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Fluvio-karstic evolution of the Taşeli Plateau (Central Taurus, Turkey)

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Abstract: Uplift history is an important factor in the structural patterns and karstification of the Taşeli Plateau. The morphological development of the study area consists of five stages according to its sedimentation, rotation, uplift, and climatic properties. (1) Shallow carbonates accumulated during the Early Miocene. (2) An emersion and drainage network developed as a result of the compressional neotectonic regime in the Late Miocene. (3) Dense joint systems were formed due to the ~40° clockwise rotation of the eastern limb of the Isparta Angle. (4) The climate of the study area changed as a result of rapid uplift from Late Pliocene to Early Pleistocene. This caused the formation of dry valleys, underground karstification on the plateau surface, and headward erosion of rivers in the southern part of the area. (5) In the last stage, the plateau surface was densely covered by solution dolines and the dry valley network turned into relict valleys due to expanding extensional cracks during Pleistocene.

Key words: Solution doline, relict valley, Taşeli Plateau, Taurus Mountains

1. Introduction

The Taurus Mountains (South Anatolian Karst Region) form a continuous karst belt between the Mediterranean Sea and the Central Anatolia Plateau. These mountains are the largest and most important karst terrain in Turkey. While presenting different lithological and structural characteristics, the Jurassic-Cretaceous and Miocene neritic limestones also played a significant role in developing the karstic landscape of these mountains (Öztürk et al., 2018b; Nazik et al., 2019). In particular, the tectonic history of these units was a determinant factor affecting the properties and density of karst landforms in the Taurus region (Doğan et al., 2017; Öztürk et al., 2018a).

High plateaus composed of Mesozoic and Tertiary limestones are the characteristic geomorphological units of the Taurus region. The gentle slopes of these plateaus are highly karstified due to tectonic and climatic effects (Klimchouk et al., 2006; Monod et al., 2006; Bakalowicz, 2015; Doğan et al., 2017; Nazik and Poyraz, 2017; Doğan and Koçyiğit, 2018; Öztürk et al., 2015, 2018b; Kuzucuoğlu, 2019). The plateau surfaces include many landforms such as gorges, dry valleys, dolines, uvalas, ponors, and springs. Due to tectonic influence, most of these karstic landforms follow the structural and orographic lineaments (Elhatip, 1997; Gunn and Günay, 2004).

Dolines (enclosed depressions) and karstic dry valleys, also called relict valleys, ancient valleys, fossil valleys, solution valleys, paleovalleys, and paleokarst valleys in various studies (Fermor, 1972; Day, 1983; Doğan and Özel, 2005; Sauro, 2013) are characteristic landforms of the high karstic plateaus in the Central Taurus Mountains (Nazik, 1992; Monod et al., 2006; Doğan et al., 2017; Öztürk et al., 2018b). Karst valleys evolved as normal valleys due to fluvial erosion in the "prekarst phase" of surface development (Dreybrodt and Gabrovšek, 2003; Košutnik, 2007) and date from the Miocene to Pliocene in the Taurus mountains (Monod et al., 2006). Then, surface drainage began to form an underground drainage network due to joints and fractures created by tectonic uplift (Monod et al., 2006; Bočić et al., 2015). Therefore, the surface drainage network on the karst plateau disappeared and became a network of dry valleys (Bočić, 2003). Subsequently, the surface drainage network was gradually replaced with solution dolines as a result of karstification (Doğan and Özel, 2005; Bočić et al., 2015; Petrović et al., 2016). These processes are described as the "reorganization of drainage by karstification" by Williams (1982). As a result, solution dolines and relict valleys were formed by a combination of karst and fluvial processes (Košutnik, 2007; Sauro, 2013), and the development of these 2 landforms is strongly related with each other (Day, 1983; Segura et al., 2007; Haryono et al., 2017). Therefore, a hypothesis can be formulated regarding the evolution of karst systems by means of the morphometric properties of these landforms.

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In this study, the morphogenetic evolution of the Taşeli Plateau is examined via the morphometric properties of dolines and relict valleys. The main aims of the study are (1) to determine the spatial distribution of dolines and relict valleys, (2) to explain the relationship between these 2 landforms, and (3) to describe the morphogenetic evolution of the Taşeli Plateau.

2. Study area

Taşeli Plateau is located in the southernmost part of the Central Taurus Mountains and on the eastern limb of the Isparta Angle (Figure 1a). The Central Taurus forms the best example of plateau karst (Figure 1b). The study area is the largest and most important karst plateau in the Central Taurus Mountains (Nazik et al., 2019). The investigated area comprises most of the Taşeli Plateau and covers 695 km^2. The mean elevation of the area is 1944 m and elevation increases gradually from north to south (Figure 2a). While the plateau surface consists of gentle slopes, the borders of the plateau comprise steep slopes (up to 81°), especially in the southern and western parts (Figure 2b). These steep slopes coincide with thrust faults (Aladağ and Bozkır Nappes, Figure 2c). The nappes consist of Mesozoic (Jurassic-Cretaceous) limestones (Çakozdağı Formation) and Late

