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Strain Analysis of the Kapıdağı Peninsula Shear Zone in the Ocaklar Granitoid, NW Turkey

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Abstract: The Kapıdağı Peninsula shear zone is a W-to NW-trending, moderately to steeply dipping, sinistral strike-slip shear zone that runs almost parallel to the northern coast of the peninsula. It is a minimum of 28 km in length and extends from Rikoz Cape in the west to the north of Çakıl village in the east. A quantitative strain analysis is presented for the shear zone evolved in the Ocaklar Granitoid by a syn-shear granitod intrusion. Deformed autoliths in the granitoids were used as strain markers. Long, intermediate and short axes of autoliths were measured in 66 subareas across the shear zone. Strain maps were constructed for the shear zone utilizing shear strain (γ) and elongation values (e_1) along the long axis of the finite strain ellipsoid. These maps show increasing shear strain and elongation toward the centre and along the long axis of the zone. Folliation and strain pattern within the shear zone indicates that steady laminar shear flow took palace during the deformation. Sinistral sense of shear indicators is found in the zone. The amount of horizontal sinistral displacement on the zone was calculated as 14.7 km from the strain profile.

Ocaklar Granitoidi İçinde yeralan Kapıdağı Yarımadası Kayma Zonunun Deformasyon Analizi, KB Türkiye

Özet: Kapıdağı Yarımadası kayma zonu yarımadanın kuzey sahiline az çok paralel olarak uzanan, batı-kuzeybatı yönelimli, dikçe eğimli, sol yönlü bir zondur. Görünür uzunluğu 28 km olan kayma zonu, batıda Rikoz Burnu'ndan başlayarak doğuda Çakıl köyü kuzeyine doğru uzanır. Ocaklar Granitoidi içinde granit intrüzyonu ile çağdaş bir makaslama hareketi ile gelişmiş kayma zonunun kantitatif deformasyon analizi sunulmuştur. Granitoidler içindeki deforme otolitler deformasyon belirteci olarak kullanılmıştır. Zon boyunca 66 asalanda otolitlerin uzun, orta ve kısa eksenleri ölçülmüş; bu ölçümlerden kayma deformasyonu (γ) ve deformasyon elipsoidinin uzun eksen boyuncaki uzama miktarları (e_1) hesaplanarak zonun deformasyon haritaları hazırlanmıştır. Bu haritalar, kayma deformasyonu ve uzama miktarı değerlerinin zonun merkezine doğru ve ayrıca zonun uzunluğu boyunca arttığını gösterir. Yapraklanma ve deformasyon dağılımının şekli, zon içindeki deformasyonun sabit laminer bir akım ile gerçekleştiğini belgeler. Zon içinde sol yönlü kayma hareketini belgeleyen özellikler bulunmuştur. Elde edilen deformasyon profilinden zon boyuncaki sol yönlü yerdeğiştirme 14,7 km olarak belirlenmiştir.

Introduction

The Kapıdağı Peninsula is located at the northern end of the Biga Massif (Figure 1). The pre-Permian Erdek Complex, made up largely of meatbasic-metaultrabasic rocks with intercalations of metasediments, constitutes the basement of the region. This metarmorphic sequence is cut by two plutonic bodies, referred to as Ocaklar and Çeltikçi granitoids, of Palaeogene age.

The Ocaklar Granitoid includes the northern portion of the Kapıdağı Peninsula (Figure 1). It is bordered to the south by the Erdek Complex. The area was first mapped by Ketin (1946) and more recently by Aksoy (1996). Rock untis of the area have been studied for their petrological and tectonic interes (Bürküt, 1966; Sarıalioğlu, 1983; Gözler et al., 1983; Okay et al., 1991). Aksoy (1995, 1996) carried out a detailed study to clarify lithological and structural features and geological evolution of the region.

