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DETERMINATION OF THE SENSE OF SHEAR USING THE ORIENTATION OF SHEAR BAND FOLIATION IN MYLONITES: FIELD EVIDENCE FROM THE KEBAN COMPLEX, EASTERN TURKEY

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ABSTRACT. — The structural features of the northern part of the Bitlis suture zone of the Alpine-Himalayan orogenic belt (Turkey) show intense internal deformations. The variable lithology and microstructural features of the high strain zones commonly found in the Keban complex are characterized by mylonitic texture. The Keban complex were formed in ancient continental margin sedimentary sequences of the northern branch of the Neo-Tethys. Single sets of shear band foliations occur within mylonite zones composed of strongly foliated phyllitic psammites. Two well defined microscopic criteria, the tails of the augen structures and smaller scale shear zones which were formed between the relatively undeformed pod shaped aggregates, are used to deduce the sense of shear in a lithologically inhomogeneous brittle-ductile shear zone of the Keban complex. The sense of shear determined in this way from the anastomosing part of the shear zone is then applied to the orientation of shear band foliation in the same shear zone. This microscopic evaluation of the structures suggests that the acute angle between the shear band foliation and the mylonitic foliation points in the shear direction as proposed by earlier research which were based on experimental studies. Therefore, the determination of sense the of shearing in the field using the orientation of shear band foliations in mylonites is suggested.

INTRODUCTION

The importance of shear band structures has become increasingly recognized in recent studies of ductile shear zones (e.g. Cobbold, 1977a, *b;* Platt and Vissers, 1980; White et al., 1980; Simpson and Schmid, 1983). Shear band foliation is a microstructure commonly found in mylonites. It is a small scale open crenulation cleavage and occurs at a low angle (typically less than 45°) to the enveloping surface of the older foliation (mylonitic foliation) defined by the average grain shape fabric (Fig. 1) (Platt, 1979; Platt and Vissers, 1980; White, 1979; White et al., 1980; Gapais and White, 1982). Shear band foliation has been intensively studied in pelitic mylonites (phyllonites) (Sibson, 1977; Bell, 1978; Platt, 1979; White, 1979; White et al., 1980), in phyllites (Platt and Vissers, 1980), in quartz mylonite (Berthe et al., 1979b; Gapais and White, 1982), and in quartzo-feldspathic mylonite (Gapais, 1979; Simpson, 1984), within the past few years. White (1979) discusses field and microstructural observations of shear band foliations in the light of experimental studies on high strain deformation of metals and concludes that the foliation resembles shear bands which form during the high strain deformation of metals, particularly during rolling.

The spacing between bands is observed to be about 280 um by Gapais and White (1982) for quartz mylonite from the Hercynian belt of Brittany in France. They measured the width of the bands at about 600 μm Platt and Vissers (1980) measured the spacing between bands from 2 cm to 20 cm for phyllitic mylonite from the Vanoise massif in the French Penninic Alps. According to Berthe et al. *(1979a,b),* White (1979), Platt and Vissers (1980), White et al. (1980), and Gapais and White (1982), shear bands develop during the late stage of the same deformation that produced the mylonitic foliation. Shear bands are believed to develop at relatively low temperatures when the rock no longer is capable of homogeneously accommodating the bulk deformation at the imposed strain rate, so that the bulk deformation is accommodated by deformation in the shear bands (Gapais and White, 1982, p. 13), an explanation similar to that given by other researchers (e.g. Berthe et al., 1979a,b; Platt, 1979; White, 1979; Platt and Vissers,1980; White et al., 1980; Passchier, 1982; Simpson, 1984).

