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Karst in Turkish Thrace: Compatibility between Geological History and Karst Type

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Abstract: Geographically, Thrace is a region located in southeastern Europe within the territories of Greece, Bulgaria and Turkey. In Turkish Thrace, karst occurs extensively in Eocene limestones, although some limited karst occurs in marble of the metamorphic series of Palaeozoic age. The karstification base is shallow to very shallow and most of the dolines and poljes have been captured by surface streams. Subsurface drainage has been changed to surface drainage in most parts of the region. Caves and cave relicts are concentrated mainly at three different altitudes, and almost all caves are horizontal or sub-horizontal. With these characteristics, Turkish Thrace hosts a distinct type of karst compared to that of other regions of Turkey, and particularly to the well-developed active Taurus karst.

In this paper, the author discusses the major controls on karst evolution and consequently the occurrence of the present karst type with special emphasis on the geological history of the region. Tectonically, the area is weakly active, implying that a relatively steady continental uplift together with sea-level changes provided the source of the energy gradient required for karstification. The erosion base is controlled mainly by impermeable units. From the geological history of the region, it is concluded that no abrupt change in the energy gradient occurred due to continental uplift. However, fluctuation in sea level due to climate change has caused more sudden changes, particularly in erosion-base levels. This suggests that, in contrast to other karst provinces of Turkey, the impact of climate change has been more pronounced in this region. Reconstruction of karst evolution on the basis of the geological history of the region suggests that karstification processes have evolved without major interruption during the neotectonic period. Thus, the evolutionary character of the Thracian karst has produced relict karst with relatively local karst aquifers compared to those existing in the Taurus karst region. Morphological and hydrological aspects of the area indicate that karstification is in a cessation phase.

Key Words: cave, karst, morphology, neotectonic, palaeogeography, Thrace, Turkey

Trakya Bölgesi Karstı: Jeolojik Tarihçe ile Karst Tipi Uyumu

Özet: Kendine özgü morfolojik ve hidrojeolojik özellikler gösteren karstik alanlar Türkiye'nin üçtebirini oluşturan karbonatlı kayaçların yayılım gösterdiği bölgelerde gözlenmektedir. Trakya, karstlaşma açısından Toros kuşağı veya İç Anadolu bölgesine göre önemli bir bölge sayılmamakla birlikte özellikle karstlaşmada etkili olan faktörler ve karstlaşma evrimini yansıtan karst türü açısından ilginç örnekler barındırmaktadır. Litoloji türü, kalınlığı ve yapısal unsurlar karstlaşmanın gelişiminde etkili olan önemli faktörler olmakla birlikte karstlaşma daha çok kimyasal erozyonu sağlayan yeraltısuyu akışını denetleyen enerji gradyanının kaynağına ve karstlaşma derinliğini denetleyen erozyon tabanının türü ve derinliğine bağlıdır. Tektonik hareketler nedeniyle yükselme ve/veya iklim değişikliklerine bağlı olarak meydana gelen deniz seviyesi değişimleri, karstlaşmayı denetleyen enerji gradyanının iki temel kaynağını oluşturur. Karstlaşma derinliğini denetleyen erozyon (karstlaşma) tabanını, karbonatlı kayaçların altında bulunan geçirimsiz birimler veya karstlaşmayı sağlayan suyun enerjisini yitirdiği deniz, göl, akarsu seviyeleri belirler. Bu bağlamda, tektonik gelişim ile iklimsel değişimler, karstlaşmayı denetleyen temel süreçler olarak ortaya çıkmaktadır. Öte yandan, karstlaşma, karbonatlı kayaçların atmosferle temas halinde olmayı gerektirir. Diğer bir deyişle, karstlaşma, karbonatlı kayacın hidrolojik çevrim içinde bulunmasını gerektirmektedir. Bu durum, karstlaşmanın büyük oranda karasal ve erozyonun hakim olduğu bir fasiyesi tanımlar. Karbonatlı kayaçların deniz veya göl suları ile örtülmesi sonucunda karstlaşma genellikle kesintiye uğrar. Denizel veya gölsel çökelimler sonucunda düşük geçirgenliğe sahip kırıntılılar altında kalan karbonatlı kayaçların yeniden karstlaşma süreçleri etkisi altında kalmaları, öncelikle yeniden hidrolojik çevrim içinde yeralabilmelerine bağlıdır. Bu süreç ise çoğunlukla uzun jeolojik dönemler gerektirdiğinden, bu tür fasiyes değişimleri karstlaşmanın kesintiye uğramasına neden olur. Kesintiye uğramış karstik birim, karasallaşma ve erozyon fasiyesine geçme sonucunda yeniden faaliyete geçebilmektedir. Görüldüğü gibi, tektonik evrimin yanı sıra paleocoğrafik gelişim de karstlaşmanın jeolojik dönemler boyunca gelişimini belirleyen bir etken olarak tanımlanabilir. Bu durumda, karstlaşma evrimi ile tektonik evrim ve eşzamanlı paleocoğrafik gelişim arasında belirli bir uyumun söz konusu olabileceği ortaya çıkmaktadır.

Trakya bölgesinde, sınırlı alanlarda yüzeylenen Eosen yaşlı kireçtaşları ile Paleozoyik yaşlı metamorfik birimler içinde yer alan mermerlerde gelişen karstik yapıların yayılımı, yoğunluğu, morfolojisi ve hidrolojik işlevleri, önemli oranda, bölgenin özellikle Miyosen'den başlayarak etkisi altında kaldığı neotektonik evrim ve buna bağlı olarak ortaya çıkan paleocoğrafik gelişim ile açıklanabilmektedir. Trakya, neotektonik bölgelendirme açısından "*tektonik aktivitesi zayıf*" Kuzey Anadolu Bölgesi kapsamındadır. Deniz seviyesinden yüksekliği nedeniyle Miyosen dönemi başlarına kadar ileri derecede aşınma etkisi altında kalan Trakya bölgesinde yayılım gösteren ancak günümüzde sınırlı alanlarda kalıntıları gözlenen karbonatlı kayaçlar yaygın bir şekilde karstlaşmış olmalıdır. Bölgede karstlaşma ve erozyonun, bölgenin orta kesimleri ile sınırlı kalan ve Miyosen ve Pliyosen dönemlerinde sırasıyla denizel/lagüner ve gölsel/akarsu fasiyeslerin etkisiyle meydana gelen örtülme dışında, kesintiye uğramadan günümüze kadar sürmüş olabileceği görülmektedir. Neotektonik hareketlerin zayıf olması, kıtasal yükselme veya alçalmalarla birlikte iklimsel değişimlere bağlı olarak deniz seviyesinde meydana gelen alçalma ve yükselmeler de enerji gradyanına önemli ölçüde katkıda bulunmuş olmalıdır. Bölgenin sürekli erozyon fasiyesi etkisi altında kalmış olması nedeniyle, karbonatlı kayaçlar incelmiş, altta yer alan geçirimsiz birimler sığlaşmıştır. Sığlaşma nedeniyle karstlaşma derinliğinin geçirimsiz birimlerle denetlendiği anlaşılmaktadır. Nitekim, Trakya bölgesinde, Eosen yaşlı kireçtaşlarında gelişmiş olan dolin, uvala ve polyelerin önemli bir kısmının günümüzde yüzeysuları tarafından kapılmış olduğu ve kapılmak üzere olduğu gözlenmektedir. Bu durum, karstik alanların en ayırıcı özelliği olan yeraltı drenajının etkisini yitirerek yüzey drenajına geçişin göstergesidir. Benzer şekilde, bölgede bulunan mağaraların büyük bir çoğunluğunun yatay ve kuru olması, karstlaşmanın evrimini tamamlamak üzere olduğunu ortaya koymaktadır. Erozyon (karstlaşma) tabanının belirteci olarak sayılabilecek mağaraların üç farklı kotta yoğunlaşması ise, bölgede jeolojik dönemler boyunca en az üç farklı evrede, görece duraylı dönemlerin meydana gelmiş olduğu şeklinde değerlendirilebilir. Yapılan gözlemler ve değerlendirmeler, Trakya bölgesinde evrimini tamamlamak üzere olan karstlaşmanın neotektonik evrim ve paleocoğrafik gelişim anlamında jeolojik tarihçeyle koşut olarak geliştiğini göstermektedir.

Anahtar Sözcükler: mağara, karst, morfoloji, neotektonik, paleocoğrafya, Trakya, Türkiye

Introduction

Geographically, Turkish Thrace is a peninsula surrounded by the Black Sea to the north, the Marmara Sea to the south, and separated from Anatolia by two straits: the Dardanelles and the Bosphorus (Figure 1). It represents the European part of Turkey. The Thrace region exhibits geographical, geological, and tectonic characteristics distinct from other parts of Anatolia, or Asian Turkey.

