3)	0
8	20-120	0
9	20-70 και 180-260	60(3)100(1)

Almost the same behaviour of the rocks was found in transect 10 (Appedix) in the middle slope whose its gradient is in range 32%-53%. In the year 2011 in some points the rocks were scattered between 0-20 cm whereas in the year 2017 the same points were scattered until the scale of 110 cm. It is noticed that the points with less gradient had no movement in 2011 whereas in 2017 had just 2 isolated rocks. The transect 11 (Appedix) in the bottom of the slope with lenth 28 m and gradient to vary from 32% to 45% meet the same criteria as the previous transects. In the year 2011 less scattered movement until 50 cm and isolated rocks until 60 cm whereas in 2017 the scattered rocks reached until 110 cm and indivitual rocks until 140 cm. Compared to transect 10, transect 11 presents 250% more movement in groups in 2011 despite in the year 2017 where the increase was 127% including also the year 2011 as it is unknown if the rocks which were found in both years are the same.

By trying to understand the influence of the slope Figure 33 was created. Taking the maximum fall of each point per transect it is obvious that transect 9 with elevated value has more fluctuaction compared to the others whose their gradient is varied. This is also supported by many surveys (Charplot, 2000; Battany, 2000; López Vicente, 2010) which proved that the steepness of the slope influence positively the amount of runoff.

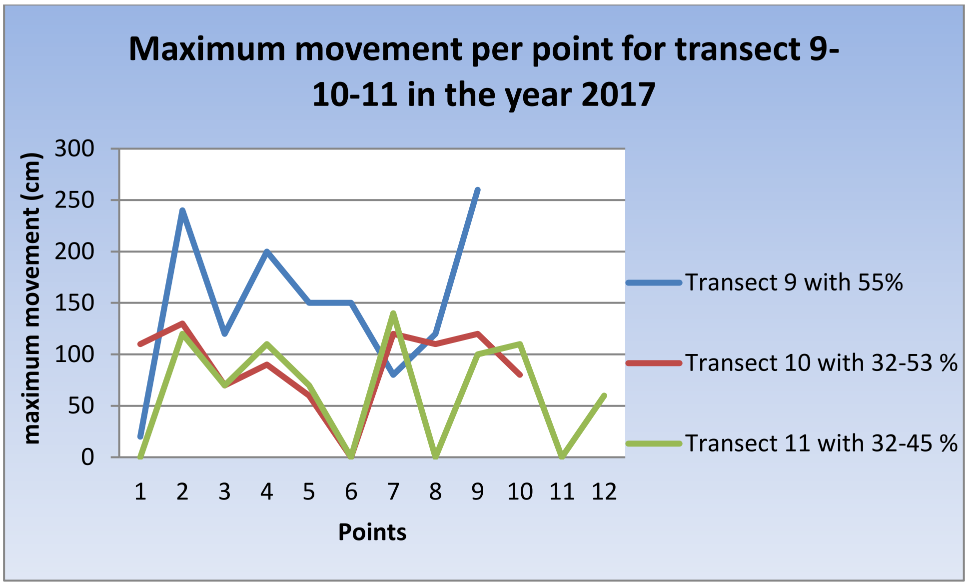


Figure 33: The maximum movement per point for transects 9, 10, 11

On the other hand, transect 11 appears to have very complicated fluctuation undependably which is at the bottom of the slope. Probably this can be explained if it is mentioned that this transect is close to doline. Doline or sinkhole is created by dissolution of underlying limestone and it has less friendly conditions than the slopes as the cold air is trapped into doline by creating frost pockets (Tsekos, 2012).

Figure 34 was designed in order to state the effect of the total precipitation in relation to the maximum movement of the transects in that lithology. The rock transportation was increased in the range of 8% to 700% based on the 2011 measurement whereas transect 9 had less movement in the year 2017.

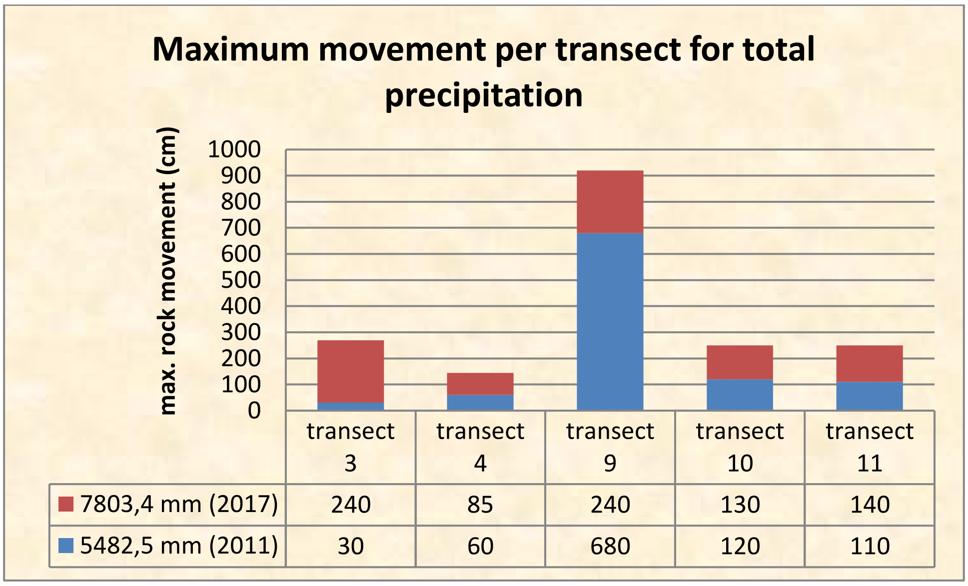


Figure 34: Maximum movement for each transect according to total precipitation

3.2.3 Mixed light and dark Gravel

The last three (3) transects 5, 6 and 7 are in a slope above to the road which leads after some meters to a place where the cars should be parked as a narrow mountaineering path starts. So the previous transects were visited through this path. Mainly these three transects consists of a mixture of light and dark gravel which are the debris of the surrounded and upland lithologies. They are situated in a water flow channel, evidence which is visual by noticing the background of Figure 35 and Figure 36. In the edges of each transect and in the whole upper slope, black karst limestone exists whereas the down slope has gravel which has been transported through the water channels from the upland positions. The impact of alternating periods of snow cover, the precipitation and the steepness of the slope were the reasons that a meaningful transportation was measured in both years.

