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SOME GEOMORPHOLOGICAL FEATURES OF THE ORHANELİ PLUTON: IMPLICATIONS FOR DENUDATION HISTORY

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ABSTRACT.- The granitic intrusions of variable age of cooling, size and mineral composition are widely exposed in the northwest Anatolia, Turkey. The nearly circular Orhaneli Pluton emplaced during the Early Eocene with some 15 km in diameter, is one of such plutonic bodies. Geomorphological features of the pluton is discussed here with special emphasis given on the denudation history. To this end, evidences from two isolated Inselberg-like hills as remnants of roof rocks in the centre of the pluton and episodically emergence of granite landforms of etch origin after unroofing process were investigated. Field data reveal the absence of granodiorite clasts within Early to Middle Miocene lacustrine deposits in the north of the pluton, implying that the pluton might has not been exposured prior to Upper Miocene as a whole. After the first exposure, the granite landforms, such as boulders, corestones and tors constituting sound evidence of an etch origin, became exposured by continual removing of regolith cover by surficial runoff. These forms of various scale were formed at first by subsurface weathering and shaped by surficial weathering processes after any stages of removal of the regolith cover. Drainage segments accounted for removal of regolith is mostly structurally controlled defined by NW-SE, NE-SW and N-S-aligned fracture systems.

Key words: Differential weathering, Weathering front, Regolith, Orhaneli Pluton, NW Turkey.

INTRODUCTION

Granite masses and associated terrains cover wide areas in the northwestern part of Anatolia, Turkey (Figure 1). One of them is the Orhaneli Granodiorite Pluton that lies within latitudes 39°52'02" N to 39°42'21" N and longitudes 28°51'38" E to 29°02'48" E, located in approximately 28 km south of the Mt. Uludağ in the northwestern part of Turkey. It has a diameter of about 15 km and a surface area of almost 200 km². As a clear example to nearly circular-shaped plutons emplaced at shallow crustal levels, the Orhaneli Granodiorite Pluton has some significant geomorphological and petrographical implications for explaining the denudation chronology of such well-exposured intrusive bodies. The two huge resistant blocks at its central part, quitely sharp contact relations with the host rocks and granite landforms provide clear evidences for denudation chronology and geomorphological evolution of the pluton.

In this study, the geomorphological development of the Orhaneli Pluton is discussed petrological, remote sensing and based on geomorphological data. The denudational history of the pluton was revealed by etching processes, which imply preferential weathering of the granodiorite and continual stripping of resultant regolith cover by the Sadagi River and its tributaries.

GEOLOGICAL AND GEOMORPHOLOGICAL SETTING

The geology of the pluton has been previously discussed by several authors (Okay, 1948; Kaaden, 1959; Altınlı, 1966; Bürküt, 1966; Özkoçak, 1969; Ataman, 1972; Bingöl et al., 1982; Emre, 1986; Harris et al., 1994; Okay et al., 1998; Delaloye and Bingöl, 2000). A general geological map, generalized stratigraphic section and cross-section of the pluton is shown in figure 2, where it can be seen that the outcrop of granodioritic rocks of Lower Eocene is bordered

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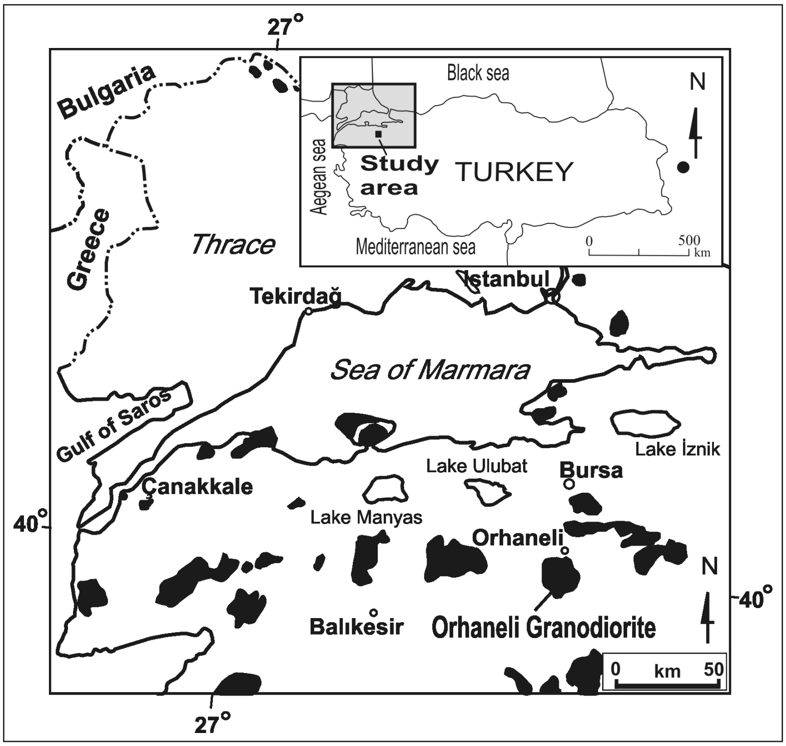

Figure 1- Location map and spatial distribution of granitic terrains in the northwest Anatolian region of Turkey.

