Determination of the relationship between tectonic and karstification using morphometric indices in Bozburun Peninsula, Marmaris, Türkiye

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ABSTRACT

Bozburun Peninsula (Marmaris) attracts attention because it contains various karstic shapes on limestones belonging to different periods and it is also an important area in terms of tectonic activity. This study examines the area sizes of the karstic shapes determined by satellite images, topographic maps and field studies, the elevations, slopes, depth value ranges and extensions where they are clustered and the fault lines affecting them have been determined. In order to explain this effect quantitatively, the elongation ratio (R_E) and elongation direction (E_A α) from morphometric shape indices were used. Poljes, on the other hand, were evaluated in more detail separately from dolines and uvalas, the pitting rates (P_R) was calculated. It was understood that in this study which Remote Sensing (RS), Geographic Information System (GIS) technologies and field observations were correlated, folds and fractures that occurred in the Western Taurus Karst Region during the paleotectonic and neotectonic periods had a positive effect on karstification, and it was determined the lie of the karstic shapes to a great extent resemblance to the lie of the faults.

Keywords: Karstification, Karst Forms, Tectonic Factors, Morphometric Indices, Bozburun Peninsula, Türkiye.

1. Introduction

Bozburun Peninsula is an important peninsula that is part of both the Aegean Sea and the Mediterranean coasts, presenting an indented appearance and hosting many coves and gulfs. The study area is located between latitudes 36◦33'-36◦55'N and longitudes 27◦57'-28◦18'E and in the southwest (SW) of the Aegean Region. The peninsula is administratively within the boundaries of Marmaris district. The area is surrounded by the Gulf of Hisarönü of the Aegean Sea in the west and the Gulf of Marmaris of the Mediterranean Sea in the east (Figure 1). Doğaner (1999), in his study on the Bozburun Peninsula; its location, she stated; it as an area starting from the south of the line drawn between Gulf of Hisarönü and İçmeler Bay, extending to Rhodes Island and containing many settlements (Bozburun, Taşlıca et al.). However, in this study, the border was expanded to include the town center of Marmaris, taking into account the basin boundaries. The study area extending in the southwest direction towards Rhodes Island has a projection area of ~440 km^2 (approximately) (Figure 1).

Bozburun Peninsula is located in the western part of the *Taurus Karst Region* (South Anatolian Karst Belt), which is an important karst belt. Micro and macro sized karst shapes are frequently encountered in the Bozburun Peninsula, as in the rest of the Taurus Mountains.

The degree of influence of the factors (geological/geomorphological features, processes, climate and time) that are effective in the development of karstic lands may vary across regions. Sub-humid characteristic conditions of the Mediterranean climate, the direction, thickness and slope of different lithological layers are known as important factors in karstification (Tuncer and Nazik, 2010; Doğan et al., 2017; Nazik and Poyraz, 2017; Öztürk, 2020; Aydın and Tuncer, 2021). When evaluated in terms of lithological structure, limestones are known as the most suitable rock for the formation of karstic lands. There are pelagic and neritic origin limestones formed in different depositional environments, varying from place to place containing different proportions of minerals or elements (calcium, clay, marl, micrite, etc.) in their composition in Bozburun Peninsula.

A large number of the karst morphology studies have been carried out in various regions of Türkiye, explaining the effect of different geological and climatic conditions on karstification. Although there are many researches on geomorphology in the study area and its close surroundings, there are no other karst studies other than a study of caves (Günhan and Öner, 2021; Günhan et al., 2018). For this reason, a detailed study is needed on the Bozburun Peninsula, which has very unique karst shapes.

The neotectonic period stretch tectonics and the strike-slip and block faults created by this tectonic and the fluvial erosions by the rivers created by the sea level changes have been extremely effective in the emergence of the morphology of the region (Doğan, 1996; Tuncer and Nazik, 2010; Akdeniz, 2011; Nazik and Poyraz, 2015). The fault lines and the extension of the karstic shapes show parallelism at most points in the area, which is located in an active tectonic region. The extensions of the faults are generally in the direction of E (East)-W (West), ENE (Eastnortheast)-WSW (Westsouthwest). However, at many points, this extensions cut by a different fault at a steep or nearly vertical angle. This situation is clearly seen in the area reflecting the tectonic characteristics of the Southwest Aegean (Tur et al., 2015; Topal, 2018). As a result, a remarkable karst pattern has appeared in the field. For this reason, constitutes main purpose of the study to explain the tectonic-karst development of the peninsula (morphological, morphotectonic and karst development relationship). In explaining this relationship, the main factors affecting the shaping of the field were determined empirically, and in this direction, geological/geomorphological features and relations were focused.

In geomorphology studies, analyzing the fields in terms of morphometric and explaining their development accordingly has come to the forefront especially in recent years. The share of progress in Geographic Information Systems (GIS) and Remote Sensing (RS) technologies is great in this subject. Studies conducted in Türkiye also show richness in this respect. Some important studies in this context are listed below: (Turoğlu, 1997; Cürebal, 2004; Erginal and Cürebal, 2007; Özdemir, 2007, 2011; Öztürk and Erginal, 2008; Bahadır and Özdemir, 2011; Sarp et al., 2011; Yıldırım and Karadoğan, 2011; Uzun, 2014; Avcı and Günek, 2015; Nazik and Poyraz, 2016; Köle, 2016; Topuz and Karabulut, 2016; Avcı and Kıranşan, 2017; Avcı and Sunkar, 2017; Geçen and Ölmez, 2017; Topal, 2018; Ege and Duman, 2020; Ege et al., 2019; İzmirli and Ege, 2019; Zorer and Tonbul, 2019; Aydın and Tuncer, 2021; Şimşek et al., 2021). However, it presents unique morphological features, no detailed study has been found on the explanation of the tectonism-karstification relationship of the area. It is thought that this study can contribute to elimination lack of the literature.

In explaining the karst pattern of the site, morphometric analysis have been resorted to with GIS and RS technologies, which are widely used in Earth science studies and enable objective results to be reached. In this context, in the study quantitative inferences were made about the topographical character of the area, its relief and the formation systematic of karstic lands by means of morphometric analyses.

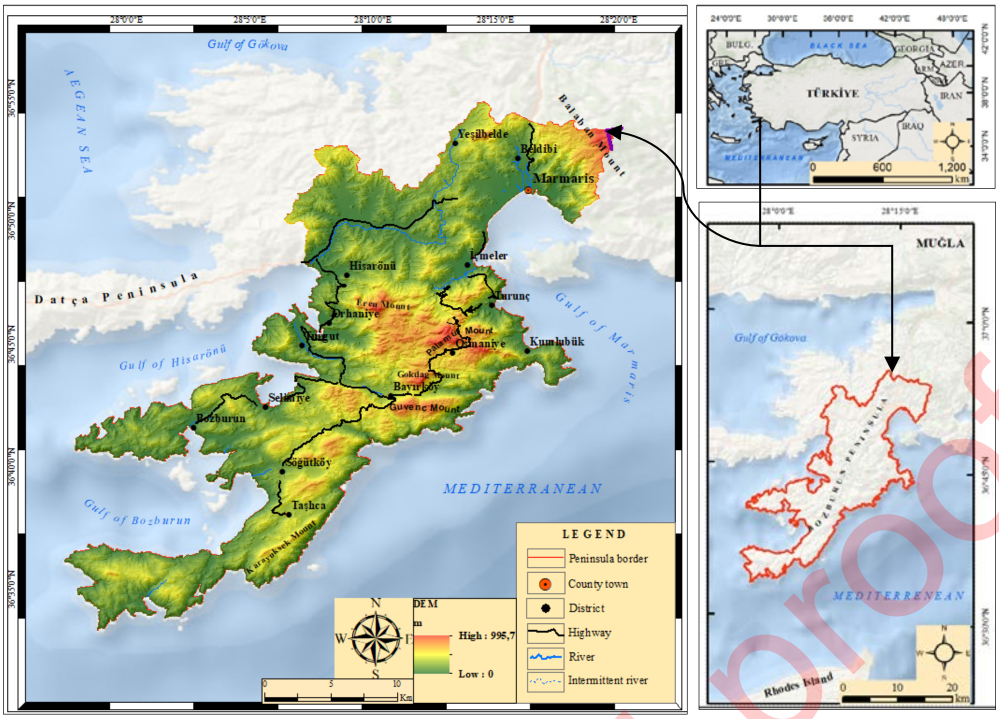


Figure 1- Location of Bozburun Peninsula.

2. Factors Affecting The Formation On The Peninsula.

2.1. Material and Method

In order to understand and describe the physical features of the site, 16 topographic maps with 1/25000 scale and 10 m isohips spacing were digitized using ArcGIS 10.5 package program in GIS environment, and geomorphology map was drawn by the same program. While detecting dolines, uvalas and poljes, images and three-dimensional data in the Google Earth Pro program were used, and the relevant locations were confirmed by field studies. These data were digitized again in GIS environment. While explaining the geological features, the geological map of the 1/100000 scale Marmaris O20 map of the General Directorate of Mineral Research and Exploration (MTA) was used.

As a result of intensive literature review; it has been observed that morphometric analyzes, which can reinforce the outputs of field studies, are used quite frequently, especially in recent years, for purposes such as making systematic inferences about the geomorphological character of the field (the valleys and drainage systems, lakes, karst terrain slopes stores and geometric explaining the formation of the pattern) and defining the field quantitatively. It has been understood that the most suitable indices to accurately determine the effect of faults on karst shapes are the *elongation ratio* (E_R) and *direction* (E_A α) from the morphometric indices (Williams, 1972; Day, 1976, 1983; Bondesan et al., 1992; Thery et al., 1999; Polat and Güney, 2013; Shanov and Kostov, 2014;

Öztürk, 2020; Öztürk et al., 2018; Ege et al., 2019; Aydın and Tuncer, 2021; Saroli et al., 2022). In order to understand the characteristics of formation of the karstic shapes in Bozburun Peninsula, apart from the elongation rate (E_R) and direction (E_A α), other geomorphological/morphometric features of the related shapes (*area size, elevation, slope values, depth, also pitting ratio for poljes (P_R)*) were included in the research. While mapping the faults in the region; digitized fault data from MTA were compared with faults detected using Landsat 8 satellite imagery in Geomatica 2016 program. As a result of the observations in the field, some of them were associated with each other, combined and missing ones were added.