Specifically, transect 5 which is in the highest elevation of 2054 m presented a scattered movement until 70 cm in the year 2011 whereas one point had a group movement until 170 cm. In the year 2017 the scattered transfer reached until 170 cm whereas the isolated rocks until 280 cm. By noticing that for the point 7 the group movement in both years is the same 170 cm, it is estimated that they were not the same rocks. The steepness 63% in combination with the rainfall and snow definitely leads to the assumption that the rocks in 2011 were transferred in the bottom of the slope and in the year 2017 new rocks were measured.

Transect 5	2011 measurement (cm)		2017 measurement (cm)	
Points	Individual	Group	Individual	Group
1	0	0	100(1)	0
2	0	0	100(1),140(1)	0-60
3	0	0-20	0	0-80
4	0	0-70	0	0-90
5	0	0-50	110(1)	0-45
6	0	0-40	0	0-60
7	0	0-170	0	110-170
8	170(3)	0-50	280(2)	90-140
9	100(1)	0-40	0	0-140

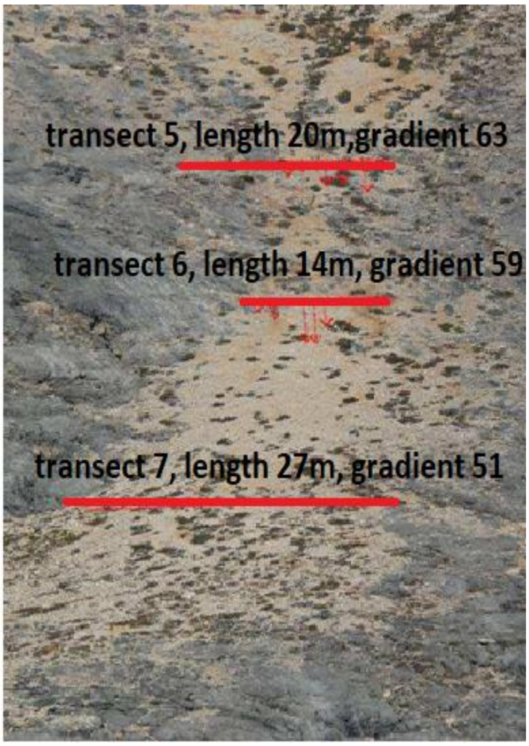


Figure 35: Photo of transects 5, 6 and 7 in 2011 where movements are placed in the surrounded tables. Individual means isolated rocks and in the bracket is how many rocks were found in that distance. Group means scattered rocks.

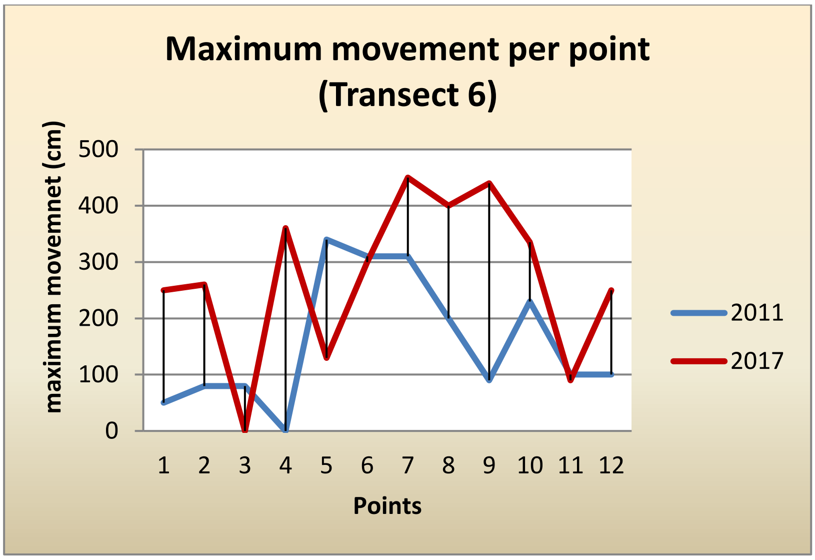
Transect 6	2011 measurement (cm)		2017 measurement (cm)	
Points	**Individual**	**Group**	**Individual**	**Group**
1	0	0-50	0	0-250
2	80(3)	0-50	0	0-260
3	80(1)	0	0	0
4	0	0	0	0-360
5	0	0-340	0	120-250
6	0	0-310	0	100-400
7	0	0-310	0	70-520
8	0	0-200	0	180-580
9	0	0-90	0	180-620
10	0	0-230	220(1),280(1),335(1)	0
11	50(1),70(1)100(1)	0-40	0	0-90
12	0	0-100	170(1),250(1)	0-120

Transect 7	2011 measurement (cm)		2017 measurement (cm)	
Points	**Individual**	**Group**	**Individual**	**Group**
1	0	0	50,70,90	0
2	50(1),80(2)	0	130(2)	0-90
3	0	0-100	0	73-210
4	0	0-120	0	60-140
5	220(1)	0-170	0	0-260
6	0	0-80	0	0-160
7	0	0-60	0	40-110
8	0	170	70(1),100(1),210(1),250(1),645(1)	0
9	0	0	0	40

Figure 36: Photo of transect 7 in 2017 and Table with movement measurements year 2011 and 2017

The assumption that not the same rocks were found in the points in both measurement years is also presented in transects 6 and 7. In transect 6 point 5 and point 6 and in transect 7 point 8 there is more scattered range than the year 2017.

