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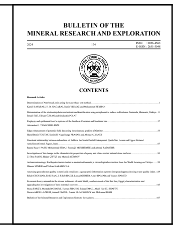
BULLETIN OF THE MINERAL RESEARCH AND EXPLORATION

CONTENTS

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 due to its various karst shapes on limestones of different ages. It is also located in an important region in terms of tectonic activity. In this study, the distribution of karst shapes determined by satellite images, topographic maps and field studies was examined. In this context, the elevation ranges (m), base and hillslope angles (%), depth (m) and pitting rates (RP), elongation ratio (RE) and directions (EA α) of the relevant shapes were determined. Then, the relationship between the faults and the quantitative results obtained was interpreted. Remote Sensing (RS), Geographic Information System (GIS) technologies, calculations and field observations used in the study; it enabled us to reveal that there is a close relationship between karstic formations such as polje, uvala and doline and geological structures such as faults, diaclasis, folds and Nappe windows. Available data also show that geological structures have a positive effect on karstification in the study area.

1. Introduction

Bozburun Peninsula is an important place due to its location between the Aegean Sea and the Mediterranean coasts. The peninsula hosts many coves and gulfs. The study area is located between latitudes 36°33'-36°55'N and longitudes 27°57'-28°18'E 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 a study her work on the Bozburun Peninsula, stated that the northern border of the peninsula can be formed by a line to be drawn between the İçmeler Bay and Hisarönü Gulf. The peninsula extending southwest from here to Rhodes Island covers many settlements (Bozburun, Taşlıca etc.). However, in this study, the border was expanded to the town center of Marmaris based on the basin boundaries. The study area extends in the southwest direction towards Rhodes Island and has a projection area of ~440 km^2 (approximately) (Figure 1).

Bozburun Peninsula is located in the western part of an important karst belt, the Taurus Karst Region of the South Anatolian 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

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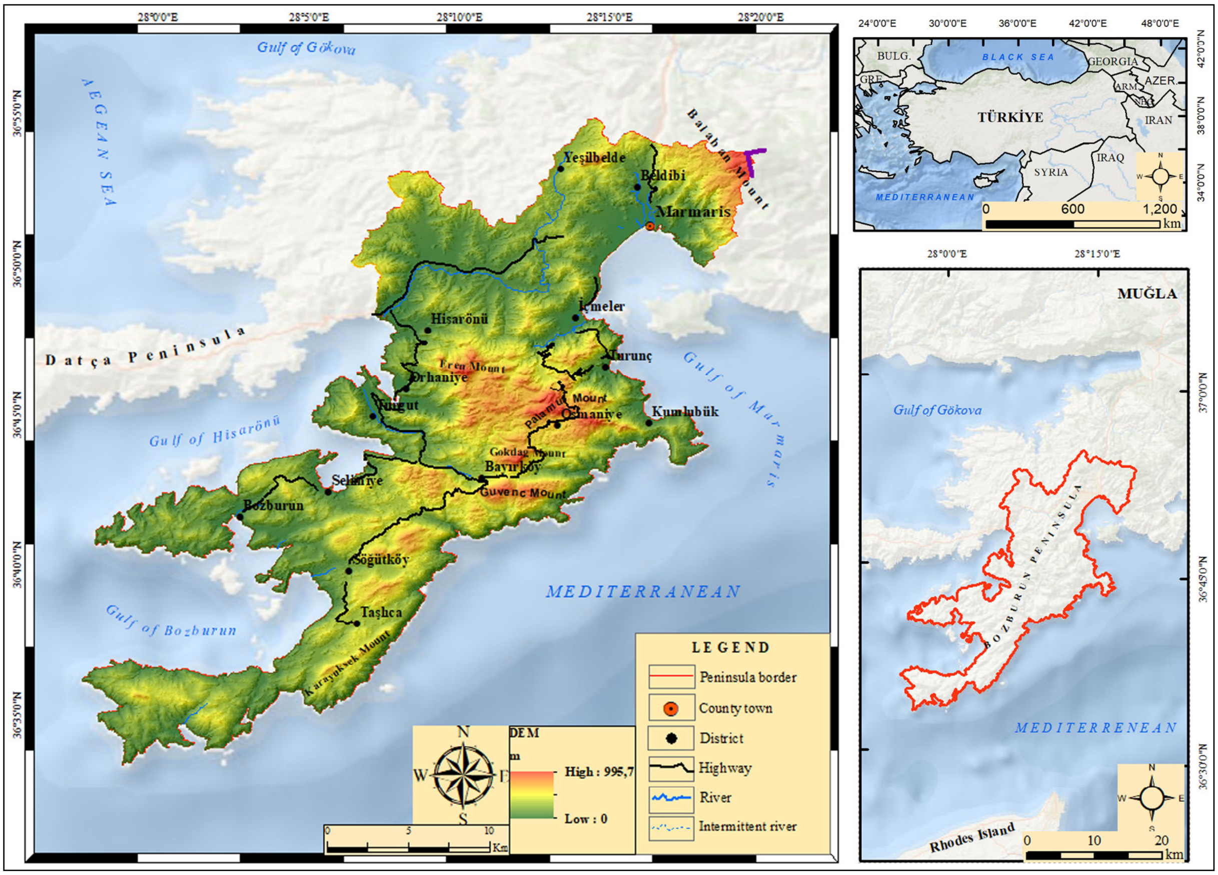

Figure 1- Maps showing the Bozburun Peninsula and its vicinity.

time) 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). Based on the lithological structure, limestones are known as the most suitable rock for the formation of karstic lands. There are pelagic and neritic limestones formed in different depositional environments inside study area. Their mineral or element composition (calcium, clay, marl, micrite etc.) displays some variations based on location in Bozburun Peninsula.

A large number of karst morphology studies have been carried out in various regions of Türkiye. The studies explain the effect of different geological and climatic conditions on karstification. Although there are many research on geomorphology in the study area and its close vicinity, karst studies are only limited to caves (Günhan and Öner, 2021; Günhan et al., 2018). For this reason, a detailed study is needed on the Bozburun Peninsula having very unique karst shapes.

The morphological appearance of the region have been determined by active tectonism, neotectonism, fluvial erosion and sea level changes due to epeirogenic movements (Doğan, 1996; Tuncer and Nazik, 2010; Akdeniz, 2011; Nazik and Poyraz, 2015). Existing data and observations imply that there is a close relationship between the faults and the elongation directions of the karstic features in the tectonically active region. The faults are generally trends along E-W, ENE -WSW directions. However, these faults are cut by different faults with and acute or right angle. This is clearly observed in the area reflecting the tectonic characteristics of the Southwest Aegea (Tur et al., 2015; Topal, 2018). As a result, a remarkable karst patterns have appeared in the study area. Hence, main purpose of the study is to shed light to the relationship between tectonism and karst formation in the peninsula. Morphometric indices have been used to explain this relationship.

In order to explain this relationship, the main factors affecting topography and geology such as trends, geological/geomorphological features and their relationships have been studied during this study.

In geomorphology studies, morphometric indices have become very important especially in recent years. The collaboration between in Geographic Information Systems (GIS) and Remote Sensing (RS) technologies is very important in this subject. Many studies have been conducted on this issue in Türkiye as well. Some important studies can be listed as (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; Aydın and Tuncer, 2021; Şimşek et al., 2021). Although, the study area presents unique morphological features, no detailed study has been found on the relationship between tectonism-and karstification. It is thought that this study may contribute to this gap.

In explaining the karst patterns of the study area, morphometric analyses have been performed using GIS and RS technologies. In this context, quantitative inferences have been made about the topographical character of the area, its relief and the formation systematic of karstic lands by means of morphometric analyses.

2. Factors Affecting the Formation of the Peninsula

2.1. Material and Method

In order to understand and describe the physical features of the site, 16 topographic maps with 1/25.000 scale and 10 m isohips 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 1/100.000 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 analyses, which can reinforce the outputs of field studies, are used quite frequently, in recent years. It is possible to explain the geomorphological character of the study area from a morphometric perspective and to define it quantitatively in this way (the valleys and drainage systems, lakes, karst terrains, slopes and to explain these geometric pattern etc.). This definition systematically provides support to the studies. One of the most suitable indices to accurately determine the effect of faults on karst shapes are the elongation ratio (R_E) and elongation direction (E_A α) from the morphometric indices (Williams, 1972; Day, 1976, 1983; Bondesan et al., 1992; Thery et al., 1999; Shanov and Kostov, 2014; Öztürk et al., 2018; Ege et al., 2019; Öztürk, 2020; 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 Elongated Ratio (R_E) and elongation direction (E_A α), other geomorphological/morphometric features of the related shapes [area size, elevation, slope values, depth, also Pitting Ratio for poljes (R_P)] 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, following 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 trends 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, 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. These structures were formed under the compression regime from the Palaeotectonic period to the present day. The units corresponding to different facies of the tectono-stratigraphic units of the Lycian Nappes have an incompatible appearance and cover a wide area in Southwestern 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 crop out. Almost all of the formations on the peninsula belong to the Mesozoic Era. Existing units in order from oldest to youngest; 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, 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). Karstification is mostly was observed inside Orhaniye and Güverdağı Formations.

The Güverdağı Formation (TRJg, Bozburun units/ Bodrum Nappes) has a structure dominated by neritic carbonate rocks. Many karst shapes have formed on the formation surface. The karstic features are also observed within dolomitic limestones in some places. This formation is overlain by the Karanasıflar Formation (*Kkn*, Bozburun units/Bodrum Nappes) unconformably. The formation is observed as extensively deformed inside the study area. Therefore, the thickness of the formation can not be determined precisely. The thickness of the formation has been estimated as about 800 m by some researchers (Bilgin et al., 1997; Şenel and Bilgin, 2010).