The granitoid rocks in the north of the Kapıdağı Peninsula have been mapped and variously called granite, gneissic granite and gneiss (Ketin, 1946), and granite and orthogneiss (Sarıalioğlu, 1983). On the basis of field relations and petrographical analysis, Aksoy (1995) recognized that these rocks represent the same plutonic event (Ocaklar Granitod) and teherefore there is no need to classify them differently. He showed that the gneissic appearence of these rocks is an expression of shearing in the crust. Published information concerning the shear zone has focused on a particular segment of the shear zone (Aksoy and Seymen, 1993; Aksoy, 1996). This study looks systematically at the whole length of the exposed shear zone. The purpose of this paper is to describe the Kapıdağı Peninsula shear zone and examine its deformational pattern.

Geological Setting

The Kapıdağı Peninsula is situated in the southern Marmara section of the Marmara region at the northern end of the Biga Massif. The areal geology is shown in Figure 1. The oldest unit in the area is the Erdek Complex (Aksoy, 1995), which consists predominantly of metabasites intercalated with micaschist, calcschist, quartzite, metasandstone and marble olistoliths. The Erdek Complex was interpreted by Aksoy (1995) as a melange before its metamorphism. He suggested that the Erdek Complex was the product of regional metamorphism before the Permian. Regional metamorphism reached the epidote-amphibolite-low amphibolite facies transition and was followed by retrograde metamorphism to lower greenschist facies conditions. Aksoy (1996) showed that it is multiply deformed.

This metamorphic sequence is intruded by two Palaeogene granitoids, called the Ocaklar and Çeltikçi granitoids (Aksoy, 1995). About half of the peninsula is underlain by the Ocaklar Granitoid. It consists of medium- to coarse-grained, leucocratic quartz diorite, tonalite and granodiorite (Sarıalioğlu, 1983; Gözler et al., 1983; Aksoy, 1995). It is frequently cut by aplite, pegmatite, quartz and lamprophyre dikes. The shear zone studied contained exposed pluton. Away from the shear zone granitodis are characterized by a holocrystalline, hypidiomorphic igneous texture. However, in the shear zone, deformed granitoids have well-developed mylonitic textures with quartz, feldspar, amphibole and biotite oriented parallel to the main floiation. Although the textures of these granitoids are different, mineral assemblages lying on both sides are the same. They are composed mainly of quartz, plagioclase, alkali feldspar, hornblende and biottie. In addition to these in the shear zone, the granitoids also contain albite, epidote, muscovite and chlorite, which are the products of dislocation metamorphism. Total radiogenic Pb age dates on zircon yielded 73.9±8 m.y. for the Ocaklar Granitoid (Bürküt, 1966). The K-Ar ages obtained were 39.8±0.6 m.y. for his unit (E. Bingöl, personal communication, 1995).