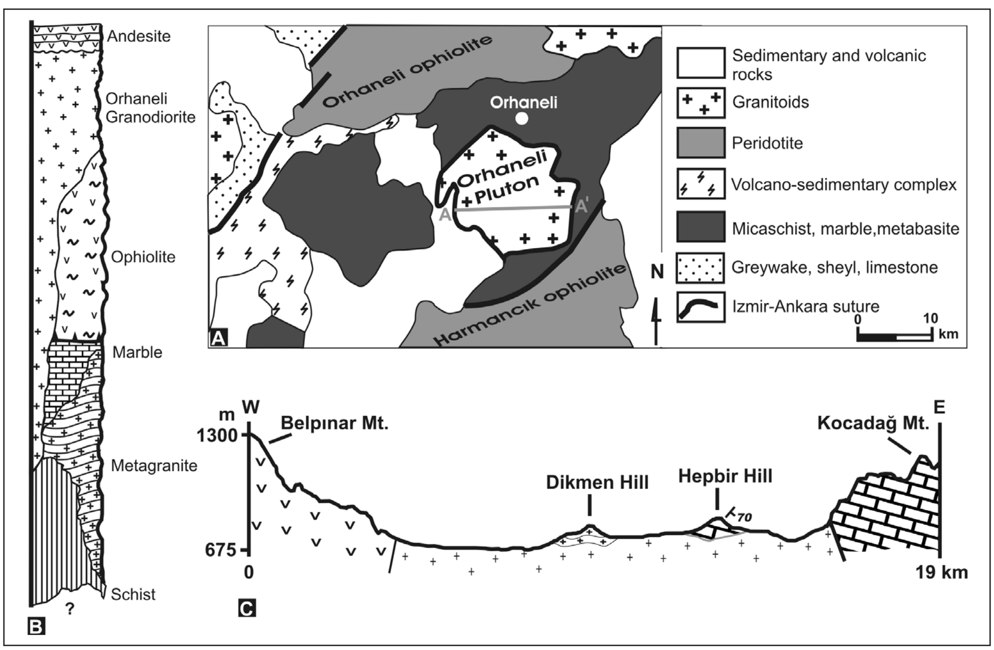

Figure 2- Generalized geological map (A) modified from Emre (1986), stratigraphic columnar section (B) and cross-section (C) of the study area.

to the east by Paleozoic schist and marble, roof remnants of which occur near Eskidanişment village.

Based on Ar/Ar laser spot analysis on biotite samples, it was explained that the pluton intruded into a metamorphic sequence at a deph of ~10 km during the Early Eocene (52.4±1.4 Ma) (Harris et al., 1994). It outcrops at an area of approximately 200 km² and consists of medium-grained granodiorite including 50-60% plagioclase, 20-25% quartz, 10-15% biotite, about 10% alkali feldspar, about 5% plus hornblende, sundry minor minerals (Harris et al. 1994), abundant microgranitoid enclaves and zircon, apatite and opaque as accessory minerals. Its texture is commonly holocrystalline granular (Figure 3A).

The host rocks of the Orhaneli Pluton are composed of schists, marbles and metagranites, among which the last two are of wider extension. They occupy a large area to the north, east and south of the pluton. Having a mosaic texture, the marble, which crops out at the eastern and southern borders of the pluton is a grey to white-coloured rock containing calcite and opaque minerals. It includes intense fractures and gives a typical section on Mt. Kocadağ to the east. A north-south trending fault that juxtaposes the marble against the pluton rocks displays a tectonic contact, along which an intense cataclasis was detected on thin sections (Figure 3B).

The metagranite defined as Belenoluk Metagranite by Emre (1986) bounds the pluton to the north and consists mainly of hornblende, quartz, plagioclase, orthoclose, opaque and abundant titanite. Its texture is holocrystalline porphyritic with commonly developed alteration on mineral grains. Metagranite and marble also cap Dikmen and Hepbir Hills, respectively (Figure 4).

