

STRUCTURAL EVOLUTION OF THE KAYABUKU
SHEAR ZONE, SOUTHERN MENDERES MASSIF,
WESTERN TURKEY

By

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CHAPTER I

INTRODUCTION

1.1. Problem Statement & Significance

One of the several post-collisional Alpine metamorphic massifs is the Menderes Massif in western Anatolia, Turkey. The massif is located within the Western Anatolia Extended Terrane (Cemen et al. 2006). During the 1990's, the massif has been recognized as one of the Cordillerean type metamorphic core complex as of the Aegean Extended Terrane, which also contains the Kazdag, Rhodope, Crete, and Cycladic Massifs (Figure 1). The Menderes Massif is a key area to examine the mechanisms of continental extensional deformation to understand the tectonic evolution of western Turkey and the Aegean region.

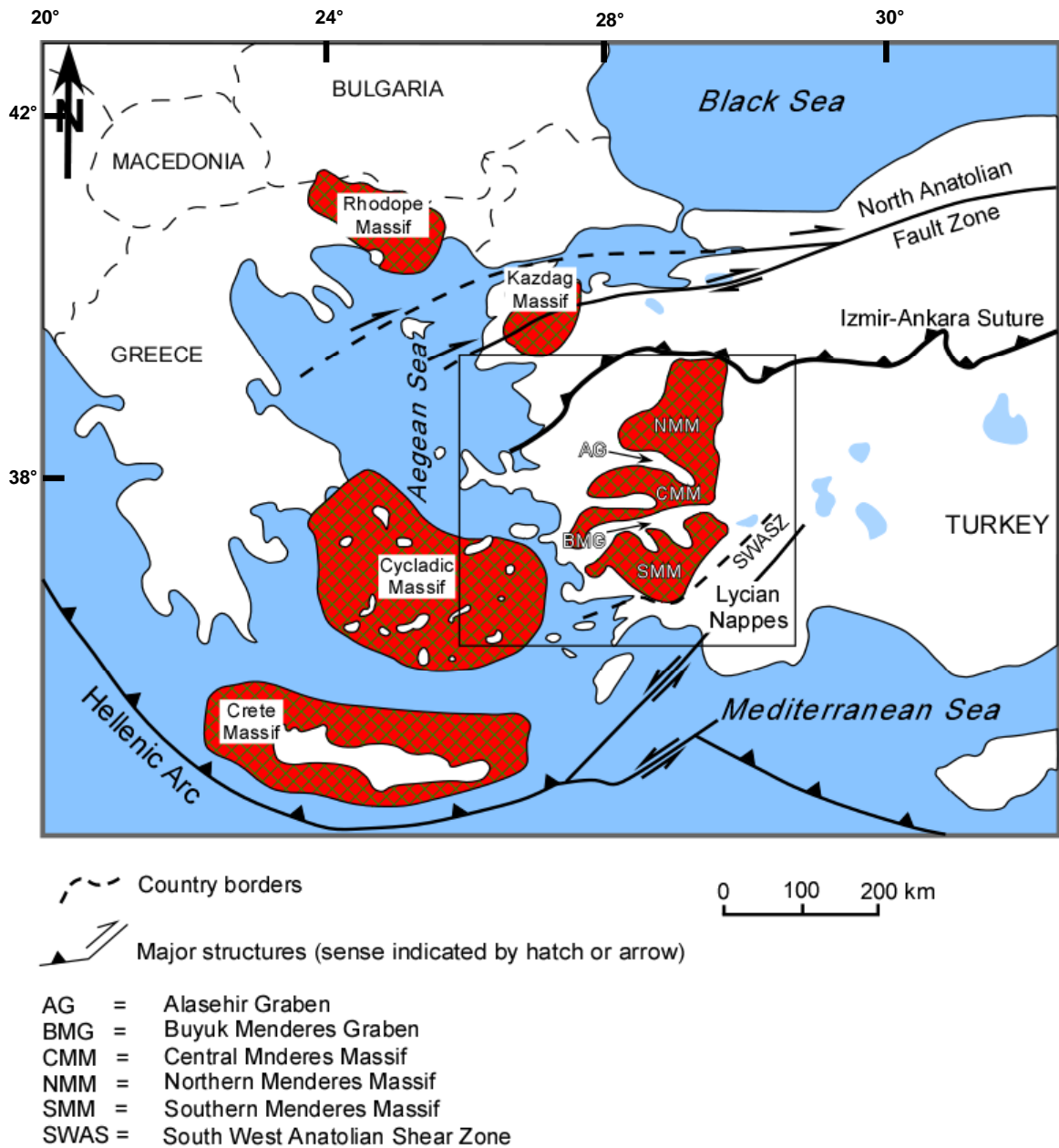


Figure 1. Generalized map of the Aegean region showing the major structural elements and the location of Alpine Metamorphic Belts. (Modified from Catlos and Cemen 2005, Cemen et al. 2006)

Many recent studies have been conducted to understand the geologic history and structural evolution of the Menderes Massif (e.g., Seyitoglu et al. 2000, 2002; Bozkurt

and Oberhansli 2001; Gessner et al. 2001b; Regnier et al. 2003; Rimmele et al. 2003; Purvis and Robertson 2004; Catlos and Cemen 2005; Cemen et al. 2006 and references therein). However, there are still many problems especially in the southern Menderes Massif. One of the main problems is the role of major extensional shear zones in the evolution of the Menderes Massif.

The Menderes Massif contains four major extensional shear zones. From north to south these are; the Simav (Isik and Tekeli 2001; Isik et al. 2003; Cemen et al. 2006); Alasehir (Hetzl et al. 1995a; Seyitoglu et al. 2000; Isik et al. 2003; Cemen et al. 2006); Buyuk Menderes (Cemen et al. 2006), and Kayabuku (Selimiye) shear zones (Bozkurt and Park 1994; Hetzel et al. 1995a; Regnier et al. 2003; Seyitoglu et al. 2004; Cemen et al. 2006). Although the first three shear zones have been well studied in recent years, the Kayabuku (Selimiye) shear zone has remained relatively unstudied. Therefore, its role in the geologic history of the Menderes Massif is unclear.

The main purpose of this study is to provide a better understanding of the geologic evolution of the Kayabuku (Selimiye) shear zone based on detailed field work, and microtectonic study.

The study area is located within the southern Menderes Massif in western Turkey, between Milas and Yatagan townships in Mugla (Figure 2). The area is characterized by a large scale south dipping shear zone known as the Kayabuku shear zone. Turkish topographic maps used in this thesis to study the shear zone are: N19 (b2, b3, b4), and N20 (a1, a2, a4).

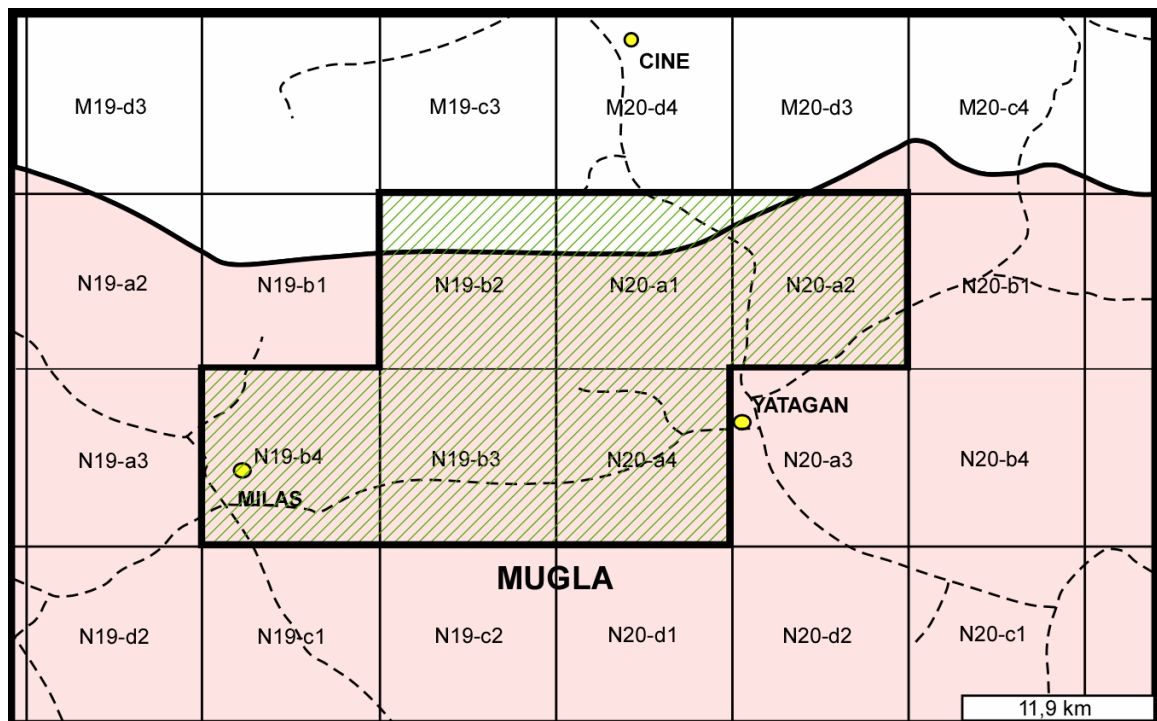
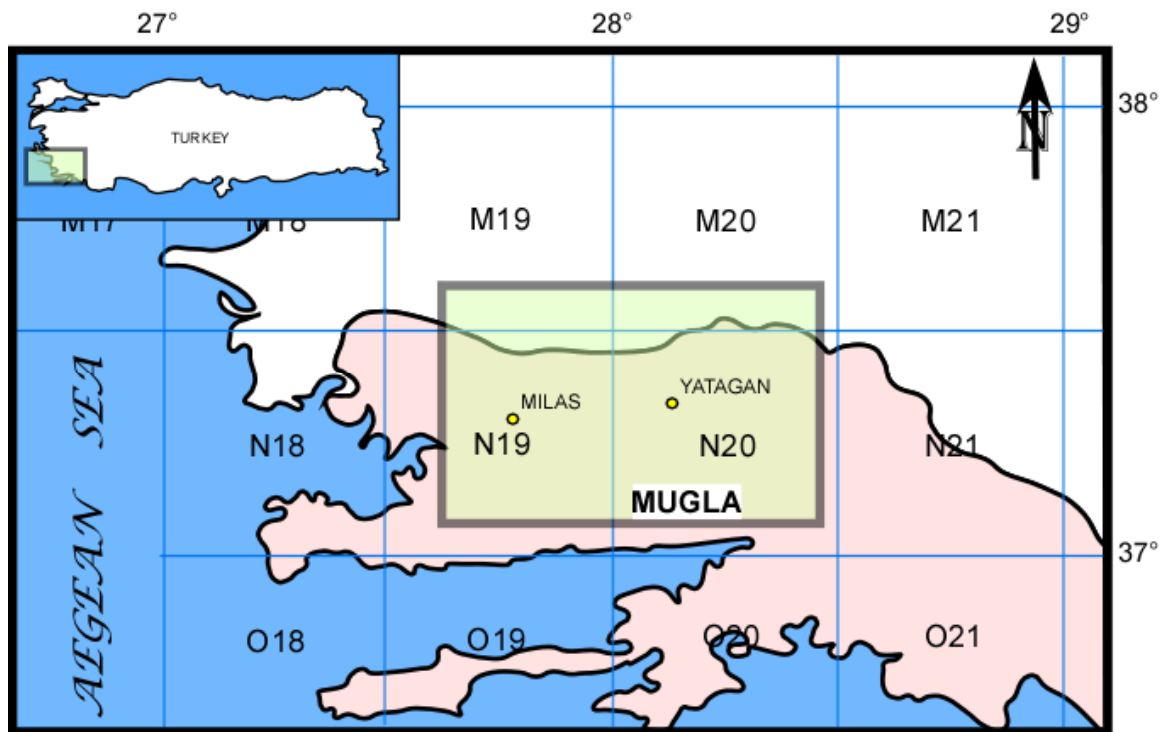


Figure 2. Location of the study area.

1.2. Methodology

1) *Literature survey*: Since 1960's, many studies have been done in western Turkey. Reserves at Middle East Technical University and General Directorate of Mineral Research & Exploration (MTA) in Turkey were obtained. Unpublished 1:25,000 scale geologic maps (N19 (b2, b3, b4) and N20 (a1, a2, a4)) of the study area were provided by Dr. Nesat Konak. In conjunction with the stated objectives of this thesis, the following has been accomplished.

2) *Field work and sampling*: A detailed field work between Milas and Yatagan townships has been conducted in a strip that is 44 km long and 3 km wide, covering six 1:25,000 unpublished geologic maps of Dr. Nesat Konak. During the field work, the geological features and rock units were examined; 7 transects have been made along the Kayabuku shear zone; 51 oriented rock samples (Table 1) were collected from different lithologies and outcrops for microtectonic and petrographic studies; detailed kinematic analyses of mesoscopic shear sense indicators have been made, and these features were photographed during the field work. Rock samples were located by using the Global Positioning System (GPS) and marked on the geologic maps.

3) *Structural cross sections*: Structural cross sections were constructed to understand the relationships between the rock units, variations in the lithology and sense of shearing along the shear zone.

4) *Laboratory analyses*: The oriented samples were cut parallel to the lineation and perpendicular to the foliation. All the information on the rocks (i.e. attitude of the foliation, and north direction) was transferred to thin sections. 106 oriented thin sections

were examined for both petrographic and structural analyses (i.e. kinematic analyses) by using petrographic microscope.

*Table 1. **A guideline for collecting oriented rock samples in the field***

- i) Strike, dip direction and dip amount of the foliation of a suitable part of the rock was recorded.
- ii) This information was marked on the rock itself. Additionally, an arrow showing the top of the sample and another arrow showing the north direction were drawn on the rock.
- iii) The rock sample was pulled out by hammer.

1.3. Geologic Overview of Western Turkey

Western Turkey is one of the most prominent regions in the world where mechanisms of post-collisional continental extension can be observed. It is located on the eastern part of the Aegean Extensional Province (Figure 1) and has experienced series of continental collisions from the Late Cretaceous to the Eocene (e.g., Sengor and Yilmaz 1981). Consequently, these continental collisions caused the formation of the major suture zones, namely the Izmir-Ankara-Erzincan Suture, Intra-Pontite Suture and Antalya Suture with the closure of the Neotethyan oceans in the Anatolian peninsula (e.g., Sengor and Yilmaz 1981; Dilek et al. 1999; Doglioni et al. 2002).

The continental platform which is referred as the Tauride-Anatolide unit lies to the south of the Izmir-Ankara-Erzincan suture and comprises several tectonic units bounded by major faults. These units include Tavsanli Zone (Okay 1984a, b), Bornova Flysch Zone (Erdogan 1990), the Afyon Zone (Akdeniz and Konak 1979; Okay 1984a, b, 2001; Sengor et al. 1984; Goncuoglu et al. 1996-1997), Menderes Massif, and Lycian

Nappes (De Graciansky 1972; Ricou et al. 1975; Collins and Robertson 1997, 1999, 2003) (Figure 3). Ozcan et al. (1988) and Goncuoglu et al. (1996-1997) suggest that the Afyon Zone and the Tavsanli Zone forms a single belt, namely the Kutahya-Bolkardag Belt.

Only the Menderes Massif will be discussed here. The reader is referred to read (e.g.) Okay (1984a, b); Goncuoglu et al. (1996-1997); Bozkurt and Oberhaensli (2001) for information on the other tectonic zones of western Turkey.

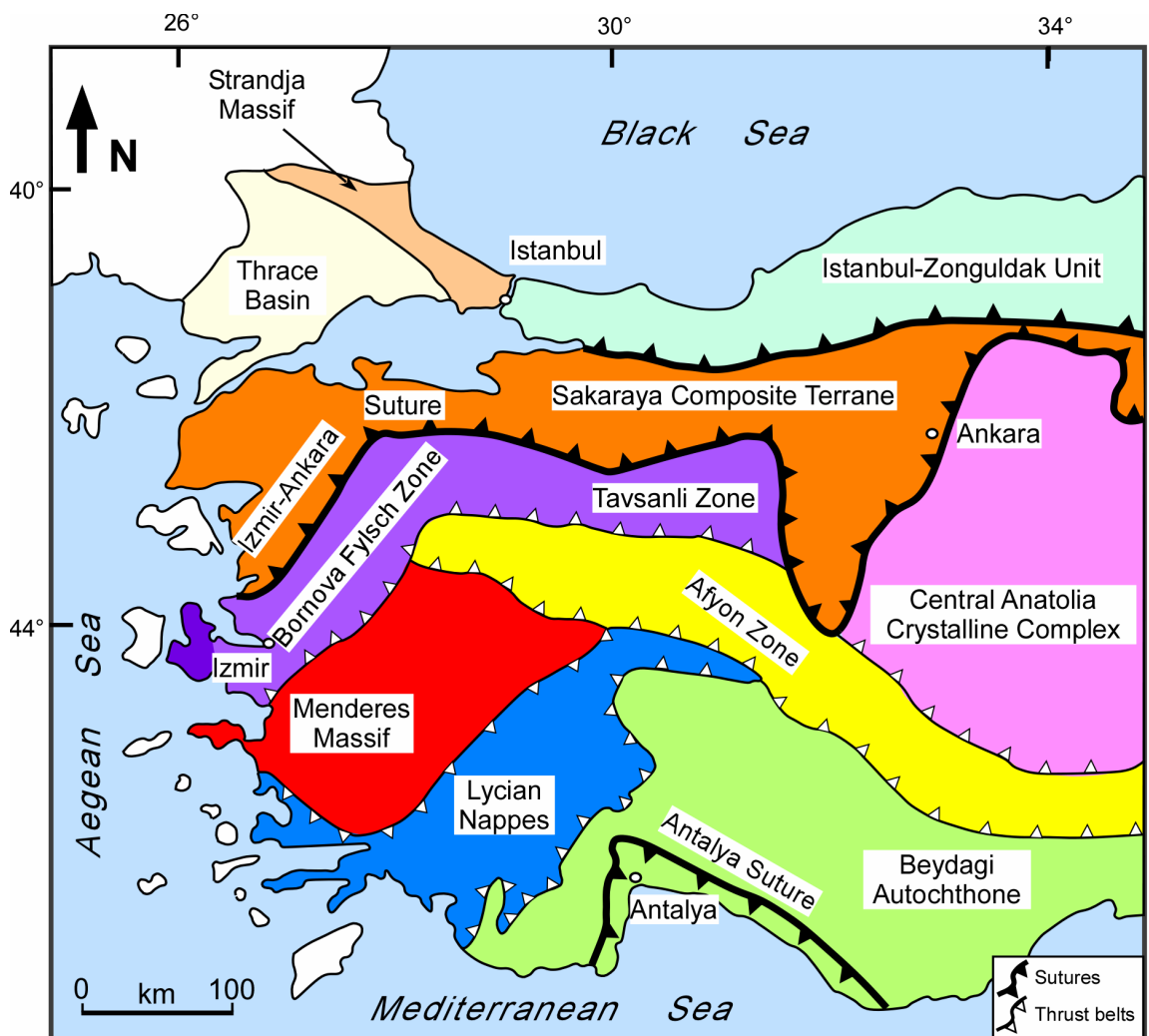


Figure 3. Simplified tectonic map of western Turkey (Modified from Okay and Tuysuz 1999)

1.3.1. The Menderes Massif

The Menderes Massif forms the western nuclei of the Anatolide belt. It is a large scale metamorphic core complex and covers an area of approximately 40 000 km² with its long axis trending NE-SW in the Western Anatolia Extended Terrane (Cemen et al. 2006). It is bounded by the Bornova Flysch and Afyon Zone to the north, and northeast; and the Lycian Nappes to the south and southeast (Okay and Tuysuz 1999).

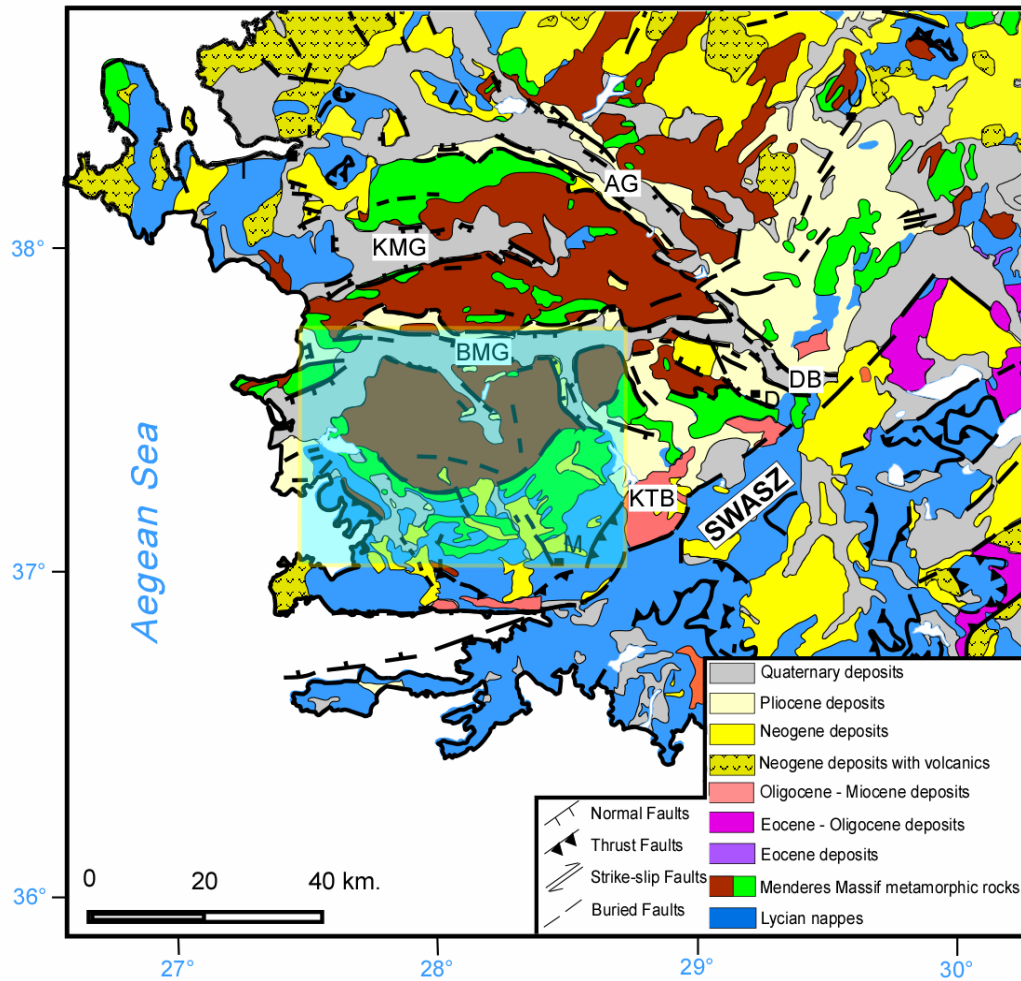


Figure 4. Simplified geologic map showing the sub-massifs of the Menderes Massif and sedimentary basins adjacent to the Southwest Anatolian Shear Zone (SWASZ). AG: Alasehir graben; BMG: Buyuk Menderes graben; DB: Denizli basin; KMG: Kucuk Menderes graben; KTB: Kale-Tavas basin (Cemen et al. 2006).

The Alasehir and Buyuk Menderes grabens divide the Menderes Massif into three sub-massifs (Sengor 1987). From north to south these are the northern (Gordes), central and southern (Cine) sub-massifs (Figure 4).

Traditionally, the metamorphic rocks of the Massif are subdivided into two distinct units, the “*core rocks*” and the “*cover rocks*”, on the basis of lithology, structure and contact relationship (e.g., Schuiling 1962; Durr 1975; Akkok 1983). However, recent studies indicate presence of nappes (Menderes nappes) that form the lowest exposed part of the Anatolide belt (see Table 2 for the correlation between the core and cover rocks, and the Menderes nappes) (e.g. Ring et al. 1999; Gessner et al. 2001a, 2001b; Okay 2001). The nappes were thrust on top of each other from Late Cretaceous to Eocene during the Alpine orogeny (Ring et al. 1999, 2001; Catlos and Cemen 2005, Thomson and Ring 2006). From structurally lowest to highest the Menderes nappes are: 1) the *Bayindir nappe*: characterized by continental margin sedimentary rocks (i.e. phyllite, quartzite and marble) of Paleozoic-Mesozoic age which subjected to a greenschist metamorphic event named as the “Main Menderes Metamorphism” in Late Eocene to Early Oligocene times; 2) the *Bozdag nappe*: consists of amphibolite facies metapelite with intercalated lenses of eclogite, amphibolite and marble lenses; 3) the *Cine nappe*: dominated by orthogneiss with local pelitic gneiss, migmatites, eclogites and amphibolites; and 4) the *Selimiye nappe*: made up of greenschist to lower amphibolite facies Late Paleozoic metasedimentary rocks (i.e. metapelite, calc-schist, metamarl, marble and quartzite).

| | | | |
|--------------------|-----------------------|-------------|--|
| Cover rocks | <i>Bayindir nappe</i> | Mesozoic | Metamorphosed continental margin sedimentary rocks (i.e. phyllite, quartzite and marble) |
| | <i>Selimiye nappe</i> | Paleozoic | Metasedimentary rocks (i.e. metapelite, calc-schist, metamarl, marble and quartzite) |
| Core rocks | <i>Bozdag nappe</i> | | |
| | <i>Cine nappe</i> | Precambrian | Orthogneiss with local pelitic gneiss, migmatites, eclogites and amphibolites |

Table 2. Correlation between the core and cover rocks, and the Menderes nappes (Modified from Regnier et al. 2007). Note that cover rocks of the massif contain other rock units such as metabauxite-bearing platform type marbles with minor schist interlayers, which do not belong to Bayindir or Selimiye nappes.

The “core rocks” consist of augen gneisses (typically orthogneiss), migmatites, metagabbros, with granulite and eclogite relicts, and medium to high grade schists (Akkok 1983; Sengor et al. 1984; Satir and Friedrichsen 1986; Candan et al. 1997; Oberhansli et al. 1997; Bozkurt and Oberhansli 2001). Augen gneisses are the dominant rock units of the “core rocks” and many studies have been done in order to understand the origin and age of the protolith of the augen gneisses. Two different protoliths have been suggested; a sedimentary protolith (e.g., Schuiling 1962; Basarir, 1970, 1975; Sengor et al. 1984; Satir and Friedrichsen 1986) and a granitic protolith (e.g., De

Graciansky 1965; Konak 1985; Konak et al. 1987). Recent studies by Bozkurt (2004) and Bozkurt and Oberhaensli (2001) proposed that the protoliths of the augen gneisses are calc-alkaline, peraluminous, S-type, late to post tectonic, tourmaline-bearing two-mica leucogranites.

The age of the augen gneisses is also contentious and there are two proposed ages; Late Precambrian-Early Cambrian (Schuiling 1962; Graciansky 1965; Basarir, 1970, 1975; Ozturk and Kocyigit 1983; Sengor et al. 1984; Konak 1985; Satir and Friedrichsen 1986, Konak et al. 1987) and Tertiary (Bozkurt et al. 1993, 1995; Erdogan 1992, 1993, Bozkurt and Park 1994). Sengor et al. (1984) suggested that the core of high grade metamorphic rocks have deformed during the Pan-African orogeny. Radiometric age determinations from the core rocks suggest that the age of the protoliths of the augen gneisses ranges from 520 Ma to 570 Ma (Hetzl and Reischmann 1996; Catlos and Cemen 2005).

The “*cover rocks*” are composed of Paleozoic low grade metasediments (schist envelope) and Mesozoic-Cenozoic marble dominated succession (marble envelope) (Sengor et al. 1984, Rimmele et al. 2003; Bozkurt and Oberhaensli 2001; Bozkurt 2004). The schist envelope is composed of garnet, kyanite, staurolite, chloritoid, and sillimanite-micaschists, quartzites, garnet amphibolites, pelitic and psammitic gneisses with black marble intercalations (Durr 1975; Basarir 1970, 1975; Akkok 1983; Ashworth and Evirgen 1984; Sengor et al. 1984; Satir and Friedrichsen 1986; Konak et al. 1987; Bozkurt 1996; Hetzel et al. 1998; Bozkurt and Oberhansli 2001; Rimmele et al. 2003) Around the Bafa lake, zircons from the psammites representing the lowermost levels of the “*cover rocks*” have been dated as 526 Ma (Loos and Reischmann 1999). Therefore an

Ordovician –Devonian age is suggested for the protolith of the lower schist envelope. The upper part of the cover schists is represented by the fossiliferous marbles (‘Goktepe marbles’; Onay 1949) which have been dated as Carboniferous (Onay 1949; Ozer and Erdem 1998). The marble envelope structurally overlies the schist envelope and consists of Upper Permian-Liassic marbles intercalated with schist and metavolcanics, Jurassic to Lower Cretaceous massive dolomitic marbles (Konak et al. 1987; Yalcin 1987), Late Cretaceous marbles containing Rudist fossils, Late Campanian-Late Maastrichtian reddish pelagic marbles (Durr 1975; Gutnic et al. 1979; Konak et al. 1987) and Upper Paleocene-Lower Eocene metaolistostrome with metaserpentine, metagabbros and metabauxite-bearing marble blocks within a schist matrix (Durr 1975; Gutnic et al. 1979; Caglayan et al. 1980; Konak et al. 1987; Bozkurt and Oberhansli 2001)

The boundary between the “*core*” and the “*cover rocks*” has been interpreted as an unconformity, named as the “supra-Pan-African unconformity” (Schuiling 1962; Ozturk and Kocyigit 1983; Sengor et al. 1984; Konak et al. 1985; Satir and Friedrichsen 1986; Konak et al. 1987). The main supporting evidence for this interpretation is the content of the Gokcay metaconglomerate in the southern Menderes Massif. It consists of deformed-elongate granite, tourmaline rich quartzite pebbles at structurally lower parts of the cover schists. Therefore, it has been interpreted as a basal conglomerate (Konak et al. 1987; Dora et al. 1998). However it is proposed that this unconformity may be located within the schists (Hetzl and Reischmann 1996). The relationship between the core and the cover rocks has also been suggested to be intrusive (Bozkurt et al. 1993, 1995; Erdogan 1992, 1993; Erdogan and Gungor 2004). The authors argued that the protoliths of the augen gneisses (*core rocks*) are Tertiary gneissoids and the contact between the

structurally overlying schists (*cover rocks*) is intrusive (Erdogan 1992; Bozkurt et al. 1993).

The contact relationship between the augen gneisses (orthogneisses) and the structurally overlying schists is has also been suggested to be tectonic (Bozkurt and Park 1994, 1997a, 1997b, 2001; Hetzel and Reischmann 1996; Ring et al. 1999; Bozkurt and Satir 2000; Bozkurt and Oberhansli 2001; Gessner et al. 2001a, 2001b, 2004; Isik and Tekeli 2001; Rimmele 2003). The boundary is interpreted as a shear zone.

The boundary between the two distinct rock units (orthogneiss and schist) of the Menderes Massif is well exposed in the southern Menderes Massif. Here, the contact corresponds to the south dipping Kayabuku shear zone which separates orthogneiss in its footwall from schist and marble rock units in its hanging wall. However, the origin of the shear zone is still controversial (i.e. compressional or extensional).

1.3.2. Metamorphism in the Menderes Massif

The Menderes Massif has been subjected to complicated and poly-phase metamorphism throughout its evolution. The timing and number of the metamorphic events are still not very clear. Pressure-temperature-time (P-T-t) conditions and precise interpretation of their relation with structural features will provide significant clue about the development of the Massif.

Table 3 (Cemen et al. 2006) summarizes P-T conditions for the Menderes Massif. P-T conditions, reported from the northern Menderes Massif, are correlated to Pan African related metamorphic events (Candan et al. 2001). In this section of the Massif, rocks experienced P-T conditions of about 5.3-9.2 kbar and 572-712°C (Table 3).

The northern section of the central Menderes Massif may have undergone a more complex metamorphism than the southern section due to its closeness to the Pontides and Anatolide-Tauride platform (Cemen et al. 2006). Akkok (1983) proposed that, so called “cover rocks” in the north may have undergone three major phases of metamorphism during the; 1) Cambro-Ordovician (Pan African related event); 2) Late Cretaceous- Early Eocene (Alpine related event); and 3) Late Oligocene to Late Miocene (Cemen et al. 2006). During the first event, rocks experienced pressure-temperature conditions of about 512-730°C and 4.9-15.1 kbar (Table 3). These conditions correspond to different metamorphic facies (i.e. eclogite and greenschist facies) depending on the location (Candan et al. 2001). The second event is associated with blueschist metamorphism, in which rocks experienced about 10 kbar and <470°C (Candan et al. 1997). During the third event, pelites may have reached greenschist to amphibolite conditions, whereas “core rocks” from Birgi and Tire may have experienced 13 kbar and 650°C (Ashworth and Evirgen 1985; Oberhansli et al. 1997).

The southern Menderes Massif has been subjected to different degrees of metamorphism and deformation since Cambrian (Table 3). P-T conditions of ~8 kbar to ~12 kbar at ~440°C to ~650°C, which are associated to Pan African orogeny, have been reported from gneiss and schist units (Candan et al. 2001; Regnier et al. 2003; Rimmelé et al. 2003). Similar metamorphic conditions (~4 kbar to ~12 kbar at ~430°C to ~675°C) have been attributed to Late Cretaceous-Early Eocene regional metamorphism (Whitney and Bozkurt 2002; Regnier et al. 2003) (Table 3). In addition, Satir and Taubald (2001) reported oxygen isotope temperatures of ~514°C to ~529°C. However the origin of this metamorphic event is unknown.

| | <i>Metamorphic event</i> | <i>Evidence</i> | <i>P(kbar)</i> | <i>T(°C)</i> | <i>Reference</i> |
|---------------------------------|--------------------------|---|---------------------|------------------|----------------------------|
| Northern Menderes Massif | M ₁ | Marble and schist; 20 km S of Kula | 5.3-8.3 | 572-612 | Candan et al. (2001) |
| | M ₁ | Marble and schist; near Salihli | 8.0-9.2 | 588-712 | Candan et al. (2001) |
| Central Menderes Massif | M ₁ | Orthogneiss core; 20 km SE of Tire | 5.1-11.9 | 512-674 | Candan et al. (2001) |
| | M ₁ | Lowermost Cine nappe | 6.2-6.4 | 620-730 | Ring et al. (2001) |
| | M ₁ | Orthogneiss core; 20 km S of Kiraz | 5.3-15.1 | 580-645 | Candan et al. (2001) |
| | M ₁ | Orthogneiss core; near Alasehir | 4.9-14.6 | 580-656 | Candan et al. (1997) |
| | M ₂ | Blueschist cover; western peninsula | 10.0 | <470 | Candan et al. (2001) |
| | M ₂ | Upper Bozdag nappe | 8.5-10.9 | 605-665 | Ring et al. (2001) |
| | M ₂ | Marble & schist; 20 km S of Alasehir | 5.6 | 600-660 | Akkok (1983) |
| | M ₃ | Pelites | 4.0-7.0 | 450-600 | Ashworth & Evirgen (1985) |
| | M ₃ | Core rocks; near Birgi and Tire | 13.0 | 650 | Oberhansli et al. (1997) |
| Southern Menderes Massif | M ₁ | Southern sub-massif | 10-12 | 440 | Rimmele et al. (2003) |
| | M ₁ | Cine nappe; 20-30 km N of Kayabuku shear zone | 8.0-11 | 600-650 | Regnier et al. (2003) |
| | M ₁ | Metasedimentary Cine nappe | 7.9±0.7 to 9.7±1.1 | 600±13 to 643±21 | Regnier et al. (2003) |
| | M ₁ | Gneiss; Southern Menderes Massif | 8.0-8.6 | 457-462 | Ashworth & Evirgen (1985) |
| | M ₂ | Selimiye nappe | 7.0±0.6 to 11.7±1.2 | 502±16 to 675±31 | Regnier et al. (2003) |
| | M ₂ | Cine sub-massif | <6.0-8.0 | 430-550 | Whitney and Bozkurt (2002) |
| | M ₂ | Cine nappe beneath the Kayabuku shear zone | 7.0 | >550 | Regnier et al. (2003) |
| | M ₂ | Metasedimentary Selimiye nappe | 4.0 | 525 | Regnier et al. (2003) |
| | M ₃ | Crystalline core of the Cine Massif | Not reported | 529±50 | Satir and Taubald (2001) |
| | M ₃ | Schist belt of the Cine Massif | Not reported | 514±67 | Satir and Taubald (2001) |

Table 3. Pressure and temperature conditions reported from the northern, central and southern Menderes Massif (Cemen et al. 2006). M₁: Pan African related event; M₂: Late Cretaceous - Early Eocene event; M₃: unknown event.

