ISTANBUL TECHNICAL UNIVERSITY ★ EURASIAN INSTITUTE OF EARTH SCIENCES

STRESS REGIME DURING THE OPENING OF THE BLACK SEA DEDUCED FROM CRETACEOUS DYKE SWARMS IN THE ISTANBUL REGION

M. Sc. Thesis by
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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ AVRASYA YER BİLİMLERİ ENSTİTÜSÜ

BATI KARADENİZ'İN AÇILMASI SIRASINDAKİ GERİLME REJİMİNİN KRETASE DAYK KÜMELERİNİN KONUMUNDAN HESAPLANMASI

YÜKSEK LİSANS TEZİ

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CONTENTS

LIST OF FIGURES

Page Number

LIST OF TABLES

Page Number

SUMMARY

The Black Sea opened as a back-arc basin north of the Pontide magmatic arc during the Cretaceous. It consists of two oceanic subbasins, the West and East Black Sea basins, separated by the Mid-Black Sea ridge. The West Black Sea basin comprises Cretaceous to Recent deposits, over 15 km in thickness, which most probably lie over an oceanic basement. The great thickness of the sedimentary infill masks any magnetic anomaly pattern that may be present in the Black Sea oceanic crust. Thus, there is no direct information on the orientation of the spreading ridge and on the stress pattern during the opening of the Black Sea. We have attempted to solve this problem through a detailed geometrical study of the Cretaceous dykes swarms in the Istanbul region south of the Black Sea .

The formation of dykes involves forces that are connected with their intrusion, regional pattern, mutual arrangement and their effects on the structure and attitude of the enclosing rocks. Most dykes are formed by the intrusion of magma into a fissure via dilating the host rock by the effect of tensional forces. During this dilation the dykes are normally emplaced along planes perpendicular to the direction of the minimum principal compressive stress (σ_3). Thus the trend of the Cretaceous dyke sheets in Istanbul region allows an estimate of the minimum compressive stress (σ_3), which is expected to be perpendicular to the spreading axis in the West Black Sea basin.

The main area of investigation covers the city of Istanbul in general, detailed investigations were carried out on both the European and Asian coasts of Istanbul and along the Bosphorus, with intensive focus on the Tarabya-Ortaköy region along the European coast and the Kanlıca-Beylerbeyi region on the Anatolian coast . In addition, some dykes have been found and investigated on the Küçükyalı-Pendik stretch of the E-5 highway on the Anatolian coast.

The previous stratigraphical investigation of the area reveals that it is made up of a Palaeozoic sedimentary sequence composed of arkose, quartzite, sandstone, shale, limestone and chert ranging from Ordovician to Carboniferous. North of Istanbul, this Palaeozoic sequence is thrust northward over the Upper Cretaceous volcanosediments. On the east of the investigation area the Palaeozoic sequence is unconformably overlain by Triassic aged units composed of conglomerate, limestone and sandstone. The Triassic sequence is in turn unconformably overlain by Upper Cretaceous (Maastrichtian) sediments composed of limestone and chert. All of these units in the investigation area is unconformably overlain by Eocene aged units composed of marn, shale and sandstone.

The Paleozoic sandstones and limestones are cut by numerous Cretaceous andesitic dykes, sills and small intrusions. Additionally, a large granodiorite in the Istanbul region, dated by the Rb/Sr method as 65 +/- 10 Ma, has intruded the Paleozoic sediments. The Cretaceous hypabyssal intrusions constitute part of the Pontide magmatic arc, and are thus related to the opening of the West Black Sea basin. The

strike of the dykes is expected to be perpendicular to the least principal stress (σ_3), and parallel to the back-arc spreading axis.

The dykes in the Istanbul region are generally composed of andesite and andesite basalt, which are light yellow, beige and green rocks with massive appearance and plenty of cracks, hard and resistant overall but altered in places. Their thickness varies from 10-20 cm to 10-11 m and their length exceeds tens of meters. The results of the petrographic studies indicate that the dykes are andesitic and basaltic with a porphyritic or ophitic texture in the form of fine granular microlitic matrix containing plagioclase, hornblende and/or augite phenocrysts 1,5-3,5 mm in length. The result of geochemical studies on the Upper Cretaceous volcanic rocks indicate that they are calc-alkaline in general.

The strike of the dykes ranges from 35° to 120° with a concentration between 65° and 95°. The average strike of the dykes is consistent with a roughly east-west trending spreading ridge, and with a least compressive stress oriented north-south. The spread in the orientation of the dykes might be related to the vicinity of the West Black Sea Fault, which was active during the opening of the Black Sea basin and formed its western termination. It may also have been caused by the sress created during the intrusion of the large granodiorite into the Palaeozoic sediments west of Alemdağ.

ÖZET

Kretase döneminde, yay arkası havzası olarak Pontid mağmatik yayının kuzeyinde açılan Karadeniz, Orta Karadeniz sırtı ile birbirinden ayrılan, Batı ve Doğu Karadeniz okyanusal alt havzalarından oluşmaktadır. Kretase'den günümüze kadar gelen ve kalınlığı 15 kilometrenin üzerinde olan çökellerden oluşan Batı Karadeniz havzası, büyük bir olasılıkla okyanusal temelin üzerinde bulunmaktadır. Büyük bir kalınlığa sahip olan bu sedimenter istif, Karadeniz okyanusal kabuğunda bulunması muhtemel manyetik anomali alanlarını gizlemektedir. Bundan dolayı, Karadeniz'in açılması sırasında yayılma sırtının konumu ve stres dağılımı ile ilgili doğrudan bir bilgi bulunmamaktadır. Karadeniz'in güneyinde bulunan Istanbul bölgesindeki Kretase dayk kümeleri üzerinde ayrıntılı geometrik çalışmalar yaparak bu problemi çözmeye çalıştık.

Daykların çoğu mağmanın çatlak içerisine, gerilim kuvvetlerinin etkisiyle çatlağı genişleterek sokulmasıyla oluşurlar. Bu sırada dayklar en küçük ana sıkıştırıcı stres (σ_3) yönüne dik düzlem boyunca hareket ederler. Buna göre de, Istanbul bölgesindeki Kretase dayklarının yönü kullanılarak Batı Karadeniz havzasının yayılma eksenine dik olması beklenen en küçük sıkıştırıcı stres (σ_3) hesaplanabilir.

Çalışma alanı genel olarak Istanbul ili olup, ayrıntılı çalışmalar Avrupa ve Anadolu olmak üzere boğazın her iki kıyısında yapılmış, Avrupa kıyısında Tarabya-Ortaköy sahili boyunca, Anadolu kıyısında ise Kanlıca-Beylerbeyi sahili ile Küçükyalı-Pendik E-5 otoyolunda yoğunlaşılmıştır.

İnceleme alanında daha önce yapılan stratigrafik çalışmalar bölgenin arkoz, kuvarsit, kumtaşı, şeyl, kireçtaşı ve çörtten oluşan ve Ordovisyenden Karbonifere kadar geniş bir yayılım gösteren Paleozoyik sedimenter istiften oluştuğunu ortaya koymaktadır. İstanbul'un kuzey kesimlerinde bu Paleozoyik istif Üst Kretase yaşlı volkanosedimentler üzerine güneyden kuzeye doğru itilmişdir. İnceleme alanının doğu kesimlerinde ise Paleozoyik istif üzerine önce, konglomera, kireçtaşı ve kumtaşlarından oluşan Triyas yaşlı istif daha sonra ise kireçtaşı ve çörtten oluşan Üst Kretase (Mestrihtiyen) yaşlı sedimentler uyumsuz olarak gelmektedir. İnceleme alanındaki bütün bu birimlerin üzerine marn, şeyl ve kumtaşlarından oluşan Eosen yaşlı birim uyumsuz olarak gelmektedir.

Paleozoyik kumtaşları ve kireçtaşları bir çok andezitik dayk, sil ve küçük sokulumlar tarafından kesilmiştir. Ayrıca, İstanbul bölgesinde, yaşı Rb/Sr metodu ile 65+/-10 Ma olarak bulunan büyük bir granodiyorit kütlesi Paleozoyik sedimentlerinin içine sokulmuştur. Kretase hipobazal sokulumu, Pontid mağmatik yayının bir parçasını oluşturduğu için Batı Karadeniz havzasının açılmasıyla ilgilidir. Daykların doğrultusunun en küçük ana stres (σ_3) yönüne dik, yay arkası açılma eksenine ise paralel olması tahmin edilmektedir.

Genellikle andezit ve andezit bazalttan oluşan, açık sarı, bej ve gri renkli olan dayklar masif görünümlü olup bol çatlak ve kırıklıdır. Genelde sert ve dayanımlı olan bu dayklar yer yer alterasyona uğramışlardır. Daykların kalınlıkları 10-20 cm

den başlayıp 10-11 m. ye kadar uzunlukları ise onlarca metreye kadar değişebilmektedir. Yapılan petrografik çalışmalar sonucunda bu daykların andezitik ve bazaltik bileşime sahip, porfirik ya da ofitik dokulu, ince taneli mikrolitik hamur içinde boyları 1,5 ile 3,5 mm arasında değişen plajioklas fenokristalleri ile hornblend ya da ojit minerallerinden oluştukları ortaya çıkarılmıştır.

Daykların doğrultuları 35° ile 120° arasında oldukça geniş bir dağılıma sahip olup, çoğunluğu 65°ile 95° arasında yoğunlaşmıştır. Daykların doğrultuları, aşağı yukarı doğu-batı yönünde yayılan sırta ve kuzey-güney yönlü en küçük sıkıştırıcı stres yönüne uyumludur. Daykların çıkış yönünün dağılımlarının geniş olması, Karadeniz havzasının oluşması sırasında aktif olan ve onun doğu sınırını oluşturan Batı Karadeniz Fay'ına yakın olmasından yahut Alemdağ batısındaki granodiorit kütlesinin Paleozoyik sedimentler içerisine sokulması sırasında oluşan gerilmeden kaynaklanabilir.

1. INTRODUCTION

The purpose of this thesis is to determine the stress regime during the opening of the Western Black Sea from the Cretaceous dyke swarms in the Istanbul region.

1.1. The Investigation Area

The main investigation area covers the city of Istanbul in general (Figure 1.1). Detailed investigations were carried out on both the European and Asian coasts of the Istanbul Bosphorus, with intensive focus on the Tarabya-Ortaköy region along the European coast and the Kanlıca-Beylerbeyi region on the Anatolian coast (Figure 1.2). In addition, the Küçükyalı-Pendik stretch on the E-5 highway was studied and the results were depicted on the map.

1.2. Aim of the Investigation

The Black Sea opened as a back-arc basin north of the Pontide magmatic arc during the Cretaceous. It consists of two oceanic subbasins, the West and East Black Sea basins, separated by the Mid-Black Sea ridge. The West Black Sea basin comprises Cretaceous to Recent deposits over 15 km in thickness, which most probably lie over an oceanic basement (Letouzey et al., 1977; Tugolesov et al., 1985; Görür, 1988; Finetti et al., 1988; Okay et al., 1994). The great thickness of the sedimentary infill masks any magnetic anomaly pattern that may be present in the Black Sea oceanic crust. Thus, there is no direct information on the orientation of the spreading ridge and on the stress pattern during the opening of the Black Sea. We have attempted to solve this problem through a detailed geometrical study of the Cretaceous dyke swarms in the Istanbul region south of the Black Sea .

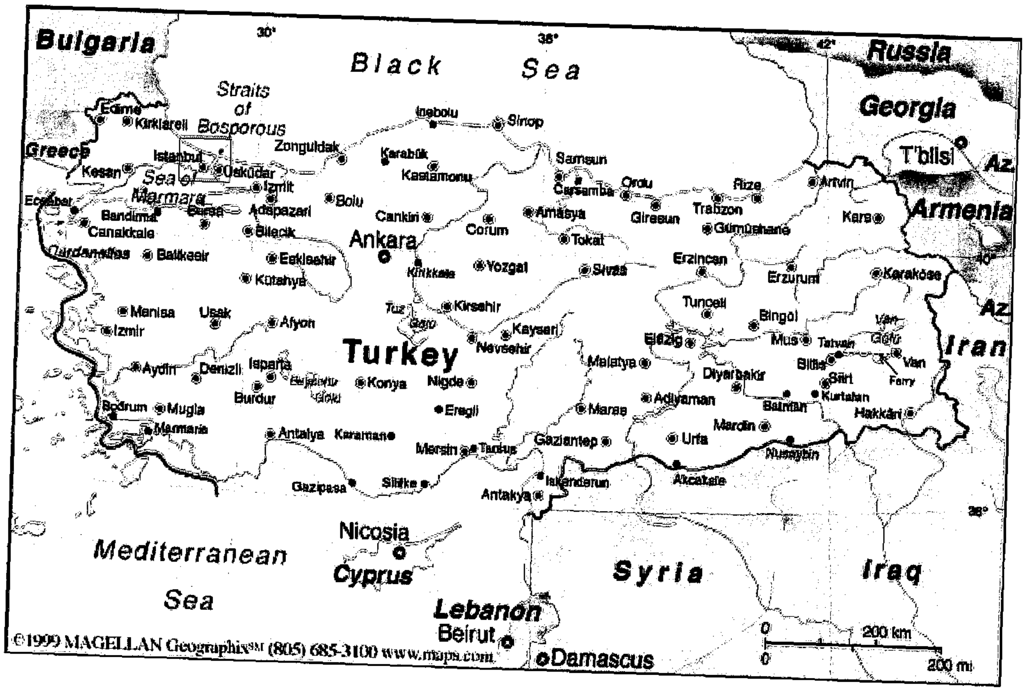

Figure 1.1. Location of the investigation area.

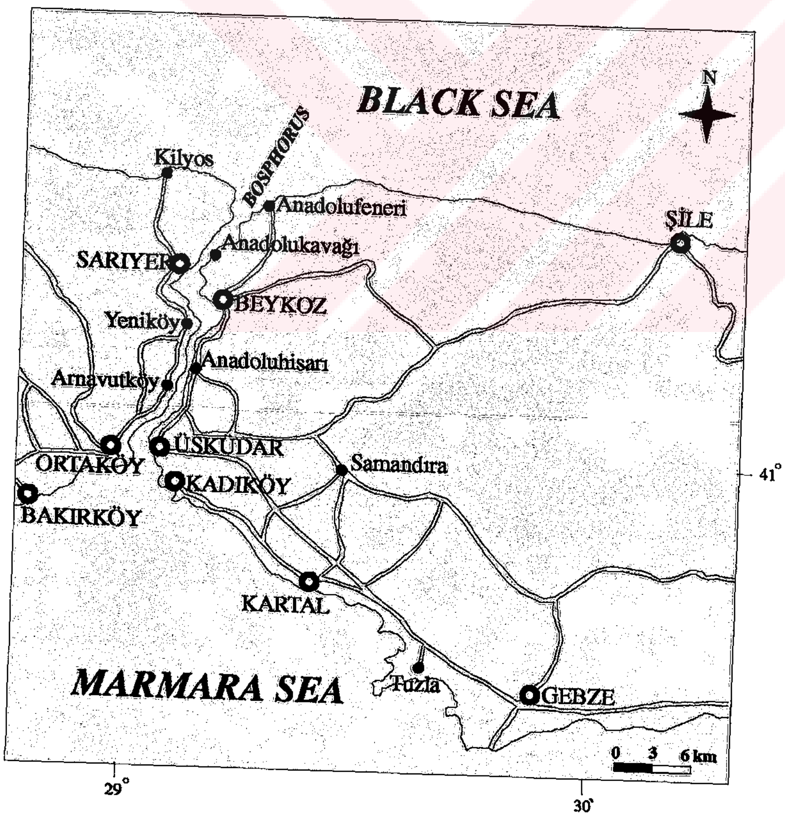

Figure 1.2. Detailed map of the investigation area.

1.3. Previous Investigations

Many investigations have been made on the geology of Istanbul. Below we mention those pertaining to this study, namely the Cretaceous sediments and dykes of the Istanbul area.

Penck (1919), during his study entitled "Grundzüge Der Geologie Des Bosphorus", found numerous andesite and diabase dykes cutting across the Palaeozoic units along the Bosphorus. He defined these dykes as the apophyses of an intrusive mass deeper in the crust. Based on the existence of andesite masses in the Eocene? and Cretaceous sediments on the Black Sea coast (Şile and its environs), he concluded the age of these dykes to be Lower-Middle Tertiary. Additionaly, he found some pieces of diabase in the Devonian limestones in the Baltalimanı region. He believes that these pieces of diabase are the same as the diabase he found deposited in the schist in Göksu Valley. Therefore, he defined the age of the diabase dykes in the Baltalimanı region to be Palaeozoic.

Ketin (1941), in his study entitled "About the Granite Massive West of Alemdağ Region", defined the granite mass on the west of Alemdağ as an intrusive mass that propagated itself into Lower Devonian units and sent apophyses to the neighbouring area. Based on his findings, he concluded that the pluton is younger than Devonian. In addition, he reported that this mass rose up during Hercynian or recently afterwards.

Okay (1947), studied the Alemdağ granite mass cut across by andesite and aplite-lamprophyre veins in his study entitled "The Geology and Petrography of the Area Bounded by Alemdağ, Karlıdağ and Kayışdağ". The petrographic analysis he carried out on this mass revealed that it was a calcalkaline granite (granodiorite).

Okay (1948), as a result of the geological studies he carried out in the region bounded by Şile, Mudarlı, Kartal and Riva, defined the Upper Cretaceous (Senonian) eruptive formations in the region as flysch, white calcareous rocks and volcanic veins. Additionally, he reported that the Palaeozoic units in the region have been cut across by Upper Cretaceous (Senonian) basalt and andesite-dacite veins.

Erguvanlı (1949), in his study entitled "The Investigation of the Hereke Pudding and Gebze Stones with Respect to Construction and the Geology of the Vicinity", dicovered andesites cutting across Triassic units in the region.

Sayar (1960), made a geological map of the Istanbul Bosphorus and its environs based on the studies of E. Chaput, W. Paeckelmann, A. C. Okay, I. Ketin, C. Erentöz, K. Erguvanlı and McCallien. Sayar also depicted the dykes of the Istanbul area on this map.

Öztunalı & Satır (1975), in their study on the Çavuşbaşı crystalline complex north of Beykoz on the Anatolian coast, dated a large granodiorite which has intruded the Paleozoic sediments as 65 +/- 10 Ma, which corresponds to the Maastrichtian stage of the Upper Cretaceous. The SE and SW sections of this granodiorite and its surrounding rocks have been cut across by andesite and dacite dykes. The andesites have porphyritic texture and they are in the form of fine granular microlitic matrix containing plagioclase and minute amounts of orthoclase and hornblende phenocrysts. The texture, form and composition of the dacites are similar to those of the andesites; however, the former contain quartz and biotite in addition.

Yeniyol & Ercan (1989/1990), as a result of their study entitled "Geology of Northern Istanbul, Petrochemical Characteristic Volcanism and its Regional Distribution in Pontides", conclude that the Upper Cretaceous volcanic rocks are calc-alkaline in general and they are of crustal origin. They are part of a group of island arc volcanites derived in a subduction zone that has developed in the compressional tectonic regime.

Okay et al., (1994), suggest that "the Istanbul zone was, until the Cretaceous, located along the Odessa shelf between the Moesian platform and the Crimea and was rifted during Aptian-Albian time Görür (1988) and moved south as a small continental fragment bounded by two large transform faults, opening in its wake the Black Sea basin. The continental fragment then collided in the early Eocene with a Cimmeride zone in the south, thereby ending the extension in the western Black Sea and deactivating both the west Black Sea and the west Crimean faults as strike-slip faults. The east Black Sea basin opened as a result of the counterclockwise rotation of an east Black Sea block around a rotation pole located north of the Crimea. This block was bounded by the west Crimean fault, the southern margin of the eastern Black Sea, and the southern frontal thrusts of the Greater Caucasus. The rotation of the east Black Sea block was contemporaneous with the rifting of the west Black Sea basin but lasted until the Miocene, resulting in continuous compression along the Greater Caucasus".

Görür et al., (1997), as a result of their study entitled "Palaeogeographic and Tectonic Position of the Carboniferous Rocks of the Western Pontides (Turkey) in the Frame of the Variscan Belt", conclude that the Carboniferous rocks between Istanbul and the Zonguldak basin, called the "Palaeozoic of Istanbul ", belong to a fragment of the Hercynian chain of uncertain origin. The Carboniferous rocks of the Istanbul zone are totally different from the other formations in Turkey but very similar to the Palaeozoic sequence of the Moesian Platform and the European coal basins. Görür et al., suggest that the "Palaeozoic of Istanbul" was part of the East European Platform and has drifted southwards during the opening of the western Black Sea basin.

Okay & Tüysüz (1999), as a result of their study entitled "Tethyan Sutures of Northern Turkey", conclude that the Intra-Pontide suture has formed during the Early Tertiary continental collisions, following the northward subduction of the Tethyan oceanic lithosphere. The suture, 800 km long, has formed during the Early Eocene and younger continental collisions linked to the opening of the Western Black Sea Basin as a oceanic back-arc basin.

Tüysüz (1999), as a result of his study entitled "Geology of the Cretaceous Sedimentary Basins of the Western Pontides", concludes that the southern passive margin of the oceanic Western Black Sea Basin consists of two tectonic units, the Istanbul Zone and the Central Pontides, bound by a N-S Araç-Daday shear zone. To the west of this shear zone the Istanbul Zone is covered by a sedimentary succession deposited in a southerly deepening continental margin basin. After the juxtaposition of the Central Pontides and the Istanbul Zone, an E-W trending extensional magmatic arc was established on these sedimentary basins in response to the northward subducting of the Neotethys to the south. This magmatic arc, which began during the Turonian, gave rise to the Western Black Sea oceanic back-arc basin.