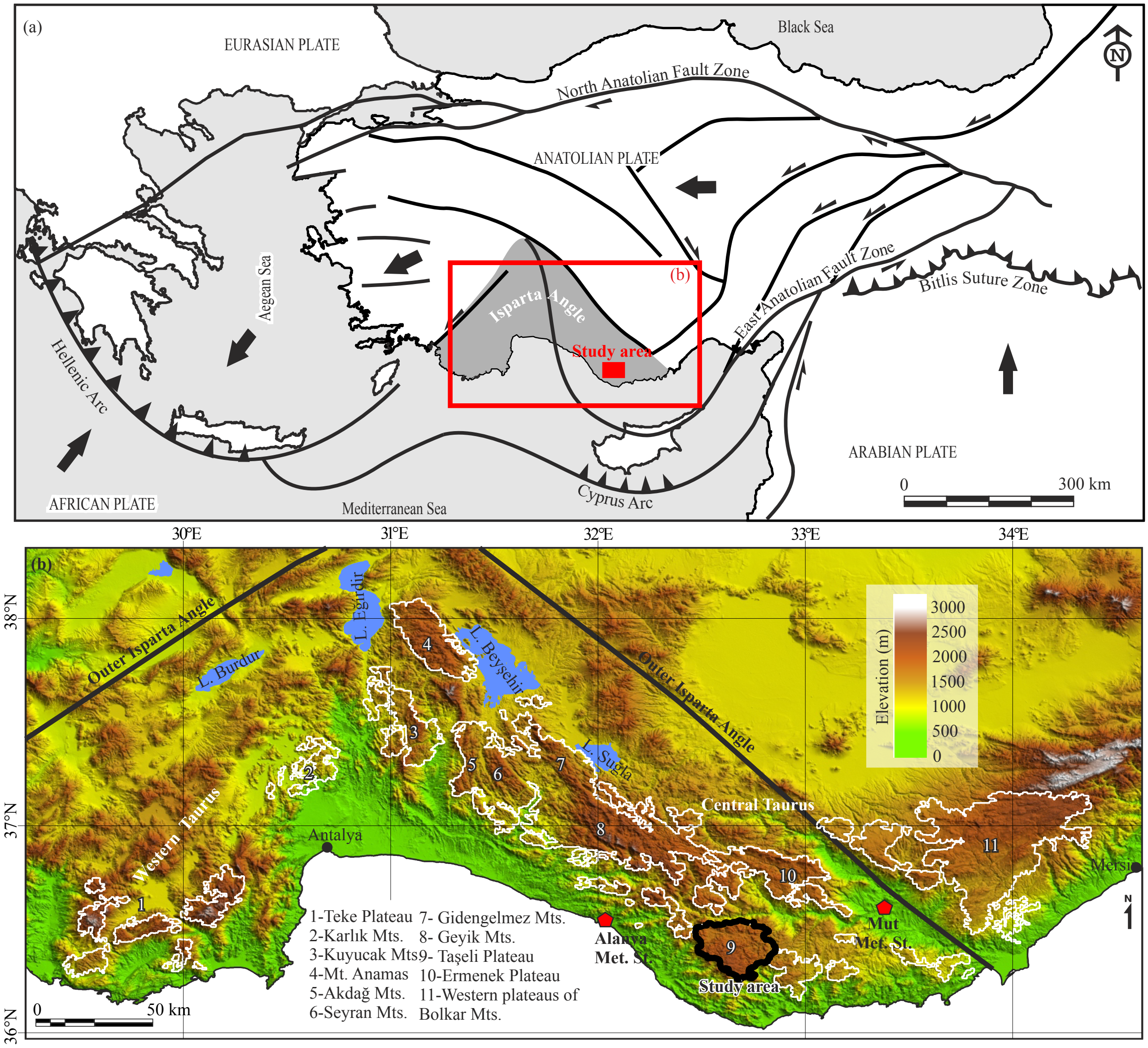


Figure 1. (a) Location of the study area and tectonic structure of Anatolian Plate (Şengör et al., 1985; Barka and Reilinger, 1997; Bozkurt, 2001; Robertson and Mountrakis, 2006; Koçyiğit and Deveci, 2007); (b) most important doline areas (Öztürk et al., 2018b) and location of the study area.

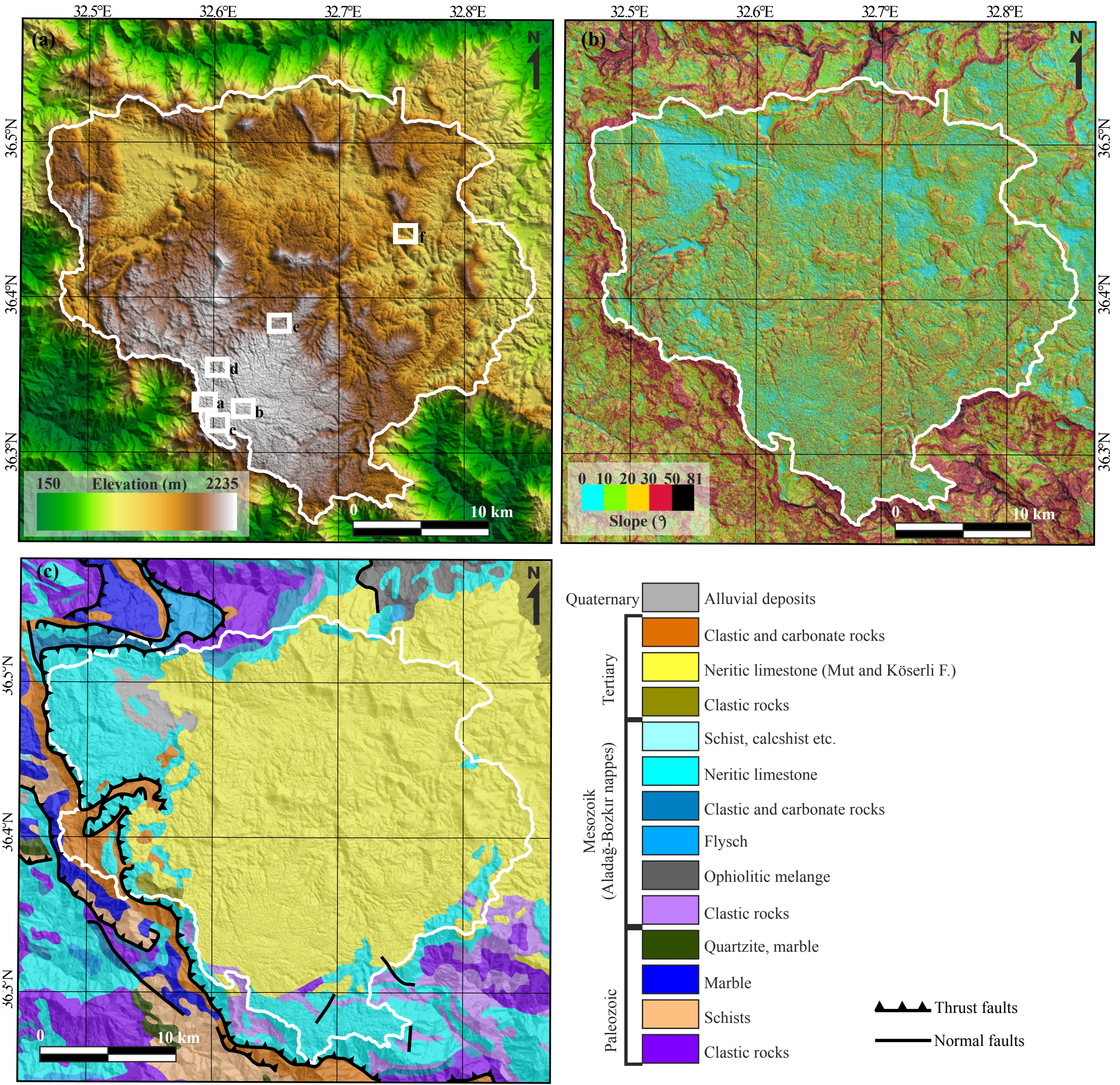


Figure 2. (a) Digital elevation, (b) slope, and (c) lithology maps of the study area (white line shows study area, lithology map adapted from Şenel, 2002a, 2002b. Frames a–f in 2a show location of photos in Figure 7).

Cretaceous ophiolitic mélange. Aladağ and Bozkır nappes are locally covered with Tertiary (Miocene) shallow marine limestones (Ilgar & Nemec, 2005). Tertiary limestones in the Mut and Köselerli formations were deposited in the Mut-Ermenek Basin (Gedik et al., 1979). These formations unconformably overlie Mesozoic limestones. The Mut-Ermenek Basin formed as a result of an orogenic collapse in the extensional back-arc regime of the Cyprus Arc (Robertson, 2000). Despite rapid multiphase uplift of the Central Taurus Mountains, Late Miocene shallow marine sediments compose the primary depositional geometry on the plateau surface (Bassant et al., 2005; Figure 3) and comprise 73% of the study area.