Moreover, trying to understand the possible relation between the two measurement years Figure 37 was created by using the maximum movement in each point. Transect 6 presents more fluctuations due to the biggest gradient compared to transect 7 which is in lowest level. The average transportation for transect 6 is 157.5 cm in the year 2011 and through the six years period is increased 73% by giving as maximum average 272.08 cm the year 2017. On the other hand, the transportation values in transect 7 are reduced compared to transect 6 whereas the increase between the measurement years is more in the level of 94%. Especially in the year 2011 the average maximum movement is 92.22 cm while in the year 2017 is 179.11 cm by having one point (number 8) which has been transported 645 cm downwards and mainly it contributes to the total average.



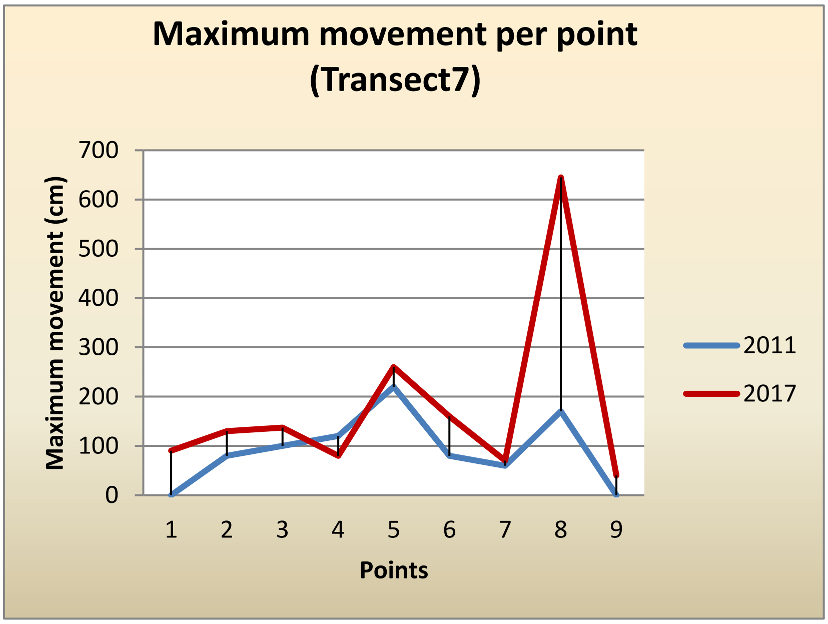


Figure 37: The maximum movement per point for transects 6 and 7 respectively.

Despite the fact that all the transects consists of the same lithology, the main characteristics of the slope plays an important role to the rock movement. A survey which was conducted in Paris basin (Pays de Caux) demonstrates that the steepness and the length of the slope in combination with the intense rainfall can influence the amount of erosion. By presenting the results of this survey the increase of steepness increases the runoff, sediment concentration and soil loss due to the flow velocity which is much higher and the infiltration is decreased (Chaplot-2000). The length of the transect is also important to have impressive transportation as due to the formula $V(x)=d(x)/(T_f(x)-T_o(x))$ (whereas $V(x)$= flow velocity, $T_f(x)$=final time that the solute passed by a sensor when the signal peaked and $T_o(x)$= initial time at which the solution was injected)(Charplot-2000) as much length in the transect as more increase in the flow velocity. Probably this explanation justifies the reason why transect 7 had so large values of rocks transportation.

In addition, by having enough precipitation during all the study years it is not surprising that the movements will be present. Intense rainfall increases flow accumulation which adds extra kinetic energy to the rocks in order to be relocated.

It is also important to mention that as these transects are close to the road, human influence is present. By observing the points but also the surrounded area, elements that animals specially goats were found. It was obvious that some points have been affected by the walking of the animals so part of the movement maybe some cm could be caused due to this situation.

3.3 General remarks of the movements

By observing the movements in all the transects and also adding the transported lengths of all the points of each transect (Table 4), some general remarks can be mentioned.

Table 4 Total transported lengths (cm)			
Transect	**2011 measurement**	**2017 measurement**	**% Difference**
1	90	483	+81.4
2	200	425	+52.9
3	50	690	+92.7
4	110	335	+67.16
5	620	1060	+41.5
6	1890	3265	+42.11
7	830	1612	+48.5
8	0	0	0
9	1070	965	-10.88
10	520	850	+32.82
11	480	890	+46.6
12	290	545	+46.79
13	315	610	+48.36

First of all, in the year 2017 measurements appear with more total movement in the range of 41% to 67% than in the year 2011 while the transect 3 and transect 1 have the highest percentage of 92.7% and 81.4 % respectively. An exception of this assumption is the transect 9 which the total movement is 10.88% less than in the year 2011. This difference is caused due to some rocks were found 6.80 m downwards in 2011 whereas in the year 2017 the maximum movement was until 2.60 m.

As it is already mentioned above by providing Figure 33 the steepness of the slope in the same lithology influences rock movement positively (López Vicente, 2010). By creating Figure 38 which demonstrates how total transported lengths are changing by increasing the slope in different lithologies, it is obvious that the influence is also positive. The 59% slope has more movement than the previous slopes whereas the slope in 65% is null due to the lithology influence as there was no movement there over the previous years. Each slope has a specific structural pattern which can provoke a variety of shears in the weak rock masses, resulting in the failure behavior to be different in several slopes (Hungr, 2004). The stability number Ns is used theoretically in order to describe the upper limit of rock strength. The formula $Ns=\gamma*H/\sigma_c$

(whereas γ=the unit weight of the rock material, H=the height of the slope and σ_c=uniaxial compressive strength of the rock) (Hungr, 2004) indicates that when the weight of the rock is more, it has a positive impact on not having rock transportation. Excess water to a slope because of precipitation or snow melting can decrease the stability of the slope by adding weight to a slope which means that gravity is more. In addition to that, saturated pores have more forces to push the grains apart (Hammah, 2009). According to these results, transect 8 by having vast rocks (Figure 39) and not being in a gully location can justify the reason why there were no transferred rocks.