In this study, after explaining both the morphometric and general geomorphological characteristics of the area and the karst shapes in the area, *Kernel Density Analysis* was performed in the GIS environment to understand where the karstification on the peninsula is concentrated. The azimuth angle of the extension directions of the faults and karst shapes was calculated with the Geo Rose 0.3.0 program. The poljes, the largest of the karst shapes, have been considered in more detail than the others.

2.2. Geological Features

The Bozburun Peninsula is lithologically included in the *Western Taurus Karst System/Region*. The Western Taurus Karst Region consists of *Lycian Nappes* which are the youngest nappes of the Taurus Mountains and autochthonous carbonate rocks belonging to it (Ekmekçi, 2003; Nazik and Tuncer, 2010; Nazik et al., 2019). Different geological formations have been pushed on top of each other in the field formed under the compression regime by the overlays that have occurred in the region from the Paleotectonic period to the present day. These units are tectono-statigraphic units of the Lycian Nappes in different facies, in large and small slices and have a dissonant appearance and occupy a large area in the southwest of Anatolia (Ersoy, 1990; Tuncer, 2021).

The study area and its surroundings are located in an important region where the *Bodrum Nappes*, *Gülbahar Nappes* and *Marmaris Ophiolitic Nappes* belonging to the Lycian Nappes are surfaced. Almost all of the formations on the peninsula belong to the *Mesozoic Era*. Existing units in order from oldest to newest; Middle-Upper Triassic *Çövenliyayla Volcanite* (spilite, basalt, tuff), Middle-Upper Triassic *Kızılcadağ Melange and Olistostrome* (contains ophiolite melange and rarely Jurassic-cretaceous cherty limestones are observed), Middle-Upper Triassic *Orluca Formation* (sandstone, claystone, calsite), Upper Triassic *Bayırköy Formation* (commonly dolomite, dolomitic limestone), Upper Triassic- Lias *Güverdağı Formation* (algal, neritic limestones predominate), Jurassic-cretaceous *Orhaniye Formation* (pelagic limestones in intensity), Cretaceous Marmaris Peridotite (peridotite, serpantine, dunit), Upper Senonian *Karanasıflar Formation* (volcanite units; spilite, basalt), Upper

Senonian *Karanasıflar Formation* (limestone and rarely volcanite breccias), Upper Senonian *Karaböğürtlen Formation* (volcanite units: spilite, basalt), Upper Senonian *Karaböğürtlen Formation* (sandstone, claystone, siltstone) (Erakman et al., 1982) (Figure 2). Among these formations, karstification is mostly was observed in Orhaniye and Güverdağı Formations.

The Güverdağı Formation (*TRJg*, Bozburun units/Bodrum Nappes), which contains a significant part of the karst shapes and is formed by dolomitic limestones in places, is covered from above by the Karanasıflar Formation (*Kkn*, Bozburun units/Bodrum Nappes) inconsistently and exhibits a very curved and fractured appearance. Therefore, the thickness of the formation could not be determined exactly, it was estimated at about 800 m (Bilgin et al., 1997; Şenel and Bilgin, 2010). The formation is of neritic origin.

The other formation in which karst formation experienced, *Orhaniye Formation* (*JKo*, Turunç units/Gülbahar Nappes) consists of calciturbidite intermediate-level micrites and chert micrites with thin-medium local thickness. The formation is excessively curled and broken. The thickness of the formation, whose upper relationship is not observed, is about 400 m (Bilgin et al., 1997; Şenel and Bilgin 2010). The formation is of pelagic origin.

It is understood that pelagic and neritic limestones formed in different periods of the Mesozoic take an important place in the field. The most common of these are neritic limestones, which were formed in different periods between the middle triassic and cretaceous -Upper Triassic-Liassic sediments predominate- (Şenel and Bilgin, 2010). These limestones belonging to the Mesozoic period are quite suitable for karstic formations in terms of their lithological characteristics (Şahin, 2005; Öztürk et al., 2018).

Bozburun Peninsula limestones is surrounded by impermeable units (spilit, basalt, etc.) and relatively less permeable and less soluble (such as dolomite) rocks from the bottom and sides. This situation has formed the boundaries of the horizontal and vertical development of the poljes in particular. The Marmaris Ophiolitic Nappes has also determined the northern boundary of the peninsula in karst formation by its impermeable units (such as serpentine) (Şenel and Bilgin, 2010; Şenel et al., 1994; Günhan et al., 2018).

It is estimated that the peninsula acquired its original shape today during the neotectonic period (especially from the end of Oligocene period) under different tectonic regimes. In total, two compression and two stress tectonics were effective in the immediate vicinity during the Neotectonic period (Tur et al., 2015). In many studies, it has been emphasized that with the opening of the *Büyük Menderes Grabens,* a 13-degree rotation event occurred counterclockwise vector, and as a result of this movement, it has been mentioned that the structural-formal elements are arranged in the NE-SW direction throughout the study area and its immediate surroundings (Tur et al., 2015; Günhan and Öner, 2021) (Figure 2).

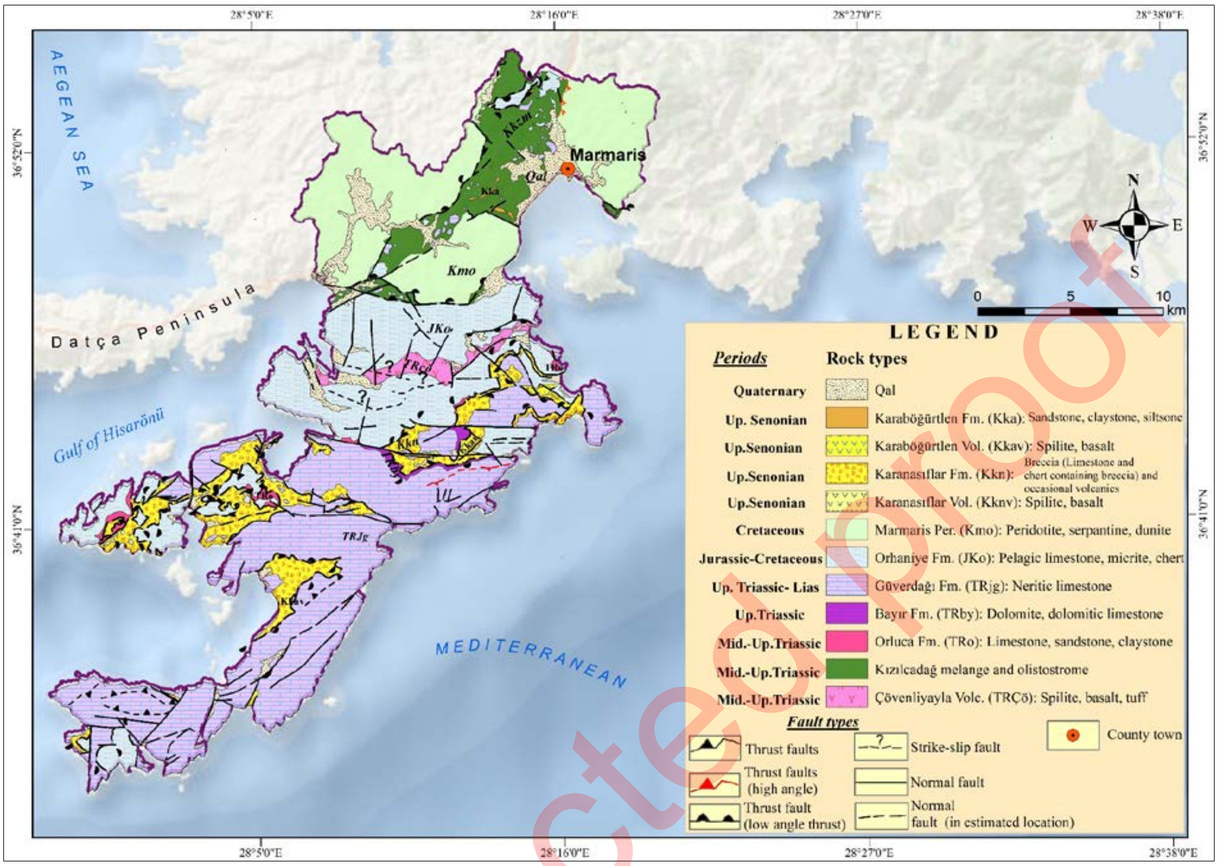


Figure 2- Geological map of Bozburun Peninsula (Şenel and Bilgin, 2010).

2.3. Tectonic Features

The study area which forms the most southwestern part of Türkiye together with the Datça Peninsula is located in an important region where the Taurus Mountains and the West Anatolian broken lines intersect. Bozburun Peninsula; undoubtedly it is quite obvious that it bears the traces of the complex tectonic evolution of the region with its folded and fractured elevations, depression basins, indented and low shores, and sometimes deep, cliff-like bays.

The peninsula is included in the Western Taurus Mountains, which form a part of the Taurus Mountains shown in the Anatolide-Tauride block in the paleotectonic classification of Türkiye. The Western Taurus Mountains start from the Aegean coast and extend to the Kırkkavak Fault Zone in the Isparta bend. On this axis, the study area is located at the boundary of the subduction zone formed by the African and Eurasian plates, which are the products of the Fenno-Sarmatian and Gondwana masses, in a NE direction since the neotectonic period. This zone is the Hellenic Arc (Crete Arc), which is also defined in the literature as a tectonic area that produces active earthquakes and volcanoes in the area where the African plate subducts under the Aegean Sea (Pichon and Angelier, 1979; Tur et al., 2015) (Figure 3).