The other unit containing karstic features, is Orhaniye Formation (JKo, Turunç units/Gülbahar Nappes). This formation consists of calciturbidite micritic interlayers and chert micrites with thin-medium local thickness. The formation is intensely deformed by tectonics. 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 era are important for the karst formation in the study area. The most common of these are neritic limestones. These formed in different periods between the middle triassic and cretaceous time interval (Şenel and Bilgin, 2010). These Mesozoic limestones are quite suitable for karstic occurences due to their lithological characteristics (Şahin, 2005; Öztürk et al., 2018).

The limestones in Bozburun Peninsula are surrounded partly both vertically and horizontally by impermeable (spilit, basalt, etc.) or relatively less permeable and less soluble rocks (such as dolomite). This features form the boundaries of the horizontal and vertical development of the poljes in particular. The impermeable levels (such as serpentine) of the Marmaris Ophiolitic Nappes control the northern boundary of the karstic formations belonging to the peninsula (Şenel et al., 1994; Şenel and Bilgin, 2010; Günhan et al., 2018).

It is estimated that the peninsula acquired its presentday configuration during the neotectonic period (since the latest Oligocene) under different tectonic regimes. These regimes include three compressions and two extensional tectonics. (Tur et al., 2015). It is emphasized in many studies that 13-degree rotation occurred counterclockwise due to development of the Büyük Menderes Graben inside and vicinity of the study area. It is also mentioned that the dominant shapes and structures are alligned along NE-SW direction throughout the study area and its close vicinity (Tur et al., 2015; Günhan and Öner, 2021) (Figure 2).

2.3. Tectonic Features

The study area is located in the southwestern most part of Türkiye together with the Datça Peninsula.

The peninsula was formed inside the Western Taurus Mountains of the Anatolide-Tauride block during the paleotectonic period. The Western Taurus Mountains start from the Aegean coast and extend to the Kırkkavak Fault Zone in the Isparta angle. The study area is located parallel to the subduction zone formed by the African and Eurasian plates, a product of the Fenno-Sarmatian and Gondwana masses. This feature has gained a NE-trend during the neotectonic period. Common earthquakes occur due to tectonic processes in the South Aegean Arc. In addition, some active volcanoes are observed in this region (Pichon and Angelier, 1979; Tur et al., 2015) (Figure 3).

Moreover, some researchers stated that the faults in the Bozburun area play an important role in the development of the current hydrological system of the study area (Nazik and Tuncer, 2010; Nazik and Poyraz, 2015; Günhan et al., 2018). Based on existing data and new field observations, it is thought that faults play an important role in the formation of karst structures. It is estimated that karst development in the region accelerated during late Pleistocene in relation to both the acceleration of seismotectonic processes and the demise of the last ice age (Tur et al., 2015; Günhan and Öner, 2021). The types of faults in the region are normal, reverse and strike-slip in character (Figure 4, 5). The trends of the faults are mostly aligned along E-W, ENE – WSW directions. However, at many points, a different fault can also cut this trend at a perpendicular or near-vertical angle.

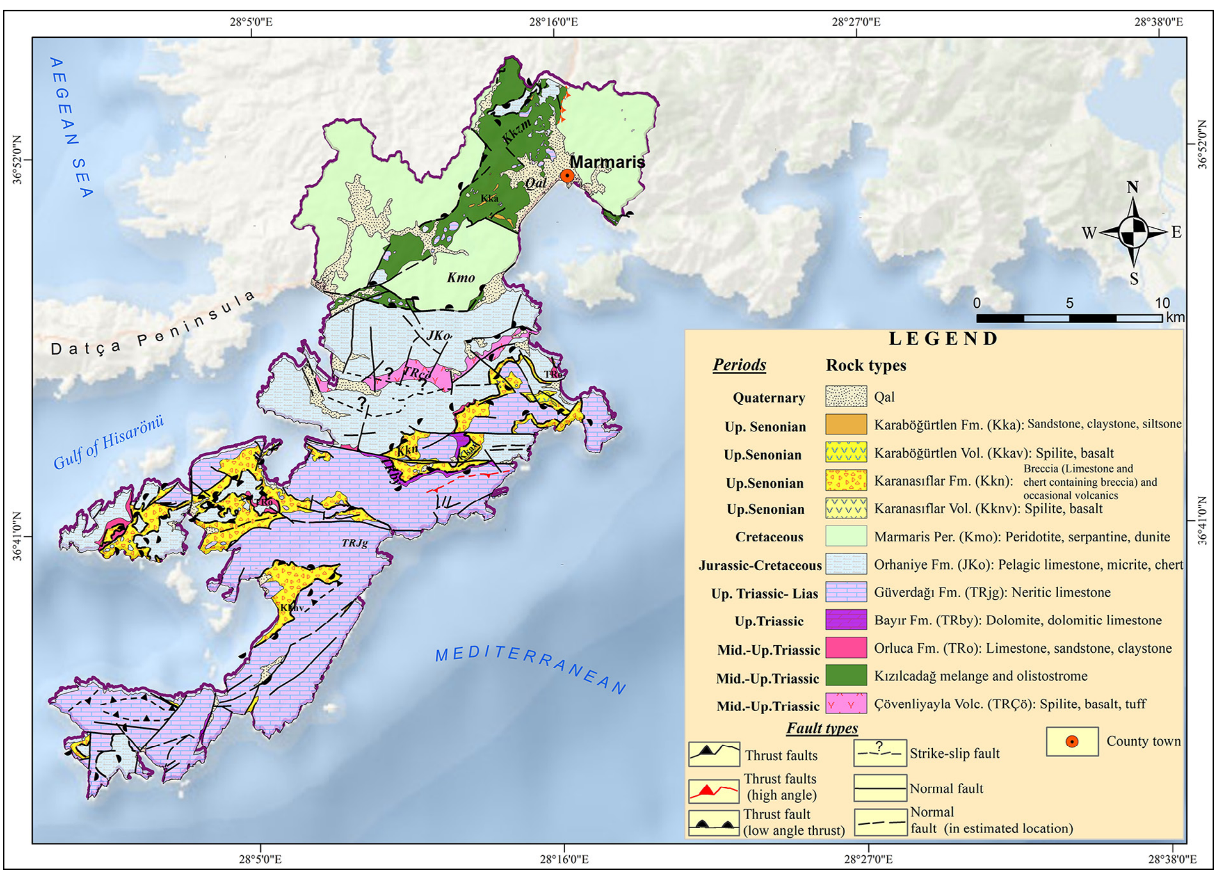

Figure 2- Geological map of Bozburun Peninsula (Şenel and Bilgin, 2010).

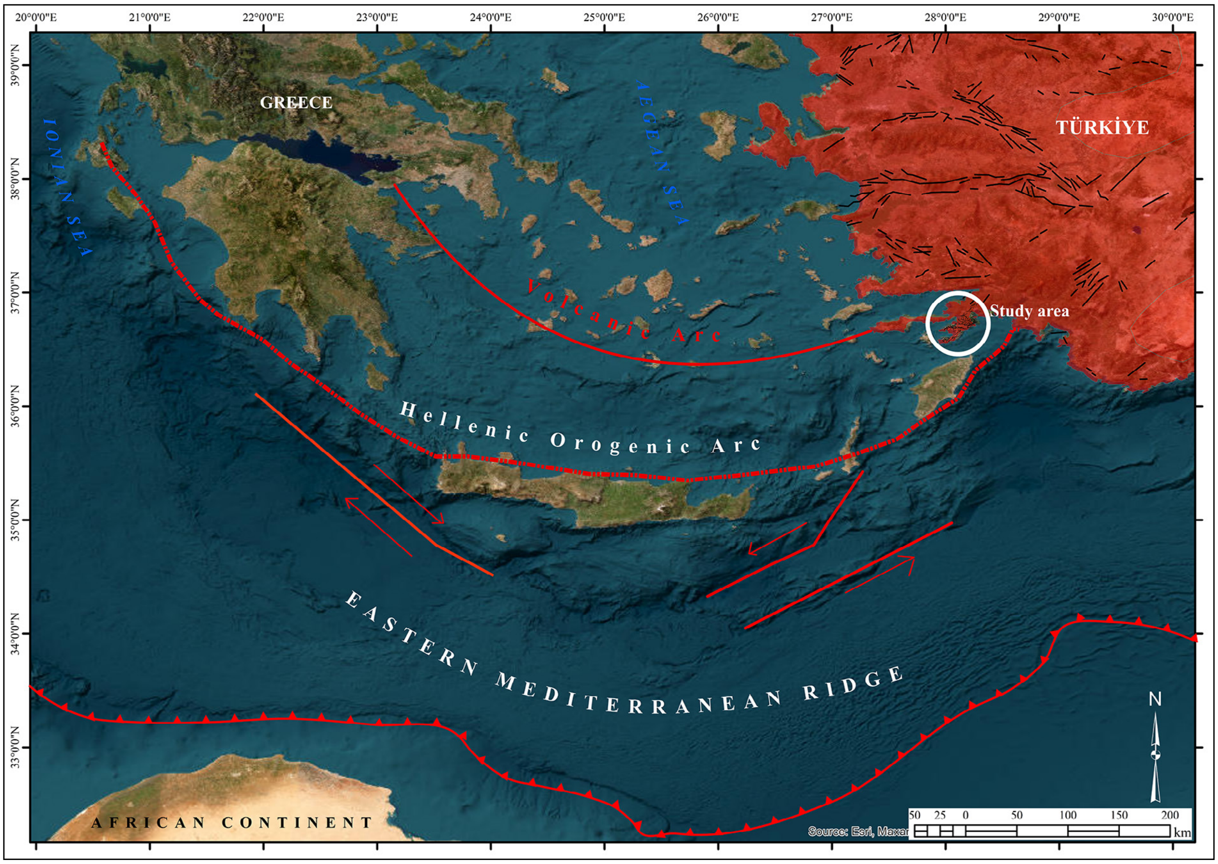

Figure 3- Map showing the main tectonic features of the Southern Aegean Arc and its surroundings.