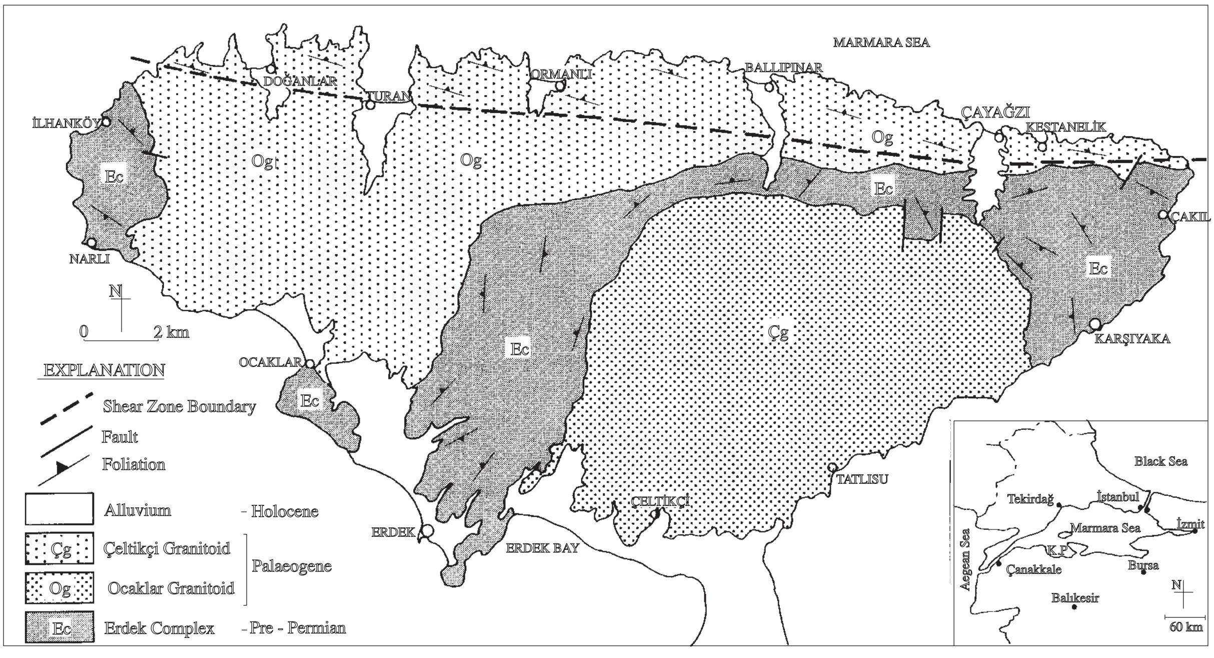

Figure 1. Geological map of the Kapıdağı Peninsula (K.P). The inset map shows the location of the study area.

The Çeltikçi Granitoid crops out in the southern part of the peninsula (Figure 1). The composition varies from diorite to hornblende-biotite granodiorite (Sarıalioğlu, 1983; Aksoy, 1995). The rock is usually fine-grained, but medium-grained phases are present in places. It is made up of quartz, alkali feldspar, plagioclase, hornblende, biotite and accessory sphene, and cut by aplite, pegmatite and quartz dikes. K-Ar ages for the Çelkitçi Granitoid gave 36.1±0.8 m.y. (E. Bingöl, personal communication, 1995).

Strain Analysis

Strain Markers and Procedure

Autoliths in the deformed mylonitic graintoids were used as finite strain markers. Away from the shear zone, in the main granitoid body, the shape of the autoliths is irregular. However, in the shear zone they are observed as variably shaped ellipsoids independent from their initial geometries. The long axes of the deformed autoliths range in size from several centimeters to 3 meters. In order to determine the deformation pattern in the shear zone, it was divided into 66 subareas. The length of the long (a), intermediate (b) and short (c) axes ad orientation of the long axis were measured for each selected subarea. Measurements were made of between thirty and one hunderd autolith axes per subarea, depending on the size of the subarea and measurement conditions. These were plotted on [(a+c)/2 ; a/c] and [(b+c)/2 ; b/c)] diagrams as described by Aksoy and Seymen (1993). The average axis ratios, corresponding to the densest points, were determined by contouring technique for each subarea from the resultant plots. Average axis lengths for each subarea were calculated by the method of Aksoy and Seymen (1993). The average axis lengths were then used to calculate the elongation values (e_1, e_2, e_3). In this method, the three-dimensional ellipsoid ($x=1+e_1$, longest), ($Y=1+e_2$, intermediate) and ($Z=1+e_3$, shortest) is obtained directly from the average axis lengths and/or from the elongation values.These give the lengths of the principal axes of the strain ellipsoid approximating most closely to the average autolith shape. Ramsay (1967) pointed out that in a shear zone developed by simple shear, there is a relationship between the principal axes of the strain ellipsoid [$(1+e_1)$ and $(1+e_3)$] and the shear strain (γ). In the method of Ramsay (1967; Fig. 3.21, p.85), shear strain (γ) is plotted against the principal strains, and lines $(1+e_1)$ and $(1+e_3)$ yield information on the shear strain (γ). By this relationship, shear strain (γ) values were also determined separately for each subarea.