Climatically, the study area is located in the transition zone between rainy and arid areas since the high southern part of the plateau forms a barrier to humid air mass advection from the Mediterranean (Kuzucuoğlu et al., 2019). While annual total precipitation increases to 1000 mm (Alanya Meteorological Station) to the west, it decreases to 350 mm (Mut Station) northeast of the study area (Figure 4a). Due

Figure 3. Nearly horizontal neritic limestones on the plateau surface (red arrows in b show scales).

to there being no meteorological station characterizing the climate of Taşeli Plateau, global gridded data was used for climatic evaluation of the study area. This dataset is spatially interpolated monthly climate data for global land areas at a very high spatial resolution (approximately 1 km; Fick and Hijmans, 2017). According to this data, the total annual precipitation amounts of the study area vary from 677 mm to 787 mm. The highest precipitation is observed in the polygonal karst area in the southern part (Figure 4a). The mean temperature on the plateau surface ranges from 6.2 °C to 11 °C, and the lowest temperatures are observed on the polygonal karst (Figure 4b). This indicates that the maximum precipitation and minimum temperatures are observed on the polygonal karst in the study area.

3. Materials and methods

Morphometric analysis of karst landforms is a useful tool for evaluation of karst areas (Jennings, 1975; Day, 1983; Bondesan et al., 1992; Bruno et al., 2008; Basso et al., 2013; Öztürk et al., 2017, 2018a; Verbovšek and Gabor, 2019). A hypothesis can be created for the evolution of karst systems by means of these morphometric analyses (Jeanpert et al., 2016; Öztürk et al., 2017). Doline morphometry in particular acts as a sensitive indicator of tectonic activity in a karst region and the orientation of the dolines' long axes provides important clues about structural systems (Day, 1983; Nazik, 1986; Öztürk et al., 2017, 2018a; Şimşet et al., 2019; Verbovšek and Gabor, 2019). Therefore, morphometric parameters of dolines are regularly applied to find links between doline properties and structures (Faivre and Reiffsteck, 2002; Florea, 2005; Öztürk et al., 2018a).

In this study, 1:25,000 scale topographic maps produced by the General Command of Mapping (Turkey) were used to determine the distribution of dolines and relict valleys on the Taşeli Plateau. The uppermost closed contour lines of dolines on these topographic maps (contour intervals are 10 m) were delineated as polygons in GIS (classical method) (Öztürk, 2018). The basic morphometric parameters (elevation, area, perimeter, long axis, short axis, elongation ratio, and circularity index) were calculated for each doline (Day, 1983; Denizman, 2003; Öztürk et al., 2017). The long axis (connecting the 2 farthest points) and short axis of dolines were drawn manually and the elongation ratios were calculated with the aid of polygons (Öztürk et al., 2018a). Elongation ratio is the ratio between the long and short axes of dolines (Bondesan et al., 1992). This ratio was used as an index of planimetric shape (Williams, 1972; Day, 1976). The orientation angles of all dolines were calculated as the azimuth of the long axis.

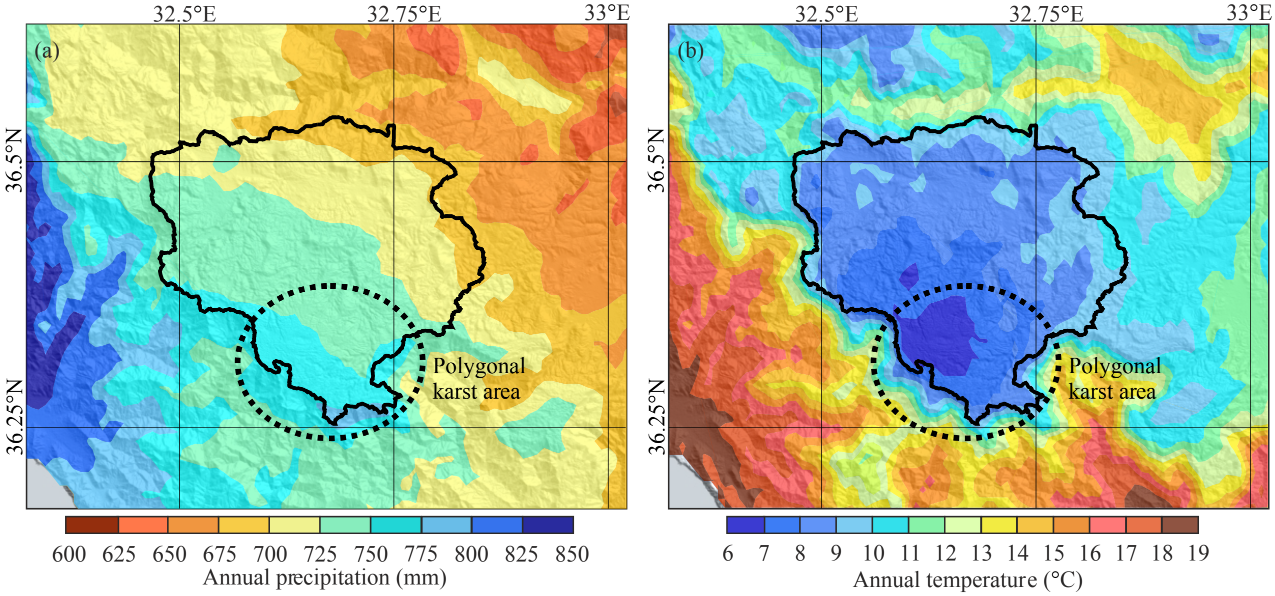


Figure 4. (a) Precipitation and (b) temperature maps of the study area (modified from Fick and Hijmans, 2017).

The drainage network on the plateau was divided into 2 categories as relict and nonrelict valleys. Relict valleys developed due to karst denudation of the primary valleys' morphology (Bočić et al., 2015). In other words, if the valleys have dolines in their thalwegs, they are classified as relict valleys. Relict valleys were determined in the present study by vectorization of theoretical thalwegs and their order was determined according to the Strahler method (Bočić et al., 2015). Then, the dolines located in relict valleys (Şener and Öztürk, 2019) and changes in their morphometric parameters were determined according to the Strahler order number.

The data sets were examined in 1 × 1 km (1 km^2) quadrats to calculate the spatial density of the dolines (dolines/km^2), relict valleys (km/km^2), and the relationship between them (Pahernik, 2012; Bočić et al., 2015). Size 25 km^2 (5 × 5 km) quadrats were used to create rose diagrams and to determine the superficial distribution of doline orientations. In addition, statistical values (minimum, 5%, 25%, medium, 75%, 95%, and maximum) were calculated to evaluate the statistical distribution of morphometric parameters (Öztürk et al., 2018b).