Throughout its tectono-metamorphic evolution, the Menderes Massif has subjected to poly-phase metamorphism and deformation. Based on the published P-T data, different geologic histories have been proposed.

1.3.3. The Southern Menderes Massif

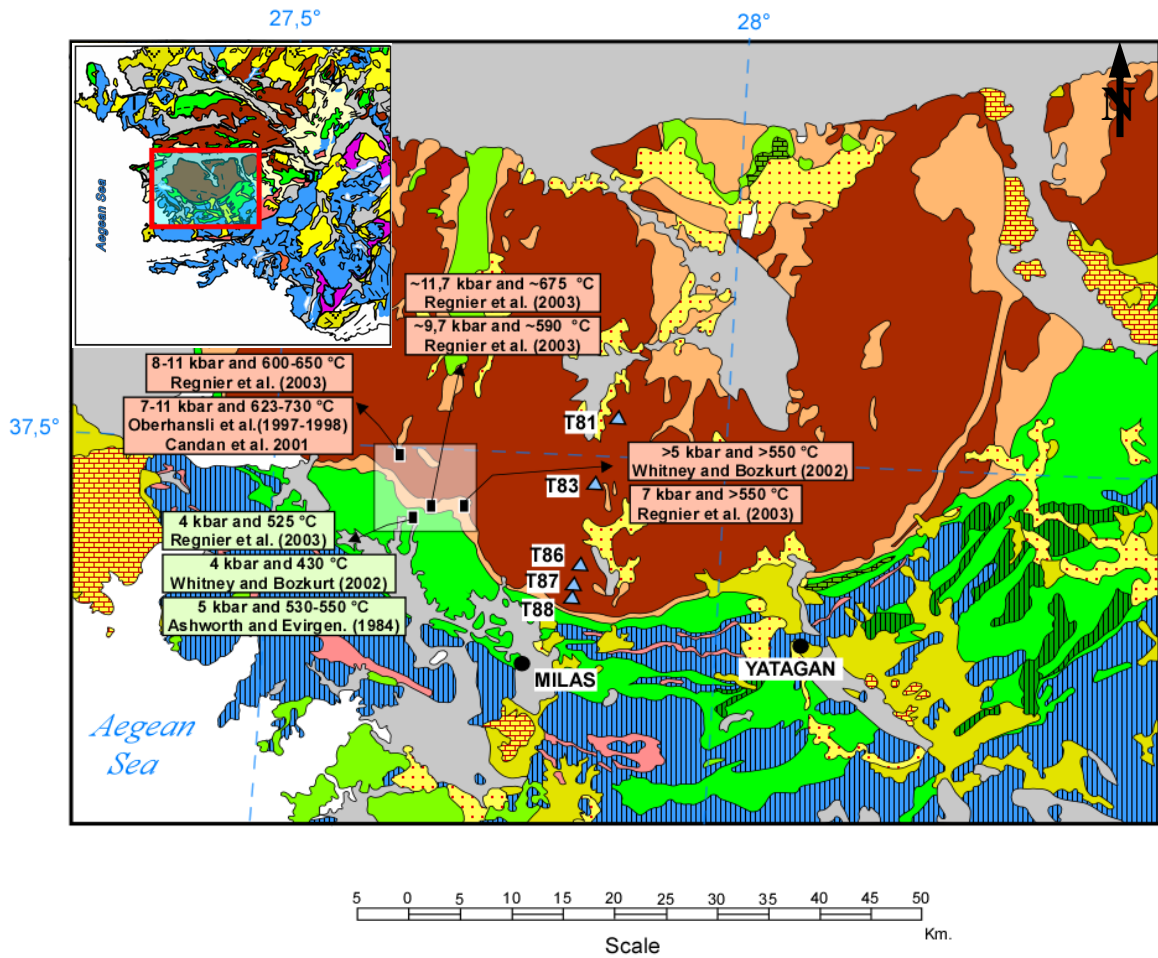
Geology of the southern Menderes Massif and the associated structures are very important within the exhumation history of the whole massif. The Kayabuku shear zone is the key area of the massif. The relationship of the shear zone with the surrounding rocks and the role of the shear zone within the evolution of the Massif has been the subject of numerous studies (e.g. Bozkurt et al. 1993; Bozkurt and Park 1994, 1997a, 1997b, 2001; Bozkurt 1996; Hetzel and Reischmann 1996; Bozkurt and Satir 2000; Whitney and Bozkurt 2002; Regnier et al. 2003, 2007; Ring et al. 2003; Bozkurt 2007). The origin (i.e. contractional or extensional), significance, and even the existence of the shear zone have been argued. In this section, previous investigations about the Kayabuku shear zone and role of the shear zone within the evolution of the Massif will be introduced.

The metamorphic rocks of the southern Menderes Massif (i.e. orthogneiss and schist), especially along the Kayabuku shear zone, contain various kinematic indicators and display NNE-SSW to NNW-SSE trending stretching lineations (Bozkurt and Park 1994; Hetzel and Reischmann 1996; Isik et al. 2003). It has been suggested that the kinematic indicators show mostly top-to-the south sense of shear (e.g. Bozkurt and Park 1994). Alternatively, the Kayabuku shear zone contains top-to-the north shear sense indicators as well (e.g. Bozkurt and Park 1994; Regnier et al. 2003, 2007; Cemen et al.

2006; Bozkurt 2007). However, these kinematic indicators have been interpreted differently. Some authors attributed top-to-the north and top-to-the south movement to N-S crustal shortening (e.g. Regnier et al. 2003, 2007; Ring et al. 2003), whereas others claim an extensional nature for the shear zone (e.g. Bozkurt and Park 1994; Whitney and Bozkurt 2002; Bozkurt 2004; Seyitoglu et al. 2004; Cemen et al. 2006; Bozkurt 2007). Bozkurt (2007) suggested that the shear zone initiated as a top-to-the north thrust fault during Alpine contractional deformation but then reactivated as a top-to-the south extensional shear zone during the exhumation of the southern Menderes Massif in Oligocene-Miocene times. Alternatively, Ring et al. (2003) claimed that the Kayabuku shear zone originated as a top-to-the south thrust fault. The supporting evidence for this argument is the $^{40}\text{Ar}/^{39}\text{Ar}$ -white-mica cooling ages of Hetzel and Reischmann (1996) which young northward and structurally downward. However, Bozkurt (2007) speculated that the plateau and isochron ages of schists are younger than the orthogneiss, therefore the $^{40}\text{Ar}/^{39}\text{Ar}$ -white-mica cooling ages young southward and not northward as suggested by Ring et al. (2003). Another argument about the nature of the shear zone and timing of the kinematic indicators has been made by Regnier et al. (2007). Regnier et al. (2007) suggested that, the Kayabuku shear zone resulted from N-S crustal shortening and there is no evidence in the shear zone that the top-to-the north shear sense indicators formed before the top-to-the south kinematic indicators as assumed by Bozkurt and Park (1994) and Whitney and Bozkurt (2002).

P-T conditions reported from the southern Menderes Massif, more specifically from the western flank of the Kayabuku shear zone (Figure 5), support the existence of a tectonic contact between the orthogneiss and schist units and give us clue about the

nature of the shear zone. P-T data published by Ashworth and Evirgen (1984), Oberhansli et al. (1997, 1998), Whitney and Bozkurt (2002), and Regnier et al. (2003) showed that the orthogneiss sequence has undergone metamorphic conditions of ~8 kbar and >550 °C, whereas the schist sequence has subjected to ~4-5 kbar and <550 °C of P-T conditions. Therefore, the difference between the grades of the metamorphism between the two distinct units of the Menderes Massif supports existence of the shear zone. Moreover, the field relationship suggest, that the shear zone is extensional, since the Kayabuku shear zone contains low grade metamorphosed rocks (schist unit; ~4-5 kbar and <550 °C) in its hanging wall block whereas, higher grade metamorphosed rocks (orthogneiss; ~8 kbar and >550 °C) in its footwall block (Figure 5).



Geological Explanations

| | | | | | |
|------------------------------|--|-------------------------|------------------------|--|--|
| Paleozoic and/or Precambrian | | Metagranite | Upper Paleocene-Eocene | | Metaflysch |
| Precambrian | | Fine grained gneiss | Middle-Upper Miocene | | Continental clastic rocks |
| Upper Paleozoic | | Undifferentiated schist | Lower-Middle Miocene | | Continental carbonate rocks |
| Upper Paleozoic | | Marble | Upper Miocene | | Continental clastic rocks |
| Jurassic-Cretaceous | | Marble | Pleistocene | | Undifferentiated continental clastic rocks |

Figure 5. Geological map of the southern Menderes Massif (digitized from 1:500,000 scale geological maps of MTA) showing sample locations of P-T data and apatite fission track ages (Modified from Bozkurt 2007).

Additional sustaining evidence for the existence and extensional nature of the shear zone is the apatite fission-track data published by Ring et al. (2003). In the southern portion of the Massif, the apatite fission-track ages young southward (Figure 6), indicating progressive unroofing of the orthogneiss (footwall rocks) towards south. Thus, the exhumation of the orthogneiss has taken place along the extensional south dipping Kayabuku shear zone.

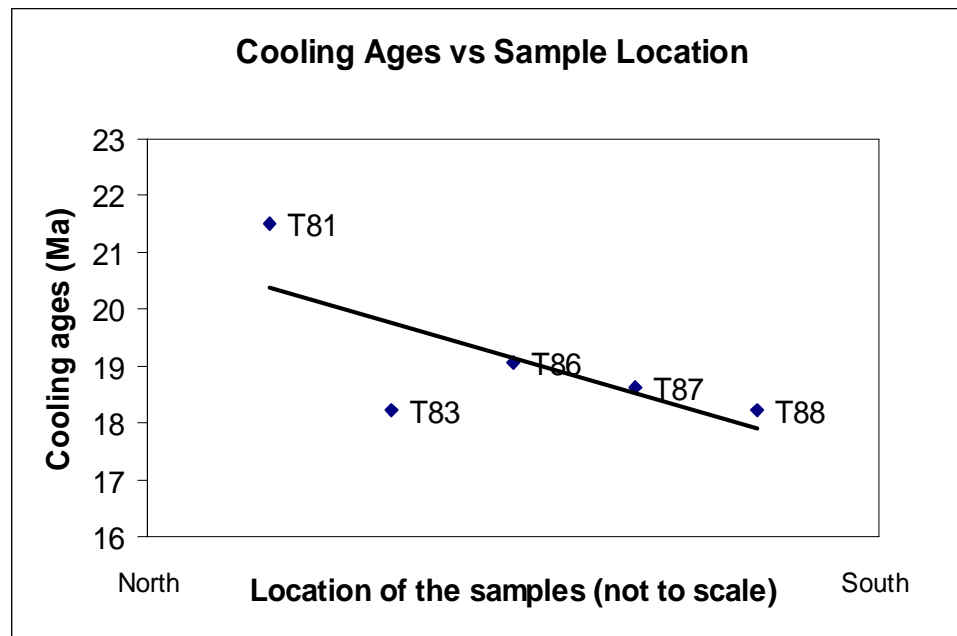


Figure 6. Results of apatite fission-track dating of orthogneiss from the southern Menderes Massif (Apatite-fission track ages are from Ring et al. 2003). Note that cooling ages of orthogneiss young towards south. See figure 5 for sample locations.

1.3.4. Proposed Tectonic Models for the Tertiary Exhumation of the Menderes

Massif

Three major models have been proposed to explain the origin and timing of the N-S directed extensional tectonism in western Turkey;

- 1) *Tectonic escape/Lateral extrusion model*: This model suggests that extension in western Turkey started with the initiation of the westward movement of the Anatolian plate along the North Anatolian and East Anatolian Fault Zones in response to the collision of Arabia and Anatolia plates (Figure 7) (e.g. Dewey and Sengor 1979; Sengor 1979; Sengor and Yilmaz 1981; Sengor et al. 1985; Cemen et al. 1993, 1999).
- 2) *Back-arc extension and subduction roll back model*: In this model, back arc extension caused by the southwest shifting of the subduction along the Hellenic arc (Figure 7) in the Early Miocene (~ 18 Ma) caused the extension (e.g. McKenzie 1978; Le Pichon and Angelier 1979, 1981).
- 3) *Orogenic collapse model*: In this model, the extension began in the Oligocene by spreading and thinning of the over-thickened crust after the formation of the Izmir-Ankara-Erzincan Suture Zone (e.g. Dewey 1988; Seyitoglu and Scott 1992; Dilek and Whitney 2000).

In a recent paper, Cemen et al. (2006) proposed that all of these three mechanisms have contributed to the extensional tectonics of the Western Anatolia Extended Terrane (WAET) which contains the Menderes Massif.

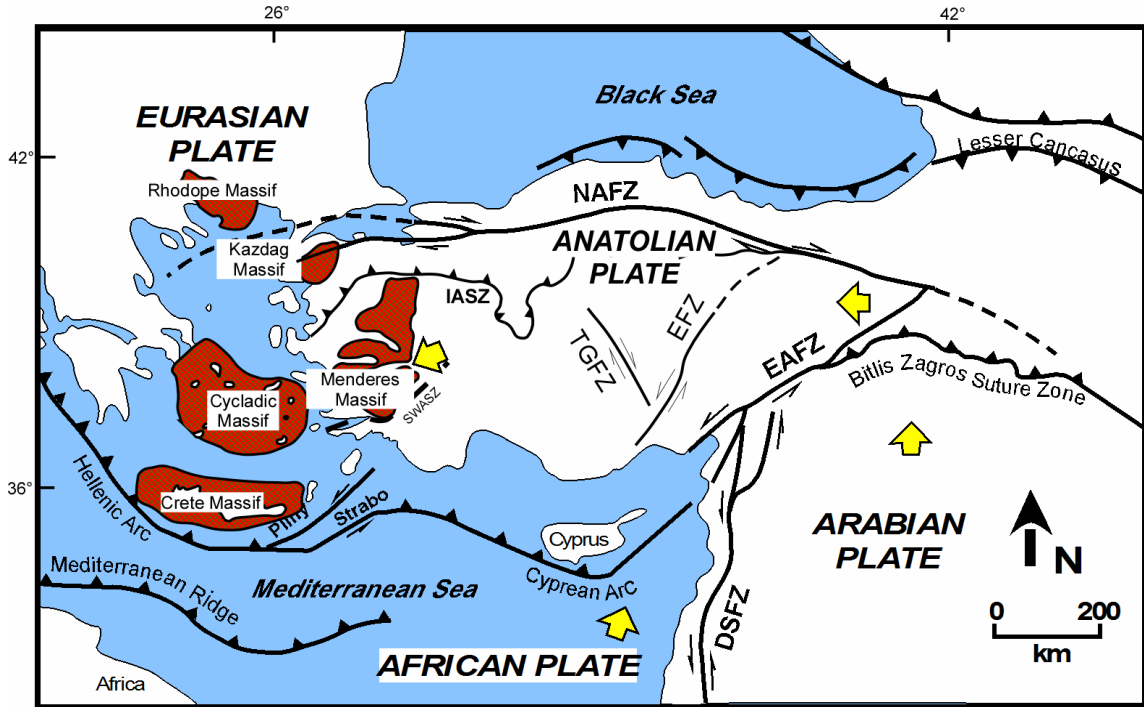


Figure 7. Simplified tectonic map of Turkey showing major structures (modified from Barka 1992 and, Bozkurt and Sozbilir 2004). DSFZ – Dead Sea Fault Zone, EAFZ – East Anatolian Fault Zone, IASZ – Izmir-Ankara Suture Zone, NAFZ – North Anatolian Fault Zone, EFZ – Eceemis Fault Zone, TGFZ – Tuzgolu Fault Zone, SWASZ – Southwest Anatolian Shear Zone. Yellow filled arrows indicate relative movement direction of African, Arabian and Anatolia plates.

They suggested that the N-S extension in the WAET is the product of three uninterrupted stages (Figure 8) triggered by different mechanisms (i.e. tectonic escape/lateral extrusion model, back arc extension model, orogenic collapse model).

The first stage started in the Late Oligocene along the South West Anatolian Shear Zone (SWASZ) by thinning and spreading of the over thickened crust after the Eocene Alpine collision that formed Izmir-Ankara Suture Zone (Figure 8a and b).

SWASZ is a north dipping extensional simple shear zone with listric geometry at depth and located at the southern margin of the Menderes Massif. The dominant top to the north-northeast shear sense indicators and a series of Oligocene extensional basins (e.g. The Oren, Yatagan and Kale-Tavas basins) located next to the shear zone that contain only carbonate and ophiolitic rock clasts are the main evidence for the existence of the shear zone. The metamorphic rocks of the Menderes Massif were started to exhume by erosion and extensional unroofing in the Late Oligocene (Cemen et al. 2006).

The second stage initiated when north dipping Alasehir and the south dipping Buyuk Menderes detachment surfaces were formed which controlled the deposition in the Alasehir and Buyuk Menderes grabens (Figure 8c) (Cemen et al. 2006). The central Menderes Massif exhumed along the Alasehir and Buyuk Menderes detachments.

The third and final stage, which is still active, was started by the initiation of the North Anatolian Fault. The high angle normal faults in the Massif, which cut and mask the earlier extensional features, and the younger grabens, such as the Kucuk Menderes graben, have formed as the N-S extensional tectonism continued in western Turkey (Figure 8d) (Cemen et al. 2006)

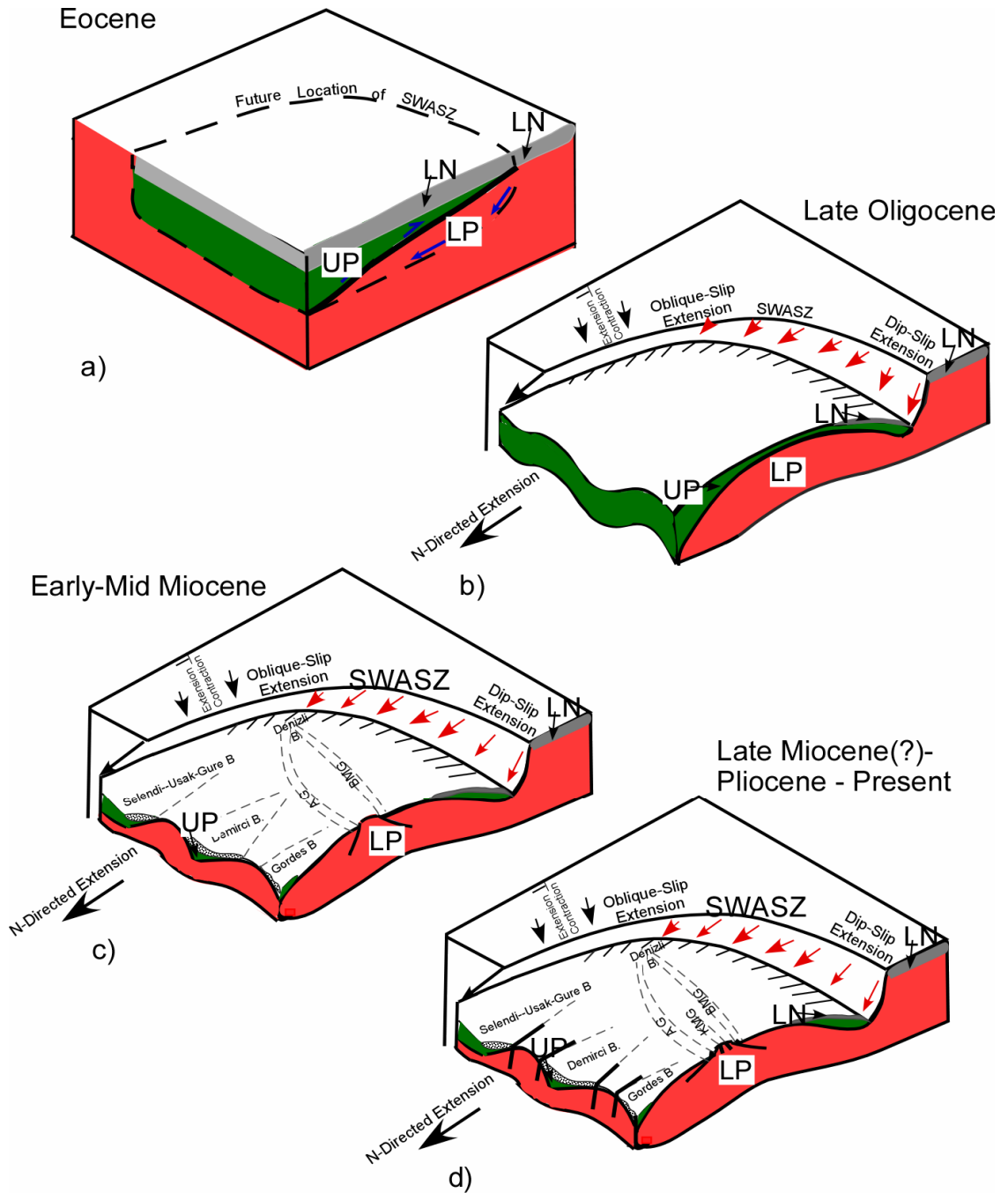


Figure 8. 3-D model showing the Tertiary structural evolution of the Menderes Massif (Cemen et al. 2006). AG: Alasehir graben; BMG: Buyuk Menderes graben; KMG: Kucuk Menderes graben; KTB: Kale-Tavas Basin; LN: Lycian nappe; LP: lower plate; OB: Oren Basin; SG: Simav graben; SWASZ: South West Anatolian Shear Zone; UP: upper plate.

An episodic, two-stage extension model has been proposed by Bozkurt and Sozbilir (2004). The first stage started in the Early Miocene (i.e. corresponding to the second stage of Cemen et al. 2006) by the orogenic collapse and/or back arc extension (Hetzl et al. 1995b; Seyitoglu and Scott 1996). In this phase metamorphic rocks of the Menderes Massif began to exhume along the Alasehir detachment. However, absence of the Late Paleozoic to Mesozoic carbonate fragments in the Alasehir graben was neglected when proposing this age for the initiation of the exhumation of the Massif.

The second stage, which corresponds to the third stage of Cemen et al. 2006, started after the “short-time gap” by the initiation of the dextral movement of the Anatolian plate along the North Anatolian Fault System in ~5 Ma and the roll back of the Aegean subduction. In addition, Bozkurt and Sozbilir (2004) claimed that the final unroofing of the Menderes Massif was brought the metamorphic rocks to the surface along the high angle normal faults.

Purvis and Robertson (2004) suggested a three stage model, named as “pulsed extension”, for the extensional tectonism in western Turkey. The first stage of the extension is related to the subduction of the African plate along the Hellenic arc which caused the formation of the northeast-southwest basins (i.e. Gordes and Selendi basins) in the Late Oligocene. Then the subduction roll-back continued during the Miocene and initiated the Alasehir graben in the second stage of the Purvis and Robertson’s (2004) “pulsed extension” model. Finally, in the Pliocene to Quaternary (~5 Ma), high-angle faulting dominated the regional tectonic setting which is related to the tectonic escape of Anatolia (Purvis and Robertson 2004).

CHAPTER II

LITERATURE REVIEW

2.1. Metamorphic Core Complexes

Metamorphic core complexes are unique structures that form as a result of major continental extension. They were first defined by Davis and Coney (1979) in the Basin and Range provinces in North American Cordillera:

“regions where extensional shear zone on a detachment has drawn up strongly foliated and lineated mylonitized lower plate rocks from the deeper part of the crust to the surface. The mylonite, in turn, is overprinted by strongly brecciated unmetamorphosed carapace of upper plate rocks during uplift. Metamorphic core complexes create asymmetrically dome like structures, which may also be formed due to regional plutonism/magmatism. The intrusions (synextensional magmatism) are the result of thermal uplift, heating the upper crust”

Two different models have been proposed for lithospheric extension and formation of metamorphic core complexes. These models are based on “pure shearing” and “simple shearing” mechanisms respectively.

2.2. Pure Shear Model:

In the pure shear model (McKenzie 1978) extension is accommodated by brittle deformation and faulting of the upper crust and ductile deformation of the lower crust. Furthermore, crustal thinning is almost uniform during continental extension and therefore, a symmetrical feature forms as a product of the extension (McKenzie 1978) (Figure 9).

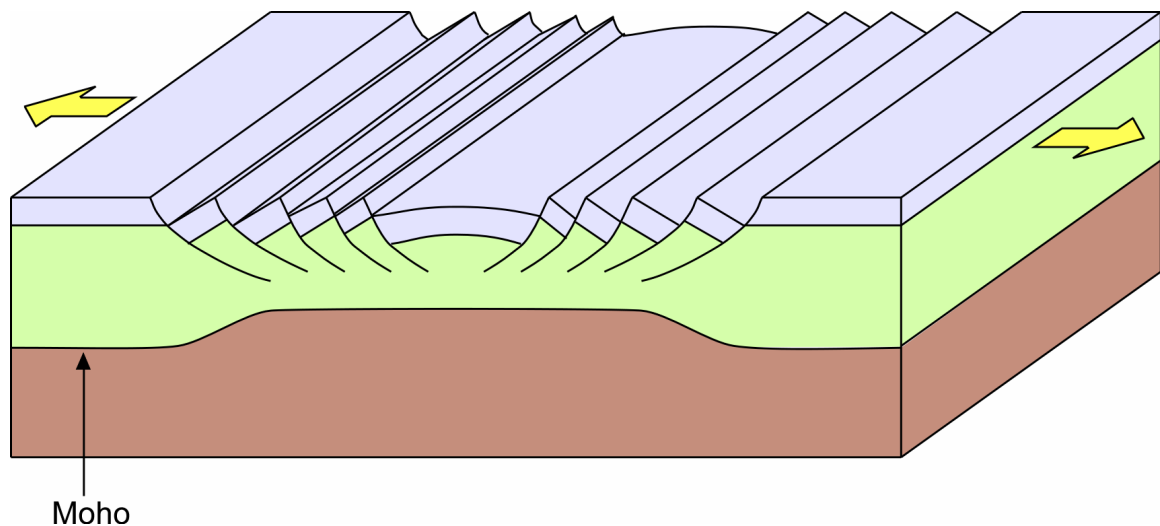


Figure 9. Model showing the extension of the continental lithosphere along a pure shear system (Modified from McKenzie 1978).

2.3. Simple Shear Models(s):

In the simple shear model (Wernicke 1981, 1985), a low angle crustal scale shear zone accommodates extension of the continental lithosphere. Axen and Bartley (1997) proposed a model named as “*rolling hinge model*” for extensional tectonics based on Wernicke’s (1981, 1985) simple shear model. They proposed that, upper level hanging-wall rocks move down-dip along the primary breakaway and deform brittlely whereas,

the footwall rocks move upward, deform ductilely, and then overprinted by brittle deformation. As the exhumation continues, partial unroofing of the footwall rocks and the mid-crustal mylonite zone takes place and a domelike structure forms due to isostatic uplift. Finally a secondary breakaway may form and compensate extension (Figure 10).

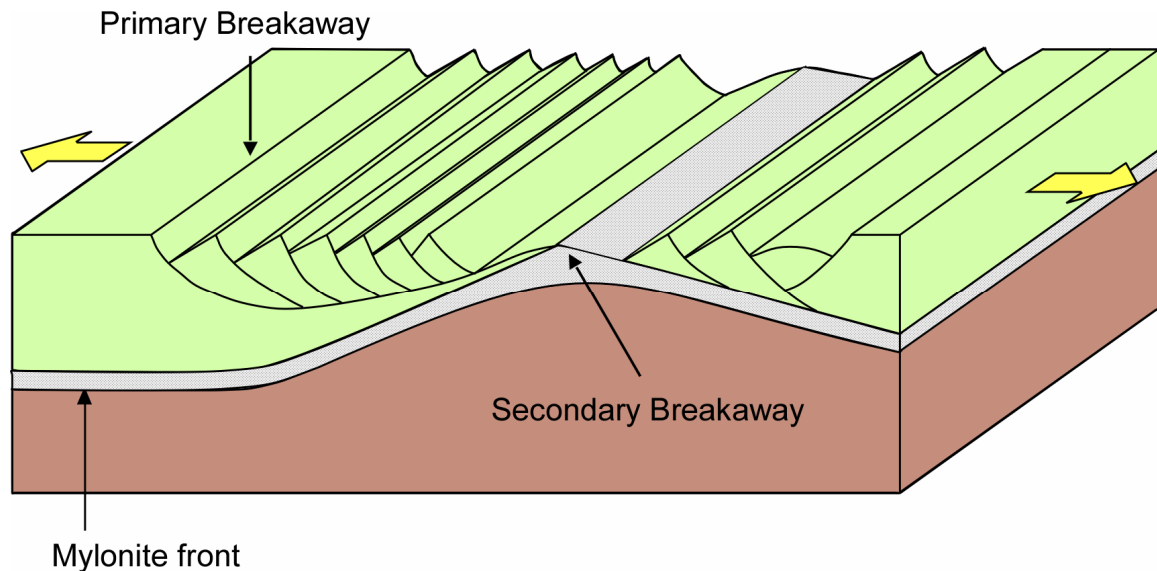


Figure 10. Model showing the extension of the continental lithosphere along a simple shear system characterized by a horizontal, crustal scale shear zone (Modified from Axen and Bartley 1997).

Buck's model (1988) suggests that the 'proximal' area of the upper crust undergoes an initial subsidence. However, during this process no lithospheric extension occurs (Buck, 1988). Lithospheric behavior at the 'distal' end of the shear zone may undergo uplift. Buck et al. (1988) indicated that the footwall of the shear zone experiences minor uplift from lateral heat of the asthenosphere that eventually sinks back to normal height after thermal cooling (Figure 11). The major difference between Axen

and Bartley's (1997) model and Buck's (1988) model is the nature of the shear zone. Based on Wernicke's (1981, 1985) simple shear model, Axen and Bartley (1997) suggested that the continental extension initiates along a large scale horizontal detachment surface, whereas Buck (1988) proposed that a steeply dipping fault which cuts through the lithosphere accommodates the extension.

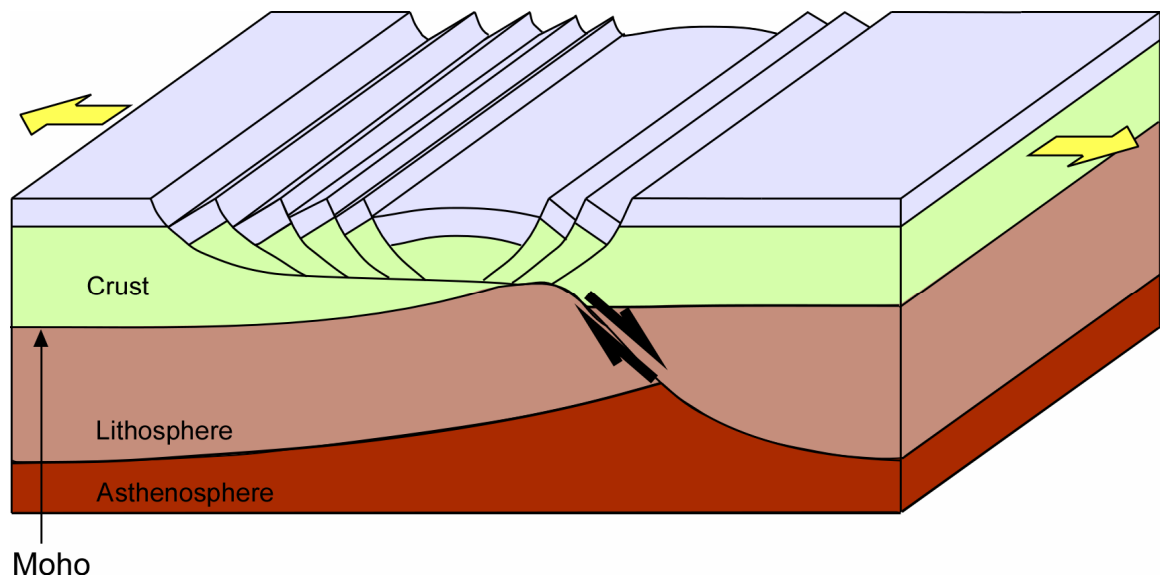


Figure 11. Model showing the extension of the continental lithosphere along a simple shear system characterized by a crustal scale shear zone (Modified from Buck 1988)

Both Wernicke and Axen (1988), and Buck (1988) proposed that presently low-angle normal faults might have formed as a result of rotation of high angle normal faults due to upward flexural bending of the footwall rocks of the fault. Although this idea has not been tested yet, it explains recent positions of low-angle normal faults by continuing flexural rotation of the lower plate rocks.

2.4. Shear Zones

The term shear zone is defined as:

“a tabular to sheetlike, planer or curvilinear zone composed of rocks that are more highly strained than rocks adjacent to the zone” (Davis and Reynolds 1996).

Shear zones are the most intensely deformed rocks and form under different temperature and pressure conditions. They are subdivided into three main types based on the deformation conditions (after Ramsay 1980):

1) Ductile shear zones: Formed in the middle to lower crust and the asthenosphere, mostly under metamorphic conditions. The sheared rocks along the ductile shear zones are known as tectonites, which are unique in appearance when compared to “normal” metamorphic rocks. Mylonites are the most common metamorphic tectonites, formed in the ductile shear zones (Davis and Reynolds 1996).