The karst of Turkish Thrace is mainly limited to Eocene limestone, although a few caves are developed within marbles of the metamorphic basement. The features identified in the region point to a typical karst morphological setting, with dolines, uvalas, poljes, caves, etc. However, subsurface drainage apparently has been converted to surface drainage, and most of the surficial karst features – such as dolines and uvalas – have been captured by streams, particularly where the impermeable units beneath the limestone are shallow. Caves are generally horizontal and of the fossil-spring type. Compared to other regions of Turkey, the karst of the Thrace region is distinctive with respect to its morphology and hydrology, which indicates a different evolutionary history from that which prevailed in other regions of Turkey. An attempt to explain the differences in karst of different regions of Turkey has been made by Ekmekçi (2003), who suggested that the type of karst in Turkey is closely related to the tectonic and coeval palaeogeographical development of the area. In the aforementioned paper, the Thrace region was included in the karst of the North Turkish Province, characterised by well-developed karst aquifers with a dominant effect of conduit flow but of moderate to low yield. The Thrace region is described as a tectonically weakly active province wherein the energy gradient required for karst development was controlled mainly by the sea-level changes of the Black Sea, and uplift was limited to relatively less E–W shortening, which caused a much lower rate of erosion compared to other areas of Turkey. According to that author, due to the palaeogeographic development, no significant interruption of karst processes has been recorded in the province and, therefore, the karst is of evolutionary character and is near its final stage.

This paper sets forth a hypothesis regarding the relationship between type and evolution of karst and the geological history, with special emphasis on tectonic and palaeogeographical development. In doing so, although the author utilises morphological and hydrological characteristics in describing the present karst, the details of individual karstic features are not given in light of the aim and scope of the paper. Instead, statistical analysis was used in order to gain a broad understanding of the phenomenon throughout the region.

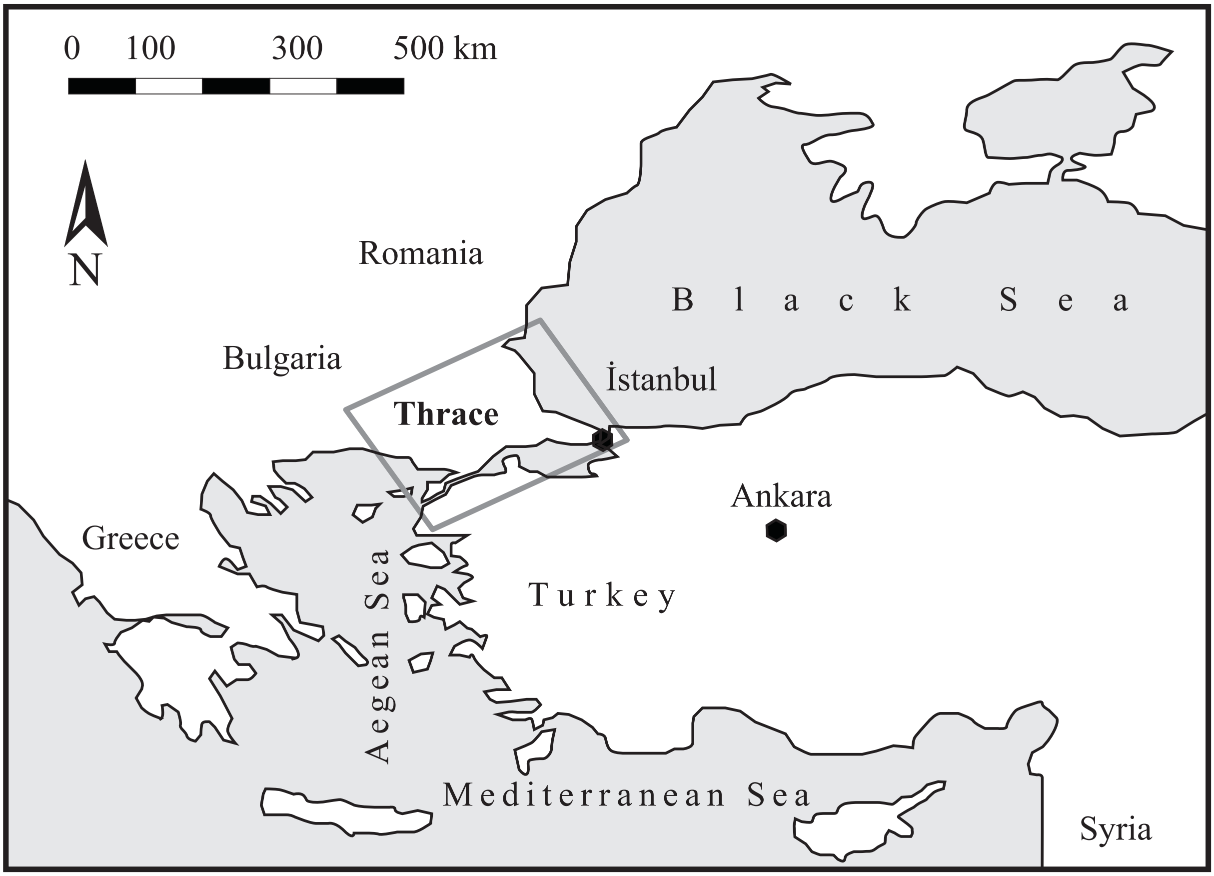

Figure 1. Location map of Turkish Thrace.

Factors Controlling Turkish Karst

Turkey is among the Mediterranean countries that have classical large-scale karst owing to extensive carbonate rock exposures which crop out over about one-third of the country. Most of the carbonate rock masses are karstified to some degree. Turkish karst, defined by type, size and hydrologic function, shows a great variety over the country. Geographical differences do not account for the variation in the type of karst because different types of karst can be observed within the same geographical region wherein climatic and geological settings are the same. Ekmekçi (2003) suggested that geological history, with special emphasis on tectonic evolution and coeval palaeogeographical development, is much more influential in the development, extension and variation of karst types in Turkey than geological setting (in terms of lithostratigraphy and structural arrangement).

Among the great variety of factors controlling karst phenomenon, lithology, tectonics, source of energy gradient, erosion base and climate can be regarded as the major ones. Mineralogical composition, thickness and mode of existence (autochthonous or allochthonous) are considered in defining the lithology as a factor controlling karstification. Tectonics should be regarded as a factor controlling karst in two different ways: it controls (a) the heterogeneity when it indicates 'lineaments' and (b) the energy gradient when it is taken as 'displacement in the crust'. Both are essential for initiation and development of karst phenomena. However, the former should be regarded as an important factor controlling the karstification *processes* rather than the *type* of karst. Discussion of karst processes is beyond of the scope of this paper. As far as the *type* is concerned, tectonics should be considered in terms of evolution and the coeval palaeogeographic development. A thorough explanation of the occurrence and distribution of karst types in Turkey requires a detailed study of the history of the source of energy gradient; it implicitly includes the tectonic evolution which controls continental uplift and periodic fluctuation in eustatic sea level due to climatic changes. Continental uplift, eustatic sea level changes, interior lake-level fluctuations and river incision are the major sources of energy gradient that initiates and enhances karst development. In addition to the energy gradient, the erosion base controls the depth of karstification and is controlled by either (i) sea level, interior lake level, major river beds or (ii) an underlying impermeable unit. Apparently, the climatic effect on karstification is not regarded as the humidity and temperature which control the corrosion processes but, more notably, the climate should mean cyclical change between glacial-interglacial periods which control both the energy gradient and erosion-base level.

When all factors described above are considered, Turkish karst can be defined as of two main types: (a) evolutionary karst, and (b) rejuvenated (or reactivated) karst. The evolutionary-karst type implies that karstification processes have been active without interruption since the exposure of carbonate rocks to atmospheric conditions and comprises a great variety of sub-types – from juvenile to relict, depending on which controlling factor dominated the process in a certain area. Rejuvenated karst, on the other hand, forms by reactivation of inactive (covered) karst systems, either by uplift and/or a drastic decline of the erosion base. This type of karst is distinguished by the development of younger karst features within older but interrupted karst (palaeokarst). In most cases in Turkey, interruption is due to choking by clastic deposits of limnic and/or fluviatile facies.

The rate of changes primarily in energy gradient, climatic conditions and erosion base, on the other hand, must have controlled temporal variation in the intensity of karstification. Hence, the change of the dominant factor in the course of geological time is not less important than the factor itself. The type of the erosion base, for instance, may be the ruling factor in a certain period, while it is lithological position in another. Therefore, it can be postulated that the evolution of karst is more directly related to *change* in dominant factor during geological time rather than to the dominant factor(s) itself.

This paper is an attempt to explain the karst type and its evolution in Turkish Thrace following the approach outlined above.

Geological Outline of Turkish Thrace

Geologically, Turkish Thrace can be subdivided into two parts; namely, the Strandja Massif and the Thrace Basin. The Strandja Massif is characterised by units belonging to pre-Tertiary time, while the Thrace Basin is a Tertiary sedimentary basin developed upon metamorphic and crystalline units of the Strandja Massif during the Middle Eocene. A simplified geological map of the Thrace peninsula is given in Figure 2. However, because the karstified rocks of the Thrace region are of pre-Neogene age, and the Neogene sequences are mostly composed of non-karstic lithologies, it is convenient to define the geological units as two major groups; namely, pre-Neogene and Neogene units.

Pre-Neogene carbonate units are characterised by marbles of the Strandja Massif and Eocene limestone that unconformably overlies the Strandja units. The Strandja Massif consists of crystalline basement and a metasedimentary cover. In their detailed stratigraphic and structural description of the Massif, Okay *et al.* (2001) reported that the Late Variscan crystalline basement is composed of Triassic and older granites and felsic gneisses. This basement is unconformably overlain by a transgressive Lower Mesozoic metasedimentary sequence. The basement is characterised by granite and gneiss of Lower Palaeozoic age. Metagranite, gneiss and amphibole schist are the common rocks that comprise the core of the massif. The core of the massif extends in a NW–SE direction and is covered by metamorphic rocks of Triassic–Jurassic age. This metamorphic cover begins with Triassic schist with transition to marbles of Middle–Late Jurassic age at the top of the sequence. According to Okay *et al.* (2001) the metasedimenatry sequence comprises metaconglomerates and metasandstones at its base that are overlain by carbonate rocks (marble) in a synclinal structure. Thus, the marbles are exposed only over a limited area in the northern part of the region where the core of the syncline is partly preserved. Extensive outcrops are present in the NNW part of the area, close to the Turkish-Bulgarian border. Cretaceous rocks are quite scarce in the region.