2. GEOMORPHOLOGY OF THE INVESTIGATION AREA

The city of Istanbul is in the Marmara Region, stretching over the Asian and the European coasts of the Istanbul Bosphorus which link the Sea of Marmara and the Black Sea. Lying roughly at the intersection of the 41^{st} parallel and the 29^{th} meridian, Istanbul is bounded by the Black Sea in the north, the Sea of Marmara in the south, the cities of Tekirdağ and Kırklareli in the west and Kocaeli in the east.

The Istanbul region is a plateau without prominent altitudes (Figure 2). The highest points of the city are on the eastern coast of the Bosphorus. The rocks in this region have not altered due to their resistance and they have remained much higher above plateau surfaces than their counterparts on the western coast. The highest of them is the Aydos hill on the Anatolian side. The Alemdağ (442 m.), Kayışdağ (434 m.) and Çamlıca (262, 228 m.) hills are also on this coast. On the European coast of the Bosphorus, the hills are not as high as those in the east. The highest point there is the Yıldız (361 m.) Range which interjects into the western regions of Istanbul.

The biggest river on the Anatolian coast of Istanbul is the Riva Creek near the village of Riva. It flows into the Black Sea with a SE-NW direction. The Göksu and Küçüksu are also rivers on the same coast. They flow into the Istanbul Bosphorus. On the European coast, there are the Sazlı Creek which flows into the Küçükçekmece Lake, the Istranca which flows into the Terkos Lake, the Istinye and Büyükdere which flow into the Istanbul Bosphorus and the Kağıthane and Alibeyköy rivers which flow into the Golden Horn.

There are three lakes on the European coast of Istanbul. The first one is the Terkos Lake, which lies 50 km northwest of Istanbul near the coast of the Black Sea. With an area of 25 km^2 and a depth of 11 m, the Terkos is a natural set lake by formation. The second lake, the Küçükçekmece, lies 15 km west of Istanbul with an area of 16 km² and a depth of 20 m. The lake was formed by the blocking of an old bay on the coast of the Sea of Marmara. The last one is the Büyükçekmece, 27 km from Istanbul, with an area of 11 km² and a depth of 3,5 m. This lake is set off from the sea by a block in the narrow section of the bay.

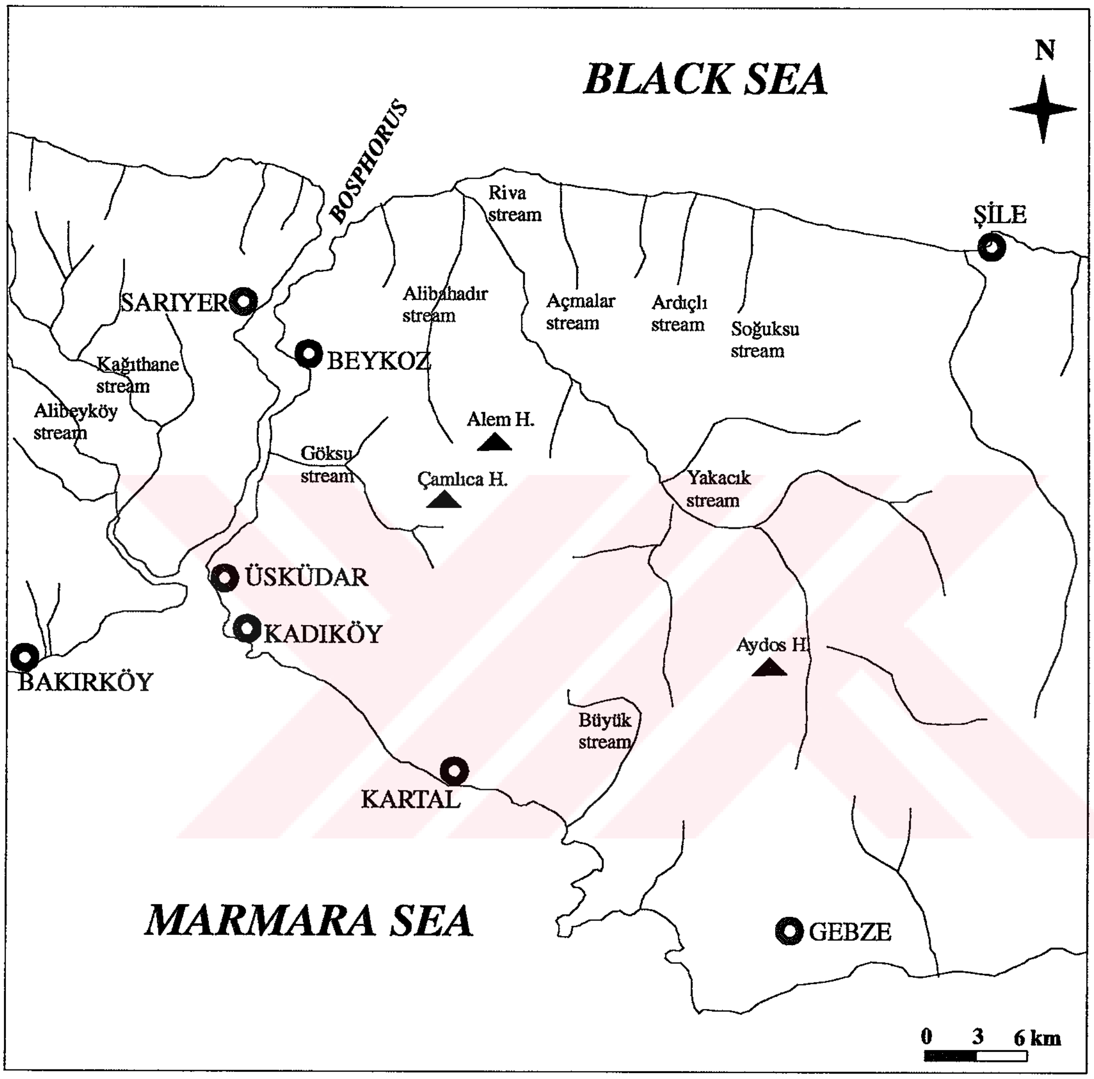

Figure 2.1. Map of the river network and peak points of the investigation area.

3. GEOLOGY OF THE BLACK SEA AND ITS SOUTHERN MARGIN

3.1. General Information

The investigation area is the Istanbul zone, which is a small continental fragment about 400 km long and 70 km wide in the southwestern margin of the Black Sea (Figure 3.1) (Okay and Tüysüz, 1999).

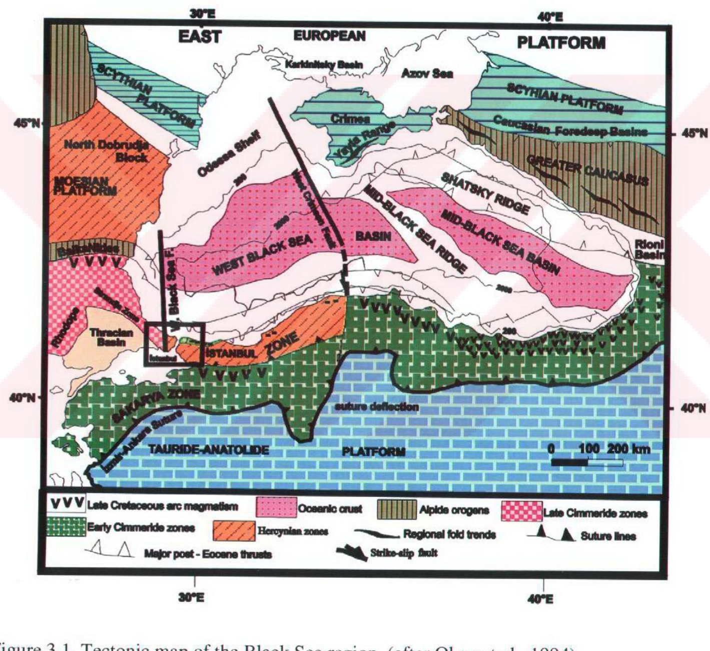

Figure 3.1. Tectonic map of the Black Sea region (after Okay et al., 1994).

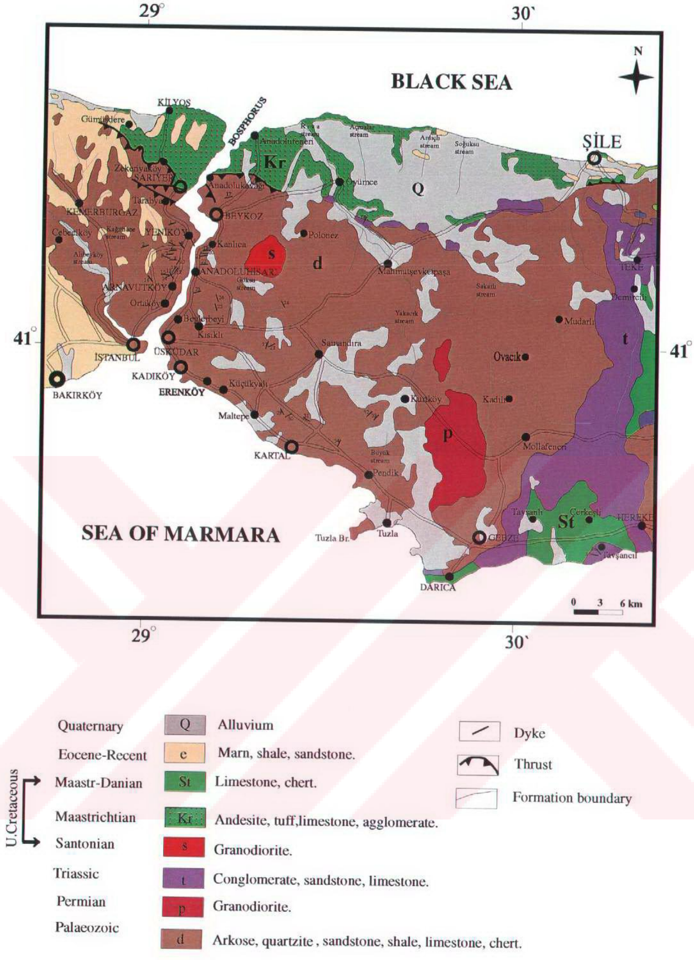

Figure 3.2. The geological map of the Istanbul region.

The stratigraphy of the investigation area, as seen in Figure 3.2, is made up of a transgressive sedimentary sequence composed of arkose, quartzite, sandstone, shale, limestone and chert ranging from Ordovician to Carboniferous (Görür et al., 1977). In the north of Istanbul, this Palaeozoic sequence is thrust northward over the Upper Cretaceous volcanosediments. On the east of the investigation area the Palaeozoic sequence is unconformably overlain by Triassic aged units composed of conglomerate, limestone and sandstone. The Triassic sequence is, in turn, unconformably overlain by Upper Cretaceous (Maastrichtian) sediments composed of limestone and chert (Özer et al., 1990). All of these units in the investigation area are unconformably overlain by Eocene aged units composed of marn, shale and sandstone.

3.2. The Palaeozoic Sequence

In the investigation area, Palaeozoic units are represented by transgressive sedimentary sequences extending from Ordovician to Carboniferous.

These Palaeozoic sequences start with the Kurtköy Formation (Önalan, 1982) of more than 1000 m. thickness, composed of conglomerate, mudstone and arkose, and generally seen in the east of the Istanbul region. The base of the unit, the conglomerate is a very hard and resistant rock composed of purple, well-rounded pebbles of lengths between 2 mm-1 cm. Towards the top, it is interbedded with pink shale. The rest of the unit consists of layers of whitish arkose deposited on the conglomerate. This unit passes gradually upward into a second unit, the Aydos Formation (Önalan, 1982), composed of quartz arenite with a thickness varying between 150-300 m. The quartz arenite is pinkish white, cross-bedded, very hard and resistant and interbedded with greenish grey shale. It has been discovered that this sequence has formed in beaches and shallow crustal areas which are affected by tides (Önalan, 1982). Based on the worm trails, and **Cruziana sp** and **Monocraterion sp** found in them, the age of these sediments is estimated to be Ordovician (Önalan, 1982).

These Ordovician sediments are followed by a 250 m. unit, the Gözdağ Formation (Önalan, 1982), composed of shale, sandstone and limestone, and generally seen on the Anatolian coast of the Istanbul Bosphorus. This unit starts with brown sandstone interbedded with green shale, and proceeds upwards with blue, very hard and resistant, thin/medium-bedded bioclastic limestones. These sediments are interpreted as a lagoonal deposit (Önalan, 1982). The age of this unit is determined to be Lower Silurian (Llandoverian) based on the brachiopods, graptolites, corals, crinoids, bryozoa and ostracods fossils found in them (Yalçınlar, 1955; Arıç-Sayar, 1962 and 1969; Haas, 1968; Önalan, 1982).

This sequence passes locally through subarkosic sandstones which are considered to be sand bars (Önalan, 1982) into a 400 m.-thick carbonate sequence known as the Gebze Limestone (Görür, 1982). The white and cross-bedded subarkosic sandstone contains fossiliferous beds which are dominated by late Llandoverian brachiopods (Haas, 1968; Ketin, 1983).

Gebze Limestone, which is widely seen on both the European and Anatolian coasts of Istanbul, is composed of limestone, calcareous mudstone, wackestone, shale and chert. This carbonate sequence formes blue and pink, massive, very hard and resistant limestones deposited in a reef and fore-reef environment (Önalan, 1982). These carbonates are estimated to be early Devonian based on the fossils of brachiopods, corals, conodonts and trilobites found in them (Haas, 1968; Önalan, 1982; Ketin, 1983). This carbonate sequence passes gradually through bluish grey coloured, nodular limestone facies into the overlying and yellowish, fossiliferous shale of early Devonian age deposited in a shelf environment (Önalan, 1982; Ketin, 1983). This nodular limestone facies is followed by shale, limestone and radiolarian cherts with the early Carboniferous age phosphate nodules (Ustaömer and Robertson, 1993). These are Middle-Upper Devonian in age and deposited in a continental slope and deep sea environment (Önalan, 1982).

Over the Devonian nodular limestone come thick Carboniferous sediments. The basal part of these sediments is made of Lower Carboniferous (Visean)

(Abdüsselamoğlu, 1963) black, thinly-bedded, very hard and resistant chert interbedded with light coloured, thinly-laminated shale, the Baltalimanı Formation (Önalan, 1982). Judging from the radiolaria fossils found in them, these sediments must have been deposited in a deep sea environment (Okay, 1947). The upper part of these sediments are made up of brown, medium/thick-bedded sandstone that is intercalated with dark grey shale and has plenty of cracks, Trakya Formation (Önalan, 1982). The age of these sediments is early Carboniferous (Visean) (McCallien, 1947; Absüsselamoğlu, 1963; Kaya, 1973, 1980) and they were deposited in a deep sea environment (Önalan, 1982).

3.3. The Mesozoic Sequence

In the investigation area, the Mesozoic period is represented by the Triassic and Upper Cretaceous sequences.

Triassic sediments, which are seen in the east of the investigation area, are composed of conglomerate, sandstone and limestone. This well-developed transgressive sequence is composed of violet conglomerate which is massive in appearance, in places thickly and irregularly bedded and comprises barely rounded pebbles at the bottom and pinkish-red, thin/medium-bedded sandstone and yellowish, fossiliferous, nodular limestone interbedded with marl at the top. The age of this sequence is Triassic (Özer et al., 1990) and it has been deposited transgressively.

In the investigation area Cretaceous is represented by two sequences. The first one, which is seen in the east of the investigation area, is composed of argillaceous limestone, the Şemsettin Limestone (Altınlı, 1968). These limestones are white or beige-coloured, thin/medium- bedded, cracked, and interbedded with marl. They have medium resistance. The age of this sequence is Upper Cretaceous (Campanian) based on the rudist and plantic foraminifers found in them (Özer et al., 1990).

The second sequence, which is seen in the northeast and northwest of the Istanbul Bosphorus, is composed of conglomerate, sandstone, siltstone, marl, shale and limestone beds and volcanic rocks interbedded with sedimentary rocks. The volcanic rocks are composed of tuff (Figure 3.3); spilite, basalt and andesite (Figure 3.4); and trachyandesite, dacite, rhyolite kind lava and agglomerate (Figure 3.5). Higly decomposed andesitic lava is prevalent. It is mainly composed of plagioclase, with lesser amounts of hornblende, biotite, augite, and trace amounts of opaque minerals. The textures of these volcanic rocks are generally porphyritic, hyaloporphyritic and pilotaxitic. The result of geochemical studies on the Upper Cretaceous volcanic rocks indicate that they are calc-alkaline in general and they are of crustal origin. They belong to the group of island arc volcanics derived in a subduction zone (Yeniyol and Ercan, 1990). The age of this sequence is given as Upper Cretaceous (Middle-Upper Maastrichtian) based on the Gastropoda (Actaonella) fossils found in them (Okay, 1948; Akartuna, 1963; Önalan, 1989).

Figure 3.3. Upper Cretaceous tuff, Sarıyer.

Figure 3.4. Upper Cretaceous andesite, Sarıyer.

Figure 3.5. Upper Cretaceous agglomerate, Sarıyer.

3.4. The Cenozoic Sequence

The Cenozoic period is represented by the Eocene to recent sediments which are seen in the north and southwest of the investigation area. These sediments which are over 650 m. in thickness are composed of black and dark grey-coloured clay; white and cream-coloured, horizontally layered limestones of medium-high resistance and generally interbedded with green clay; marls of weak-medium resistance; crimson-coloured, loosely bound pebbles, sand and clay. The Eocene-Recent deposition started with land and shallow sea sediments; followed by deep sea sediments, and ultimately by land and shallow sea sediments (Yıldırım and Savaşkan, 2002) .

3.5. The Quaternary

The Quaternary-aged unit exposed more prominently in the east of the investigation area is composed of loosely-bound pebbles, sand, clay and silt. This unit is formed by the decomposition of rocks much older in age and their subsequent erosion-triggered deposition in river beds.

3.6. The Black Sea Basin

The Black Sea is a 423000 km^2 elliptical basin, 70% of which lies below the shelf edge, with a maximum water depth of 2206 m (Ross et al., 1974). The Black Sea opened as a back-arc basin north of the Pontide magmatic arc during the Cretaceous. It consists of two oceanic subbasins, the West and the East Black Sea basins, separeted by the Mid-Black Sea ridge (Figure 3.1).

Investigations show that these two basins have different structures (Letouzey et al., 1977; Tugolesov et al., 1985; Finetti et al., 1988). The east-west oriented West Black Sea basin comprises flat-lying, undisturbed, Cretaceous to recent deposits over 15 km in thickness, which most probably lie over an oceanic basement (Görür, 1988). On the other hand, the north-west trending East Black Sea basin has sediments which are up to 12 km thick and lie over an oceanic basement intersected by a large number of faults (Finetti et al., 1988).

The Istanbul zone was, until the Cretaceous, located along the Odessa shelf between the Moesian platform and the Crimea and was rifted during Aptian-Albian time (Görür, 1988) and moved south as a small continental fragment bounded by two large transform faults and opening in its wake the Black Sea basin (Figure 6.1) (Okay et al., 1994). The continental fragment then collided in the early Eocene with a Cimmeride zone in the south, thereby ending the extension in the western Black Sea and deactivating both the west Black Sea and the west Crimean faults as strike-slip faults. The east Black Sea basin opened as a result of the counterclockwise rotation of an east Black Sea block around a rotation pole located north of the Crimea. This block was bounded by the west Crimean fault, the southern margin of the eastern Black sea, and the southern frontal thrusts of the Greater Caucasus. The rotation of the east Black Sea block was contemporaneous with the rifting of the west Black Sea basin but lasted until the Miocene, resulting in continuous compression along the Greater Caucasus."

4. DYKE DEFINITION AND TYPES

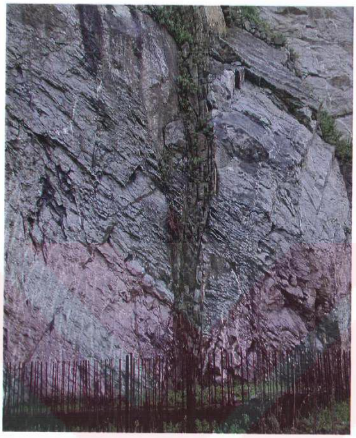

Figure 4.1. Dyke sample from Istanbul.

The dyke is a sheet of intrusive igneous rock that forms as a result of magma being injected into the fracture of rocks (Figure 4.1). During the injection, dykes crystallize below the ground and they are exposed when the surrounding rock is eroded. Dykes owe their name to the fact that they form by shooting vertically upwards or downwards through rocks. Most dykes are prominent on the surface of the Earth, because the rocks that constitute them are stronger than the country rocks through which they intrude. Dykes are generally vertical or have steeply-inclined walls, and they arise roughly perpendicular to the Earth's surface. They form discordant intrusions, because dyke walls generally cut across pre-existing foliations and structures in their country or host rocks.

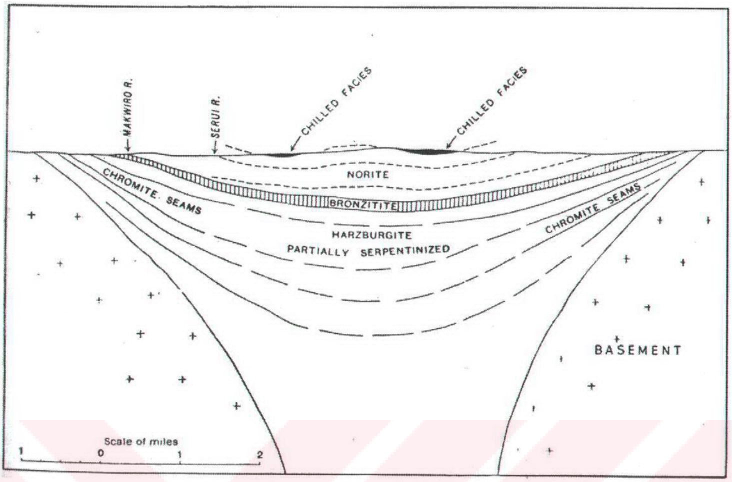

Figure 4.2. Section across the Great Dyke of Southern Rhodesia (After Lightfoot, 1940).