2) Brittle-ductile shear zones: Formed by a change in physical conditions (e.g. increasing strain rate, increasing fluid pressure), during shearing or by reactivation of the shear zone under conditions different from those in which the zone first formed. When conditions change from ductile to brittle, brittle structures overprint the ductile structures. Vice versa, when conditions change from brittle to ductile, ductile fabric may overprint the brittle structures. However the latter may be more difficult to identify since the ductile fabric may totally overprint the brittle structures (Davis and Reynolds 1996).

3) Brittle shear zones: Formed in the upper crust in relatively rapid strain rates by brittle deformation processes. Brittle shear zones are characterized by breccias, fractures, faults and fault gouge. The thickness of a brittle shear zone increases with increasing displacement (Davis and Reynolds 1996).

2.5. Kinematic Indicators in Shear Zones

Kinematic indicators in shear zones are used to determine the sense of shear. The Menderes Massif has experienced Cenozoic extension. Therefore, shear sense indicators are the essential features that can resolve the structural evolution of the area. Generally shear sense indicators are observed at outcrops (mesoscopic) or in thin sections (microscopic). The following is a brief review of the most common shear sense indicators.

2.5.1. Shear Bands and S-C Fabrics

Shear bands are known as minor shear zones of very high strain within the main shear zone and the complete structure is called “shear band cleavage” (Davis and Reynolds 1996; Passchier and Trouw 2005).

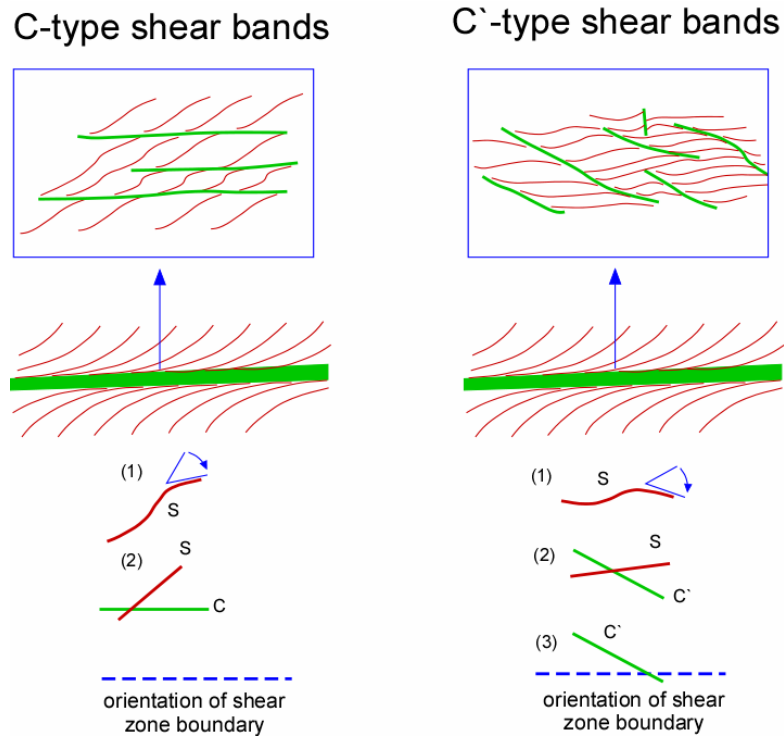


Figure 12. Two types of S-C foliation pairs which are common in ductile shear zones.

The shear zone is shown with typical foliation curvature. (Passchier and Trouw 2005).

There are two types of shear band cleavages: C-type and C'-type (Passchier and Trouw 2005) (Figure 12). C-type shear band cleavage is part of an S-C fabric that consists of S-planes and C-planes (Berthe et al. 1979a, b; Vernon et al. 1988; Lister and Snoke 1984; Krohe 1990; Toyoshima 1998; Passchier and Trouw 2005). The C-type shear bands in S-C fabrics are most common around feldspar porphyroclasts and parallel to shear zone boundaries whereas, C'-type shear bands are most common in medium grade shear zones (especially in deformed grains) and oblique to shear zone boundaries (Figure 13) (Passchier and Trouw 2005). In addition, C'-type shear band cleavage can overprint S-C fabrics (Berthe et al. 1979b).



Figure 13. C' type shear band cleavage with dextral shear from the Menderes Massif. Width of view 20 cm (Passchier and Trouw 2005).

2.5.2. Porphyroclasts

Porphyroclasts are relatively large, single crystals surrounded by a fine-grained matrix. They form by diminution of the grain size in the matrix, and are found in mylonites and cataclasites as they are remnants of a more coarse-grained original fabric. Feldspar, garnet, muscovite, hornblende and pyroxenes are the most common minerals that form porphyroclasts (Passchier and Trouw 2005).

Generally, porphyroclasts have attached polycrystalline rims that differ in structure or composition from the matrix. These structures are known as “porphyroclast systems” and can be used to determine the sense of shearing (Figure 14). If the rim has the same composition as the porphyroclast, the structure is called as a *mantled porphyroclast* (Figure 14a, and 14b). On the other hand, if the rim is composed of a different material, the structure is known as a *porphyroclast with strain shadow* (Figure 14a) (Passchier and Trouw 2005).

Mantled porphyroclasts are divided into 4 main types (Figure 14b) based on the shape of the wings (Passchier and Simpson 1986). Passchier and Trouw (2005) defined the main types of the mantle porphyroclasts as follows:

“Phi (Φ) objects have straight centerlines and are symmetrical with respect to the porphyroclast. Sigma (σ) type has wings with curved centerlines and is asymmetric; the wing extends off the top of one side and the bottom of the opposite side, a pattern referred to as ‘stair stepping’. Delta (δ) type has strongly curved wings that are asymmetrical with respect to the porphyroclast. The last type is complex porphyroclast which have several sets of wings.”

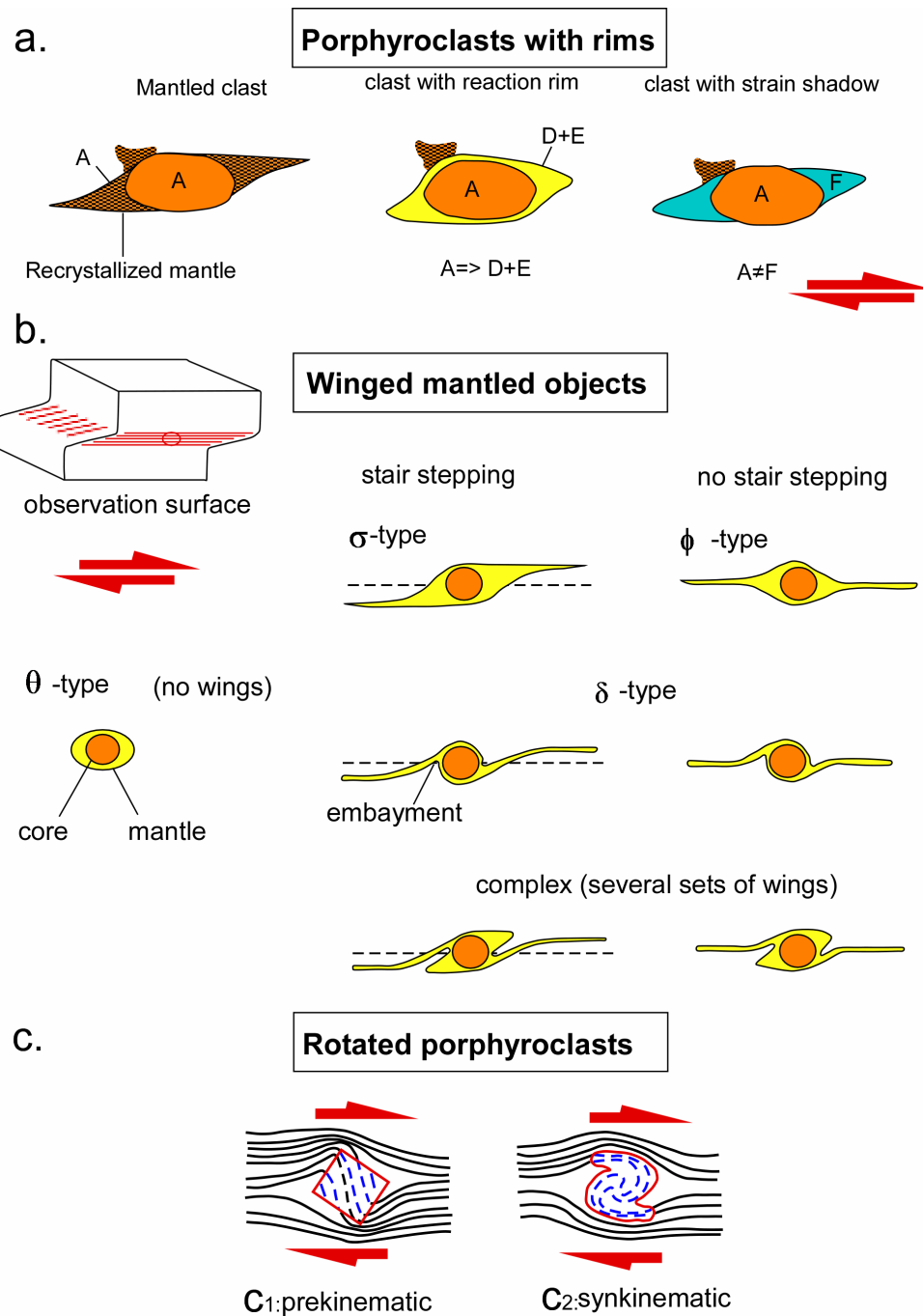


Figure 14. a) Schematic diagram of single crystal porphyroclasts with rims A, B, D, E and F refer to mineral times. b) Classification of mantled porphyroclasts. Dextral sense of shear (Passchier and Trouw 2005). c₁, c₂) Schematic diagram showing rotated porphyroclast textures. Shear sense and relative time of formation of the porphyroclast can be determined (see text for explanation; Vernon 1976).

Within a shear zone, porphyroclasts of equant crystals tend to rotate in response to shearing (Marshak and Mitra 1988). Garnet and albite are the most common minerals which show rotation and sense of shearing. The sense of rotation is indicated by the pattern of inclusion trails or relict foliation in the grain. It is also possible to determine the relative timing development of foliation with time of growth of the porphyroclast (Marshak and Mitra 1988) (Figure 14c). If the porphyroclast formed before development of the shear zone, then trail or relict foliation within the porphyroclast should be planar (Figure 14c₁). If the inclusion trails with sigmoid shapes are present within the porphyroclast, it means that the porphyroclast formed during development of the shear zone (Figure 14c₂) (Vernon 1976).

2.5.3. Mineral Fish

Mineral fishes are defined as lens shaped crystals (porphyroclast), usually oblique to the mylonitic foliation, embedded in a finer grained matrix in a mylonite (Passchier and Trouw 2005). Muscovite and biotite are the most common minerals to form mineral fish (Figure 15a). They are excellent kinematic indicators and generally observed in thin section (Figure 15b).

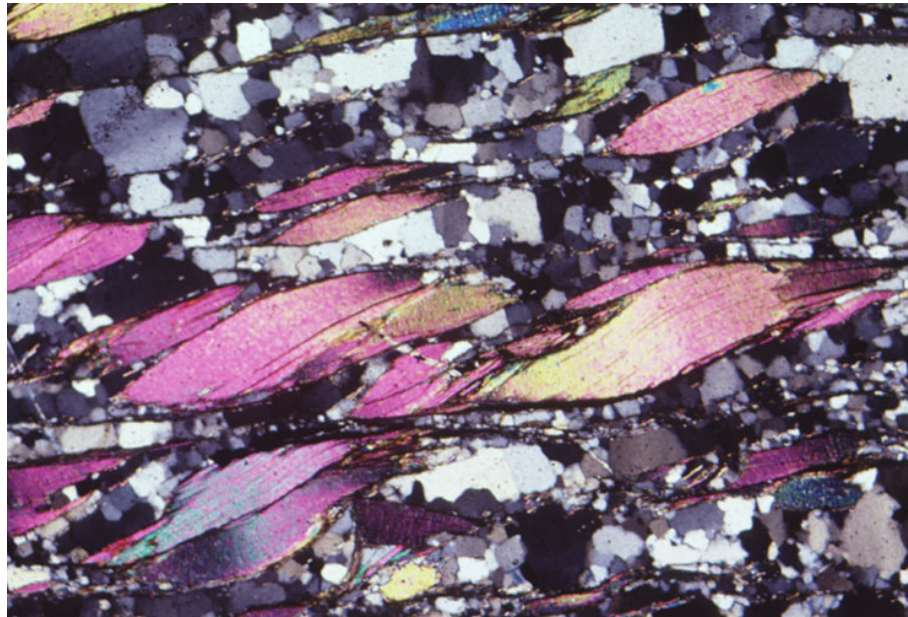
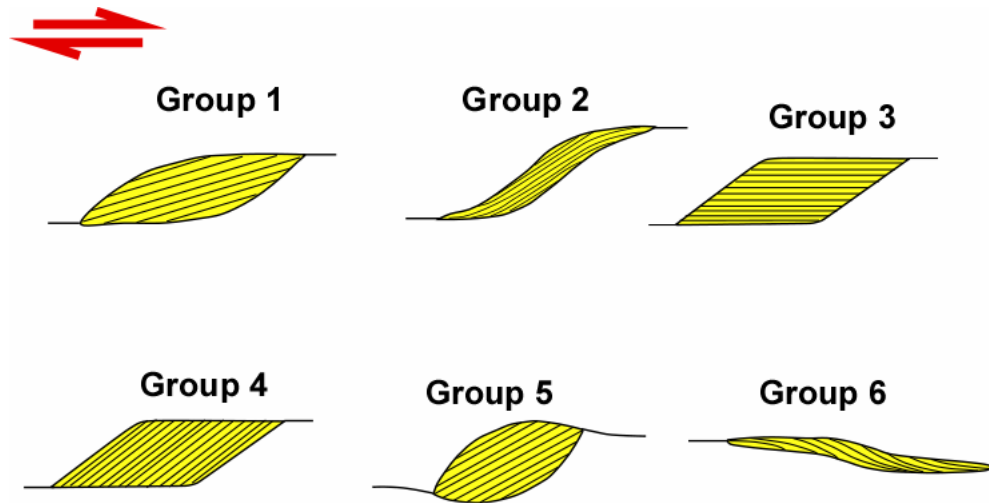


Figure 15. a) Schematic diagram of the main types of mica fish recognized in thin section; b) Photomicrograph of mylonitic quartzite with mica fish arranged between C-type shear bands (width of view 4 mm). Both figures show dextral sense of shear (Passchier and Trouw 2005).

2.5.4. Fractures and Displaced Grains

Fractures can form along weak planes of rigid minerals in a deforming ductile matrix. As the shearing continues, the rigid grains rotate, and the fragments of each grain slide past one another along the cracks. Consequently, the grain extends in the flow direction and the individual fractures develop synthetic and/or antithetic to the overall shear sense (Marshak and Mitra 1988) (Figure 16).

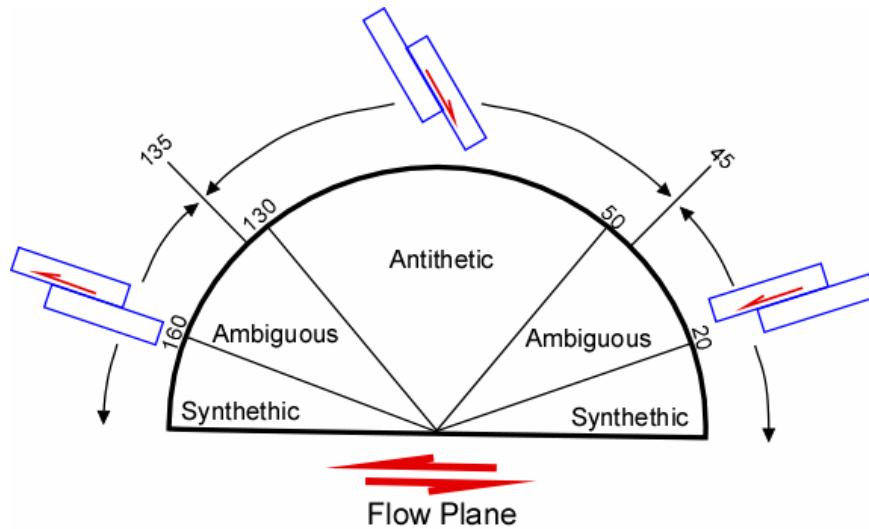


Figure 16. Schematic diagram showing that synthetic and antithetic shearing depends on initial orientation of fractures with respect to the flow plane (from Marshak and Mitra 1988).

Synthetic fractures form at a low-angle to the main direction of shearing and show the same sense of shearing with the overall shear sense. On the other hand, antithetic fractures initiate at a high-angle to the main shear sense and show opposite sense of shearing to the overall shear sense. However, rotation may cause initial high-angle fractures to reach a low-angle orientation during deformation. Therefore, fractures which are either at very high angles or very low angles to the main shearing plane should be used to determine the sense of shearing (Marshak and Mitra 1988).

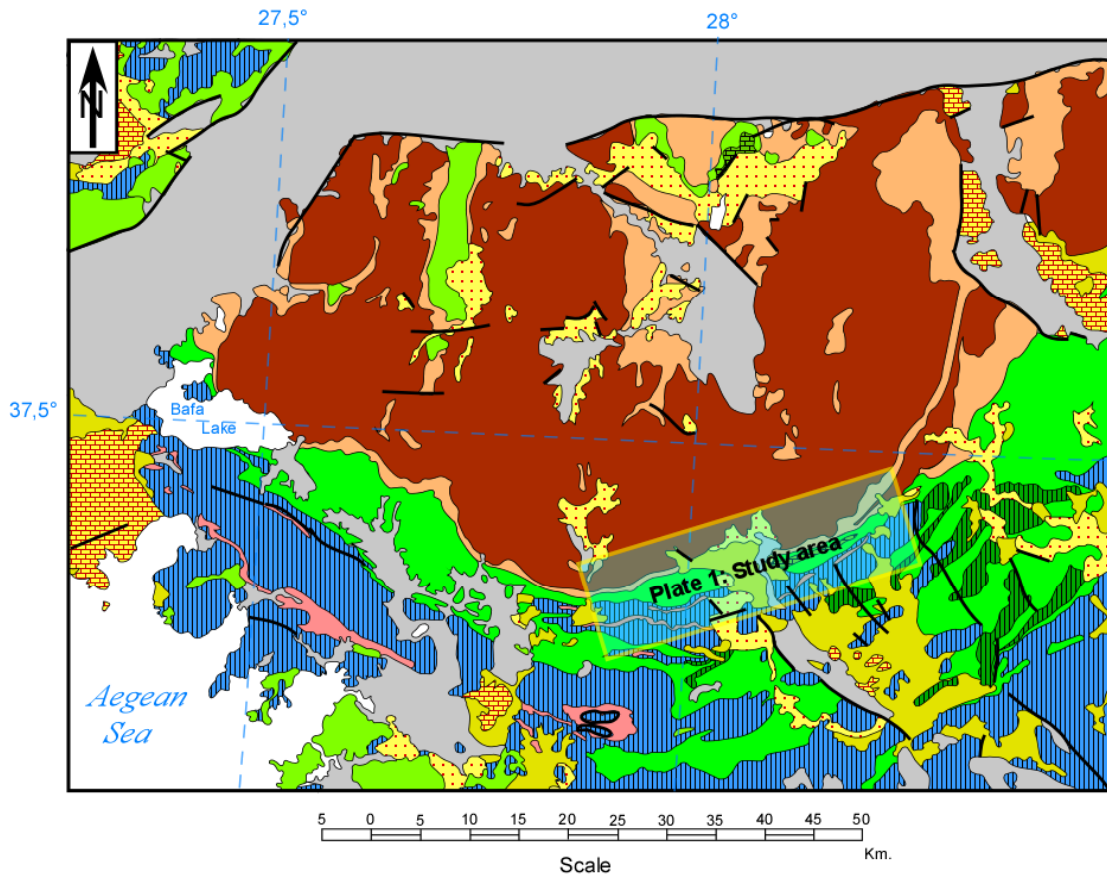
CHAPTER III
TECTONO-STRATIGRAPHY & PETROGRAPHY OF THE
SOUTHERN MENDERES MASSIF

3.1. Introduction

Tectono-stratigraphic units of the southern Menderes Massif have been considered under three groups by Konak et al. (1987). These are;

- 1- Cine Group (core rocks of the Menderes Massif)
- 2- Kavaklidere Group (Paleozoic cover rocks of the Menderes Massif)
- 3- Marcal Group (Mesozoic cover rocks of the Menderes Massif)

Kayabuku shear zone separates highly deformed metamorphic rocks composed of augen gneiss (orthogneiss) in its footwall, from schist and marble rock units in its hanging wall (e.g. Diniz et al. 2006) (Figure 17, Plate 1). Figure 18 shows the generalized columnar section of the rock units exposed in the study area.



Geological Explanations











| | | | |
|------------------------------|---|--|----------------------------|
| Paleozoic and/or Precambrian |  | Metagranite | } Foot-wall block rocks |
| Precambrian |  | Fine grained gneiss | |
| Upper Paleozoic |  | Undifferentiated schist | } Hanging-wall block rocks |
| Upper Paleozoic |  | Marble | |
| Jurassic-Cretaceous |  | Marble | |
| Upper Paleocene-Eocene |  | Metaflysch | } Neogene units |
| Middle-Upper Miocene |  | Continental clastic rocks | |
| Lower-Middle Miocene |  | Continental carbonate rocks | |
| Upper Miocene |  | Continental clastic rocks | |
| Pleistocene |  | Undifferentiated continental clastic rocks | |

Figure 17. Geological map of the southern sector of the Menderes Massif (digitized from 1:500,000 scale geological maps of MTA).

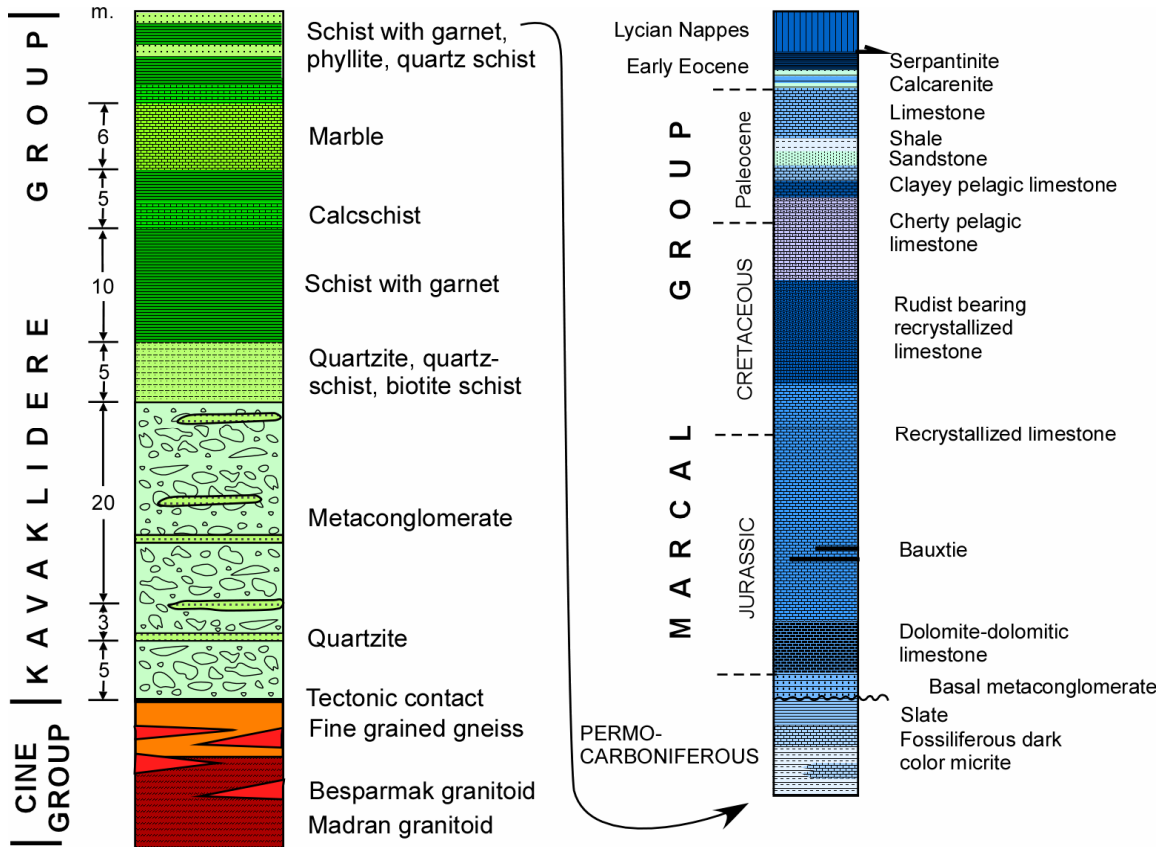


Figure 18. Columnar section of Cine, lower Kavaklidere, and Marcal Groups (Modified from Konak et al. 1987).

3.2. Cine Group

The Cine Group is composed of augen gneisses, fine grained gneisses, and various schists. Within the study area, the group is well exposed between the town of Yatagan and Yenikoy village (Figure 19, Plate 1).

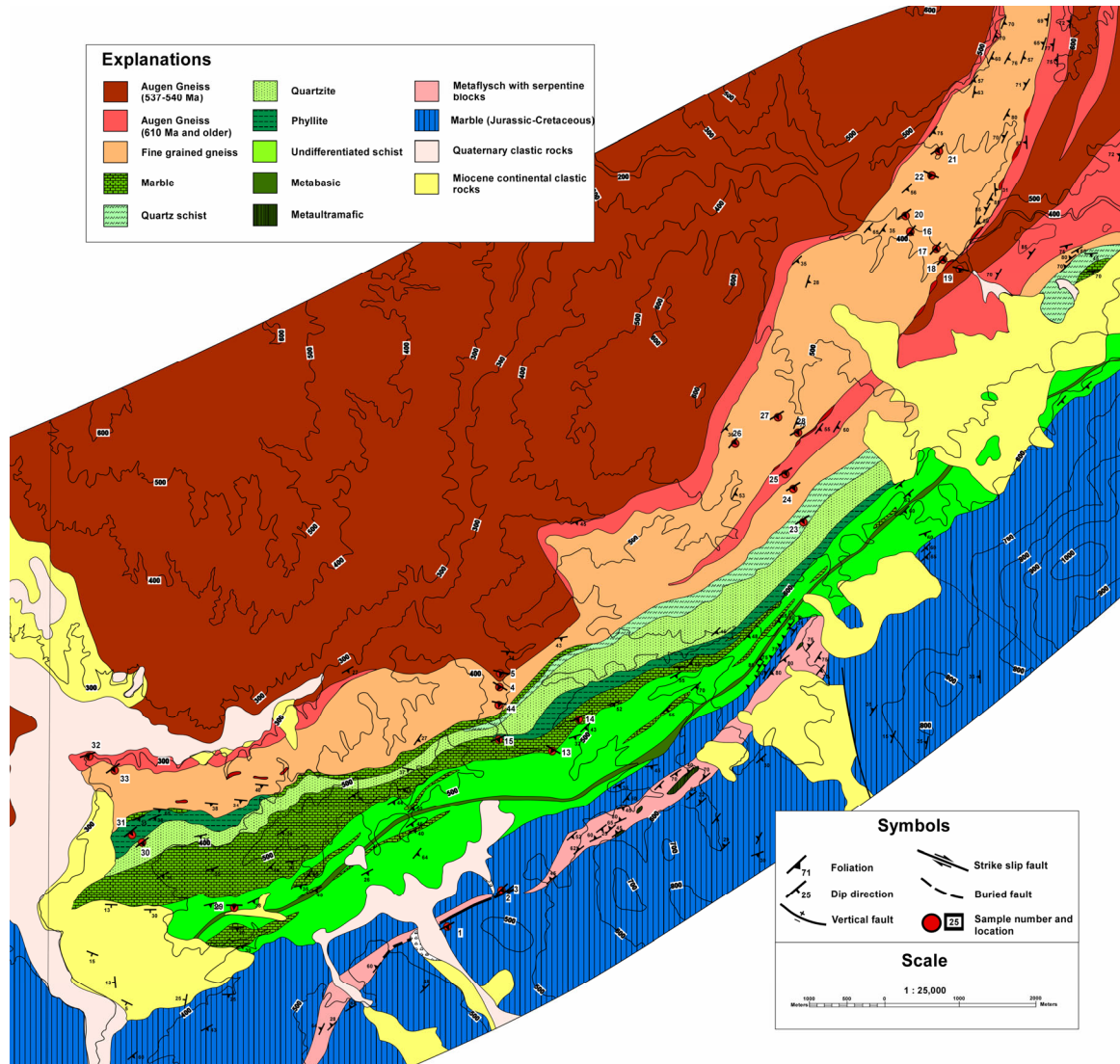


Figure 19. Geological map of the area between Cine and Yatagan (digitized from 1:25,000 unpublished geologic maps of Dr. Nesat Konak).

The Cine group consists of mainly augen gneisses of granitic origin. (e.g. Bozkurt et al. 1995; Bozkurt and Oberhaensli 2001; Bozkurt 2004). Two different types of augen gneiss have been observed in the study area (Plate 1); 1) Madran Metagranitoid and 2) Basparmak Metagranitoid

The Madran Metagranitoid is distinguished by its flat topography and reddish to brownish color (Figure 20). North of the Kayabasi village, foliation planes strike about N80E and dips about 50-55°S (Plate 1). The metagranitoid is rich in dark color minerals and contains sillimanite in thin section (personal communication with Dr Nesat Konak 2006). The size of the augens ranges from 1 to 5 cm and made up of feldspar, quartz, muscovite, and biotite. The Madran Metagranitoid has been radiometrically dated as 610 Ma and older (Konak et al. 1987; personal communication with Dr Nesat Konak 2006), and it grades into fine grained gneisses.

The Basparmak Metagranitoid is characterized by its steep topography and massif structure (Figure 21). It mainly consists of light color minerals such as quartz, feldspar (plagioclase, orthoclase, and microcline), white mica, and biotite. Another characteristic feature of the Basparmak metagranitoid is that its marginal zones contain tourmaline (Konak et al. 1987). Moreover, the Basparmak Metagranitoid cuts the Madran Metagranitoid and fine grained augen gneisses. The age of the rocks has been determined as 537-540 Ma (personal communication with Dr. Nesat Konak 2006) which validates the cross-cutting relationship as well.



Figure 20. Augen gneiss (Madran Metagranitoid), south of Cobanlar village (GPS:96380E, 40871N)



Figure 21. Augen gneiss (Basparmak Metagranitoid) from the north of Milas. (GPS: 73790E, 36930N)

Alternating sequence of fine grained gneisses (Figure 22), garnet bearing schists, micaschists and quartz schist constitute the upper most level of the Cine Group in footwall of the Kayabuku shear zone (Plate 1). These metamorphic rocks show lateral and vertical gradation with each other. Fine grained augen gneiss is the dominant rock unit of the uppermost part of the Cine Group and contains well developed shear sense indicators.



Figure 22. Fine grained gneiss from the north of Kadikoy (GPS: 96474E, 40886N)

In thin section, augen gneisses of the Cine group are generally characterized by large feldspar porphyroclasts surrounded by a matrix of quartz, muscovite, and biotite.



Figure 23. (Sample ED-05; GPS: 02138E, 41927N) Photomicrograph of orthogneiss from the north-west of Kafacakaplancik.

Sample ED-05 (Orthogneiss, GPS: 02138E, 41927N) is located to the north of Kafacakaplancik and mainly composed of coarse grain microclines. It contains quartz, plagioclase, K-feldspar, muscovite and, biotite minerals (Figure 23). Large porphyroclasts of K-feldspar are indication of igneous protolith. Moreover, a distinctive texture known

as “flame perthite texture” has been observed within the K-feldspar minerals.

This type of texture is usually found in low-grade metamorphic rocks of granitic origin (Parsons et al. 2005). Another interesting feature of this sample is; biotite has pleochroism from olive-green to pale-brown. This can be an indication of retrogression of biotite and fluid rock interaction (personal conversation with Dr. Elizabeth J. Catlos 2006). In addition, presence of large and fine quartz grains can be an indication of heterogeneous metamorphism or effect of deformation due to shearing.

The uppermost part of the Cine group contains alternating sequence of fine grained gneiss and schist. In thin section, fine grained gneiss is generally composed of quartz, biotite, and muscovite minerals whereas; schist is characterized by garnet, mica, and plagioclase minerals. Micas mainly define the foliation.

Sample ED-10 (Fine grained gneiss, GPS: 84711E, 37719N) is located to the west of Zeytin. Quartz, biotite and muscovite are the major minerals which form this rock. Biotite shows a distinct foliation and zoning. Quartz grains gets finer within the mica layers and it can be speculated that, the fine grained quartz minerals may have formed from the decomposition of large quartz porphyroblasts (Figure 24).

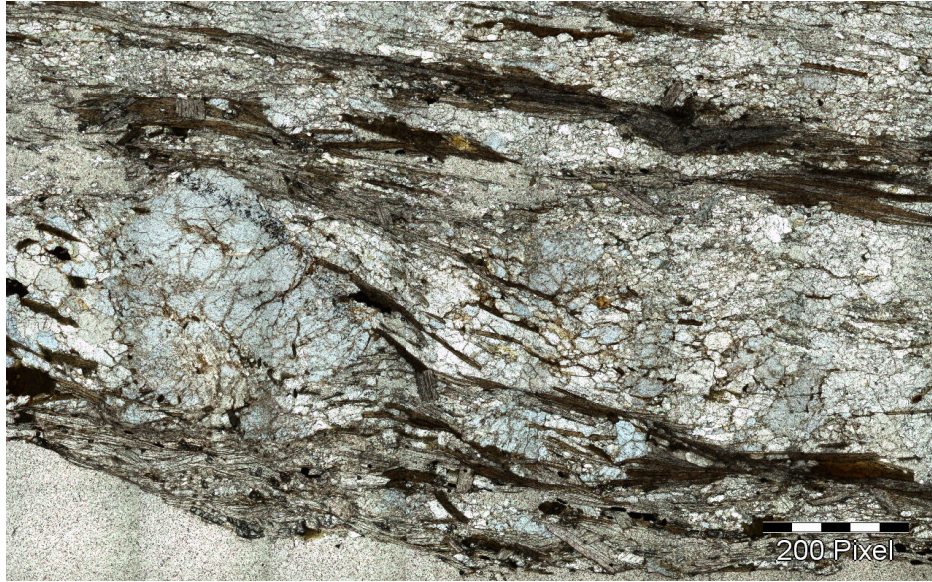


Figure 24. (Sample ED-10; GPS: 84711E, 37719N) Photomicrograph of fine grained augen gneiss from the Katrancı village (west of Zeytin).