Also the slope 63% seems to have less total transportation than the slope 59% but this can be justified by taking into consideration that these transects were in gravel locations. When the locations were visited, transect 6 had some rock movements until 6.20 m downwards whereas transect 5 until 2.80 m. As a result, total transported lengths in transect 6 are more than the transect 5 but it is doubted if this can come to a safe conclusion as there were probably transported rocks which were not found.

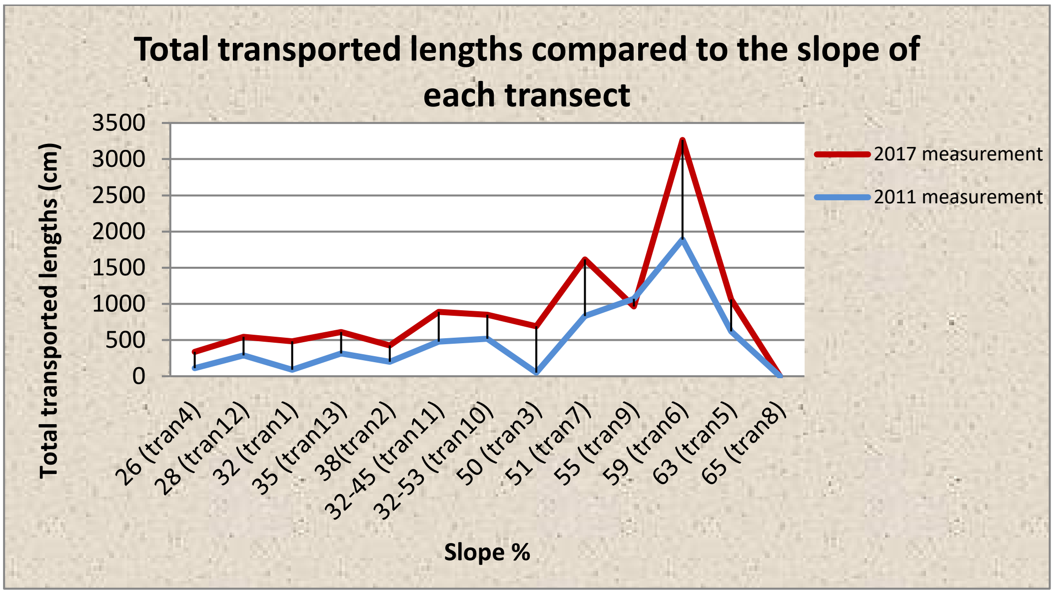


Figure 38: total transported lengths according to different slope angles in each transect

Figure 39: painted rocks in one point of transect 8

On the other hand, it is not visual how the length of the transect can affect rock movement. In paragraph 3.2.3 it is mentioned that more length can cause more flow velocity (Charplot, 2000) in the same lithologies but in different lithologies Figure 40 proves that there is no a specific relation. Additionally, the more length in transect increases the possibility of having more movement due to more faults which can appear through the materials and the collaboration of these faults (Papathanou, 2004). That is a very common phenomenon in a landslide where a huge part of mass is sliding down.

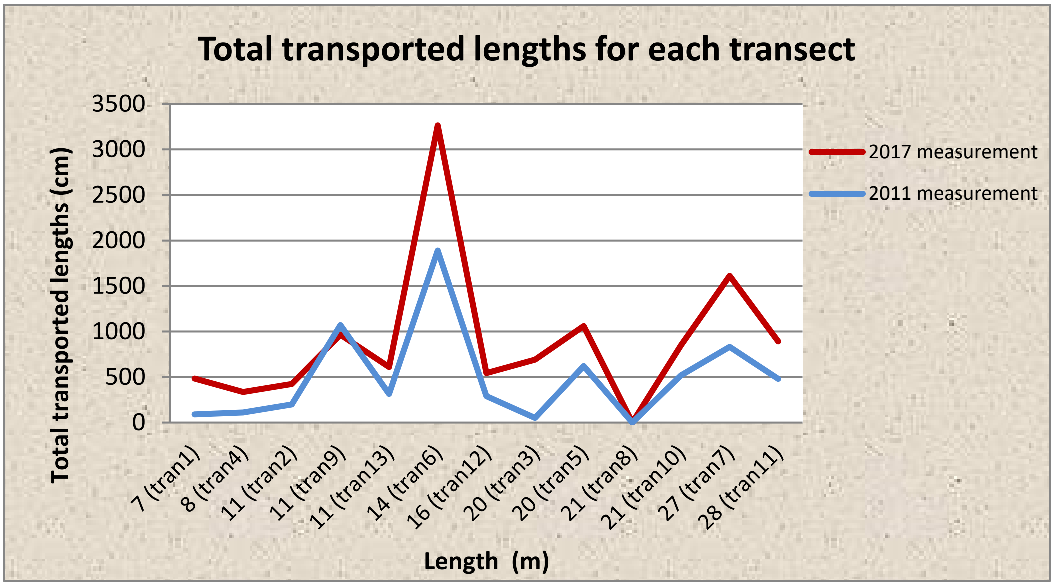


Figure 40: total transported lengths ordered by different lengths of total slope for each transect

Furthermore, the lithologies which have not changed their composition have less possibility to be affected from landslide and erosion as they maintain their properties and their original strength. This can be stated by the movements in re-crystalline limestone compared to the platy limestone which are more intense (Figure 41). Also, the areas with platy limestone have more karst landscape as a consequence the water of rainfall to penetrate directly to the deep aquifer without remaining on the surface long term periods by causing important erosion (Malagò, 2016).