The length of dykes varies between a few meters and many kilometers and it is partly determined by the nature of exposures. The largest dyke in the world is the Great Dyke of Southern Rhodesia in southeast Africa with a width of 3 km. to 12 km. at outcrop and a length of 540 km. (Lightfoot, 1940). It contains basic and ultrabasic rocks that demonstrate strong bending and seems to be funnel-shaped in cross section (Figure 4.2). The thickness of dykes varies from a few centimeters to hundreds of meters. However, quite thin dykes may extend for fairly long distances. For instance, Monchiquite dykes in Bendigo, Australia, 0,5-1 m. wide extend vertically downwards in mines for over 1200 m. without notable change and they probably extend very much further (Hills, 1965). The same applies to lamprophyre dykes at Woods Point and Walhalla in Victoria, Australia (Hills, 1952).

Dykes generally are restricted by chilled margins. Chilled margins are formed during the intrusion of dykes, as a result of the more rapid cooling of dyke margins than the centre of dykes. Therefore, they are much finer grained compared to the centre of dykes. At these chilled contacts, there are selvedges of glass with only a few centimetres of thickness. These selvedges of glass are also formed by the result of chilling of the liquid magma against the cooler wall rocks.

Cooling of dykes by radiation and conduction of heat from their two approximately parallel boundary surfaces commonly results in well-developed columnar jointing approximately at right angles to the dyke walls (Figure 4.3), and in the case of nearly vertical dykes, the exposed masses of columns may look surprisingly like great stacks of cordwood (Macdonald, 1972).

Figure 4.3. Dyke with columnar jointing, Islands of Kauai, Hawaii (Macdonald, 1972).

Dykes are classified according to the number of intrusions of magma and the kinds of magma that intrude. The first type, which is called a "*simple dyke*", is formed as a result of a single intrusion of magma. The second, the "*multiple dyke*", is formed as a result of two or more intrusions of the same kind of magma. The third type is called a "*composite dyke*". This is formed by the intrusion of two or more chemically or minerologically different kinds of magma. The last type is the *differentiated dyke*", which is formed by the intrusion of homogeneous magma which separates into unlike portions at depth or in place and thus hardens into more than one variety of rock. An example of this type of dyke at Brefven, Sweden, Winge (1896) has seperated into granite porphyry, intermediate rock and olivine diabase rocks (Figure 4.4).

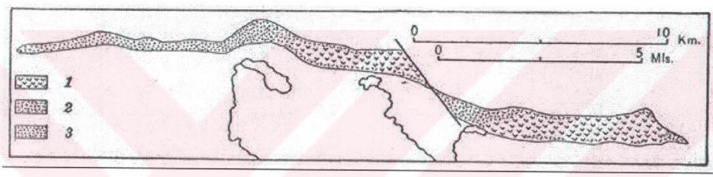

Figure 4.4. Plan of the great differentiated dyke at Brevfen, Sweden (After Winge, 1896). 1, granite porphyry; 2, intermediate rock; 3, olivine diabsae.

Groups of hundreds or thousands of individual dykes concentrated at varying frequencies in a direction parallel to each other form what are called "*dyke swarm*"s. Swarms are most concentrated around plutonic centers. Anderson (1951) suggests that they may have been formed by the roughly perpendicular rise of magma supplied from below or horizontal spreading of it from already existing magma chambers, along fractures which spread laterally in two directions from plutonic centers functioning as areas of weakness.

The most outstanding example of dyke swarms is the Mull Swarm in Scotland, formed around a ring dyke system. This Tertiary tholeiite dyke swarm is notable for the strongly marked concentration of the dykes as they pass through the central complexes of Mull, Ardnamurchan and Skye, which are aligned on the NNW trend of the dykes in that area (Figure 4.5) (Richey, 1948).

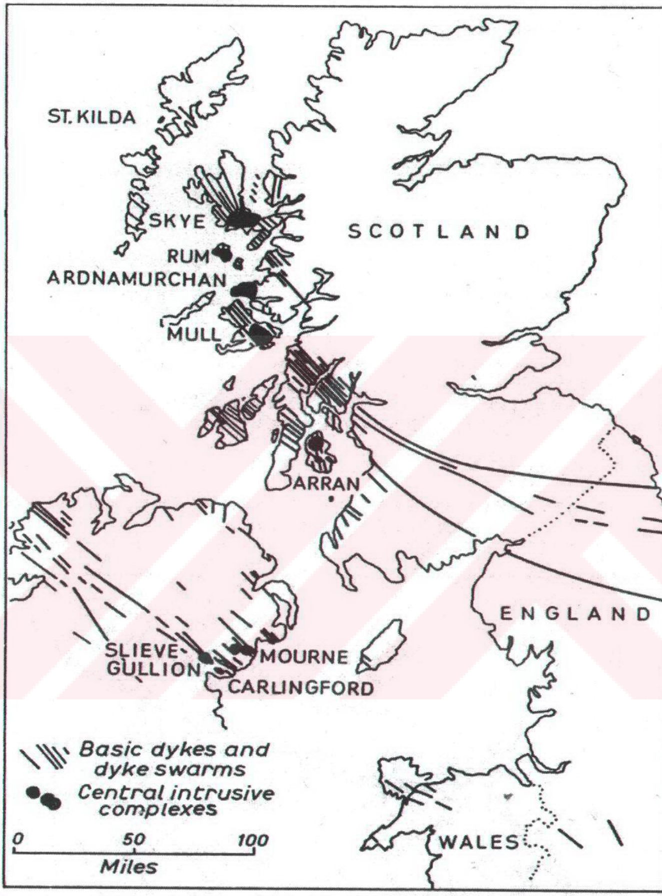

Figure 4.5. Map of Tertiary dikes and volcanic centers, Scotland (After Richey, 1948).

Another example of dyke swarms is the Middle Devonian Woods Point dyke swarm in Victoria, Australia (Figure 4.6), notable for the curving outline of the edge of the swarm, but more so for the rich gold deposits associated with the dykes (Hills, 1952).

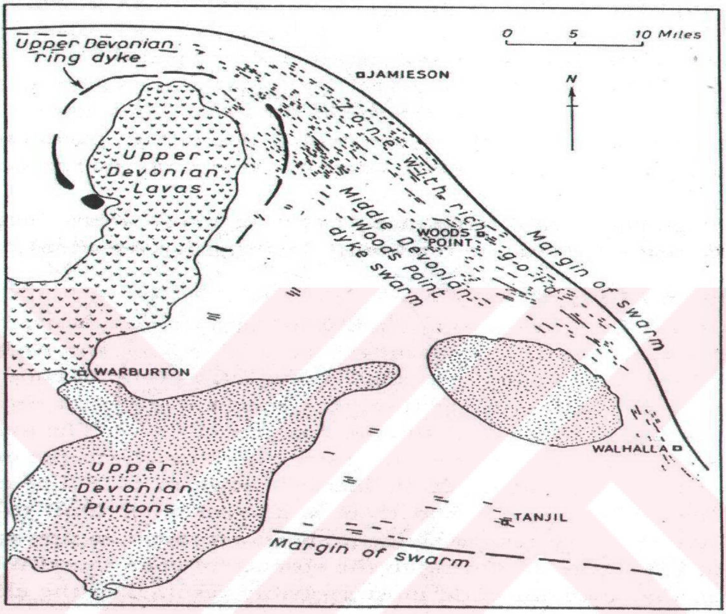

Figure 4.6. The Woods Point dyke swarm, Victoria, Australia (Hills, 1922).

5. DYKES IN ISTANBUL

5.1. Previous Investigations

Penck (1919), during his study entitled “Grundzüge Der Geologie Des Bosphorus”, found numerous andesite and diabase dykes cutting across the Palaeozoic units along the Bosphorus. He defined these dykes as the apophyses of an intrusive mass deeper in the crust. Based on the existence of andesite masses in the Eocene? and Cretaceous sediments on the Black Sea coast (Şile and its environs), he concluded the age of these dykes to be Lower-Middle Tertiary. Additionaly, he found some pieces of diabase in the Devonian limestones in the Baltalimanı region. He believes that these pieces of diabase are the same as the diabase he found deposited in the schist in Göksu Valley. Therefore, he defined the age of the diabase dykes in the Baltalimanı region to be Palaeozoic.

Ketin (1941), in his study entitled “About the Granite Massive West of Alemdağ Region”, defined the granite mass on the west of Alemdağ as an intrusive mass that propagated itself into Lower Devonian units and sent apophyses to the neighbouring area (Figure 5.2). Based on his findings, he concluded that the pluton is younger than Devonian. In addition, he reported that this mass rose up during Hercynian or recently afterwards.

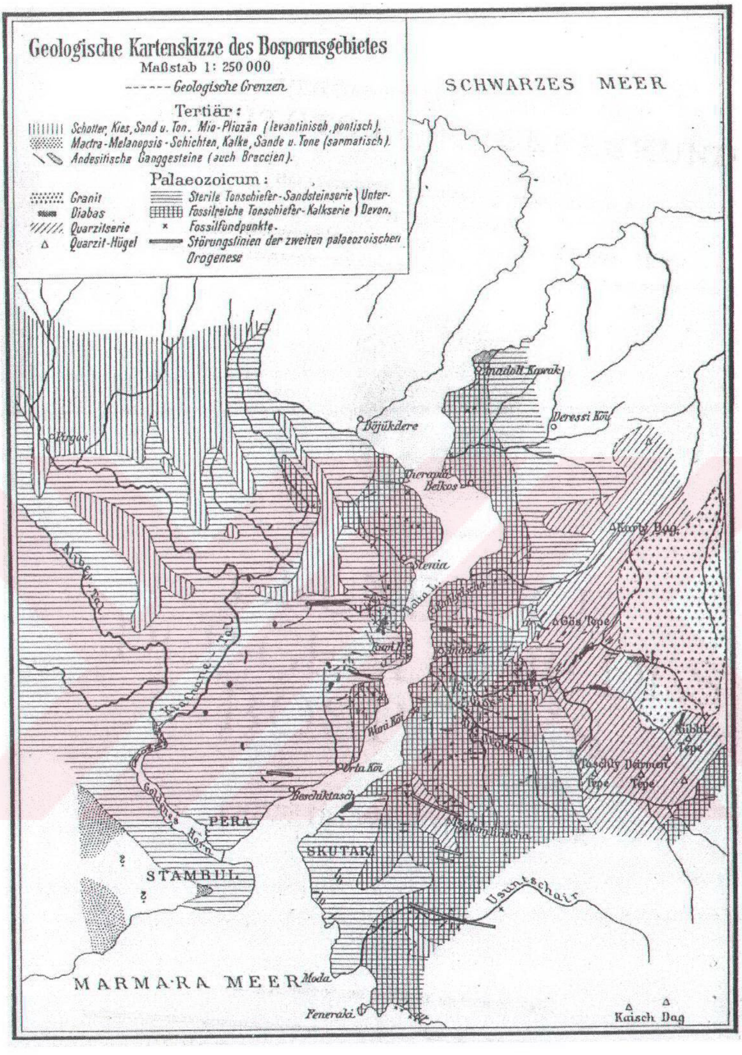

Figure 5.1. Geological map of the Istanbul Bosphorus and its environs (Penck, 1919).

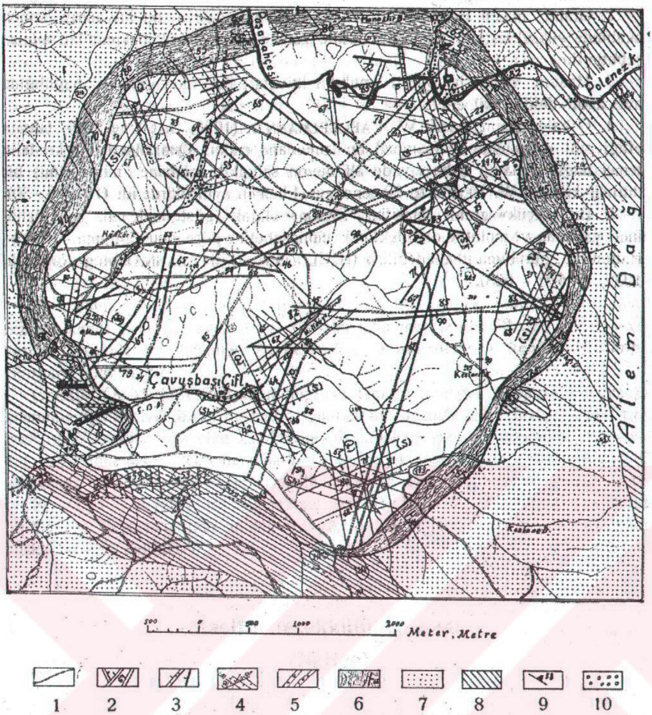

Figure 5.2. Geological map of the granite massive, west of the Alemdağ (Ketin, 1941).

1. The border of the granite mass
2. Aplite veins
3. Basic and semi-basic veins
4. Fissures (S and Q) and extension zones
5. Granite apophysis in the neighboring region

6. Contact zones

7. Sandstone and sandy schist

8. Quartzite

9. Bedding direction and dip

10. Alluvial formations

Okay (1947), studied the Alemdağ granite mass cut across by andesite and aplite-lamprophyre veins in his study entitled "The Geology and Petrography of the Area Bounded by Alemdağ, Karlıdağ and Kayışdağ" (Figure 5.3). The petrographic analysis he carried out on this mass revealed that it was a calcalkaline granite (granodiorite).

Okay (1948), as a result of the geological studies he carried out in the region bounded by Şile, Mudarlı, Kartal and Riva, defined the Upper Cretaceous (Senonian) eruptive formations in the region as flysch, white calcareous rocks and volcanic veins (Figure 5.4). Additionally, he reported that the Palaeozoic units in the region have been cut across by Upper Cretaceous (Senonian) basalt and andesite-dacite veins.

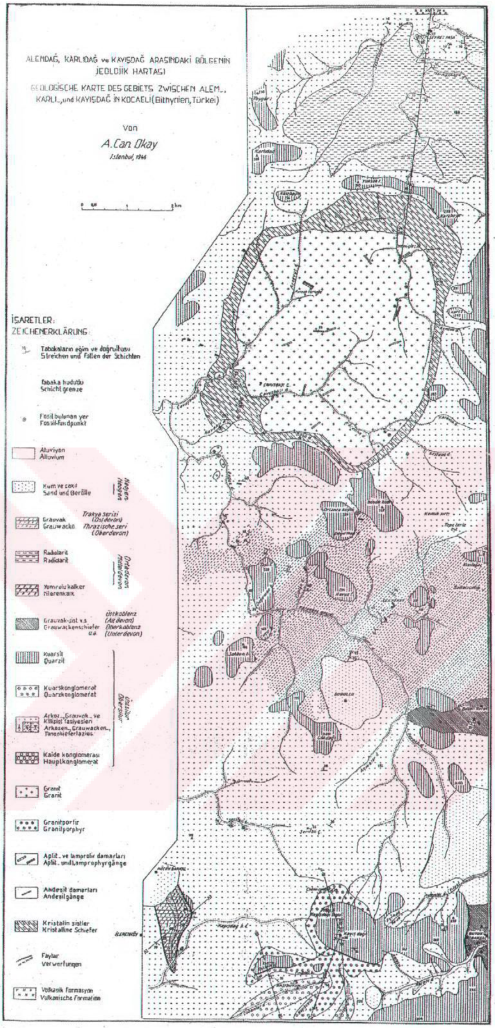

Figure 5.3. Geological map of the area bounded by Alemdağ, Karlıdağ and Kayışdağ (Okay, 1947).

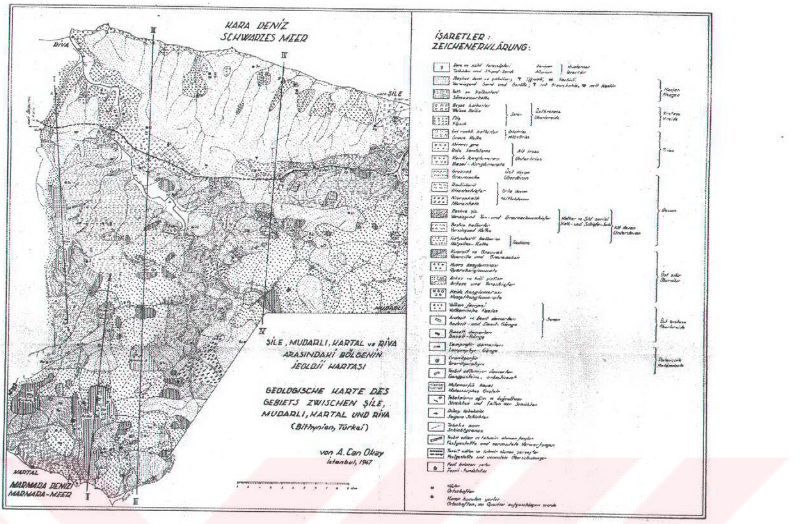

Figure 5.4. Geological map of the area bounded by Şile, Mudarlı, Kartal and Riva (Okay, 1948).

Erguvanlı (1949), in his study entitled "The Investigation of the Hereke Pudding and Gebze Stones with Respect to Construction and the Geology of the Vicinity", dicovered andesites cutting across Triassic units in the region (Figure 5.5).

Sayar (1960), made a geological map of the Istanbul Bosphorus and its environs based on the studies of E. Chaput, W. Paeckelmann, A. C. Okay, I. Ketin, C. Erentöz, K. Erguvanlı and McCallien (Figure 5.6). Sayar also depicted the dykes of the Istanbul area on this map.

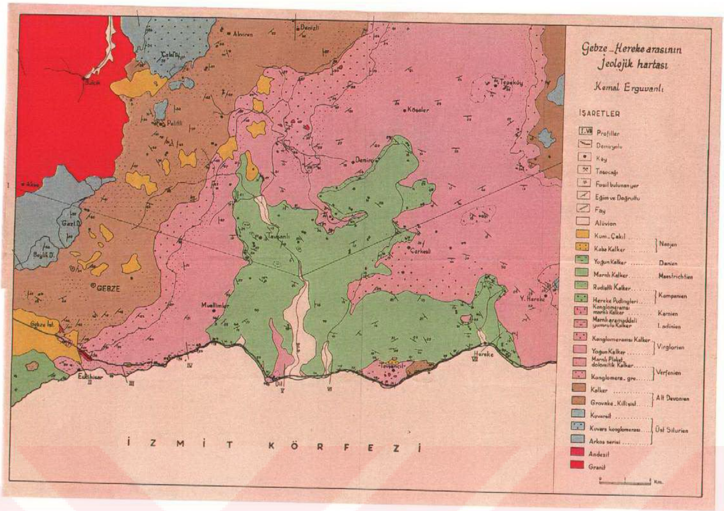

Figure 5.5. Geological map of the area between Gebze and Hereke (Erguvanlı, 1949).

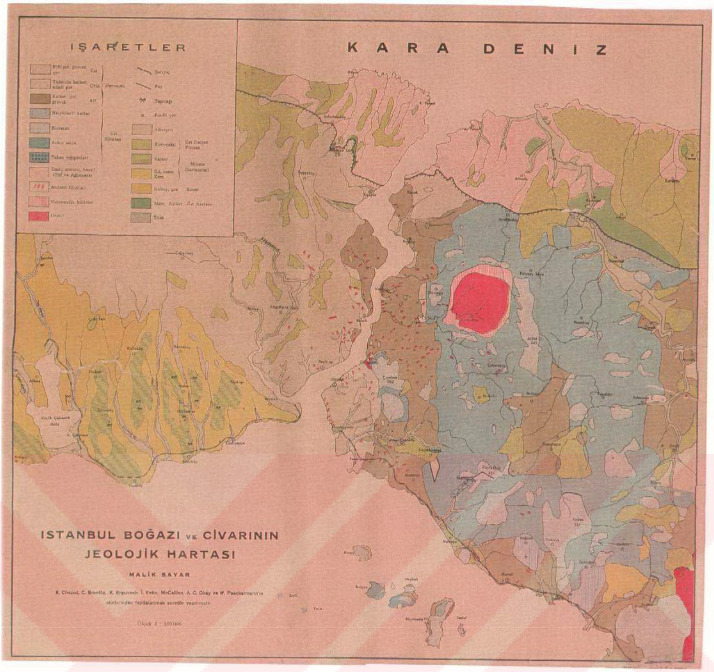

Figure 5.6. Geological map of the Istanbul Bosphorus and its environs (Sayar, 1960).

5.2. General Description of Dykes in Istanbul

In the Istanbul region 60 dykes were found; 39 of these dykes were clearly defined and described individually in this study. Most of these dyke sheets concentrated along the western and eastern coasts of the Istanbul Bosphorus cut across the Palaeozoic sediments. In addition, 2 dykes in the Tavşancıl region cut across the Triassic sediments and there are no dykes cutting across the Eocene units. Furthermore, there is a large granodiorite west of the Alemdağ which has intruded into the Palaeozoic sediments. The age of this granodiorite has been dated by the Rb/Sr method as 65+/-10 Ma, which corresponds to the Maastrichtian stage of the Upper Cretaceous (Öztunalı and Satır 1975). The presence of this Upper Cretaceous granodiorite indicates that there was volcanic activity in the region during that time. This is the most conclusive evidence for dating the age of the dykes. As a result, it can firmly be concluded that the dykes were formed during the Upper Cretaceous in the Istanbul region.