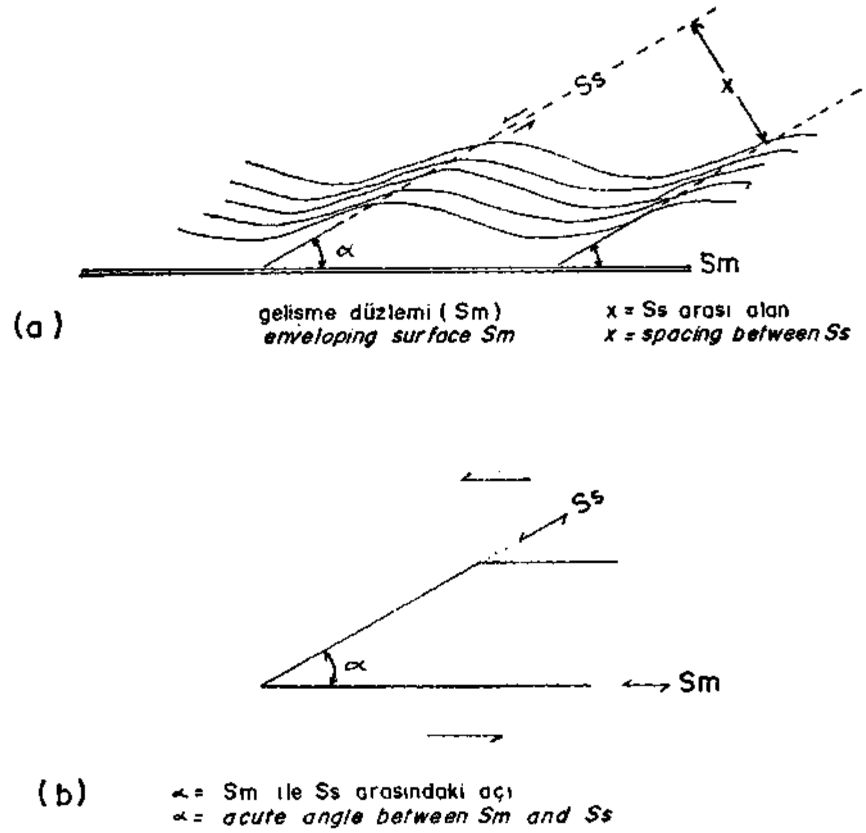


Fig. 1 - a - Geometry of shear band foliation (modified after Platt and Vissers, 1980, fig. 9); b - The acute angle between shear band foliation (S_s) and mylonitic foliation (S_m) points in the shear direction (data compiled from White et al., 1980; Simpson and Schmid, 1983).

Platt (1979), Platt and Vissers (1980), and Passchier (1982) referred to shear band foliation found in mylonites as «extensional cremilation cleavage». Platt and Vissers (1980, p. 397) described extensional crenulation cleavage as «sets of small scale ductile shear bands along the limbs of very open microfolds in the foliation. The sense of movement on the shear bands is such as to cause a component of extension along the older foliation».

Usually two sets of shear bands may develop at a low angle (less than 45°) to the mylonitic foliation (Platt and Vissers, 1980; White et al., 1980). In the light of experimental studies White et al. (1980, p. 178 and 186) proposed that if only one set of shear bands is formed in a mylonitic rock, the acute angle between the shear band foliation and the mylonitic foliation always points in the shear direction. Similar results were obtained by Simpson and Schmid (1983). Platt and Vissers (1980, p. 407-410) invoke that two sets of shear band foliations may form as a consequence of symmetric coaxial progressive deformation. They also note that a single set of shear bands probably develops as a result of asymmetric coaxial or noncoaxial progressive deformations.

Let us consider a small square of mylonitic rock with a mylonitic foliation undergoing a coaxial progressive deformation where the principal directions of the incremental strain are parallel to the principal directions of the total strain at each instant during the progressive deformation (Fig. 2a and b). In progressive deformation, the principal incremental strain and the total strain are defined by principal stretches (i.e. S^I : principal directions of incremental stretch, S^T : principal directions of total stretch) (Means, 1976, p. 226). In the case of symmetric coaxial progressive deformation, where the direction of maximum incremental stretch (S_1^I) and the direction of maximum total stretch (S_1^T) are both parallel to the mylonitic foliation at each instant, two conjugate sets of shear bands may initiate at a low angle (45° or less) to the pre-existing mylonitic foliation (Fig. 2a), as stated by Platt and Vissers (1980). At each instant during a coaxial progressive deformation the axes of the incremental and total strain ellipses (or ellipsoids) correspond to each other (Figs. 2a and b). This suggests that during the symmetric coaxial progressive deformation both sets of the shear bands will rotate toward the direction of maximum principal stretches (S_1^I and S_1^T) and the mylonitic foliation (S_m) with same rate, and they will remain active throughout this progressive deformation history. Platt and Vissers (1980, p. 407) assert that «simultaneous activity of both sets will be difficult: they will probably have to alternate, or operate on different scales».

During an asymmetric coaxial progressive deformation where the direction of maximum incremental stretch (S_1^I) and the direction of maximum total stretch (S_1^T) are both oblique to the mylonitic foliation (S_m), two sets of shear bands asymmetric with respect to the mylonitic foliation may form (Platt and Vissers, 1980) (Fig. 2b). In Fig. 2b, the acute angle between the first set of the shear bands and the mylonitic foliation is greater than the acute angle between the second set and the mylonitic foliation. With the coaxial progressive deformation, these shear band foliations will rotate toward the direction of maximum principal stretches (S_1^I and S_1^T) with same rate. The acute angle between shear bands (both 1 and 2 in Fig. 2b) and the mylonitic foliation decreases with the rotation. The second set becomes parallel to the mylonitic foliation first. At this instant, the second set may probably become inactive, because it requires a reverse slip direction on the mylonitic foliation (Fig. 2b) (Platt and Vissers, 1980). The first set of the shear bands therefore remains active as a single set of shear bands.

An example of a noncoaxial progressive deformation where the principal directions of the incremental stretch (S^I) are not parallel to the principal directions of the total stretch (S^T) at any instant during the progressive deformation is shown in Fig. 2c. At each instant during the noncoaxial progressive deformation the axes of the incremental and total strain ellipses (or ellipsoids) do not correspond to one another. Therefore at each instant during the noncoaxial progressive deformation the two conjugate sets of shear bands will rotate toward the direction of maximum incremental stretch (S_1^I) with different rates. In this case, simple shearing is assumed to be parallel to the S_m combined with flattening parallel to S_3^I (Fig. 2c). The second set of the shear bands shown in Fig. 2c will rotate with a greater rate than the first one. The second shear band that rotates faster will become inactive when it reaches the point where it is nearly parallel to the mylonitic foliation. The first set becomes dominant and remains active (Platt and Vissers, 1980) in the same sense of shear direction implied for the whole rock body undergoing the progressive deformation.