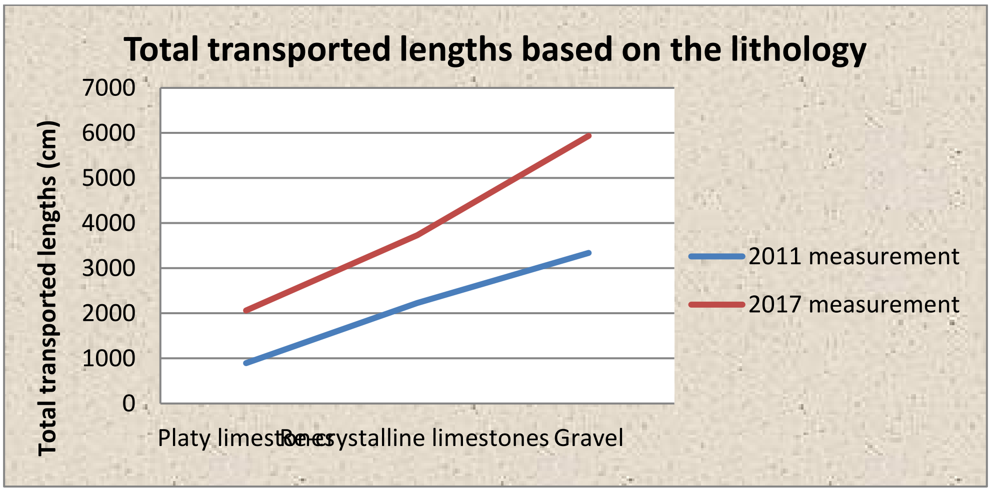


Figure 41: total transported lengths ordered by different lithologies

By observing all the Figures above (Figure 38, 40 and 41) and the analysis which is written for each transect individually, the transect 6 has the most rock movement in both measurement years as it combines the biggest slope gradient and the most dissolved lithology. On the other hand, all the transects which are in platy limestone had totally in both measurement years, less rock transportation due to the lithology properties and they don't have very steep slopes. Despite the fact that transect 3 and 4 are in re-crystalline limestone their total transported lengths are less compared to platy limestone, evidence which enforces the research to conclude that the steepness of the slope has the most important role to the movement, as both of them have the smallest gradient.

Taking into consideration the meteorological conditions, the period from September 2011 to August 2017 includes winter months with extremely low temperatures compared to the period from September 2008 to August 2017. Mainly the years 2012, 2015 and 2017 have months with minimum temperatures -6.9°C, -6.7°C and -7.4°C respectively, whereas in the year 2011 only in one month the temperature was -6.4°C. Despite this fact the average minimum temperature during winter months, is almost the same in both periods, as for the first period it is -3.3°C and for the second one is -3.5 °C. Since there are no snow data of the study region and the values of the lowest temperatures are almost the same, it is extremely difficult to mention in which period the snow had more influence.

On the other hand, precipitation has a big influence on rock movement. By noticing Figure 42 and the previous Figures 28 and 34 in specific lithologies, it is obvious that when the precipitation is increased, more rock transportation is expected. By observing Figures 38, 41 and 42, transect 6 had the maximum rock movement in 2017 due to its slope and lithology properties in combination with the high precipitation. Its slope and lithology properties are much more crucial because it also had the maximum rock transportation in the year 2011 despite the fact that the precipitation was less. Transects 5 and 7, which are located in the same lithology as transect 6, have the second and third biggest rock transportation which can mainly be justified due to the gradient of the slope.

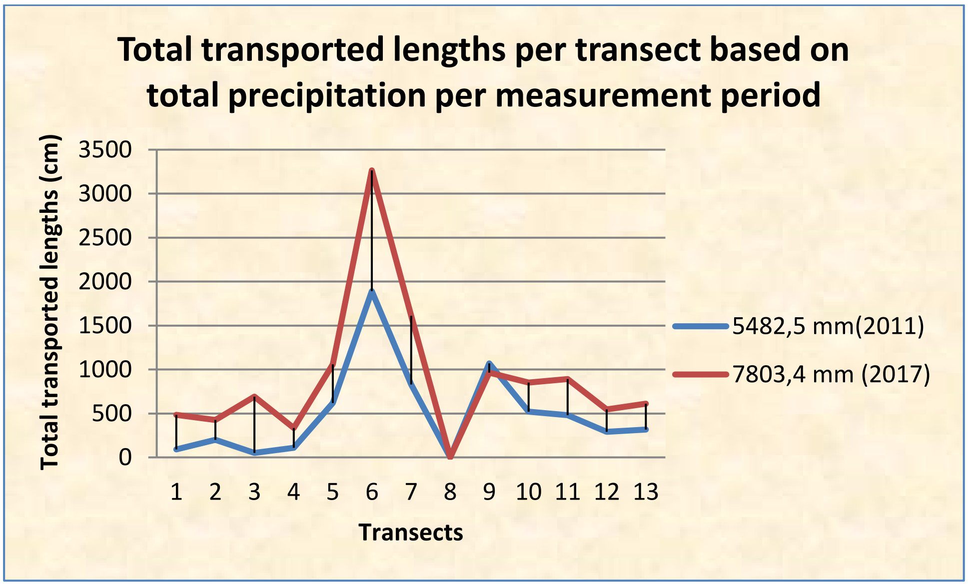


Figure 42: total transported lengths ordered by the total precipitation of each period

The most impressive remarks were to justify what had probably happened in transect 8 and transect 9. For transect 9, as it has already been mentioned, the factor that there are uncertainties from organizing the experiment well, probably caused the existence of less movement in 2017 compared to 2011. The slope is quite steep and under the influence of high precipitation it is a bit strange that there was not more rock transportation in 2017. Of course the influence of more tectonic forces in the second period definitely leads to the assumption that there were more transferred rocks which were not found. Transect 8 is the exception of the results by not giving any movement under none of the parameters' influence. One explanation which can be given is that the lithology has kept its strength and its properties in the maximum scale.