The dykes in Istanbul are generally light yellow, beige and green rocks with massive appearance and plenty of cracks. They are hard and resistant overall but altered in places. Their thickness varies from 10-20 cm to 10-11 m and their length exceeds tens of meters (Figure 5.7). The result of the petrographic studies indicate that the dykes are andesitic and basaltic with a porphyritic texture in the form of fine granular microlitic matrix containing plagioclase, hornblende and/or augite phenocrysts of lengths 1,5-3,5 mm.

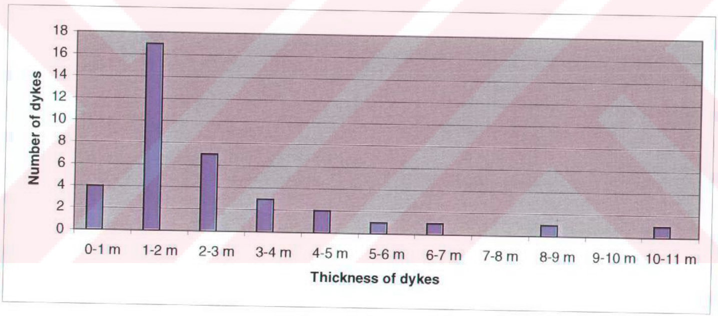

Figure 5.7. Thickness diagram of 39 dykes in the Istanbul region.

The strike of the dykes ranges from 35° to 120° with a concentration between 65° and 95° (Figure 5.8-5.9). The average strike of the dykes is consistent with a roughly east-west trending spreading ridge, and with a least compressive stress oriented north-south. The wide spread in the orientation of the dykes might be related to the vicinity of the West Black Sea Fault, which was active during the opening of the Black Sea basin and formed its western termination.

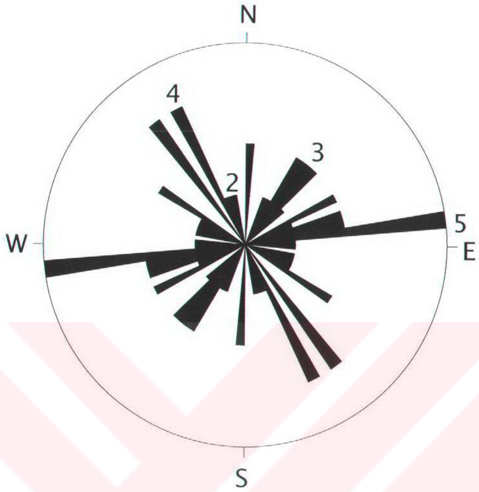

Figure 5.8. Strike diagram of 39 dykes in the Istanbul region.

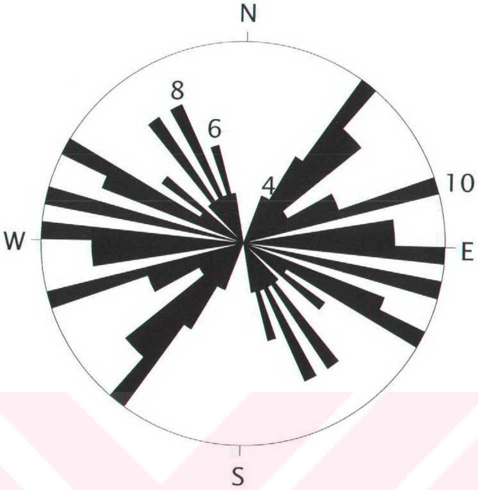

Figure 5.9. Strike diagram of 60 dykes in the Istanbul region.

5.3. Individual Dykes

60 individual dykes were located in the investigation area. Detailed investigations were carried out for 39 of these dykes (Table A.1, A.2, A.3). Below is a detailed description of the most prominent of these individual dykes presented in three categories: the European Coast, the Anatolian Coast and the Büyükada.

5.3.1 Category 1 : The European Coast

The European coast has arbitrarily been divided into eight regions for purposes of mapping precision. Photographs and pertaining data have also been provided (In all photomicrographs, the long dimension is 2 mm).

5.3.1.1 REGION 1 : TARABYA

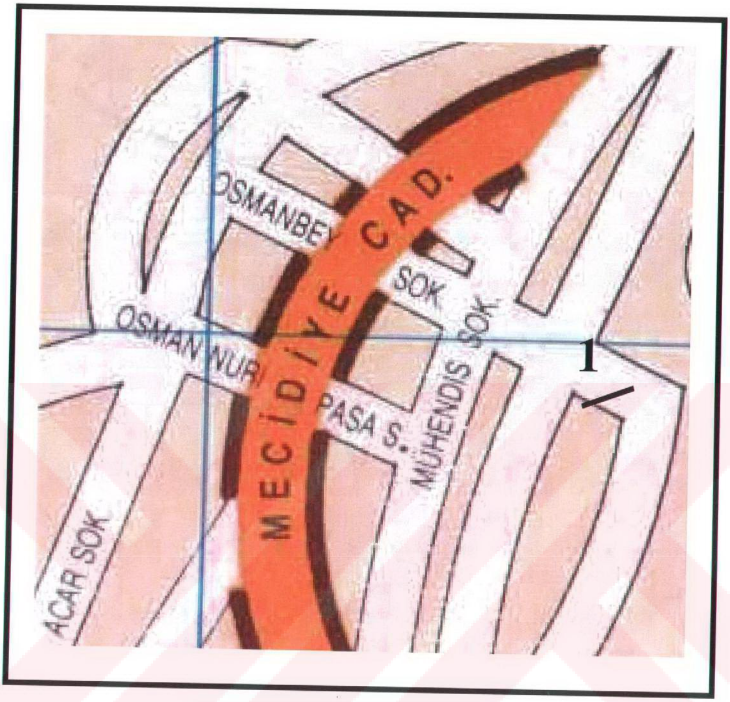

Figure 5.10. Location of dyke in Tarabya.

Figure 5.11. Andesite dyke intruding into Devonian siltstones, Tarabya (1).

Andesite dyke is yellowish beige, massive in appearance, slightly altered and deformed with plenty of cracks (Figure 5.11). There are crushed zones on the contact zone with the host rock. It has a thickness of 4 m. and a length of 13 m. minimum. The strike and the dip of the dyke are 70° / 90°.

It is composed of a fine granular matrix with porphyritic texture, containing plagioclase phenocrysts of lengths 2-4 mm. and hornblende micro-phenocrysts of lengths 0,5-1.0 mm.

The host rock is Devonian siltdstone, dark gray, hard and resistant in general but altered around the crushed zone, thin-bedded, deformed with plenty of cracks and interbedded with light green shale, which constitutes 10% of its mass. The strike and dip of bedding is 155° / 42° NE.

5.3.1.2 REGION 2 : AYAZAĞA

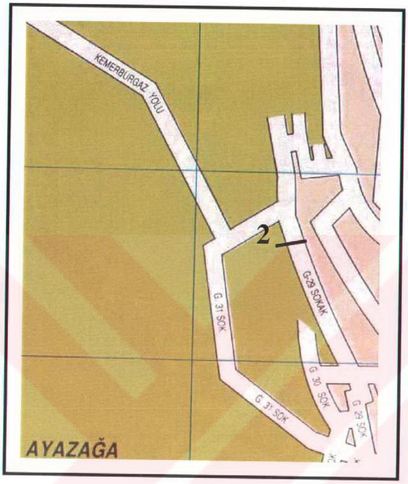

Figure 5.12. Location of dyke in Ayazağa.

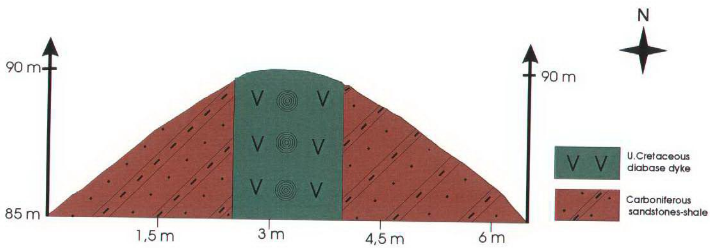

Figure 5.13. Sketch of acidic dyke intruding into Carboniferous shales, Ayazağa (2).

Highly decomposed acidic dyke is yellow, massive in appearance and altered, with onion-like exfoliation formations due to the alteration (Figure 5.13). It has a thickness of 1.5 m. and a length of 5 m. minimum. The strike and dip of the dyke are 80° / 90°.

The host rock is Carboniferous sandstone, brown, hard and resistant, medium/thick-bedded, deformed with a few cracks and interbedded with green shale, which constitutes 10% of its mass. The strike and dip of bedding is 5° / 50° SE.

5.3.1.3 REGION 3 : İSTİNYE - EMİRGAN

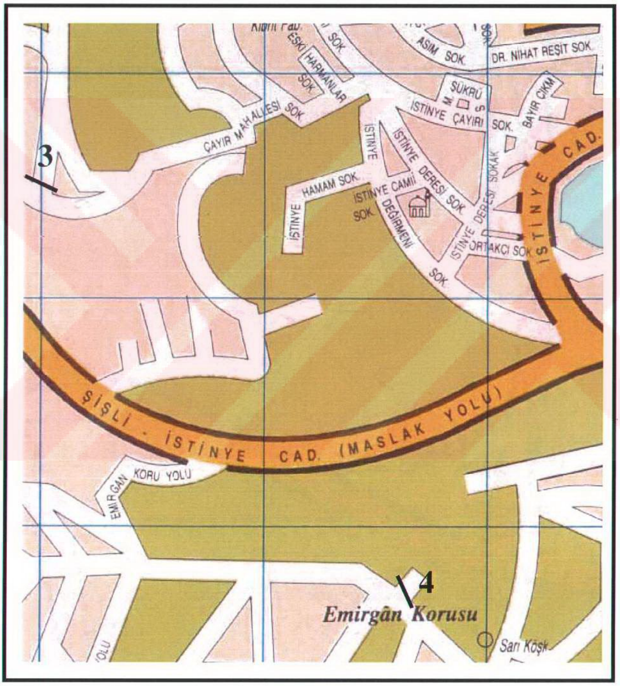

Figure 5.14. Locations of dykes in İstinye - Emirgan.

Figure 5.15. Andesite dyke intruding into Carboniferous clastics, İstinye (3).

Andesite dyke is yellowish beige, massive in appearance, very hard and resistant but slightly altered in places with plenty of cracks (Figure 5.15). It has a thickness of 2.70 cm. and a length of 6 m. minimum. The strike and dip of the dyke are 115° / 90°.

The petrographic study of the dyke has revealed that it is a fine granular microlitic matrix composed of 70% plagioclase and 30% hornblende phenocrysts with porphyritic texture (Figure 5.16-17).

The host rock is Carboniferous sandstone, dark brown, massive in appearance, altered and deformed with a few cracks.

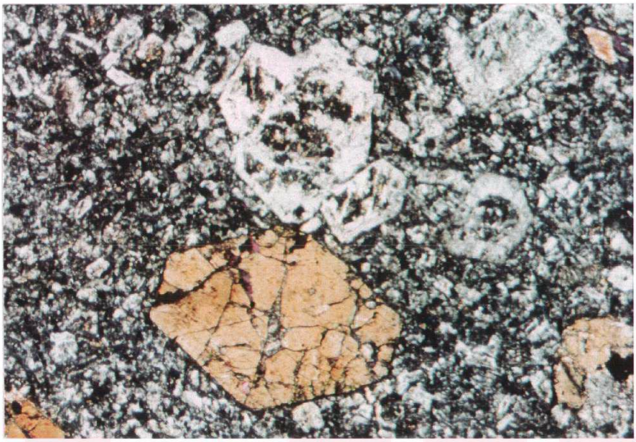

Figure 5.16. Photomicrographs from the andesite dyke, İstinye.

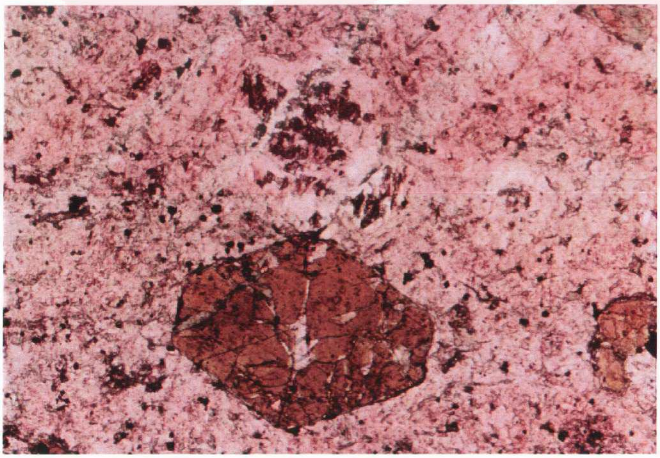

Figure 5.17. Photomicrographs from the andesite dyke, İstinye.

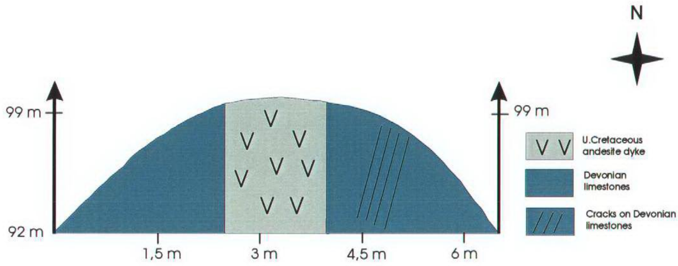

Figure 5.18. Sketch of andesite dyke intruding into Devonian limestones, Emirgan (4).

Andesite dyke is green, massive in appearance and altered. There are crushed zones on the contact zone with the host rock (Figure 5.18). It has a thickness of 1.5 m. and a length of 7 m. minimum. The strike and dip of the dyke are 155° / 90°.

It is composed of a fine granular microlitic matrix with porphyritic texture, containing plagioclase phenocrysts of lengths 1-5 mm. and hornblende micro-phenocrysts of lengths 0.4-1.0 mm.

The host rock is Devonien limestone, blue, quite hard and resistant, highly deformed with plenty of cracks and calcite veins.

5.3.1.4 REGION 4 : POLİGON

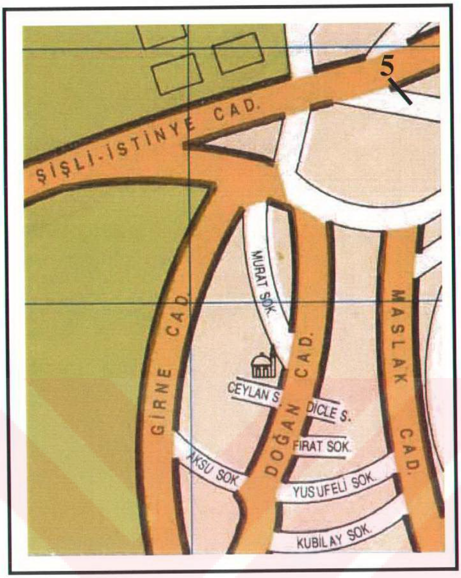

Figure 5.19. Location of dyke in Poligon.

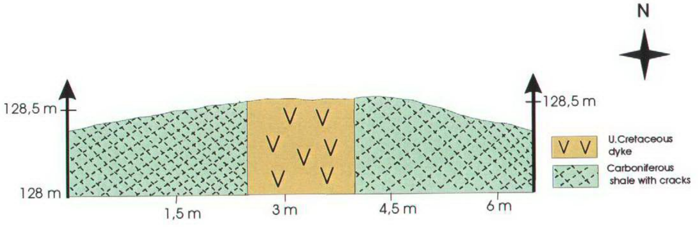

Figure 5.20. Sketch of the andesite dyke intruding into Carboniferous shales, Poligon (5).

Andesite dyke is light green, massive in appearance, very hard and resistant but deformed with plenty of cracks (Figure 5.20). There are crushed zones on the contact zone with the host rock. It has a thickness of 1.5 m. and a length of 50 cm. minimum. The strike and dip of the dyke are 140° / 90°.

It is composed of a fine granular microlitic matrix with porphyritic texture, containing plagioclase phenocrysts of lengths 1-4 mm. and hornblende micro-phenocrysts of lengths 0.4-0.7 mm.

The host rock is Carboniferous shale, light green, altered and highly deformed with plenty of cracks.

5.3.1.5 REGION 5 : I.T.U. CAMPUS

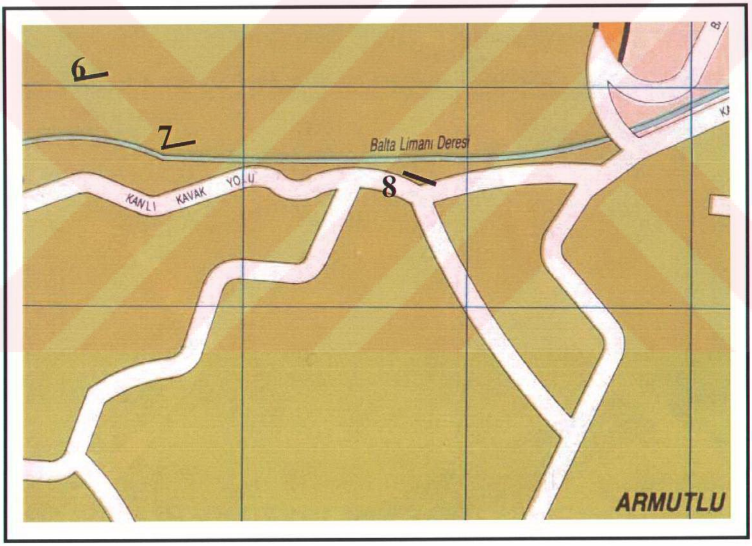

Figure 5.21. Locations of dykes in I.T.U. Campus.

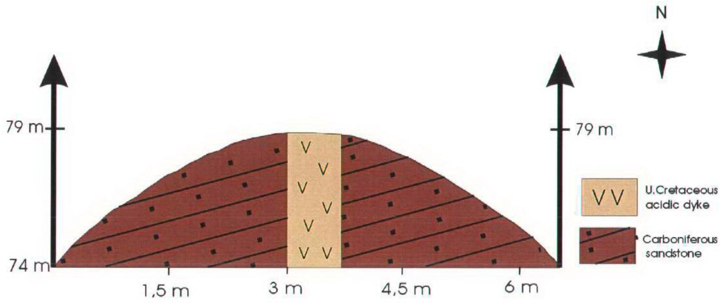

Figure 5.22. Sketch of the acidic dyke intruding into Carboniferous sandstones, I.T.U. Campus (6).

Highly decomposed acidic dyke is yellow, massive in appearance, altered and deformed with plenty of cracks (Figure 5.22). It has a thickness of 70 cm. and a length of 5 m. minimum. The strike and dip of the dyke are 80° / 90°.

The host rock is Carboniferous sandstone, brown, altered, medium/thick-bedded and highly deformed with plenty of cracks and crushed zones. The strike and dip of bedding is 35° / 15° SE.

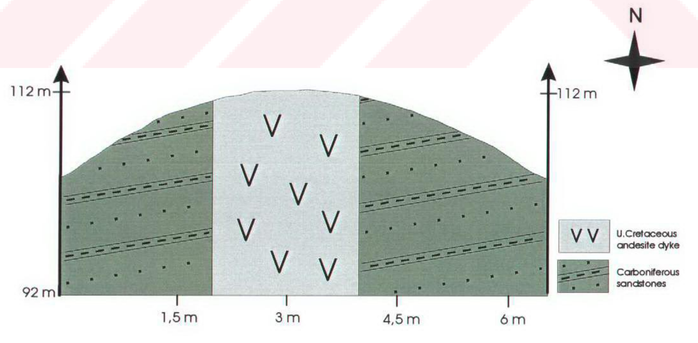

Figure 5.23. Sketch of andesite dyke intruding into Carboniferous sandstones, I.T.U. Campus (7).

Andesite dyke is green, massive in appearance, very hard and resistant, and deformed with plenty of cracks (Figure 5.23). It has a thickness of 2 m. and a length of 20 m. minimum. The strike and dip of the dyke are 80° / 90°.

It is composed of a fine granular matrix with porphyritic texture, containing plagioclase phenocrysts of lengths 2-3 mm. and hornblende micro-phenocrysts of lengths 0.5-1 mm..

The host rock is Carboniferous sandstone, dark green, hard and resistant, thick-bedded, deformed with plenty of cracks and interbedded with shale, which constitutes 10% of its mass. The strike and dip of bedding is 110° / 10° NE.

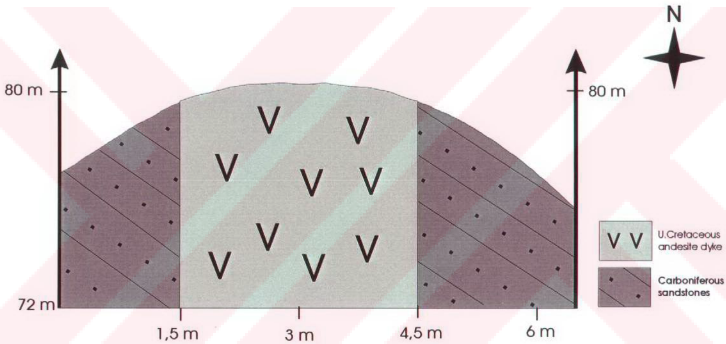

Figure 5.24. Sketch of the andesite dyke intruding into Carboniferous sandstones, I.T.U. Campus (8).

Andesite dyke is light green, massive in appearance, very hard and resistant and deformed with plenty of cracks (Figure 5.24). It has a thickness of 3 m. and a length of 8 m. minimum. The strike and dip of the dyke are 110° / 90°.

It is composed of a fine granular matrix with porphyritic texture, containing plagioclase phenocrysts of lengths 2-3 mm. and hornblende micro-phenocrysts of lengths 0.5-1 mm..