While the above review focuses mostly on the shear band foliation developed in pelitic, quartzitic, and quartzofeldsphatic mylonites, this paper is concerned with a detailed description of shear band structures within phyllitic psammites and calcareous mylonites within a 15 m wide brittle-ductile shear zone in the Keban metamorphic complex of Eastern Turkey. This study shows field evidence to determine the sense of shear using the orientation of shear band foliatipn in high strain rocks. The results of microstructural studies on shear band foliation are compared with the interpretation of White et al. (1980) and Simpson and Schmid (1983) for deducing the sense of shear in high strain rocks displaying one set of shear band foliation.

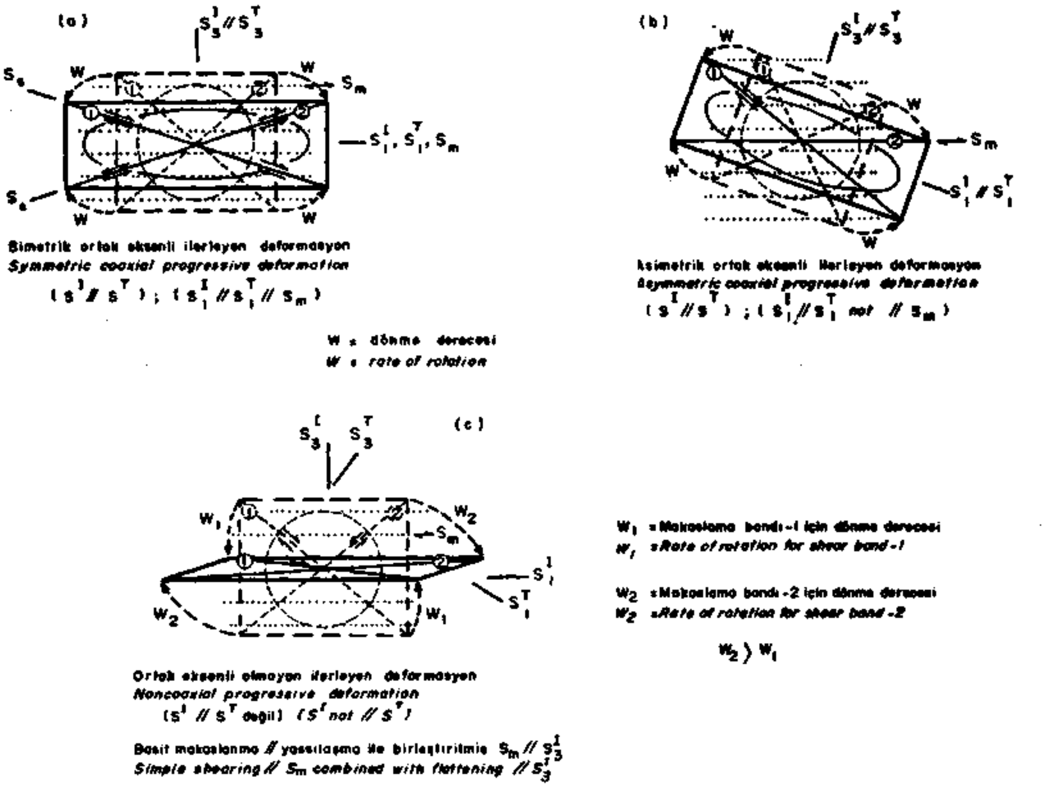


Fig. 2 - Shear band development.

a - Symmetric coaxial progressive deformation where the direction of S_1^I, the direction of S_1^T, and S_m are all parallel to one another; b - Asymmetric coaxial progressive deformation where S_1^I and S_1^T are parallel to each other in each instant but oblique to S_m. S_m is assumed to be a passive marker during the formation of S_s ; c - Noncoaxial progressive deformation where the S_1^I, S_1^T, and S_m are all oblique to one another. S_1^I - Direction of maximum incremental stretch; S_1^T - Direction of maximum total stretch; S_3^I - Direction of minimum incremental stretch; S_3^T - Direction of minimum total stretch; S_m - Mylonitic foliation; S_s - Shear band foliation (see text for discussion) (cf. Platt and Vissers (1980, Fig. 11) and White (1979, Fig. 2)).

GEOLOGICAL OUTLINE OF THE KEBAN METAMORPHIC COMPLEX

The Keban metamorphics are complexly deformed, and form the most northerly structural slice within the Bitlis suture zone of the Alpine-Himalayan orogenic belt in Eastern Turkey (Fig. 3). They are tectonically intercalated between the Mesozoic Munzur limestone and the Maastrichtian ophiolites of the Ovacık unit (Özgül et al., 1978) in the north, and the Campanian-Maastrichtian Elazığ volcanic island arc complex (Hempton and Savcı, 1982) in the south (Fig. 3a). Three main lithological units are distinguished in the Keban metamorphic complex. They are marble, phyllitic psammite and limestone units. The contacts between these unist are all folded thrusts (Fig. 3b) or brittle-ductile shear zones in the sense of Ramsay (1980).