The best measurements were made on the surfaces, particularly along the shore line and roadcut exposures (Figure 2). Three types of surfaces are defined. Type 1 surfaces are nearly parallel to the foliation. Surfaces of this type are suitable for measuring the long (a) and

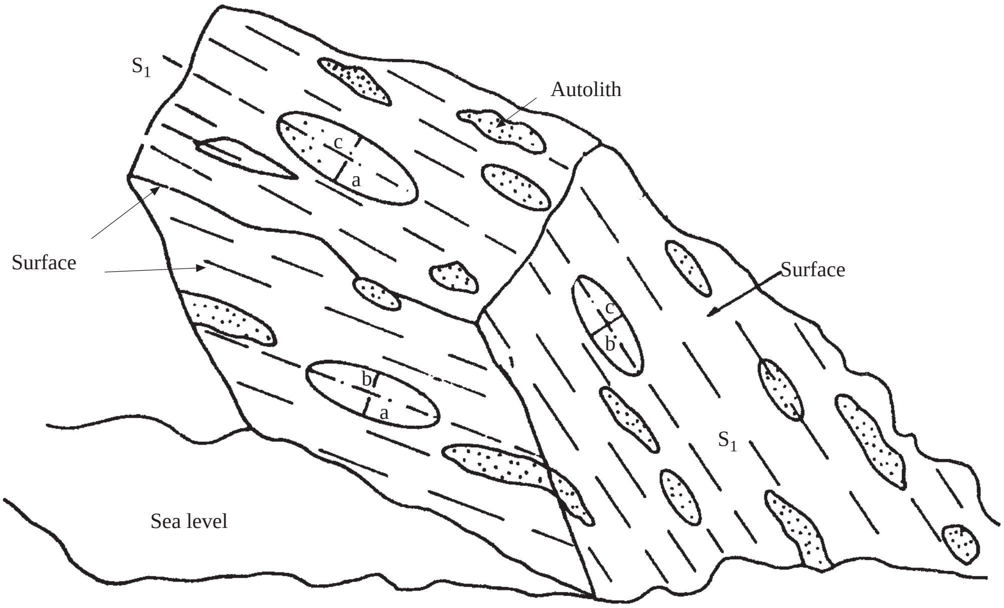

Figure 2. Schematic illustration of surfaces on which measurements of deformed autoliths were made at outcrops. The long (a), intermediate (b) and short (c) axes of deformed autoliths can be determined on the surfaces perpindicular to one another. S_1 represents follation.

intermediate (b) axes and orientation of the autoliths. Type 2 surfaces, on which most of the measurements were made, are nearly perpendicular to the foliation. These surfaces are horizontal joint and exfoliation surfaces where long (a) and short (c) axes of the autoliths can be measured. Type 3 surfaces, forming the vertical joint surfaces, are nearly perpendicular to the foliation. These types of surfaces are suitable for measuring intermediate (b) and short (c) axes of the autoliths. Thus, from three axes of the autoliths only one of the a-b, a-c or b-c axis pairs can be measured at the outcrop. It was also impossible to measure the three axes together.

Deformation within the Shear Zone

The Kapıdağı Peninsula shear zone on the north of the peninsula lies within a granitoid body (Ocaklar Granitoid) which intrudes the metamorphic Erdek Complex. The shear zone, a map of which is given in Figure 3, extends E-W from Rikoz Cape in the west, via just south of Doğanlar, Turan, Ormanlı, Ballıpınar, Çayağzı and Kestanelik villages, towards the north of Çakıl village in the east. It is a well-foliated and poorly lineated zone of deformation. Thus defined, it has an apparent length of about 28 kilometers. Previous workers (Ketin, 1946; Sarıalioğlu, 1983) described the shear zone as a gneiss.

From the shoreline to the shear zone boundary hat described above, the intensity of deformation decreases progressively and foliation becomes indistinct. Autoliths, finer grained than the host granitoid, are comprised mainly of mafic mineral clusters. Within the shear zone, these have become strongly ellipsoidal ad show elongation parallel to the foliation. There is no sign of deformation at the south of the shear zone. The shear zone has diffuse gradational contact with the unstrained main granitoid body. This feature of the Kapıdağı Peninsula shear zone indicates that it is a continuous ductile shear zone, as described by Burg and Laurent (1978), for isotropic rocks such as granitoids.

In the shear zone, granitoids are made up of quartz, feldspar, hornblende and biotite. Plagioclases are partly replaced by epidote and sericite. Magmatic zoning in plagioclase is still visible despite alteration. Biotite minerals are locally replaced by chlorite, which may indicate progressive deformation in the shear zone. Quartz crystals are recrystallized and stretched within the foliation.