The host rock is Carboniferous sandstone, gray, hard and resistant, medium/thick-bedded and highly deformed with plenty of cracks. The strike and dip of bedding is 170° / 32° SW.

5.3.1.6 REGION 6 : BALTALİMANI

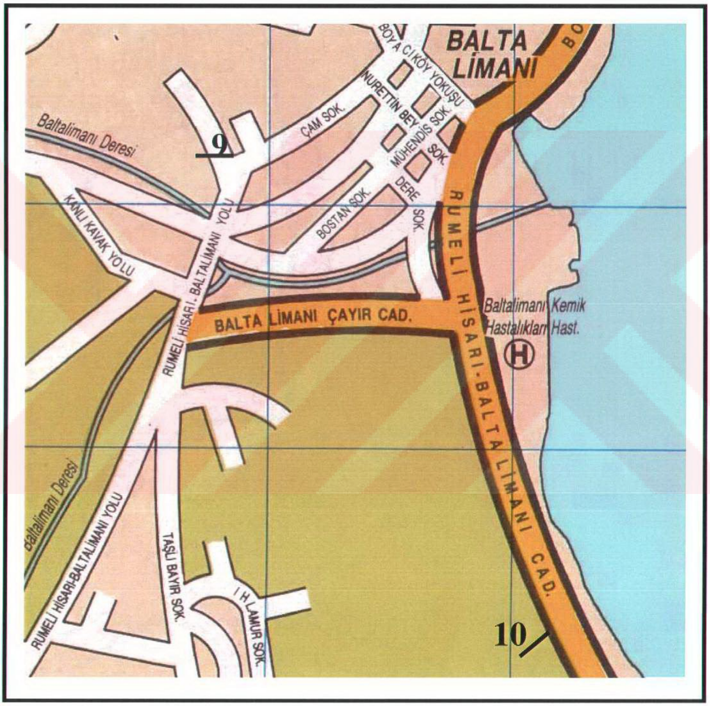

Figure 5.25. Locations of dykes in Baltalimanı.

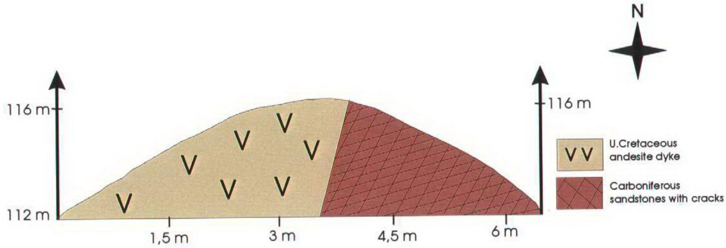

Figure 5.26. Sketch of andesite dyke intruding into Carboniferous sandstones, Baltalimanı (9).

Andesite dyke is light yellow, massive in appearance, very hard and resistant but altered in places, and deformed with plenty of cracks (Figure 5.26). It has a thickness of 2 m. minimum and a length of 4 m. minimum. The strike and dip of the dyke are 90° / 75°N.

It is composed of a fine granular matrix with porphyritic texture, containing plagioclase phenocrysts of lengths 1-5 mm. and hornblende micro-phenocrysts of lengths 0.4-0.9 mm..

The host rock is Carboniferous sandstone, altered, thin-bedded and deformed with plenty of cracks.

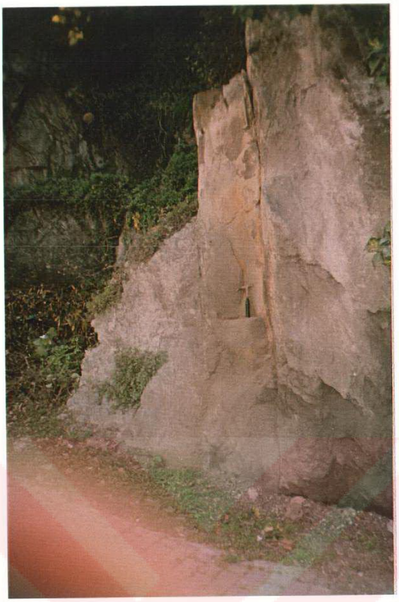

Figure 5.27. Diabase dyke intruding into Devonian limestones, Baltalimanı (10).

Diabase dyke is dark yellow, massive in appearance, very hard and resistant but altered in the contact zone with the host rock (Figure 5.27). It has a thickness of 1.5m. and a length of 15m. minimum. The strike and dip of the dyke are 30° / 82° NW.

It is composed of a fine granular matrix containing plagioclase and augite micro-phenocrysts and has intersertal texture.

The host rock is Devonian nodular limestone, blue in color, quite hard and resistant, medium/thick-bedded and interbedded with light blue shale, which constitutes 10% of its mass.

5.3.1.7 REGION 7 : BEBEK - ÇAMLIBAHÇE - ARNAVUTKÖY

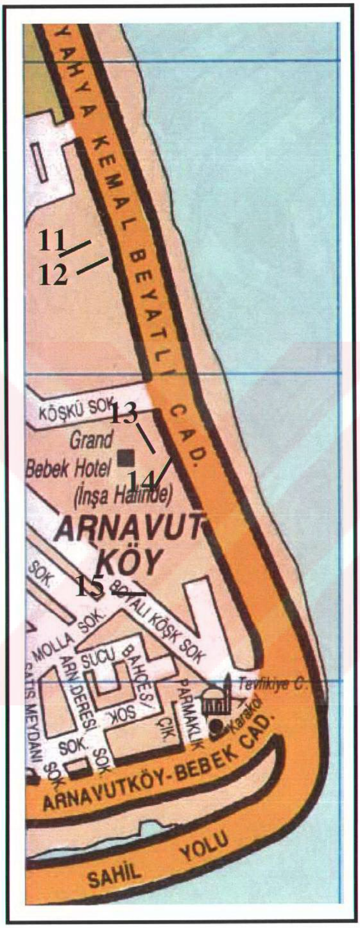

Figure 5.28. Locations of dykes between Bebek – Arnavutköy

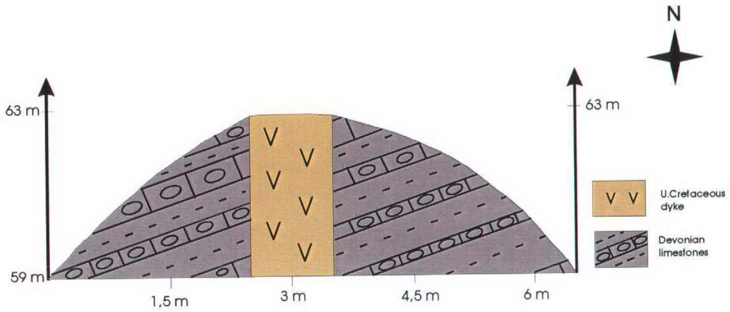

Figure 5.29. Sketch of acidic dyke intruding into Devonian limestones, Bebek (11).

Highly decomposed acidic dyke is yellow, massive in appearance and highly altered (Figure 5.29). It has a thickness of 60 cm. and a length of 4 m. minimum. The strike and dip of the dyke are 35° / 90°.

The host rock is Devonian nodular limestone, light gray in color, quite hard and resistant, thick-bedded and interbedded with dark gray shale, in amounts gradually decreasing from the bottom layers to the top. The bedding strike and dip are 135° / 20° SW.

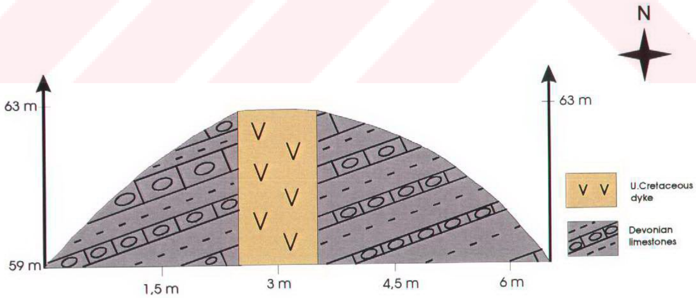

Figure 5.30. Sketch of andesite dyke intruding into Devonian limestones, Bebek (12).

Andesite dyke is yellow, massive in appearance, very hard and resistant but altered in places, and deformed with plenty of cracks (Figure 5.30). It has a thickness of 1 m. and a length of 4 m. minimum. The strike and dip of the dyke are 35° / 88° E.

It is composed of a fine granular microlitic matrix with porphyritic texture, containing plagioclase phenocrysts of lengths 1-3 mm. and hornblende micro-phenocrysts of lengths 0.4 mm. - 1 cm..

The host rock is Devonien nodular limestone, light green in color, quite hard and resistant, thick-bedded and interbedded with dark green shale, in amounts gradually decreasing from the bottom layers to the top. The bedding strike and dip are 135° / 20° SW.

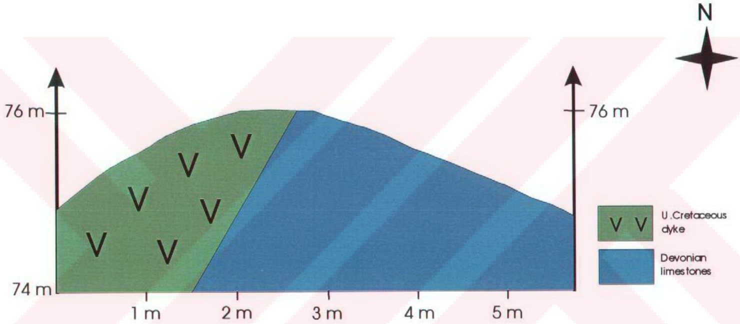

Figure 5.31. Diabase dyke intruding into Devonian limestones, Çamlıbahçe (13).

Diabase dyke is green, massive in appearance, very hard and resistant but slightly altered in places, and deformed with plenty of cracks (Figure 5.31). It has a thickness of 1,5 m. minimum and a length of 2 m. minimum. The strike and dip of the dyke are 150° / 60° NE.

It is composed of a fine granular microlitic matrix with porphyritic texture, containing plagioclase micro-phenocrysts of lengths 0.5-1 mm. and augite phenocrysts of lengths 1-4 mm.

The host rock is Devonian limestone, bluish green in color, massive in appearance and quite hard and resistant. It has calcite veins.

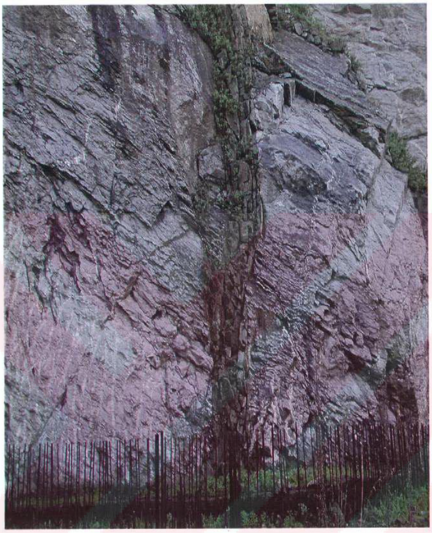

Figure 5.32. Diabase dyke intruding into Devonian limestones, Çamlıbahçe (14).

Diabase dyke is green, massive in appearance, very hard and resistant, and deformed with plenty of cracks (Figure 5.32). It has thin calcite veins. There is a crushed zone in the contact zone with the host rock. It has a thickness of 60 cm. and a length of 15 m. minimum. The strike and dip of the dyke are 60° / 90°.

It is composed of a fine granular microlitic matrix with porphyritic texture, containing plagioclase micro-phenocrysts of lengths 0.5-1 mm. and augite phenocrysts of lengths 1-4 mm.

The host rock is Devonian limestone, bluish green in color, massive in appearance and quite hard and resistant. It has calcite veins.

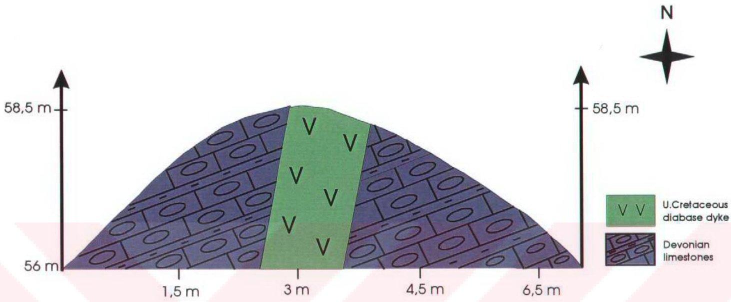

Figure 5.33. Sketch of diabase dyke intruding into Devonian limestones, Arnavutköy (15).

Diabase dyke is dark green, massive in appearance, and very hard and resistant. It has thin calcite veins (Figure 5.33). It has a thickness of 1 m. and a length of 2.5m. minimum. The strike and dip of the dyke are 92° / 80° N.

The petrographic study of the dyke has revealed that it is a fine granular microlitic matrix composed of 35% hornblende phenocrysts rods and 15% decomposed pyroxene (augite), randomly interspersed with 50% plagioclase phenocryst rods. It has intersertal texture (Figure 5.34-35).

The host rock is Devonien nodular limestone, blue in color, medium-bedded, quite hard and resistant with a few cracks and plenty of calcite veins. It is interbedded with light blue shale, which constitutes 10% of its mass. The bedding strike and dip are 75° / 20° NW.

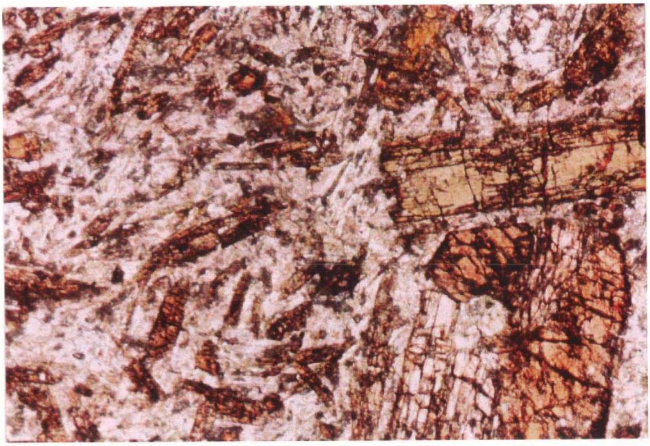

Figure 5.34. Photomicrographs from the diabase dyke, Arnavutköy.

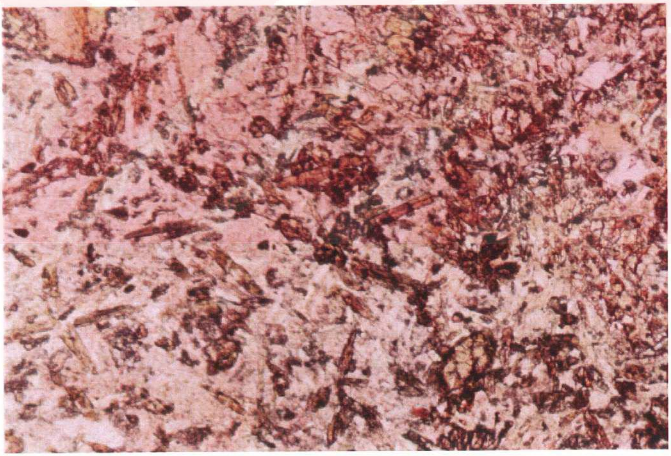

Figure 5.35. Photomicrographs from the diabase dyke, Arnavutköy.

5.3.1.8 REGION 8 : ULUS

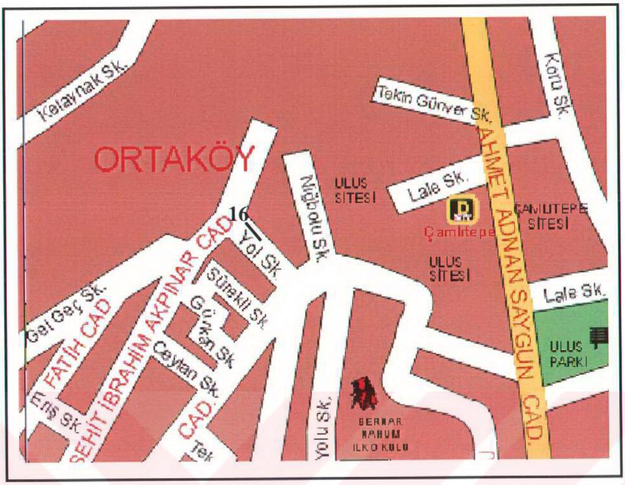

Figure 5.36. Location of dyke in Ulus.

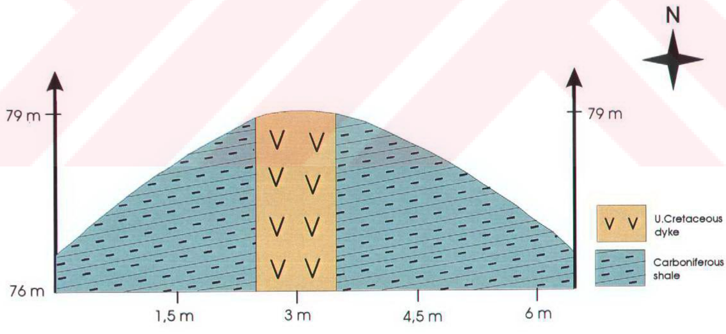

Figure 5.37. Sketch of acidic dyke intruding into Carboniferous shales, Ulus (16).

Highly decomposed acidic dyke is brown, massive in appearance, highly altered, and deformed with plenty of cracks (Figure 5.37). It has thin calcite veins. It has a thickness of 1 m. and a length of 3 m. minimum. The strike and dip of the dyke are 140° / 90°.

The host rock is Carboniferous shale, blue in color, slightly altered, thin/medium-bedded, highly deformed with crushed zones and plenty of cracks. The bedding strike and dip are 5° / 10° NW.

5.3.2 Category 2 : The Anatolian Coast

Dykes of the Anatolian coast have been presented in 13 groups for purposes of mapping precision. Photographs and pertaining data have also been provided (In all photomicrographs, the long dimension is 2 mm).

5.3.2.1 REGION 1 : YALIKÖY

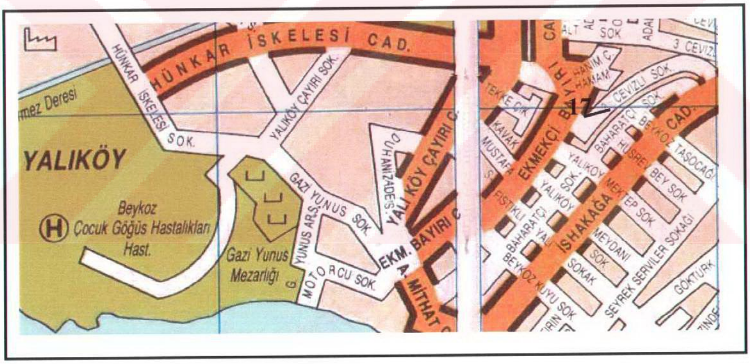

Figure 5.38. Detailed map of dyke in Yalıköy.

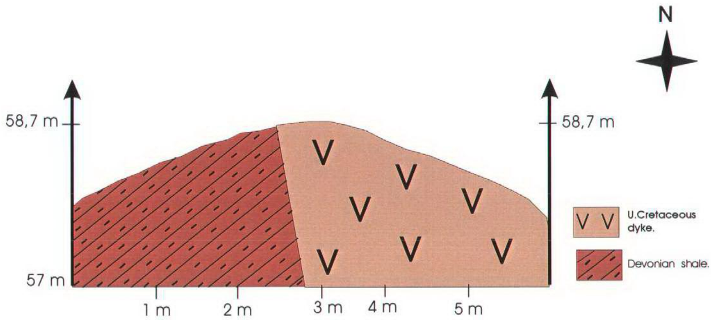

Figure 5.39. Sketch of andesite dyke intruding into Devonian shale, Yalıköy (17).

Andesite dyke is yellow, massive in appearance, altered and deformed with plenty of cracks (Figure 5.39). It has a thickness of 1 m. minimum and a length of 2 m. minimum. The strike and dip of the dyke are 75° / 82° SE.

It is composed of a fine granular matrix with porphyritic texture, containing plagioclase phenocrysts of lengths 1-3 mm and altered hornblende micro-phenocrysts of lengths 0.5-1 mm.

The host rock is Devonian shale, light brown in color, altered, thin-bedded and deformed with crushed zones and plenty of cracks. The bedding strike and dip are 175° / 42° NW.

5.3.2.2 REGION 2 : ZERZEVATÇI

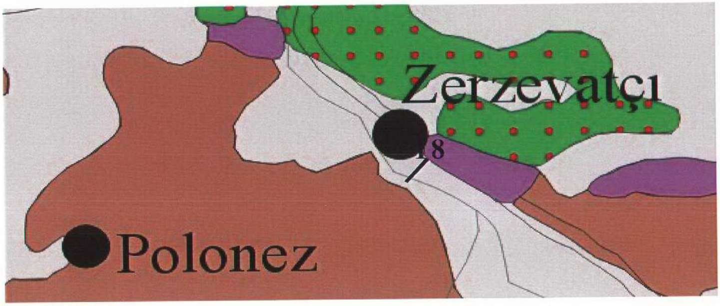

Figure 5.40. Location of dyke in Zerzevatçı.

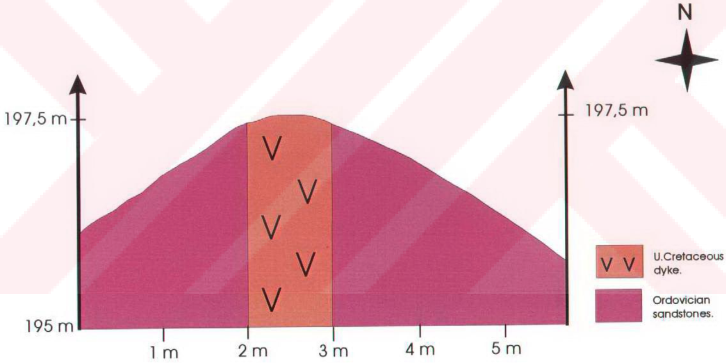

Figure 5.41. Sketch of diabase dyke intruding into Ordovician sandstones, Zerzevatçı (18).