The marble unit is composed of calote crystals which comprise 95-98 % of the rock. In between the calcite crystals, there are some muscovite (1-2 %) and epidote (2-3 %) crystals. The marble unit also locally shows 1 to 50 m thick amphibolite interlayers around the Pertek area (Perinfek, 1979).

The phyllitic psammites are pervasively interlayered with calcschist layers which range from 1 cm to 20 cm in thickness. The phyllitic psammite is a dark gray, fine grained rock consisting of 75-80 % quartz, 10-15 % muscovite-sericite, 5 % iron-oxide, 4 % chlorite, 4 % calcite, 2 % epidote, and very rare graphite and plagioclase. The calcschist interlayers are composed of 40-45 % calcite, 25-30 % quartz, 10-15 % muscovite-sericite, 10 % iron-oxide, 5 % chlorite, and very rare plagioclase feldspars. The structurally highest metamorphic unit consists of limestones with a mineral composition: 85-95 % calcite, 2-5 % iron-oxide, 3 % quartz, 2 % plagioclase, 2-3 % epidote, and very rare muscovite.

These ancient continental margin sedimentary sequences were formed between Palaeozoic (?) and the Triassic times (Kipman, 1981), and experienced low grade greenschist metamorphism during the Jurassic to the Lower Cretaceous (Savcı, 1983). They are cut by hypabyssal syenite porphyries intruded during the late Cretaceous (Savcı, 1983). In the Keban metamorphics, at least two phases of penetrative deformation are documented. There is also evidence for one nonpenetrative deformation. For more detailed description of the geological setting and tectogenic history of the Keban metamorphic complex, the reader is referred to Savcı (1983).

MINERALOGY AND MICROSTRUCTURES OF SELECTED MYLONITES

The descriptions of fault rocks given below are from ductile deformational parts of the brittle-ductile shear zone. Figure 4 is a schematic map and cross sectional view of this northeast trending and southeast dipping brittle-ductile shear zone which contains a number of lithologies (i.e. phyllitic psammite, calcschist, and limestone).

The mylonitic body formed in the brittle-ductile shear zone (Fig. 4) shows a progressive change in its texture within 15m from northwest to southeast across the zone. To the northwest, the mylonitic rocks become much finer grained. The stage in this development of the sequence is shown in Figs. 4, 5, and 7.

The first example to be described is a highly strained calcschists of the Keban metamorphic complex. They are composed of 40-50 % quartz, 20 % muscovite-sericite-chlorite, and 20-30 % calcite. Calcite usually occurs in the form of pod shaped aggregates up to 1.5 cm. The sheared, foliated calcite-quartz-mica-chlorite rich material surrounding the remnant unsheared calcite pods define an anastomosing shear zone (Figs. 4b and 5) in the sense of Simpson (1983). The average preferred