Sample ED-04 (Muscovite schist, GPS: 02120E, 41723N) is located to the north-west of Kaplancık village. Muscovite, quartz and plagioclase are the dominant minerals forming this rock (Figure 25). In addition, iron oxides and minor amounts of biotite have been observed within this thin section. Generally, plagioclase grains show twinning, quartz grains show undulatory extinction, and micas are aligned parallel to the foliation surface (Figure 25). One of the characteristic features of this sample is, near the edges of the muscovites, grains get finer. In turn this may suggest us that edges of the muscovites could have turned into fibrous sillimanite.



Figure 25. (Sample ED-04; GPS: 02120E, 41723N) Photomicrograph of muscovite schist.

Sample ED-18 (Garnet-mica schist, GPS: 07943E, 47651N) is located to the north of Kadikoy and mainly composed of garnet, biotite, muscovite, chlorite and quartz. In this thin section, high grade textures are retained but as the temperature and pressure of metamorphism decline, high grade minerals are replaced by lower grade ones (e.g. Garnets have sub to euhedral geometry but they have broken down and retrograded into chlorite (Figure 26)). It is also suggested that some porphyroblast of biotite have formed from muscovite.



Figure 26. (Sample ED-18; GPS: 07943E, 47651N) Photomicrograph of garnet-mica schist.

Sample ED-27 (Garnet-mica schist, GPS: 05806E, 45441N) is composed of garnet, muscovite, biotite, quartz, plagioclase, staurolite, chlorite, and contains opaque and accessory minerals as well. Garnets have subhedral geometry and retrograded into iron oxides (Figure 27). Moreover, some of the garnets have disappeared entirely and turned into iron oxides as a result of weathering.



Figure 27. (Sample ED-27; GPS: 05806E, 45441N) Photomicrograph of garnet-mica schist.

Sample ED-33 (Mica schist, GPS: 96618E, 40754N) is located to the south of Cobanlar village. Biotite is the major mineral seen in this sample and two different generations of biotite formation was observed. First one is oriented randomly, whereas the second one follows the foliation direction (Figure 28).

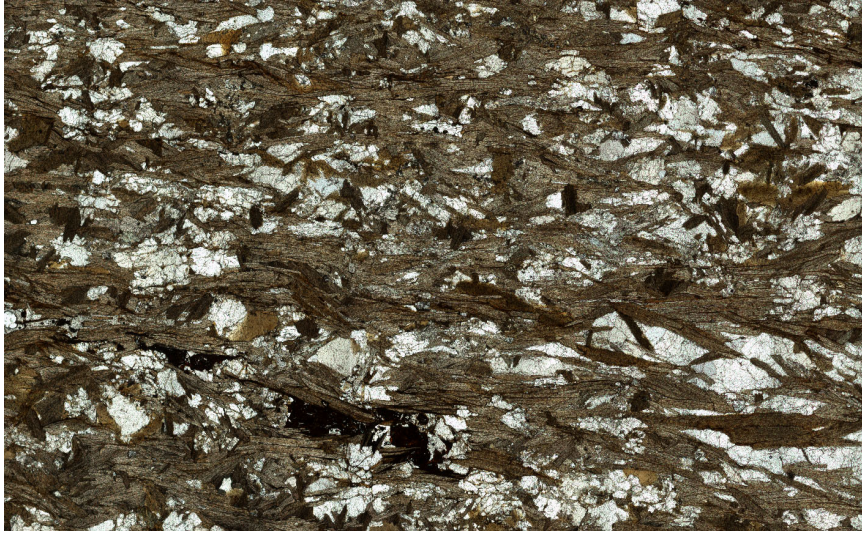


Figure 28. (Sample ED-33; GPS: 96618E, 40754N) Photomicrograph of mica schist showing two generations of biotite formation.

3.3. Kavaklıdere Group

The Paleozoic sequence that overlies the Cine Group and underlies the Marcal Group is called the Kavaklıdere Group. The contact relationship between the Cine Group and the Kavaklıdere Group (Figure 29) has been interpreted as tectonic (i.e. Kayabuku shear zone) by Hetzel and Reischmann (1996), Ring et al. (1999), Bozkurt and Satir (2000), Bozkurt and Oberhänsli (2001), Gessner et al. (2001a, 2001b, 2004), and Rimmelé (2003). The nature of the shear zone has been annotated as extensional because stretching lineations are parallel to the direction of the extension.

The low grade metamorphic rocks within this group are mainly composed of garnet-mica schist, chloritoid schist, quartz-mica schist, quartzite, calcschist, marble, phyllite, metabasic, and metaultramafic (Figure 30a, 30b; Figure 31a, 31b).



Figure 29. The contact relationship between the Cine (augen gneisses) and the Kavaklidere Group (cover schists) (GPS:72496E, 36212N). Looking northward.

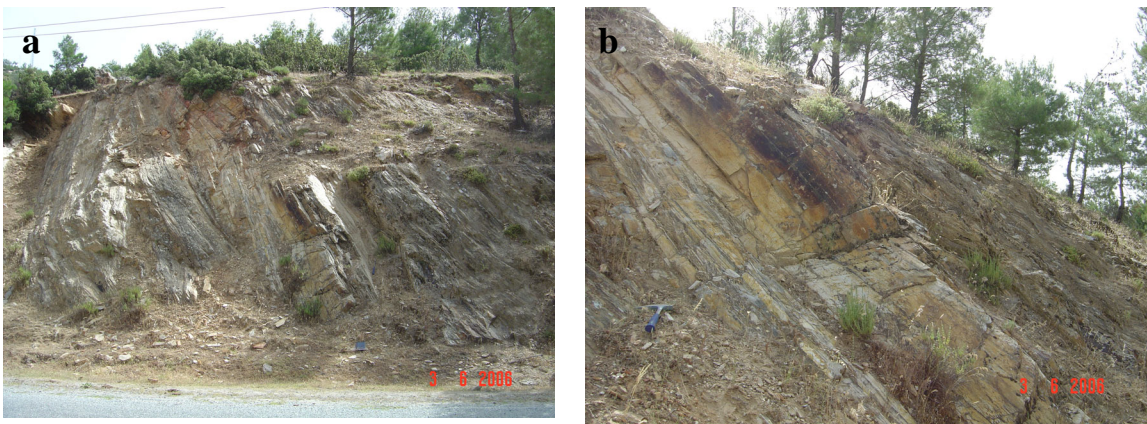


Figure 30. Photos showing alternating marble and quartz schist of the Kavaklidere Group (GPS: 02282E, 41051N). The attitude of foliation is N63E/33°SE.

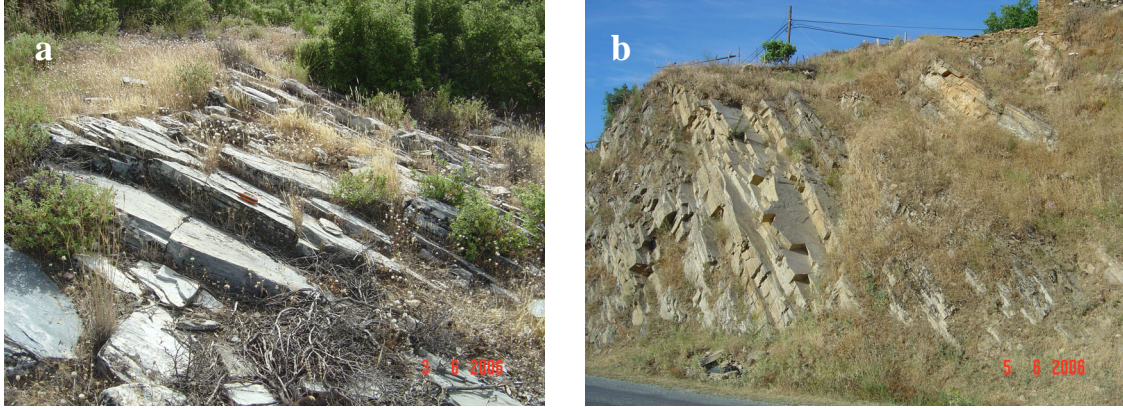


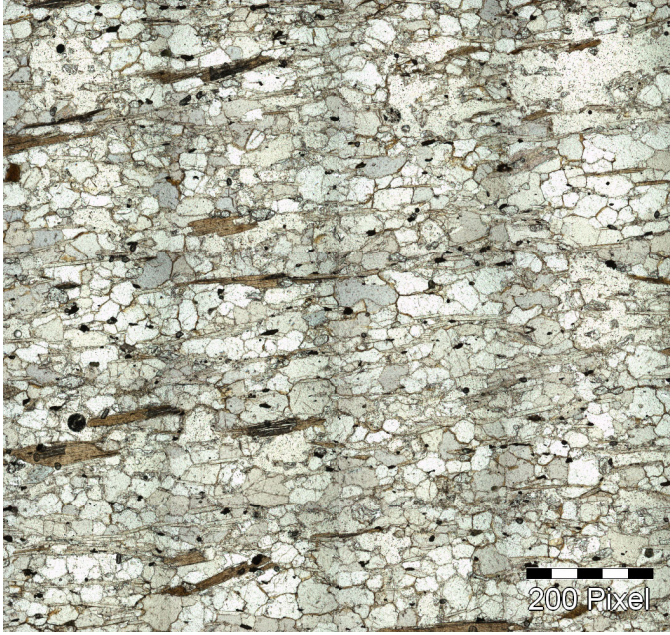
Figure 31. Photos showing marble units of the Kavaklidere Group a) The orientation of foliation is N60E/26°SE (GPS: 03282E, 41340N; see photomicrograph of sample ED-14). b) The orientation of foliation is N79W/52°SW (GPS: 02092E, 41439N).

The base of the Kavaklidere Group contains a metaconglomerate unit which grades horizontally into quartzites and vertically upward into quartzites, quartz schists, garnet schists, phyllites, and calcschists (Konak et al. 1987). However, the metaconglomerate sequence is not present in the study area.

The metaconglomerate is overlain by a sequence of quartzite, quartz-mica schist, chloritoid schist, garnet-mica schist, calcschist, marble, phyllite, metabasic, and metaultramafics. The upper part of this sequence has been dated as Late Devonian(?)–Carboniferous to Late Permian (Onay 1949; Schuiling 1962; Boray et al. 1973; Caglayan et al. 1980; Konak et al. 1987)

In thin sections, the rocks of the Kavaklidere group have a variety of minerals such as; quartz, muscovite, biotite, chlorite, garnet, tourmaline, and calcite. Generally muscovite, biotite and chlorite minerals define the foliation.

Sample ED-23 (Quartzite, GPS: 06218E, 44079N) is located between the



Kaplancik and Kadikoy villages to the north of Yenikoy. It contains quartz, muscovite, tourmaline, apatite, and zircon minerals (Figure 32). Quartz shows undulose extinction with deformation bands and muscovite crystals are weakly deformed.

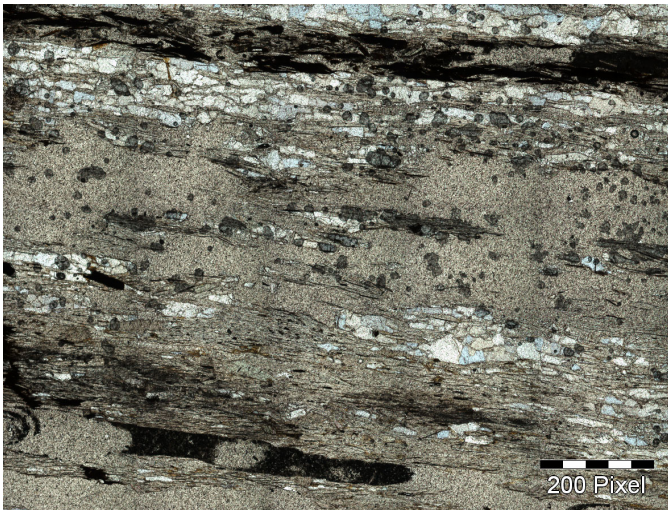
Figure 32. (Sample ED-23; GPS: 06218E, 44079N) Photomicrograph of quartzite. Note that mica fish shows left-lateral shear sense.

Sample ED-15 (Quartz-mica schist, GPS: 02282E, 41051N) is located to the north of Kafacakaplancik and contains considerable amount of iron oxides in it. Iron oxides are usually found in cracks and veins of the rock (Figure 33). In addition, quartz has uniform size and distribution. Zoned tourmaline minerals have been also observed within this thin section.



Figure 33. (Sample ED-15; GPS: 02282E, 41051N) Photomicrograph of quartz-mica schist.

Sample ED 30 (Quartz-mica schist, GPS: 97107E, 39729N) is located to the south



of Cobanlar village and mainly composed of quartz, biotite and muscovite minerals. Micas follow the foliation direction and are generally surrounded by a fine grained matrix (Figure 34).

Figure 34. (Sample ED 30; GPS: 97107E, 39729N) Photomicrograph of quartz-mica schist.

Sample ED-35 (Garnet-chlorite-biotite schist, GPS: 86104E, 37755N) is located to the west of Zeytin. There are both prograde and retrograde chlorite minerals within this sample. Some of the chlorite minerals are in the matrix of the rock, whereas some of

them are adjacent to garnets (Figure 35). In turn, this suggests us that garnets might have retrograded into chlorites. Furthermore, garnets contain quartz inclusions in their core. However, no quartz inclusions have been observed in the rim of these garnets. Thus, it can be suggested that, as garnets were growing the environmental conditions might have been changed.



Figure 35. (Sample ED-35; GPS: 86104E, 37755N) Photomicrograph of garnet-mica schist showing the relation between chlorite and garnet minerals.



Sample ED-14 (Marble, GPS: 03282E, 41340N) is located to the north of Kaplancik and mainly composed of intercalated fine and coarse grained calcite minerals. Fine grained zone represents a micro-shear zone within the rock (Figure 36). Graphite and rutile were observed in this thin section.

Figure 36. (Sample ED-14; GPS: 03282E, 41340N) Photomicrograph of a graphitic marble.

3.4. Marcal Group

The Marcal Group, which is referred as Mesozoic-Lower Tertiary cover rocks of the Menderes Massif, unconformably overlies the Kavaklidere Group and shows a tectonic relationship with the overlying Lycian Nappes. The group is mainly composed of dolomite, dolomitic limestone, recrystallized limestone, and cherty pelagic limestone (Konak et al. 1987).

At its base, the group contains reddish metaconglomerate and grades vertically into thin to medium bedded metasandstone, metasilstone, yellowish dolomite with dolomitic limestone alternation and a thick sequence of dolomite-dolomitic limestones

(Konak et al. 1987). This sequence is vertically followed by the Mesozoic recrystallized limestone sequence. These off white-dark colored limestones are medium to coarse crystalline, medium to thick bedded, locally laminated and jointed parallel to the bedding planes. *Clypelina Jurassica* (Faure), *Trocholina* sp., *Cuneolina* sp., and *Reophax* sp., fossils found within the recrystallized limestone suggest Jurassic-Lower Cretaceous, and the upper levels that contain rudist fossils suggest Upper Cretaceous age (Konak et al. 1987). The rudist bearing limestone is conformably overlain by cherty and clayey pelagic limestone and its age has been determined as Upper Cretaceous-Paleocene, based on the presence of *Globigerina* sp., *Globorotalia* sp., and *Globotruncana* sp. fossils (Konak et al. 1987). Subsequently, the pelagic limestone grades into a sequence composed of sandstone, shale, and crystalline limestone alternations which are overlain by the serpentine and diabase blocks at the upper levels of the Marcal Group.

Tectono-stratigraphic units of the southern Menderes Massif formed by the Cenozoic extensional tectonics in the region are overlain by the Neogene basinal sediments (Plate 1; Figure 37).



Figure 37. Panoramic picture showing the relationship between the Neogene basins and the metamorphic rocks of the southern Menderes Massif (GPS: 96618E, 40754N; looking southward).

CHAPTER IV

STRUCTURAL GEOLOGY

4.1. Introduction

The main structural feature which characterizes the study area is the Kayabuku shear zone. It is the most southerly of the four extensional shear zones of the Menderes Massif. The others are Simav, Alasehir and Buyuk Menderes detachments (Figure 38). The rocks within the shear zone are highly deformed, both ductilely and brittlely.

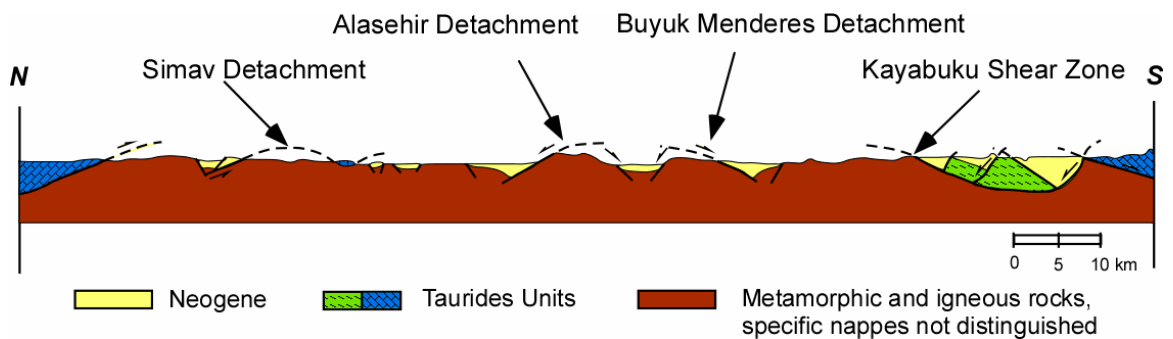


Figure 38. Simplified cross-section along the Menderes Massif showing the four low angle detachment surfaces (Cemen et al. 2006).

4.2. Kayabuku Shear Zone and Associated Structures

The south-dipping Kayabuku shear zone of the southern Menderes Massif contains well developed mesoscopic and microscopic shear sense indicators, and separates orthogneiss in its footwall from schist and marble rock units in its hanging wall (e.g. Diniz et al. 2006). It extends from west (Bafa) to east (Karacasu) in the form of an arc and more or less defines the boundary between the orthogneiss and schist (Plate 1). Within the shear zone, average attitude of the foliation planes between the towns of Milas and Yatagan is measured as N82E/50°S (Figure 39).

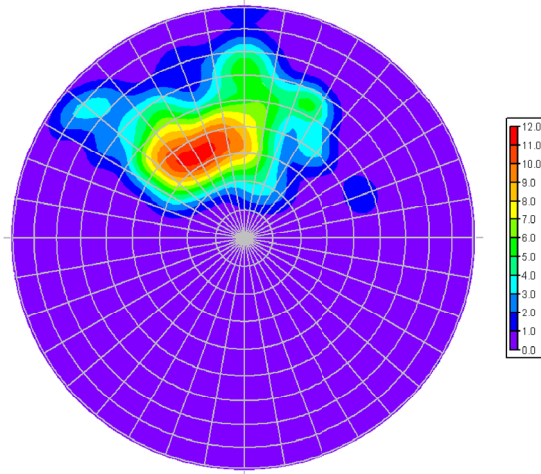


Figure 39. Stereonet plot showing the average attitude of the foliation planes between the towns of Milas and Yatagan.

The hanging wall of the Kayabuku shear zone contains a south-dipping normal fault zone, discontinuously exposed between the schist and marble units (Figure 40 a, b) (Diniz et al. 2006). The contact between the hanging wall and footwall block extends from NE to SW and can be seen very clearly to the south of Kafacakaplancik and Nebikoy villages (Plate 1). The attitude of the fault plane is measured as N53E/45°SE which is almost parallel to the foliation planes of the surrounding units. Although the fault is not a very large scale fault, it gives us important evidence about the structural

evolution of the Kayabuku shear zone, and transition from ductile to brittle deformation during the N-S extension.

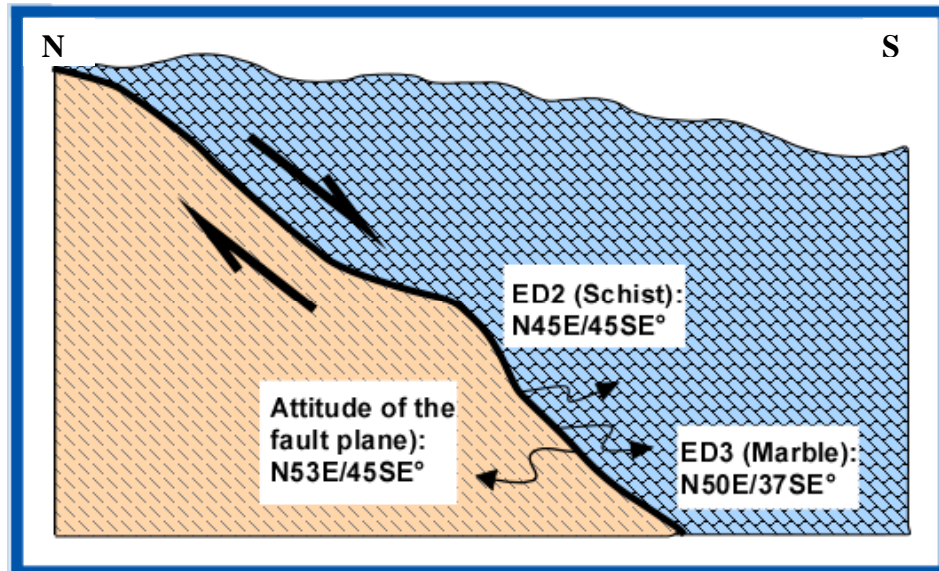


Figure 40 a) Photograph of the fault zone separating the marble unit in its hanging wall from the schist unit in its footwall block. b) Sketch diagram showing the relationship between the marble and the schist units (GPS: 01310E, 38650N).

Field observations suggest that the fault zone formed during the later stages of the extension, when the deep buried rocks of the Menderes Massif exhumed to the surface along the Kayabuku shear zone. The rocks within the shear zone have been subjected to brittle deformation, as the hanging wall rocks of the shear zone moved towards south.

4.3. Kinematic Analysis along the Kayabuku Shear Zone

Shear zones accommodate relative displacement of the surrounding rocks so they are very important in determining the sense of movement. The sense of movement along the shear zones must be consistent with the models that have been suggested for the exhumation of the Menders Massif.

In the southern Menderes Massif, the Kayabuku shear zone is exposed in an area 44 km long and 3 km wide within the Turkish topographic maps of N19 (b2, b3, b4), and N20 (a1, a2, a4). In order to better establish geometric relations between the rock units, 7 transects have been made and 51 oriented rock samples were collected along the shear zone. In addition structural cross-sections have been constructed along these transects.

15 oriented rock samples, from various transects and rock units, show well developed shear sense indicators. Table 4 shows the mineral assemblage and location of these samples.

| Sample | GPS Location (UTM) | Mineral Assemblage |
|---------------|---------------------------|---|
| <i>ED-9</i> | 85225E, 37530N | garnet+muscovite+biotite+chlorite+chloritoid+quartz+feldspar |
| <i>ED-16</i> | 07521E, 48018N | garnet+chlorite+biotite+muscovite+quartz+staurolite+zircon |
| <i>ED-17</i> | 07730E, 47743N | garnet+biotite+muscovite+quartz+allanite(?) |
| <i>ED-20</i> | 07439E, 48387N | biotite+muscovite+quartz+tourmaline+sillimanite+ilmenite(?) |
| <i>ED-23</i> | 06218E, 44079N | biotite+muscovite+feldspar+quartz+tourmaline+apatite+zircon |
| <i>ED-27</i> | 05806E, 45441N | muscovite+biotite+garnet+plagioclase+chlorite+staurolite+quartz |
| <i>ED-28</i> | 06196E, 45340N | garnet+biotite+chlorite+muscovite+quartz+feldspar |
| <i>ED-29</i> | 98493E, 38822N | garnet+chlorite+muscovite+biotite+graphite+feldspar+quartz |
| <i>ED-32</i> | 96474E, 40886N | biotite+muscovite+plagioclase+quartz |
| <i>ED-35</i> | 86104E, 37755N | biotite+muscovite+chlorite+garnet+feldspar+quartz+zircon |
| <i>ED-40</i> | 78576E, 35469N | muscovite+biotite+quartz+feldspar |
| <i>ED-42</i> | 78275E, 35005N | chloritoid+garnet+muscovite+quartz+feldspar |
| <i>ED-45</i> | 72212E, 35627N | chloritoid+muscovite+feldspar |
| <i>ED-46</i> | 72218E, 35773N | garnet+muscovite+biotite+graphite+plagioclase+quartz |
| <i>ED-47</i> | 72361E, 36054N | garnet+chloritoid+biotite+muscovite+quartz+feldspar |

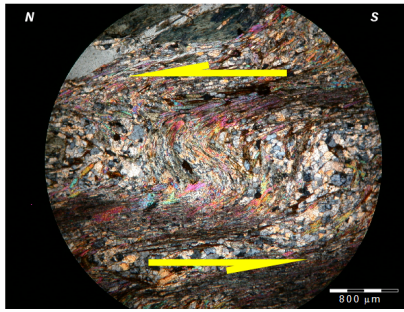
Table 4. Mineral assemblage and location of the rock samples

4.3.1. Transect 1 (Cross section A-A')

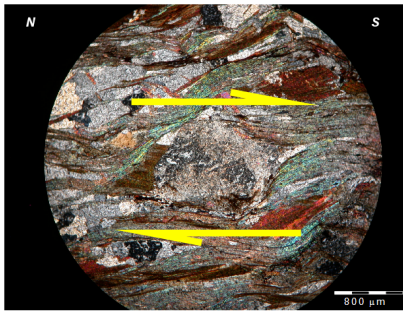
Transect 1 has been made along the easternmost part of the study area, in the vicinity of Kadikoy (Plate 2). Structural cross-section along A-A' (NW-SE) (Plate 2) shows the relationship between the rock units and location of the kinematic indicators. Generally, foliation planes strike NE-SW, almost parallel to the Kayabuku shear zone. In addition, Miocene continental clastic rocks overlay the hanging wall and footwall block rocks of the shear zone (Plate 2).

Seven oriented rock samples (ED-16, 17, 18, 19, 20, 21, and 22) were collected from the orthogneiss and fine grained gneiss units of the Cine group. Samples ED-16 (GPS: 07521E, 48018N), ED-17 (GPS: 07730E, 47743N) and ED-20 (GPS: 07439E, 48387N) show well-developed microscopic shear sense indicators such as σ -type mantled porphyroclast, rotated garnet porphyroclast with strain shadows of quartz, and folded foliation planes respectively (Figure 41). Samples ED-17 (garnet + biotite + muscovite + quartz + allanite(?)) and ED-20 (biotite + muscovite + quartz + tourmaline + sillimanite, ilmenite(?)) show top-to-the north sense of movement, whereas ED-16 (garnet + chlorite + biotite + muscovite + quartz + staurolite + zircon) shows top-to-the south (Plate 2). Therefore, it is suggested that the shear zone has subjected to at least two deformation events; top-to-the north (D_1), and top-to-the south (D_2)

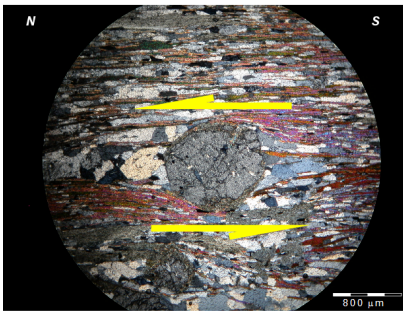
TRANSECT 1 (A-A')



Sample ED-20: Folded mineral grains showing top-to-the north sense of shear



Sample ED-16: σ -type porphyroblast showing top-to-the south sense of shear



Sample ED-17: Rotated garnet porphyroblast, surrounded by fine grained matrix, showing top-to-the north sense of shear

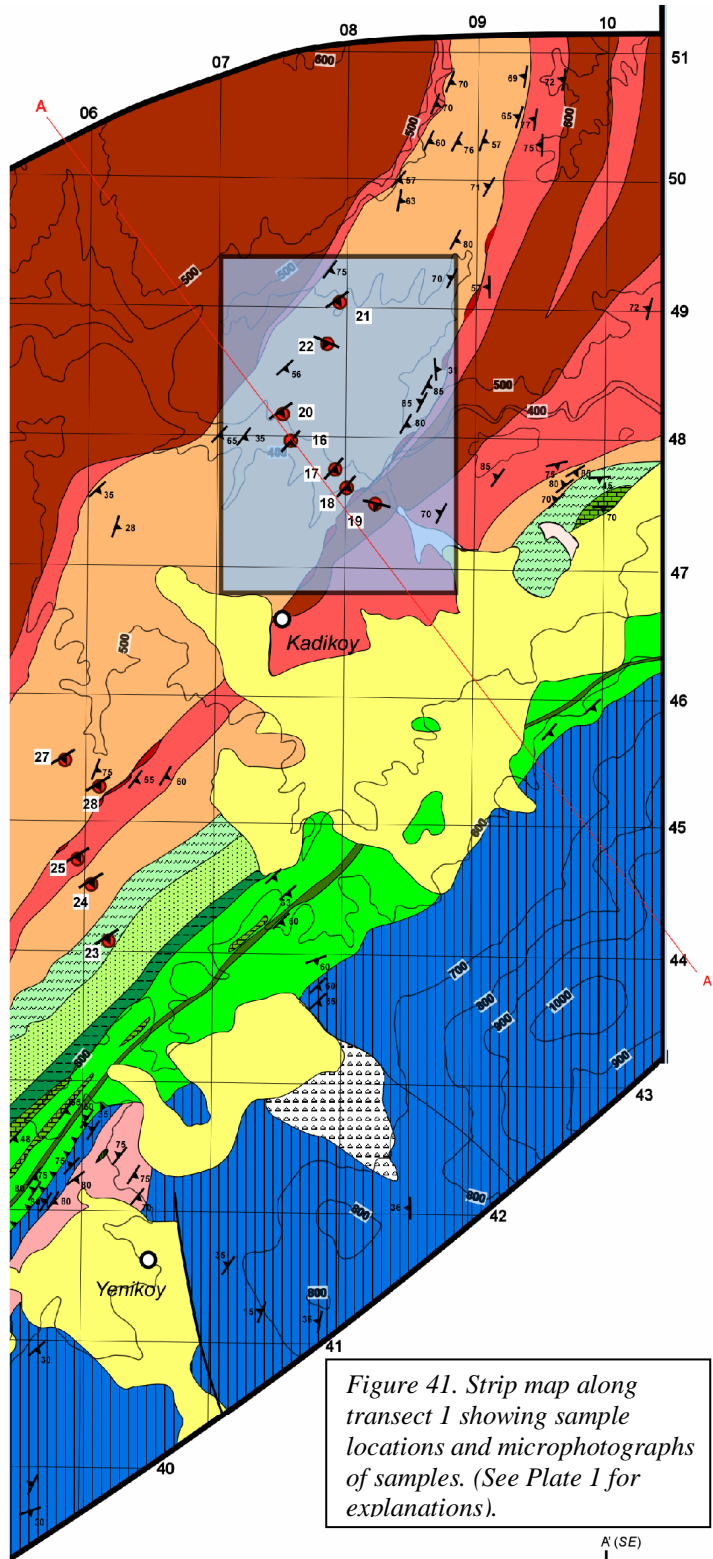
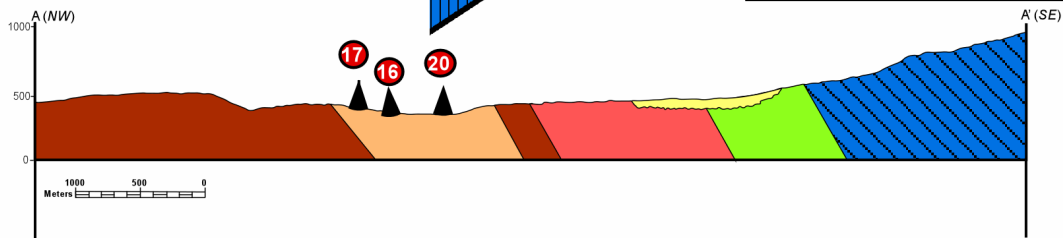


Figure 41. Strip map along transect 1 showing sample locations and microphotographs of samples. (See Plate 1 for explanations).



4.3.2. Transect 2 (Cross section B-B')

Transect 2 has been made in the vicinity of Yenikoy (Plate 3). Six oriented rock samples (ED-23, 24, 25, 26, 27, and 28) were collected both from the hanging wall and footwall rocks of the Kayabuku shear zone along B-B' (NNW-SSE). Foliation planes strike NE-SW and dip $\sim 55^\circ$ towards south and mainly characterized by parallel alignment of muscovite and biotite minerals in microscopic scale. Although attitude of the foliation planes differ slightly from each other, they are consistent with the general trend across the shear zone.

Samples ED-23 (GPS: 06218E, 44079N), ED-27 (GPS: 05806E, 45441N), and ED-28 (06196E, 45340N) contain excellent shear sense indicators (Plate 3). For example, ED-27 (fine grained gneiss, made up of muscovite + biotite + garnet + plagioclase + chlorite + staurolite + quartz) has both brittlely and ductilely deformed mylonitic quartz and δ -type garnet porphyroclast with strain shadows of quartz, ED-28 (fine grained gneiss, made up of garnet + biotite + chlorite + muscovite + quartz + feldspar) has rotated garnet porphyroclast, and ED-23 (quartz schist, made up of biotite + muscovite + feldspar + quartz + tourmaline + apatite + zircon) has biotite fish (Figure 42). The former two samples which are from the footwall block rocks of the shear zone show top-to-the north movement. On the other hand, the sample from the hanging wall block (ED-23) indicates top-to-the south movement. In addition, a mesoscopic kinematic indicator (asymmetric quartzite) showing top-to-the north sense of shearing has been observed in the second transect (Figure 42, Plate 3; GPS: 05210E; 45220N). These different kinematic indicators are attributed to D_1 and D_2 events; as is the case in transect 1.