4. Results and discussion

4.1. Doline morphometry and paleodrainage pattern

A total of 14,284 dolines and 4391 relict valley segments were detected over a 694.4 km^2 area on the Taşeli Plateau from the examination of the 1/25,000 scale topographic maps. Dolines and relict valleys are found from 1500 m to 2300 m a.s.l. (Figure 5). They exhibit a more homogeneous distribution than other doline areas in the Taurus Mountains (Öztürk et al., 2017, 2018a). The mean elevation of the dolines is 2011 m and 50% and 90% of them are located between 1895–2140 m and 1760–2230 m, respectively (Table 1). Maximum doline density reaches 120 dolines/km^2 on the plateau surface. According to the classification of doline density by Faivre and Pahernik (2007), 37.7% of the study area is characterized by low density (<10 doline/km^2), 48.3% with moderate density (10–40 doline/km^2), 10.7% with high density (40–70 doline/km^2), and only 3.1% with very high density (>70 doline/km^2; Figure 6a). Interestingly, the greatest proportion of dolines is located between 1900 m and 2250 m a.s.l. (~73% of all dolines); this accords with the highest and southernmost part of the plateau (Figure 6a). In other words, the polygonal karst area corresponds to the highest, most rainy, and coldest region on the plateau surface (Figure 6a). In the southern part, gentle slopes, which have the highest doline density (Figures 7a–7d), suddenly switch to steep slopes without dolines (Figures 2b and 7a). This change is related to accelerated headward erosion by rivers as a result of tectonic uplift. The formation of these steep slopes is explained in section 4.2.

The paleodrainage pattern of the plateau is characterized by a multibasinal and dendritic pattern (Figure 6b). According to the flow direction of the paleorivers, almost all the plateau surface was drained from the south to the Ermenek River in the north by 3 major rivers that originate in the southern polygonal karst area. Interestingly, runoff from the plateau surface to the south hardly ever occurs.

Relict valleys cover the entire plateau surface as well as correlating with doline distribution (Figure 6c). For

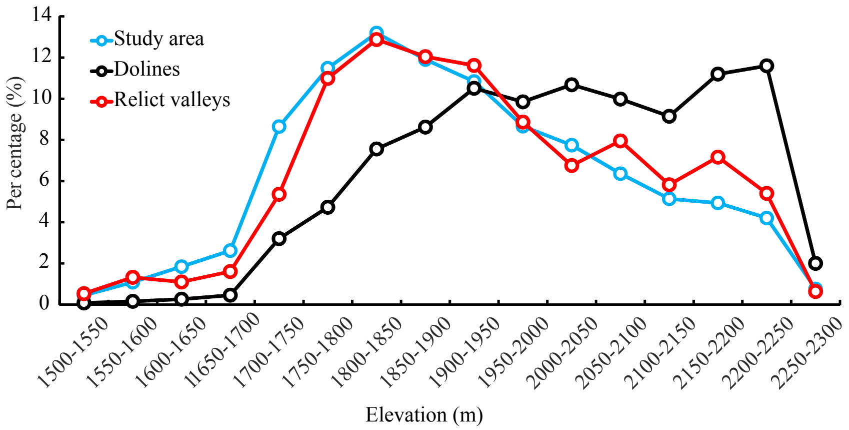


Figure 5. Change of elevation in the number of dolines, study area, and relict valleys.

Table 1. Values of morphometric parameters for all dolines.

	Elevation (m)	Area (m^2)	Perimeter	Short axis (m)	Long axis (m)	Elongation ratio	Circularity index
Min.	1520	37	23	7	8	1.00	1.01
5%	1760	187	51	14	17	1.03	1.05
25%	1895	381	73	20	26	1.16	1.09
Med.	2020	895.5	115	28	43	1.38	1.15
75%	2140	2567	203	47	76	1.78	1.31
95%	2230	12908	562	109	201	2.76	2.16
Max.	2300	705221	8889	1120	2187	10.30	16.09
Mean	2011	3979	198	42	69	1.58	1.33

example, 87% of the study area has a density of >2 km/km^2 relict valleys. The maximum relict valley density reaches 7 km/km^2 in the polygonal karst area. A positive correlation is observed between doline density and relict drainage density (r: 0.52; Figure 6d). A similar relationship is observed on other karst plateaus (Bočić et al., 2015; Öztürk et al., 2017, 2018a; Şener and Öztürk, 2019). These results indicate that the plateau surface was eroded by numerous paleorivers. Relict valley density is one of the most important factors for determining the spatial distribution of doline density (Figures 7d–7f).

Also, relict valleys affect the morphometric properties of dolines. According to the morphometric parameters of dolines located inside relict valleys (or relict valley dolines), the dimensions and values of the morphometric parameters of dolines increase in parallel with the stream order number (Figure 8). There are strong positive correlations between Strahler order numbers of relict valley and quartiles of morphometric parameters of dolines (Table 2). These correlations show that while the smallest and most circular dolines were found in 1st order relict valleys, the largest and most complex-shaped dolines (>3 circularity and 2.5 elongation ratio) were found in 5th and 6th order relict valleys (Figure 8). This tells us that the spatial distribution of the elongation ratio and circularity index is in accordance with Strahler order numbers ≥3 (Figures 9a and 9b).

Tectonic structure, especially joint density and orientation, exerts a strong effect on the development, density, orientation, and distribution of dolines on the gentle slopes of high karst plateaus (Orndorff et al., 2000; Jemcov et al., 2001; Faivre and Pahernik, 2007). Doline orientation is of great importance while researching the tectonic and geomorphologic evolution of karst regions (Nazik, 1986; Mihljević, 1994; Öztürk et al., 2017; Menezes et al., 2020). For this purpose, the long axis orientation of dolines is used to indicate the direction of tectonic structures and provides important clues about fracture systems (Öztürk et al., 2017, 2018a). As shown in Figure 10a, the dominant direction of the dolines is NW–SE.

Rose diagrams, representing the distribution of doline orientation in equally-spaced parts of the study area,