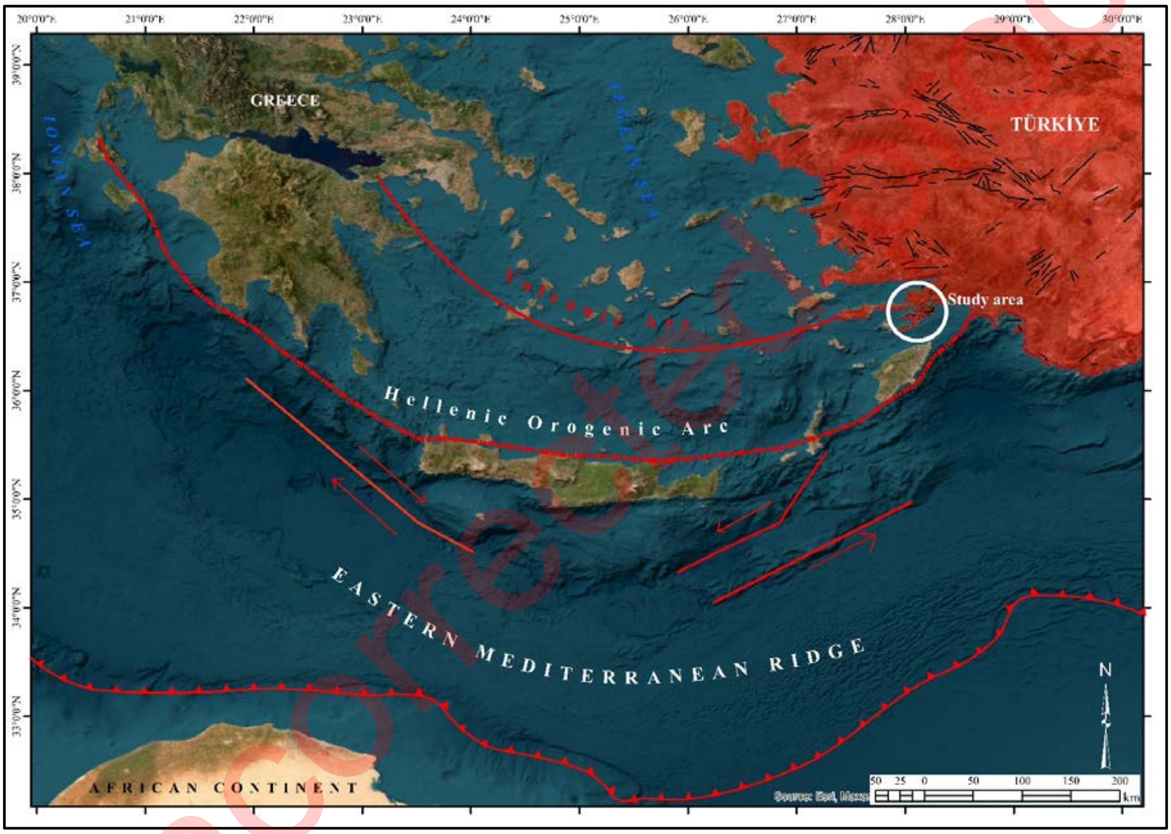


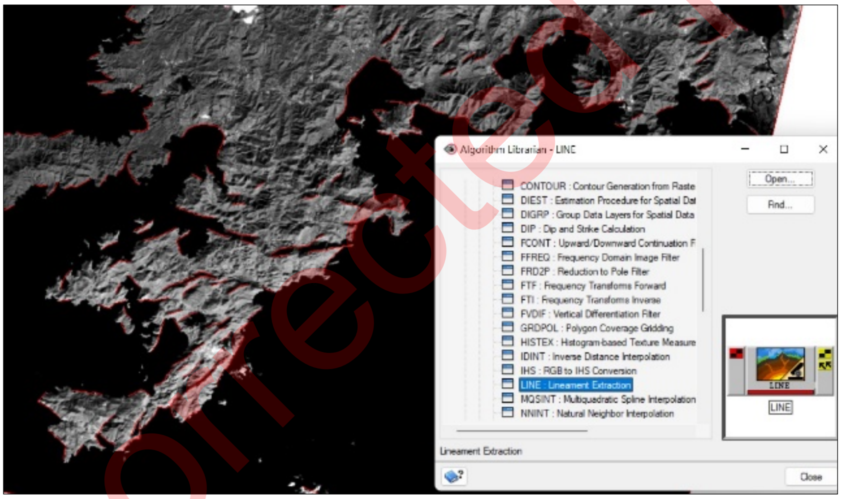
Figure 3- Hellenic Arc.

In addition to the many active faults found to have formed in the neotectonic period in the field, it has been emphasized in current studies that these faults enable the establishment of underground and above-ground hydrological relationship between different structural units (Nazik and Tuncer, 2010; Nazik and Poyraz, 2015; Günhan et al., 2018). In this context, as a result of literature research, and field observations it is believed that these faults had a decisive influence in the formation of karst terrains. It is estimated that karstic development in the region accelerated at the end of the Pleistocene thanks to both the acceleration of seismotectonic processes and the end of the last ice age (Tur et al., 2015; Günhan and Öner, 2021). The types of faults in the field are normal, reverse, strike-slip faults (Figure 4, 5). The stretches of the faults are mostly in the direction of "*E-W, ENE -WSW*".

However, at many points, a different fault can also cut this extension at a perpendicular or near-vertical angle. This situation can be clearly seen on the Bozburun Peninsula, which reflects the tectonic characteristics of the Southwestern Aegean (Uluğ et al., 2005; Gündoğdu et al., 2015; Gündoğdu et al., 2020; Tur et al., 2015; Topal et al., 2016; Günhan and Öner, 2021; Dikbaş et al., 2022).

The Rhodes Fault, one of the most important active faults in the region, produced a magnitude 6.3 earthquake on May 23, 1961 off the Gulf of Marmaris. In the solutions of the P wave focal mechanism, it was understood that this earthquake was caused by the reverse faulting component (Ersoy et al., 2000). In addition to the Marmaris Bay, Gökova Bay and Hisarönü Bay and their immediate surroundings are locations with high tectonic/seismic activity, where dozens of significant earthquakes with a magnitude above 5 have been experienced. It is possible to find the pre-20th century earthquakes witnessed by humanity in historical documents (Kırkan et al., 2023).

Figure 4- Detection of fault linearity in Geomatica 2016.



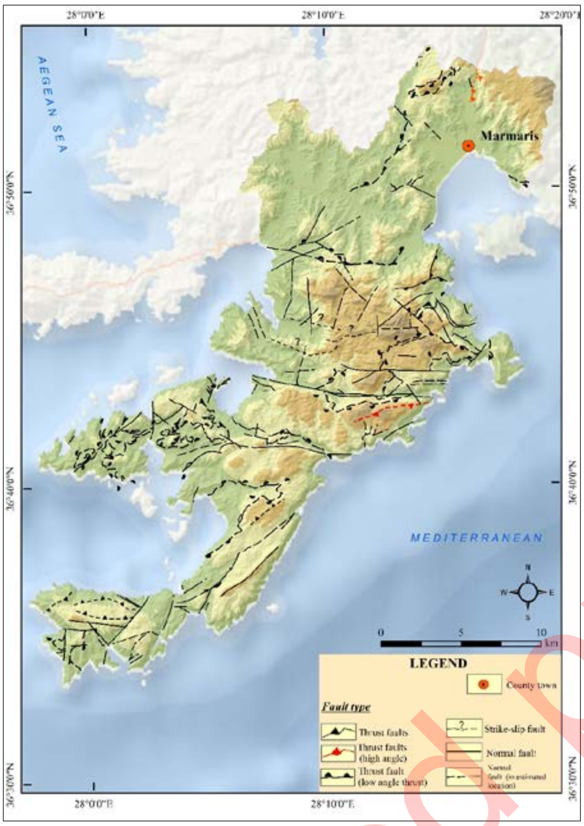


Figure 5- Fault map of Bozburun Peninsula.

2.4. Geomorphic Features

The Taurus belt of Anatolia is very rich in terms of karst areas. Since the middle of the Cretaceous, it has taken its current shape with the compression and uplift of the submarine carbonate platform and volcanics. These folds also contain small fractures in various areas and the micro-basins formed by them. The karst development continued in this direction with the effect of physical and chemical decomposition in the research area, the main skeleton of which was shaped by faults with normal, reverse, and strike-slipe characteristics (Erol, 1983, 1990; Akay and Uysal, 1988; Şimşek et al., 2021). Faulting has been effective in the formation of hills, valleys and even many plains with many folds and fractures (Taşlıgil, 2008).

It is estimated that the geomorphological and karst processes in the field began with the rise of Anatolia in the Middle Miocene and the retreat of the Lower Miocene sea, and that humid and warm climatic conditions accelerated karst formation during the period when the Lycian Nappes were deployed to the region. Probably, karstification that became stagnant in the Pleistocene ice age, and towards the end of this period (Late Pleistocene), both the end of the Ice Age and the acceleration of seismic activity in the region during this period enabled karstification to take its current pattern (Öztürk, 2020; Günhan and Öner, 2021). With the rejuvenation of the field in general during this period, the karstification also started in the paleovalleys. Especially at many points, it has been found that the fluvial effect comes to the fore in uvala formations. At some points, distortions in the existing karst shapes have occurred, especially in the young fold lines. Due to these distortions, the shapes detected here were not included in the study.

Caves are valuable in classifying carbonate aquifers and determining the range of aquifer types that occur (Ford and Williams, 2007). In a local area, it was observed that the epicarstic control came to the fore and many caves were formed in this context (Figure 6).

The caves on the peninsula are mostly clustered around the Bayırköy Polje and on the Güverdağı Formation. These caves were formed under the control of epicarst. Some of these also contain a water source. These caves have developed under paleotectonic control. However, the movements in neotectonics have gave them their original shape. The sediment shapes in it also indicate this. On the other hand this inference is supported by the overlap of extension directions with neotectonic faults (Nazik and Poyraz, 2015; Günhan et al. 2018). Some of the information that can be obtained from the limited number of cave studies carried out in the peninsula is shown in Table 1.

Although it can be said that the caves in the area generally acquired a suspended structure as a result of the neotectonic activity, the underground-surface drainage relationship was newly established at some points and limited at some points by the control of different lithological units (Günhan and Öner, 2021). From this point of view, they are both perched and rare, small and irregularly patterned (White, 1969).

It is possible to come across small erosional plains characteristic of the Menteşe Region, especially in the middle and southern parts of the peninsula. Again, depending on the faulting, especially the uvala and polje show a specific extension. The list of poljes is as follows: Hacıağaç Polje (P1), Kuyucak Polje (P2), Osmaniye Polje (P3), Bayırköy Polje (P4), Kızılköy Polje (P5), Selimiye Polje (P6), Avlana Polje (P7), Ortaören Polje (P8), Söğüt Polje (P9), Ağlan Polje (P10), Taşlıca Polje (P11), Sindilli Polje (P12) and Serçelimanı Polje (P13) (Figure 7).