Shear zones are defined as plane-strain and no-volume change structures (Ramsay, 1967; Ramsay and Graham, 1970). Therefore, assuming plane-strain and no-volume change, the strain chart is used to compare values of shear strain (γ) and elongation (e_1) for 66 subareas across the shear zone (Figures 4 and 5). Shear strain values increase towards the central part of the shear zone and also along its length, as shown in Figure 4. It can be seen that the contours of shear strain are not completely parallel to each other. If the deformation along the shear zone were simple shear alone, the contours of the shear strain would be expected to be parallel. Within the shear zone, however, the contours grow closer to the centre of the zone where the strain is strogest, indicating that there is a close relationship between the intensity of foliation and shear strain within the shear zone.

Elongation values (e_1) along the long axis of the finite strain ellipsoid ($x=1+e_1$) also increase toward the centre of the zone (Figure 5). These reach 335 % in the centre of the shear zone . It is thus clear that shearing caused elongation along the shear zone and shortening perpendicular to the shear zone boundary. Values of shear strain (γ) and elongation (e_1) show a slight increase from west to east.

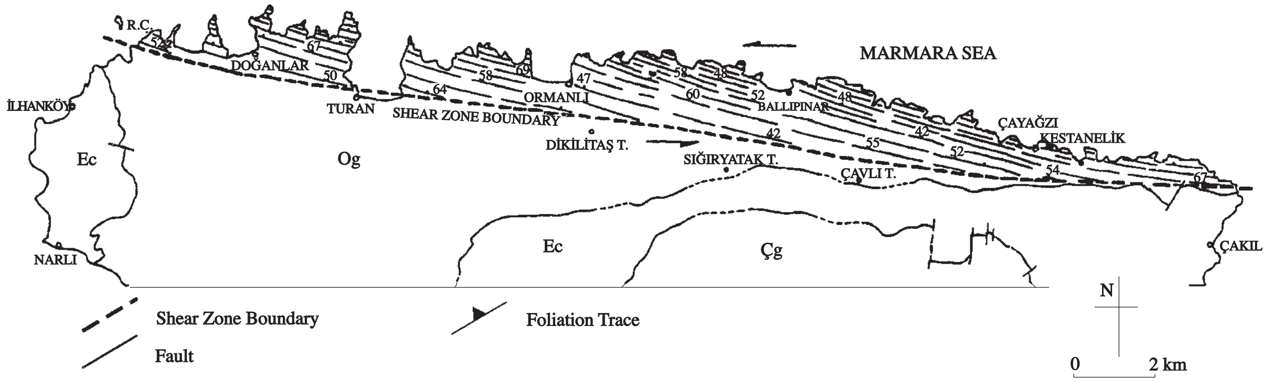

Figure 3. Map of the shear zone within deformed granitoids, north of the Kapıdağı Peninsula. Unit abbreviations as in Figure 1. R.C. = Rikoz

Width of the Shear Zone

In order to determine the strain variation in the shear zone, the autolith axis was measured along the seven sections perpendicular to the shear zone wall. Shear strain (γ) and elongation (e_1) values in the X-direction calculated from the measurements show that the most deformed central part of the shear zone from where these values decrease toward the edges can be distinguished (Figures 4 and 5). The northern edge of the shear zone lies under the Marmara Sea. Therefore, the undeformed outer part of the zone was observed only along its southern edge.

It is known that the most deformed central parts of shear zones are symmetrical in respect to their undeformed outer walls (Ramsay and Graham, 1970). This feature was also determined for the Kapıdağı Peninsula shear zone. Hence, the width and thickness of the shear zone were calculated as 4.4 km and 3.5 km, respectively. Since the northern edge of the shear zone is covered by the Marmara Sea, variation in width along the trend is not known.