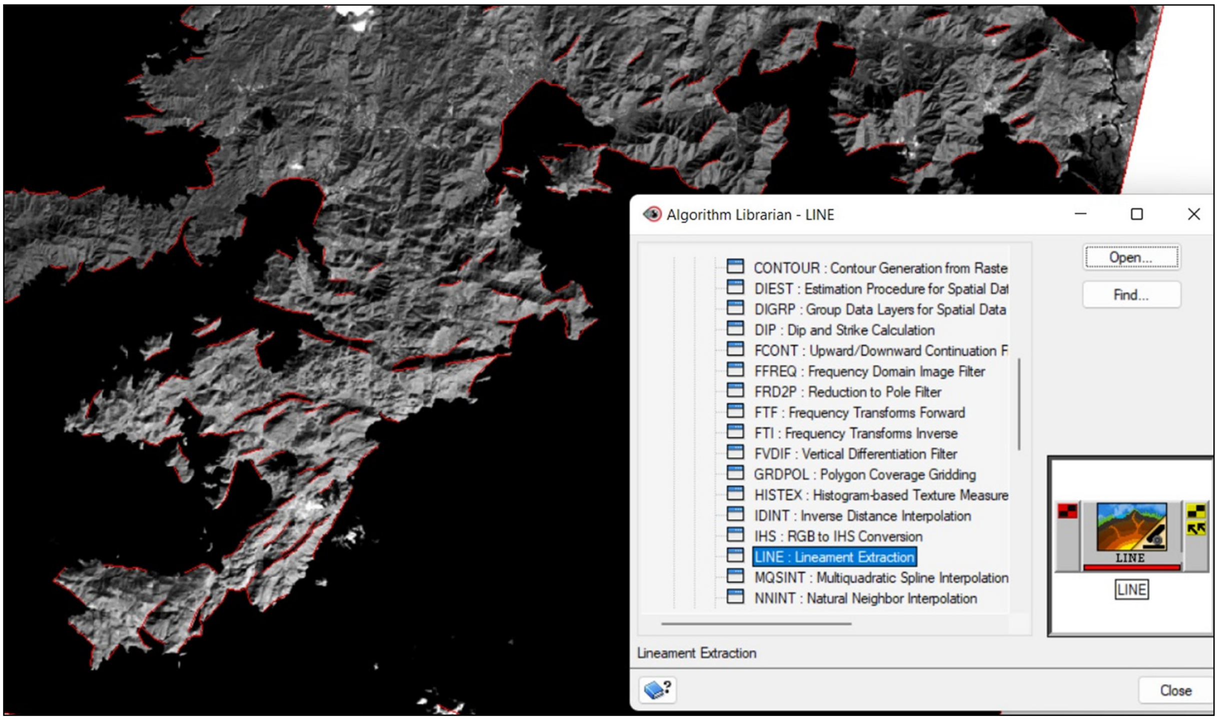

Figure 4- Detection of fault linearity in Geomatica 2016.

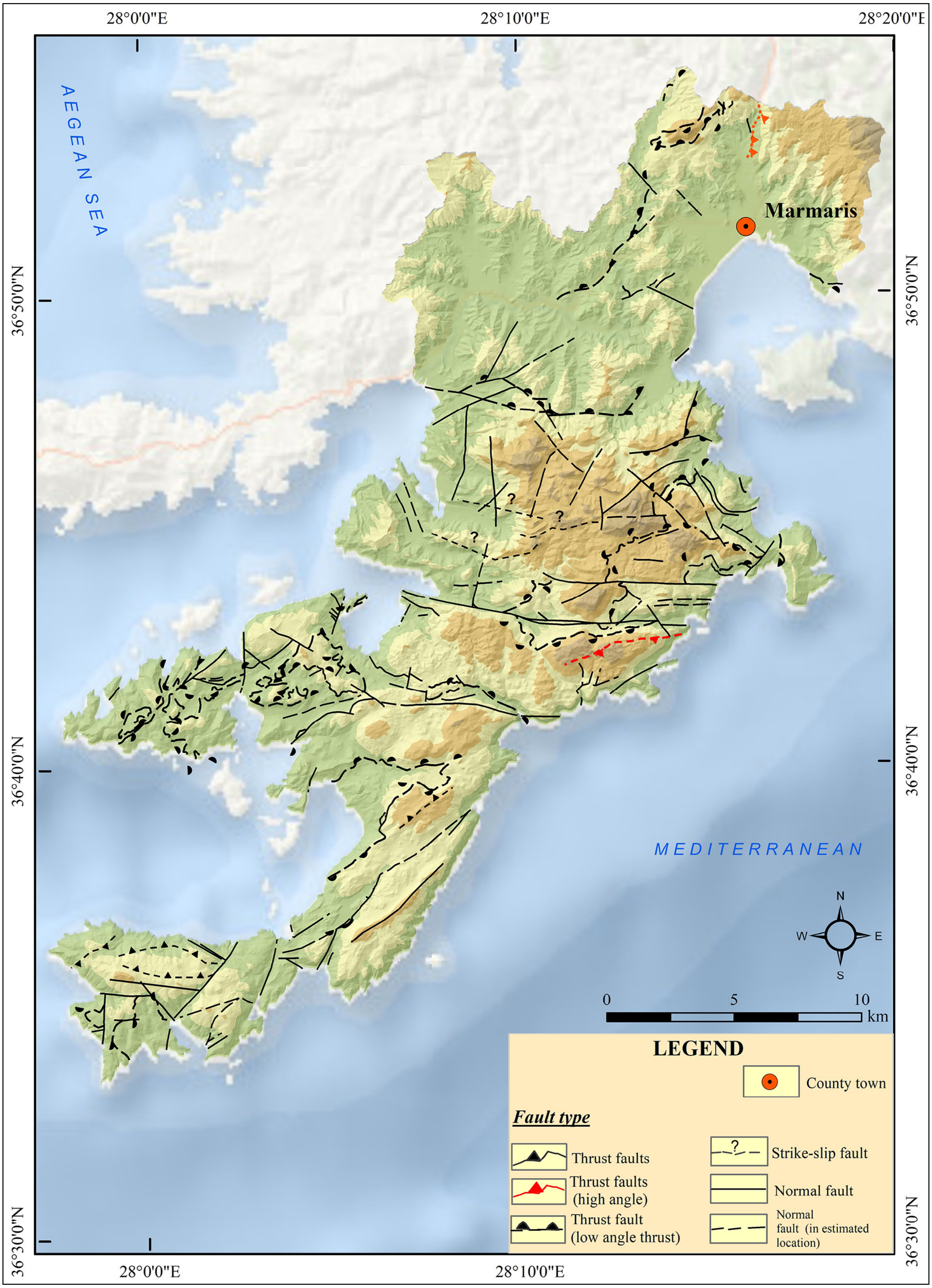

Figure 5- Morphotectonic map of the Bozburun Peninsula.

This can be clearly observed on the Bozburun Peninsula reflecting the tectonic characteristics of the Southwestern Aegean Region (Uluğ et al., 2005; Gündoğdu et al., 2015, 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 6.3 magnitude earthquake on May 23, 1961 in the offshore Gulf of Marmaris. The P wave focal mechanism, solution of the earthquake indicate that this earthquake was originated from a reverse faulting event (Ersoy et al., 2000). In addition to the Gulf of Marmaris, Gulf of Gökova and Gulf of Hisarönü and their immediate surroundings exhibit high tectonic/seismic activity. Many earthquakes with magnitudes above 5 have occurred in this region. Some ancient earthquakes were reported by some researchers in the region (Kırkan et al., 2023).

2.4. Geomorphic Features

The Taurus belt of Anatolia is very rich in terms of karst shapes. The current shape of the belt occured due to uplift of the submarine carbonate platform and volcanics. The area includes many relatively small scale faults and related micro basins formed by the local tectonism. The karst development continued in relation to physical and chemical decomposition in the research area. The formation of the karstic features seem to be controlled dominantly by faults (Erol, 1983, 1990; Akay and Uysal, 1988; Şimşek et al., 2021). Hills, valleys and many plains have occured in relation to faulting and folding in the study area (Taşlıgil, 2008).

It is suggested that the geomorphological and karst processes in the area has begun with the retreat of the sea since the Lower Miocene and the rise of Anatolia during the Middle Miocene (Şengör et al., 1985). In addition, the humid and warm climatic conditions intensified karst formation during the emplacement of the Lycian Nappes at that time. It is proposed that the karstification ceased during the Pleistocene ice age (Öztürk, 2020). Some studies also suggested that the ending of the Ice Age and the intensified seismic activity also enabled the karstification in the region during the Last Pleistocene. It is thought that the current karstic patterns developed since then (Öztürk, 2020; Günhan and Öner, 2021). Moreover, it is thought that the karst revival in the study area mainly developed along paleovalleys during this period. Some findings suggest that some uvala formations is located along river beds in some locations in the study area. It is also observed that some existing karstic features are degraded along younger folds and fractures in some locations. These were not included in the our study because they had a damaged structure.

Caves are valuable in classifying carbonate aquifers and determining the range of aquifer types (Ford and Williams, 2007). It is observed that some epikarstic processes dominate the karstification in some local areas and many related caves have been observed inside the study area (Table 1, Figure 6). The epikarstic caves are mostly distributed around the Bayırköy Polje and on the Güverdağı Formation in the peninsula. Some of these features also constitute a some water resources in the study area. It is estimated that these caves start to develope during the paleotectonic period. However, some recent studies suggest that the neotectonic processes seem to reshape the existing elements (Nazik and Poyraz, 2015; Günhan et al., 2018). Some sedimentary units support this view.

Although it can be said that the caves in the study area have generally gained a “hanging” structure as a result of the neotectonic activity, the underground-surface drainage relationship has been newly established at some points and limited at others due to the controls of different lithological units. When evaluated from this perspective, they are both perched and rare, small and irregular in pattern.