Figure 6- The location of the caves clustered around Bayırköy (Modifiedfrom Günhan et al., 2018).

Table 1- Information discovered about the caves in the area where the caves are most densely clustered (around Bayırköy) in the study area (Günhan et al., 2018 and Günhan and Öner, 2018).

Cave names	***Altitude (m)***	***Direction***	***Depth (m)***	***Azimuthal directions of faults***	***Known features***
Mahalbaşı	430	Horizontal	102	-	-
Bozenyakası	~400	-	-	-	-
Kayaini	477	Vertical	50	N-S	-Fossil cave -*Popcorn* calcite deposition
Katranlı Çengirek	458	-	116	N-S	-The mouth of the cave is in the form of a sinkhole. - Debris present
Torudibeği 1	506	Vertical	51	N-S	-Abundant fault breccias
Torudibeği 2	~450	-	-	N-S	-
Sakızeği	333	Vertical	126	N-S, WSW-ENE	-Debris present
Kirpiyeri	188	-	-	-	In the form of a small cavity.
İkizincirli Çengirek	174	Vertical	131	WNW-ESE	-Cave chimneys (old and still in formation).
Üçgül	~150	Vertical	-	-	-
Armelli	150	Horizontal	62	-	-

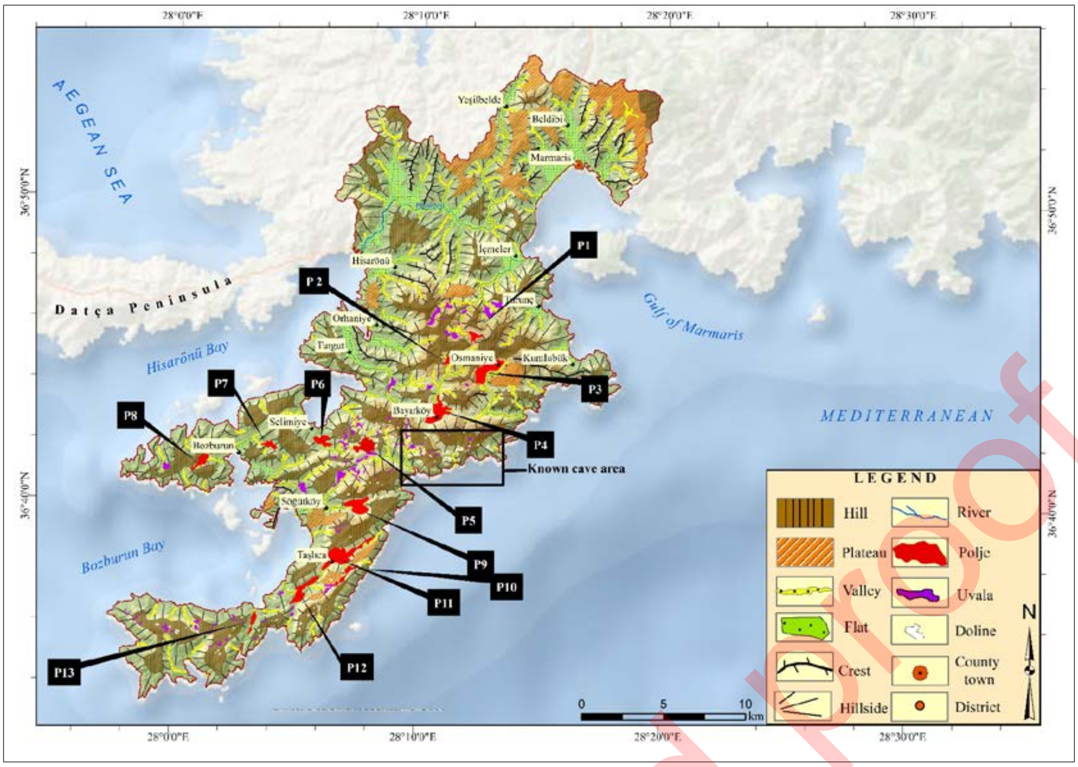


Figure 7- Geomorphology map of Bozburun Peninsula.

3. Results

3.1. General Geomorphological Characteristics of Dolines and Uvalas

Dolines, which are one of the karstic erosion/dissolution forms, are according to different formation systematics; are classified as dissolution, collapse, covered and subsidence dolines (Ford and Williams 1989; Doğan, 2004; Öztürk et al., 2018*a*). Dolines are an important shape as they give specific information about the morphological development of the land (such as making inferences about the morphotectonic development process). This information can be transformed and made meaningful in quantitative ways (Öztürk, 2018*a*). In the study area, which is approximately 440 km^2, 107 characteristic *dissolution dolines* were detected by field studies and by image analyses in the Google Earth program. The distribution of the dolines in the field coincides with the highly fractured structure of the neritic limestones. This situation has been observed in some primary, locally secondary or lower level fault fractures.

Uvalas are generally larger depressions than dolines, formed by the merging of dolines close to each other (Cvijic, 1893; Sür, 1994; Kranjc, 2013). Bonacci, an important karst researcher, described poljes, a large karst shape from the uvalas, as "areas of not less than 0.5 km^2 in size" (Bonacci, 2004; Ege, 2017). Therefore, while detecting uvalas in this study; provided that it is formed by the merger of at least two dolines; the dissolution units, whose area is smaller than 0.5 km^2, whose base is covered with terra rossa, and which remain in the pit relative to their surroundings, was taken as basis. In this way, 81 uvalas were detected throughout the peninsula. Uvalas, like dolines, are generally located in joints and fractures on neritic limestones. The uvalas are located on the study area in the contact points of pelagic and neritic limestones where layers with dolomitic interfaces exist even where they are basically intertwined with each other and with different structural units or locally in places superimposed on these other units, and tectonic windows where it is considered these by fluvial effects is thought to have grown. These probably also have paleovalleys features.

Based on field observations and related literature studies, dolines and uvalas in the peninsula; the areal size (m^2, km^2), elevation steps (m), Elongation ratio (D_E) and direction (E_A α), density (Kernel density analysis) and depth (m) were evaluated. This paper attempts to understand the extent of the relationship between dolines, uvalas, and tectonism.

3.1.1. Areal Size

The smallest doline in the field has an area of 233 m^2, and the largest doline has an area of 11292 m^2. The average doline size is calculated as 3824 m^2. In the areal size histogram of the peninsula dolines the range of 233 m^2- 2333 m^2 is the largest with 40 dolines. This is followed by a range of 2333.1 m^2- 4433 m^2 with 32 dolines. 67% of the dolines are under 4433 m^2. It can be thought that the tectonic effect (continuous rejuvenation of the land, fragmentation and cracks in the thrusts) played a large part in this. In an important study, those smaller than 27000 m^2 were considered as small dolines (Brinkmann et al., 2008; Öztürk, 2018*b*). In this framework, all dolines in the field are classified as *"small dolines"*.

It is known that uvalas, which is a form of dissolution larger than itself, are formed by the merger of dolines, but with the tectonic effects mentioned above, very small dolines that are too close to each other can easily merge and become uvalas, thus, very small uvalas can be formed by the merger of two very small dolines. For this reason, 19% of the uvalas in the peninsula are smaller than the largest doline, and the majority of the dolines (75%) are larger than the smallest uvalas (Figure 8a, b).

It is possible to say that a lot of fragmentation and deterioration that occurred as a result of tectonism in the field also negatively affected the size of the uvalas; 67 (~70%) of the uvalas in the field are under 70.6 thousand m^2. Although it is seen that there is no specific spatial size classification for the uvalas in some modern geomorphology studies, various classifications of ulavas have been made in many studies in the past. In this context it seems possible that the uvalas on the peninsula can be classified as small uvalas, with values far away from even 0,5 km^2 (Brinkmann et al., 2008; Aguilar et al., 2016) (Figure 8).

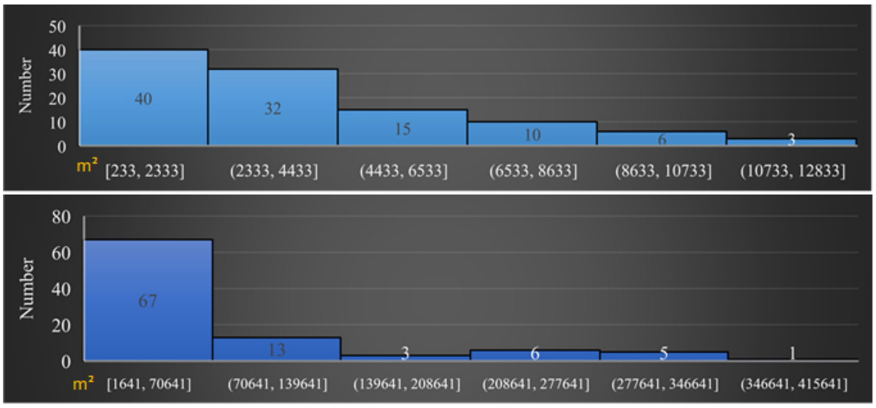


Figure 8- Histogram graphs; a) Sizes of dolines b) Sizes of uvalas.

3.1.2. Elevation Steps (Histogram)

Most of the dolines (~61%) in the Bozburun Peninsula are located at altitude values between 201-450 m (Figure 9). In this narrow range, no significant correlation was detected with temperature, humidity and precipitation values. In other words, the relatively small differences in values in this narrow range in local climatic conditions did not play a significant role in karstification. When evaluated in terms of the presence of rock, it was determined that almost all of the dolines were formed on neritic limestones. In terms of the presence of rocks, since it is seen that almost all of them are formed on neritic limestones, the reason for the concentration of dolines in these altitude ranges (201-450 m) is mostly due to the cracks and pits formed along the anticline surfaces (especially on the slopes above 8%) caused by the orogenic movements and geomorphological development under the influence of tectonism since the Miocene is considered.

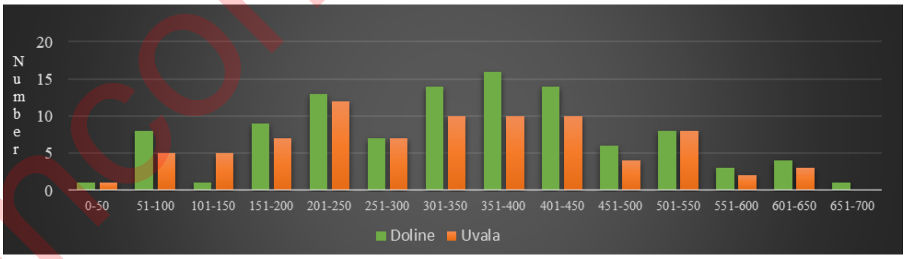


Figure 9- Histogram of the elevation ranges (m) where dolines and uvalas are located.