TRANSECT 2 (B-B')

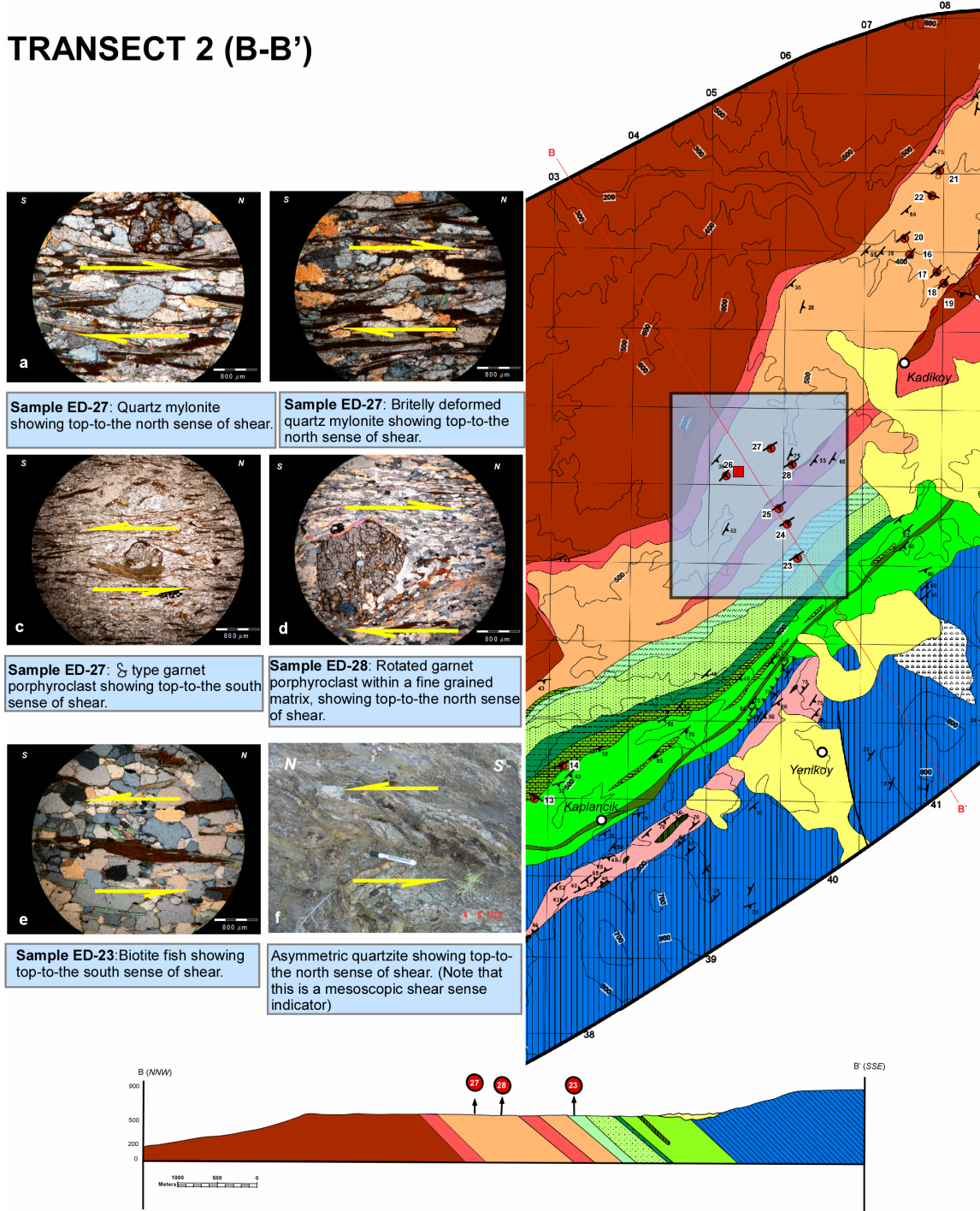


Figure 42. Strip map along transect 2 showing sample locations and microphotographs of samples. (See Plate 1 for explanations).

4.3.3. Transect 3 (Cross section C-C')

The third transect has been made in the vicinity of Kafacakaplancik, almost parallel to Cine highway (Plate 4). Along this transect, all of the rock units of the shear zone are well exposed. This transect was one of the best areas to identify and understand the relationship of the rocks units of the study area. Attitude of the foliation planes ranges from NE-SW to E-W and dips $\sim 40^{\circ}$ - 55° towards south. A south dipping normal fault, separating schist and marble units, was observed along transect 3 (Plate 4). Although nine oriented rock samples (ED-1, 2, 3, 4, 5, 13, 14, 15, 44) were collected along transect 3, no kinematic indicators have been found.

4.3.4. Transect 4 (Cross section D-D')

Transect 4 has been made between the vicinity of Nebikoy and Cobanlar (Plate 5). Foliation planes are mainly defined by mica minerals and strike NE-SW to E-W. Oriented rock samples ED-29, 30, 31, 32, and 33 were collected along this transect both from the hanging wall and footwall block rocks of the shear zone. Quartz mylonite, σ -type porphyroclasts with strain shadows, and folded mica minerals from samples ED-29 (graphitic schist, made up of garnet + chlorite + muscovite + biotite + feldspar + graphite + quartz; GPS: 98493E, 38822N) and ED-32 (orthogneiss, made up of biotite + muscovite + plagioclase + quartz; 96474E, 40886N) suggest top-to-the south sense of movement (Figure 43, Plate 5). However, mesoscopic scale asymmetric quartzite (GPS: 96380E, 40871N) shows top-to-the north sense of shearing; as is the case in transect 2.

In addition, ED-32 is characterized by two different foliation planes, one is defined by elongated quartz ribbons (S_1), and the other one is defined by parallel

alignments of biotite and muscovite minerals (S_2). Here, S_2 is associated with top-to-the south sense of shearing (D_2).

TRANSECT 4 (D-D')

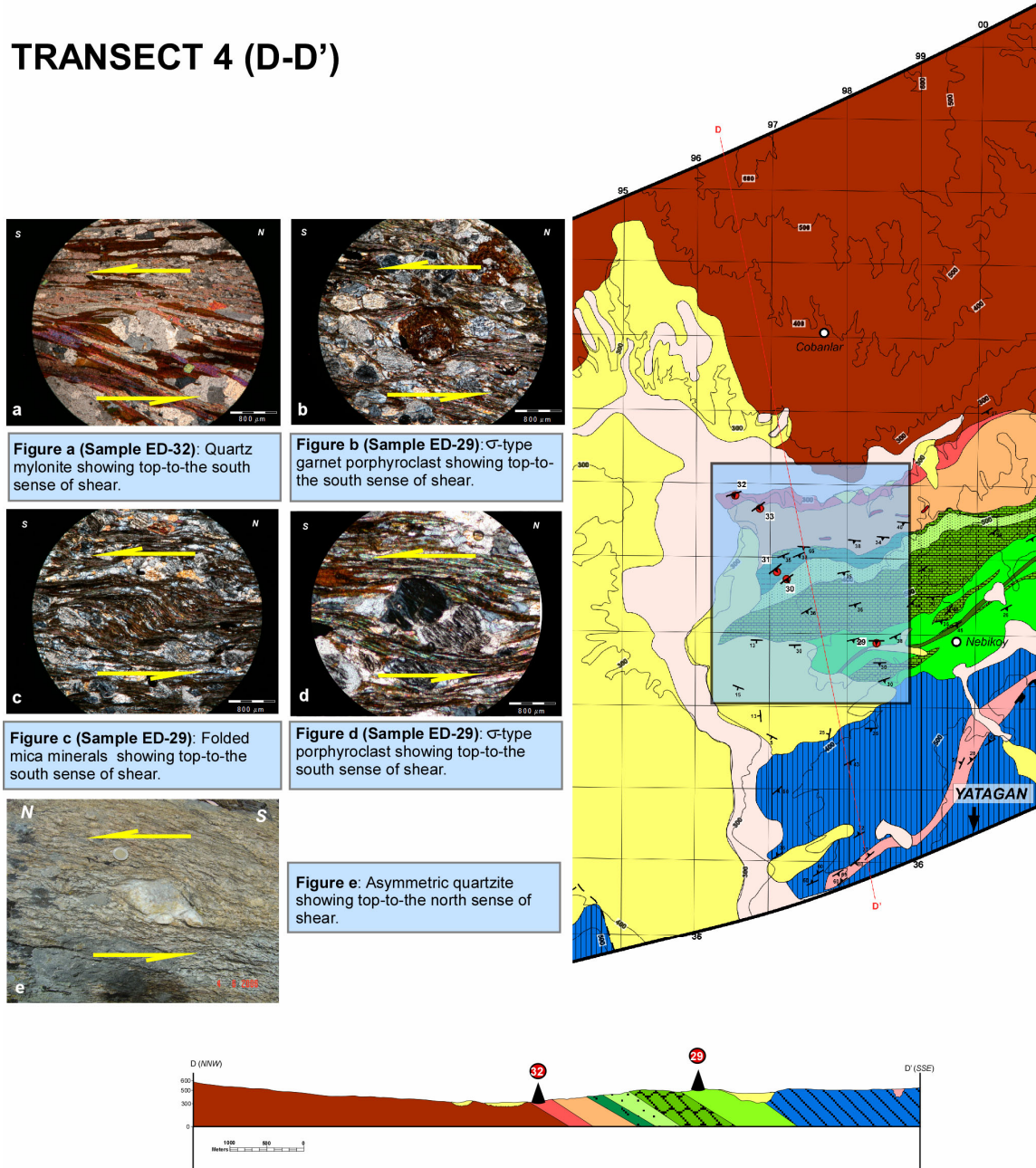


Figure 43. Strip map along transect 4 showing sample locations and microphotographs of samples. (See Plate 1 for explanations).

4.3.5. Transect 5 (Cross section E-E')

Structural cross-section E-E' (NNW-SSE) has been constructed along this transect to demonstrate the variations and relationships between the rock units (i.e. orthogneiss and schist) (Plate 6). The boundary between the two distinct rock units of the Kayabuku shear zone and foliation planes strike almost E-W and have a moderate angle (~40°S) compared to other divisions of the study area. Only two samples, ED-09 (muscovite garnet schist; GPS: 85225E, 37530N) and ED-35 (biotite schist; GPS: 86104E, 37755N), out of eight oriented rock samples show kinematic indicators (Plate 6, Figure 44). Rotated garnet porphyroclast in ED-9 (garnet + muscovite + biotite + chlorite + chloritoid + quartz + feldspar) suggests top-to-the north sense of shear, whereas biotite fish in ED-35 (biotite + muscovite + chlorite + garnet + feldspar + quartz + zircon) which is oblique to the mylonitic foliation and embedded in a finer grained matrix shows top-to-the south sense of movement (Figure 44).

TRANSECT 5 (E-E')

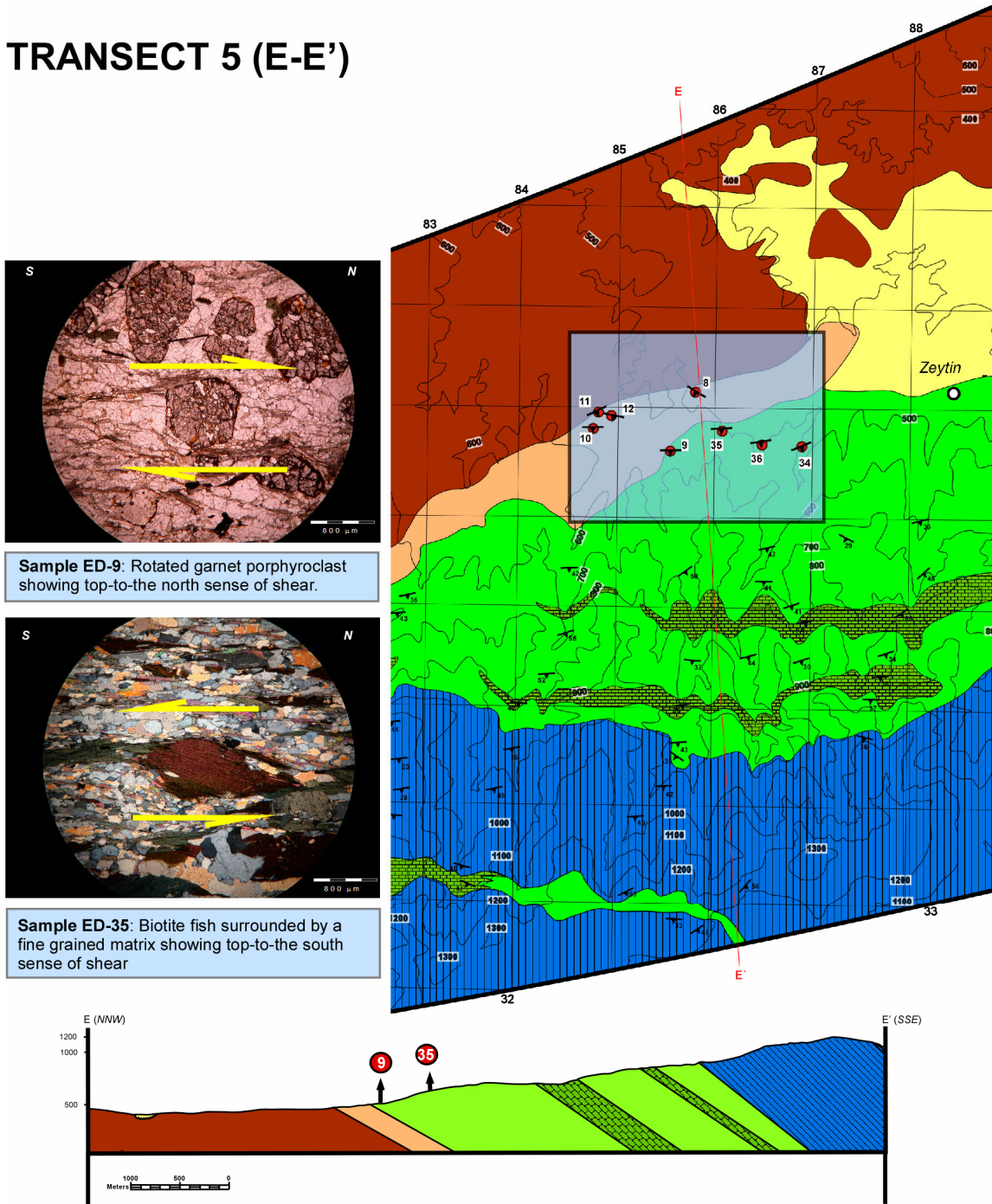
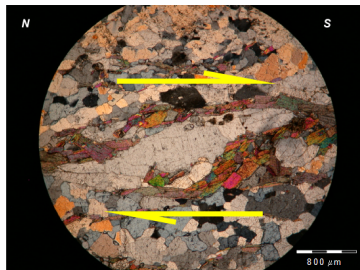


Figure 44. Strip map along transect 5 showing sample locations and microphotographs of samples. (See Plate 1 for explanations).

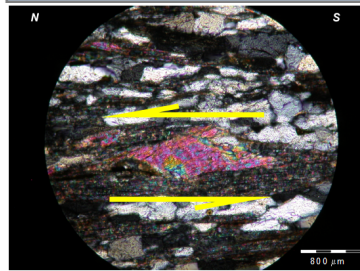
4.3.6. Transect 6 (Cross section F-F')

Seven oriented rocks samples (ED-37, 38, 39, 40, 41, 42, and 43) were collected along transect 6 and two of them, ED-40 and ED-42, show ductile and brittle shear sense indicators (Plate 7, Figure 45). Foliation planes in ED-40 (orthogneiss, made up of muscovite + biotite + quartz + feldspar; GPS: 78576E, 35469N) are defined by longest dimensions of elongate quartz ribbons and plagioclase. Kinematic indicators, such as asymmetric quartz mylonite, suggest top-to-the south sense of movement (Figure 45). ED-42 (schist, made up of chloritoid + garnet + muscovite + quartz + feldspar; GPS: 78275E, 35005N) show both top-to-the north and south sense of shearing within the same thin section (Figure 45). Top-to-the south shear senses have been overprinted by brittle deformation which produced a variety of fracture sets (Figure 45, Plate 7). This may suggest that, top-to-the south sense of brittle shearing (D_2) may have taken place when the metamorphic rocks of the shear zone were close to the surface.

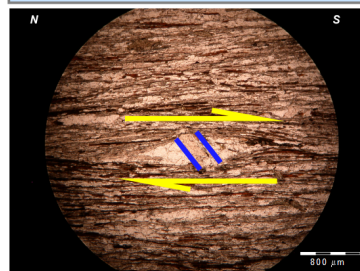
TRANSECT 6 (F-F')



Sample ED-40: Quartz mylonite showing top-to-the south sense of shear.



Sample ED-42: σ -type porphyroblast of feldspar showing top-to-the north sense of shear.



Sample ED-42: Fragmented quartz mylonite showing top-to-the south sense of shear. The top-to-the south shear sense has been overprinted by brittle deformation.

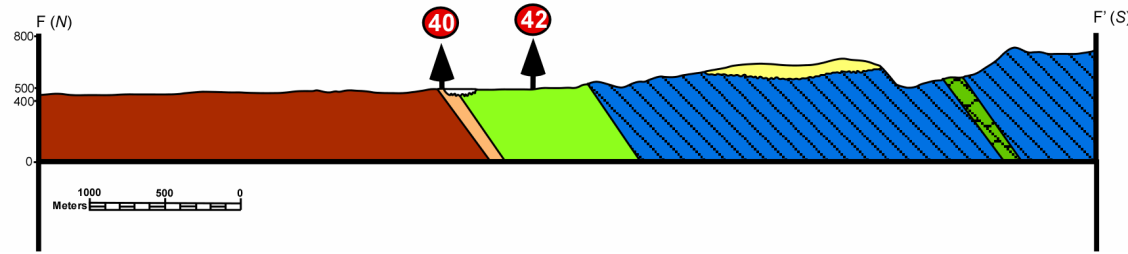
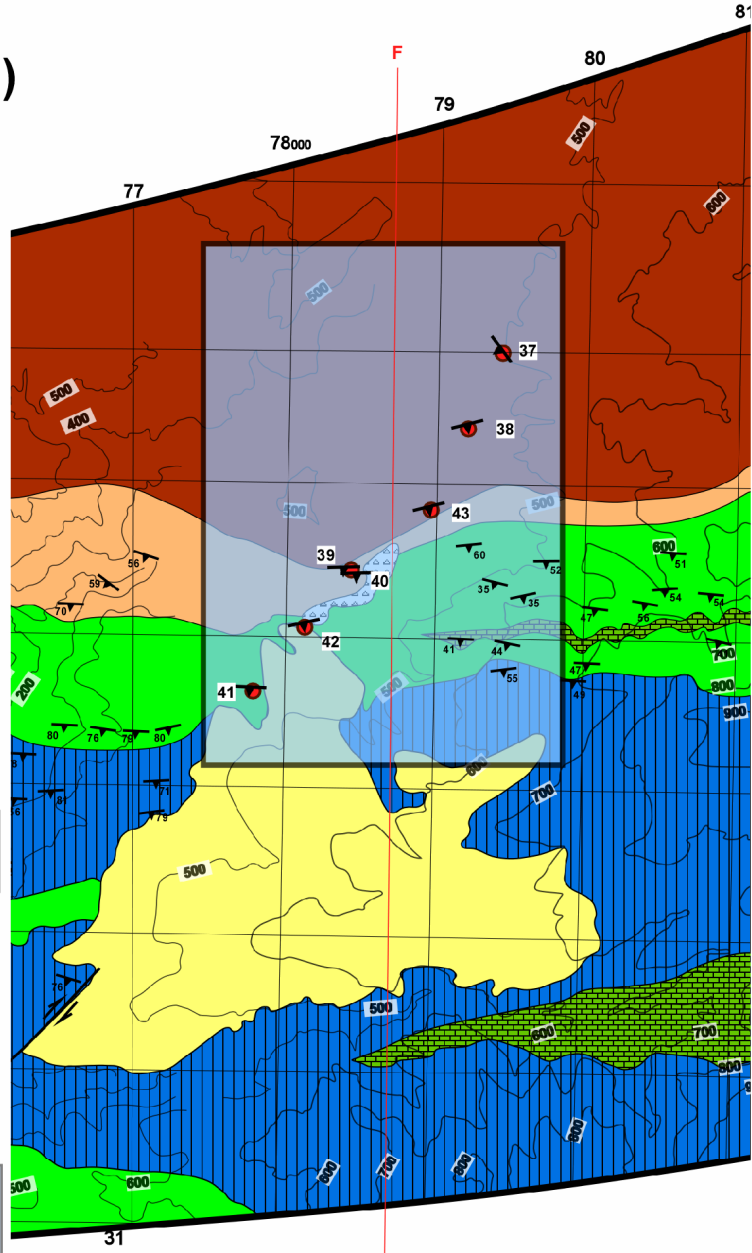


Figure 45. Strip map along transect 6 showing sample locations and microphotographs of samples. (See Plate 1 for explanations).

4.3.7. Transect 7 (Cross section G-G')

Transect 7 has been made along the westernmost part of the study area, to the northeast of Milas (Plate 8). As is the case of other parts of the study area, Quaternary and Miocene clastic rocks of sedimentary basins overlay the metamorphic rocks. Generally, strikes of the foliation planes of the metamorphic rocks range from E-W to NE-SW and dip $\sim 60^\circ$ S. Attitude of the foliation planes are almost identical across the hanging wall and footwall block rocks of the Kayabuku shear zone.

Seven samples (ED-45, 46, 47, 48, 49, 50, 51) were collected along this transect from orthogneiss and schist units. Samples ED-45 (garnet schist, made up of chloritoid + muscovite + feldspar; GPS: 72212E, 35627N), ED-46 (garnet schist made up of, garnet + muscovite + biotite + graphite + plagioclase + quartz; GPS: 72218E, 35773N), and ED-47 (garnet-chloritoid schist, made up of garnet + chloritoid + biotite + muscovite + quartz + feldspar; GPS: 72361E, 36054N) show spectacular shear sense indicators such as, syn-kinematic rotated garnet porphyroclasts, strain shadows, and σ -type feldspar porphyroclasts (Plate 8, Figure 46). Kinematic indicators in these rocks samples, as well as in the other transects, suggest that they have been deformed dominantly by top-to-the south sense of shearing (Plate 8). However, rotated garnet porphyroclasts and strain shadows of quartz in ED-47 indicate that metamorphic rocks of the shear zone have been deformed by both top-to-the north and top-to-the south shearing.

TRANSECT 7 (G-G')

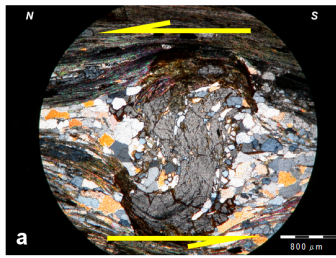


Figure a (Sample ED-47): Syn-kinematic rotated garnet porphyroblast showing top-to-the north sense of shear.

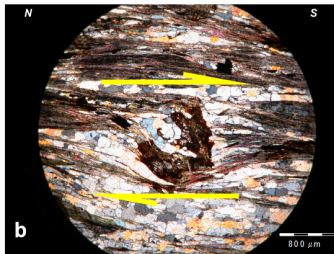


Figure b (Sample ED-47): δ -type garnet porphyroblast showing top-to-the south sense of shear.

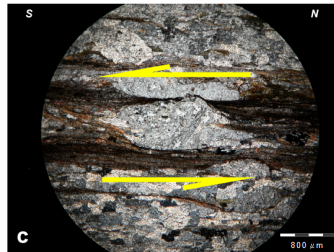


Figure c (Sample ED-46): σ -type feldspar porphyroblast showing top-to-the south sense of shear.

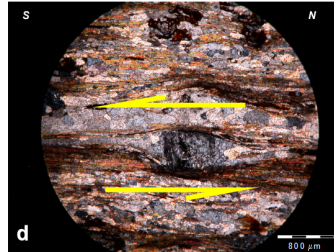


Figure d (Sample ED-45): σ -type porphyroblast showing top-to-the south sense of shear.

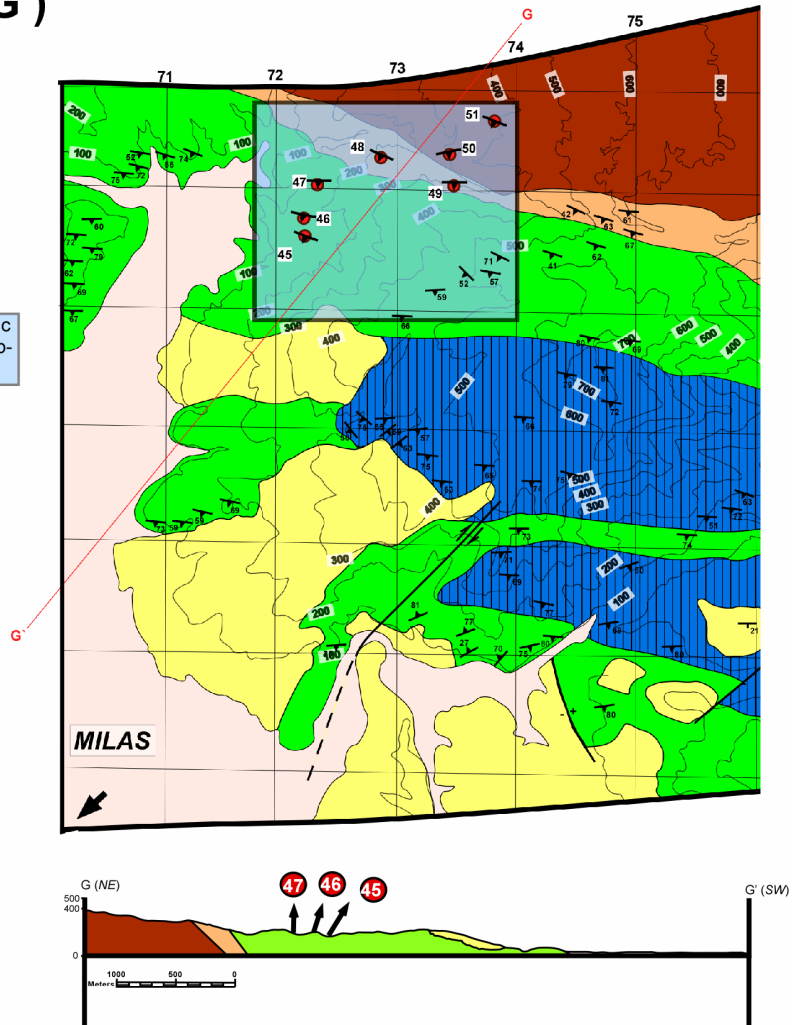


Figure 46. Strip map along transect 7 showing sample locations and microphotographs of samples. (See Plate 1 for explanations).

The oriented rock samples described above contain shear sense indicators such as σ and δ -type porphyroclasts, rotated porphyroclasts, strain shadows, micro-folds, fractured and displaced grains, and mica fish. Most of the shear sense indicators show traces of ductile deformation. However, in few samples, ductile shear sense indicators have been overprinted by brittle deformation.

On the basis of kinematic framework and overprinting relationships, two regionally deformation events have been observed associated to the extension; top-to-the north (D_1) and top-to-the south (D_2) which overprinted the former one. D_1 is represented by ductile fabrics, whereas D_2 is related to both ductile and brittle deformation. Therefore it is suggested that, the shear zone have been subjected to at least two deformation phases (D_1 and D_2) during the N-S directed extension.

4.4. Kinematic Model

A three-dimensional (3-D) model is proposed to explain the evolution of the southern Menderes Massif and role of the Kayabuku shear zone within the N-S Cenozoic extensional regime of western Turkey (Figure 47). Findings regarding the kinematics of the shear zone (i.e. D_1 : top-to-the north movement and D_2 : top-to the south movement), published age data (e.g. Ring et al. 2003), and previous studies (e.g. Seyitoglu et al. 2004, Cemen et al. 2006) are considered as the basis of the proposed model.

Following the Late Cretaceous to Eocene contractional deformation (Figure 47a) (Sengor and Yilmaz 1981), N-S extensional tectonism in western Turkey started as early as Late Oligocene along a major north-dipping shear zone (main breakaway fault) (Figure 47b). The shear zone has been named as Datca-Kale main breakaway fault by Seyitoglu

et al. 2004 and South West Anatolia Shear Zone (SWASZ) by Cemen et al. (2006). One of the main evidence for existence of the SWASZ is presence of a series of Oligocene extensional basins located adjacent to the shear zone (Figure 47b). The proposed model for the initiation of the N-S extension is very similar to a simple shear rolling hinge model (e.g. Axen and Bartley 1997). In this stage, the first deformation event (D_1) is linked to the northward movement of the hanging wall rocks of the SWASZ in response to extensional regime. The detailed description and role of the SWASZ lies outside the scope of this research, and readers are referred to available literature for further information (e.g. Cemen et al. 2006)

In Early Miocene, unroofing caused the isostatic doming and brought the metamorphic rocks of the southern Menderes Massif to the surface along the Kayabuku shear zone (Figure 47c). The Early Miocene age is confirmed by Ring et al.'s (2003) fission track ages (cooling ages ~20 Ma). During the exhumation of the core rocks of the massif, the hanging wall block rocks of the Kayabuku shear zone moved relatively towards south. Therefore, the second deformation event (D_2) which overprinted the former one (D_1) is associated with the top-to-the south movement along the Kayabuku shear zone (Figure 47c). Furthermore, as the extension continued, the hanging wall block rocks of the shear zone have experienced brittle deformation in Early Pliocene (Figure 47d). This event is supported by the brittle deformation fabrics which overprinted the D_2 deformation event as well as the locally south dipping brittle fault zone observed to the south of Kafacakaplancik and Nebikoy villages.

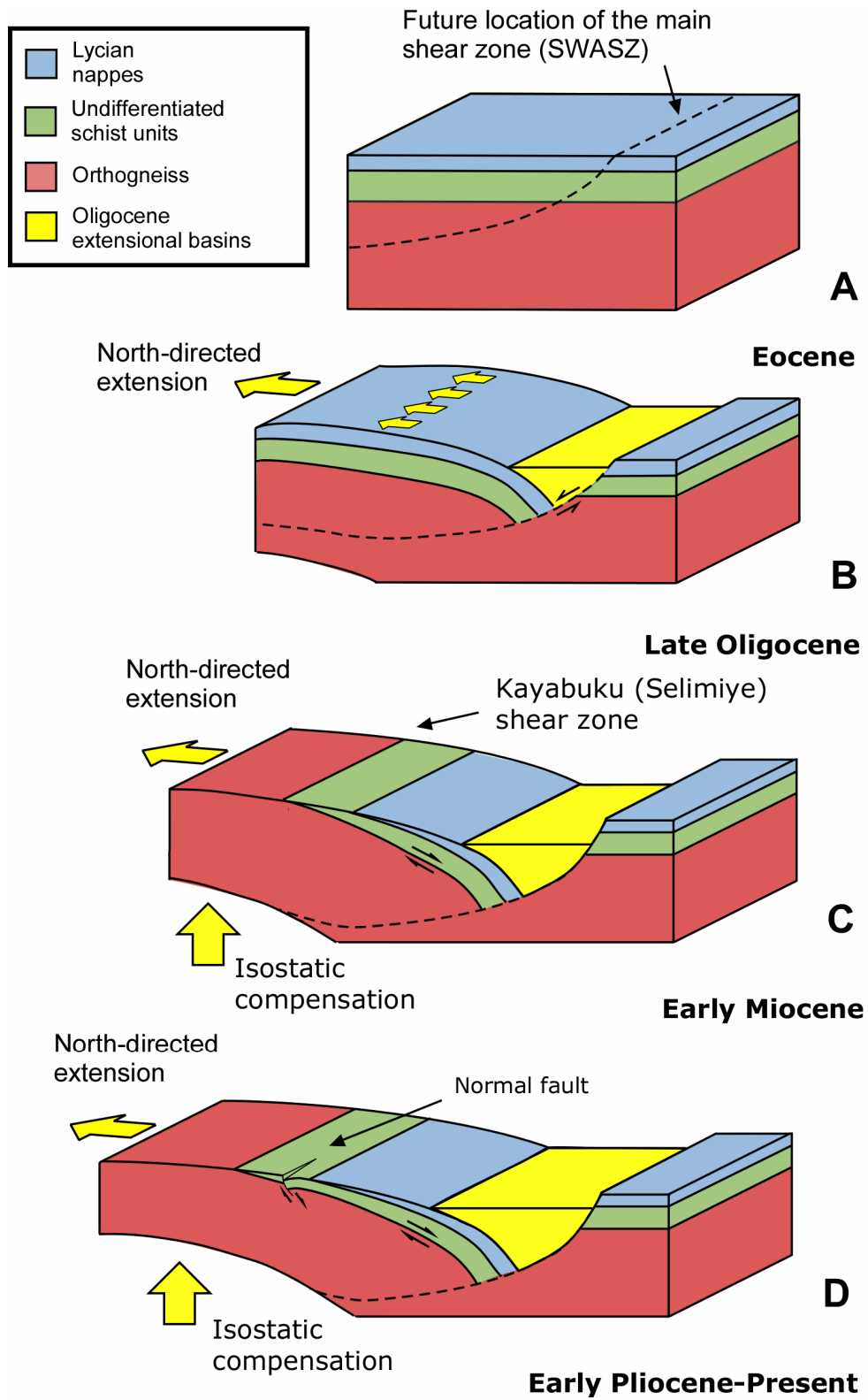


Figure 47. Kinematic model showing evolution of the southern Menderes Massif along the Kayabuku shear zone.

CHAPTER 5

CONCLUSIONS

The following conclusions were reached regarding the nature of extension within the Kayabuku shear zone.

- 1) In the southern Menderes Massif, orthogneiss and fine grained gneiss are separated from various schist (i.e. garnet-mica schist, chloritoid schist, quartz-mica schist, quartzite, calcschist, phyllite, metabasic, and metaultramafic) and marble units by the crustal scale, south-dipping extensional Kayabuku shear zone.
- 2) Average attitude of the foliation planes, within the shear zone between the town of Milas and Yatagan, is measured as N82E/50°S.
- 3) Stretching mineral lineations in the study area range from N10E to N30E, indicating that they are parallel to the shear sense indicators measured along the other parts of the Massif.
- 4) The Kayabuku shear zone contains well-developed shear sense indicators such as rotated porphyroclasts, strain shadows, mica fish, asymmetric quartz ribbons, micro-folds, and fractures and displaced grains indicating that the shear zone has been subjected to at least two deformation phases; D₁: top-to-the north and D₂: top-to-the south.

5) D_1 deformation event is characterized by ductile fabrics. On the other hand, D_2 is represented by both ductile and brittle deformation. In addition, D_2 deformation event has been overprinted by south directed brittle deformation. In turn this suggest that D_2 (top-to-the south) fabrics overprint D_1 (top-to-the north) fabrics.

6) The hanging wall of the Kayabuku shear zone is locally brittlely deformed by a south-dipping normal fault zone, discontinuously exposed between the schist and marble units. This is an indirect evidence to support the overprinting relationship between the two deformation events D_1 and D_2 .