To the western border the pluton is also in contact with and is in part overlain by Miocene volcanics forming steep erosional scarps. The lavas resting on the metamorphic associations in

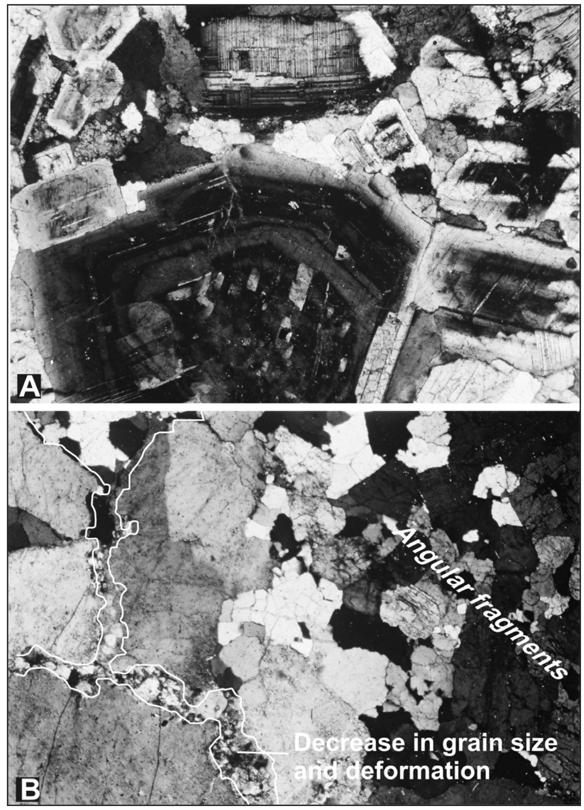

Figure 3- Photomicrographs of samples: a zoned crystal in granodiorite at inner parts of the pluton (A) and intense cataclasis along N-S trending contact zone (B).

the area are commonly characterized by andesite and dacite in composition, and consist of plagioclase, biotite and opaque minerals set in a vitrophric texture. An isotopic age of 17.6±0.2 Ma (Okay et al., 1998) from tuff samples resting on andesitic flows near Büyükorhan dates these volcanic to Early Miocene. They actually constitute an eastern extension of Miocene volcanics defined in western and northwestern Anatolian parts of Turkey (Ercan, 1979; Ercan et al., 1990).

From geomorphological point of view, the Orhaneli Pluton is characterized by a slightly dissected ondulated plateau with an average altitude between 750-950 m above sea level (Figure 4). It is surrounded by higher ridges and ranges