On the elevation histogram of the uvalas, the range of "201-450 m" is remarkable, just like the distribution of dolines. In this case, the presence of cracks (diaclase) in the bend axes affected by faulting, nappes windows and fractures caused by direct faults in the relevant steps has been decisive. On these steps, especially at medium and high slope degrees, uvalas and paleovalleys that have been subjected to periodic rejuvenation and degraded in places have also been found. In fact, it has been observed that fluvial processes have restarted in some locations due to the slope of the hillside along with the dolines connected to the main uvalas.

3.1.3. Slope

According to the slope analyzes made in ArcGIS 10.5 program and the slope groups defined by adapting from Oakes (1958), more than 60% of the peninsula (278 km^2) is located in the slope groups of the very steep slope class between 15% and 40%. The average slope is about 21.2%. It has been observed that inclines of the slope most of the karstic depressions, including the poljes, are located above 8%. Inclination fractures and cracks are important in this sense. The base slopes of the figures are generally included in the slope groups up to 8%. A considerable number of distorted dolines and uvalas were also encountered on the strongly sloping/steeply sloping (15% and above), and it was understood that they are still in the formation stage in the paleovalleys floors, which are rising with the effect of tectonism (Figure 10).

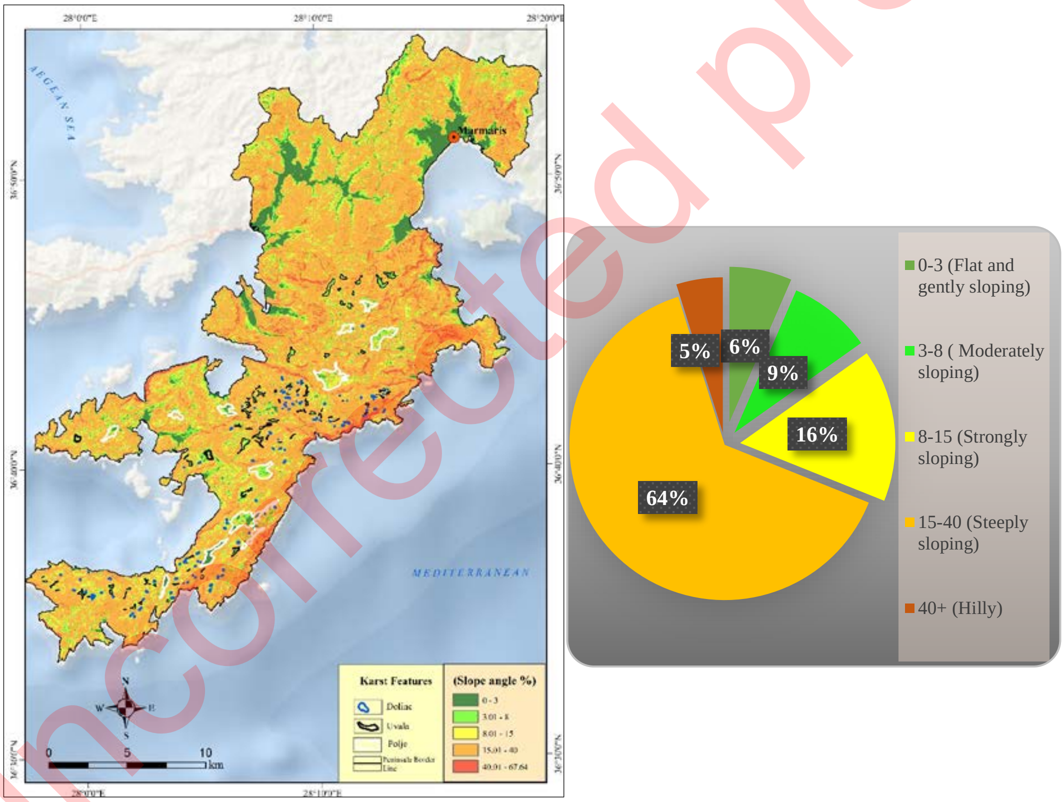
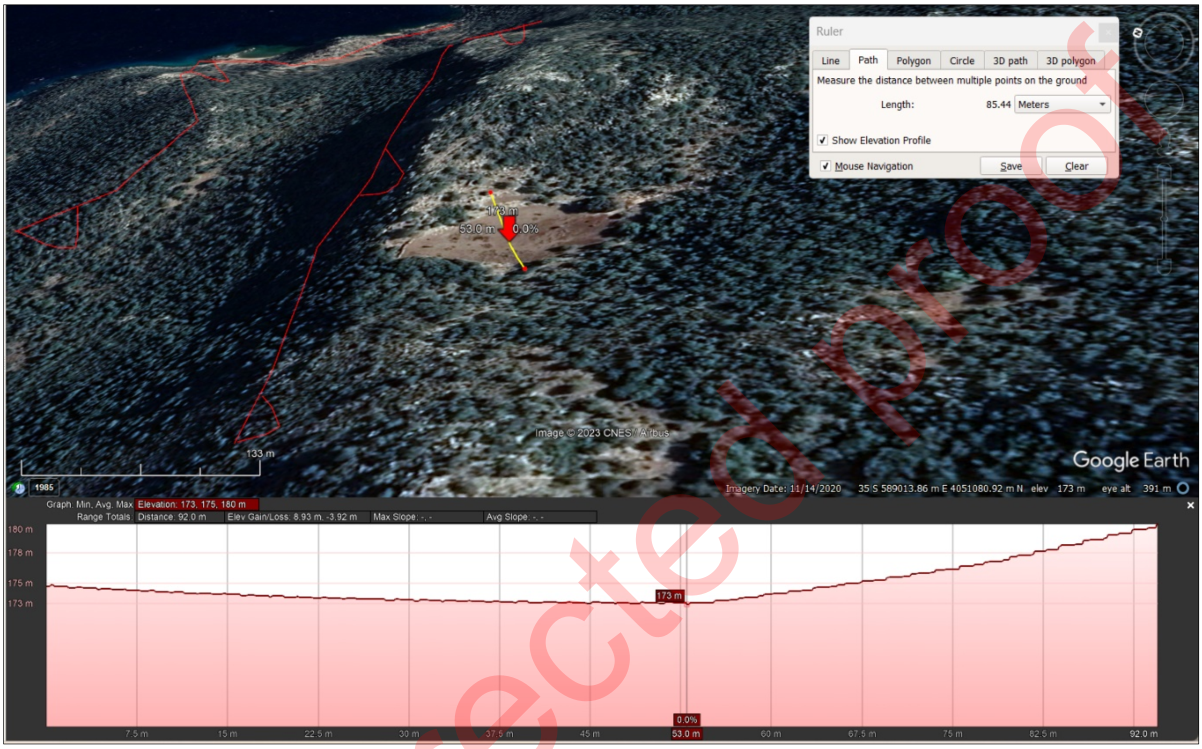


Figure 10- The slope situation on the peninsula and the distribution of karst shapes.

3.1.4. Depth

The depths of the dolines in the field vary between 1-11 m. In the calculations and observations, it was understood that the average depth of the dolines in the peninsula is 2.5 m. These shapes, which are included in the *dissolution doline* group, which has a widespread distribution on karst areas, are quite common in the Taurus Mountains. It has been determined that secondary and tertiary faults rather than main fault lines are effective in the formation of dolines on the peninsula, whose extensions do not directly overlap with the main fault lines in general (Figure 11). However, the continuous rejuvenation of the land by these faults also updated the morphological base level, increased the slope in places and prevent the dolines to deepen further. It has even caused deterioration in many places (Keskin and Yılmaz, 2016). On the contrary, the depth of the doline usually reaches 5-6 meters in various locations, especially between two effective fault lines. At another point where different faults intersect, even a doline with a depth of 11 meters was detected (Figure 12).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Measure the distance between multiple points on the ground
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Figure 11- Developed in a crack formed by a fault, example of a dissolution doline reaching 5 m in depth (Google Earth Pro 2020 image).

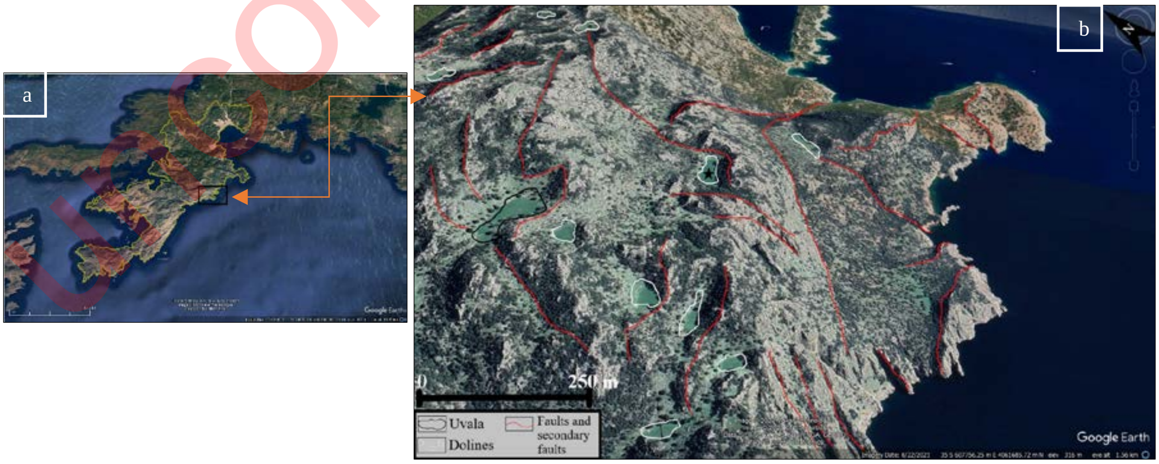

Figure 12- a) A section from the location where the dolines are concentrated. b) The deepest doline of the field (11 m, star-marked) located where different scale the fault lines intersect (used from the Google Earth Pro satellite images).

Uvala depths have a wide range ranging from 1 to 45 m in the study area. The average depth is 11.8 m. Considering that the areal sizes of uvala shapes are generally several times larger than dolines, this value at depth seems normal.