Diabase dyke is brown, massive in appearance, very hard and resistant, and deformed with plenty of cracks (Figure 5.41). It has a crushed zone in the contact zone with the host rock. It has a thickness of 1 m. and a length of 3 m. minimum. The strike and dip of the dyke are 40° / 90°.

It is composed of a fine granular matrix with porphyritic texture, containing (clinopyroxene) augite phenocrysts of lengths 0.5-2 mm and plagioclase micro-phenocrysts.

The host rock is Ordovician sandstones, purple in color, massive in appearance, very hard and resistant but altered in places, and deformed with plenty of cracks. It has calcite veins with a thickness of 2 mm-3 cm.

5.3.2.3 REGION 3 : KANLICA

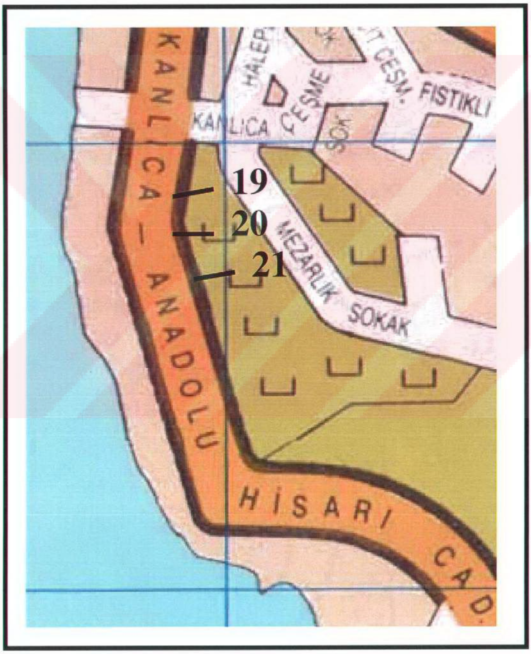

Figure 5.42. Location of dykes in Kanlıca.

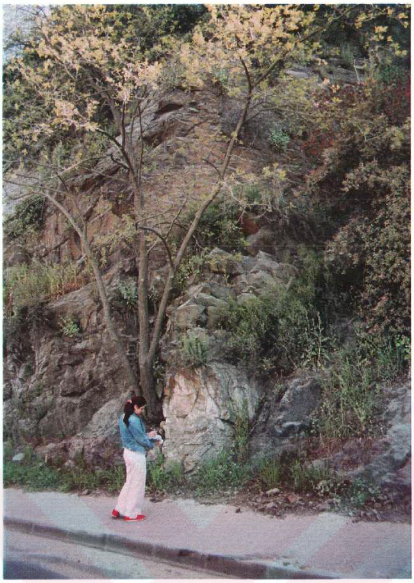

Figure 5.43. Diabase dyke intruding into Devonian sandstones, Kanlıca (19).

Diabase dyke is light green, massive in appearance, very hard and resistant, and deformed with plenty of cracks (Figure 5.43). It has a thickness of 1.80 m. and a length of 8 m. minimum. The strike and dip of the dyke are 80° / 90°.

The petrographic study of the dyke has revealed that it is composed of a fine granular matrix with intergranular texture, containing plagioclase micro-phenocrysts, highly decomposed clinopyroxene micro-phenocrysts and amphibole needles (Figure 5.44-45).

The host rock is Devonian limestone, blue in color, massive in appearance,very hard and resistant and deformed with plenty of cracks.

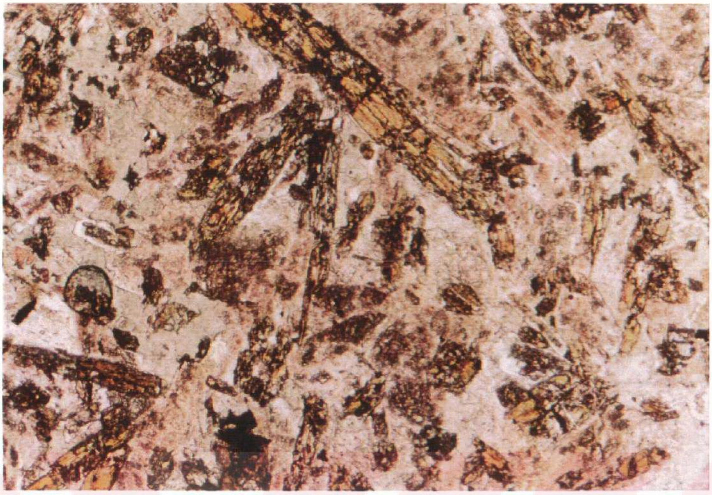

Figure 5.44. Photomicrographs from the diabase dyke, Kanlıca.

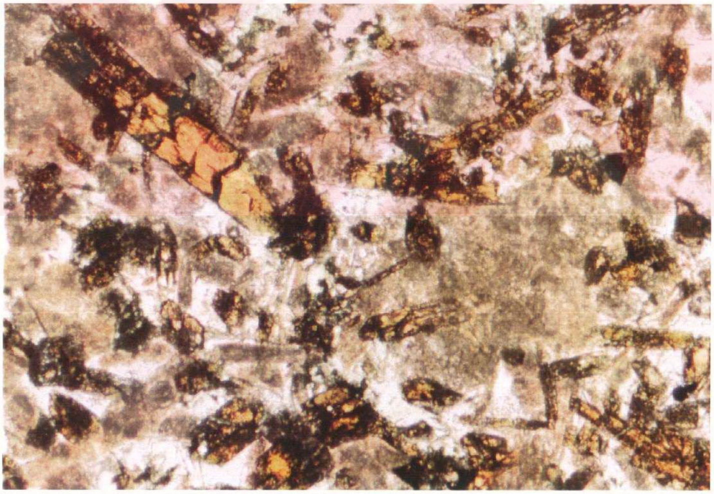

Figure 5.45. Photomicrographs from the diabase dyke, Kanlıca.

Figure 5.46. Diabase dyke intruding into Devonian limestones, Kanlıca (20).

Diabase dyke is green, massive in appearance, very hard and resistant, and deformed with an abundance of cracks (Figure 5.46). It has a thickness of 40 cm. and a length of 3 m. minimum. The strike and dip of the dyke are 90° / 90°.

The petrographic study of the dyke has revealed that it is composed of a fine granular matrix with intergranular texture, containing plagioclase micro-phenocrysts, chloritised pyroxene micro-phenocrysts and magnetite-ilmenite dilation zones (Figure 5.47-48).

The host rock is Devonian limestone, blue in color, massive in appearance,very hard and resistant and deformed with plenty of cracks.

Figure 5.47. Photomicrographs from the diabase dyke, Kanlıca.

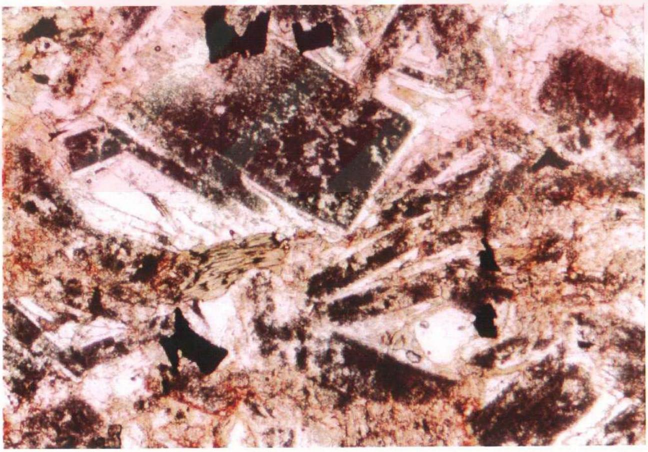

Figure 5.48. Photomicrographs from the diabase dyke, Kanlıca.

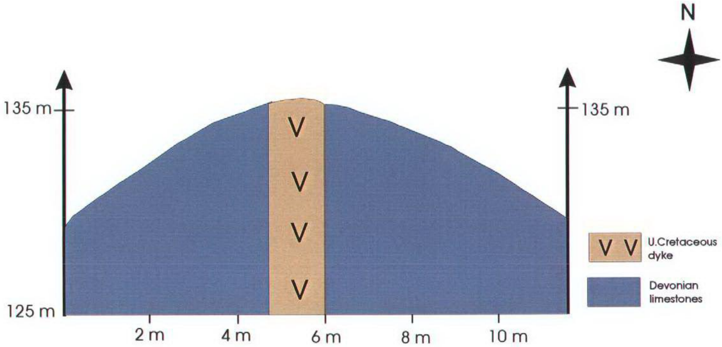

Figure 5.49. Sketch of andesite dyke intruding into Devonian limestones, Kanlıca (21).

Andesite dyke is yellow, massive in appearance, very hard and resistant, and deformed with a few of cracks (Figure 5.49). It has a thickness of 1 m. and a length of 10 m. minimum. The strike and dip of the dyke are 80° / 90°.

It is composed of a fine granular matrix with porphyritic texture, containing plagioclase phenocrysts of lengths 0,5-1,5 mm and hornblende phenocrysts of lengths 1-3 mm.

The host rock is Devonian limestone, blue in color, massive in appearance,very hard and resistant and deformed with plenty of cracks.

5.3.2.4 REGION 4 : ANADOLUHİSARI

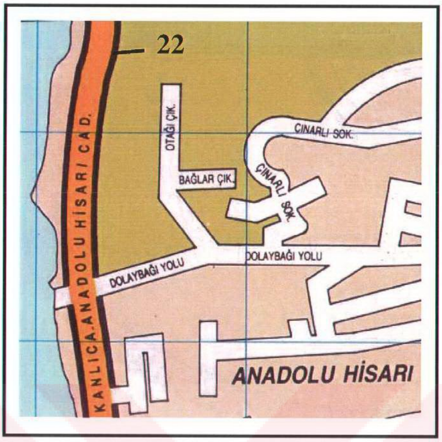

Figure 5.50. Location of dyke in Anadoluhisarı.

Figure 5.51. Diabase dyke intruding into Devonian shales, Anadoluhisarı (22).

Diabase dyke is green, massive in appearance, very hard and resistant, and deformed with an abundance of cracks (Figure 5.51). It has a thickness of 1 m. and a length of 3 m. minimum. The strike and dip of the dyke are 85° / 90°.

It is composed of a fine granular matrix with intergranular texture, containing plagioclase micro-phenocrysts and clinopyroxene micro-phenocrysts (augite).

The host rock is Devonian shale, bluish green in color, massive in appearance,slightly altered and highly deformed with an abundance of cracks.

5.3.2.5 REGION 5 : VANİKÖY

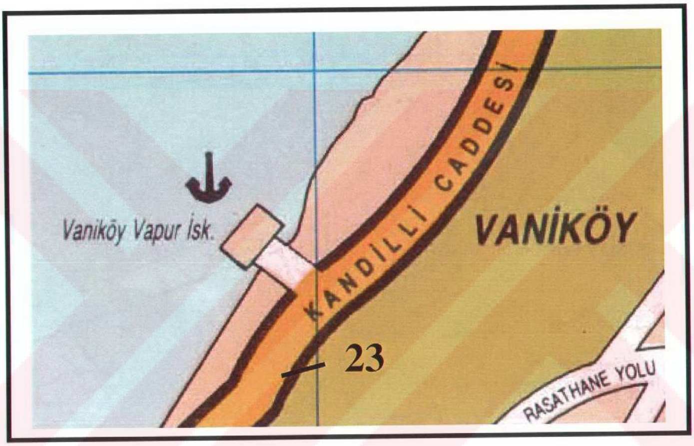

Figure 5.52. Location of dyke in Vaniköy.

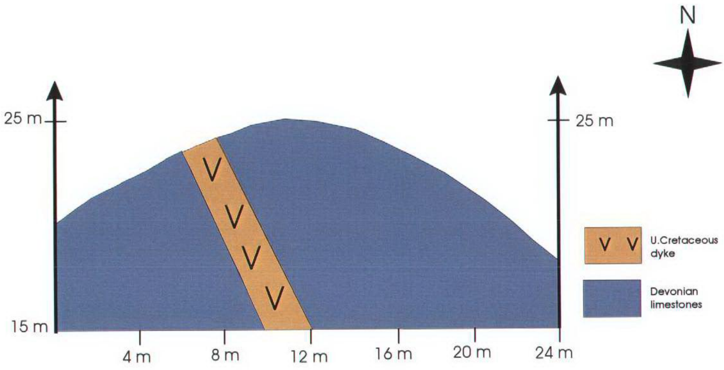

Figure 5.53. Sketch of andesite dyke intruding into Devonian limestone, Vaniköy (23).

Andesite dyke is yellow, massive in appearance, very hard and resistant, and deformed with a few cracks (Figure 5.53). It has a thickness of 4 m. and a length of 10 m. minimum. The strike and dip of the dyke are 75° / 65°NW.

It is composed of a fine granular matrix with porphyritic texture, containing plagioclase phenocrysts of lengths 0,5-1,5 mm, and hornblende phenocrysts of lengths 1-3 mm.

The host rock is Devonian limestone, blue in color, massive in appearance, very hard and resistant and deformed with crushed zones.

5.3.2.6 REGION 6 : BAHÇELİEVLER

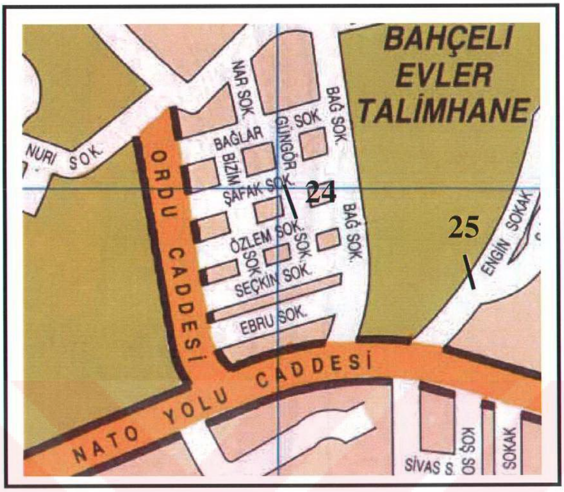

Figure 5.54. Location of dykes in Bahçelievler.

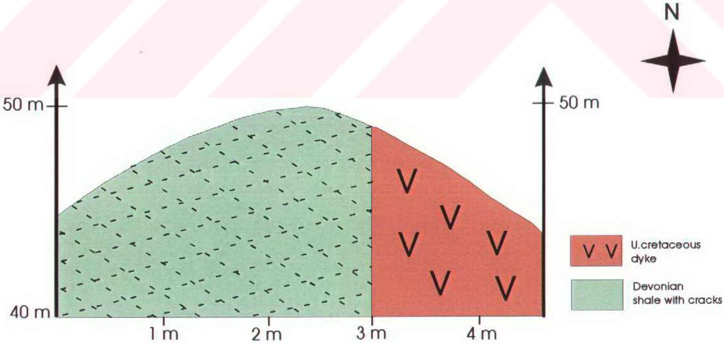

Figure 5.55. Sketch of andesite dyke intruding into Devonian limestone, Bahçelievler (24).

Andesite dyke is brown, massive in appearance, altered, and deformed with plenty of cracks (Figure 5.55). It has a thickness of 10 m. and a length of 2.5 m. minimum. The strike and dip of the dyke are 160° / 90°.

It is composed of a fine granular matrix with porphyritic texture, containing plagioclase phenocrysts of lengths 2-7 mm and hornblende micro-phenocrysts of lengths 1-3 mm.

The host rock is Devonian shale, light green in color, slightly altered, thin-bedded, highly deformed with an abundance of cracks.

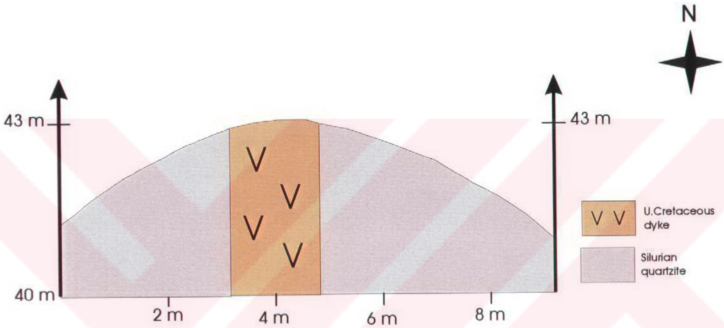

Figure 5.56. Sketch of acidic dyke intruding into Silurian quartzite, Bahçelievler (25).

Highly decomposed acidic dyke is yellow and massive in appearance (Figure 5.56). It has a thickness of 1.5 m. and a length of 3 m. minimum. The strike and dip of the dyke are 165° / 90°.

The host rock is Silurian quartzite, cream-white in color, white at the cross-section, very hard and resistant, bad-bedded and deformed with plenty of cracks.

5.3.2.7 REGION 7 : ÇEKMEKÖY

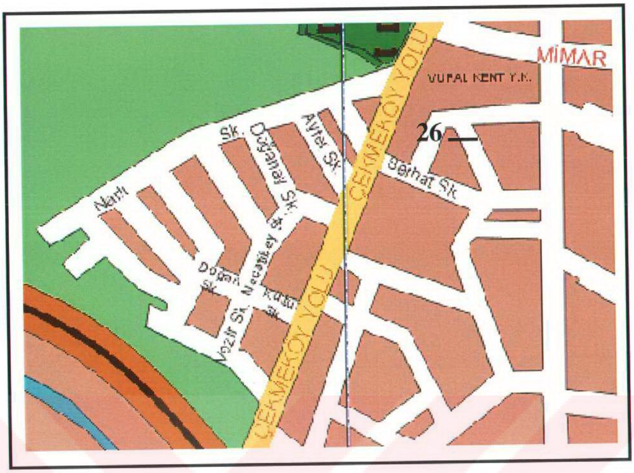

Figure 5.57. Location of dyke in Çekmeköy.

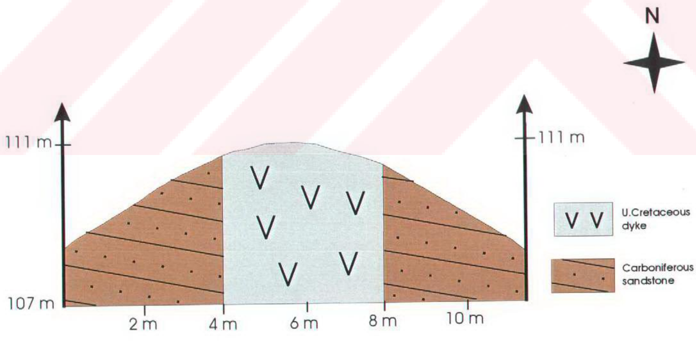

Figure 5.58. Sketch of andesite dyke intruding into Devonian limestone, Çekmeköy (26).

Andesite dyke is beige, massive in appearance, altered and deformed with plenty of cracks (Figure 5.58). It has a thickness of 2 m. and a length of 4 m. minimum. The strike and dip of the dyke are 150° / 90°.

It is composed of a fine granular matrix with porphyritic texture, containing plagioclase phenocrysts of lengths 1-7 mm and hornblende micro-phenocrysts of lengths 1-1,5 mm.

The host rock is Carboniferous sandstone, brown in color, very hard and resistant, medium/thick-bedded, deformed with plenty of cracks. It is interbedded with light green shale which constitutes 50% of its mass. The bedding strike and dip are 15° / 10° SE.

5.3.2.8 REGION 8 : DUDULLU

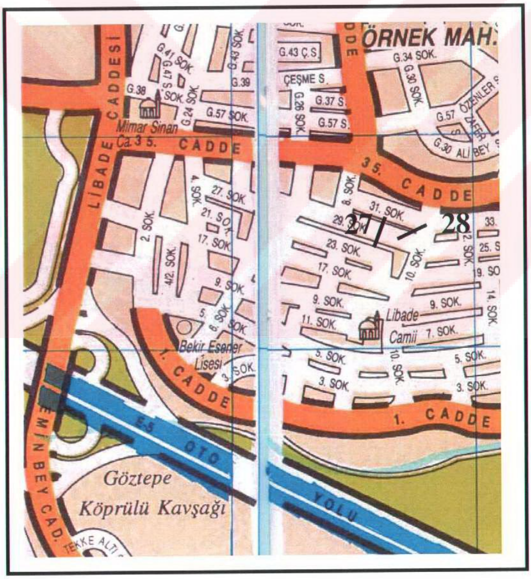

Figure 5.59. Location of dykes in Dudullu.

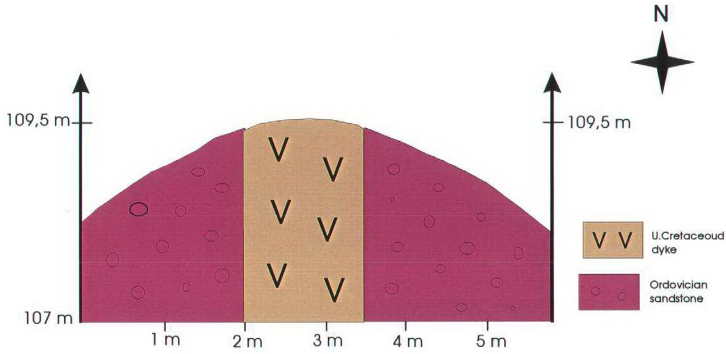

Figure 5.60. Sketch of diabase dyke intruding into Ordovician sandstone, Dudullu (27).