It is possible to come across small “erosion plains” characteristic of the Menteşe Region, especially in the central and southern parts of the peninsula. Here too, due to faulting, especially uvala and poljes show a specific trend. The list of poljes is as follows: Hacıağaç Polje (P1), Kuyucak Polje (P2), Osmaniye

Table 1- Some know caves and their brief characteristic properties in the study area (See Figure 7. The caves are mosly populated around Bayırköy area) (Günhan et al., 2018 and Günhan and Öner, 2021).

Cave names	**Altitude (m)**	**Direction**	**Depth (m)**	**Trend 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	–	–

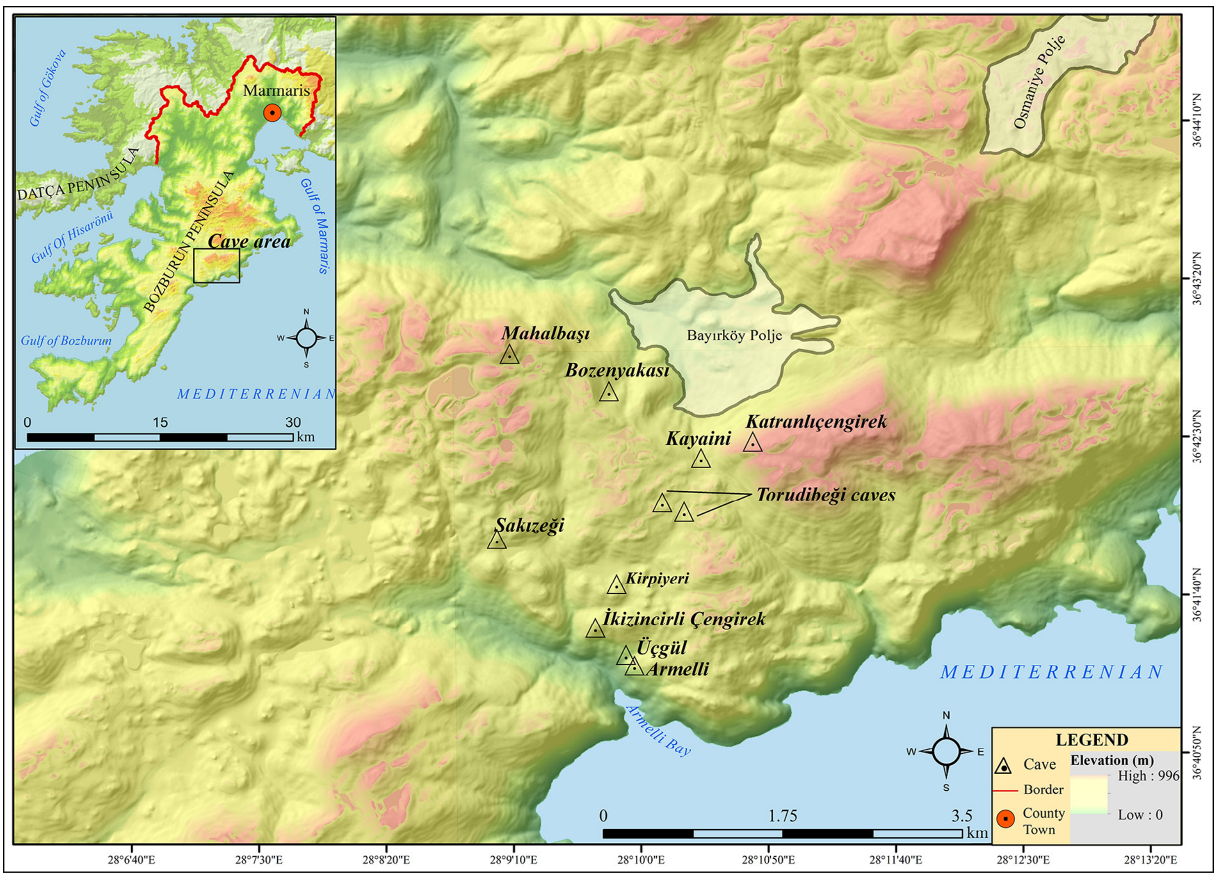

Figure 6- The location of the caves clustered around Bayırköy (modified from Günhan et al., 2018).

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).

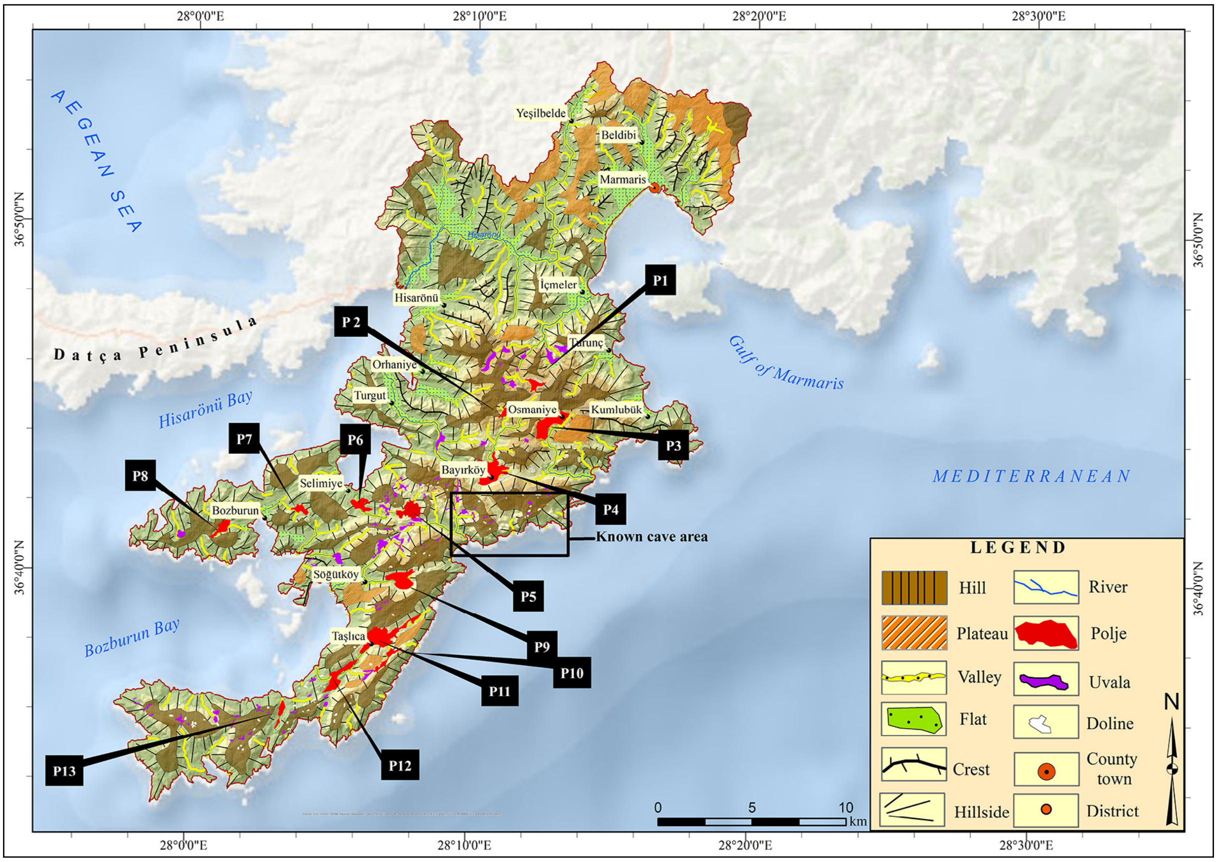

Figure 7- Geomorphology map of Bozburun Peninsula.

3. Discussion

3.1. General Geomorphological Characteristics of Dolines and Uvalas

Dolines, one of the karstic erosion/dissolution forms, have different formation systematics. They are classified as dissolution, collapse, covered and subsidence dolines (Ford and Williams, 1989; Doğan, 2004; Öztürk et al., 2018*a*). Dolines are important morphological shapes. Because they provide specific information about the morphological development of an area. Dolines also may provide quantitative results suitable for geomorphologic analysis (Öztürk, 2018*a*). As a result of the studies carried out using the Google Earth program, 107 characteristic dissolution dolines have been identified in an area of approximately 440 km^2. The distribution of the dolines in the field coincides with highly fractured neritic limestones. These morhological features are distributed along some large-scale or smaller-scale faults.

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 as a large karstic features originated from the uvalas with not less than 0.5 km^2 in size (Bonacci, 2004). In this study, following criteria have been taken into account during the determination of the uvalas. The criteria are: 1) the shape should be formed by the merging of at least two dolines, 2) the area should be smaller than 0.5 km^2, 3) base of the shape should be covered with terra rossa, 4) the area should be a depression and 5) the at the base rocks should be soluble. Based on these 81 different uvalas have been determined throughout the peninsula during this study. Uvalas, similar to dolines, are generally observed along joints and fractures located mainly inside neritic limestones. In addition, some uvalas in the study area were found in the contact areas of pelagic and neritic layers, where there were layers with dolomitic interfaces and even intertwined with each other and with different structural units, and in some places they were superimposed on these other units (volcanites, etc.), settled in the thrust windows and grew with the fluvial effect. These probably also have paleovalley characteristics.

Based on field observations and related studies, the size (m^2, km^2), elevation steps (m), elongation ratio (R_E) and elongation direction (E_A α), density (Kernel density analysis) and depth (m) of dolines and uvalas have been evaluated in the peninsula. This paper also attempts to understand the extent of the relationship between poljes, 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. Dolines identified in the study area have been evaluated using areal size histogram (Figure 8). Based on this data, the areal size of 40 dolines corresponding to the maximum number range varies between 233 m^2 and 2333 m^2. 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 is thought that the tectonic effect (continuous reactivation of the land, fragmentation and fracturing along the thrusts and normal faults) played a significant role. In the literature, the dolines smaller than 27.000 m^2 are 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 dissolution feature larger than itself, are formed by the merging of dolines. However, as mentioned above, very small dolines that have developed due to tectonic effects and that are very close to each other may easily merge and become uvala. Therefore, very small uvalas can be formed by the merging of the two very small dolines. Such uvalas are also observed in the study area. Based on the available data, 19% of the uvalas in the study area are smaller than the largest dolines. Moreover, the majority of dolines (75%) are larger than the smallest uvala(Figure 8).