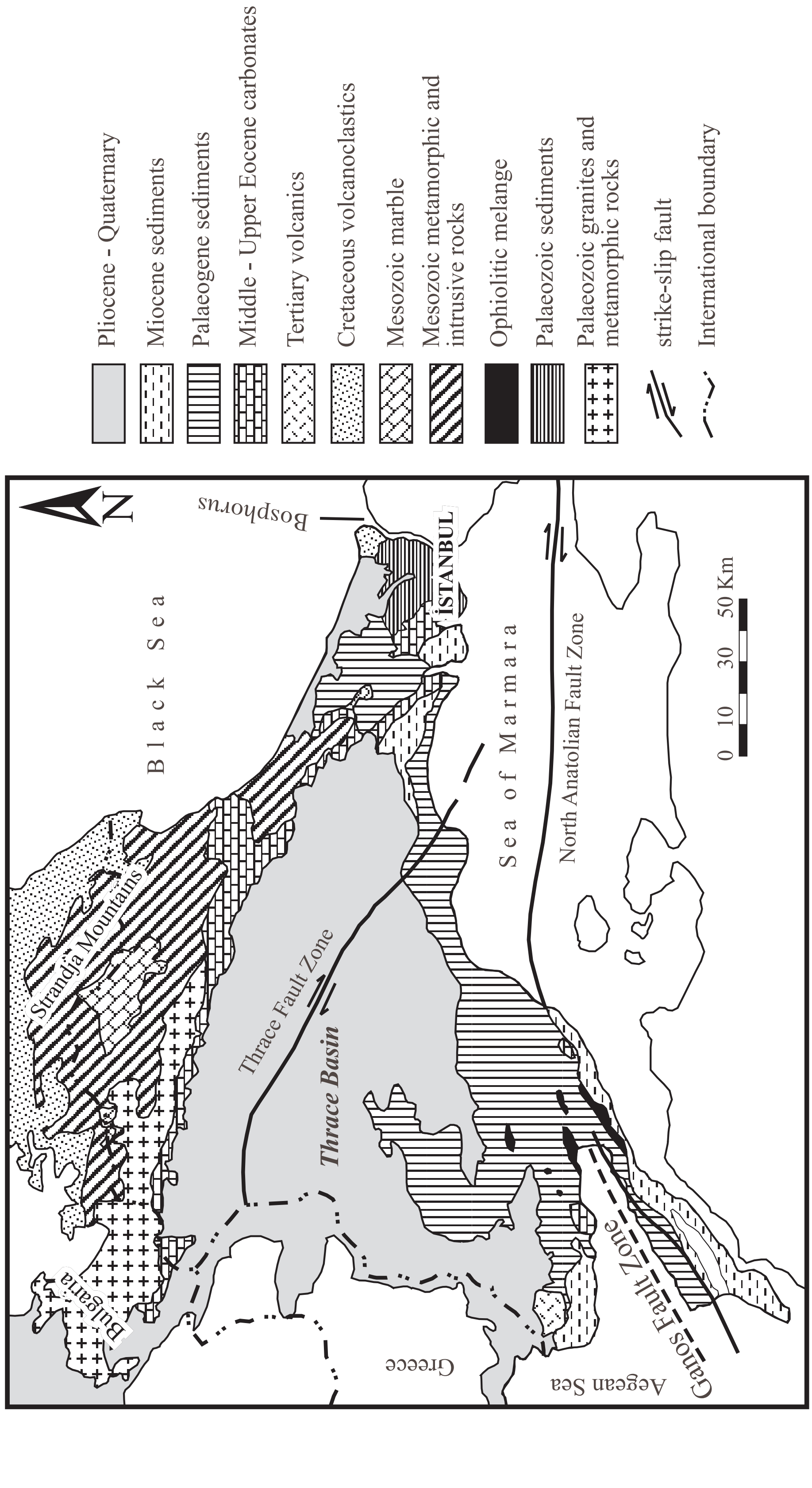

Figure 2. Geological map of Turkish Thrace (modified and simplified from Turgut & Eseller 2000).

In the Middle Eocene, both carbonates and clastics were deposited on shelf areas of the Tertiary basin. Eocene rocks comprise conglomerate-sandstone and an alternation of sandstone and marl at its base. This alternation is overlain by Middle–Upper Eocene reefal limestone (Doust & Arıkan 1974) that extends as a narrow strip along the southern flank of the Strandja Massif in the north (Figure 2). The thickness of this limestone may reach 150 m in relation to the palaeotopographic surface. The reefal limestone grades into oolitic limestone intercalated with marls of Late Eocene–Early Oligocene age. This series ends with sandstone intercalated with Upper Oligocene–Lower Miocene claystone and siltstones.

In spite of exhibiting many different facies associations as a consequence of relatively rapid environmental change, the Neogene sequences comprise non-carbonate lithologies – mainly clastics of fluviatile, lacustrine and rarely marine origin. In light of the aim of the paper, details of the Neogene sequences are not given here, but can be found in Doust & Arıkan (1974), Keskin (1974), Kasar (1987), Perinçek (1987), Görür & Okay (1996), Sakınç *et al.* (1999) and Turgut & Eseller (2000).

Structurally, the Thrace region is characterised primarily by two major fault zones: the Thrace Fault Zone (TFZ), first identified by Perinçek (1987); and the Ganos Fault Zone (GFZ) (Yaltırak 1996). These two major fault zones were active during the Neogene, affected the depositional environments and, therefore, controlled the palaeogeographical development of the region to a great extent. According to Perinçek (1991), the TFZ originally developed during the Middle–Late Miocene around Kırklareli, in the northern part of the region, and migrated to the south creating two other fault zones there (Figure 2). This fault functioned as a strike-slip fault until the early Late Miocene and became a normal fault in the Late Miocene (Sakınç *et al.* 1999). The GFZ, on the other hand, existed since the Eocene but was inactive until late Middle Miocene when it was reactivated as a strike-slip fault (Yaltırak 1996; Yaltırak *et al.*1998; Sakınç *et al.* 1999).

Present Status of Karstic Features in Turkish Thrace

Surface Features

Dolines and sinkholes are the most common karstic features noted in the study area covered by Eocene limestone. Uvalas exist where dolines are near each other. Caves also exist in the area but their existence is evaluated separately below. Structural analyses have demonstrated that karstic features are located at intersections of major faults (Ekmekçi & Günay 1997; Ekmekçi 1998). In contrast with the active-juvenile karst observed in other regions of Turkey, particularly the Taurus region, the carbonate rocks surrounding the karst depressions in Thrace region are fairly low and the depressions are either flooded permanently or have been captured by surface streams. In the study area, the drainage pattern suggests that surface drainage is more pronounced than subsurface drainage in the Eocene limestones. Several closed depressions, such as dolines and uvalas, are flooded even during dry seasons, some of which are today perennial shallow lakes and swamps. It is worth noting that many of these dolines have already been captured or are about to be captured by a surface stream, demonstrating that surface drainage is becoming active in the basin. This landscape implies that the erosion (karstification) base level is marked by impermeable metamorphic units that are near the surface. The results of a geophysical survey conducted by UKAM (1996) at and around the flooded and dry dolines corroborates this deduction, in so far as the survey revealed that the metamorphic units are as shallow as 10 meters below the surface. Dolines that have already been captured or are about to be captured by a stream are located where the base level is relatively shallow and the thickness of the carbonate rock does not exceed 50 meters.

Caves of Turkish Thrace

A total of 25 caves of Turkish Thrace were explored and surveyed within the framework of an inventory study by Nazik *et al.* (1998). Three of these caves developed within marbles (Figure 3). Most of the caves are of the fossil-spring type, almost horizontal and ideal water-table caves (Table 1). According to the four-state model of Ford & Williams (1989), the caves explored in Turkish Thrace hint at State-4, characterised by high fissure frequency or high porosity and, therefore, low resistance to flow, low gradient, low piezometric surface, and water table conditions (Ford & Williams 1989, p. 262, *figure 7.14*).