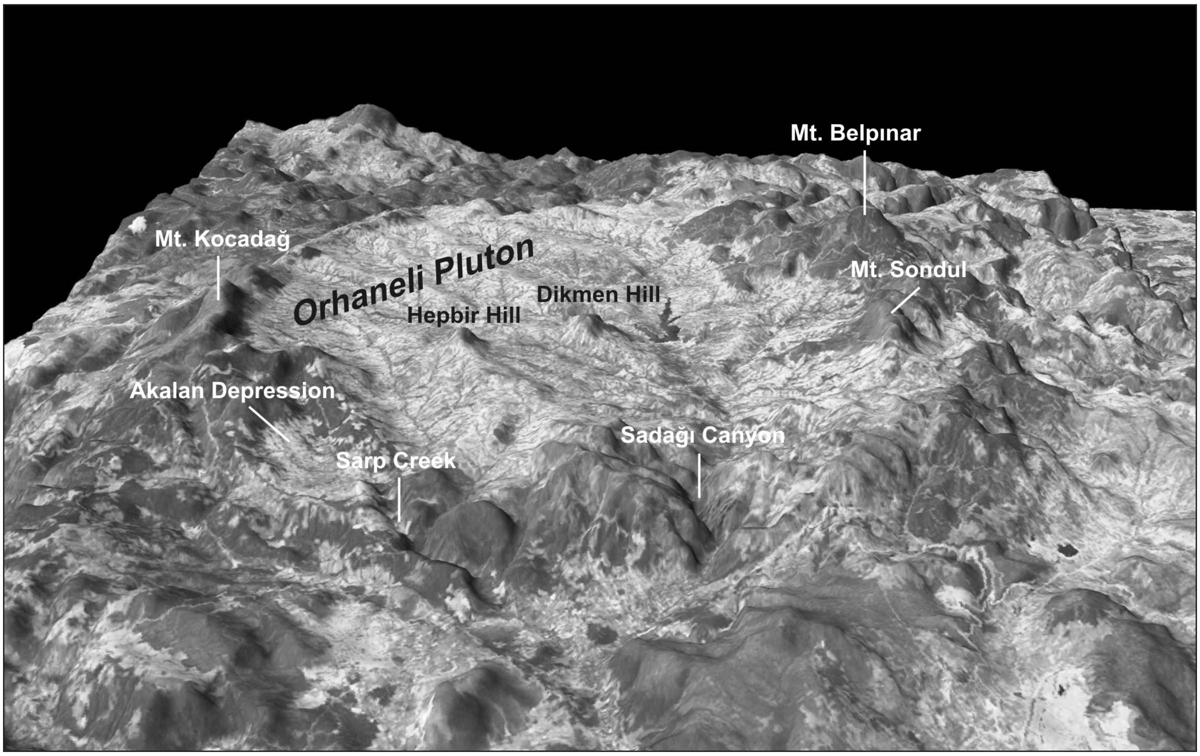

Figure 4- Digital Elevation Model of the Orhaneli Pluton and its surroundings (note the circular dome surface and two inselberg-like hills in the central part). Drainage channels of the to main streams, Sadağı and Sarp Rivers, are severely controlled by NW-SE trending fractures. In addition, a dendritic drainage pattern with high bifurcation ratio is dominant. View direction is southward.

reaching up to 1400 m in altitude, the highest of which are Mt. Belpınar (1391 m) underlained by silicic volcanic rocks to the west and Mt. Kocadağ (1323 m) formed by marbles to the east. They are seperated from the pluton by north-south-trending escarpments with approximately 200 m high. The granodioritic rocks have been eroded to form a rolling plain (or plateau) between these highlands.

The plateau, which is sparsely coated with vegetation, is characterized by low erosional surfaces seperated by slightly incised broad valleys. Two Inselberg-like hills, i.e. Dikmen and Hepbir Hills, in central part of the pluton form conspicious anomalies in morphology of the area, since they are more resistant to weathering and erosion. The lowland is drained by the Sadağı River and its tributaries, which runs northwards through the 300-450 m deep Sadağı Canyon. Most of the stream channel network that drain the pluton area is joint controlled.

METHODS

A digital terrain model (DTM) digitizing 20-meter-interval contours from 1/25.000-scaled topographic maps has been produced to characterize mathematically topographic features. DTM was superimposed with Landsat ETM satellite images (2000) using ERDAS Imagine 8.3 Software. Distribution of the lineaments determined from satellite images were compared with 545 fracture measurements performed on fresh rock exposures to explain relationships between fracture patterns and construction of drainage network.

Standard thin sections of many rock samples were produced to examine mineral fabrics and compositions and traces of shearing deformation of mineral grains.

DISCUSSION

Preferential weathering of the granodioritic rocks and stripping of regolith

The Orhaneli Pluton is situated at a lower elevation than the surrounding metamorphic terrain both because of its composition and because of its closely spaced fractures. It is well known that biotite, plagioclase and hornblende are particularly susceptible to attack by water (e.g. Goldish 1938; Loughnan, 1969). The percentages of plagioclase (50-60%), quartz (20-25%) and biotite (10-15%) are thus of great importance for velocity of weathering and the resulting thickness of regolith. In other words, the weathering-prone mineral content of the granodiorite has determined erosional lowering of the pluton relative to the adjacent metamorphic terrains.

In many parts of the study area, where the regolith is partly stripped, some specific granitic forms, such as corestones, boulders and tors of various size and shape give numerous exposures as clear evidences of epigene weathering processes developed on the weathering front (Mabbutt, 1961). These specific forms are of subsurface initiation in origin (Twidale and Bourne, 1975) and are the result of rapid or episodically stripping of weathering mantles or regoliths as previously imparted by several authors (Twidale and Bourne, 1975; Twidale,1993). During the field study, it was observed that boulders with 50 cm to 2 m high have a circular shape because of spheroidal weathering or exfoliation. The exfoliation slabs on boulders are equal to or thinner than 1-2 cm. Their distribution and geometry is controlled almost everywhere by vertical and sheet fracture patterns. In road cuttings, the visible thickness of the regolith cover under these stripped forms was measured as thick as 3 to 5 m. The regolith with light colour contains abundant quartz and alkaline feldspar grains and some decomposed microdioritic enclaves. The quartz veins are also difficult to observe due to intensive weathering.

The closely spaced fractures typical of the upper part of the pluton have allowed ready penetration of meteoric water, resulting in the differential weathering of the fracture-defined blocks. This circumstance has caused the formation of corestones in a grus (Figures 5A and B), in many instances with "onion skin" texture. After the evacuation of the grusified rock, corestone boulders were exposed (Figure 5C). This process commonly occurs in granite terrains, as previously referred to multistage landform development by Twidale (1993).

In many exposures of corestones and tors, sheet fractures cut by vertical fractures are well developed. The thickness of slabs seperated by sheet fractures reaches up to 1 m (Figure 5D). Although these fractures have been habitually ascribed to pressure release consequent on erosional offloading in the existing literature (Gilbert, 1904; Chapman, 1956), the geometry of the horizontal slabs and sheet fractures in the study area are a little distinct and support some evidences of tectonic impacts discussed by Twidale et al. (1996).