Andesite dyke is light yellow, massive in appearance, altered, and deformed with plenty of cracks (Figure 5.60). It has a thickness of 1.5 m. and a length of 4 m. minimum. The strike and dip of the dyke are 20° / 90°.

It is composed of a fine granular matrix with porphyritic texture, containing plagioclase phenocrysts of lengths 1-3 mm and hornblende micro-phenocrysts of lengths 0.5-1 mm.

The host rock is Ordovician sandstone, purple in color, massive in appearance, altered and deformed with plenty of cracks. It is composed of a fine granular matrix containing well-rounded pebbles of lengths 0.5-3 cm.

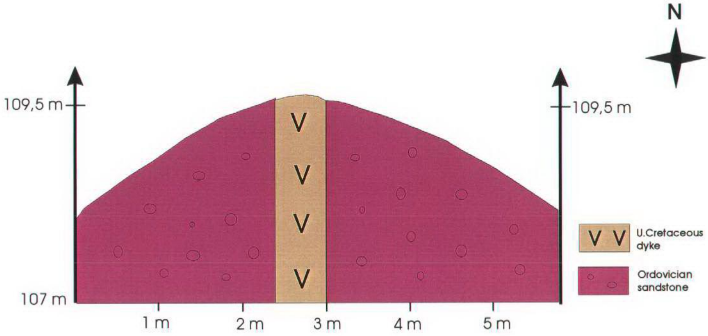

Figure 5.61. Sketch of andesite dyke intruding into Ordovician sandstone, Dudullu (28).

Highly decomposed acidic dyke is beige and massive in appearance (Figure 5.61). It has a thickness of 60 cm. and a length of 4 m. minimum. The strike and dip of the dyke are 65° / 90°.

The host rock is Ordovician sandstone, purple in color, massive in appearance, altered and deformed with plenty of cracks. It is composed of a fine granular matrix containing well-rounded pebbles of lengths 0.5-3 cm.

5.3.2.9 REGION 9 : ALTAY ÇEŞME

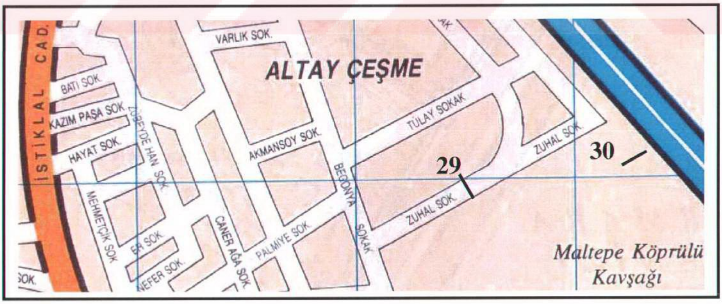

Figure 5.62. Locations of dykes in Altay Çeşme.

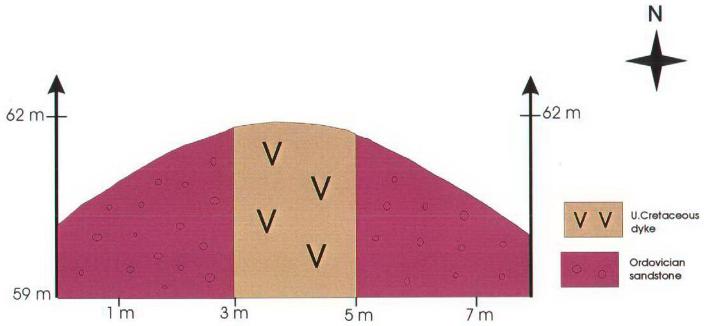

Figure 5.63. Sketch of diabase dyke intruding into Ordovician sandstone, Altay çeşme (29).

Andesite dyke is yellow, massive in appearance, altered and deformed with plenty of cracks (Figure 5.63). It has a thickness of 2 m. and a length of 3 m. minimum. The strike and dip of the dyke are 150° / 90°.

It is composed of a fine granular matrix with porphyritic texture, containing clinopyroxene (augite) phenocrysts of lengths 0.5-2 mm and plagioclase micro-phenocrysts.

The host rock is Ordovician sandstone, purple in color, massive in appearance, very hard and resistant and deformed with plenty of cracks. It is composed of a fine granular matrix containing well-rounded pebbles of lengths 0.5-2 cm.

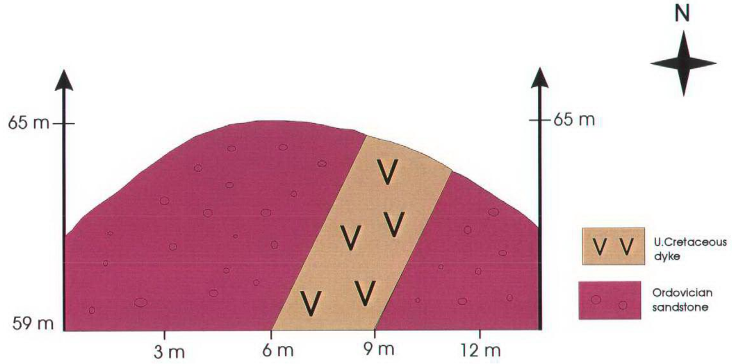

Figure 5.64. Sketch of andesite dyke intruding into Ordovician sandstone, Altay çeşme (30).

Andesite dyke is yellow, massive in appearance, very hard and resistant and deformed with plenty of cracks (Figure 5.64). It has a thickness of 3 m. and a length of 6 m. minimum. The strike and dip of the dyke are 65° / 60°NW.

It is composed of a fine granular matrix with porphyritic texture, containing clinopyroxene (augite) phenocrysts of lengths 0.5-2 mm and plagioclase micro-phenocrysts.

The host rock is Ordovician sandstone, purple in color, massive in appearance, very hard and resistant and deformed with plenty of cracks. It is composed of a fine granular matrix containing well-rounded pebbles of lengths 0.5-2 cm.

5.3.2.10 REGION 10 : MALTEPE

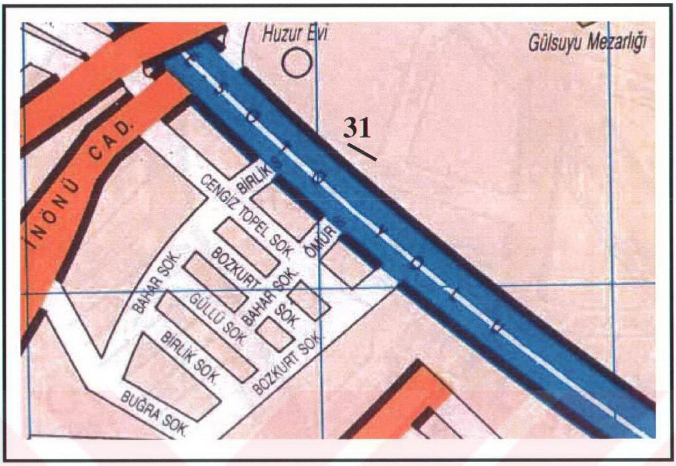

Figure 5.65. Location of dyke in Maltepe.

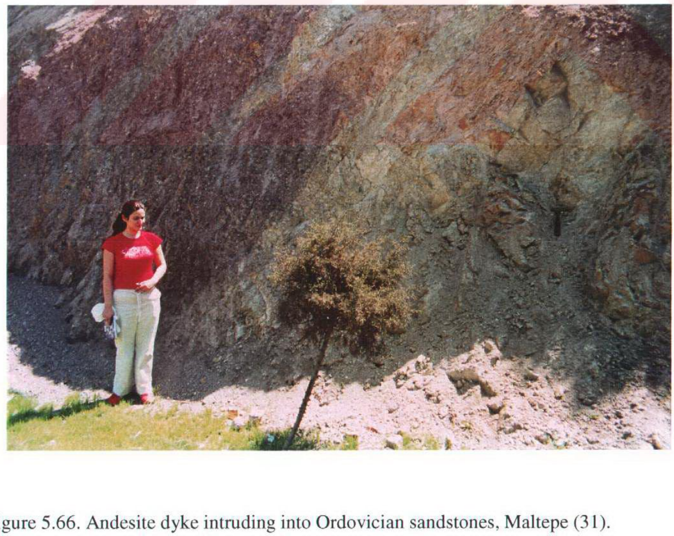

Figure 5.66. Andesite dyke intruding into Ordovician sandstones, Maltepe (31).

Andesite dyke is light yellow, massive in appearance, very hard and resistant but slightly altered in places (Figure 5.66). It has a thickness of 5 m. and a length of 12 m. minimum. The strike and dip of the dyke are 120° / 65°NE.

It is composed of a fine granular matrix with porphyritic texture, containing plagioclase phenocrysts of lengths 2-7 mm and hornblende phenocrysts of lengths 0.5-1 mm.

The host rock is Ordovician sandstonestone, purple in color, massive in appearance, very hard and resistant and deformed with plenty of cracks. It is composed of a fine granular matrix containing well-rounded pebbles of lengths 3 mm-1 cm.

5.3.2.11 REGION 11 : KURTKÖY

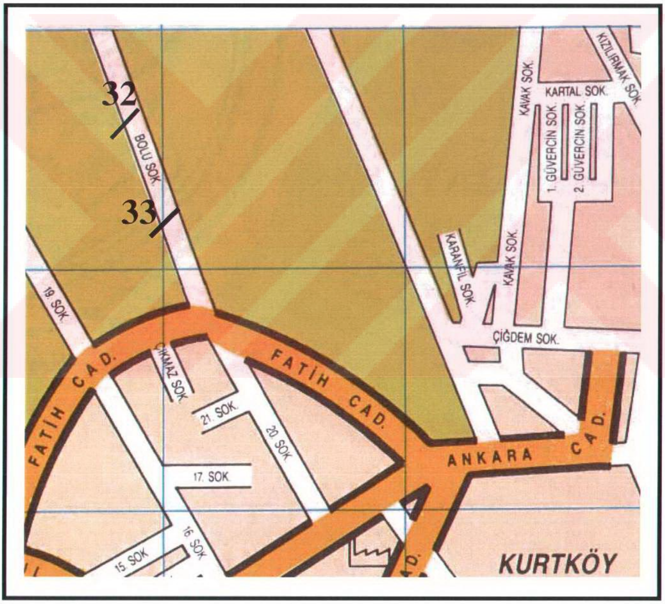

Figure 5.67. Locations of dykes in Kurtköy.

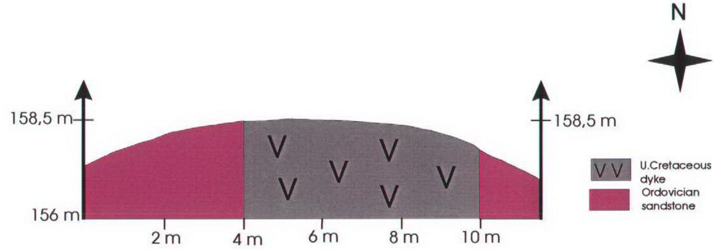

Figure 5.68. Sketch of acidic dyke intruding into Ordovician sandstone, Kurtköy (32).

Acidic dyke is gray, massive in appearance, very hard and resistant but altered in places and deformed with plenty of cracks (Figure 5.68). There is a crushed zone in the contact zone with the host rock. It has a thickness of 6 m. and a length of 2,5 m. minimum. The strike and dip of the dyke are 43° / 90°.

The host rock is Ordovician sandstonestone, purple in color, massive in appearance, very hard and resistant and deformed with plenty of cracks.

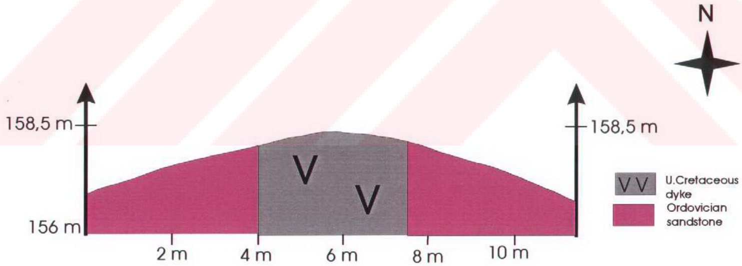

Figure 5.69. Sketch of acidic dyke intruding into Ordovician sandstone, Kurtköy (33).

Acidic dyke is gray, massive in appearance, altered and deformed with plenty of cracks (Figure 5.69). There is a crushed zone in the contact zone with the host rock. It has a thickness of 3,5 m. and a length of 2,5 m. minimum. The strike and dip of the dyke are 45° / 90°.

The host rock is Ordovician sandstonestone, purple in color, massive in appearance, very hard and resistant but altered in places and deformed with plenty of cracks. It has calcite veins with a thickness of 1 mm-2 cm.

5.3.2.12 REGION 12 : PENDİK

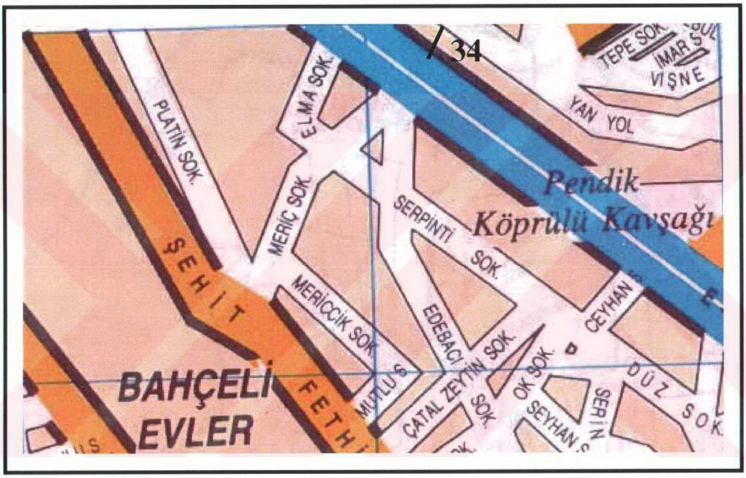

Figure 5.70. Location of dyke in Pendik.

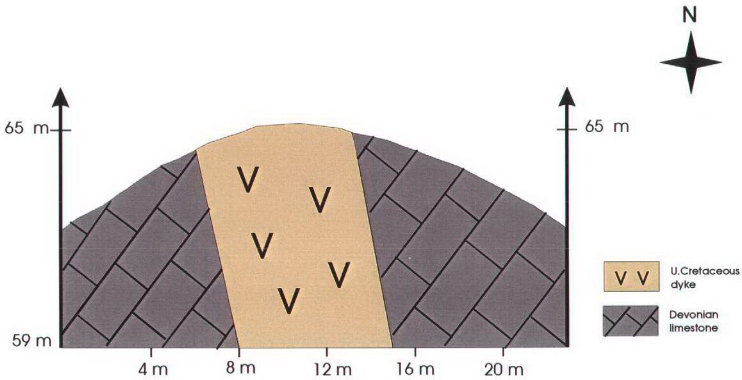

Figure 5.71. Sketch of andesite dyke intruding into Devonian limestone, Pendik (34).

Andesite dyke is light yellow, massive in appearance, altered, and deformed with plenty of cracks (Figure 5.71). It has a thickness of 5 m. and a length of 10 m. minimum. The strike and dip of the dyke are 25° / 80° SE.

It is composed of a fine granular matrix with porphyritic texture, containing plagioclase phenocrysts of lengths 1-4 mm and hornblende phenocrysts of lengths 0.5-1 mm.

The host rock is Devonian limestone, gray in color, very hard and resistant, medium/thick-bedded, deformed with crushed zones and plenty of cracks. It has a number of calcite veins. The bedding strike and dip are 160° / 53° SW.

5.3.2.13 REGION 13 : TAVŞANCIL

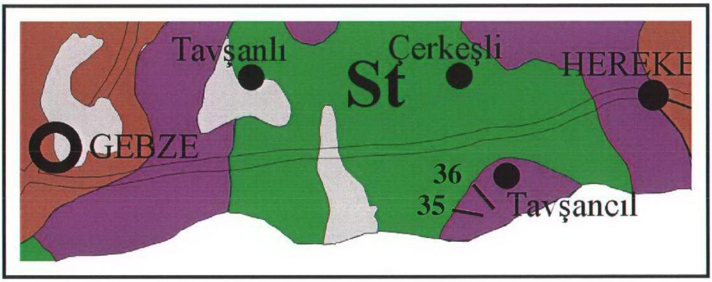

Figure 5.72. Locations of dykes in Tavşancıl.

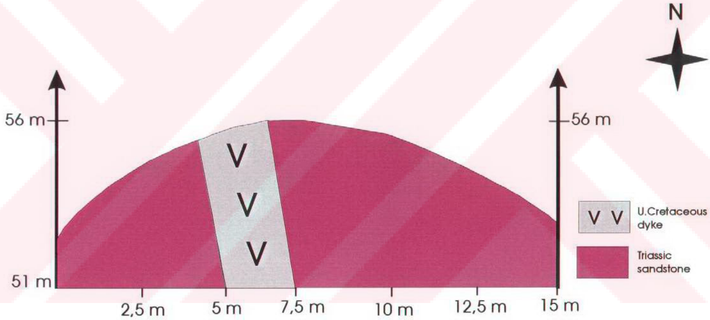

Figure 5.73. Sketch of andesite dyke intruding into Triassic sandstone, Tavşancıl (35).

Andesite dyke is beige, massive in appearance, slightly altered and deformed with plenty of cracks (Figure 5.73). It has a thickness of 1,5 m. and a length of 5 m. minimum. The strike and dip of the dyke are 100° / 80° NE.

It is composed of a fine granular matrix with porphyritic texture, containing plagioclase phenocrysts of lengths 1-4 mm and hornblende micro-phenocrysts of lengths 0.5-1 mm.

The host rock is Triassic sandstone, purple in color, massive in appearance, very hard and resistant, and deformed with crushed zones and plenty of cracks.

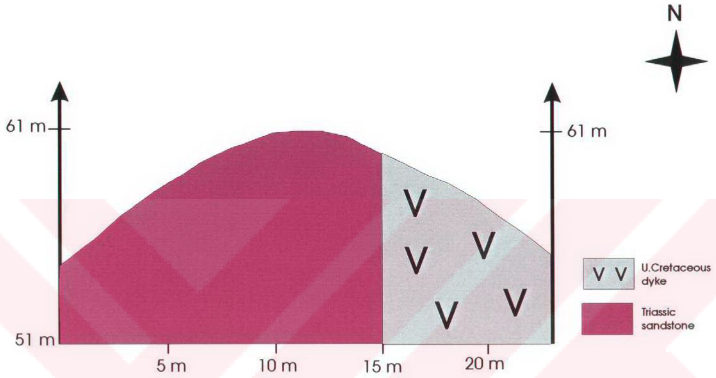

Figure 5.74. Sketch of andesite dyke intruding into Triassic sandstone, Tavşancıl (36).

Andesite dyke is beige, massive in appearance, slightly altered and deformed with plenty of cracks (Figure 5.74). There is a crushed zone in the contact zone with the host rock. It has a thickness of 8 m. minimum and a length of 10 m. minimum. The strike and dip of the dyke are 140° / 90°.

It is composed of a fine granular matrix with porphyritic texture, containing plagioclase phenocrysts of lengths 1-4 mm and hornblende micro-phenocrysts of lengths 0.5-1 mm.

The host rock is Triassic sandstone, purple in color, massive in appearance, very hard and resistant, and deformed with crushed zones and plenty of cracks.

5.3.3 Category 3 : Büyükada

Three dykes have been located on the Büyükada, one on the Cape of Dil, and two on the Cape of Ayine (Figure 5.75).

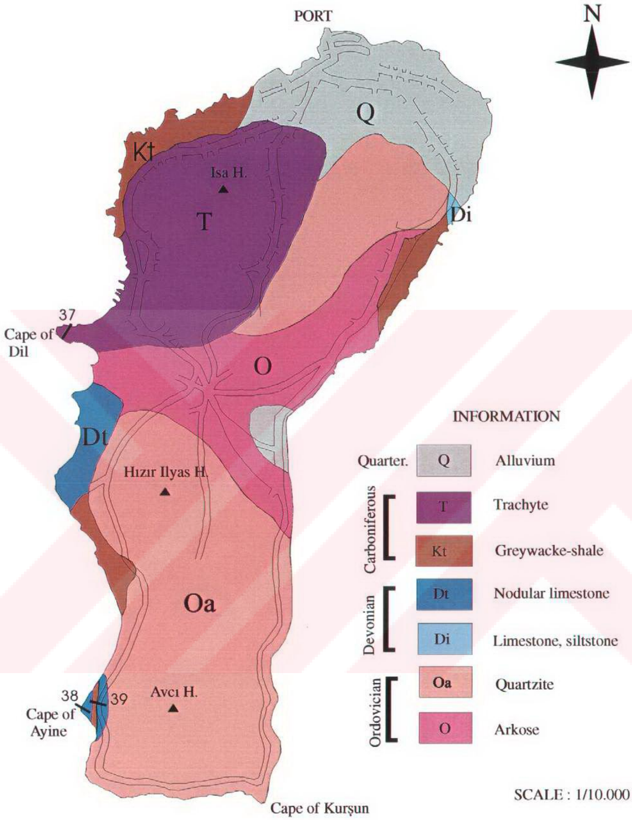

Figure 5.75. Geological map of Büyükada (Önalan, 1982 modified).

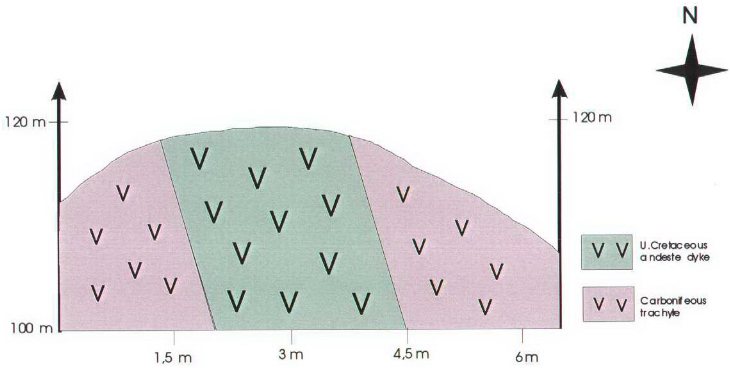

Figure 5.76. Sketch of andesite dyke intruding into Carbonif. Trachytes, Cape of Dil (37).