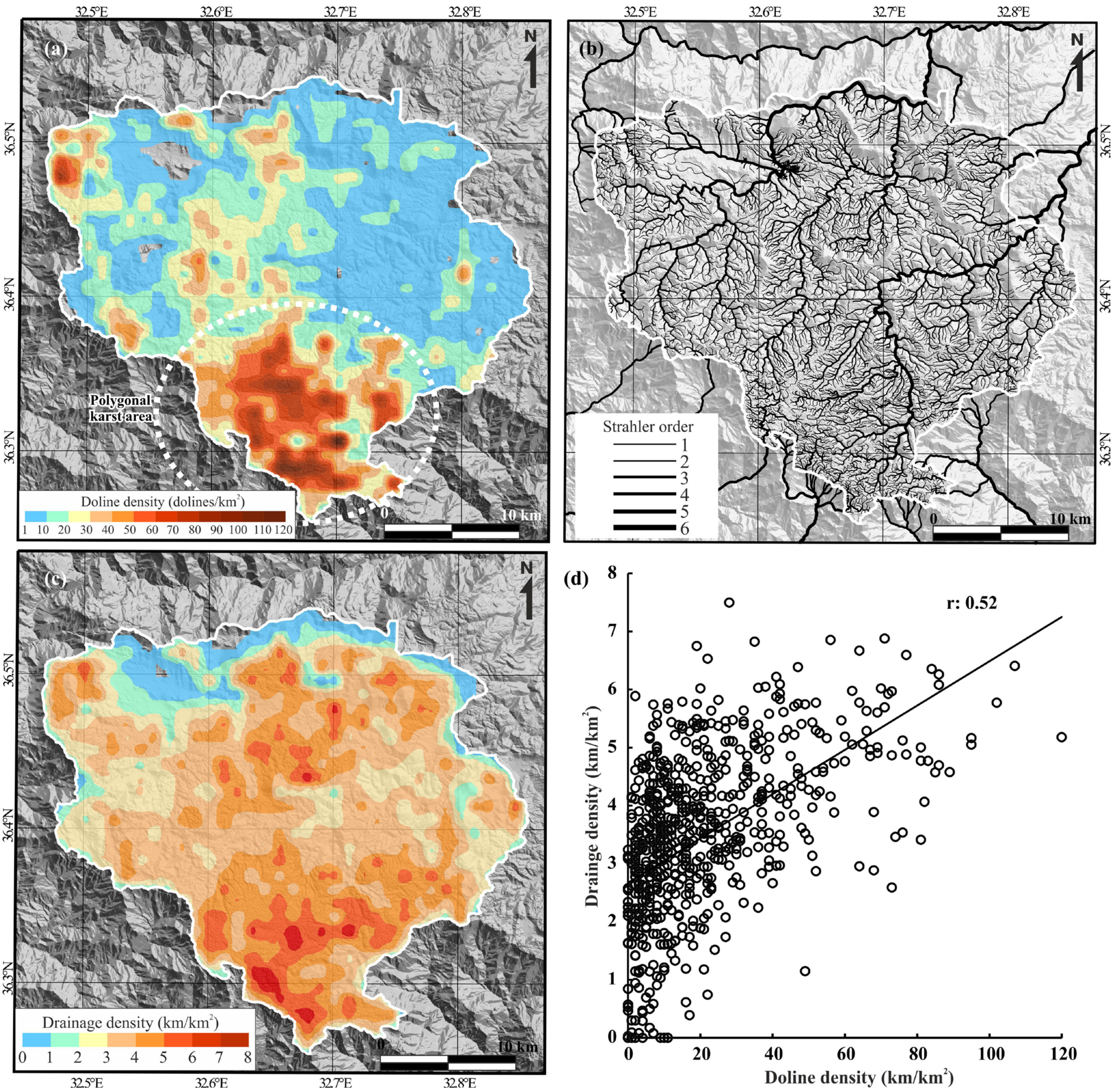


Figure 6. Spatial distribution of (a) doline density, (b) reconstructed relict drainage network shown by Strahler order, (c) relict drainage density (white line shows study area), and (d) correlation between relict drainage density and doline density.

provide evidence of the regional orientation of lineaments (Öztürk et al., 2017). Therefore, a total of 32 rose diagrams were created from the 25 km^2 (5 × 5 km) grids in order to illustrate the difference in distribution of the long axis orientations (Figure 10b). All gridded rose diagrams have a similar orientation and NW–SE dominates. This shows that there are no important structural differences causing a change of doline orientation on the plateau surface. Consequently, orientation in Figures 10a and 10b is in accordance with the tectonic evolution of the study area.

4.2. Geomorphological evolution

The Taurides were formed between the Tauride carbonate platform and Central Anatolian crystalline complex due to closure of the Neotethys Ocean in the era from the Eocene to Middle Miocene (Şengör and Yılmaz, 1981; Şaroğlu et al., 1983). The Bozkır and Aladağ nappes were emplaced in the north from Late Cretaceous to Middle-Late Eocene (Özgül, 1976). The Ecemiş and Beyşehir faults were formed as a result of N–S compression between Upper Eocene and Lower Oligocene (Akay and Uysal, 1988).

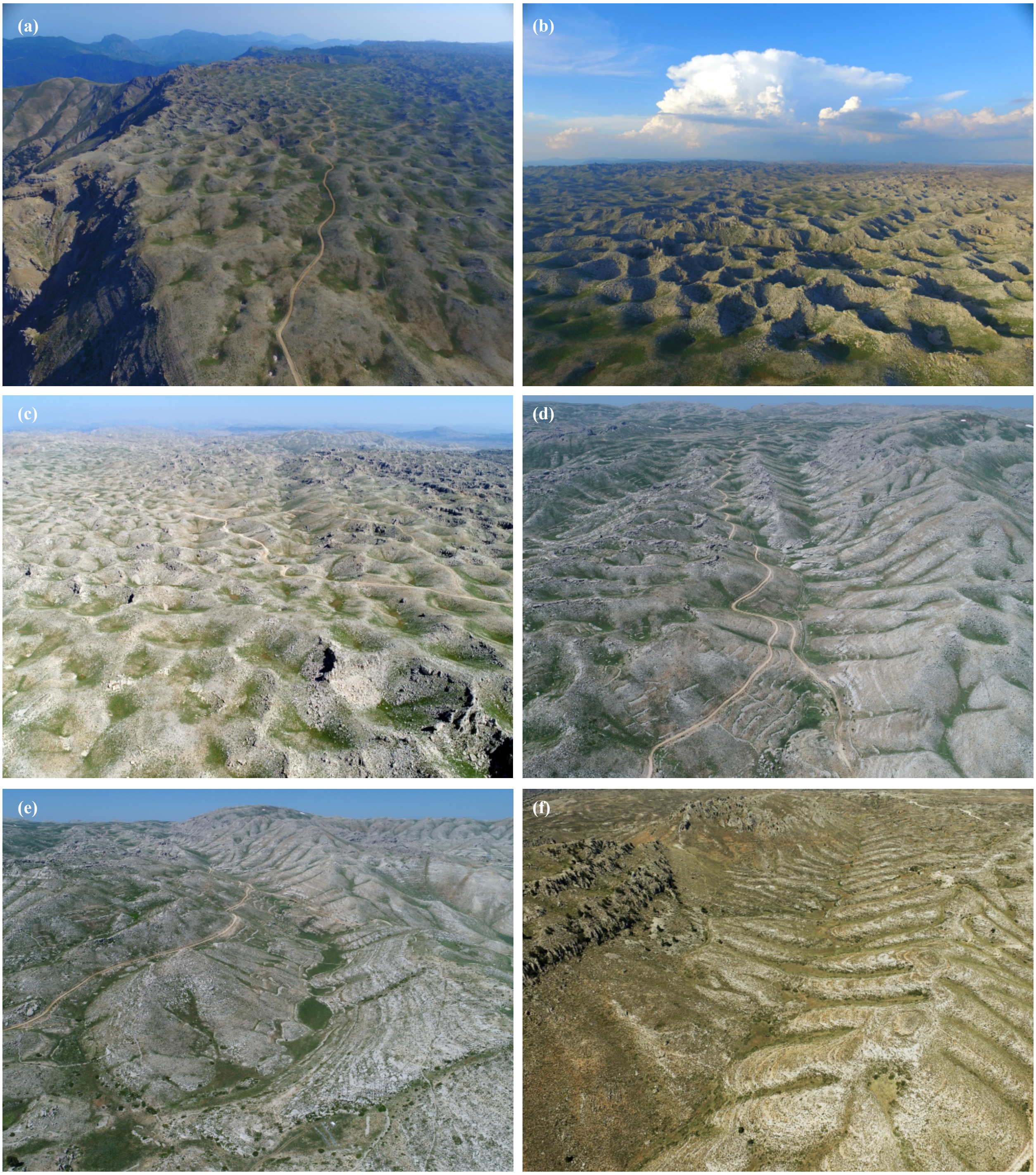


Figure 7. Aerial photos of the plateau surface (locations shown in Figure 2a).