In both sections of regoliths and tor exposures, sheet fractures were observed to have a shape of partly upward arching and frequent diagonal fractures with, somewhere, abundant quartz veins (Figure 5B). Because of scarcity of typical great fresh rock exposures, sheet fractures having more thickness in depth were not possible to observe for a detailed discusion here.

Relations between structure, drainage and geomorphology

Major faults and fractures are shown in figure 6. In addition to their effects on river patterns, the

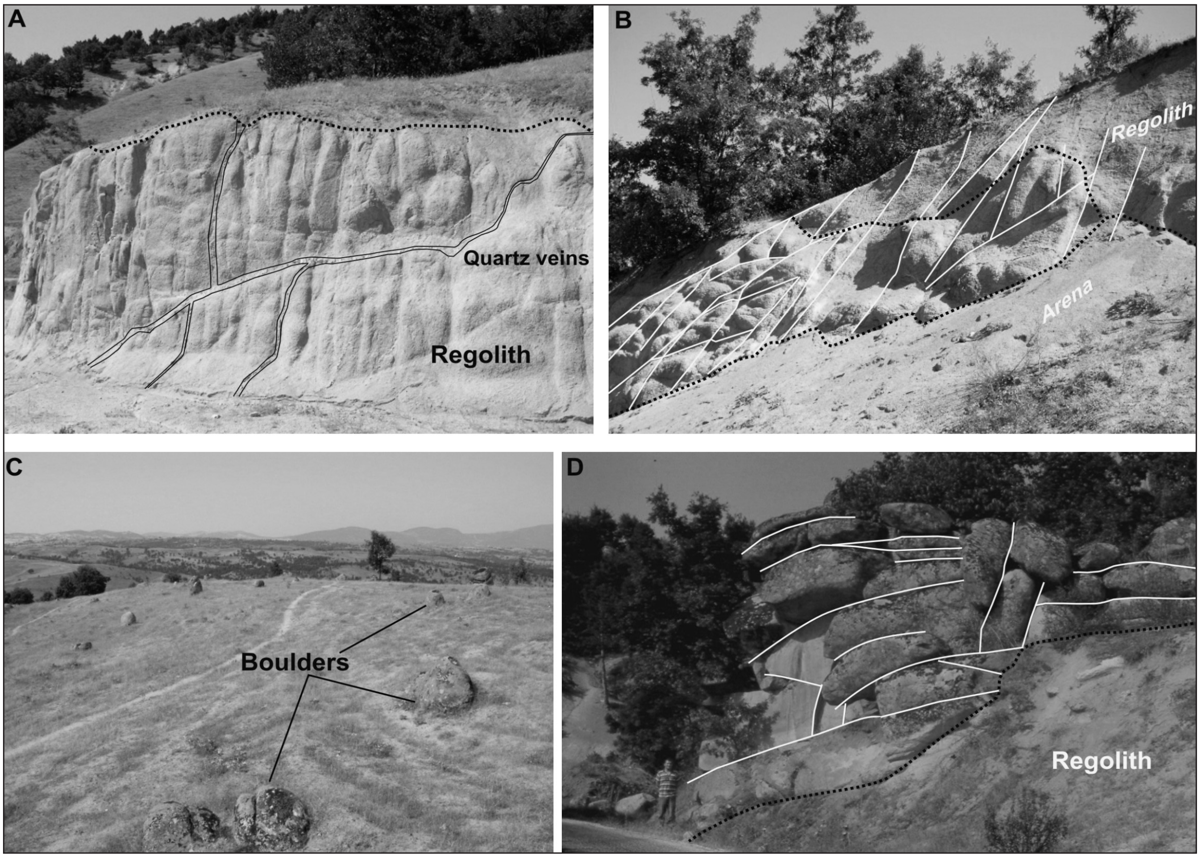

Figure 5- A typical section for regolith cover with some thin quartz veins (A), sheet and cross fractures among newly exposed corestones (B), stripped boulders on a flat erosional surface (C) and an example of boulder formation with dense sheet fractures stripped from regolith cover (D).

pluton is bounded on its eastern side by a fault which juxtaposes the granitic rocks against Paleozoic marble. The topographic expression of this structure corresponds to a linear scarp on marbles. The north-south trending steep slope along this linear scarp corresponds to a fault-line scarp, which has been identified from a thin section with clear evidence of cataclastic deformation (Figure 3B).

In addition to facilitating the weathering of the granodiorite, fractures are also lines of weakness that controlled not only the alignment of streams and rivers but also determined which of them evolved into major waterways. Numerous field measurements of fractures demonstrate that NW-SE, NE-SW and N-S orientations are prevalent (Figure 6). These orientations coincide with the dominant azimuths of the lineaments determined from Landsat ETM satellite images. These partings have determined the development of many angular stream patterns.