In addition, the geotechnical properties for each geology have a crucial role to seismic vulnerability as the disintegration of the materials makes them lose their connectivity in case of ground acceleration. Mainly the oldest formations have more beneficial behavior so as not to be influenced by earthquakes like the case of platy limestone (Sarris, 2010). This can also be supported by the formula 4 in paragraph 3.1 and the tables which are combined in this formula by giving different values in each index which are based on its seismic sensitivity. The lower the value of the index is, as better resistance the geology has to the earthquakes results. So platy limestone has the number 4 whereas the gravel has the number 9 which means that it can easily fail (Katsaounis, 2010).

Another formula which is known as Coulomb stress change, $\Delta CFF = \Delta\tau + \mu' * \Delta\sigma_n$ (whereas ΔCFF= Coulomb Fault Failure, μ'=effective friction factor, Δτ=shear, positive in the direction of slip and $\Delta\sigma_n$= normal shear, positive if the fault is unclamped) justifies that every event which causes shears in the materials can also cause slow-slip events and movements (Steer, 2014). According to a survey in Taiwan the Chi-Chi earthquake caused 3.7% density of landslides while the typhoon Toraji had similar distribution but it caused 6.6% landslides (Hovius, 2011). Despite the difficulty to estimate an accurate rate between earthquake and erosion, an article of Bruce Malamud (2004) mentions that erosion rates due to earthquake- generated landslides is generally h=0.1-2.5 mm/year^{-1}, southern California has a rate of h=0.02-0.2 mm/year^{-1}, Japan with more seismicity has h=0.2-7 mm/year^{-1} while Greece tends to have h= 0.01-0.7 mm/year^{-1}, the same as Turkey.

According to Sarma and Bhave (1974), the factor of safety against rock movement and landslide due to earthquake forces is estimated by the formula FS= 1+b*kc (whereas b= is a variable factor depending on the geometry of the slope and kc= the crucial acceleration in order to have a board line balance in the slope). It is mentioned that the steeper the slope is, the less value of b factor is (Sarma, 1974). As a result, in the study area transect 6 is estimated to have been influenced more from earthquake forces compared to transect 4 and 12 with the less gradient.

Despite the formulas the study area will always present seismicity. According to method BAN which is an effort to predict earthquakes by recording Seismic Electric Signals in each region, the seismicity in an area follows the same behavior through the years despite the size of the earthquakes (Garyfallidis, 2012). So the study area will always be under tectonic pressure, hence, rock movement and uplifts will be part of this process.

4. Conclusion

The objective of present work is to analyze the rock movement of Lefka Ori mountains in the south western part of Crete by mentioning the meteorological and geomorphologic conditions of the area. As Crete is located in the boarder of the Eurasian and African tectonic plates, many earthquakes can happen yearly thus an extra interest is focused on how the earthquakes can influence the movement. All these parameters were mentioned by using the experiment which has been conducted between August 2008 and August 2017.

By setting 13 transects in elevation of 1953 m until 2147 m, in a variety of slopes, lengths and in 3 different lithologies, some general conclusions have been drawn. The lack of accurate meteorological data in the region, due to the absence of stations in such a high altitude, had as a result to estimate the precipitation of the study area by using three (3) closest stations and the direction of the wind based on literature (Rackham, 1996). The difficulty to have accurate meteorological data in the combination with the transects that were visited only in August of the year 2011 and 2017, caused to uncertainty about the movements which were found. In some cases like transect 2 and transect 13, the 2011 measurement movement was bigger than the 2017 measurement movement. It would have been more efficient to have paid more visits during the year and mainly during the winter when the precipitation is more and snow is also present in order to be completely sure of how precipitation and snow influence rock transportation. This was not possible because the area is inaccessible due to extreme weather conditions.

In addition, the three different types of lithology in the area indicate that the movement is related to the percentage of dissolution of the original lithology. As a result, platy limestone areas have less movement whereas the gravel locations have the maximum rock transportation according to Table 4. The re-crystalline limestone has a variety of rock movements depending on the heterogeneous structure and the percentage of the disintegration of the limestone. Also the steepness of the slope influences positively the rock transportation. By adding the transported lengths in each transect the assumption that more gradient causes more transportation is obvious, exempted the type of lithology.

By using statistical analysis, no empirical models were found in order to predict the values of the year 2017, based on the measurements of the year 2011. On the other hand, not having counted the rocks and not having been noted down which rocks have been moved in the year of the experiment, it was extremely difficult to estimate the statistics and be accurate that in both years the same rocks were found. By not conducting the experiment correctly, limited data came out which also means limited use of programs. For example, in the case of re-crystalline limestone where all the transects are in the same part of the study area, by having 5 more transects, in total 10 would be useful to do kriging which means to produce a predicting map of movements for the whole area of this lithology.

Finally, the density and the size of the earthquakes stimulate more movement. That can be justified by comparing the seismicity of the area before the first and the second measurement and the values of the measurement. Between the years 2011 and 2017, larger earthquakes have happened in comparison to the period 2008-2011, in which there were more earthquakes but in lower size. Earthquakes provoke extra forces on the materials and cracks can be caused resulting in rocks to lose the connectivity and slide down.