Carbonates were deposited unconformably in a shallow marine environment over the Mesozoic limestones during the Early Miocene. Subsequently, the compressional neotectonic regime of the Isparta Angle (Figure 1a) commenced in Late Miocene (Şengör et al., 1985; Koçyiğit and Deveci, 2007).

The Isparta Angle is a reverse V-shaped morphotectonic structure (Koçyiğit and Deveci, 2007) that has played a critical role in the tectonic evolution of the Western and Central Taurus Mountains (Robertson et al., 2003). According to paleomagnetic studies, the eastern limb of the Isparta Angle underwent a clockwise rotation of

Table 2. Correlation coefficients between Strahler order numbers of relict valley and quartiles of each morphometric parameters of dolines.

	Area	Perimeter	Short axis	Long axis	Elongation ratio	Circularity
Lower quartiles	0.91	0.93	0.96	0.94	0.92	0.96
Median	0.94	0.96	0.97	0.97	0.74	0.97
Upper quartiles	0.96	0.95	0.98	0.97	0.93	0.94

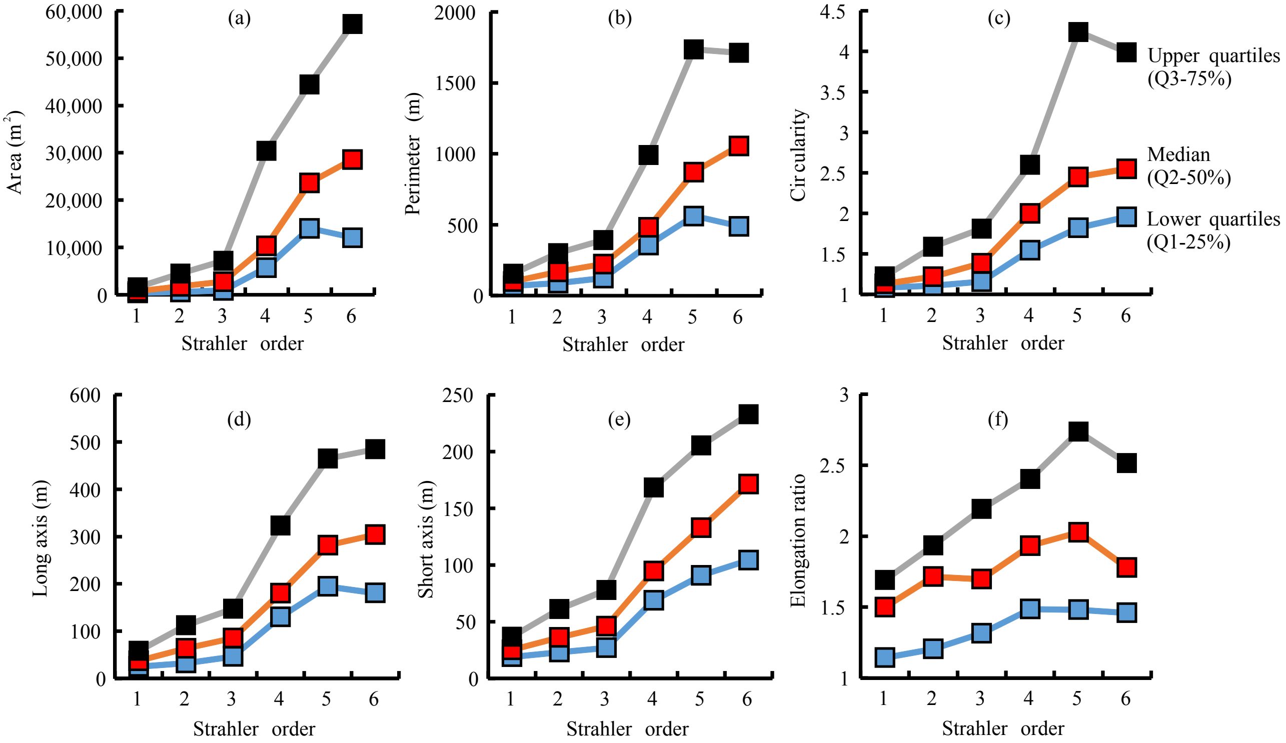


Figure 8. Change in morphometric parameters of relict valley dolines in relation to Strahler orders.

~40° since Late Eocene (Kissel et al., 1993). This rotation created fault and joint systems running in a predominantly NW–SE direction in the study area. A slab break-off likely occurred first beneath Eastern Anatolia in Mid-to-Late Miocene. Alternatively, the break-off near Cyprus occurred in Late Pliocene to Early Pleistocene in association with the collision of the Eratosthenes Seamount (Schildgen et al., 2014). Hence, the extensional neotectonic period in the Isparta Angle began in Late Pliocene (Koçyiğit and Deveci, 2007). The Late Pliocene–Quaternary period mainly corresponds to a time of extension in the Taurus Mountains (Robertson et al., 2003).

Rapid uplift, which started with the extension of the Taurus Mountains, occurred after Early Pleistocene (Öğretmen et al., 2018). This extension in the Taurus Mountains led to extensional fractures at the highest plateau surfaces. As a result, limestone platforms were carved by deep canyons and caves during the Pliocene and Pleistocene (Bakalowicz, 2015). While this multiphase uplift was occurring, Late Miocene shallow marine sediments preserved the primary depositional geometry of the plateau surface (Bassant et al., 2005; Figure 3). Although the region has been subject to various tectonic regimes, the extensional uplift phase has continued up to the present (Schildgen et al., 2012). In particular, uplift and extensions during Pleistocene triggered a process whereby the surface drainage turned into underground drainage. Surface karstification, relict valleys, and dolines developed as a result of these extension processes.