The course of Sadağı Stream and its right bank tributary are obvious examples. The 400 m-deep Sadağı Canyon is controlled by a NW-SE trending fault located at the east of Hepbir Hill (Figure 7A). The longitudinal profile of the Sadağı River reflects changes in the physical and chemical properties of the bedrock geology, and shows a graded curve in metagranite rocks because of the effect of the Sadağı Fault with a

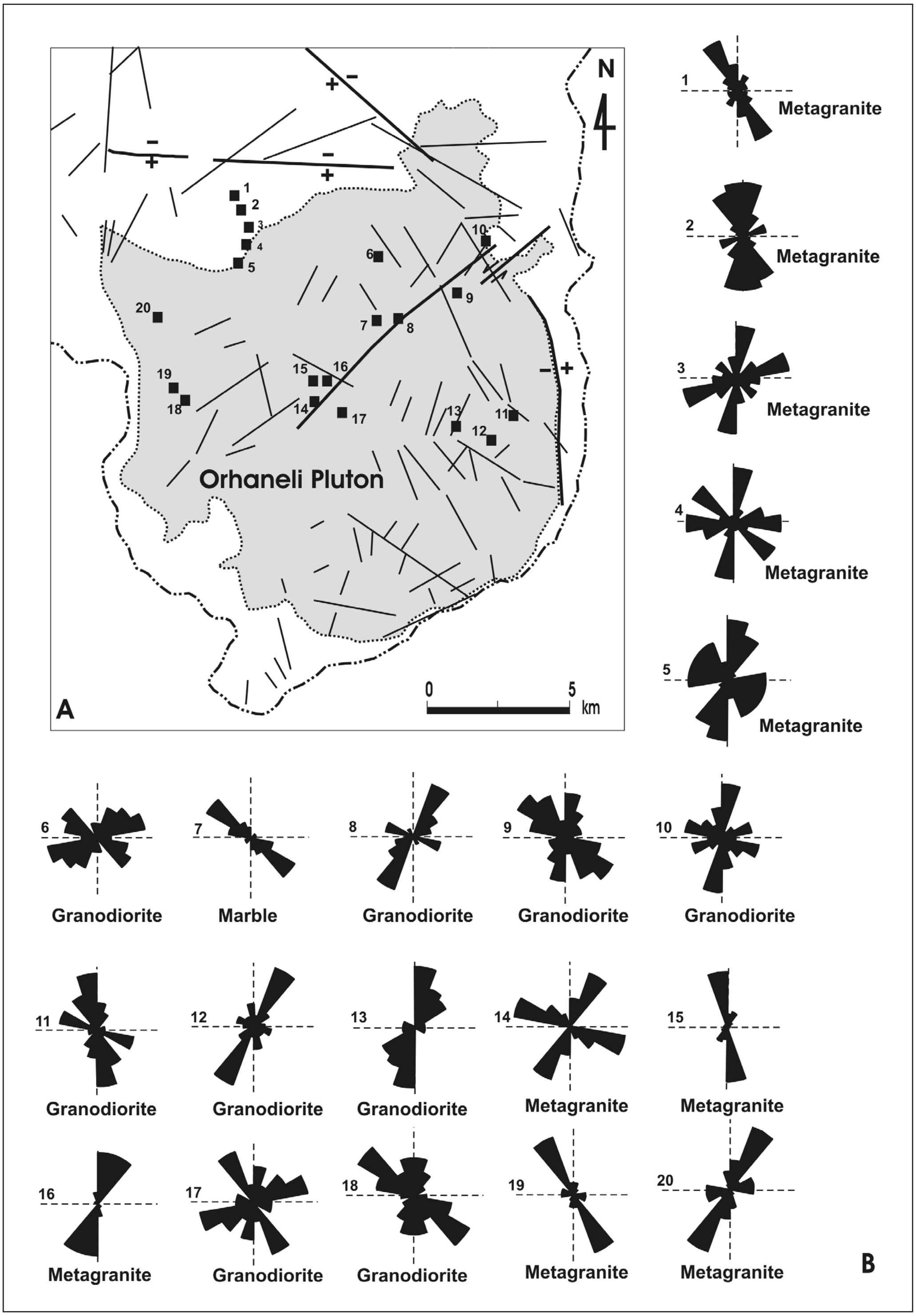

Figure 6- Distribution of main faults and fractures in the study area (A) and rose diagrams representing predominant fracture azimuths in measurement locations (B).