It seems that the extensive tectonic deformations have negatively affected the size of the uvalas in the study area. It is detected here that 67 (~70%) of the observed uvalas are smaller than 70600 m^2. The uvalas observed on the peninsula are much smaller than 0.5 km^2. Therefore, it is deemed here appropriate to include the uvalas inside small uvala class (Brinkmann et al., 2008; Aguilar et al., 2016) (Figure 8).

3.1.2. Elevation Steps (Histogram)

Most of the dolines (~61%) in the Bozburun Peninsula are located at altitudes between 201-450 m (Figure 9). It is estimated that climatic conditions will not make a significant difference in this narrow range.

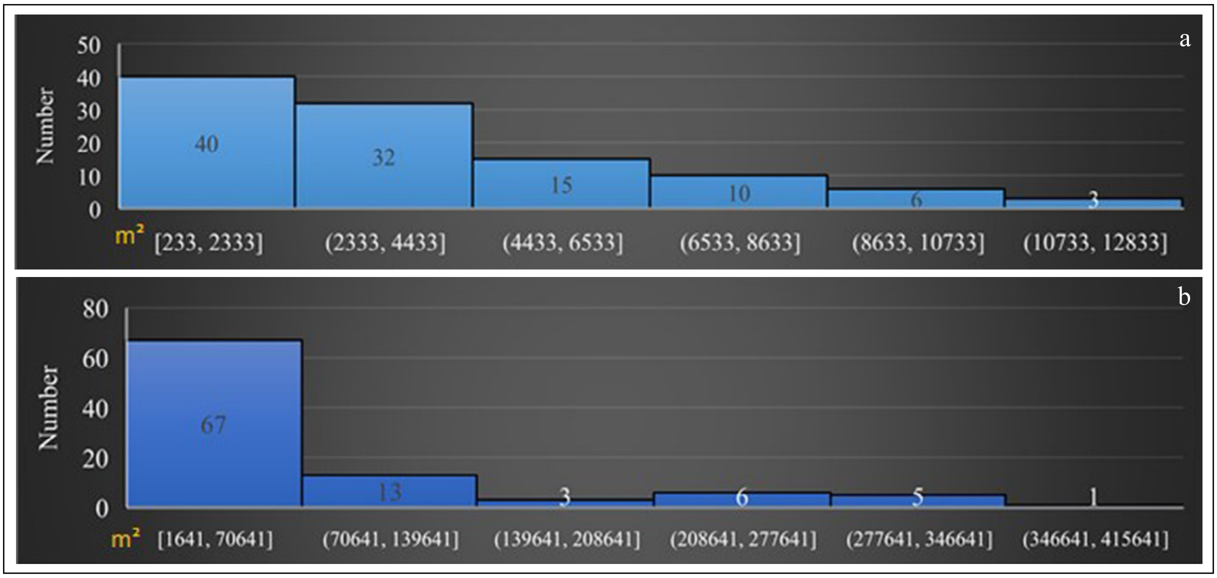

Figure 8- Histogram graphs; a) sizes of dolines, and b) sizes of uvalas.

It can be thought that the fact that the fractures and pits formed along the anticline surfaces, caused by the geomorphological development under the influence of orogenic movements and tectonism that have become more intense since the Miocene, coincide with these elevation ranges is more decisive in the distribution of dolines. The elevation histogram of uvalas is very similar to that of dolines (i.e. 201-450 m). The distribution and elongation directions of uvalas are very similar to dolines due to same structural features. In these levels, partially degraded uvalas and paleo-valleys are observed due to periodic reactivation, especially on medium to high slopes. In addition, it has been also observed that fluvial processes have reactivated the karstic features in some places due to high slope values of the hillsides along the dolines connected to the main uvalas.

3.1.3. Slope

According to the slope analysis performed in ArcGIS 10.5 program, the slope groups determined by using Oakes (1958). Based on this, 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 most of the karst shapes, including poljes, have slope values exceeding 8%. The presence of knickpoint and fractures is important in this sense. The base slopes of the karstic features are generally included in the slope groups up to 8%. Areas with steeply-sloping (15% and above) includes significant amounts of degraded dolines and uvalas. It is understood that they are still in the formation phase in relation to tectonism along paleo-valley floors (Figure 10).

3.1.4. Depth

The depths of the dolines in the field vary between 1-11 m. In the calculations and observations, it has been 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 elongation direction do not directly overlap with the main fault lines in general (Figure 11). On the contrary, the depth of the dolines 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).

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. The Morphometric Indices: Elongation Ratio (R_E) and Elongation Direction (E_A α)

In the field, dolines that have been exposed to periodic rejuvenation and degradation 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 ratios of karstic shapes. The elongation ratio is calculated by taking the ratio of the long axis to the short axis of the doline or related karstic shape

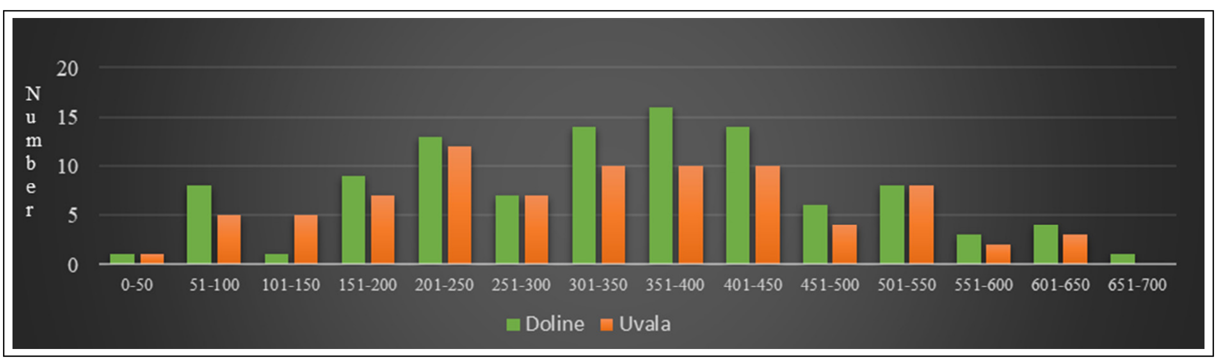

Figure 9- Histogram of the elevation ranges (m) where dolines and uvalas are located.

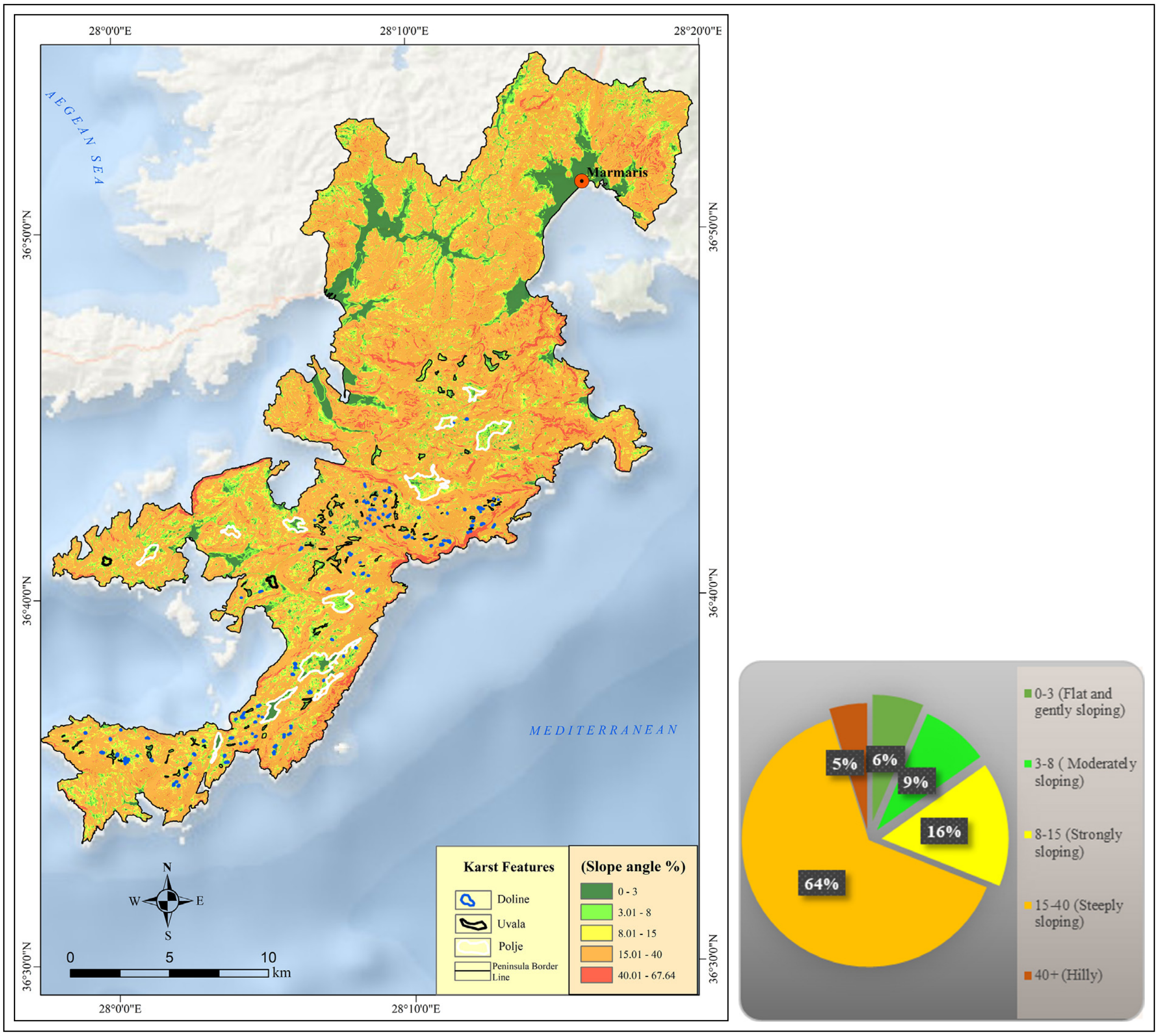

Figure 10- The distribution of slope and karst shapes in the study area.