As well as tectonic uplift, the sea level and climate had an important effect on karstification. Notably, the ~1.5 km drawdown of the Mediterranean Sea during the Messinian Salinity Crisis (Krijgsman et al., 1999) and Quaternary sea-level changes (Öğretmen et al., 2018)

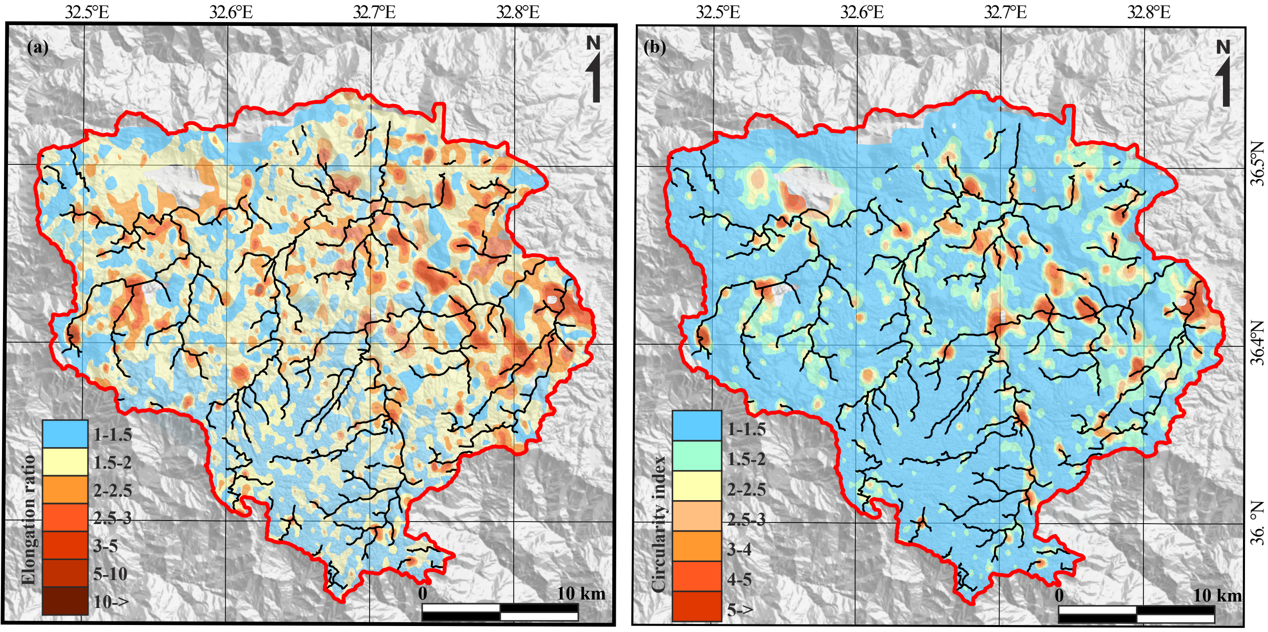


Figure 9. (a) Spatial distribution of elongation ratio and (b) circularity index of all dolines. (Black lines show relict valleys having ≥3 Strahler order number).

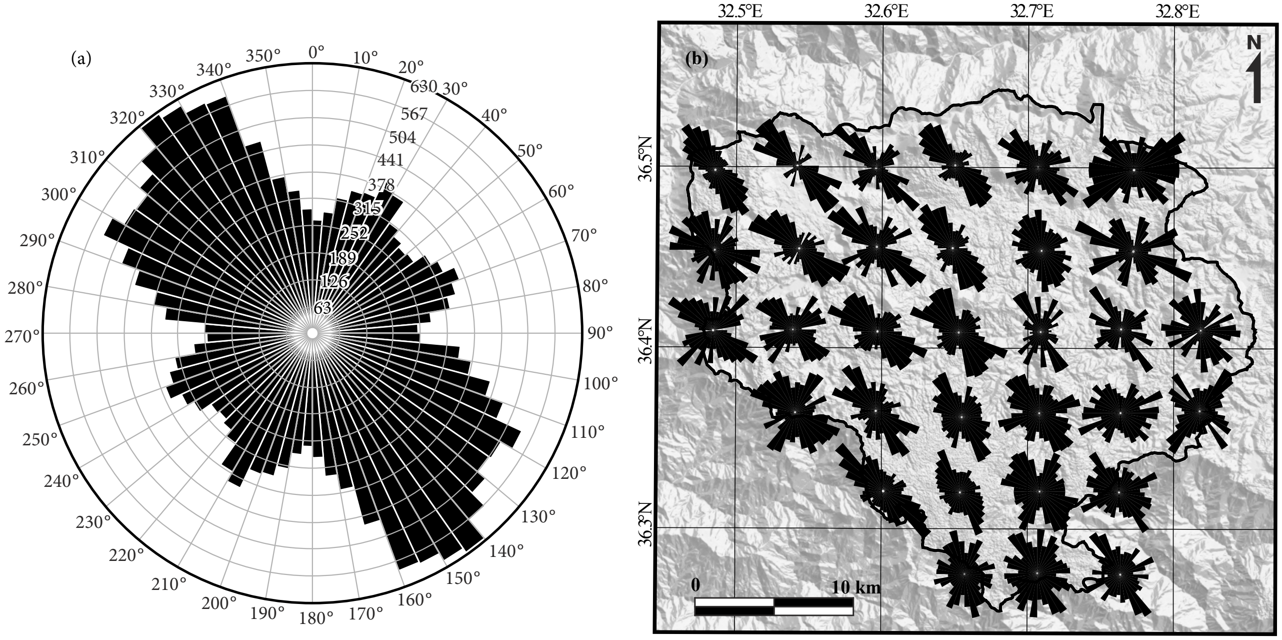
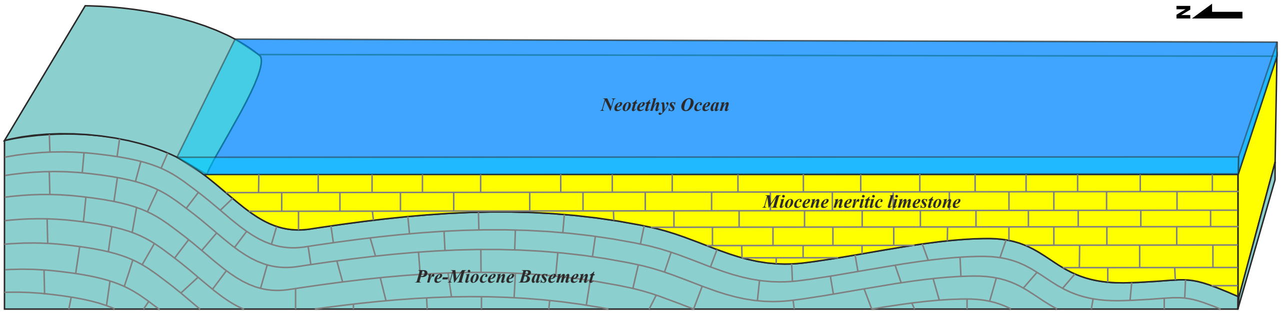