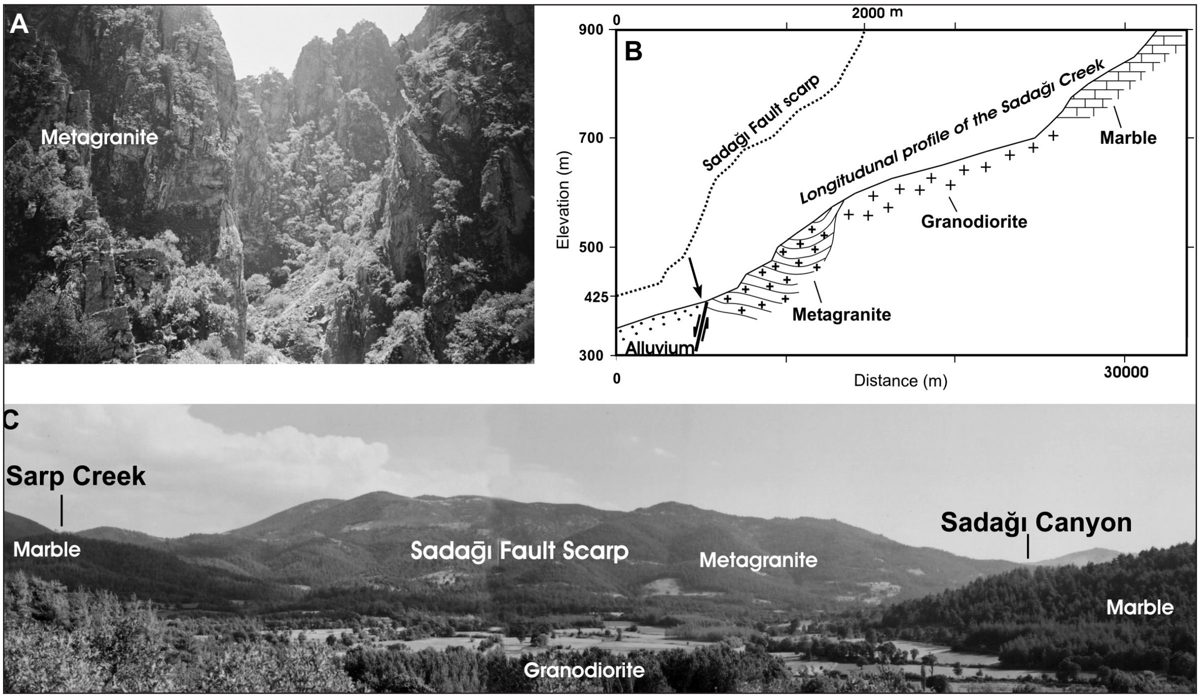

Figure 7- The Sadağı Canyon (A), longitudinal profile of the Sadağı Stream (B) and E-W-oriented Sadağı Fault (C) (the small depression in foreground developed on an apophysis of the Orhaneli Pluton. The Orhaneli Pluton remains behind the Sadağı fault scarp).

visible scarp of 300 m high (Figure 7B). The Sadağı Fault with east-west direction (Figure 7C) has allowed river incision and this in turn has caused the regolith to be stripped by the river and its tributaries.

In addition to the orthogonal subvertical fracture systems, sheeting joint sets define slabs up to one meter thick. Though commonly attributed to pressure release caused by erosional offloading (e.g. Gilbert, 1904), a critical factor for the development of fractures in granitic terrains (e.g. Chapman, 1956), these partings may primarily be due to tectonic compression (Dale, 1923; Twidale et al., 1996). The systematic orientations consistent with remotely sensed lineaments ought to be suggestive of tectonic stress fields, because they were observed not only on granodiorite but also on marble and metagranite exposures. For instance, the point eight measurement location situated in the top of the Hepbir Hill composed of marble, shows an evident NE-SW trending fracture system, which is very similar with those of points 12, 16, and 20 in metagranite exposures (Figure 6A and B). This orientation is also the common trend of many of the granodiorite exposures.

The cross fractures are observed on metagranite exposures, indicating various tectonic stresses. The similar orientations of the fractures in points 14, 15, 16, 19 and 20, measured on the Dikmen Hill are in good aggrement with those of points 1-5 along the Sadağı Canyon in the north.

Original denudation history

The Orhaneli Pluton has an intended shaped roof, a typical polygonal shape and very steeply dipping walls through contact zone with host rocks (Figure 8 A and B). Its eastern margin dis-

Figure 8- The Kocadağ block (A), a thin residual of marble on granodiorite near Eskidanişment village (B), Dikmen and Hepbir Hills (C) and Miocene silicious volcanics (D).

plays a conspicious discordant contact, along which various annular and radial dykes were observed in field surveys. A typical cataclastic deformation was also observed under thin section images taken from rock samples along this sharp contact. This deformation microstructure might be an indicator for a north-south-trending fault that juxtaposes the pluton rocks against the host rock.