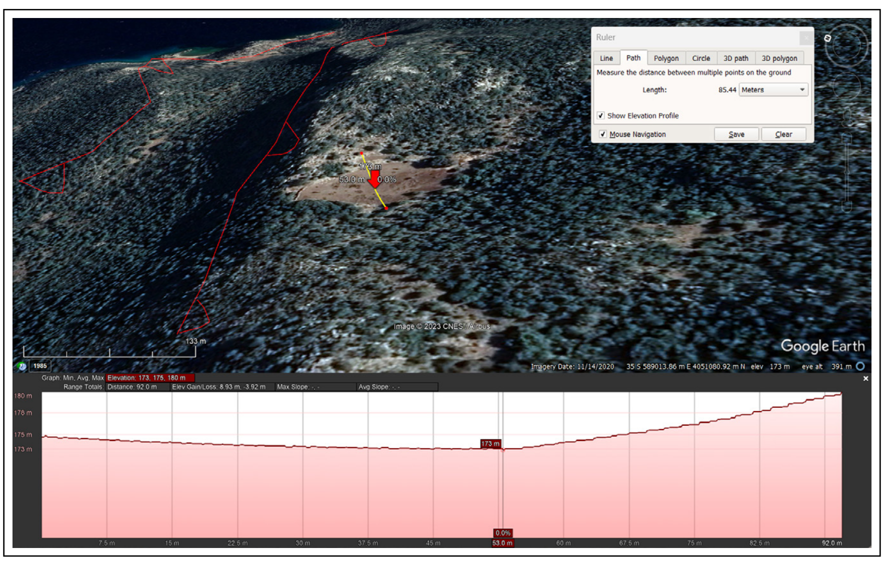

Figure 11- Developed in a crack formed by a fault, example of a dissolution doline reaching 5 m in depth (Google Earth Pro 2020 image).

Figure 12- Resp., a) a Google Earth image of the Bozburun Peninsula., b) The deepest doline (11m) of the Bozburun Peninsula is marked with a black star in the image. This doline is located in the ESE direction of Bayır Village.

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 feature (Öztürk, 2018*b*). Basso et al. (2013) subdivided the elongation ratio into 4 categories (Table 2). In this context, 65% of the dolines in the field are in the elongated class. There are many elongated dolines in the region that extend diagonally to each other and are sensitive to fluvial degradation. These dolines, also due to the effect of neotectonism, combined to form elongated uvalas. Most of dolines (%65) and uvalas (%76) has an elongated form in the peninsula.(Figure 13). Almost half of the uvalas in the field are located exactly on a fault, and extend parallel to the faults (Figure 14).

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

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

Elongation ratio (R_E)	Geometry of Shape
Less than 1.21 (R_E < 1.21)	Circular, semi-circular
1.21 to 1.65 (1.21 < R_E) < 1.65)	Semi-elliptical
1.65 to 1.8 (1.65 < R_E < 1.8)	Elliptical
Greater than 1.8 (R_E > 1.8)	Elongated

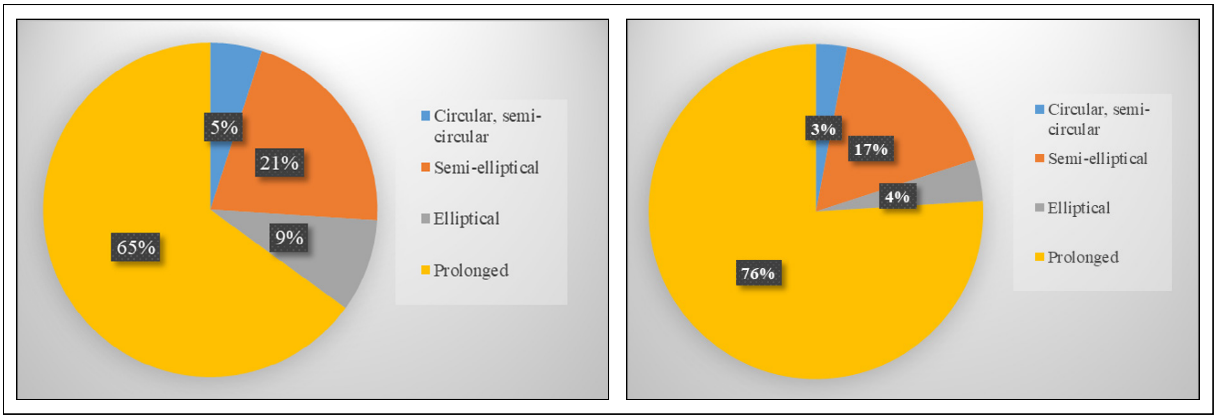

Figure 13- Elongation ratio graphs of dolines (left) and uvalas (right).

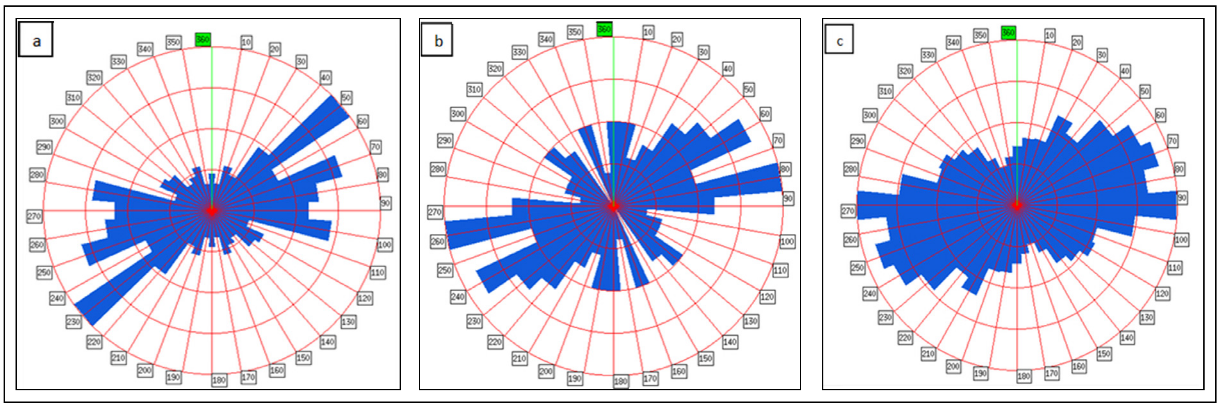

Figure 14- Rose diagrams of the elongation directions of; a) dolines, b) uvalas and c) faults in the study area.

3.1.6. Density

Dissolution dolines are pit-like shapes where the surface-groundwater relationship is established, and are formed as a result of chemical and physical erosion around the diaclasis, faults and layer joints that are weak in terms of karstic dissolution (Sür, 1994; Doğan and Yeşilyurt, 2004). In the study area, fields where these conditions come together at different levels have a determinative effect on the density of dolines. Especially the dolines around the Bozburun and Selimiye faults are located in Nappe windows and the hillslope angles are over 8 percent. This view is supported by fault data obtained from Google Earth image analysis, 1/100.000 scale geological maps prepared by MTA, and field observations. (Figure 15).

The distribution of uvalas in the study area is more compatible with the presence and elongation of the faults compared to the distribution of dolines. It is clear that the weakness of the structural lines as well as the larger fractures 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 elongation direction 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).

3.2. Properties and Morphometry of Poljes

The largest shapes formed as a result of karstification are poljes. Poljes are formed by