To sum up, the results of this study set the starting point to understand what happens in Lefka Ori by using qualitative analysis. All the above mentioned, illustrate that the area, being under the influence of these parameters should attract the future interest by providing much useful information in order to understand natural processes of rock movement.

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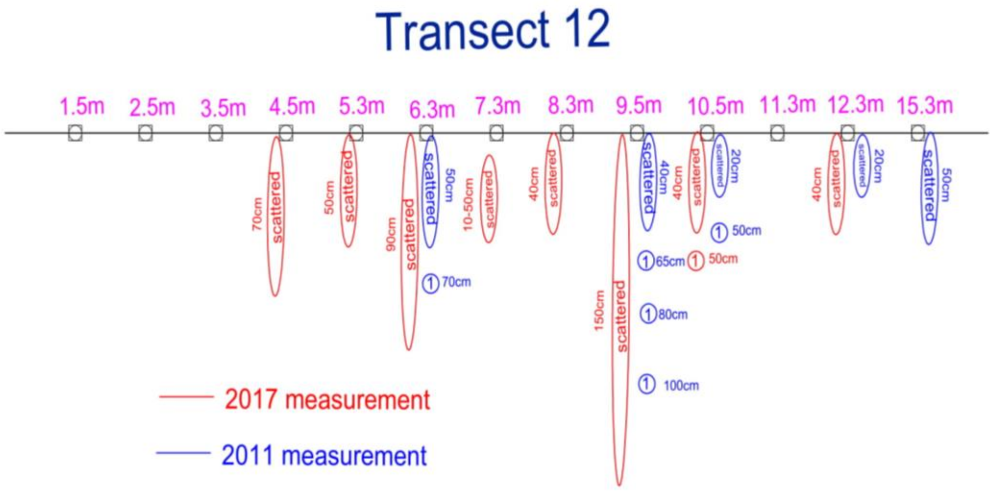
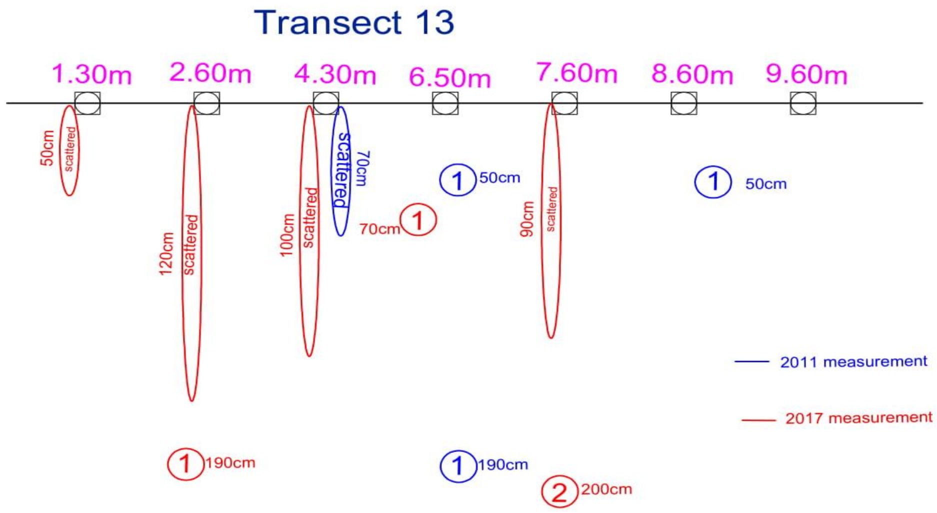
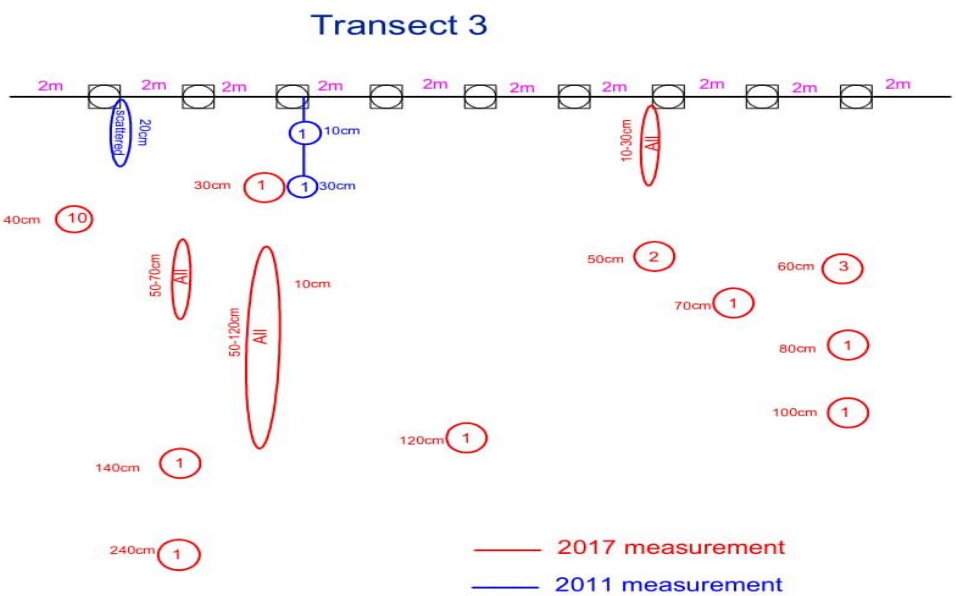
Appendix



Transect 12	2011 measurement (cm)		2017 measurement (cm)	
Points	**Individual**	**Group**	**Individual**	**Group**
1	0	0	0	0
2	0	0	0	0
3	0	0	0	0
4	0	0	0	0-70
5	0	0	0	0-50
6	70(1)	0-50	0	0-90
7	0	0	0	10.-50
8	0	0	0	0-40
9	65(1),80(1),100(1)	0-40	0	0-150
10	50(1)	0-20	65 (1)	0-40
11	0	0	0	0
12	0	0-20	0	0-40
13	0	0-50	0	0