The caves are concentrated at elevations between 150 and 200 meters (Figure 4). The two longest caves explored were 2720 and 1650 m in length with altitudes

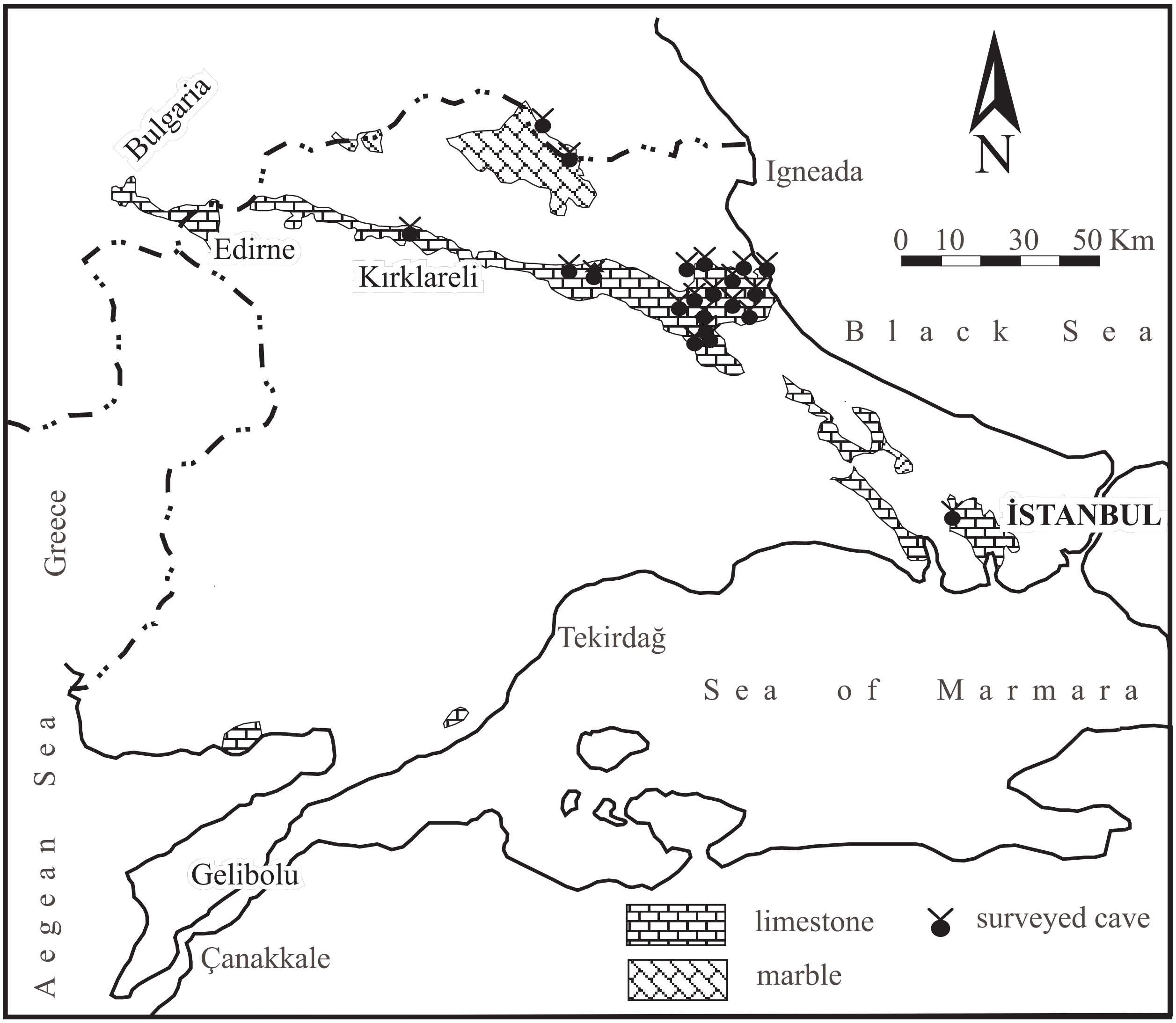

Figure 3. Distribution of carbonate rocks and caves in Turkish Thrace (from Nazik *et al.* 1998).

of 345 m and 70 m, respectively. The longest caves are preserved in marble most probably because of its higher resistance to erosion. The stratigraphic position of the marble perhaps also preserved the marble-hosted from faster destruction. The length of the other caves range between 10 m and 570 m (Figure 5). Figure 6 depicts cave depth relative to the cave entrances. Only six of the caves ascend from the entrance, but no more than 20 m. The descending caves, on the other hand, do not go down more than 40 m from the entrance.

The frequency distribution of the caves with respect to altitude suggests that there are more than two levels where caves are concentrated. The Bhattacharya (1967) method was used to separate the frequency distributions, assuming that the caves are normally distributed at each level. This analysis revealed that the frequency distribution of the caves comprises three statistically different cohorts of caves (Figure 7). The calculated mean altitudes and the separation indices of the cohorts distinguished by the Bhattacharya Method are given in Table 2. By this method, it appears possible to deduce things about the phenomenon using some measured properties of the features. It is not our interest to know the details of every individual feature but, instead, we

Table 1. Inventory of caves explored in Turkish Thrace (from Nazik *et al.* 1998).

No	Cave	Location		Elevation (m a.s.l)	Total Length (m)	Depth (± m)	Type	Hydrology
		Town	Village					
1	Çiftlik	Kofçaz	Çağlayı	2	183	-22	H	F
2	Koyunbaba	Merkez	Koyunbaba	40	532	13, -15	H	F
3	Dupnisa	Demirköy	Sarpdere	45	2720	+61	H	A
4	Bektaşın Sayalar	Vize	Hamidye	70	32	-11.5	SH	F
5	Kurudere	Vize	Hamidye	70	70	+7.5	H	F
6	Bostanlıktarla	Vize	Kışlacık	115	98	-12.5	H	I
7	Kovantaşı	Vize	Kışlacık	125	270	-25	H	F
8	Kızılağaç	Vize	Kızılağaç	130	205	-27.5	H	I
9	Yenesu	Vize	Balkaya	140	1620	+18	H	A
10	Selimin	Vize	Evrenli	150	140	-10	H	F
11	Domuzdere	Vize	Balkaya	160	300	-2	H	F
12	Pestilin	Vize	Evrenli	162	105	-0.2	H	F
13	Soğucak	Vize	Soğucak	170	40	0	H	F
14	Kocaçayırlar	Vize	Sergen	170	53	-5	H	F
15	Bağlar	Vize	Sergen	170	318	+10, -12	SH	F
16	Koca-I	Vize	Pazarlı	180	24	+2	H	F
17	Alişahin	Vize	Aksicim	185	130	+2	H	A
18	Deniz	Vize	Kıyıköy	240	33	+0.5	H	A
19	Kıyıköy	Vize	Kıyıköy	280	365	+10.5	H	F
20	Kaptanın	Vize	Kıyıköy	295	39	-9.5	SH	F
21	Ceneviz	Saray	Bahçeköy	305	570	+6,-26	H	I
22	Saklısu	Saray	Bahçeköy	345	75	-34	H	F
23	Horataşı	Saray	Ayvacık	370	65	-3	H	F
24	Küçük Kalaslı	Saray	Ayvacık	435	17	0	H	F
25	Koca-II	Saray	Kavacık	470	47	+8.5, -2	H	F

H: Horizontal SH: Subhorizontal F: Fossil A: Active I: Intermittent

would like to group specific features using some characteristic values (statistics).

Characterization of Karst Type in Turkish Thrace

Karstification is well developed within two carbonate units in the region: marble and limestone. Jurassic marble is thick- to thin-bedded, white-grey in colour and saccharoidal in texture; locally it is intensely fractured. The total thickness of this unit is restricted to the surrounding metamorphic units of the Strandja Massif and varies widely. The Eocene limestones are white to greyish-white, and contain abundant macrofossils and microfossils. Furthermore, they are intercalated with sandy-clayey layers, and are medium- to thin-bedded with a gentle dip. The present thickness of the unit ranges from 0 to 150 m, depending on the palaeotopography of the basement.

The metamorphic basement also played an important role as the erosion (karstification) base. Impermeable units such as claystone-siltsone layers beneath the Eocene limestone also limit depth of karstification. In a limited area around Kıyıköy where Eocene limestone is exposed by the sea, the Black Sea itself marked the erosion base. Almost all springs currently discharge from the contact between the limestone and the underlying impermeable units. In the coastal area, however, some spring caves are found to discharge at sea level. Although not observed during field studies, it is likely that there are some shallow submarine discharges where the limestone meets the sea, and the underlying impermeable units are deep.

Morphological and hydrological characteristics of karst defined in Turkish Thrace reveal a relict stage of “evolutionary type” karst. This type of karst implies that the karstification processes have been active continuously