3.1.5. A Morphometric Index: Elongation Ratio (E_R) and Direction (E_A α)

In the field, dolines that have been exposed to periodic rejuvenation and deteriorated in places are frequently encountered in medium-high inclined locations. In this respect, it can be thought that faulting in the neotectonic period affected the elongation rates of karstic shapes. The elongation rate is calculated by taking the ratio of the long axis to the short axis of the doline or related karstic shape in many studies (Bondesan et al., 1992; Aydın and Tuncer, 2021) (Formula 1). At this point, the long and short axis should intersect each other at an angle of 90°. If the value moves away from 1, it means that the shape moves away from circularity and resembles an elliptical (Öztürk, 2018*b*). Basso et al. (2013) classified the elongation rates into 4 categories (Table 2). In this context, 65% of the dolines in the field are in the elongated class. The neotectonic processes in the region have been decisive on the elongation rates of the shapes, as they were formed as a result of the merging of the elongated dolines, most of which are open to fluvial shaping and extending obliquely to each other of the uvalas. Thus, most of the dolines (65%) and uvalas (76%) are elongated in the peninsula (Figure 13). Almost half of the uvalas in the field are located exactly on a fault, and the extension of most of them is parallel to the faults (Figure 14).

$$E_R = \frac{Long\ axis\ (m)}{Short\ axis(m)} \text{ (Formula 1).}$$

Table 2- Classes of elongation ratio (from Basso et al., 2013; Öztürk, 2018*a*, *b*; Aydın and Tuncer, 2021).

Elongation rate value(E_R)	***Geometry of Shape***
Less than 1.21 ($E_R < 1.21$)	*Circular, semi-circular*
1.21 to 1.65 ($1.21 < E_R) < 1.65$)	*Semi-elliptical*
1.65 to 1.8 ($1.65 < E_R < 1.8$)	*Elliptical*
Greater than 1.8 ($E_R > 1.8$)	*Prolonged*

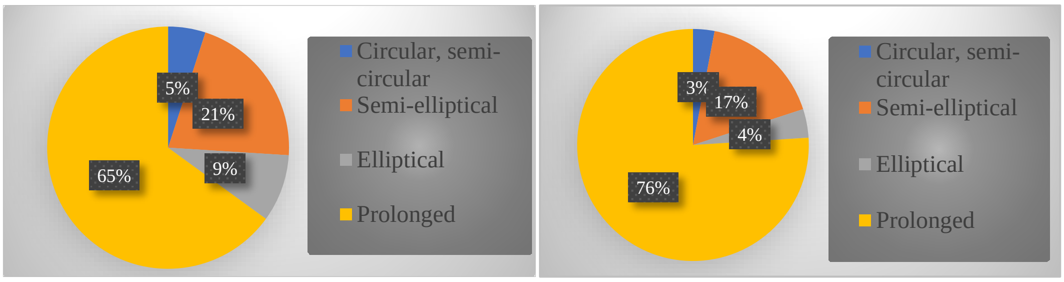

Figure 13- Elongation rate graphs of dolines and uvalas.

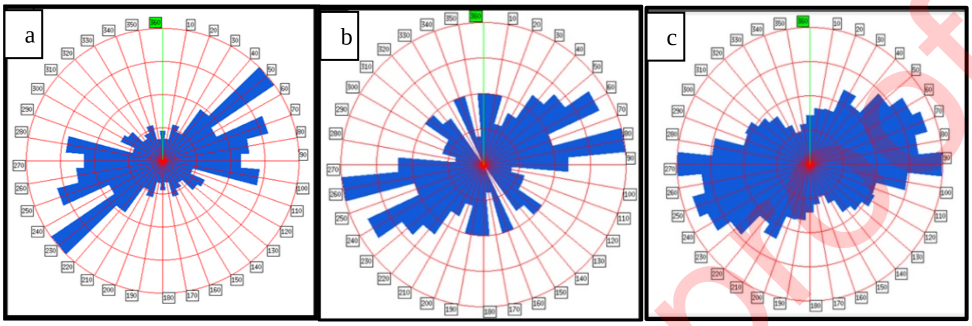

Figure 14- Rose diagrams of the extension directions of the doline, uvala and faults in the field: a- Dolines; NE-SW predominantly; b- Uvalas; ENE-WSW weighted; c- Faults; E-W; ENE-WSW weighted.

3.1.6. Density

Dissolution dolines are closed depressions, which are very common in the Anatolian terrain, are permeable, weak resistance areas in terms of karstic dissolution, formed as a result of the evacuation of cracks, faults and layer joints by chemical erosion, where the surface-ground water relationship is established (Sür, 1994; Doğan and Yeşilyurt, 2004). In the study area, there are many areas where these conditions come together at different levels. A zone between Bozburun and Selimiye faults, especially in the south of Bayırköy, where neritic limestone is common, was folded and even broken in places by tectonic movements. The slopes of the dolines here generally have values above 8 percent. They are seated in the cracks on the crests of the hills, and in the synclines and nappe windows between the high-sloping hills. The fault data obtained as a result of the analysis of satellite images, the detailed 1/100000 scaled geological maps of the MTA and the field observations made confirm this inference. This situation leads us to the conclusion that -contrary to the general belief-, dolines can be widely seen on sloping lands in various karstic regions where fault activity is very prominent (Figure 15).

The distribution of uvalas in the field is more compatible with the presence and extension of faults compared to the distribution of dolines. It is clear that the weakness of the structural lines as well as the larger cracks following the fault and the depressions formed by the direct fault have a great effect here. Many uvalas sitting on the pelagics between Turunç and Hisarönü Bay, where faults of different characters exist, prove this inference.

The extension of the poljes directly coincides with the locations of the fault lines. This overlap and the general characteristics of the poljes are mentioned in the next section. The names of the poljes identified in the study and named according to their location are from north to south; *Hacıağaç Polje, Kuyucak Polje, Osmaniye Polje, Bayır (Bayırköy) Polje, Kızılköy Polje, Selimiye Polje, Avlana Polje, Ortaören Polje, Söğüt Polje, Ağlan Polje, Taşlıca Polje, Sindilli Polje, Serçelimanı Polje* (Figure 16-18, Table 3).

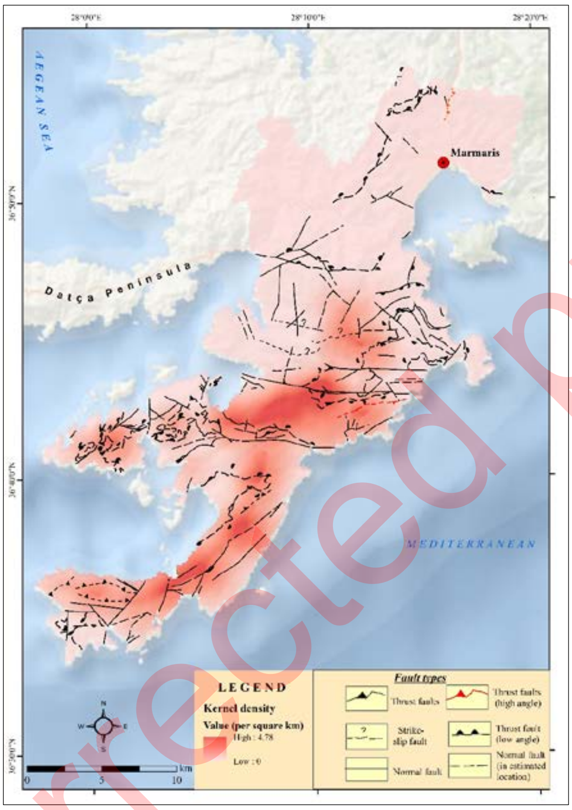

Figure 15- Density is consist of all karstic shapes and its compared with the fault system in the field.

3.2. Properties and Morphometry of Poljes

The largest shapes formed as a result of karstification are poljes. Poljes are formed by providing optimum conditions for karstification. For karstification and polje formation in many sources; In addition to the importance of the lithological unit (limestone, dolomite, even conglomerate or breccia) and climatic conditions (Mediterranean climate), it was emphasized that tectonic activities also play a triggering role. Poljes are large flats or sometimes bowl-like shapes that remain in a pit relative to their base (Ford and Williams, 1989; Sür, 1994; Doğan, 2003; Ege, 2015*a*, 2015*b*, 2017).

In this study, before the poljes were identified, the literature on the detection and morphometric properties of poljes was reviewed in detail, just as in the determination of other karstic shapes, and field observations were classified and reported with a systematic approach. Poljes have converted to digital data in Google Earth Pro and ArcMap 10.5; it was re-examined by overlapping with the 1/25000 sheets. While determining the boundaries of the polje base, the bedrock residues where the slope erosion continues were taken as the boundary reference, and sensitivity was paid to distinguish the terra-rossas clearly at the base. Gams (1978), on the other hand, emphasizes that for a depression to be considered a polje, three criteria must be met: 1- a flat bottom (may be terraced) in the rock or loose sediments (breccia, miles, alluvium etc.), 2- a closed basin with steeply rising edge slopes (for example in this study 18%), and 3- karst drainage system. Gams (1978) divided the poljes into 5 classes considering these features: 1) *Border polje*, 2) *Peripheral polje,* 3) *Piedmont polje*, 4) *Overflow polje* and 5) *Piezometric level polje*.

According to Bonacci (2004), poljes with an area between 0.5 km^2 and 10 km^2 are considered as small poljes. However, considering all the literature, it has been seen that the spatial definition cannot be applied strictly. Mainly, hydrological and geomorphological criteria were taken as reference (Şimşek et al., 2021). In this context, determined in the field; 13 poljes, the largest of which is 1.6 km^2 (Bayırköy Polje) and the smallest 0.25 km^2 (Serçelimanı Polje), are evaluated in the small polje class. The morphometric properties of the detected poljes are important in terms of understanding the tectonic influence on the morphology (Table 3). Evaluation started from the north (Figure 16-18).

The *Hacıağaç Polje (P1)* developed at the point where two faults intersect. The diameter/depth ratio of the semi-elliptical and plate-shaped polje was calculated as 12.22. The polje, at the bottom of which alluvial deposits are observed, was originally formed on Cretaceous pelagic limestones. It is bounded by spilites at the bottom and hillsides. The sinkholes at the bottom are used for agricultural irrigation and animal husbandry.