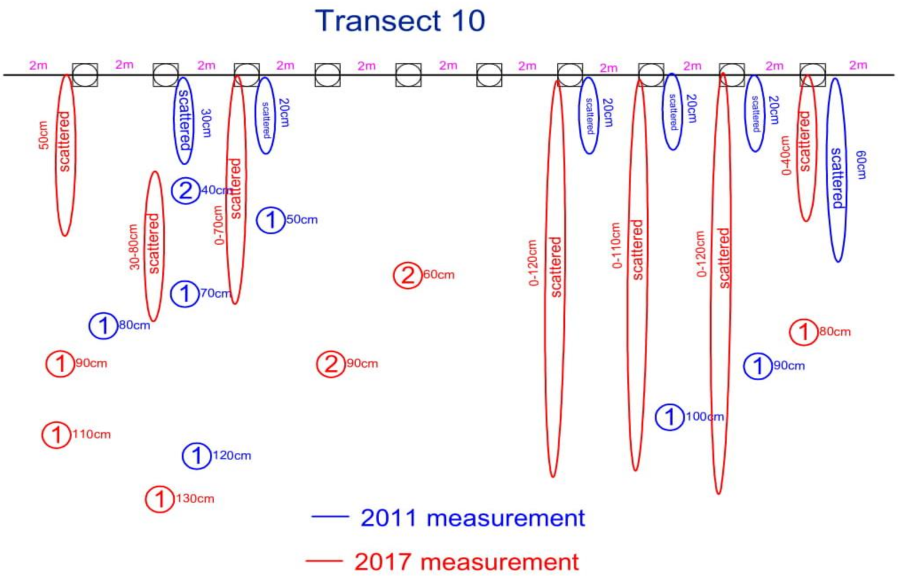


Transect 13	2011 measurement (cm)		2017 measurement (cm)	
Points	**Individual**	**Group**	**Individual**	**Group**
1	0	0	0	0-50
2	0	0	190(1)	0-120
3	0	0-75	0	0-100
4	50(1),190(1)	0	70(1)	0
5	0	0	200(2)	0-90
6	50(1)	0	0	0
7	0	0	0	0



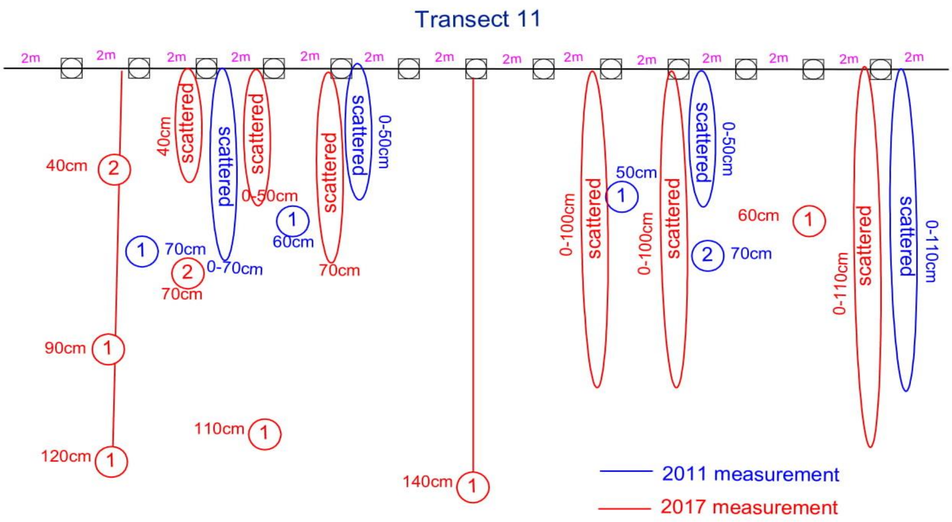
Transect 3	2011 measurement (cm)		2017 measurement (cm)	
Points	**Individual**	**Group**	**Individual**	**Group**
1	0	0-20	40	0
2	0	0	140(1),240(1)	50-70(all)
3	10(1),30(1)	0	30(1)	50-120(all)
4	0	0	0	0
5	0	0	120	0
6	0	0	0	0
7	0	0	50(2)	0-30(all)
8	0	0	70	0
9	0	0	60(3),80(1),100(1)	0

The photo shows the point 7 the year 2017 which has one rock in 50 cm and the others are scattered between 10 and 30 cm.



Transect 10	2011 measurement (cm)		2017 measurement (cm)	
Points	**Individual**	**Group**	**Individual**	**Group**
1	80(1)	0	90(1),110(1)	0-50
2	40(2),70(1),120(1)	0-30	130(1)	30-80
3	50(1)	0-20	0	0-70
4	0	0	90(2)	0
5	0	0	60(2)	0
6	0	0	0	0

7	0	0-20	0	0-120
8	100(1)	0-20	0	0-110
9	90(1)	0-20	0	0-120
10	0	0-60	80 (1)	0-40



Transect 11	**2011 measurement (cm)**		**2017 measurement (cm)**	
Points	**Individual**	**Group**	**Individual**	**Group**
1	0	0	0	0
2	70(1)	0	40(2),90,120	0
3	0	0-70	70(2)	0-40
4	60(1)	0	110(1)	0-50
5	0	0-50	0	0-70
6	0	0	0	0
7	0	0	140	0
8	0	0	0	0
9	50(1)	0	0	0-100
10	70(2)	0-50	0	0-110
11	0	0	0	0
12	0	0	60	0
13	0	0-110	0	0-110