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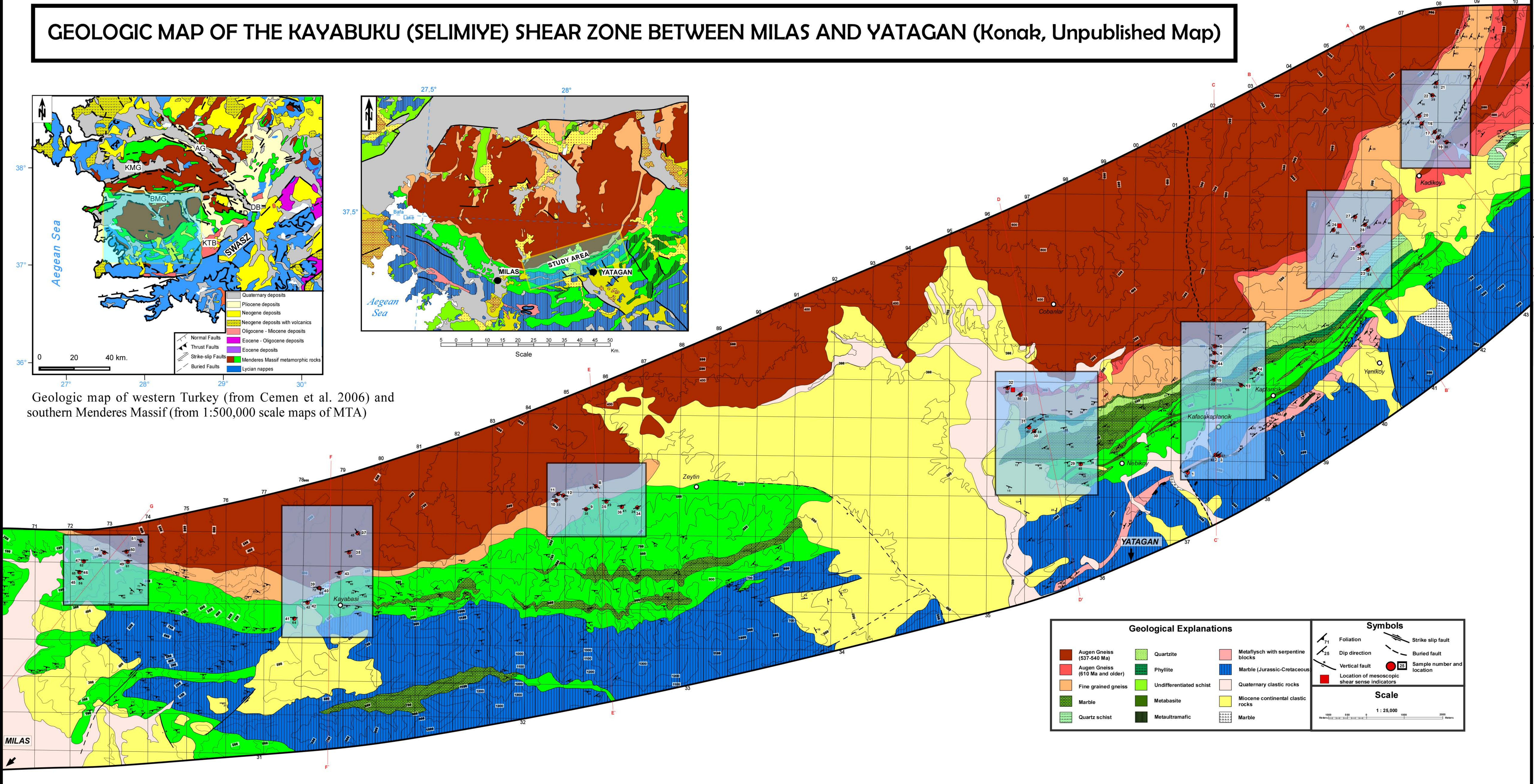
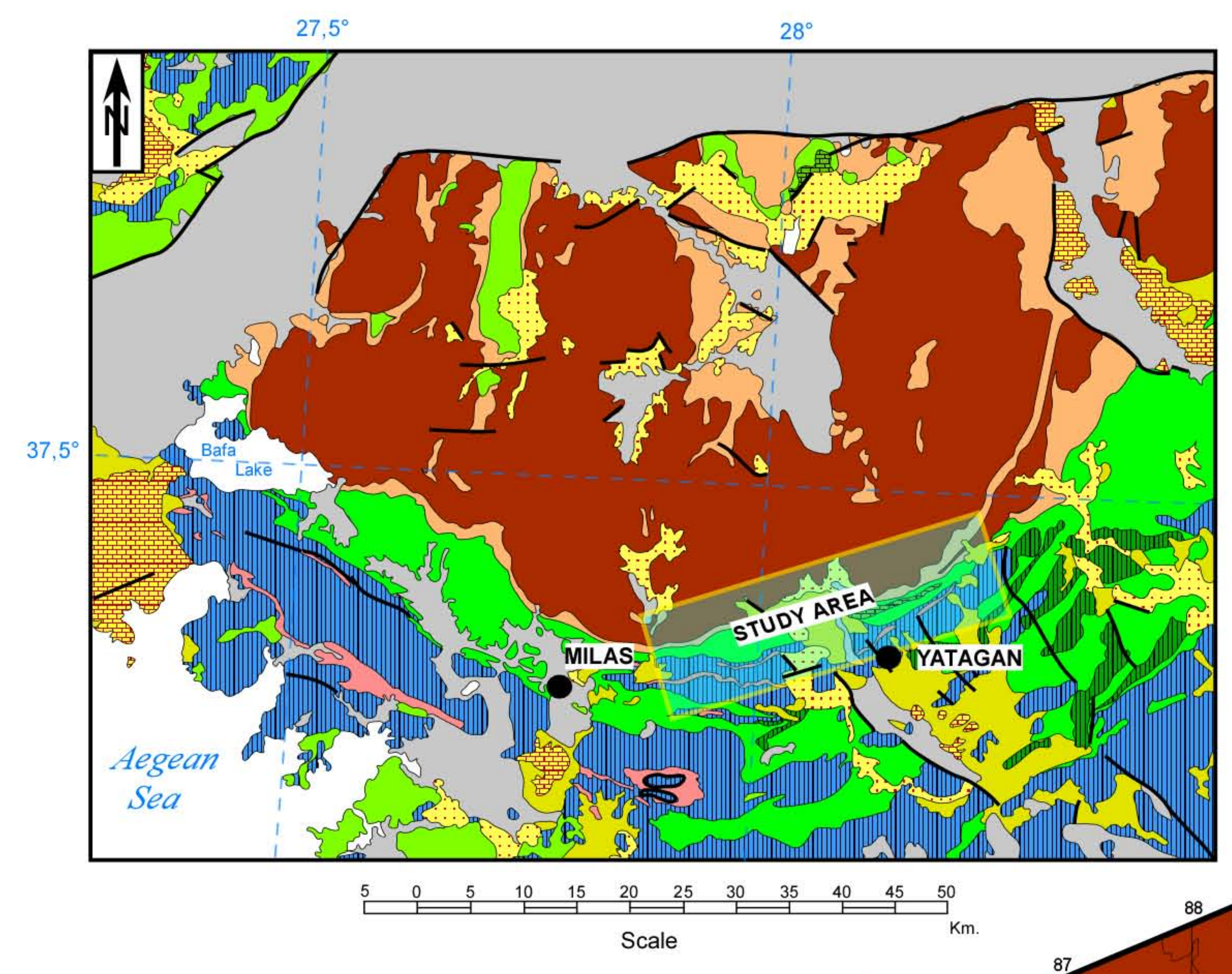
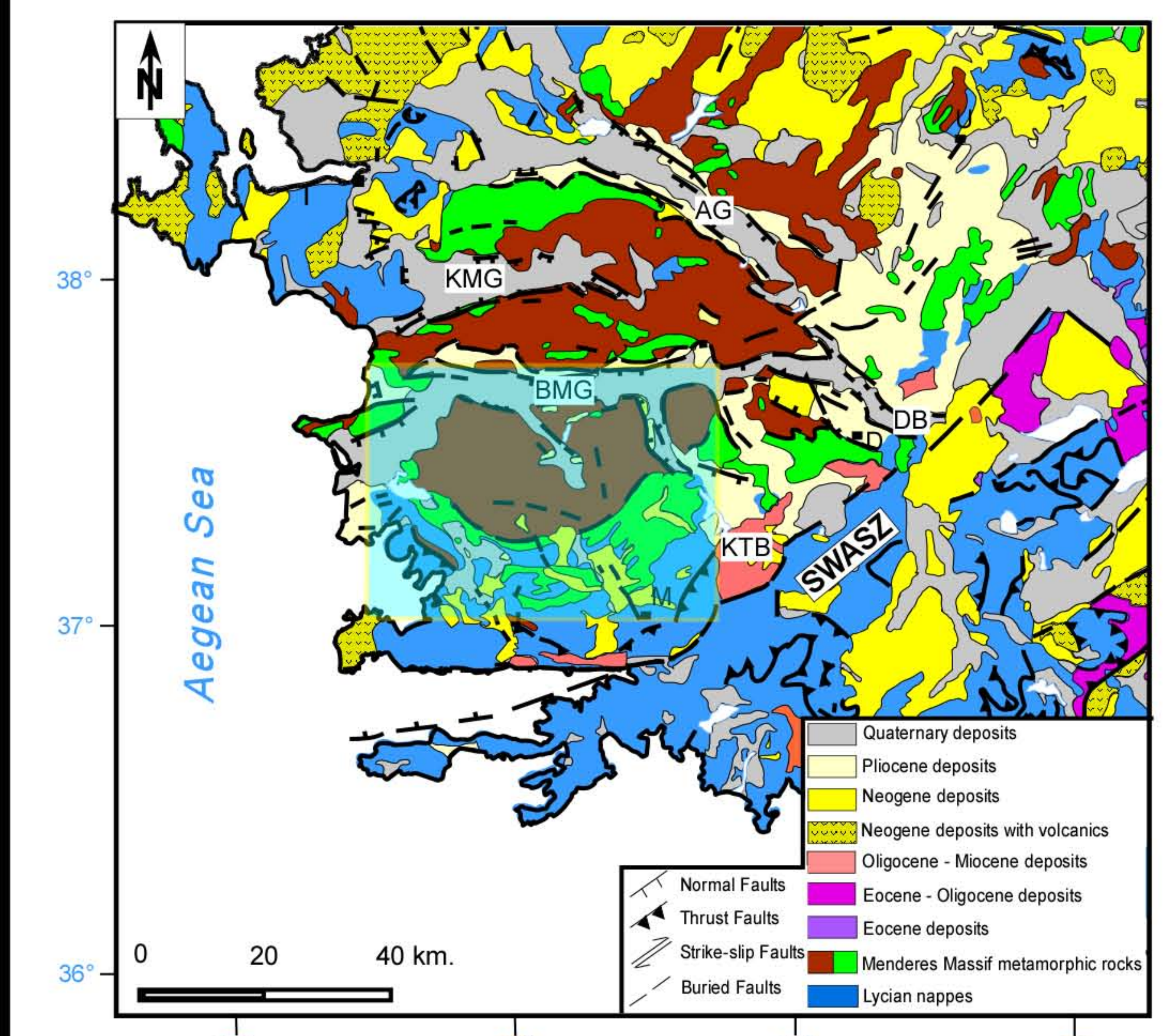
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GEOLOGIC MAP OF THE KAYABUKU (SELIMIYE) SHEAR ZONE BETWEEN MILAS AND YATAGAN (Konak, Unpublished Map)



TRANSECT 1 (A-A')

Explanations

| | | | |
|--|---------------------------------|--|-----------------------------------|
| | Augen Gneiss (537-540 Ma) | | Metabasic |
| | Augen Gneiss (610 Ma and older) | | Metaultramafic |
| | Fine grained gneiss | | Metaflysch with serpentine blocks |
| | Marble | | Marble (Jurassic-Cretaceous) |
| | Quartz schist | | Quaternary clastic rocks |
| | Quartzite | | Miocene continental clastic rocks |
| | Phyllite | | Marble |
| | Undifferentiated schist | | |

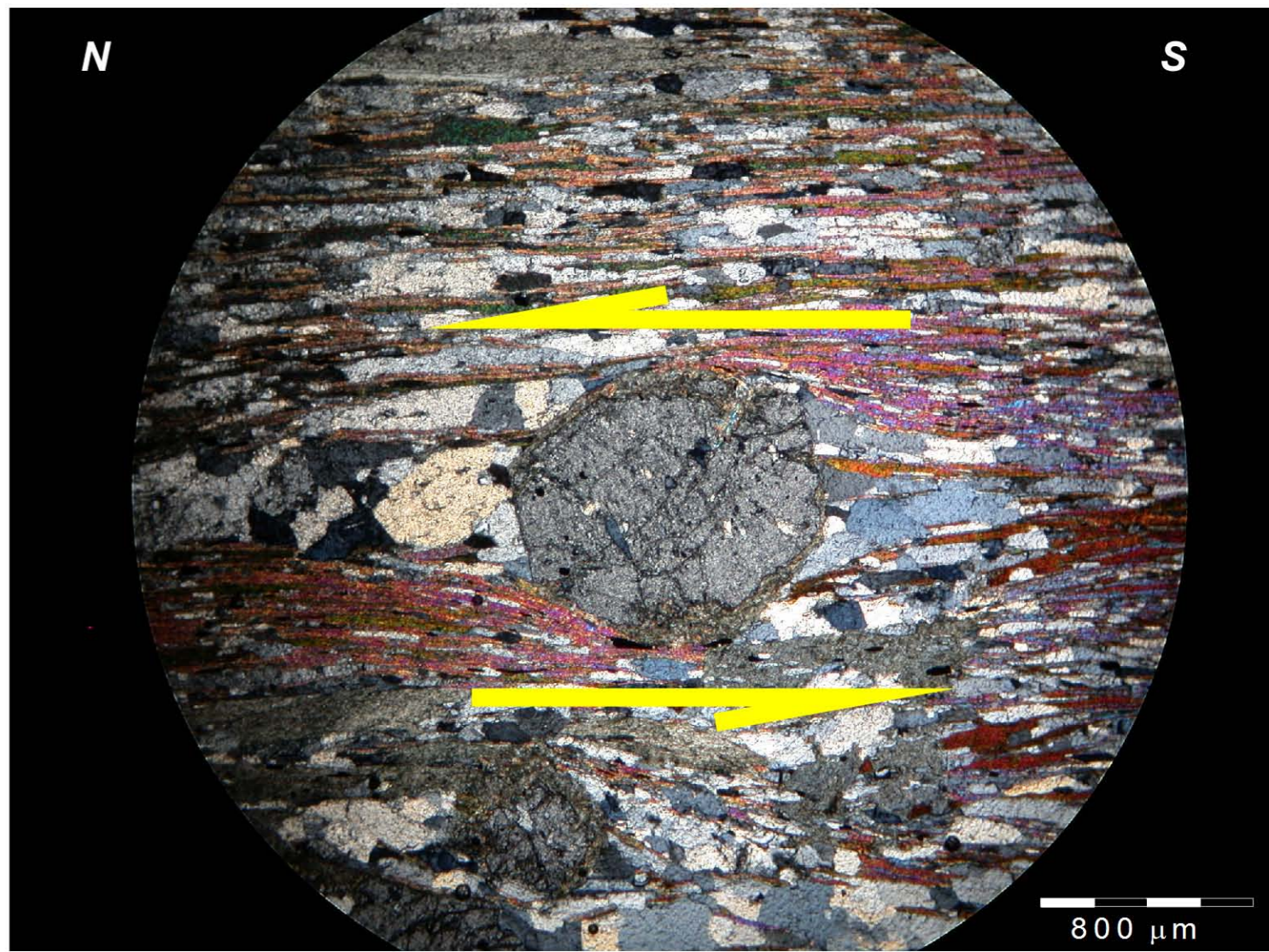
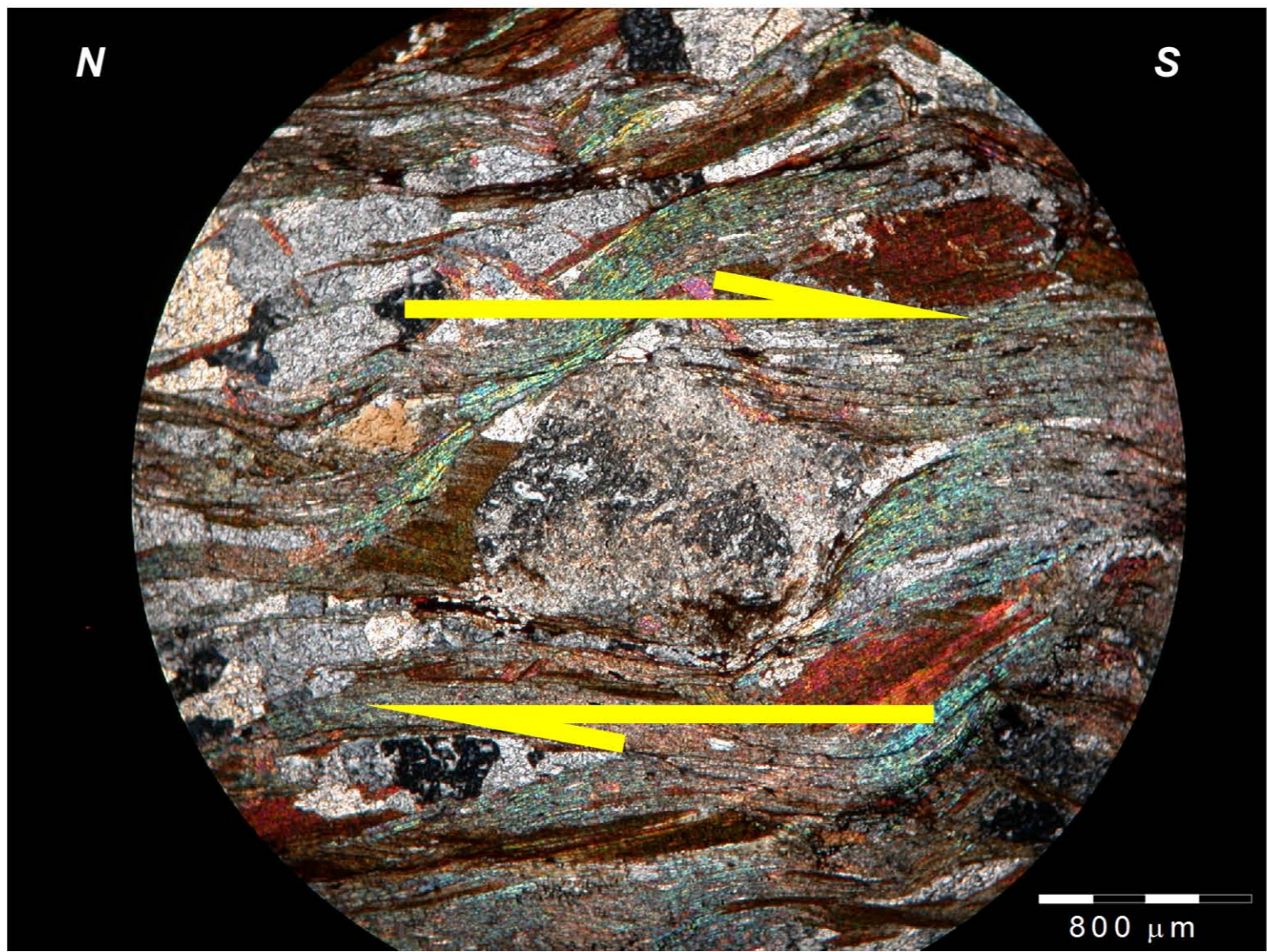
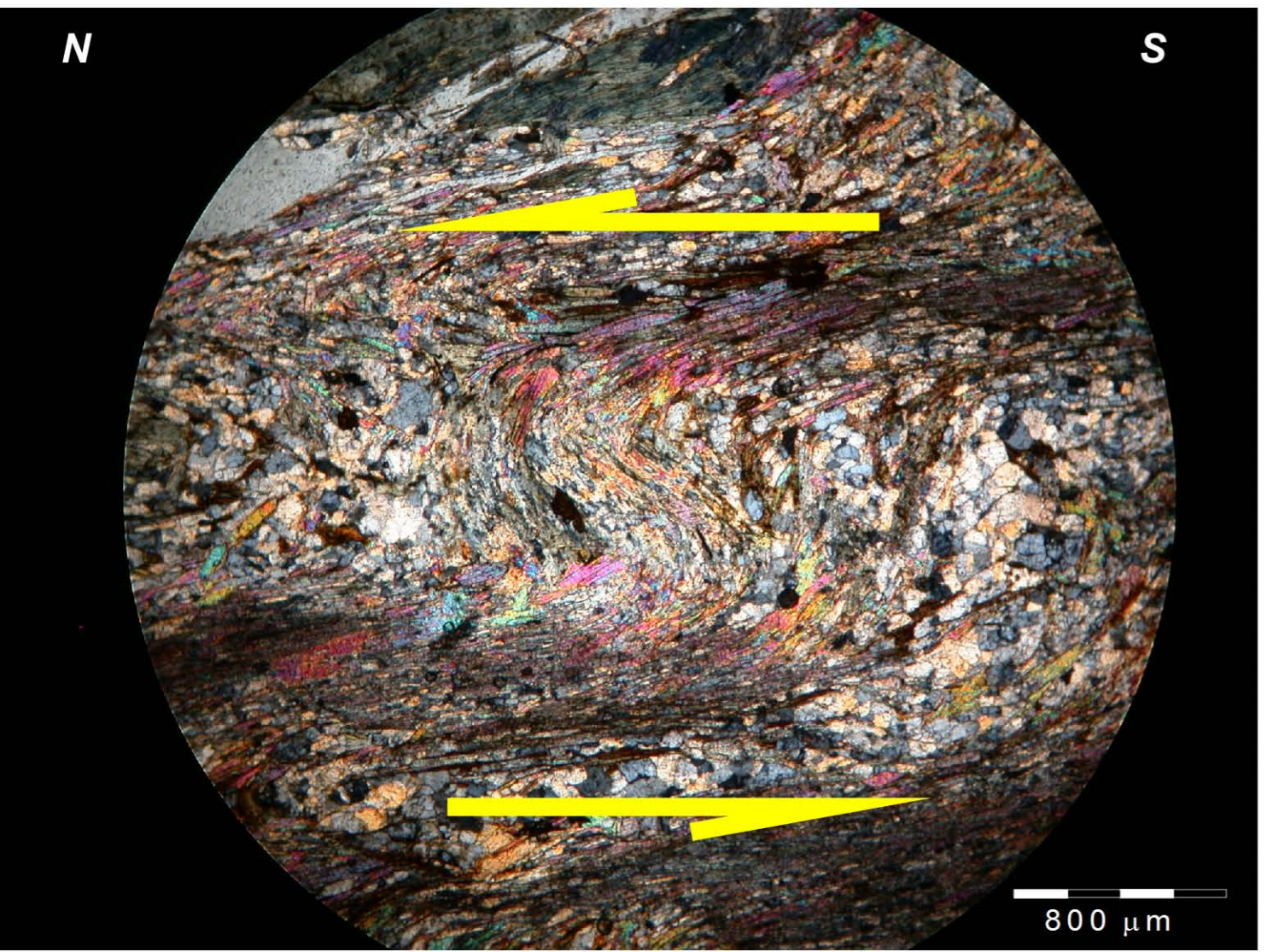
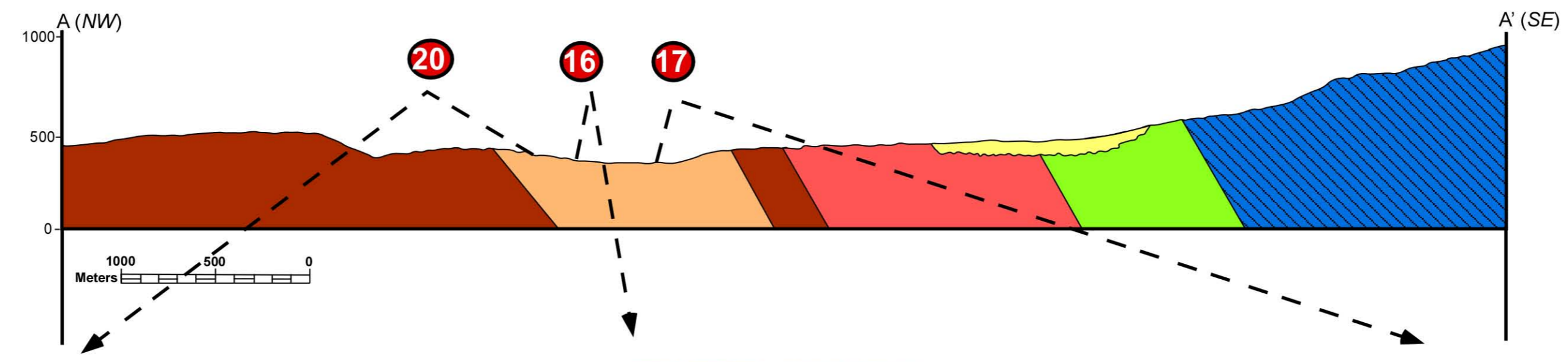
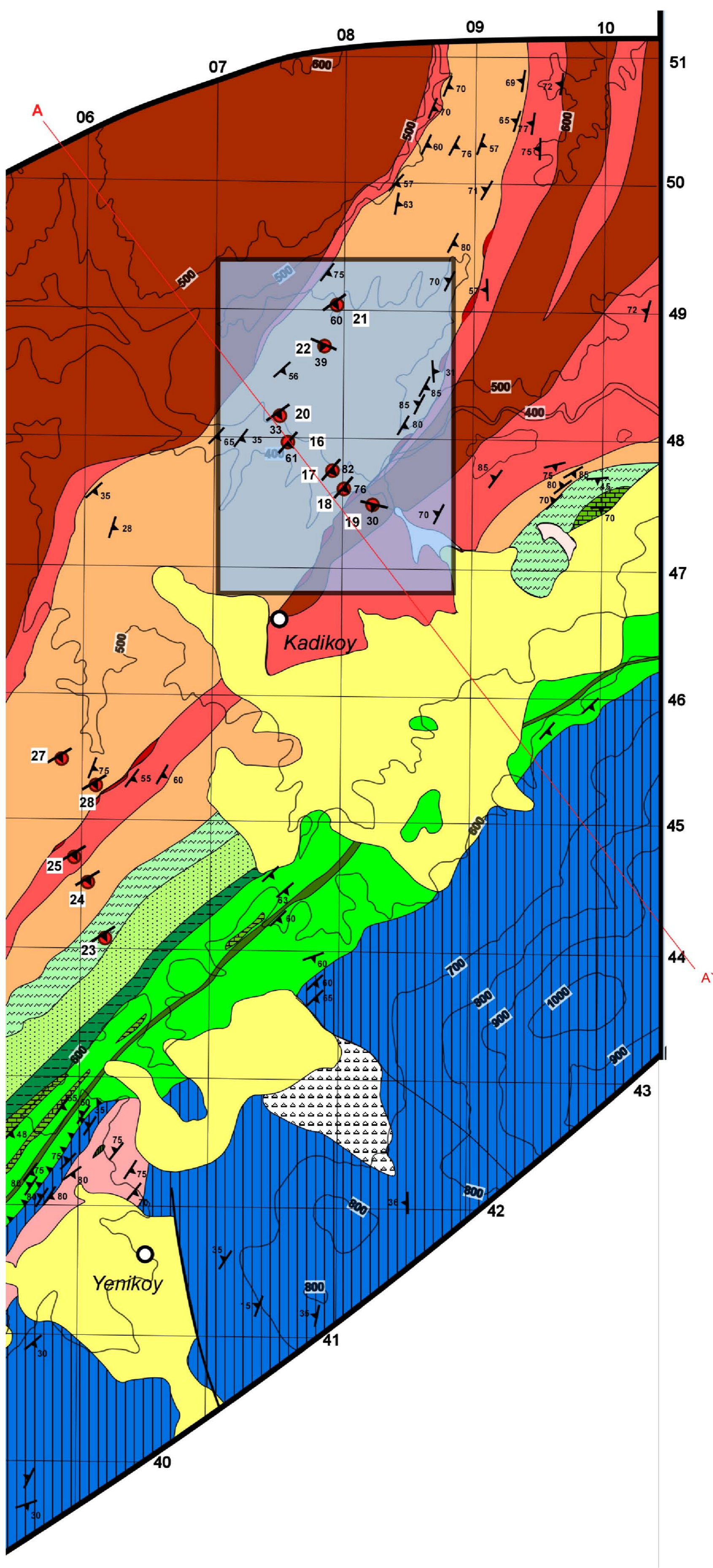
Symbols

| | | | |
|--|----------------|--|----------------------------|
| | Foliation | | Strike slip fault |
| | Dip direction | | Buried fault |
| | Vertical fault | | Sample number and location |

Scale

1 : 25,000

Meters 1000 500 0 1000 2000



Sample ED-20: Folded mineral grains showing top-to-the north sense of shear

Sample ED-16: σ - type porphyroblast showing top-to-the south sense of shear.

Sample ED-17: Rotated garnet porphyroblast, surrounded by fine grained matrix, showing top-to-the north sense of shear

TRANSECT 2 (B-B')

Explanations

| | | | |
|--|---------------------------------|--|-----------------------------------|
| | Augen Gneiss (537-540 Ma) | | Metabasic |
| | Augen Gneiss (610 Ma and older) | | Metaultramafic |
| | Fine grained gneiss | | Metaflysch with serpentine blocks |
| | Marble | | Marble (Jurassic-Cretaceous) |
| | Quartz schist | | Quaternary clastic rocks |
| | Quartzite | | Miocene continental clastic rocks |
| | Phyllite | | Marble |
| | Undifferentiated schist | | |

Symbols

| | | | |
|--|----------------|--|----------------------------|
| | Foliation | | Strike slip fault |
| | Dip direction | | Buried fault |
| | Vertical fault | | Sample number and location |