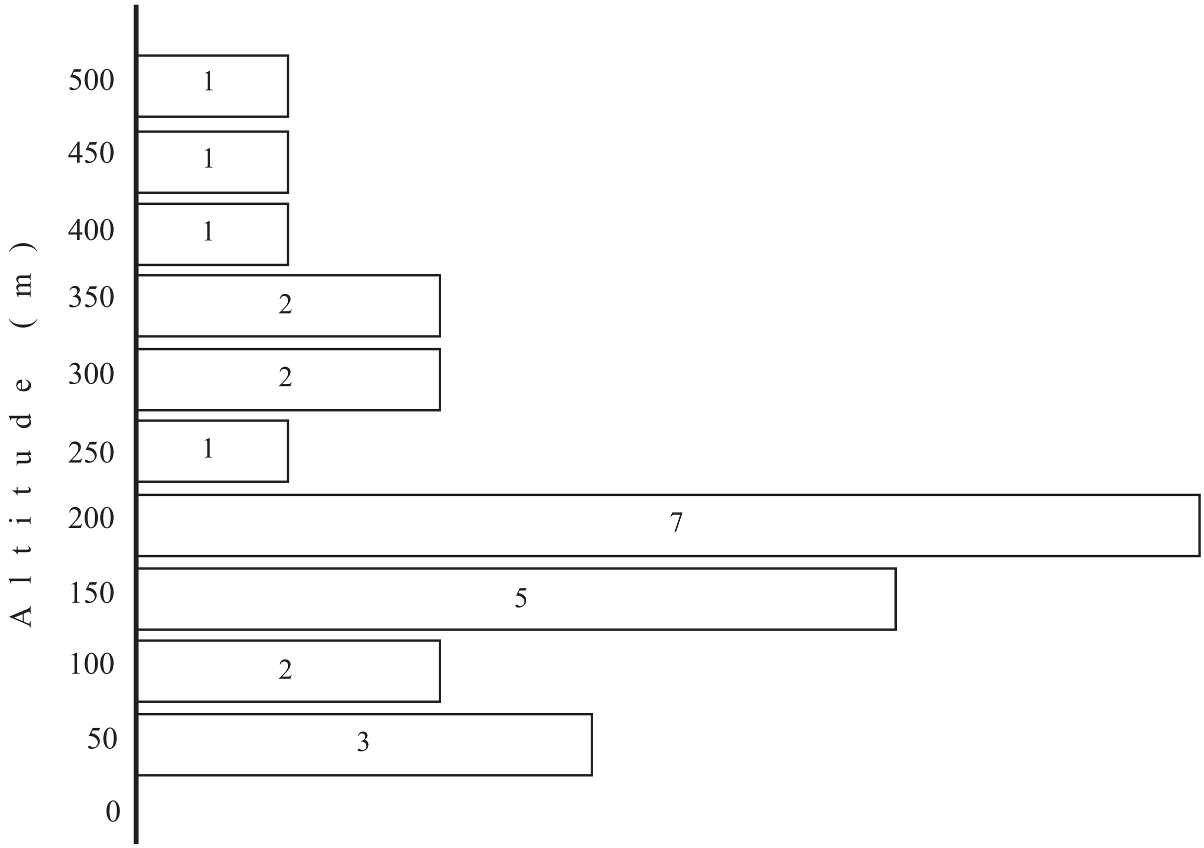

Figure 4. Frequency of caves with respect to altitude. Numbers in bars indicate numbers of caves.

since the carbonate rocks were exposed to erosional conditions, although dissolution processes may have diminished for short periods during improper climatic conditions. A shallow erosion base, marked by impermeable metamorphic basement, suggests a steady, probably slow uplift of the continent, such that carbonate rocks were also eroded by karst processes down to the impermeable units. However, the concentration of cave entrances (or more correctly, karstic spring outlets) at different elevations should be interpreted as due to relatively rapid uplifts in the region, through which the karstification base was adjusted to a lower elevation. The sum of the evidence suggests that karstification has almost ceased, the underground cavities are clogged, and the impermeable layer beneath karst is quite shallow. The present aspects of the karst in the Eocene rocks reflects a typical "final stage" of karst appearance in so far as the subsurface drainage is almost completely transformed into surface drainage, following Cvijic (1918) who originally defined the stages of karst evolution (Ford & Williams 1989, p. 453, *figure 9.43*).

Compatibility of Karst Evolution with Geological History in Thrace Region

Because karstification is a phenomenon driven by various physical and chemical processes that all require an energy gradient regardless of lithological properties, it is essential to define the source and the history of the energy gradient that governs these processes in order to understand well the evolution of karst in a particular region. As outlined above, the energy gradient may be created in two major ways: through continental uplift or sea-level drop. The former is controlled by tectonics while the latter is typically a consequence of climatic change. In addition to energy gradient, palaeogeography controls the continuity of karstification processes. Generally speaking, erosional facies favour karst processes while

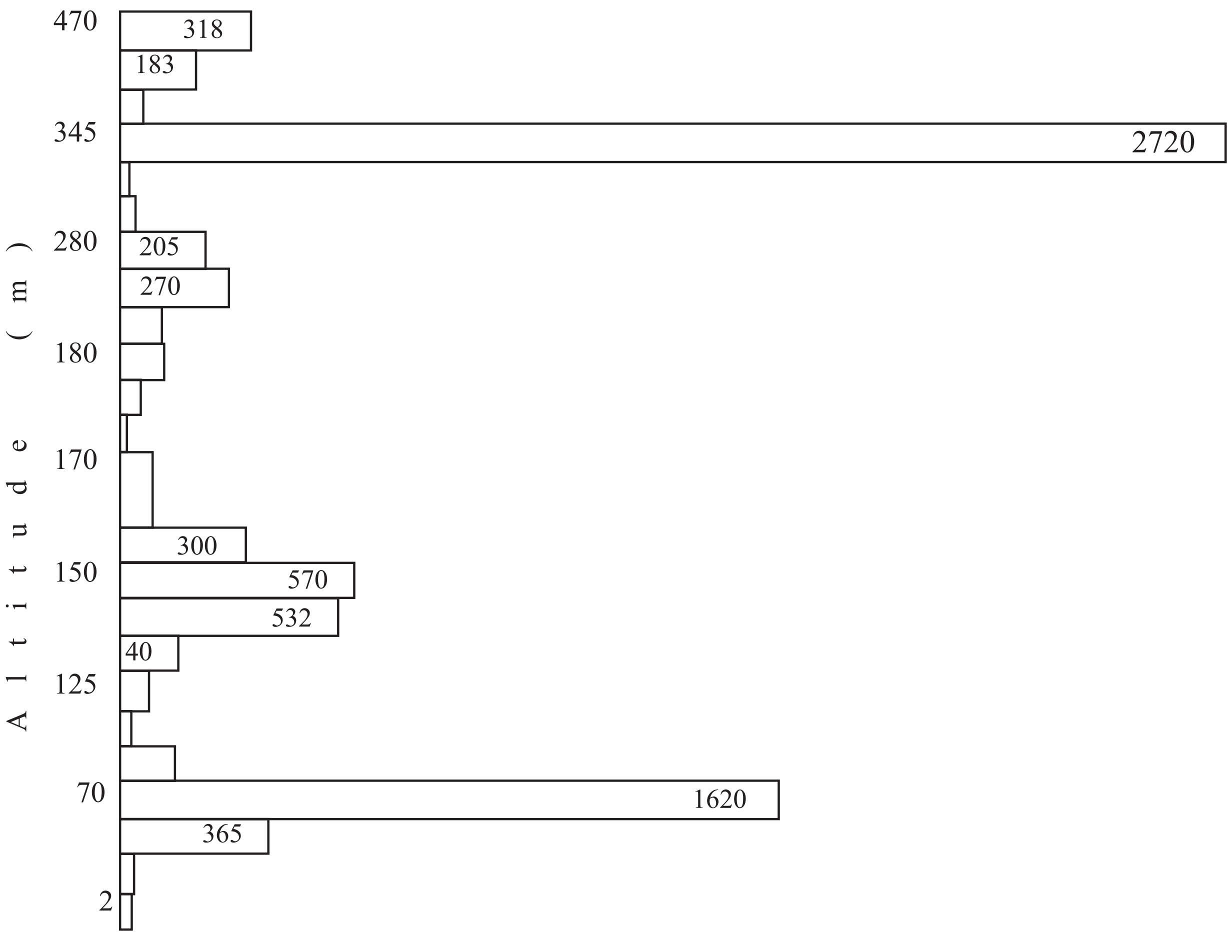

Figure 5. Length-altitude relation of caves in the study area. Numbers in bars indicate length of caves.

depositional facies interrupt karstification (Klimchouk & Ford 2000). Regeneration of an energy gradient, on the other hand, may re-activate an interrupted karst, producing a multiphase or rejuvenile karst type (Ford & Williams 1989; Lowe 2000). Karstification and the evolution of karst seem to be closely related to the tectonic and palaeogeographical development of the area of interest. Compatibility of karst evolution with the geological history – in terms of neotectonic evolution – and the coeval palaeogeographical development is discussed below for the Thrace region.

For Turkish Thrace, palaeogeographic development – corresponding to the tectonic evolution – was rather static compared to other regions of Turkey (Şengör *et al.* 1985; Şaroğlu 1994; Görür 1998; Bozkurt 2001; Bozkurt & Mittwede 2001). Information on the tectonic evolution and palaeogeographic development of Thrace during the Neogene given herein is based mainly upon the detailed study of Sakınç *et al.* (1999).