Andesite dyke is light pink, massive in appearance, and altered, with oxidized iron veins (Figure 5.76). It has a thickness of 2.5 m. and a length of 20 m. minimum. The strike and dip of the dyke are 32° / 75° NW.

It is composed of a fine granular matrix with porphyritic texture, containing decomposed plagioclase phenocrysts of lengths 1-2 mm and amphibole(hornblende) phenocrysts of lengths 0,5-1,5 mm.

The host rock is Carboniferous trachyte, light orange in color, hard and resistant, thin/medium-bedded, with plenty of oxidized iron veins. The bedding strike and dip are 35° / 50° SE.

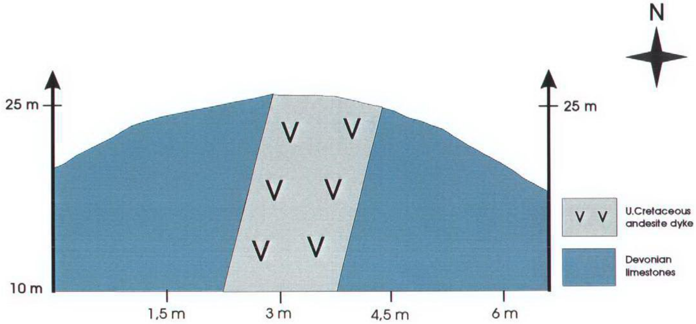

Figure 5.77. Sketch of andesite dyke intruding into Devonian limestones, Cape of Ayine (38).

Andesite dyke is beige, massive in appearance, very hard and resistant, and deformed with plenty of cracks (Figure 5.77). There is a crushed zone in the contact zone with the host rock. It has a thickness of 1.5 m. and a length of 15 m. minimum. The strike and dip of the dyke are 120° / 76° NE.

It is composed of a fine granular matrix with porphyritic texture, containing plagioclase phenocrysts of lengths 1-2 mm and amphibole(hornblende) phenocrysts of lengths 0,5-1,5 mm.

The host rock is Devonian nodular limestone, light blue in color, quite hard and resistant, medium/thick-bedded, folded in places and deformed with calcite veins and plenty of cracks. It is interbedded with gray shale, which constitutes 10% of its mass. There are a number of crushed zones.

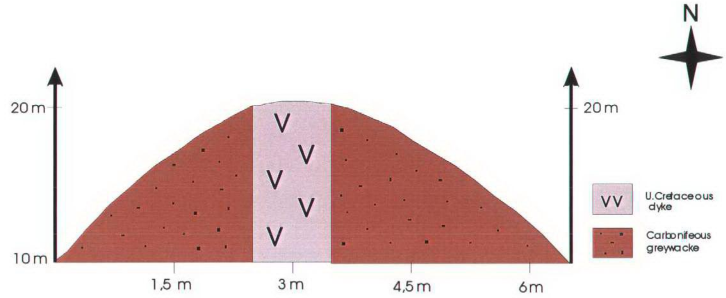

Figure 5.78. Sketch of acidic dyke intruding into Carbonif. greywacke, Cape of Ayine (39).

Acidic dyke is pinkish beige, massive in appearance, and highly altered with plenty of oxidized iron veins (Figure 5.78). There is a crushed zone in the contact zone with the host rock. It has a thickness of 2 m. and a length of 10 m. minimum. The strike and dip of the dyke are 105° / 90°.

It is composed of a fine granular matrix with porphyritic texture, containing plagioclase phenocrysts of lengths 1-3 mm. and amphibole (hornblende) micro-phenocrysts of lengths 0,5-1 mm..

The host rock is Carboniferous graywacke, brown in color, quite hard and resistant, bad-bedded, and deformed with plenty of cracks and oxidized iron veins.

6. DYKES AND STRESS

6.1. Stress

To understand stress a definition of force must first be made. Force is defined as a vector quantity which has both a magnitude (the amount of force) and a direction. A mass on which a force is acting moves in the direction of the force; however, where rocks are concerned, there is no motion. To conserve *Newton's Third Law of Motion*, in other words, to maintain equilibrium, a force acting on a rock is counterbalanced by the reaction of that rock, equal in magnitude but opposite in direction to the force. This system comprising two equal but opposite forces acting on a mass is called ***stress***. The magnitude of the stress depends on the magnitude of the force and on the size of the surface area on which it acts.

A force **F** acting on a mass is the product of two stresses. One stress acts perpendicular to the surface and is called ***normal stress***; the other acts parallel to the surface and is called ***shear stress*** (Figure 6.1).

As these concepts are to be used in actual rocks, stress must be analysed in three dimensions. In three dimensions shear stress in further resolved into τ_1 and τ_2 . The result is three stresses perpendicular to each other (Figure 6.2).

In a system where shear stresses are zero; in other words, $\tau_{xy} = \tau_{yz} = \tau_{zx} = 0$, there are three mutually perpendicular planes through which normal stresses cross. These planes are called ***principal stress planes*** and the normal stresses across them are called ***principal stress axes.*** These axes have been designated σ_1 , σ_2 and σ_3 . σ_1 is the greatest principal stress, σ_2 is the intermediate, and σ_3 is the least principal stress. Stress at any point described by giving the direction and magnitudes of these principal stresses. These three mutually perpendicular stress axes are called ***the stress axial cross*** (Figure 6.4).

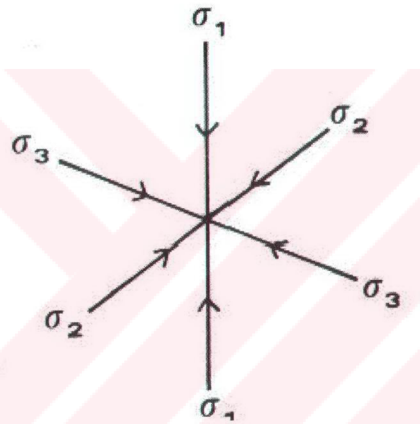

Figure 6.4. The stress axial cross (principal stress axes $\sigma_1 > \sigma_2 > \sigma_3$).

6.2. The Dynamics of Dyke Formation Related Stress

The formation of dykes involves forces that are connected with their intrusion, regional pattern, mutual arrangement and their effects on the structure and attitude of the enclosing rocks. Most dykes are formed by the intrusion of magma into a fissure via dilating the host rock by the effect of tensional forces (Marinoni, 2000).

There is general horizontal stress acting on the body of dykes in transverse directions (Anderson, 1951). If magmatic pressure is even slightly greater than the general horizontal pressure, tension will develop at the tip of the magma in a horizontal direction. The plane on which the tension acts naturally curves. On the surfaces of the curved plane, extension tension develops, while on the other side of the plane compression tension develops. At a point where the tension is maximum, a fracture begins. This fracture is usually perpendicular to the plane through which it develops. Magma moves up through this fracture and solidifies into a dyke. In the majority of cases dykes form their own paths as explained. However, in a few number of cases they have invaded pre-existent and nearly vertical faults which may be parallel or transverse to the general direction of the dyke system.

There are magma reservoirs far below the crust of the Earth, and that the magma probably wedges through the irregularities of the surrounding rocks in places where the magma pressure is greater than the principal pressures of the rocks (Anderson, 1951).

In the Istanbul region 60 dykes were found; 39 of these, the contact zone of which could be seen clearly, were included in this study. The strike of these 39 dykes ranges from 45° to 160° with a concentration between 80° and 150°. The trend of these dyke sheets allows an estimate of the minimum compressive stress (σ_3), based on the fact that dykes are normally emplaced along planes perpendicular to the direction of the minimum principal compressive stress (σ_3) (Anderson, 1936; Polard, 1987). This trend is expected to be perpendicular to the spreading axis in the West Black Sea basin.

Istanbul region during that time, which indicates the dykes in the region were formed during the Upper Cretaceous.

The dykes in Istanbul are generally light yellow, beige and green rocks with massive appearance and plenty of cracks. They are hard and resistant overall but altered in places. Their thickness varies from 10-20 cm to 10-11 m and their length exceeds tens of meters (Figure 5.7). The result of the petrographic studies indicate that the dykes are andesitic and basaltic with a porphyritic texture in the form of fine granular microlitic matrix containing plagioclase, hornblende and/or augite phenocrysts of lengths 1,5-3,5 mm.

The distrubution of the strikes of the dykes in the Istanbul region, the total 60 and the best 39, are shown in Figures7.1 and 7.2 respectively. As shown in Figure 7.2, the greatest concentration of the strikes is at N 80° E which is consistent with a roughly east-west trending spreading ridge, and with a least compressive stress oriented north-south. Thus, it is most probably related to the opening of the West Black Sea Basin. As also shown in Figure 7.2 the weak concentration of the strikes is at N 45° E which might be related to the vicinity of the West Black Sea Fault. This fault was active during the opening of the Black Sea basin and formed its western termination. In the same figure, there is a third dykes concentration at N 150° E. However the reason for this dyke concentration is not clear. It may have been caused by the stress created during the intrusion of the large granodiorite into the Palaeozoic sediments west of Alemdağ.

7. CONCLUSIONS

The main investigation area covers the city of Istanbul in general (Figure 1). Detailed investigations were carried out on both the European and Asian coasts of the Istanbul Bosphorus.

The 15-km-thick sedimentery infill that covers the West Black Sea basin masks any magnetic anomaly pattern that may be present in the Black Sea oceanic crust. Thus, there is no direct information on the orientation of the spreading ridge and on the stress pattern during the opening of the Black Sea. The purpose of this study was to solve this problem through a detailed geometrical study of the Cretaceous dyke swarms in the Istanbul region south of the Black Sea.

The stratigraphy of the investigation area, as seen in Figure 3.2, is made up of a transgressive sedimentary sequence composed of arkose, quartzite, sandstone, shale, limestone and chert ranging from Ordovician to Carboniferous. In the north of Istanbul, this Palaeozoic sequence is thrust northward over the Upper Cretaceous volcanosediments . On the east of the investigation area the Palaeozoic sequence is unconformably overlain by Triassic aged units composed of conglomerate, limestone and sandstone. The Triassic sequence is in turn unconformably overlain by Upper Cretaceous (Maastrichtian) sediments composed of limestone and chert . All of these units in the investigation area are unconformably overlain by Eocene aged units composed of marn, shale and sandstone.

In the Istanbul region 60 dykes were found; 39 of these dykes were clearly defined and described individually in this study. Most of these dyke sheets concentrated along the western and eastern coasts of the Istanbul Bosphorus cut across the Palaeozoic sediments. In addition, 2 dykes in the Tavşancıl region cut across the Triassic sediments and there are no dykes cutting across the Eocene units. Furthermore, there is a large granodiorite west of the Alemdağ which has intruded into the Palaeozoic sediments. The age of this granodiorite has been dated by the Rb/Sr method as 65+/-10 Ma, which corresponds to the Maastrichtian stage of the Upper Cretaceous. According to this evidence, there was volcanic activity in the

The stress at any point of a mass can be illustrated on a cube (Figure 6.3). Since this cube represents a very small point, the forces acting on each surface maybe considered equal in magnitude. In figure 6.3 the letter **F** has been designated to represent these forces. The force acting on each surface can be resolved into three components (the figure only includes 3 of the forces for purposes of clarity), all perpendicular to each other. Since stress is a system in which there is no motion the components of the forces which correspond to shear stress, namely τ_1 and τ_2 must balance. In other words, $\boldsymbol{\tau_{xy}} = \boldsymbol{\tau_{yx}}$ $\boldsymbol{\tau_{xz}} = \boldsymbol{\tau_{zx}}$ and $\boldsymbol{\tau_{yz}} = \boldsymbol{\tau_{zy}}$. Therefore there are, in effect, six stress components, three of which are normal stresses $\boldsymbol{\sigma_x}$, $\boldsymbol{\sigma_y}$, $\boldsymbol{\sigma_z}$, and three shear stresses, $\boldsymbol{\tau_{xy}}$, $\boldsymbol{\tau_{yz}}$, $\boldsymbol{\tau_{zx}}$.

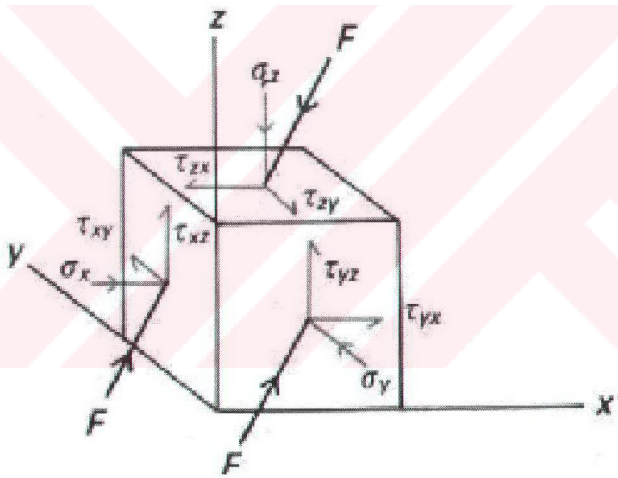

Figure 6.3. Stress components for an infinitesimal cube acted on by opposed compressive forces F.

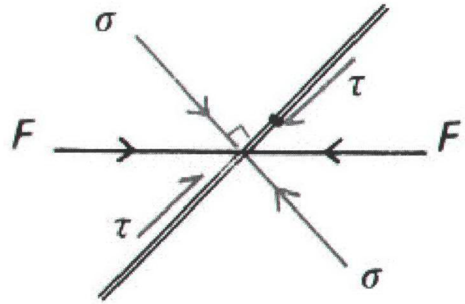

Figure 6.1. Normal stress σ perpendicular to the plane and shear stress τ parallel to the plane produced by opposed forces F acting on a plane (in two dimensions).

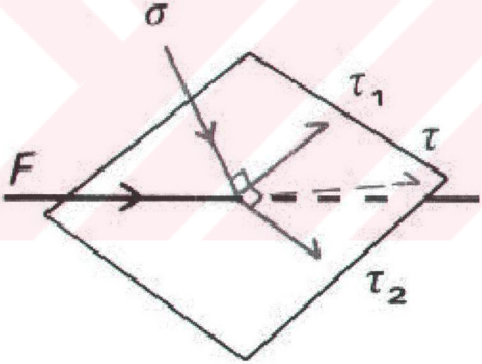

Figure 6.2. In three dimensions, shear stress τ can be further resolved into τ_1 and τ_2 at right angles giving three stresses, all mutually at right angles, resulting from the forces F.

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APPENDIX A TABLES

Table A.1. Dyke locations and sizes in the European coast of Istanbul.

OBSERVATION NUMBER	LOCATION	GPS VALUE	STRIKE AND DIP DIRECTION	THICKNESS AND LENGTH
1	Tarabya	N:41° 08,07' E:29° 02,97	70 / 90 [1] ☻☻☻	T: 4,0 m. L: 13,0 m. (min.)
2	Ayazağa	N:41° 07,37' E:28° 59,80'	80 / 90 ☻☻☻	T: 1.5 m. L: 5,0 m. (min.)
3	İstinye	N:41° 07,56' E:29° 02,23'	115 / 90 ☻☻☻	T: 2.7 m. L: 6,0 m. (min.)
4	Emirgan	N:41° 06,69' E:29° 03,37'	155 / 90 [2] ☻☻	T: 1.5 m. L: 7,0 m. (min.)
5	Poligon	N:41° 06,69' E:29° 02,43'	140 / 90 ☻☻	T: 1.5 m. L: 50 cm. (min.)
6	I.T.U Cam.	N:41° 06,06' E:29° 01,31'	80 / 90 ☻☻☻	T: 70 cm. L: 5,0 m. (min.)
7	I.T.U Cam.	N:41° 05,90' E:29° 01,63'	80 / 90 ☻☻☻	T: 2,0 m. L: 20,0 m. (min.)
8	I.T.U Cam.	N:41° 05,94' E:29° 01,00'	110 / 90 ☻☻☻	T: 3,0 m. L: 8,0 m. (min.)
9	Baltalimanı	N:41° 05,91' E:29° 02,96'	90 / 75 N ☻☻☻	T: 2,0 m. (min.) L: 4,0 m. (min.)
10	Baltalimanı	N:41° 05,59' E:29° 03,29'	30 / 82 NW ☻☻☻	T: 1.5 m L: 15,0 m. (min.)
11	B.Bebek	N:41° 04,39' E:29° 02,67'	35 / 88 SE ☻☻	T: 1,0 m. L: 4,0 m. (min.)
12	B.Bebek	N:41° 04,39' E:29° 02,67'	35 / 90 ☻☻	T: 60 cm. L: 4,0 m. (min.)
13	Çamlıbahçe	N:41° 04,19' E:29° 02,71'	150 / 60 ☻☻☻	T: 1,5 m. (min.) L: 2,0 m. (min.)
14	Çamlıbahçe	N:41° 04,19' E:29° 02,71'	60 / 90 ☻☻☻	T: 60 cm. L: 10,0 m. (min.)
15	Arnavutköy	N:41° 04,18' E:29° 02,68'	92 / 80 N ☻☻☻	T: 1,0 m. L: 2.5 m. (min.)
16	Ulus	N:41° 03,91' E:29° 01,64'	140 / 90 ☻☻☻	T: 1,0 m. L: 3,0 m. (min.)

[1] ☻☻☻ Dyke contact zone with host rock best defined.

[2] ☻☻ Dyke contact zone with host rock moderately defined.

Table A.2. Dyke locations and sizes in the Anatolian coast of Istanbul.

OBSERVATION NUMBER	LOCATION	GPS VALUE	STRIKE AND DIP DIRECTION	THICKNESS AND LENGTH
17	Yalıköy	N:41° 08,87' E:29° 05,95'	75 / 82 SE ●●	T:1,0 m. L:2,0 m. (min.)
18	Zerzevatçı	N:41° 06,86' E:29° 09,47'	40 / 90 ●●	T:1,0 m. L:3,0 m. (min.)
19	Kanlıca	N:41° 05,84' E:29° 03,85'	80 / 90 ●●	T:1,8 m. L:8,0 m. (min.)
20	Kanlıca	N:41° 05,84' E:29° 03,89'	90 / 90 ●●●	T:40 cm. L:3,0 m. (min.)
21	Kanlıca	N:41° 05,84' E:29° 03,89'	80 / 90 ●●●	T:1,0 m. L:10,0 m. (min.)
22	Anadoluhisarı	N:41° 05,44' E:29° 04,02'	85 / 90 ●●	T:1,0 m. L:3,0 m. (min.)
23	Vaniköy	N:41° 03,74' E:29° 03,24'	75 / 65 NW ●●	T:4,0 m. L:10,0 m. (min.)
24	Üsküdar	N:41° 03,35' E:29° 04,71'	160 / 90 ●●	T:10,0 m. (min.) L:2,5 m. (min.)
25	Üsküdar	N:41° 03,33' E:29° 04,05'	165 / 90 ●●●	T:1,5 m. L:3,0 m. (min.)
26	Çekmeköy	N:41° 02,22' E:29° 10,40'	150 / 90 ●●●	T:2,0 m. L:4,0 m. (min.)
27	Dudullu	N:41° 00,57' E:29° 09,38'	20 / 90 ●●●	T:1,5 m. L:4,0 m. (min.)
28	Dudullu	N:41° 00,57' E:29° 09,38'	65 / 90 ●●●	T:60 cm. L:4,0 m. (min.)
29	Maltepe	N:40° 56,33' E:29° 08,14'	150 / 90 ●●●	T:2,0 m. L:3,0 m. (min.)
30	Maltepe	N:40° 56,33' E:29° 08,14'	60 / 65 NW ●●●	T:3,0 m. L:6,0 m. (min.)
31	Maltepe	N:40° 55,87' E:29° 08,67'	120 / 65 NE ●●●	T:5,0 m. (min.) L:12,0 m. (min.)
32	Kurtköy	N:40° 55,35' E:29° 17,86'	43 / 90 ●●●	T:6,0 m. L:2,5 m. (min.)
33	Kurtköy	N:40° 55,35' E:29° 17,86'	45 / 90 ●●●	T:3,5 m. L:2,5 m. (min.)
34	Pendik	N:40° 52,86' E:29° 15,01'	25 / 80 SE ●●●	T:5,0 m. L:1,0 m. (min.)
35	Tavşancıl	N:40° 46,22' E:29° 34,16'	100 / 80 NE ●●	T:1,5 m. L:5,0 m. (min.)
36	Tavşancıl	N:40° 46,22' E:29° 34,16'	140 / 90 ●●	T:8,0 m. L:10,0 m. (min.)

Table A.3. Dyke locations and sizes in Büyükada.

OBSERVATION NUMBER	LOCATION	GPS VALUE	STRIKE AND DIP DIRECTION	THICKNESS AND LENGTH
37	Cape of Dil	N:40° 51,67' E:29° 06,80'	32/ 75 NW ☻ ☻	T: 2,5 m. L: 20,0 m. (min.)
38	Cape of Ayine	N:40° 49,20' E:29° 06,60'	120 / 76 NE ☻ ☻ ☻	T: 1.5 m. L: 15,0 m. (min.)
39	Cape of Ayine	N:40° 49,20' E:29° 06,60'	105 / 90 ☻ ☻ ☻	T: 2,0 m. L: 10,0 m. (min.)

APPENDIX B THE GEOLOGICAL MAP OF ISTANBUL