Scale
1 : 25,000
Meters 1000 500 0 1000 2000 Meters

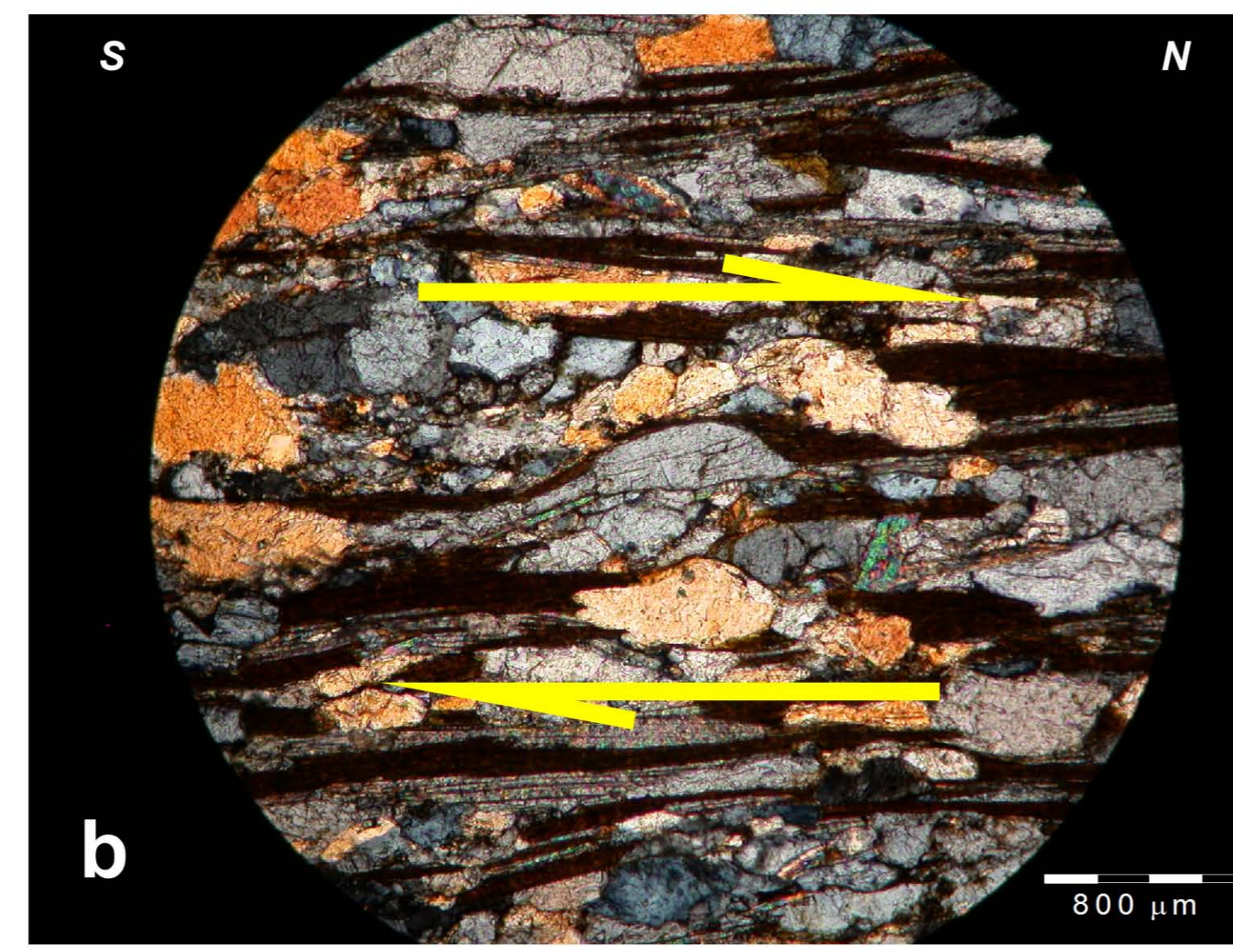
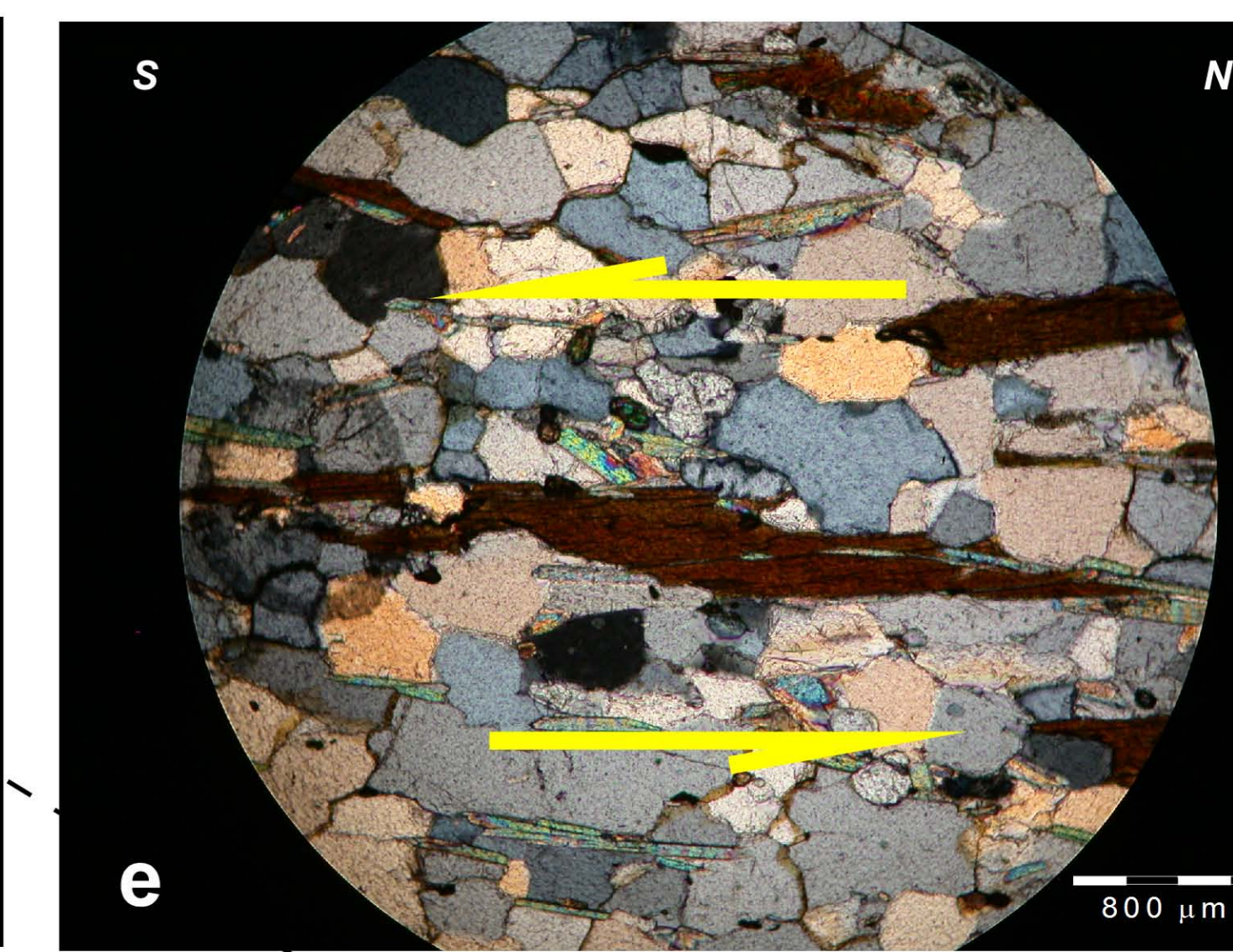
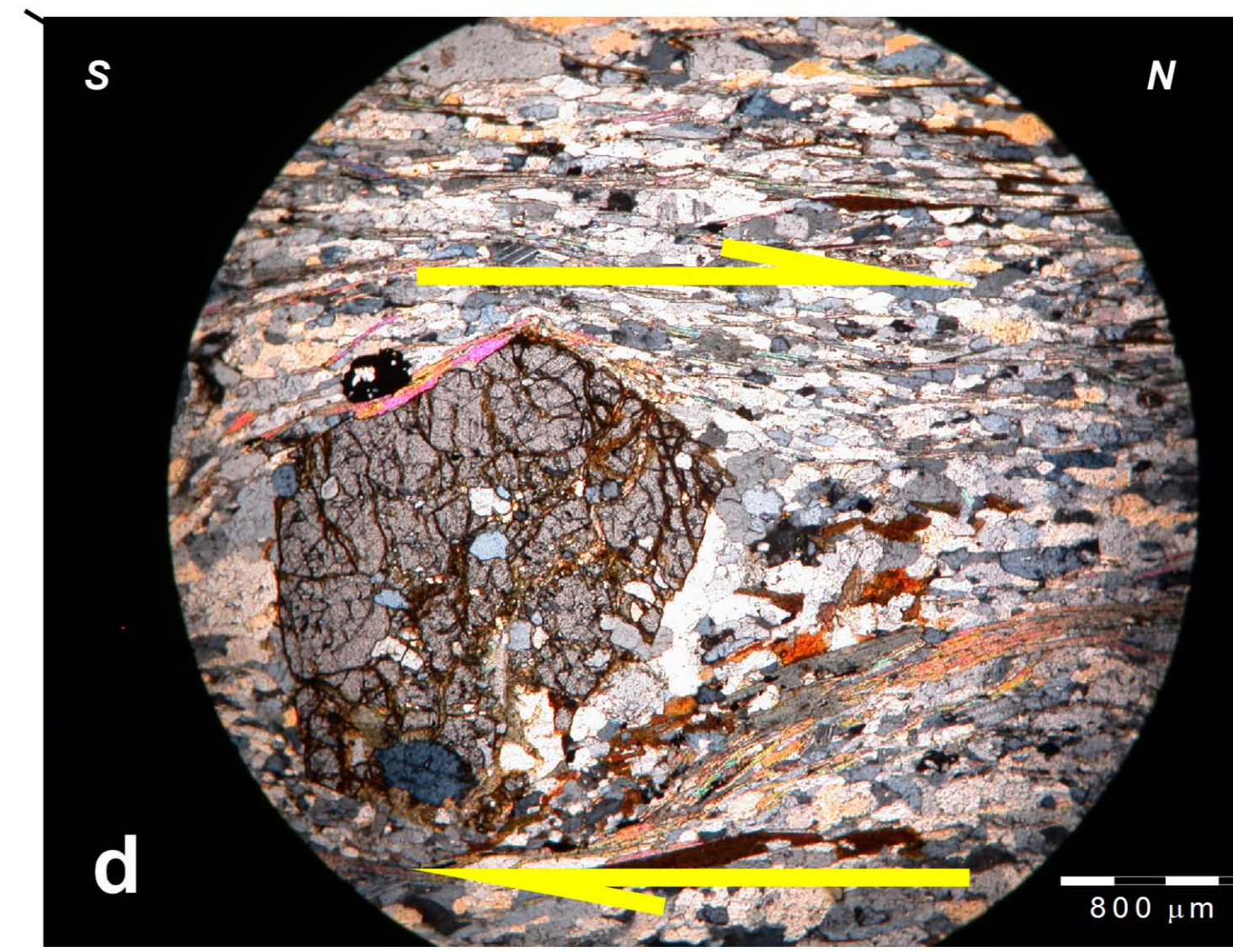
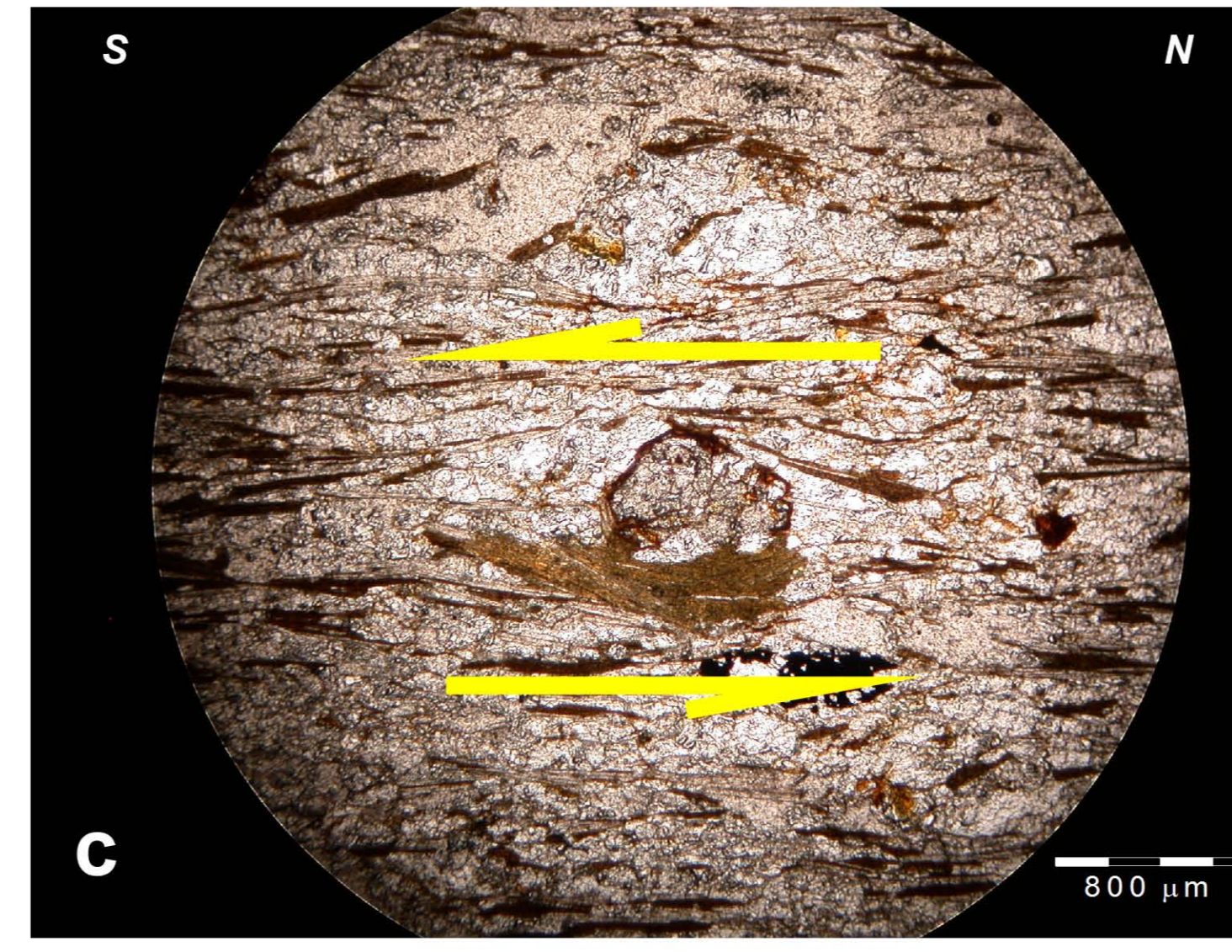
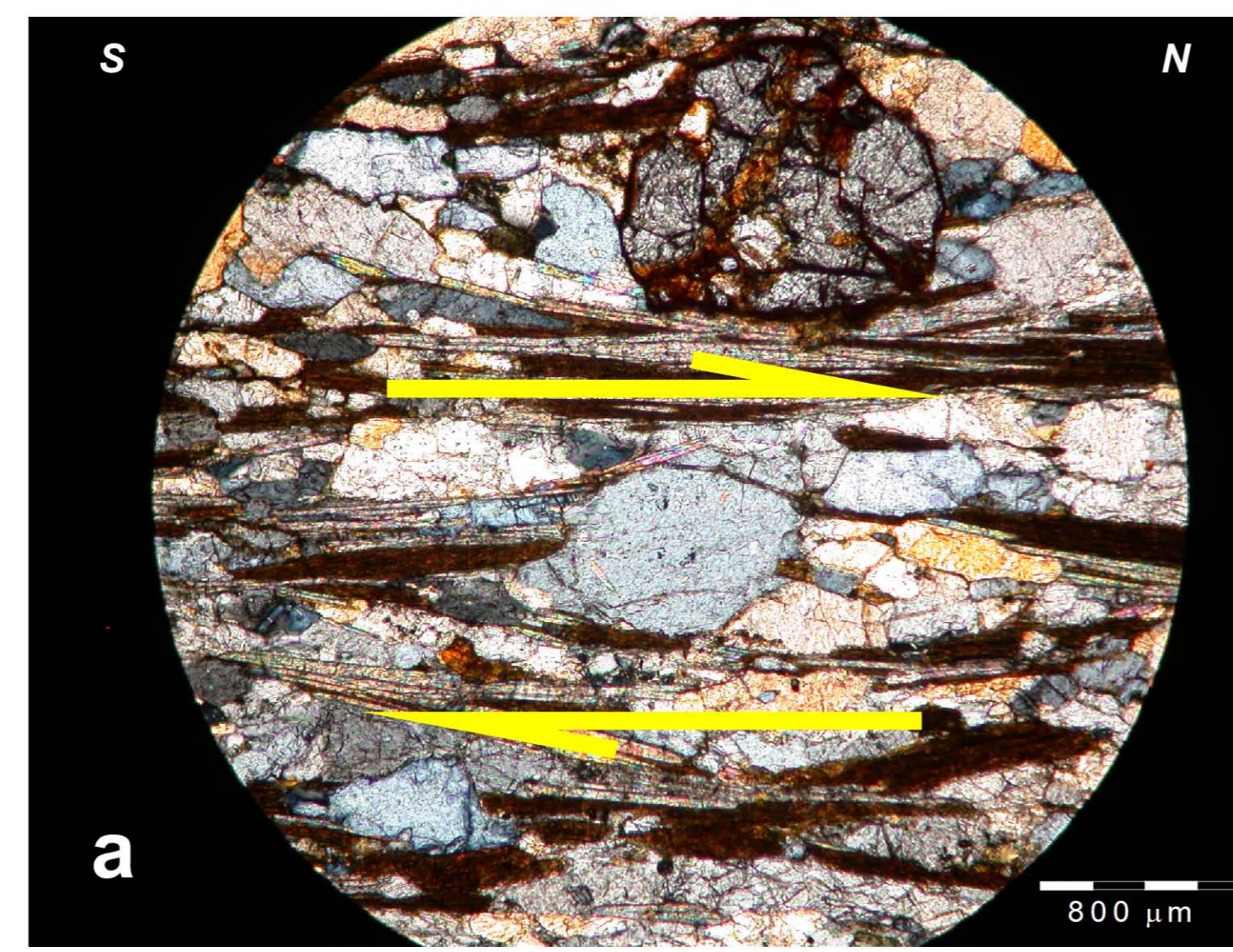
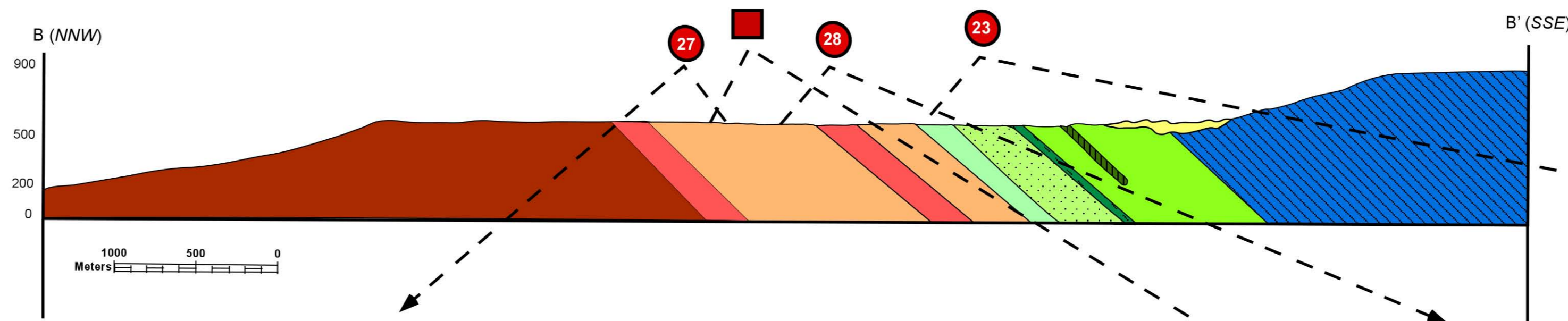
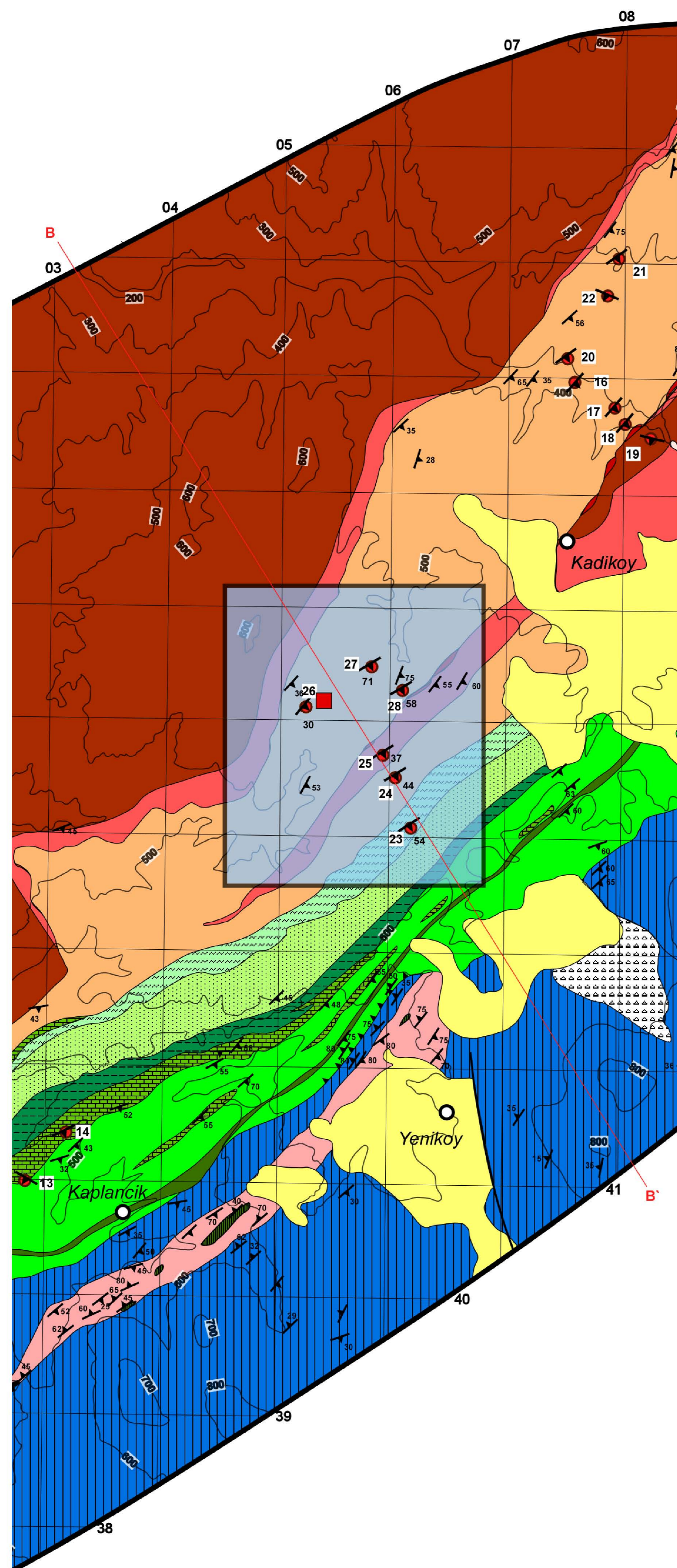


Figure a (Sample ED-27): Quartz mylonite showing top-to-the north sense of shear.

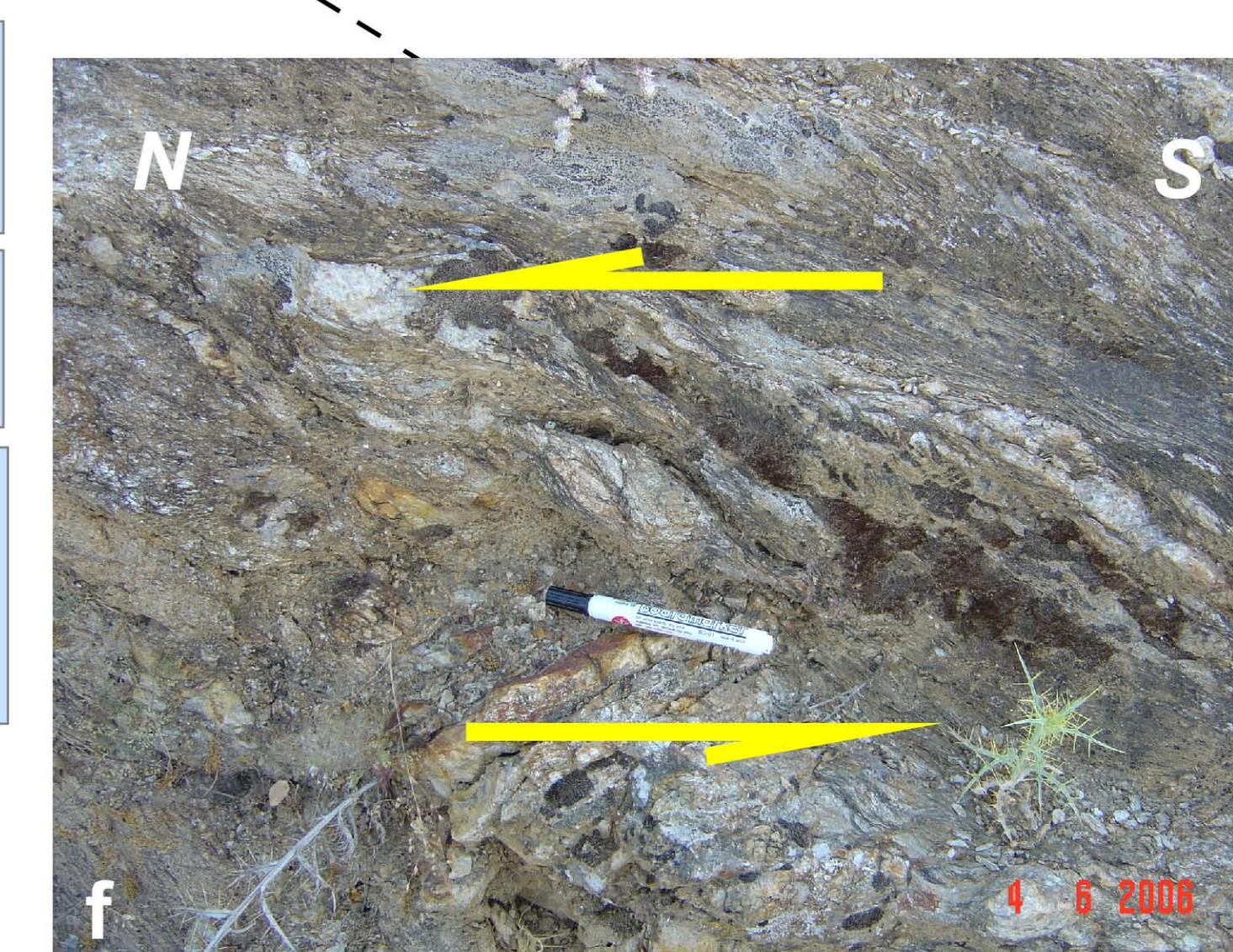
Figure b (Sample ED-27): Brittly deformed quartz mylonite showing top-to-the north sense of shear.

Figure c (Sample ED-27): S-type garnet porphyroblast showing top-to-the south sense of shear.

Figure d (Sample ED-28): Rotated garnet porphyroblast, within a fine grained matrix, showing top-to-the north sense of shear.









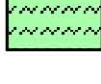

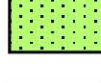
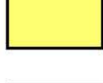



Figure e (Sample ED-23): Biotite fish showing top-to-the south sense of shear.

Figure f: Asymmetric quartzite showing top-to-the north sense of shear. (Note that this is a mesoscopic shear sense indicator) GPS: 05210E; 40871N)









TRANSECT 3 (C-C')

Explanations

| | | | |
|--|---------------------------------|---|-----------------------------------|
|  | Augen Gneiss (537-540 Ma) |  | Metabasic |
|  | Augen Gneiss (610 Ma and older) |  | Metaultramafic |
|  | Fine grained gneiss |  | Metaflysch with serpentine blocks |
|  | Marble |  | Marble (Jurassic-Cretaceous) |
|  | Quartz schist |  | Quaternary clastic rocks |
|  | Quartzite |  | Miocene continental clastic rocks |
|  | Phyllite |  | Marble |
|  | Undifferentiated schist | | |

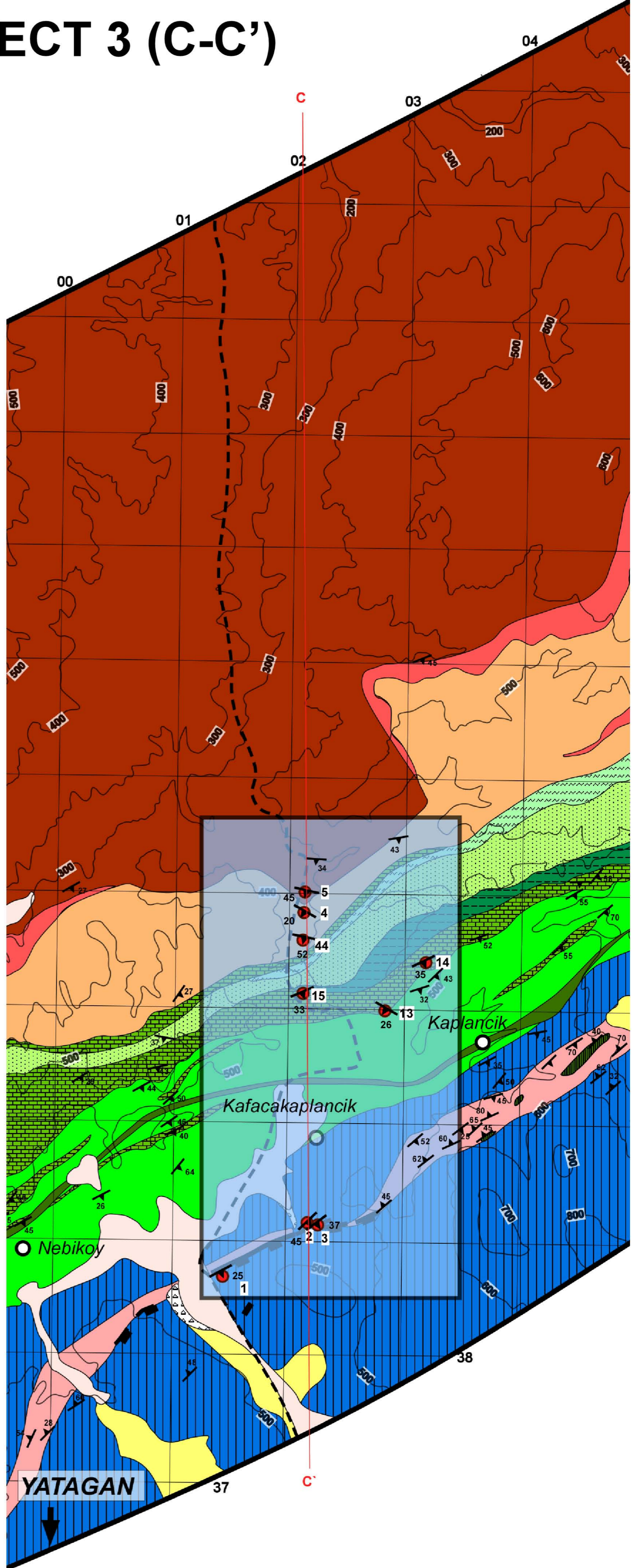
Symbols

| | | | |
|---|----------------|---|----------------------------|
|  | Foliation |  | Strike slip fault |
|  | Dip direction |  | Buried fault |
|  | Vertical fault |  | Sample number and location |

Scale

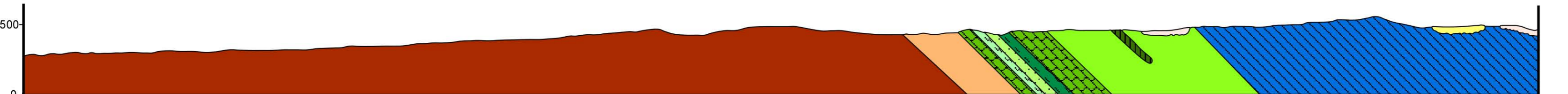
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Meters 1000 500 0 1000 2000 Meters



C (NNW)

C' (SSE)



Meters 1000 500 0

TRANSECT 4 (D-D')

Explanations

| | | | |
|--|---------------------------------|--|-----------------------------------|
| | Augen Gneiss (537-540 Ma) | | Metabasic |
| | Augen Gneiss (610 Ma and older) | | Metaultramafic |
| | Fine grained gneiss | | Metaflysch with serpentine blocks |
| | Marble | | Marble (Jurassic-Cretaceous) |
| | Quartz schist | | Quaternary clastic rocks |
| | Quartzite | | Miocene continental clastic rocks |
| | Phyllite | | Marble |
| | Undifferentiated schist | | |