The *Kuyucak Polje (P2)* is located approximately 1.5 km southwest of Hacıağaç. The Kuyucak Polje is located on a secondary fault, in a syncline. The diameter/depth ratio of the elliptical polje was found to be 19.72. Kuyucak Polje is 1.5 km away from the Senonian aged low angle thrust fault forming another polje (Osmaniye) from the southeast, and its long axis exactly coincides with the strike of this fault. The shape, whose bottom consists of pelagic limestones, has dry drainage.

Another karst shape located 1.5 km southeast of Kuyucak that is the *Osmaniye Polje (P3)*. It is surrounded by a Senonian low angle fault from the northwest. The elongated form and direction of the polje were formed by this fault. The diameter/depth ratio was found to be 31.33. This ratio shows that the pitting is less than the Hacıağaç and Kuyucak poljes. The bottom and hillsides of the polje are covered with breccias and limestone blocks in places.

It is seen that the drift and normal faults create unconformity in the layers in the south of the polje. Dolomites crop out in this region and spilites and basalts are also encountered in places. A relatively new active drainage was observed southeast of the base of the polje.

The largest polje of the field named *Bayırköy Polje (P4)*, which was formed directly on the Selimiye Fault Zone is located southwest of Osmaniye Polje. In this region, the main faults and secondary cracks of different characteristics cut each other and these caused the polje in question to be in circular form. For this reason, the polje does not show a certain direction of extension. The diameter/depth ratio is 13.87. There are settlement areas and gardens in the polje which developed on neritic limestones. The surrounding valleys were probably rejuvenated during the neotectonic period. Therefore, there is a thick alluvial layer at the base of the polje (Figure 17). The polje is a completely closed basin. Probably the aquifer level is higher than other poljes. There are many karst springs around the shape and active water is seen in its sinkholes.

Kızılköy Polje (P5) is located 3 km southwest of Bayırköy Polje. The polje is circular form due to intertwining both low angle thrust and normal faults. A large number of hums were found in the Kızılköy Polje. Diameter/depth ratio of this polje is 21.16. There are abundant limestone containing breccias on the slopes and bottom. Alluviums also have an important place in the polje base with dry drainage. Sinkholes were detected at several points, and it was observed that there was water in these sinkholes from time to time. There are settlements and gardens in the polje.

Approximately 1.3 km west of Kızılköy, there is the *Selimiye Polje (P6)*, where a village settlement was established. The deepest point of the polje, which is 600 m from the shore, is 60 m. The extension of the figure shows parallelism with the extension of the low angle thrust and normal fault. Its form is semi-elliptical and its diameter/depth ratio is 8.17. The periphery and base of the polje, which developed on pelagic limestones, mostly consists of breccias. Sand and mudstones were also encountered in the polje. The seismic movements in the neotectonics rejuvenated the paleovalley in the basin and allowed it to rise 60 m from the shore. The west part of the polje has started the active fluvial processes again due to the slope failure and the increasing the gradient of basement. There are karstic springs on the slope separating the polje from the shoreline. It is estimated that the ground water level in the polje fed from the northern slopes and karst springs is high.

Approximately 2.3 km southwest of Selimiye is the *Avlana Polje (P7)*, which is also shaped by a drift fault and its direction of extension also conforms to this. This polje is in the elongated class in terms of its form. The diameter/depth ratio is 7.95. This rate is the lowest among the poljes in the field and is the proof that the shape is more pitted than the others. The lithological structure is again composed of pelagic limestones and breccias. There is a periodical stream in the polje, and this stream is caught by a paleovalleys stream in the south, which is active again, and pours into Bozburun Bay. Possibly, there are neotectonic effects in the outward opening of the drainage here. In the polje, there are summer cottages used for touristic purposes and a sub-village settlement.

About 3 km southwest of Avlana is the *Ortaören Polje (P8)*, which is also shaped by a drift fault and has a similar extension to this fault. Polje is in the elongated class in form. The diameter/depth ratio was calculated as 17.63. The shape appeared to develop mainly on pelagics. At the bottom, there are lime-containing breccias.

Another polje on the peninsula is the *Söğüt Polje (P9)*. The semi-elliptical karst shape was surrounded and elongated by the drift type fault. The diameter/depth ratio of the figure is 14.64. Neritic limestones and breccia form the main lithological structure of the polje. It is surrounded by steep slopes (over 40%). The areas where the slope of the hillsides decreases are terraced for pasture use. Seasonal drainage is available. In the polje, there are a few houses that form the lower settlement of Söğüt village.

Approximately 2 km south of Söğüt Polje, there is the *Taşlıca Polje (P10)* that develops on the ground broken by a normal fault. The diameter/depth ratio of the polje is 26.5. The shape was formed on limestones of neritic origin. An intense karstic drainage has developed in the polje with many sinkholes and hums. Polje basin is separated from Ağlan Polje, which is very close (~200 m east), by a small and narrow threshold. It seems likely that these two poljes will merge in the future.

Ağlan Polje (P11), which is parallel to Taşlıca Polje and formed on the edge of the normal fault, is the polje with the highest elongation rate in the field (6.76). The diameter/depth ratio of the polje is 28.09. An artificial pond was created in the part where the sinkhole is located in the polje. The pond here is used for irrigation and animal husbandry.

Another polje that is very likely to merge with the Taşlıca Polje is the *Sindilli Polje (P12)* in the elongated category, which is also separated from the south of Taşlıca by a small threshold, shaped by a normal and drift fault. The diameter/depth ratio is the highest value in the field; it is 49.96. The shape is rather shallow. Beekeeping and animal husbandry are carried out in the polje, where there are several sinkholes, and there are remains of an ancient city on the terraced slopes.

Approximately 2.3 km south of Sindilli Polje, *Serçelimanı Polje (P13)* is located on a normal fault and has the highest elongation rate (4.44) in the field. The diameter/depth ratio of the figure was calculated as 34.42. The coast is reached by descending a small threshold (~15 m) from both ends of the polje, which has an average floor height of 27 m (Table 3, Figure 16-18).

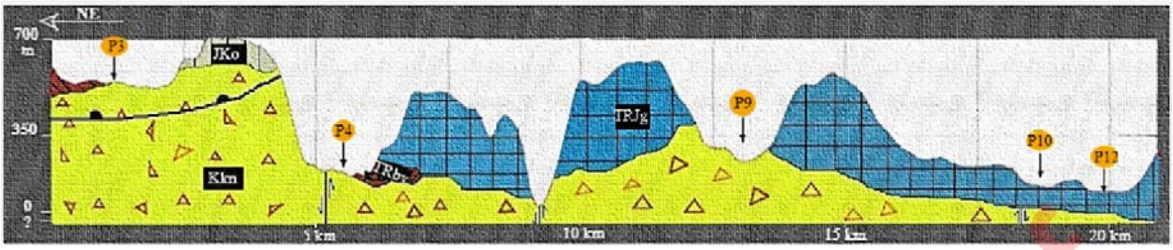

Figure 16- A sample section showing some poljes in the study field (P3: Osmaniye Polje, P4: Bayırköy Polje, P9: Söğüt Polje, P10: Taşlıca Polje, P12: Sindilli Polje; NE (Northeast)-SW (Southwest); *TRby: Bayırköy Formation*, *TRJg: Güverdağı Formation*, *JKo: Orhaniye Formation, Kkn: Karanasıflar Formation;* shaped on the section Google Earth Pro and it has been scaled to Şenel and Bilgin (2010).

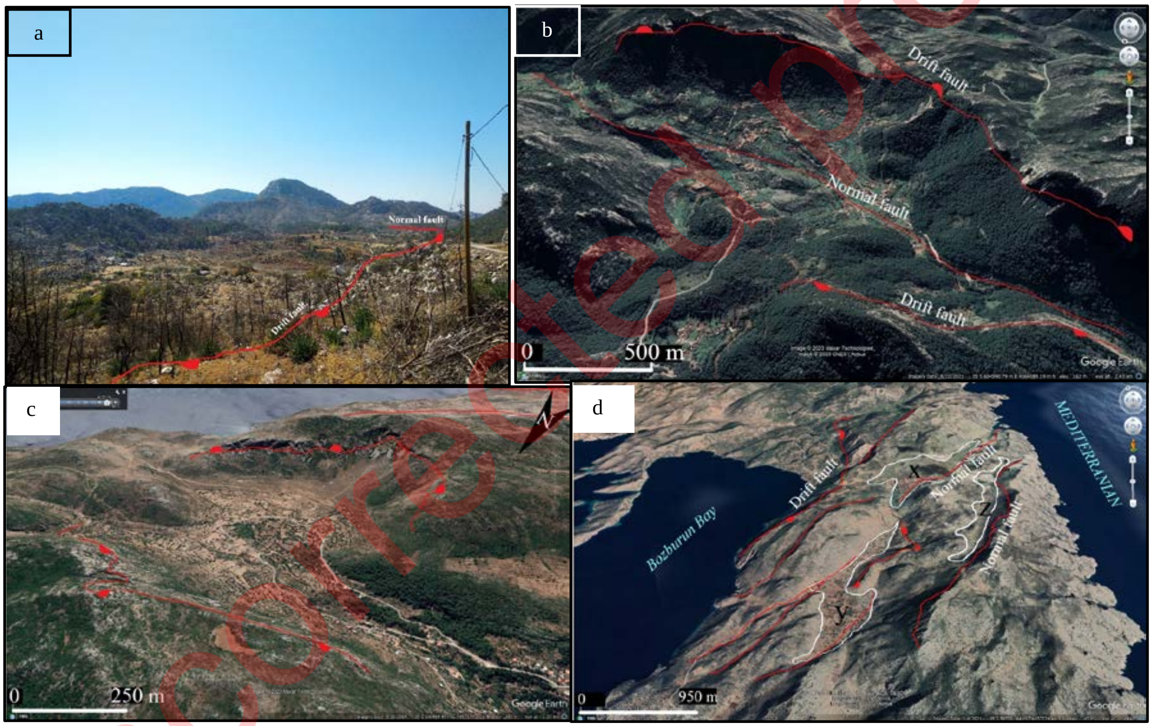

Figure 17- a) View of the Osmaniye Polje from northwest, b) Google Earth image of the Bayır Polje; the largest polje of the site and where different types of faults intersect, c) The Söğüt polje was shaped by low angle thrust fault, d) x, y and z (Taşlıca, Sindilli (Aşağı Taşlıca) and Ağlana Polje). A view from the south of the faults that triggered the forms of the poljes.