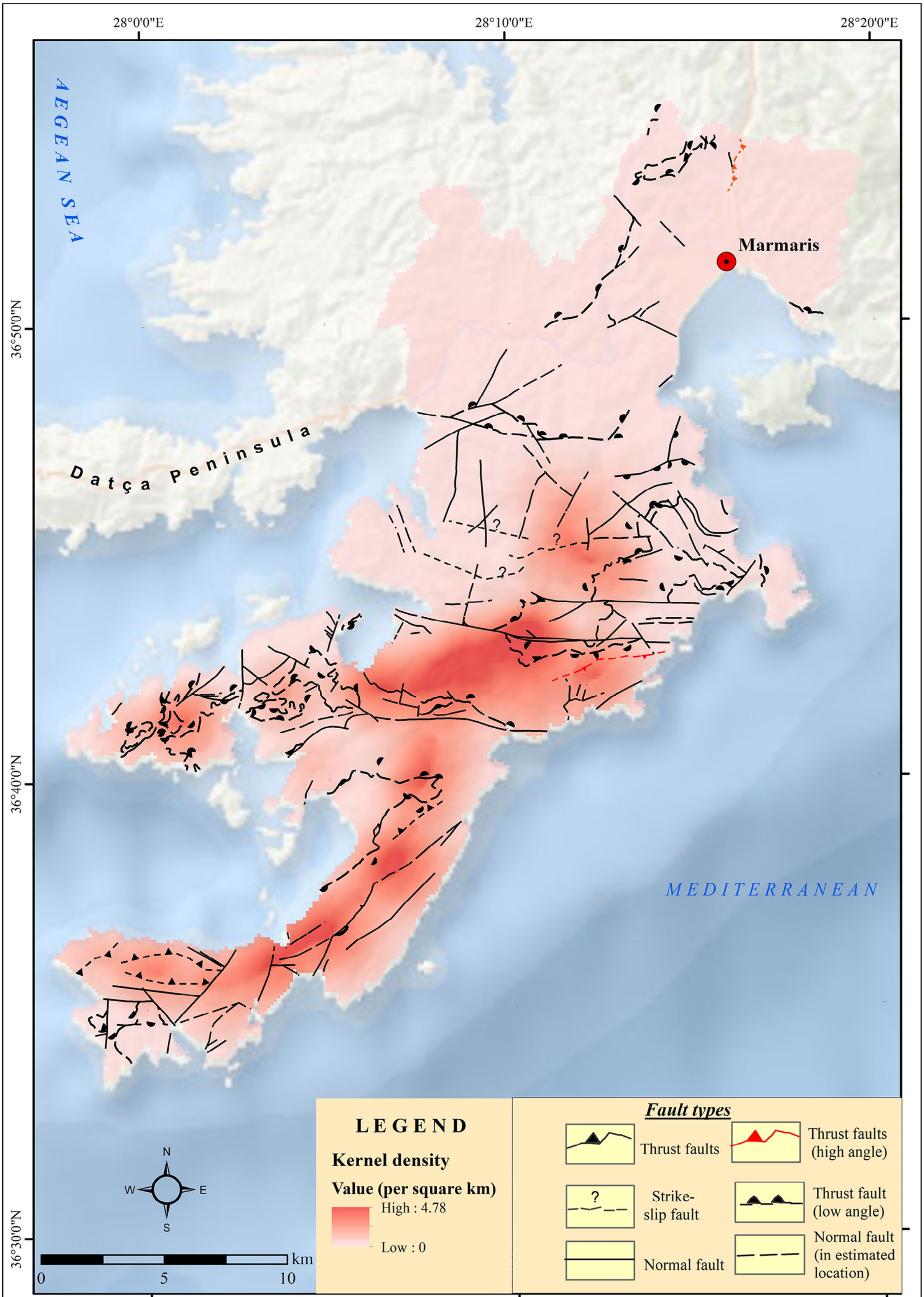

Figure 15- Map showing Polje Kernel density distribution and the faults in the Bozburun Peninsula.

providing optimum conditions for karstification. In addition to the lithological structure, tectonic activities and climatic conditions also play a triggering role for karstification and polje formation. Poljes are generally bowl-like depressions that are close to elliptical shape. (Ford and Williams, 1989; Sür, 1994; Doğan, 2003; Ege, 2015*a*, *b*, 2017).

In this study, before the poljes were identified, the literature on the detection and morphometric properties of poljes were reviewed in detail, just as in the determination of other karstic shapes. Then, the data coming from the 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-evaluated by using the 1/25000 topographic maps. While determining the boundaries of the polje base, the bedrock remnants, where the slope erosion continues, have been taken as the boundary reference. In addition, care has been taken to clearly distinguish the terra-rossa on the floor of the polje. Gams (1978), on the other hand, emphasizes that three criteria must be met for a depression to be considered as a polje. They are: 1) presence of a flat bottom (may be terraced) in rocks or loose sediments, 2) presence of a closed basin with high flanks (e.g. 18% in this study) and 3) presence of a karst drainage system. In addition to this, 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 is seen that the areal size cannot be applied strictly. Mainly, hydrological and geomorphological criteria are taken as a reference during definition (Şimşek et al., 2021). In this study, 13 poljes are classified as small. Their sizes range between 0.25 km^2 (Serçelimanı Polje) and 1.6 km^2 (Bayırköy Polje). The morphometric properties of the detected poljes are important in terms of understanding the tectonic influence on the morphology (Table 3). Polje evaluation starts from the north towards south (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 ponors 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 is the Osmaniye Polje (P3). It is surrounded by a Senonian low angle thrust 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 cavity is less than the Hacıağaç and Kuyucak poljes. The bottom and hillsides of the polje are covered with breccias and limestone blocks in places. 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 fractures with different character cross cut each other. The intersection caused the polje in question to be in circular form, and the polje does not present a certain elongation direction. The diameter/depth ratio is 13.87. There are settlements and gardens in the polje which developed on neritic limestones. The surrounding valleys were probably reactivated during the neotectonic period. Therefore, there is a thick alluvial layer at the base of the polje (Figure 16-18). 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 observed in its ponors.

Kızılköy Polje (P5) is another polje located 3 km southwest of Bayırköy Polje. The polje has a circular form due to intersection of both low angle thrust fault and normal fault. A large number of hums (residual hill) 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 at the bottom. Alluvium also have an important place in the polje base with dry drainage. Ponors were detected at several points, and it is observed that there is water inside these ponors from time to time. There are settlements and gardens in the polje.

The Selimiye Polje (P6) is the another polje observed in the study area. It is located approximately 1.3 km west of Kızılköy. There is a village inside this polje. The polje is 600 m away from the shore line and its maximum depth is 60 m. The elongation direction of the shape is parallel to the trend of the low angle thrust fault and normal fault. Its has is semi-elliptical shape and its diameter/depth ratio is 8.17. The periphery and base of the polje, which developed on pelagic limestones, mostly consists of breccias. Sandstone and mudstones are also observed in the polje. The seismicity due to neotectonic activity reactivated the paleovalley in the basin and allowed it to rise 60 m above the shoreline. The west of the polje seems to have started to experience active fluvial processes again, probably due to the knickpoint that occurred later and the increase in the base slope. There are some karstic springs on the slope separating the polje from the shoreline. It is estimated that the groundwater level of the polje, which is feed by the northern hillsides and karst sources, is high.

Avlana Polje (P7) is the another polje and located approximately 2.3 km southwest of Selimiye. This feature is also controlled by a thrust fault and its elongation direction also conforms to this. This polje is in the elongated class in terms of its form. The diameter/depth ratio is 7.95. This ratio is the lowest compared to other poljes in the study area. This value also shows that the shape has the highest hillslope angle compared to the others. The lithology of the shape consists of pelagic limestones and breccias, as in the others. There is a seasonal stream in the polje. This stream flows through a reactivated paleovalley and reaches Bozburun Bay in the south. Neotectonics appears to play an important role in the development of this shape. In the polje, there are summer cottages used for touristic purposes and a sub-village settlement.

Ortaören Polje (P8) is the another polje observed in the study area. This feature is located about 3 km southwest of Avlana polje. It seems that the development of Ortaören Polje is also controlled by a thrust fault and displays a similar trend compared to this fault. The is in the elongated class in terms of its form. The diameter/depth ratio was calculated as 17.63. The shape appears to develop mainly on pelagics sediments. The base of the polje consists of calcareous breccia.

Another polje on the peninsula is the Söğüt Polje (P9). This is semi-elliptical karst shape and elongated by a thrust 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 high hillslope angle (over 40%). The hillsides were artificially terraced by local people for pasture use. Seasonal drainage is available. In the polje, there are a few houses that form the lower settlement of Söğüt village.

Taşlıca Polje (P10) is the another polje observed in the study area and located in approximately 2 km South of Söğüt Polje. This shape seems to develop on top of a thrust or normal fault. The diameter/depth ratio of the polje is 26.5. The shape has formed on neritic limestones. An intense karstic drainage system has developed in the polje with many ponors and hums. Taşlıca Polje is seperated from Ağlan Polje in the east by a small and narrow cill. It seems likely that these two poljes will merge in the future.

Ağlan Polje (P11), parallel to Taşlıca Polje, formed on the edge of a normal fault. The elongation ratio of this shape (6.76) is the highest compared to the others. The diameter/depth ratio of the polje is 28.09. There is an artificial pond in a ponor belonging to the Polje. This pond is used for irrigation and animal husbandry purposes by the local people.

Another polje that is very likely to merge with the Taşlıca Polje in the feature is the Sindilli Polje (P12). This shape is classified here as the elongated. Sindilli Polje is also separated from Taşlıca polje by a small threshold in the south, and seems to have developed under the control of a thrust and normal fault. The diameter/depth ratio is the highest value in the study area (i.e. 49.96). The shape is rather shallow compared to the others. Beekeeping and animal husbandry are carried out in the polje. There are several ponors, and some remnants 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 ratio (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, 17).

4. Results

With this study, the formation and elongation directions of the karstic features in the study 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). So-called Quaternary thrust faults generally play a major role in the development of the poljes in the study area. The normal faults that develop close to thrust faults also play an important role in the formation of karstic features. The trends of both fault types generally coincide with karst shapes. It is thought that there is a dominant direction in the tectonic evolution of the area and that the torsion movement continues counterclockwise from this axis, which 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). The second possiblity is the study 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. 107 dolines, 81 uvalas and 13 poljes have been identified during this study in the Bozburun Peninsula. 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 reactivation and related faults, rather than climatic effects. It is estimated that the erosion cycle will at these slope grades until the karst base level is reached. It has been observed that dolines and uvalas with flanks greater than 15% have a degraded structure. While the average depth of the dissolution dolines are as 2.5 m, the average depth of the uvalas are 11.8 m. Available data suggest that the depth of karst shapes has a positive correlation with the fault presence. It is seen that majority of dolines and uvalas and all of the poljes overlap with faults. The elongation direction (EA α) of dolines and uvalas have a very close relationship with the azimuthal strikes of the faults and overlap in many places. Most of the dolines (65%) and uvalas (76%) in the peninsula are elongated in nature. It has been determined that almost half of the uvalas in the field are located exactly on a fault.

Based on the lithology, it has been observed that there are more karstic shapes on the neritic limestones compared to the pelagic limestones. This is because, neotectonic faults affect neritic limestones more than pelagic limestones. In addition, joints and faults, especially nappes, that developed parallel to the Bozburun and Selimiye faults intensifies and trigger karstification.

Table 3- Some characteristics of poljes determined in this study (Gams, 1978, 1998; Ford and Williams, 1989; Bonacci, 2004).