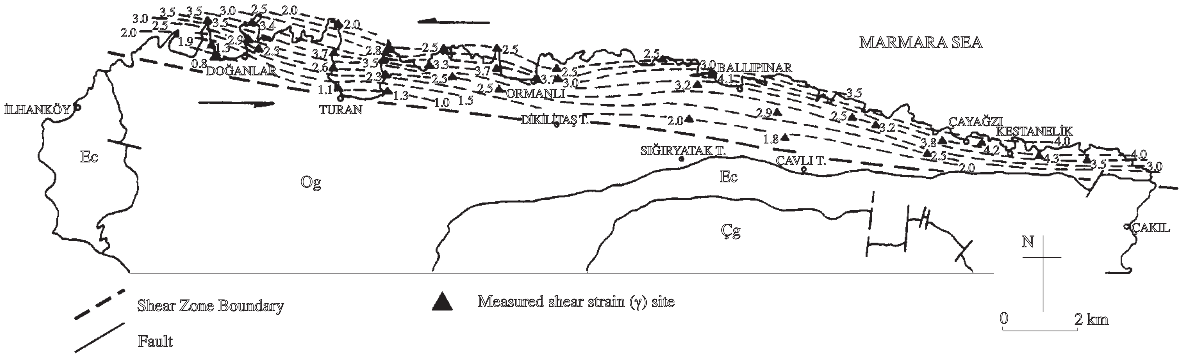

Figure 4. The Kapıdağı Peninsula shear zone showing variation in shear strain(γ). Unit abbreviations as in Figure 1.

Foliation

The foliaiton pattern in the Kapıdağı Peninsula shear zone is very simple (Figure 3). Approximately 300 foliation attitudes were measured along it. The foliation dip varies between 30° and 75°, but averages between 45° and 65°. The mean foliation orientations strike N 80° W and dip 52° NE (Figure 6). Most variations in the folitation orientations occur in margins of the shear zone where the strain is weak.

Foliation is predominantly defined by the orientation of deformed quartz, feldspar and amphibolite grains and by mica folia wrapping around feldspar porphyroclasts. Towards the east of the zone in places, the granitoids display a well-developed foliation defined by compositional and grain-size differences. Foliation is intense in the central part of the shear zone, where the strain is high, and gradually decreases towards the margins of the zone.

The mean orientation of the long axis of the deformed autoliths strikes N 80°-90° W (Figure 7). Autolith orientations generally run parallel to the orientation of foliation in the most highly deformed part of the shear zone. The orientation of foliations in this part of te zone is used to determine the sehar plane attitude. The Kapıdağı Peninsula shear zone is a foliated zone of deformation striking N 80°-90° W and dipping 52° NE. This orientation is also used as an estimate of the long axis of the finite strain ellipsoid. These values indicate that the foliation lies within a few degrees of the shear plane orientation.

Lineation is poorly developed in the zone. Where it is developed, it is almost horizontal and is formed by elongate aggregates of hornblende, biotite, quartz and feldspar.

Sense and Amount of Displacement

In the Kapıdağı Peninsula shear zone, sinistral strike slip deformation is indicated by S-C fabric (S and C designate foliation and shear plane, respectively) (Figure 3) and a symmetric pressure shadows.

Displacement on the shear zone is difficult to determine because there are no geological markers that allow correlation across it. However, the magnitude of displacement can be calculated by the equation $d=t\gamma$ (d: displacement, t: thickness, γ: shear strain, Ramsay,