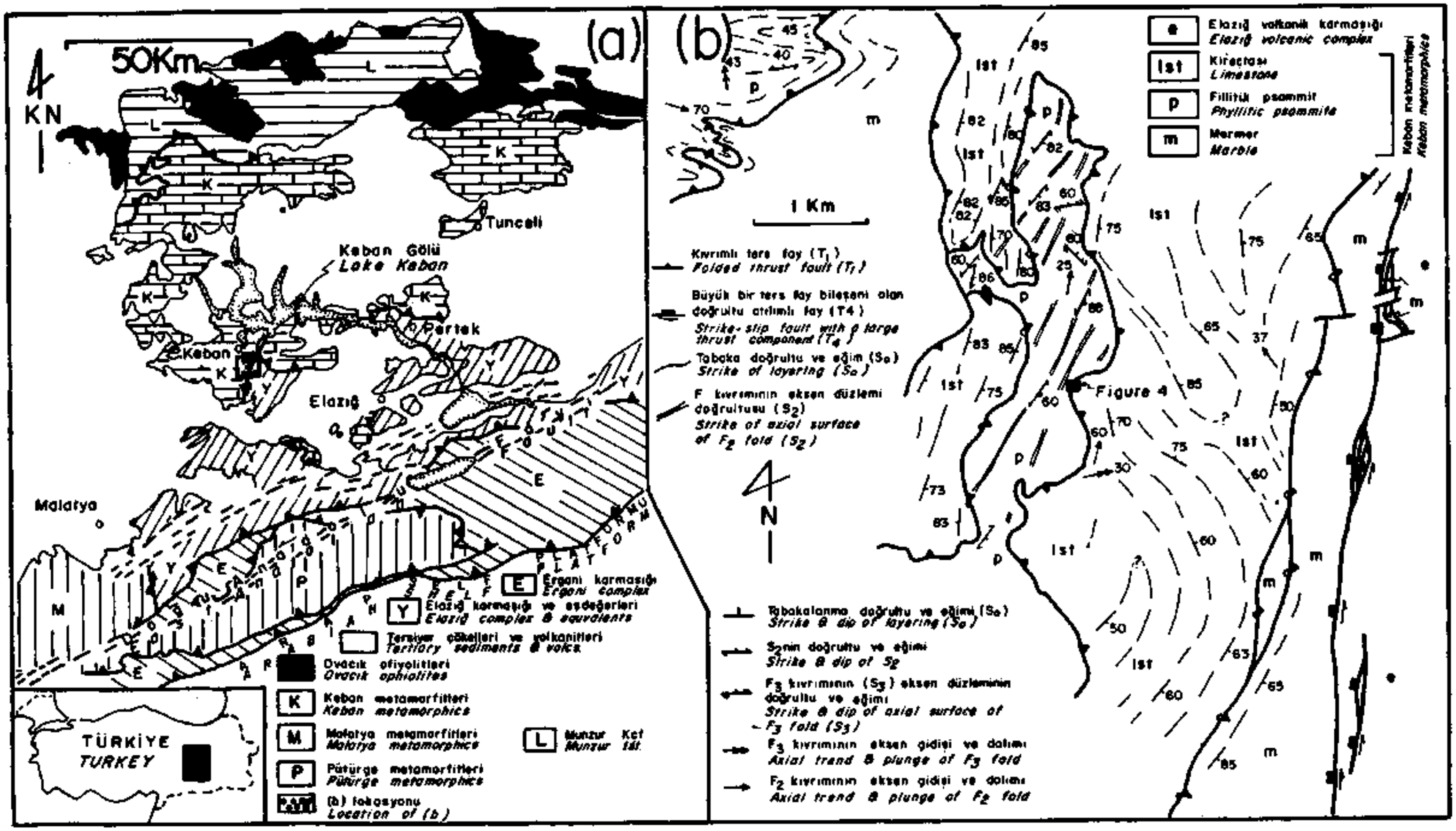


Fig. 3 a - Simplified geological map and tectonic setting of the Elazığ area, Eastern Turkey. In conjunction with the author's own observations, the map is compiled and somewhat reinterpreted from MTA (1961 *a,b*), Perinçek (1979), and Şengör and Yılmaz (1981); b - Simplified form surface and tectonic map of the Keban metamorphic complex, near Keban.

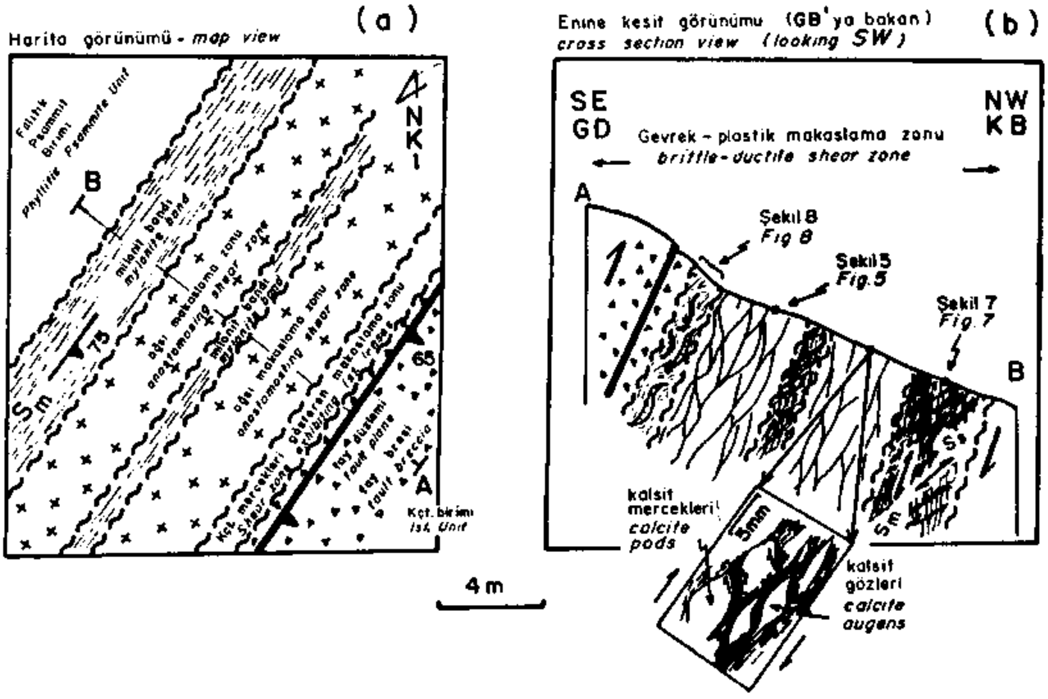


Fig. 4 - A schematic map (a) and cross section view (b) of the brittle-ductile shear zone studied.