During the Early–Middle Miocene period, the Thrace peninsula was almost completely under terrestrial conditions except for some small areas in the west that were invaded by marine waters. The Strandja mountains in the north and the Koru-Ganos mountains in the south were the major erosional areas supplying clastic materials to the deposional basin in the southwest. The central part, covered by Oligo–Miocene lithologies, was the surface exposed to weathering (Figure 8). In so far as the Oligo–Miocene sequence of the basement was affected by intense erosion (Sakınç *et al.* 1999), it is possible to postulate that karstification of the Eocene limestones may have begun where it was exposed to weathering conditions. On the other hand, no karst processes should be expected in areas that were submerged by marine

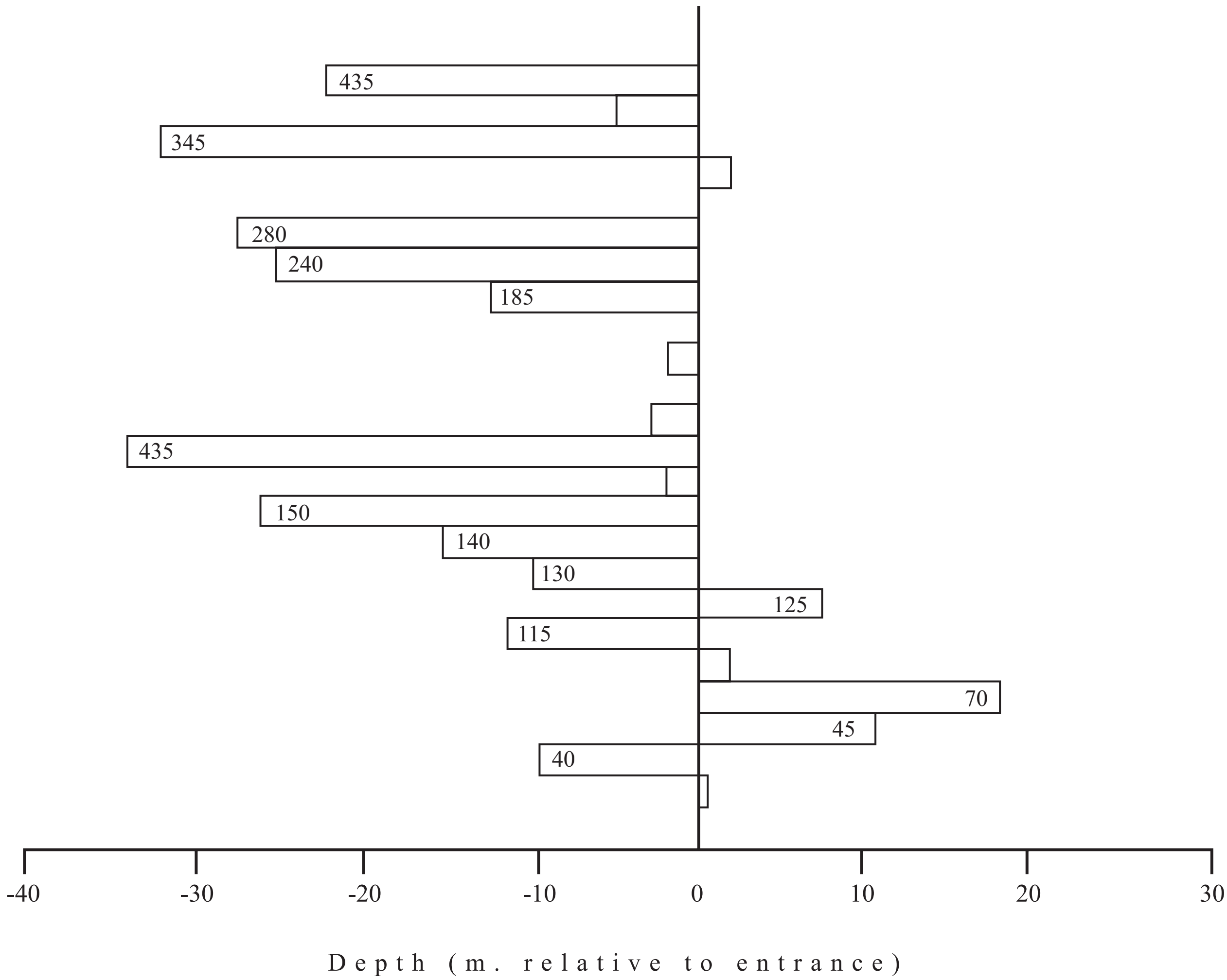

Figure 6. Depth-altitude relation of caves in the study area. Numbers in bars indicate altitude of caves.

waters in the northwestern and western parts of the region.

During the late Middle–early Late Miocene period, the Strandja mountains were uplifted and tilted to the north as a consequence of the development of the strike-slip Thrace Fault Zone. Similarly, the southern part of the Thrace peninsula was an erosional area mainly controlled by the Ganos Fault Zone. Large amounts of erosional material derived from the erosional areas in the north and the south were transported to the lowland basin situated in the central Thrace region (Figure 9). The material transported by rivers subsequently covered the Oligo–Miocene surface which was exposed to weathering in the central part of the region. The continued uplift of the Strandja mountains resulted in regression of the Black Sea (Paratethys). As the Black Sea shoreline retreated from land, new areas were exposed to weathering and karstification along the northern edge of the Strandja mountains. This situation changed the marine facies in some areas to erosional facies, modified the erosion base to a lower level, and enhanced the energy gradient thereby initiating and/or accelerating karst processes. Karstification must have continued (and even been promoted in other areas) under erosional conditions during this period.

Although extension of erosional areas did not change significantly during the Late Miocene, the deposional basin changed from fluviatile-limnic to marine facies as a result of Mediterranean ingression (Figure 10). This ingression also affected the Black Sea coastline. A rise in

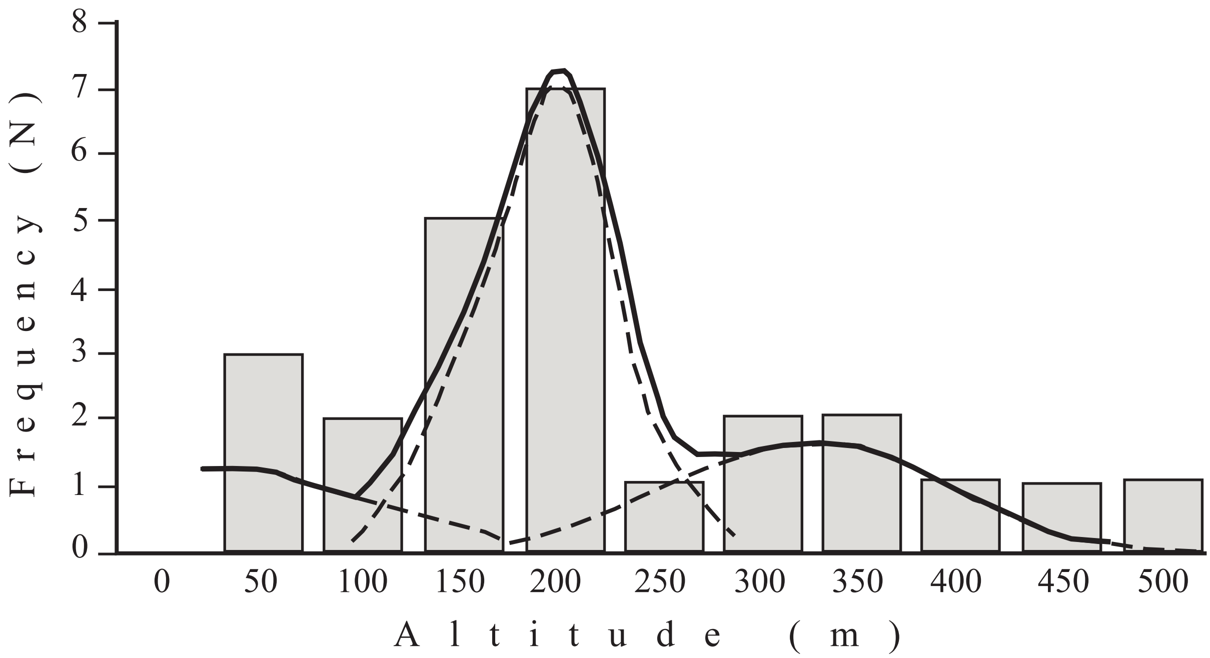

Figure 7. Separation analysis for frequency distribution of caves.

Table 2. Results of separation analysis. Separation is statistically meaningful for SI ≥ 2.

Cohort	Mean Altitude (m)	Separation Index (SI)
1	25	Not available
2	185	2.90
3	343	4.99

the level of the Black Sea associated with Mediterranean ingression was accompanied by inland migration of the shoreline of the Black Sea. Accordingly, the northern edge of the Strandja mountains changed from erosional facies to marine and/or beach-dune facies. Thus, we can speculate that karstification ceased along the northern edge of the Strandja-İstanbul line during the Late Miocene because the limestones were inundated by marine waters. Sakınç *et al.* (1999) reported that this palaeogeographical scenario did not change significantly during the Messinian when the Mediterranean Sea was dessicated. As a result, the erosion base was modified back to a higher level and the energy gradient was decreased between the erosional surface and the erosion base. This situation must have diminished karstification processes in the region during the Late Miocene.

Because of uplift related to intense activity of the Ganos Fault Zone (Yaltırak 1995), an erosional regime dominated in the Thrace peninsula during the Pliocene period (Sakınç *et al.* 1999). The Strandja mountains represented the erosional area – including the small areas invaded by marine water during the Middle–Late Miocene. Erosional areas in the southern part enlarged greatly during the Pliocene causing considerable contraction of the central fluvial basin (Figure 11). Based on the palaeogeographic setting, it can be suggested that the carbonate rocks exposed in the northern part of the Strandja mountains continued to karstify. On the other hand, erosion of the Middle–Late Miocene overburden covered the Eocene limestone in eastern Thrace (İstanbul peninsula) must have been started in Pliocene period. The karst in this area must have been reactivated and enhanced after its exhumation.

Based on the foregoing summary of the geological history, the concentration of caves at certain levels can be interpreted to mark erosion-base levels at different periods of karstification. Statistical analysis has revealed that at least three cohorts of cave concentration can be differentiated. Concentration of caves at different altitudes may be considered an indication of karstification base levels in different phases of neotectonic evolution.