Table 3- General characteristics table of poljes prepared in accordance with the literature (Gams, 1978, 1998; Ford and Williams, 1989; Bonacci, 2004; cited in Ege, 2017).

Name of polje (north to south)	**Square- (km^2)**	**Morphological characteristic**	***Elongation ratio (ER) = (Long axis/short axis)***	***Direction of extension (E_A α)***	***The altitude of the deepest point of the sole. (m)***	**Rocks present in Polje.**	***Polje depth (altitude difference between the highest and lowest point of the polje basin) - m).***	***Diameter/depth = Pitting rate (P_R)***
Hacıağaç Polje (P1)	0.28	Border	1.52 (semi-elliptical)	-	506	Limestone (pelagic)	271	12.22
Kuyucak Polje (P2)	0.29	Structural	1.76 (elliptical)	NE-SW	505	Limestone (pelagic)	155	19.72
Osmaniye Polje (P3)	1.08	Border	4.77 (elongated)	NE-SW	415	Breccia (limestone predominant)	181	31.33
Bayırköy Polje (P4)	1.61	Border	1.19 (circular)	-	154	Limestone (Neritic)-Dolomite-Breccia (Limestone predominant)	611	13.87
Kızılköy Polje(P5)	1.32	Border	1.23 (circular)	-	232	Limestone (Neritic)-Dolomite-Breccia (Limestone predominant)	241	21.16
Selimiye Polje (P6)	0.46	Border	1.53 (semi-elliptical)	-	60	Limestone (neritic)	360	8.17
Avlana Polje (P7)	0.26	Border	2.01 (elongated)	E-W	70	Limestone (neritic)	349	***7.95 (Deep)***
Ortaören Polje (P8)	0.40	Border	2.45 (elongated)	NE-SW	84	Limestone (pelagic)	192	17.63
Söğüt Polje(P9)	0.85	Border	1.6 (semi-elliptical)	-	195	Breccia (Limestone predominant)-Limestone (neritic)	348	14.64
Ağlan Polje (P10)	0.33	Structural	6.76 (elongated)	NE-SW	246	Limestone (neritic)	172	28.09
Taşlıca Polje (P11)	1.5	Structural	3.11 (elongated)	NE-SW	182	Limestone (neritic)	388	26.50
Sindilli Polje (P12)	0.66	Structural	4.19 (elongated)	NE-SW	124	Limestone (neritic)	386	***49.96 (Shallow)***
Serçelimanı Polje (P13)	0.25	Structural	4.44 (elongated)	NNE-SSW	17	Limestone (neritic)	97	34.42

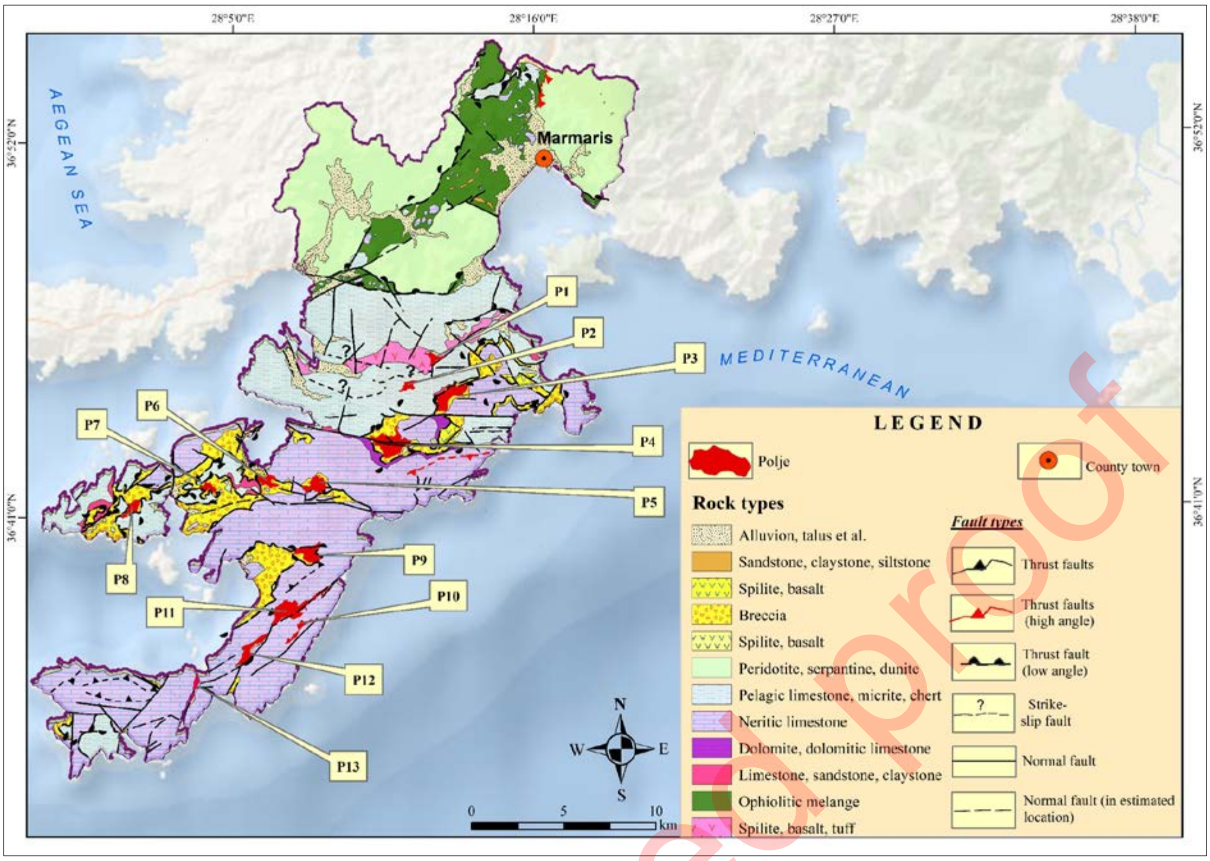

Figure 18- Distribution of polje in the field and geological structure of the field.

4. Conclusion

On the Bozburun Peninsula, 107 dolines, 81 uvalas and 13 polje were identified. As a result of the evaluations, it is seen that the dolines and uvalas in the peninsula display a highly fragmented appearance, and the dolines and uvalas in the area are classified as small dolines and uvalas (Bonacci, 2004; Brinkmann et al., 2008). In the study, the density of dolines and uvalas in this region, which are concentrated in the altitude steps in the range of 200-450 m, is explained by the presence of neotectonic rejuvenations and faults in these locations, rather than climatic differences. Most of the slopes of the dolines and uvalas formed between the windows and cracks between the nappes are above 8%. It is estimated that the erosion cycle starts at these slope grades until the karst base level is reached. Doline and uvala with slopes of 15% and above were generally found to be in distorted a structure. The average depth of the dolines included in the dissolution doline group is 2.5, while the uvalas are 11.8 m has been calculated. As a result of the observations, it was understood that the faults had a positive effect on the depth. It is seen that a significant amount of dolines and uvalas and all of the poljes overlap with faults due to their location. The extensions of the karstic shapes of dolines and uvalas show a very close appearance with the azimuthal extensions of the faults (EA α) and even overlap at many points. Most of the dolines (65%) and uvalas (76%) in the peninsula are elongated. It has been determined that almost half of the uvalas in the field are located exactly on a fault.

When evaluated in terms of lithology, it has been observed that there are more karstic shapes on the neritic limestones compared to the pelagics. The reason for this is that the neotectonic faulting affects the neritic limestones more and the windows between the cracks and nappes that trigger karstification (especially the Bozburun and Selimiye faults formed and located between these two faults) occur mostly in these rocks.

Bonacci (2004), poljes with an area between 0.5 km^2 and 10 km^2 are considered as small poljes. In other words, the lower limit for poljes was accepted as 0.5 km^2. In the study, the general criteria that Gams (1998), discussed for poljes were also taken into consideration and it was understood that this lower limit could be taken as "0.25 km^2" for the study area. Gams's (1998), important criteria in the definition of polje; the presence of a wide plain developed on the bedrock and lower than its surroundings and the presence of sediments (breccia, clays, etc.) accumulated in these plains, the marginal slopes of the slopes on the edges of the plains (especially 15% and above) and the fact that the plains have a karstic drainage line. Especially, when the general view of the peninsula relief is evaluated in terms of poljes, it gives more concrete information to the researcher in terms of the effectiveness of the faults. 13 poljes meeting these characteristics were found in the field (Gams, 1998; Bonacci, 2004). It has been determined that *eight* of the poljes are borderline and *five* of them are structural. The extensions of poljes and other karstic shapes, where the long axis is considerably longer than the short axis, are in terms of primary intermediate directions; predominantly NE-SW oriented. It has been determined that the circular or semi-elliptical forms (those that do not show a clear extension) are located in areas where many faults are intertwined this time.

5. Discussion

With this study, the formation and extension of the karstic shapes in the area can be shown as evidence that the seismotectonic processes in the region mostly took place in a counterclockwise direction with a bending movement of approximately 8-13°, as emphasized in previous studies (Tur et al., 2015; Günhan et al., 2018). Traces of the drift faults are quite evident in the poljes and normal faults have formed in places near these faults which are generally attributed to the Quaternary. The extension direction of both fault types generally coincides. It is thought that the dominant direction (roughly NE-SW) in the tectonic evolution of the field is still in question, and that the buckling movement continues in this direction, and it is open to discussion (Pichon and Angelier, 1979; Şengör et al., 1985; Seyitoğlu and Scott, 1991; Uluğ et al., 2005).

The fact that the tertiary lands are not encountered intensively from the Cretaceous until the Quaternary in the research area can be explained in two ways: First, the possibility that the Tertiary formations were largely submerged by sea waters due to the transgression experienced after the Pleistocene glacial period (18000 years BP). It is possible that the area, which started to rise with the Alpine Orogeny that started at the end of the Cretaceous, never experienced marine or lacustrine conditions at that time, and that karstification continued uninterruptedly after the Cretaceous until today. In order to evaluate these possibilities, detailed geological and geomorphological studies are needed throughout the peninsula, including coastal measurements.

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