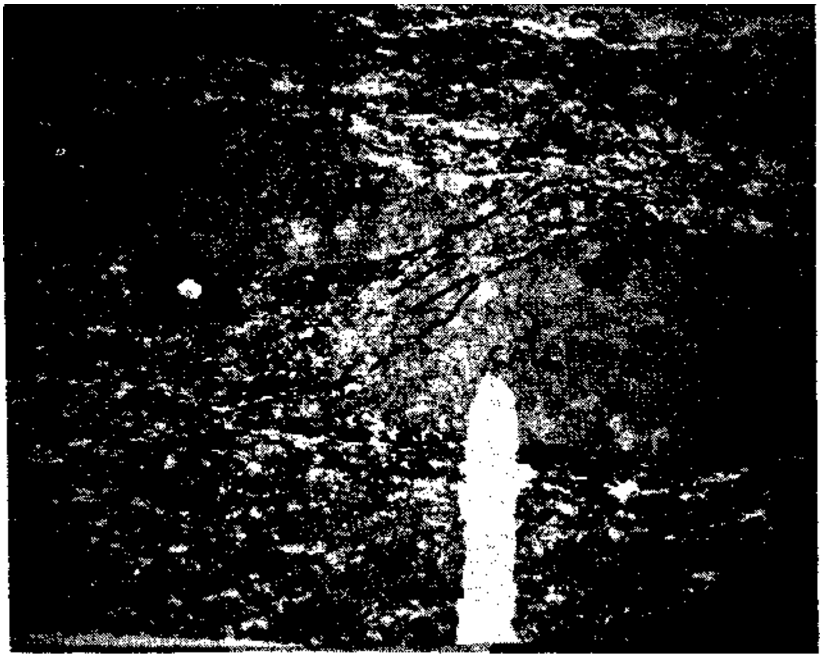


Fig. 5 - Photomicrograph of relatively unsheared calcite pods surrounded by strongly foliated ductile matrix (calcite- quartz-mica-chlorite) (polarized light; section perpendicular to the intermediate strain axis) (cf. Fig. 6b).

dimensional orientation of quartz, muscovite, sericite, and chlorite grains defines a mylonitic foliation. Simpson and Schmid (1983, p. 1282-1283) show that if the tails of the retort-shaped grains (augen) are comprised of fine grained material of the same composition as the augen material, they can then be used to deduce the shear direction. They demonstrate that these tails extend along the foliation plane in the shear direction (Fig. 6a). In this anastomosing shear zone, the tails of the calcite augen are composed of much finer grained calcite crystals. Moreover, between the calcite pods, smaller scale shear zones often occur at a low angle (30° to 35°) to the major shear zone defined by mylonitic foliation which surrounds the calcite pods and augens. As is shown in Fig. 5, the sense of displacement in this small scale shear zone between the calcite pods is southeast-over-nortwest. Simpson (1983, p. 63) shows that in an anastomosing shear zone the small shear zones between the relatively undeformed pods have the same sense of displacement as that of the major shear zones surrounding the pods (Fig. 6b). Using the criteria indicated above, i.e., asymmetry of augen structures (Fig. 6a) and shear direction in small shear zones formed between relatively undeformed pods (Fig. 6b), the sense of shearing is also determined as southeast-over-northwest (Fig. 5).

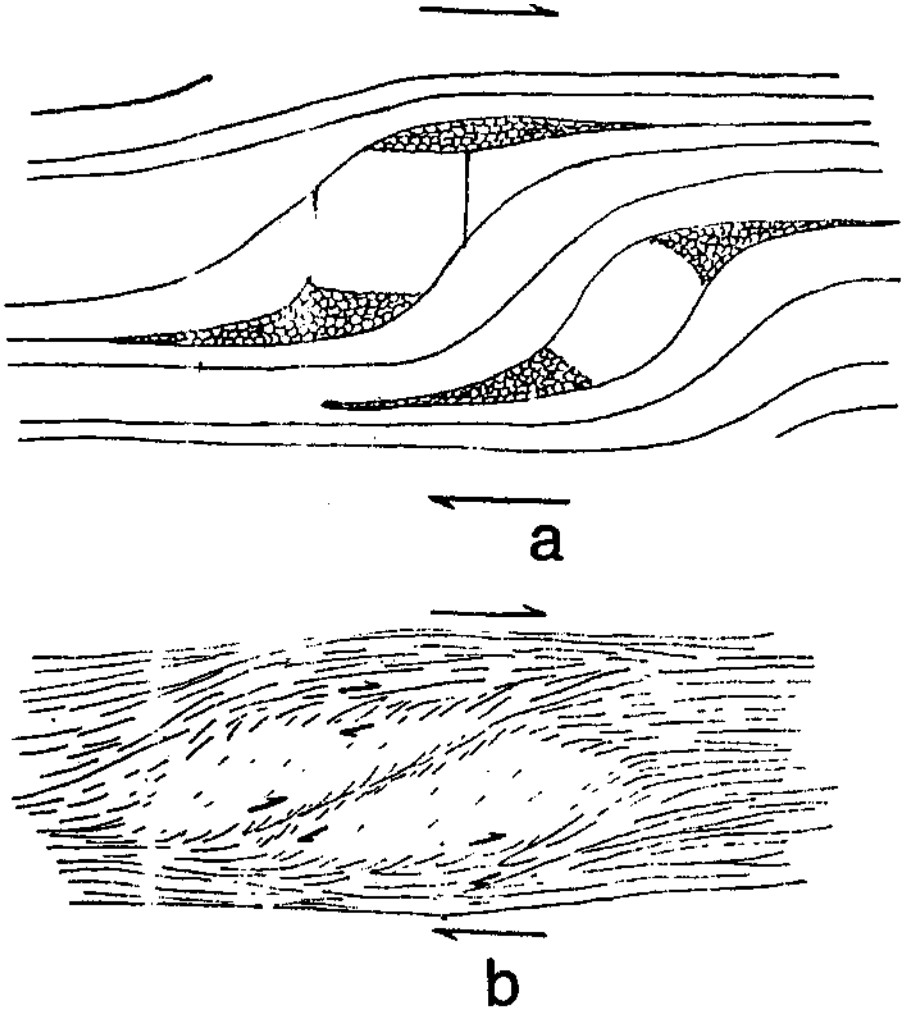


Fig. 6 a - The tails of the retort-shaped augens extend along the foliation plane in the shear direction (after Simpson and Schmid, 1983, Fig. 4); b - Small ductile shear zone between relatively undeformed pod-shaped aggregates has same sense of displacement as the major shear zones which surround the pods (after Simpson, 1983, Fig. 2a).