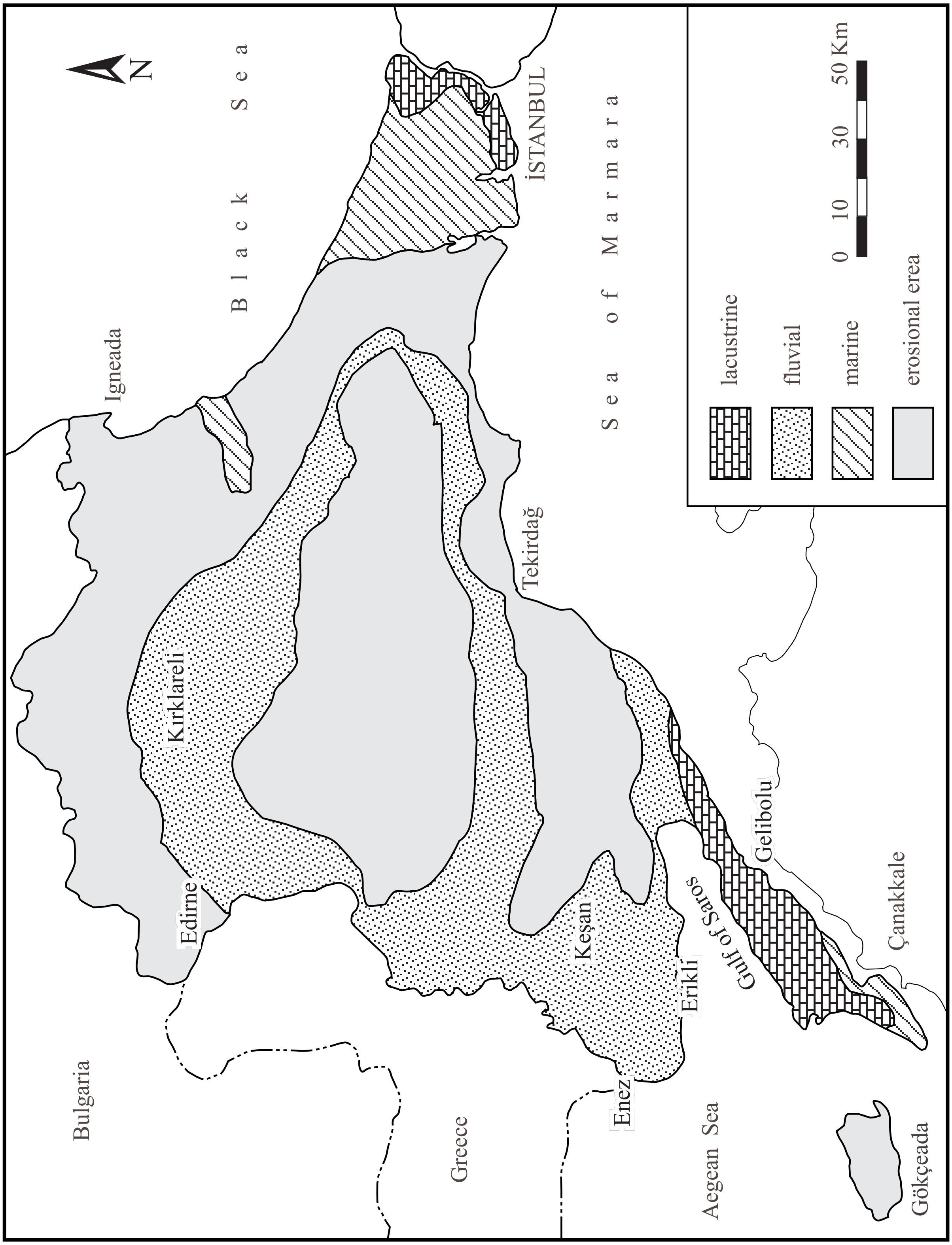

Figure 8. Palaeogeographical facies of Turkish Thrace during the early Middle Miocene (simplified from Sakınç *et al.* 1999).

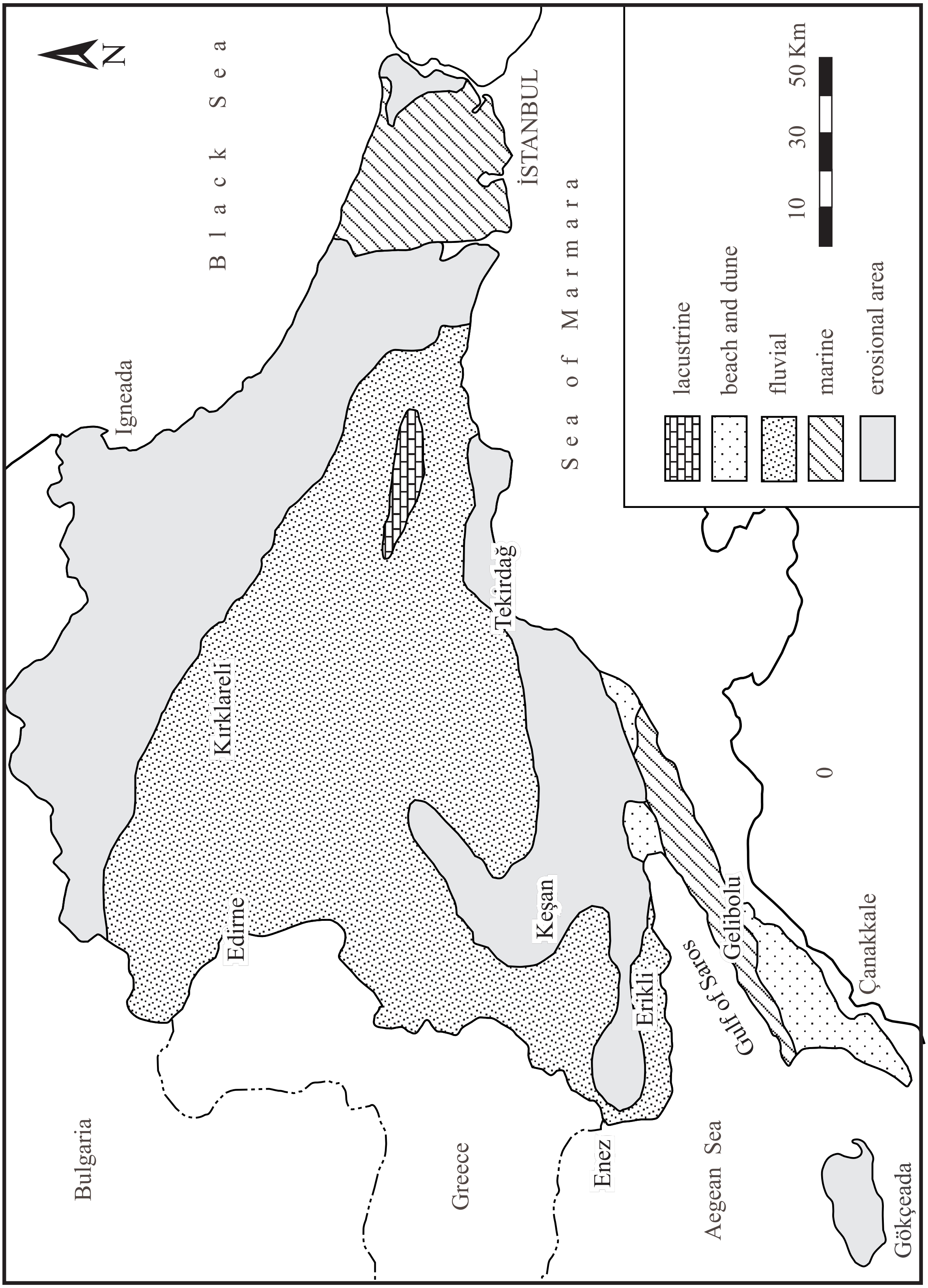

Figure 9. Palaeogeographical facies of Turkish Thrace during the late Middle Miocene period (simplified from Sakınç *et al.* 1999).