From geomorphological point of view, the presence of two erosion-resistant hills at central part of the pluton and linear fault segments on eastern and southern contacts may have some important implications for denudation chronology of the pluton area. These hills, Dikmen and Hepbir Hills, are formed by metagranite and marble, respectively, and have been preserved in central part of the pluton. They are found at almost the same NW- SE alignment (Figure 4 and 8C). The size of the blocks are about 750 m and 1000 m above sea level respectively.

A thin section analysis of metagranite sample taken from the Dikmen Hill showed that it is composed of quartz, orthoclase, pertite, plagioclase, hornblende, titanite and apatite set in a holocrystalline porphyritic texture. Another sample from its contact with granodiorite, however, displayed a well developed cataclasis in primary magmatic minerals, such as quartz, plagioclase, orthoclase and biotite. The Hepbir Hill is, however, located at 500 m northeast of the Dikmen Hill. It is composed of calcite and opaque minerals set in a mosaic texture. In thin section interpretation, a partly developed cataclastic deformation was determined in mineral fabric of a granodiorite sample taken from its eastern margin. Similar microdeformation structure existed in the samples collected from the contact zone of the marble with the granodiorite, implying that both roof rocks and their remnants were affected by tectonic forces prior to the exposure.

The unique approach on the timing of first exposure of the pluton was suggested by Okay et al. (1998), who indicated that a tuff exposure (Figure 8D) with an isotopic date of 17.6±0.2 Ma at the western contact is indicative of Early Miocene. Nevertheless, this idea is not supported due to the absence of granodiorite clasts within Lower to Middle Miocene lacustrine deposits at the north of the pluton. Thus the initial period of denudation chronology of the pluton would be at least the Late Miocene as evidenced by the widespread extension of an planation surface cutting roof rocks with the Miocene deposits at a regular level.

The rolling planation surface preserved on the adjacent metamorphic terrains may have its equivalent in the Orhaneli granitic plain. The height difference may simply reflect differential erosion. The development of the Sadağı Canyon may simply have facilitated removal of the granitic regolith from the lower plain. On the other hand the Sadağı River may have controlled the evacuation of a thick regolith and be responsible for the present rocky plain which would thus be younger than the high paleosurface. There are no traces of younger cover deposits along the valley to infer relative age of the canyon.

The widespread occurrence of boulders, corestones and tors that constitutes clear evidence of an etch origin (Twidale and Vidal Romani, 2004) indicates that subsurface weathering is an important part of the denudation history of the Orhaneli Pluton. These form could be indicative for discontinuous (or episodic) progression of the weathering front. Nevertheles, absence of weathering rinds on corestones and boulders in the study area indicates that any pause might had not occured in the advance of the weathering front. Thus, stripping of the regolith have long been continued, and these residual features had later exposured from a thick cover of regolith. The fact that the weathering front is not exposed anywhere may also suggest that the subsurface weathering is an ongoing process caused by shallow groundwaters. The etching process that might had been operating since the Late Mio-cene, can therefore be supposed for the Orhaneli Pluton.

CONCLUSION

Based on petrological analysis, remote sensing data and field observations the following results were obtained:

Radiometric age of 17.6±0.2 Ma from biotite grains of dacitic tuffs at the western contact as indicative of initial exposure of the pluton would be a minimum age. However, granodiorite clasts are not found within the Early-Middle Miocene aged limnic sequences in the north of the pluton, indicating likely that it might had not been entirely exposured prior to the Late Miocene.

The Inselberg-like hills cut by a slightly inclined erosional surface with similar elevation to those located on the western and eastern country rocks are probably indicative of the remnants of roof rocks. However, their transition with the surrounding granodiorite is everywhere represented by microstructural deformations, suggesting tectonic effects or possible faults. The same deformations occur along the pluton-host rock contact as possible evidences for brittle deformation during or after the pluton emplacement.

Fracture measurements obtained from fresh rock exposures indicate an evident NW-SE fracture orientation. When this medium is evaluated with numerous lineament distributions determined from LANDSAT ETM (2000) satellite images, the principal vector was found to be 24.61°. Thus, it is concluded that NW-SE, NE-SW and N-S lineament patterns are prevailent in the study area. These fractures are of importance as both they controlled the development of the streams and facilitated the weathering of the granodiorite.

Many granitic landforms, such as boulders, corestones and tors formed by subsurface weathering constitute sound evidence of an etch origin in the study area. Thus, subsurface weathering and following stripping of the regolith have played an important role in the rapid denudation of the Orhaneli Pluton. The etching process is suggested to have been operating since the Late Miocene, which is thought to be exposure period for the pluton. The fracture-controlled Sadağı River and its tributaries also might have been responsible for stripping of the regolith, and thus causing the pluton area to have had a well-defined circular depression.

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