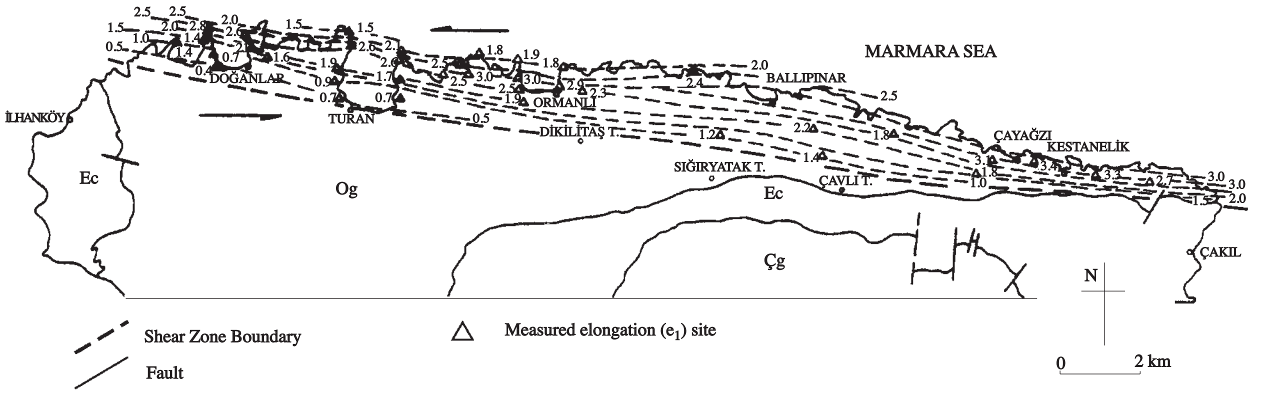

Figure 5. The Kapıdağı Peninsula shear zone showing variation in elongation (e_1) in the long axis of finite strain ellipsoid. Unit abbreviations as in Figure 1.

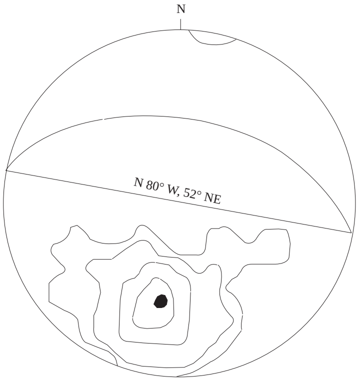

Figure 6. Lower-hemisphere stereographic projections of poles to folia tion (S_1) in the shear zone. The great circle represents aver age orientation of foliation. Contours are 0.17%, 0.85%, 5%, 13.8%, and 21 % per 1 % area.

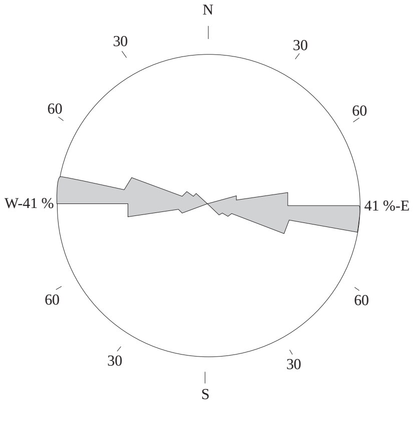

Figure 7. Rose diagram of the orientation of the long axis of the deformed autoliths

1967). Within the shear zone, 14.7 km of sinistral displacement is estimated over a 3.5 km thickness, resulting in a moderate shear strain (γ=4.2). Calculated displacement values across the shear zone slightly increase from west to east (12.4 km to 14.7 km), indicating that the width of the shear zone may also increase with increasing displacement.

Discussion and Conclusions

The shear zone lies on the north of the Kapıdağı Peninsula. It is a high strain zone striking N 80° W and dipping 52° NE.

Foliation orientations are constant in the zone. The consistent orientation of foliation and lack of folding in the shear zone indicates that flow occurred in a constant direction parallel to the foliation. The foliation orientation in the most highly deformed central part of the zone is almost parallel to the shear zone wall. These structural characteristics, as pointed out by Davison et al. (1995), suggest that the flow was steady laminar. Thus, it may be concluded that there is a strong relationship between the velocity of laminar flow and the intensity of foliation. It has been suggested that this type of flow pattern is common in the middle and lower part of the crust (Boullier, 1986; Davison et al., 1995; Hanmer et al., 1997). The laminar shear flow and structural pattern indicate that the Kapıdağı Peninsula shear zone was formed during syn-shear granitoid intrusion.

The shear zone has a sinistral sense of horizontal displacement. The displacement on the zone has been calculated as 14.7 km from the strain profile presented here. In the shear zone, sinistral shearing associated with horizontal extension is related to and resultant from strike slip deformation. The movement on the shear zone occured at 39.8±0.6-73.9±8 m.y. as constrained by total radiogenic Pb and K/Ar dating (Bürküt, 1966; E. Bingöl, personal communication, 1995).

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