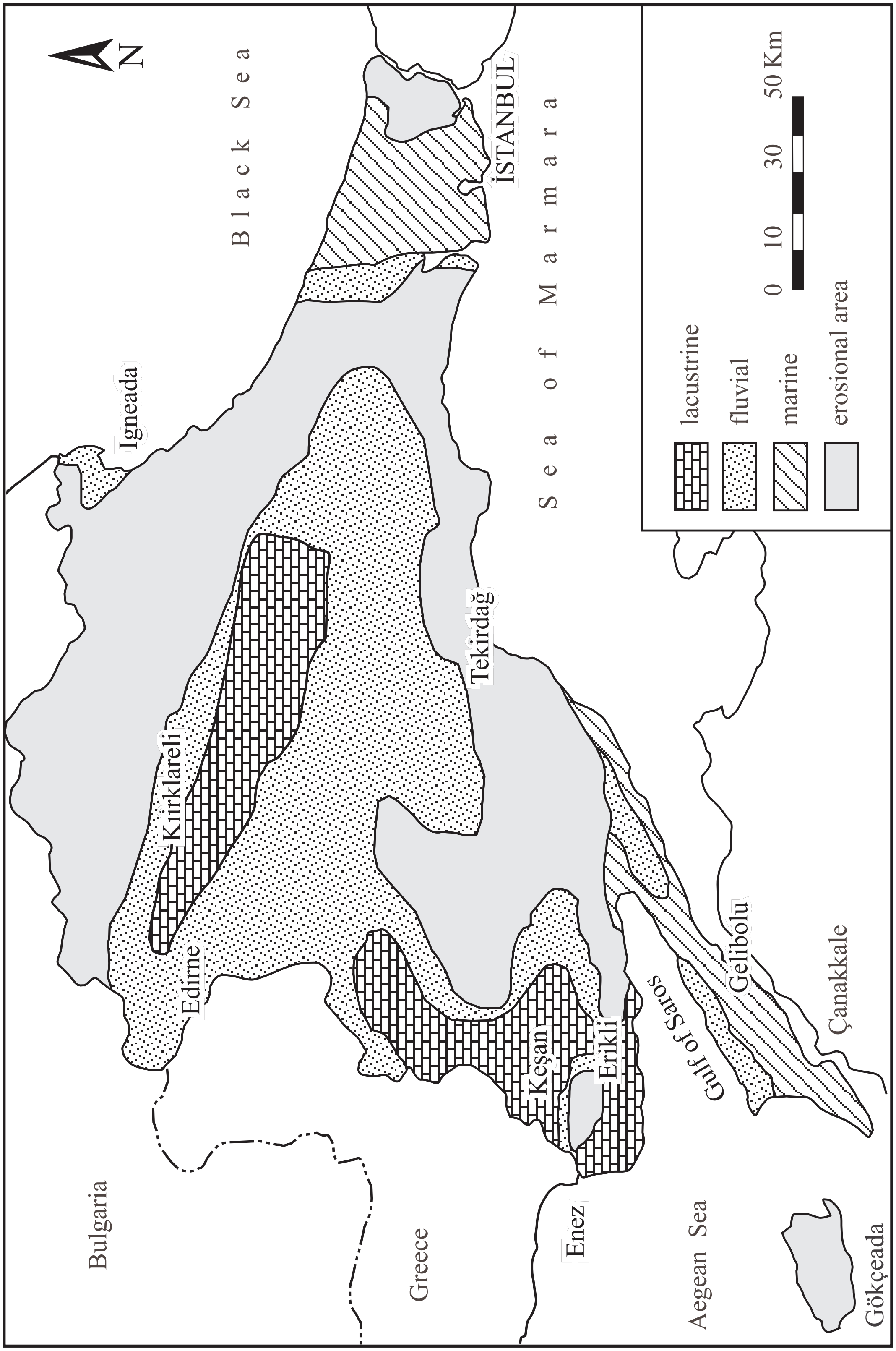

Figure 10. Palaeogeographical facies of Turkish Thrace during the Late Miocene (simplified from Sakınç *et al.* 1999).

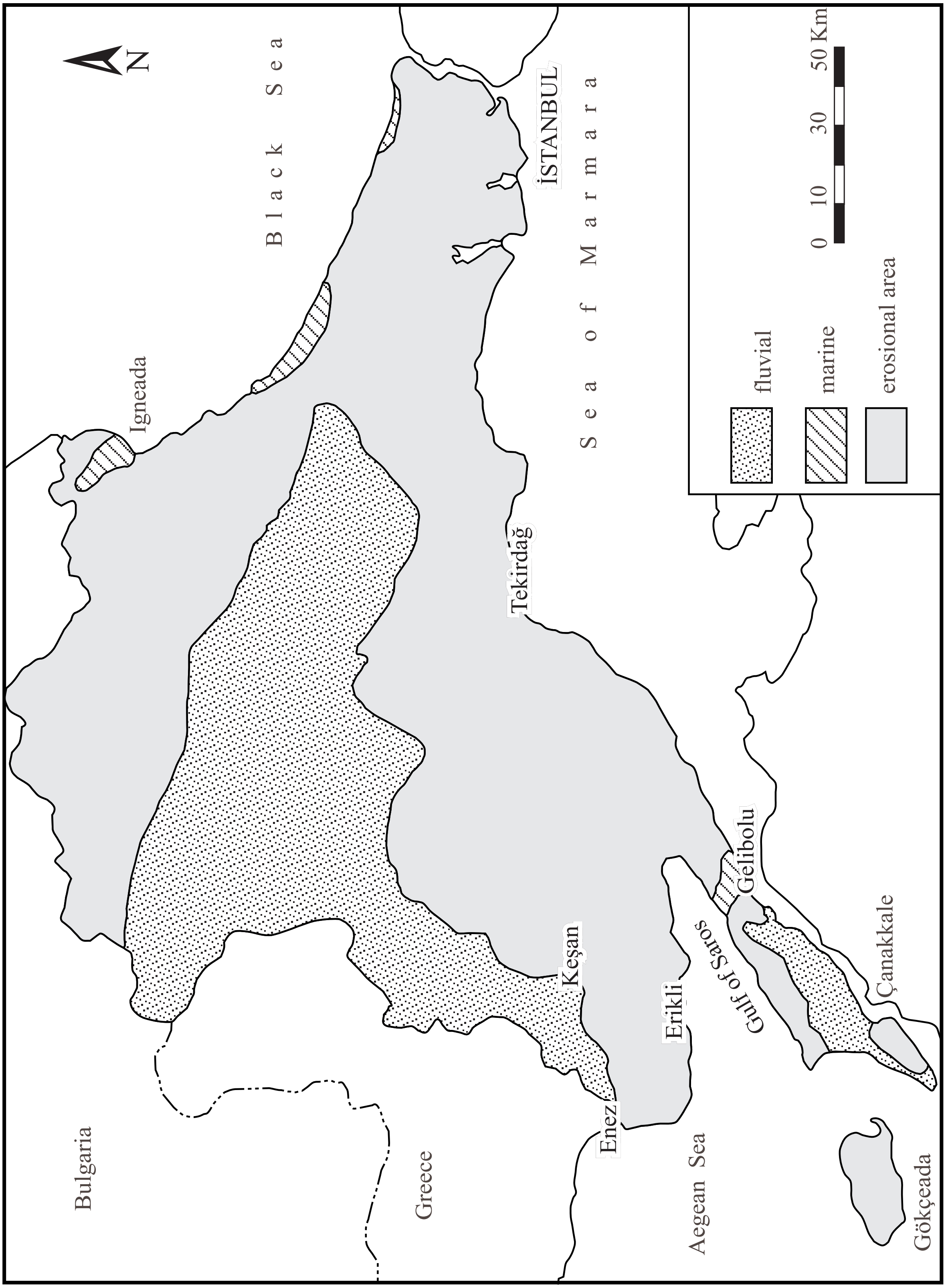

Figure 11. Palaeogeographical facies of Turkish Thrace during the Late Pliocene (simplified from Sakınç *et al.* 1999).

The change in karstification base resulted in concentration of spring outlets that are now identified as cave entrances at different levels, about 25, 185 and 343 m above the sea level, as revealed by the statistical analysis. It is noteworthy that the elevation difference between levels of concentration is ~ 160 m; this may suggest that continental uplift occurred under a relatively static tectonic regime (with some long stable periods which mark erosion-base levels). This situation is in agreement with the hypothesis put forward by Şengör *et al.* (1985) who suggested that movements during the neotectonic period in northern Turkey were so small that tectonic deformation can only be explained by limited E–W shortening.

Concluding Remarks

Karst of Turkish Thrace exhibits some distinct morphological and hydrological characteristics compared to other karst provinces of Turkey. Morphologically, dolines and uvalas are among the most common surface features, and caves characterise subsurface karst in this region. However hydrologically, these morphological features function as ordinary non-karstic geomorphological features rather than as karstic structures. Keeping in mind that karst is characterised not only by its unique morphology but also by associated special hydrology, existence and extent of subsurface drainage is a decisive factor. Closed depressions without subsurface drainage are not indicative of well-developed karst even where located in carbonate terrains. On the other hand, depressions without subsurface drainage most commonly hint at 'dying' karst, as is the case in Turkish Thrace. Closed depressions, known as dolines and uvalas, are permanently flooded, not because water input is in excess of the water leaked through sinkholes, but mostly because the sinkholes are completely clogged or wiped out. Additionally, almost all of the explored caves are horizontal to sub-horizontal. Hydrologically, they are either of fossil or ideal water-table type, indicating the final stage of karstification.

In order to arrive at a rational explanation for what makes the karst in this particular region different, the major factors that governed karstification were first identified and rated according to their effects, and then geological events that may have modified these factors over geological time were discussed. Subsequently, an attempt was made to demonstrate the compatibility between evolution of karst and the geological history in terms of neotectonic evolution and coeval palaeogeographical development.

The major factor which affected karst type in Turkish Thrace was the development of the energy gradient. The erosion base that controlled the depth of karstification was the secondary factor active in producing this type of karst. The energy gradient was produced via the combined effects of continental uplift and eustatic sea-level changes. The metamorphic basement marked the general ersosion base. The erosion base was modified by eustatic sea-level changes rather than continental uplift because changes in sea level were more rapid than the rather steady continental uplift. Examination of the geological history allows us to draw similar conclusions related to karst evolution.

Review of the present status of karst morphology and hydrology in Turkish Thrace reveals that karstification may have been continuously active in the marbles of the Strandja Massif and in the Eocene limestones during the neotectonic period. The Strandja mountains always constituted the highland and were not covered by marine or fresh waters except for some small areas in the İstanbul peninsula. Relatively steady continental uplift created the energy gradient required for the karstification process. Fluctuation of eustatic sea level due to climatic change also affected the energy gradient. Concentration of caves at certain elevations is interpreted as marking stable periods in karst development. Under an erosional regime, the carbonate rocks were karstified and simultaneously eroded; thereby the impermeable rocks underlying the carbonate rocks became so shallow that underground drainage was impeded and closed depressions were captured by streams.

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