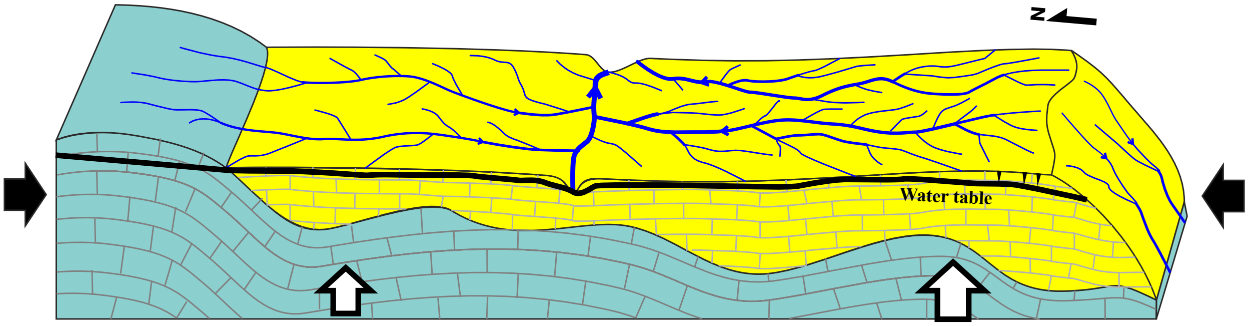
Figure 10. (a) Rose diagrams for long axes of all dolines and (b) within 25 km^2 grids.

altered the base level of karstification (Klimchouk et al., 2006). Climatic characteristics of the Taurus region also changed due to tectonic uplift (Meijers et al., 2018). The southern part of the Taşeli Plateau formed a barrier to humid air mass advection from the Mediterranean (Kuzucuoğlu et al., 2019).

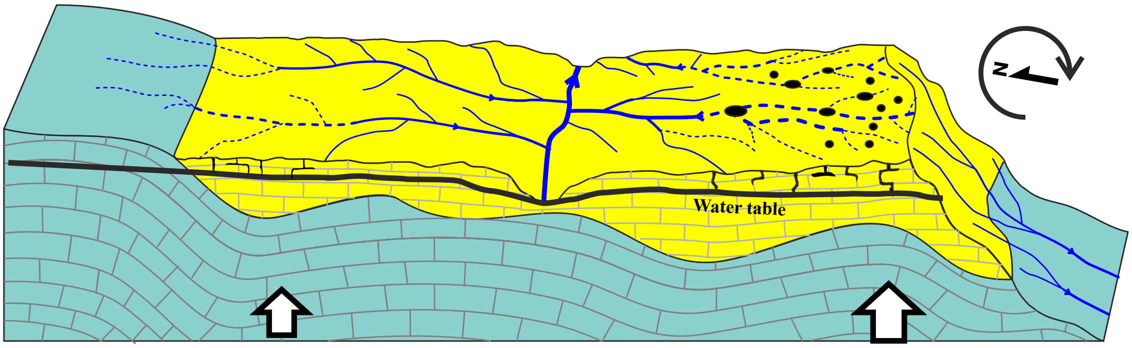
To summarize the above, the fluvio-karstic development of the study area took place in 5 stages. (1) Firstly (sedimentation stage), neritic carbonates were deposited in a shallow marine environment during the Early Miocene (Figure 11a). (2) Secondly (emersion phase), these carbonates started to uplift with the



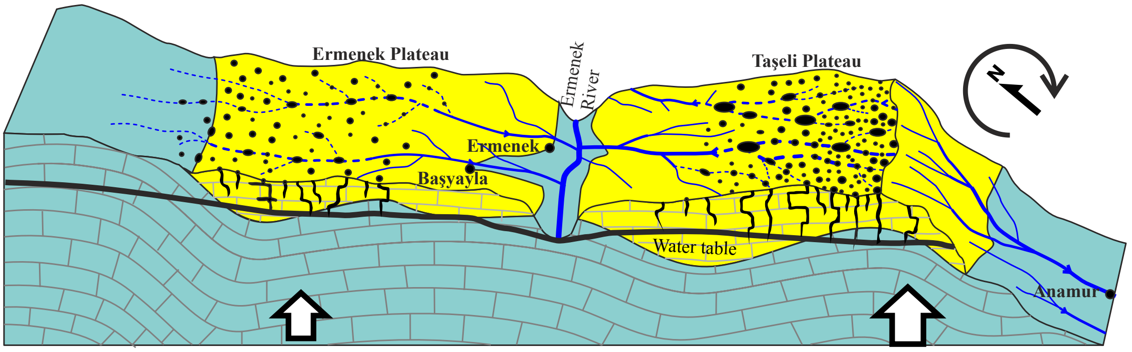
(a) Early Miocene (Sedimentation)



(b) Late Miocene (Compression + uplift = emersion + drainage network)



(c) Pliocene-Early Pleistocene
(Uplift + extension + rotation = dry valley + karstification + headward erosion)



(d) Late Pleistocene (Uplift + extension + changed climate = intense karstification + headward erosion)

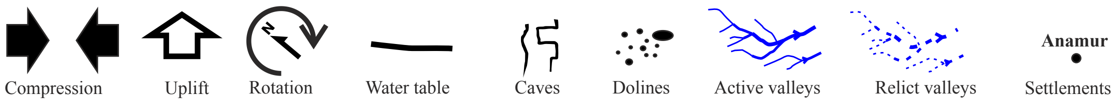


Figure 11. Fluvio-karstic development stages of the study area.

compressional neotectonic regime of the Isparta Angle in Late Miocene; the drainage network also began to develop during this period (Figure 11b). (3) Thirdly (rotation phase), fault and joint systems were created by the ~40° clockwise rotation of the eastern limb of the Isparta Angle and crack systems developed in a NW–SE direction in the same stage. (4) Fourthly (rapid uplift and extensional phase), the study area rapidly uplifted due to slab break-off from Late Pliocene to Early Pleistocene. This rapid uplift caused the climate to change; temperatures decreased while precipitation increased. Furthermore, a dry valley pattern formed on the surface in parallel with underground karstification and the headward erosion of rivers accelerated, especially on the southern part of the plateau during this stage (Figure 11c). (5) In the last stage (surface karstification), the plateau surface was covered by polygonal karst and dry valleys turned into relict valleys due to extensional cracks during Pleistocene. Headward erosion also caused the formation of steep slopes and destroyed dolines in the southern part, from Pleistocene to present (Figure 11d).

5. Conclusion

The Taşeli plateau, the largest and the most important karst plateau in the Central Taurus Mountains, is densely covered by solution dolines and relict valley networks. A total of 14,284 dolines were detected on the plateau surface in an area of 694 km^2 and the maximum doline density is 120 dolines/km^2. Paleodrainage networks on the plateau surface are characterized by a multibasinal and dendritic pattern. Almost all the plateau surface is drained by 3 major rivers into the Ermenek River. The dimensional values of the doline parameters increase with the Strahler order number of the relict valleys. The development of these landforms is closely related to the tectonic and climatic evolution of the area. Morphogenetic evolution of the plateau surface consists of 5 stages: (1) sedimentation, (2) emersion, (3) rotation, (4) rapid uplift and extension, and (5) karstification or "reorganization of drainage by karstification". The last stage especially is very important in terms of karstification. At this stage, the plateau surface was covered by solution dolines and relict valleys due to extensional cracks during Pleistocene. In conclusion, tectonic phases (multiuplifts and rotation), fluvial development, and climatic change are the main factors explaining the present morphology of the Taşeli Plateau.

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