The second example to be described is a phyllitic psammite mylonite of the Keban metamorphic complex. It is composed of 75-85 % quartz, 10-15 % muscovite-sericite-chlorite, 5 % feldspar, 1-5 % iron-oxide, and about 1 % epidote. In these strongly foliated mylonites, the preferred dimensional orientation of quartz, feldspar, muscovite, sericite, and epidote grains or aggregates define a well developed mylonitic foliation (S_m) (Fig. 7). As readily observed in Fig. 7, this rock also shows a shear band foliation (S_s) which is about 30° oblique with respect to the mylonitic foliation. Generally, shear band foliation is defined by the preferred mineral elongation of micas. Where affected by a shear band, the mylonitic foliation trends into parallelism with the shear band boundary (Fig. 7). The spacing between bands varies from 100 to 780 µm. The width of the bands is usually 10 to 170 µm. As is mentioned in the introduction, according to White et al. (1980) and Simpson and Schmid (1983) the angular relationships between the shear band foliation (S_s) and the mylonitic foliation (S_m) define the sense of shear (Fig. 1b). Using this criterion, the direction of shearing in this mylonite determined as southeast-over-northwest as well (Fig. 7).

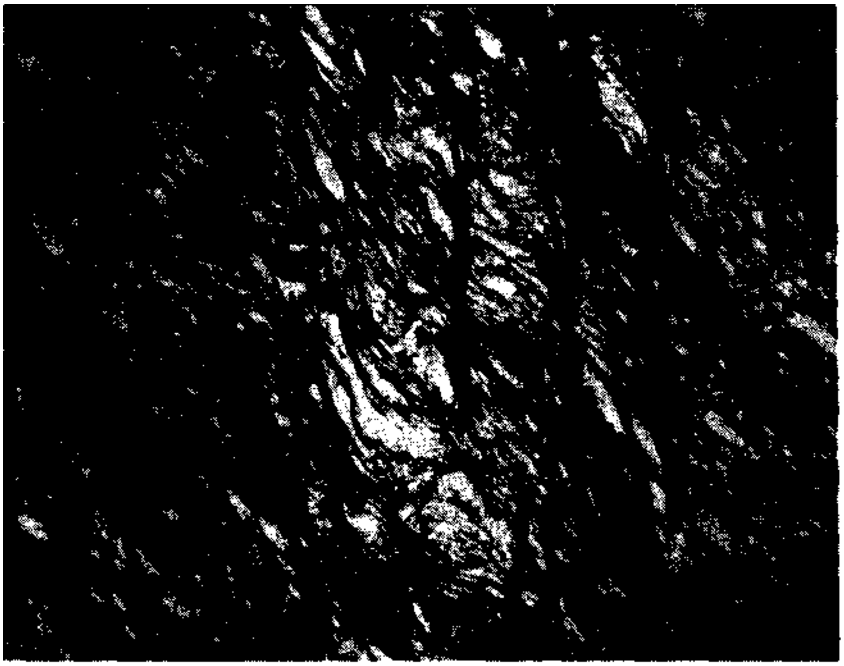


Fig. 7 - Photomicrograph of shear band structure within the phyllitic psammite - mylonite studied (polarized light; section perpendicular to the intermediate strain axis). Shear band foliation (S_s) is defined by the vertical dark zones. Within these zones mylonitic foliation (S_m) has been reoriented. White grains are mostly quartz. Dark fine-grained material is mica and chlorite. The average angle between S_m and S_s is 30° and the spacing between bands is up to 500 µm. Shear sense is southeast-over-northwest.