Name of polje (from north to south)	Area (km^2)	Morphological characteristic	Elongation ratio (R_E) = (Long axis/short axis)	Elongation Direction (E_A α)	The altitude of the deepest point of the sole. (m)	Lithology of the polje.	Polje depth (altitude difference between the highest and lowest point of the polje basin) -m).	Diameter/depth = Pitting ratio (R_P)
Hacıağaç Polje (P1)	0.28	Boundary	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	Boundary	1.19 (circular)	-	154	Limestone (Neritic)-Dolomite-Breccia (Limestone predominant)	611	13.87
Kızılköy Polje(P5)	1.32	Boundary	1.23 (circular)	-	232	Limestone (Neritic)-Dolomite-Breccia (Limestone predominant)	241	21.16
Selimiye Polje (P6)	0.46	Boundary	1.53 (semi-elliptical)	-	60	Limestone (neritic)	360	8.17
Avlana Polje (P7)	0.26	Boundary	2.01 (elongated)	E-W	70	Limestone (neritic)	349	***7.95 (Deep)***
Ortaören Polje (P8)	0.40	Boundary	2.45 (elongated)	NE-SW	84	Limestone (pelagic)	192	17.63
Söğüt Polje(P9)	0.85	Boundary	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

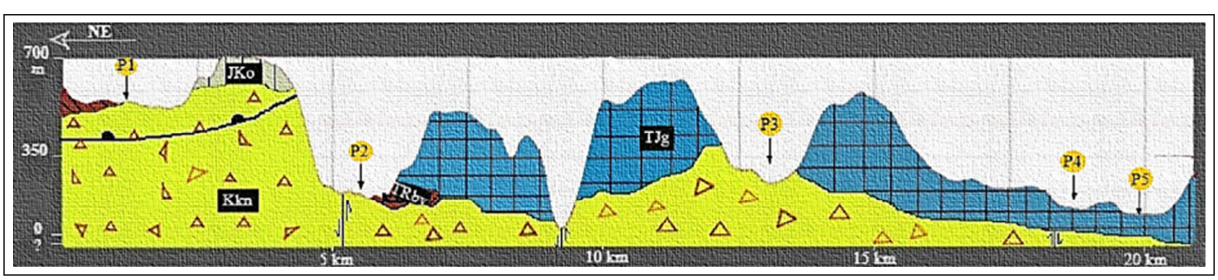

Figure 16- A cross section showing some poljes in the study field Hacıağaç Polje (P1), Kuyucak Polje (P2), Osmaniye Polje (P3), Bayırköy Polje (P4), Kızılköy Polje (P5), NE (Northeast), TRby: Bayırköy Formation, TRJg: Güverdağı Formation, JKo: Orhaniye Formation, Kkn: Karanasıflar Formation; shaped on the section Google Earth Pro and it has been scaled to Şenel and Bilgin (2010).

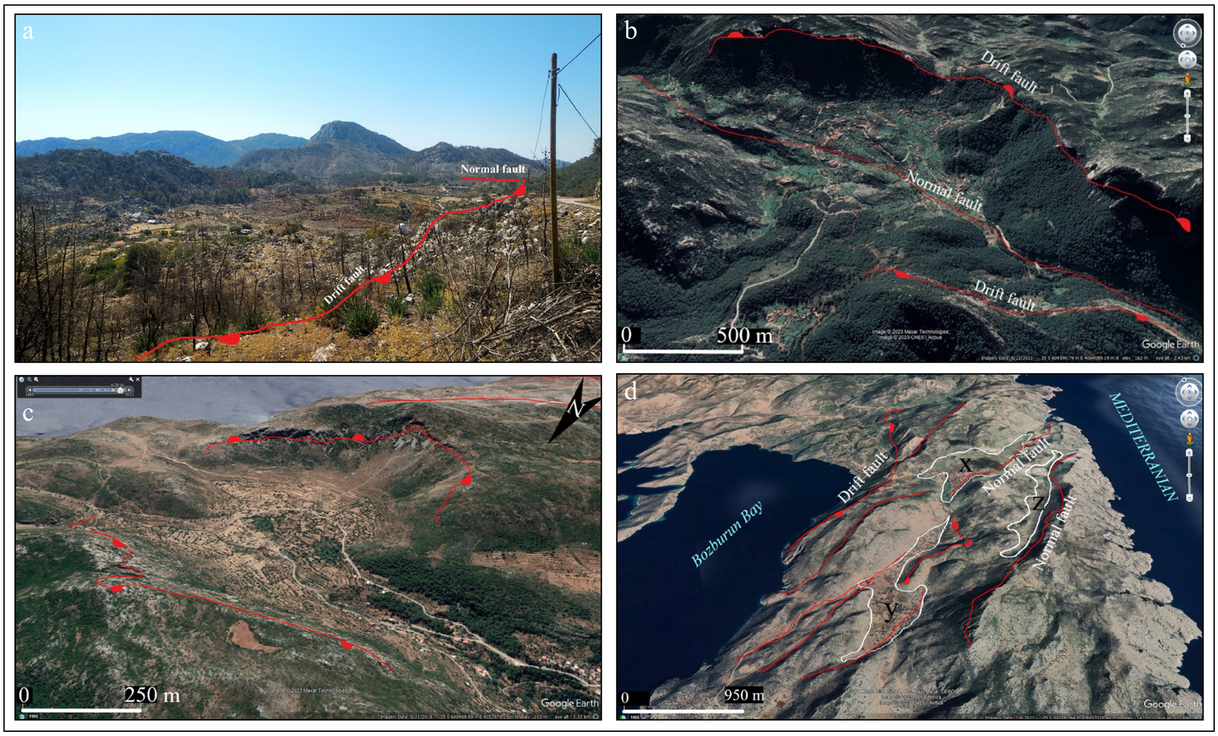

Figure 17- a) View of the Osmaniye Polje from northwest, b) Google Earth image of the Bayır Polje; the largest polje occured in the intersection of the faults in the study area, c) the Söğüt polje occured under the control of a low angle thrust fault, and d) x, y and z (Taşlıca, Sindilli (Aşağı Taşlıca) and Ağlana Polje). A view from the south almost parallel to the faults.

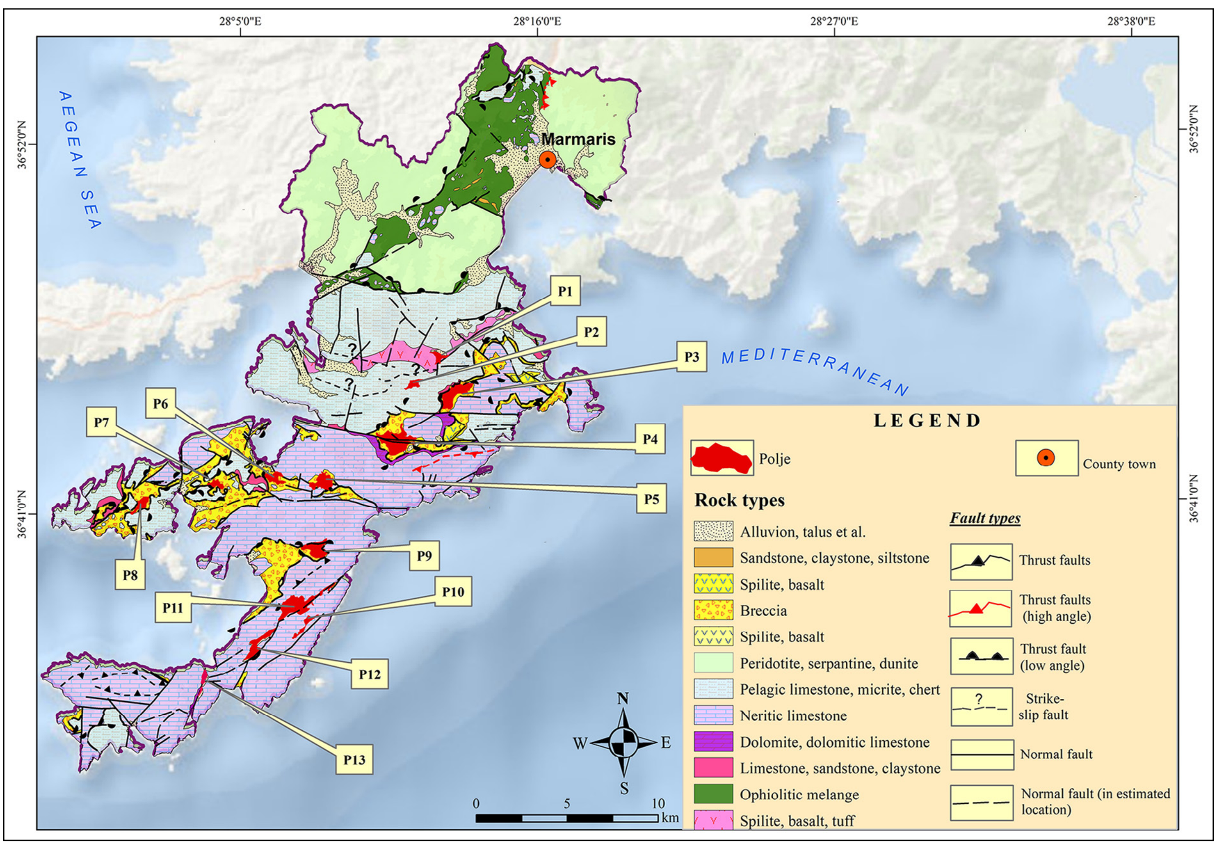

Figure 18- Figure showing the geological elements and polje locations.

Based on the literatüre, poljes with an area between 0.5 km^2 and 10 km^2 are considered as small poljes (Bonacci, 2004). Based on the criteria suggested by Gams (1998), it is suggested here that 0.25 km^2 is more appropriate for the lower limit of small poljes within the scope of this study. 13 poljes meeting these characteristics have been found in the field based on the Gams (1998) and Bonacci (2004). It has been determined that eight of the poljes are classified as boundary while five of them are classified as structural type based on the origin. The main elongation directions are NE-SW in ellipsoidal karst shapes. Circular or semi-elliptical (i.e., non-ellipsoidal) karst shapes predominantly coincide with the different fault intersections in this study.

Acknowledgements

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