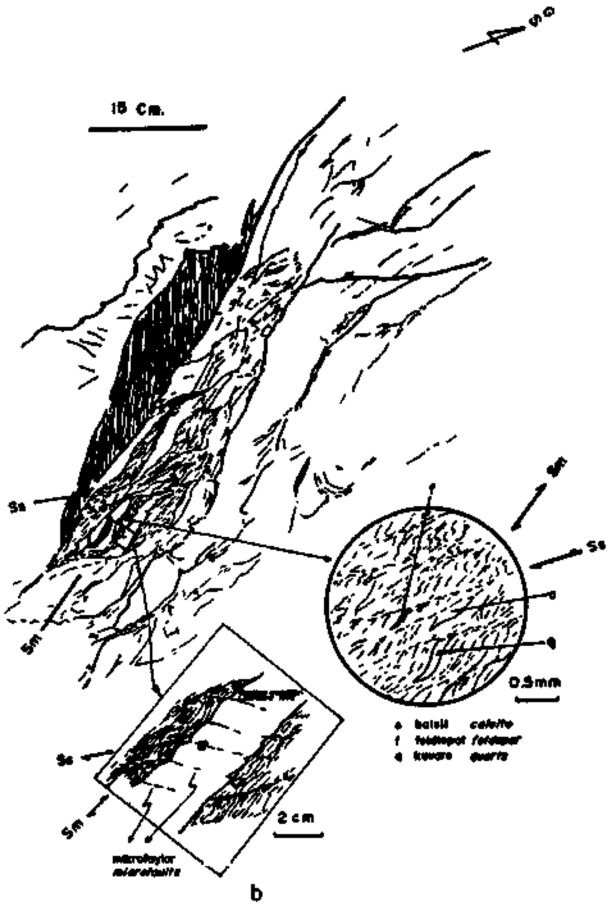
From the foregoing, it is concluded that the «sense of shear» observations at the microscopic scale (i.e., asymmetry of augen structures (Fig. 6a) and shear direction in small shear zones formed between relatively undeformed pods (Fig. 5)) corroborate the similar observation and conclusions based on the position of shear bands with respect to mylonitic foliation (Fig. 7). Therefore, the above result based on a field evidence is consistent with shear band interpretation of White et al. (1980) and Simpson and Schmid (1983).

The third example studied consists of a limestone-calcschist unit within the same brittle ductile shear zone (Fig. 4). This part of the shear zone, which is about one meter thick, is characterized by limestone lenses and quartz-mica rich calcschist layers between these lenses. At an outcrop scale, mylonitic foliation is defined by long axes of relatively unsheared limestone lenses which are up to 20 cm long and 2 to 5 cm wide; by grain shapes of calcite, quartz and feldspar, and by elongation of muscovite crystals which formed between the limestone lenses in zones 1 to 4 cm thick (Fig. 8). The thin mylonitic zones are composed of 35 % quartz, 25-35 % calcite, 5-7 % feldspar and 20 % muscovite-sericite-chlorite. In these thin, strongly foliated zones, there are some small scale open crenulation cleavages occurring at a low angle (35°) to the enveloping surface of the mylonitic foliation (Fig. 8). Where affected by these open crenulation cleavages, the mylonitic foliation trends into parallelism with these crenulation boundaries. Spacing between the crenulation cleavage surfaces varies between 500 and 850 µm. These open crenulation cleavages have similar characteristics to those shown in Fig. 7 and are interpreted as shear band foliation due to their resemblance to similar features described by White (1979), White et al. (1980), and Gapais and White (1982). Based on the angular relationships between the shear band foliation and the mylonitic foliation (Fig. 1b) the sense of movement determined in this way is also southeast-over-northwest (Fig. 8).Moreover, where affected by shear bands, tips of the limestone lenses curve and trend into parallelism with shear band boundaries (Fig. 8). In the main body of limestone lenses, microfaults cut across the lenses at a high angle (58°) to the mylonitic foliation. These microfaults occur only in the limestone lenses. The sense of displacement for microfaults formed in the limestone lenses is in the same sense as the shear band foliations developed between the lenses (Fig. 8). The shear band structures are interpreted in the same way as Gapais and White (1982) in that at the same high strain-rate, the deformational mechanism was brittle in the limestone lenses and more ductile in the quartz-mica rich zones. These quartz-mica rich zones consist of strongly foliated, thin ductile shear zones between relatively little deformed limestone lenses. Therefore, the two rock types with different physical properties have quite different behavioral responses the deformation. Brittle and ductile deformations may occur in close proximity within the same shear zone at the same time. It is concluded that when the bulk deformation cannot be accommodated by the dominant deformation process at the imposed strain rate, it is accommodated by deformation in the form of ductile shear bands in the quartz-mica rich calcschist and by deformation in the form of brittle microfaults in the limestone lenses.

CONCLUSIONS

Two well defined microscopic criteria are used to deduce the sense of shear in a lithologically inhomogeneous brittle-ductile shear zone of the Keban metamorphic complex. They are: (1) The tails of the asymmetric augen structures which extend along the foliation plane, and allow the sense of shear to be determined (Fig. 6a, Simpson and Schmid, 1983); (2) In anastomosing shear zones, the sense of shear determined in a smaller scale shear zones which were formed between the relatively undeformed pod shaped aggregates is in the same direction with the major shear zone surrounding these aggregates (Fig. 6b, Simpson, 1983), In the ductile mylonite bands found in the same shear zone (Fig. 4), the acute angle between the shear band foliation and the mylonitic foliation points in the same shear direction determined for the anastomosing shear zone showing asymmetric augen structures and relatively unsheared calcite pods (Fig. 5). This result is consistent with the sense of shearing interpretation of White et al. (1980) and Simpson and Schmid (1983) for high-strain mylonites exhibiting a single set of ductile shear band foliations. The Keban mylonites with a single set of shear band foliation may have been formed during a noncoaxial progressive deformation.

Fig. 8 a - A shear zone showing brittle deformational features (microfaults) in limestone lenses, and ductile deformational features (mylonitic foliation (S_m) and shear band foliation (S_s)) in the more ductile quartz-mica rich strongly foliated thin zones formed between the limestone lenses (cross section view).



Şek. 8b - A sketch drawn from Fig. 8a.

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