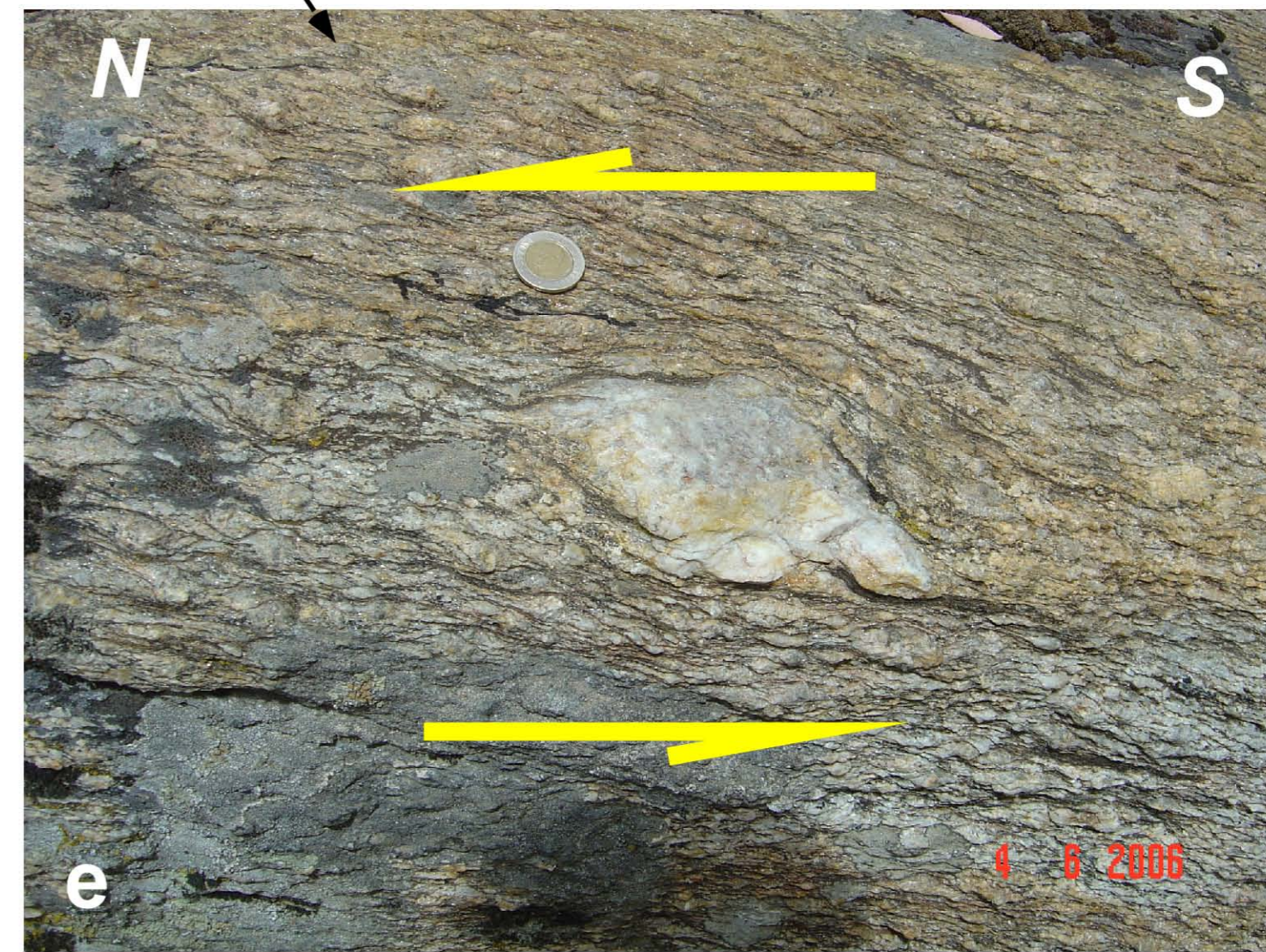
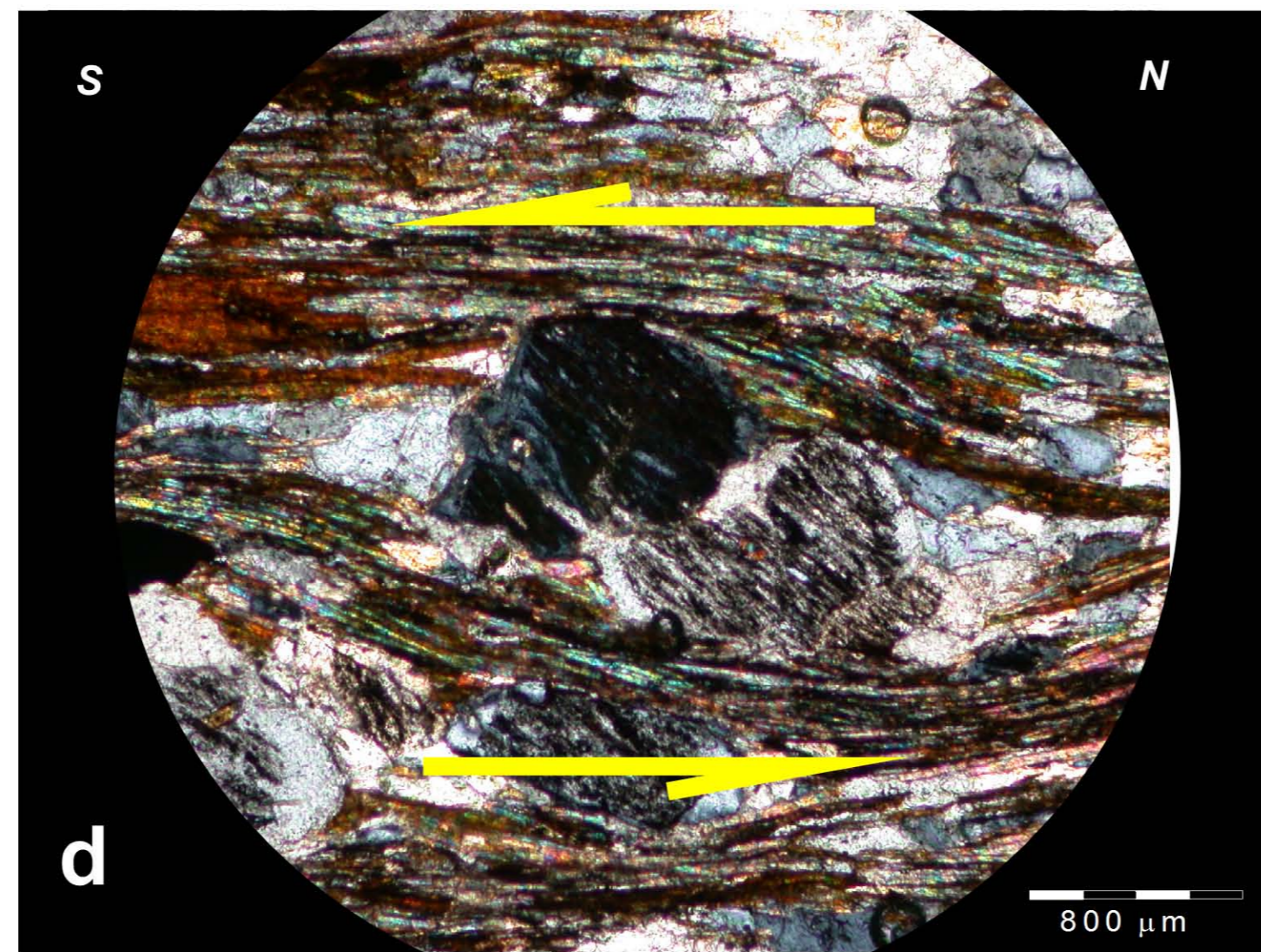
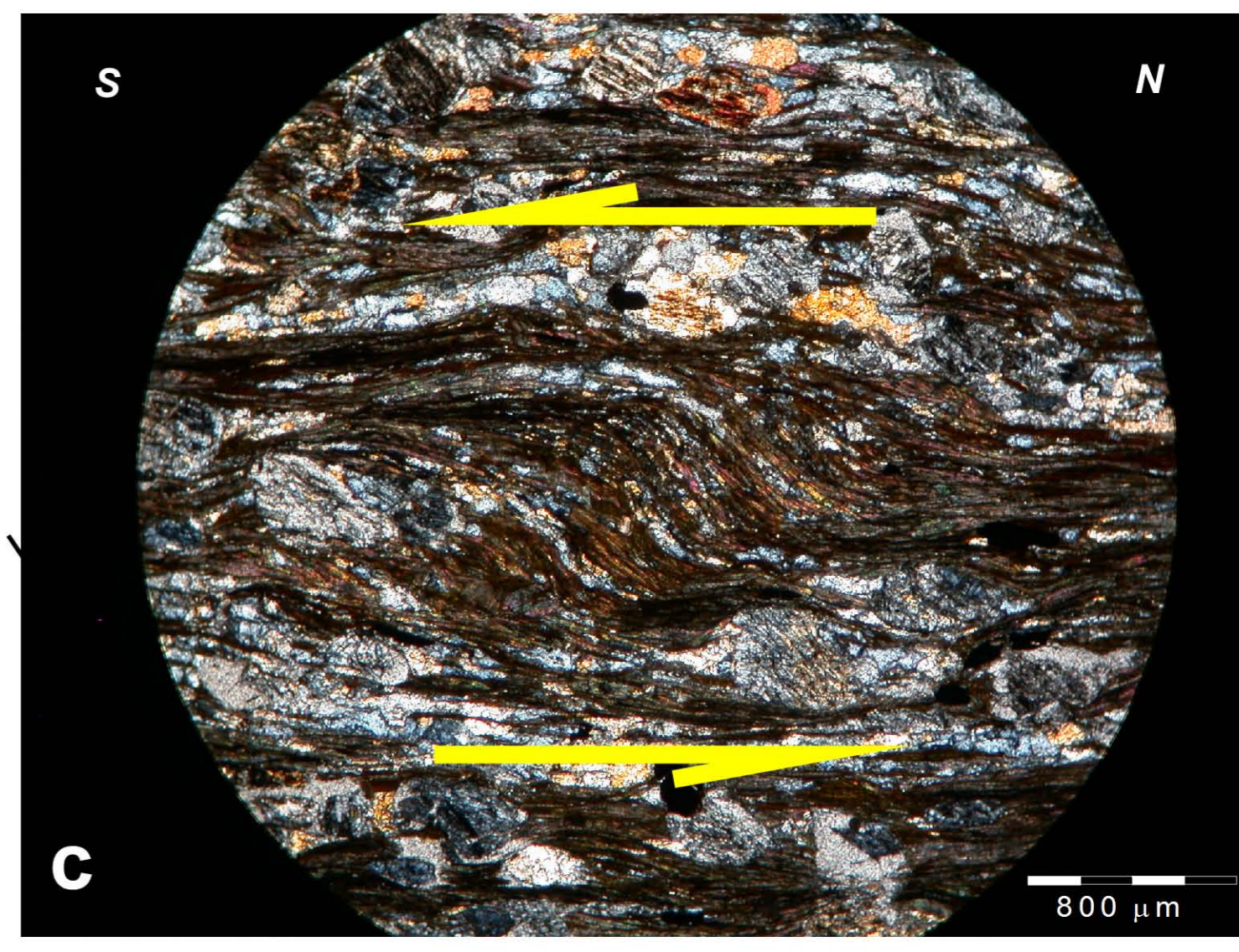
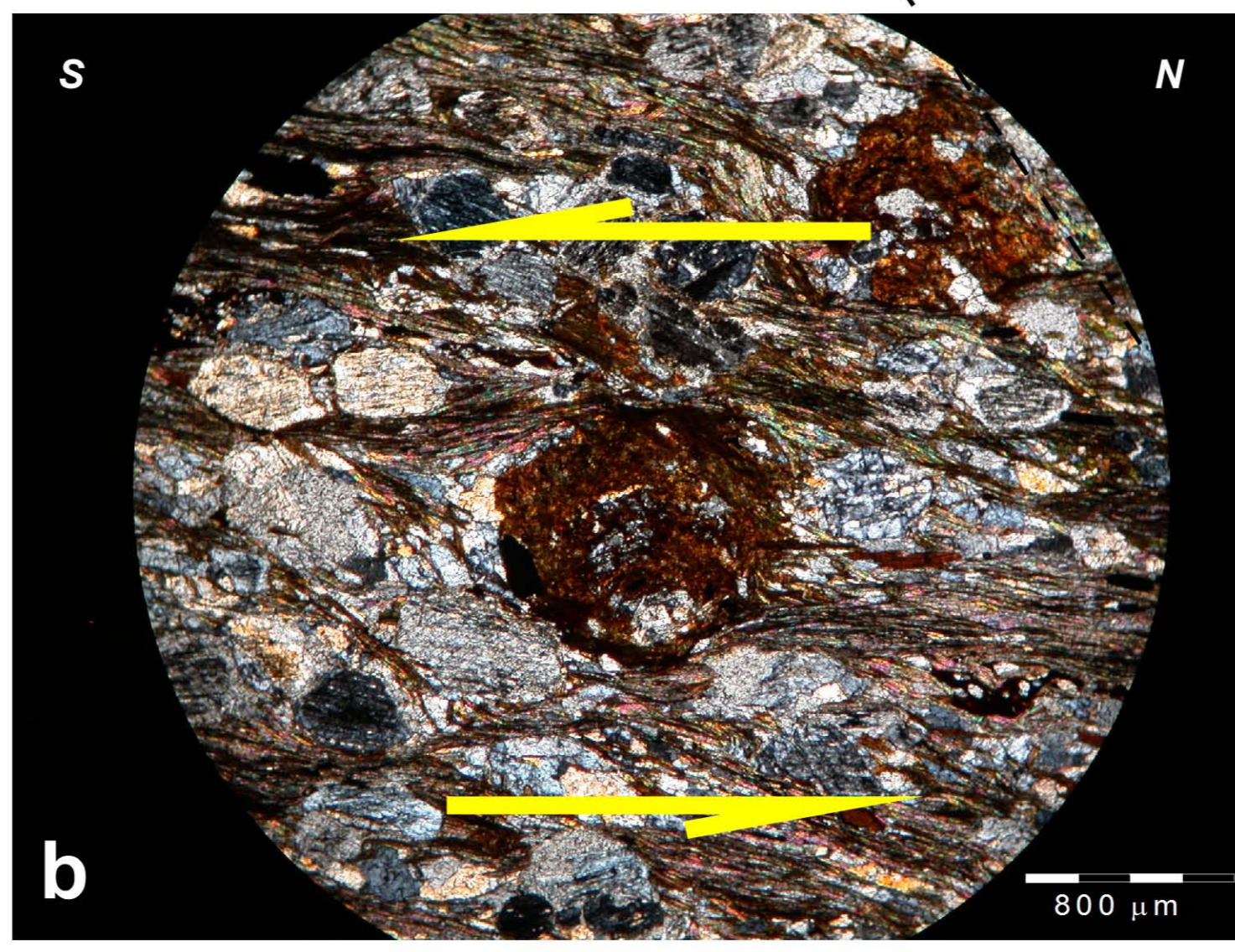
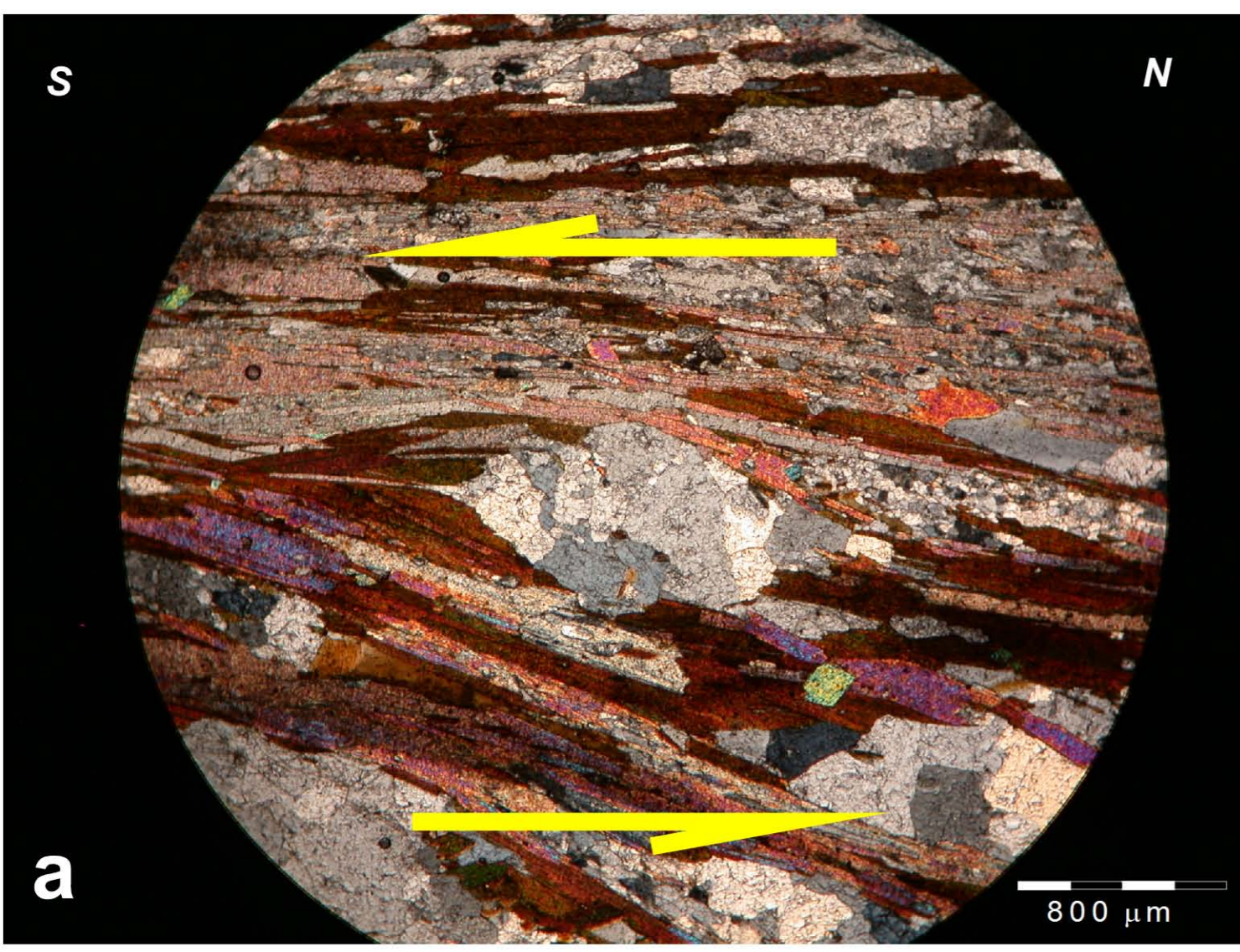
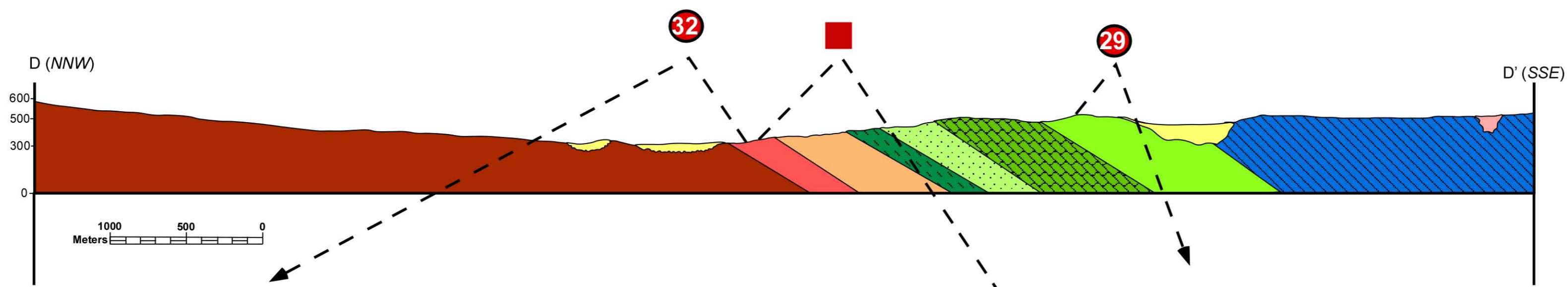
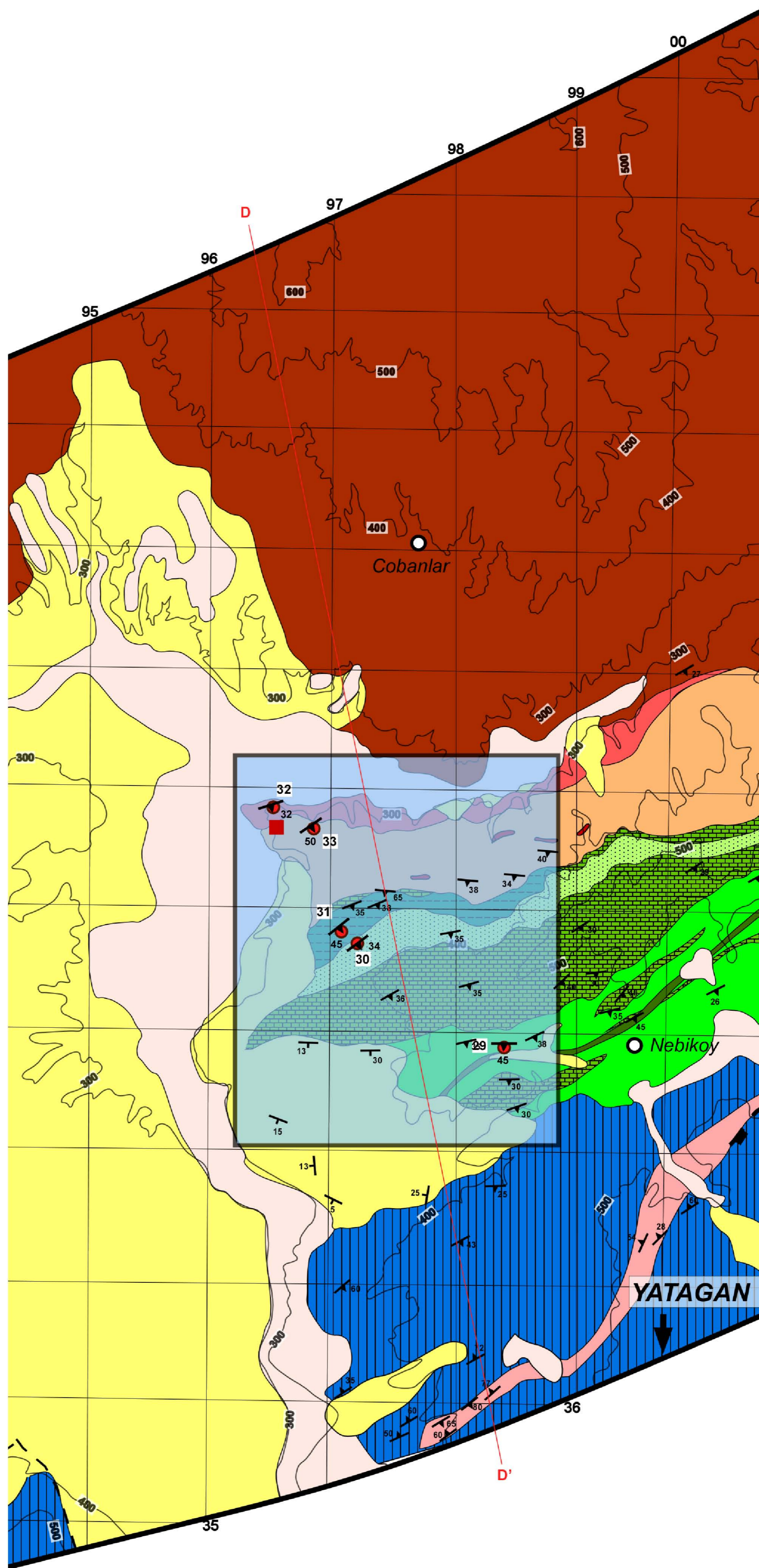
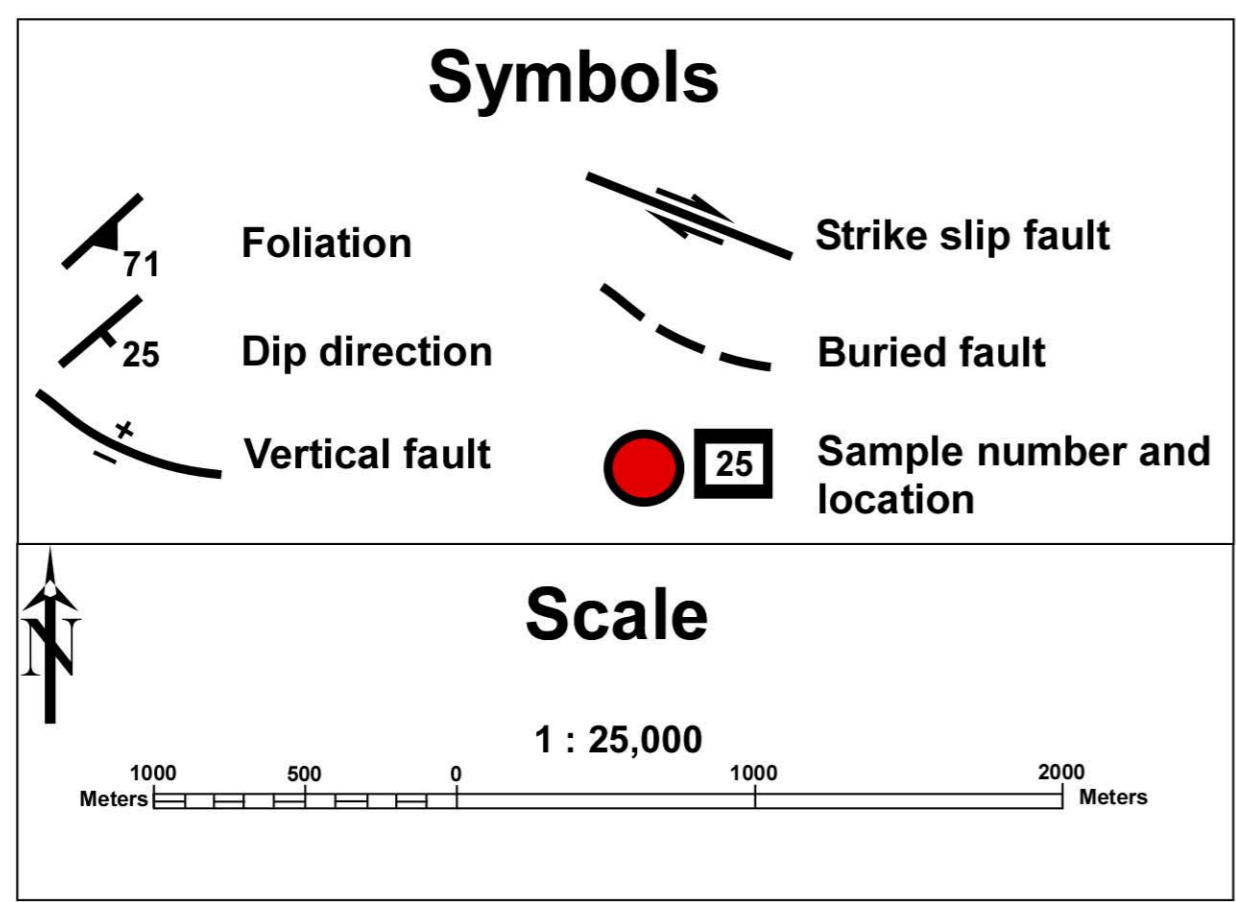


Figure a (Sample ED-32): Quartz mylonite showing top-to-the south sense of shear.

Figure b (Sample ED-29): Γ - type garnet porphyroblast showing top-to-the south sense of shear.


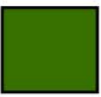


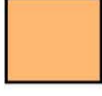
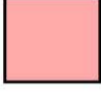
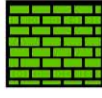



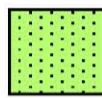
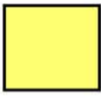
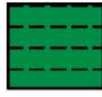
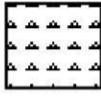
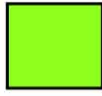
Figure c (Sample ED-29): Folded mica minerals showing top-to-the south sense of shear.

Figure d (Sample ED-29): Γ - type porphyroblast showing top-to-the south sense of shear.



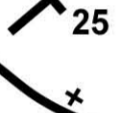



Figure e: Asymmetric quartzite showing top-to-the north sense of shear. GPS: 96380E; 40871N

TRANSECT 5 (E-E')

Explanations

| | | | |
|---|---------------------------------|---|-----------------------------------|
|  | Augen Gneiss (537-540 Ma) |  | Metabasic |
|  | Augen Gneiss (610 Ma and older) |  | Metaultramafic |
|  | Fine grained gneiss |  | Metaflysch with serpentine blocks |
|  | Marble |  | Marble (Jurassic-Cretaceous) |
|  | Quartz schist |  | Quaternary clastic rocks |
|  | Quartzite |  | Miocene continental clastic rocks |
|  | Phyllite |  | Marble |
|  | Undifferentiated schist | | |

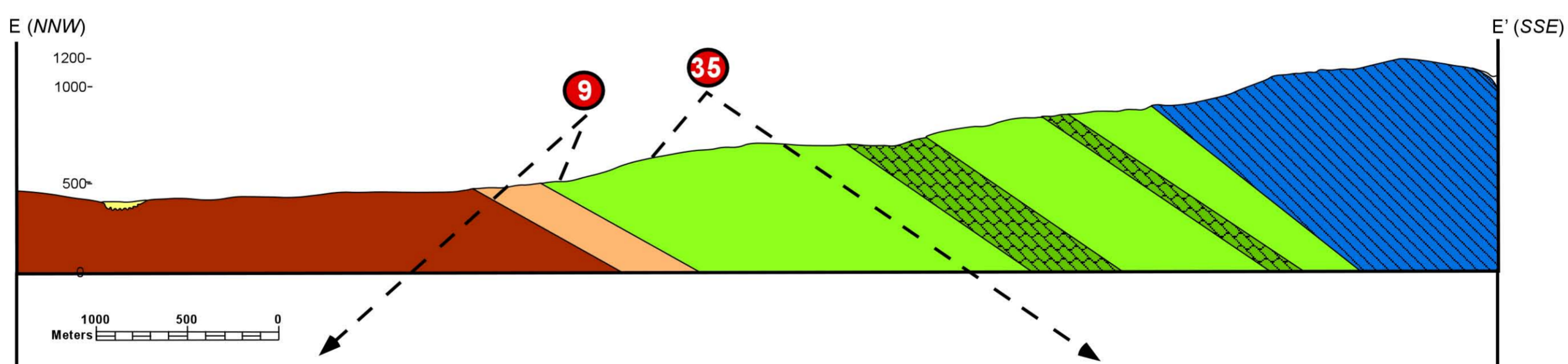
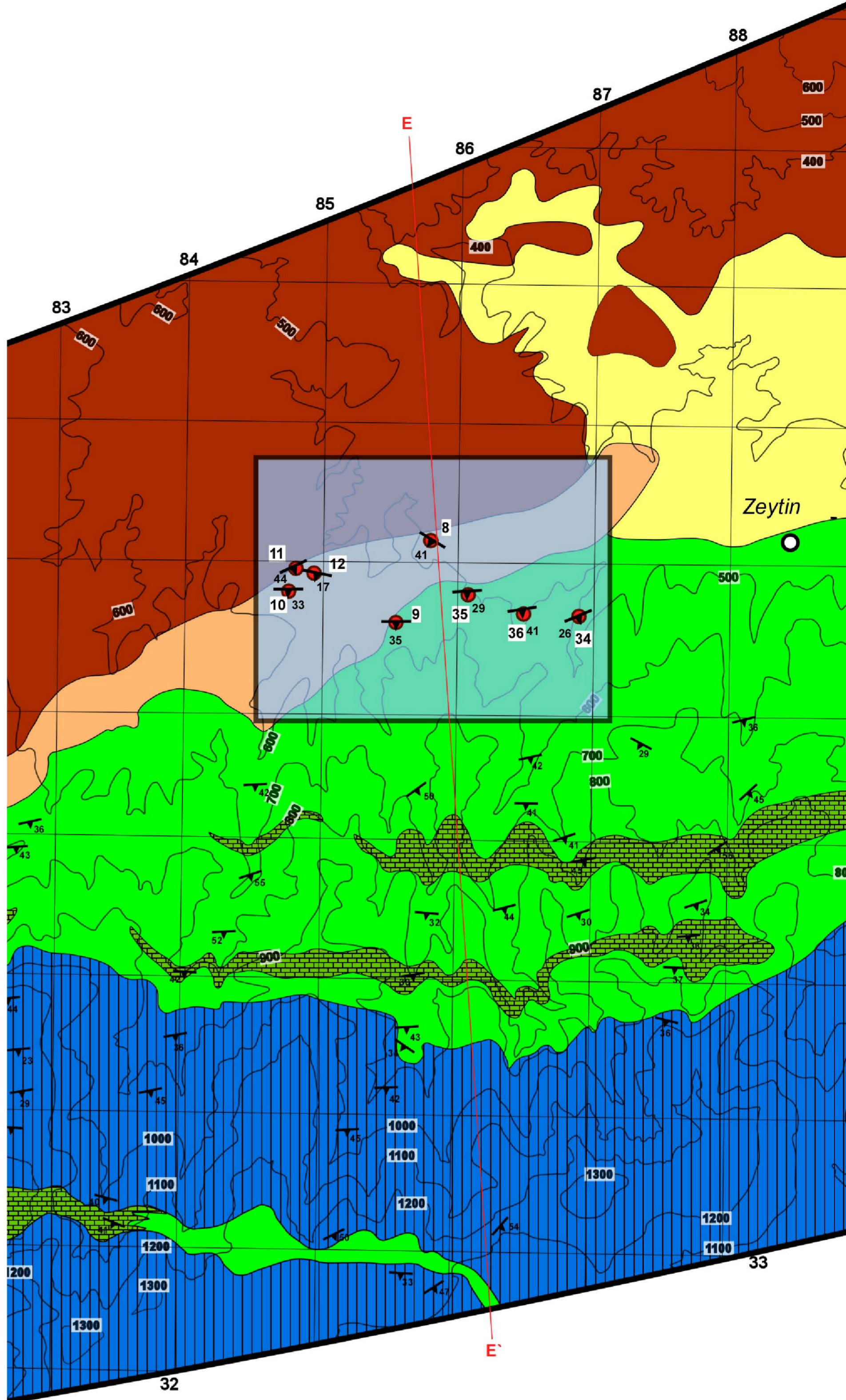
Symbols

| | | | |
|---|----------------|---|----------------------------|
|  | Foliation |  | Strike slip fault |
|  | Dip direction |  | Buried fault |
|  | Vertical fault |  | Sample number and location |

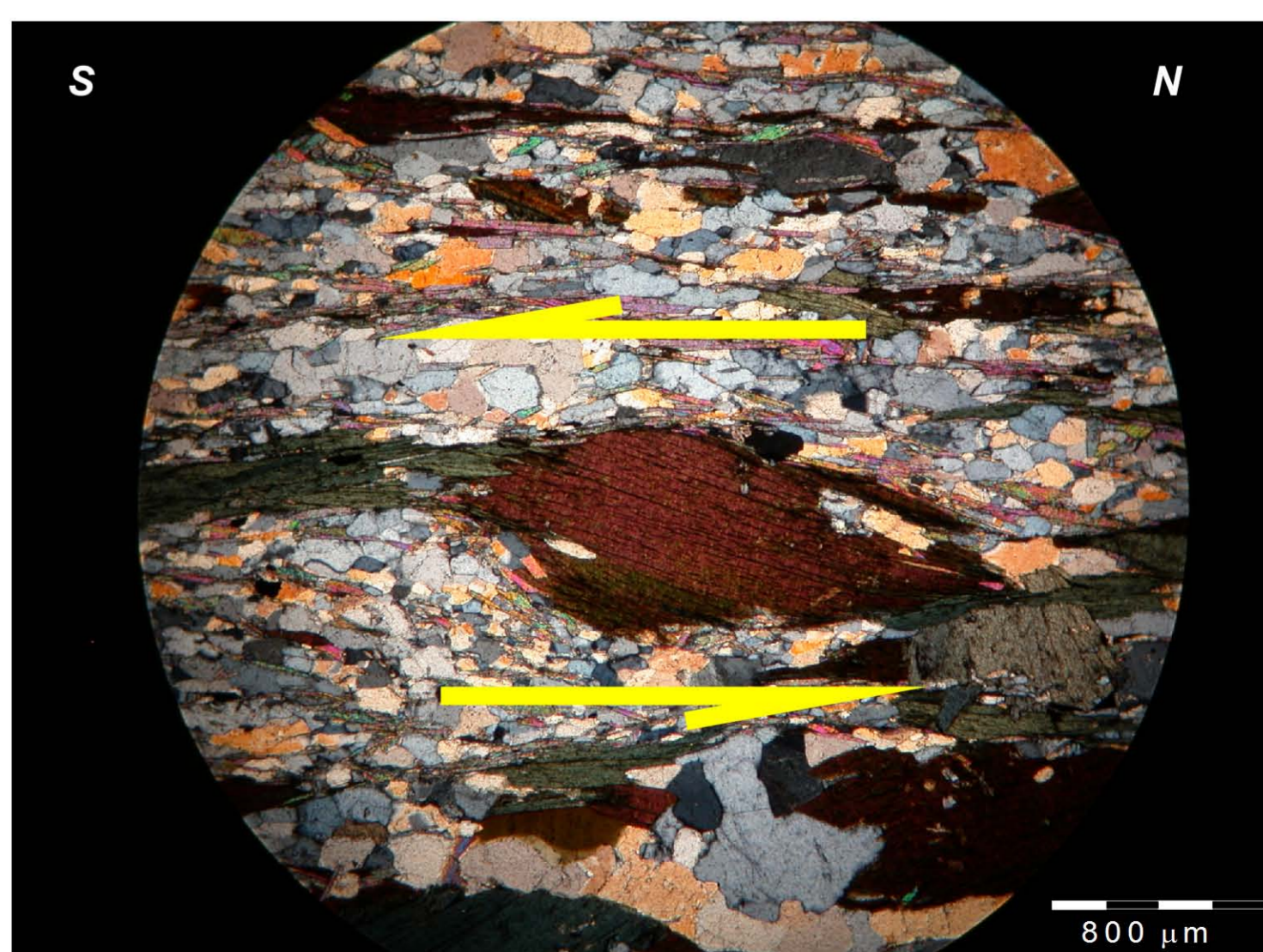
Scale

1 : 25,000

Meters 1000 500 0 1000 2000 Meters

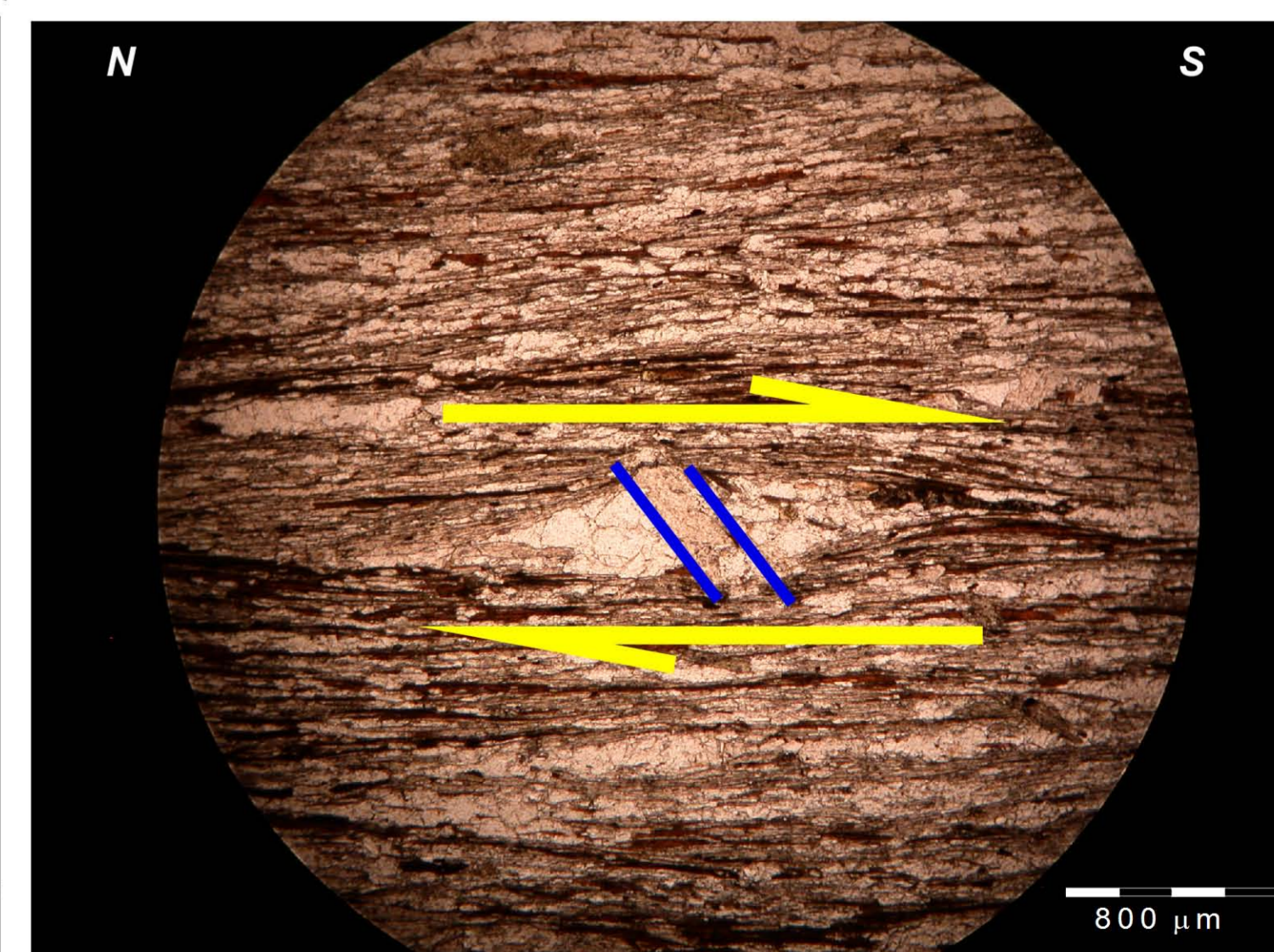
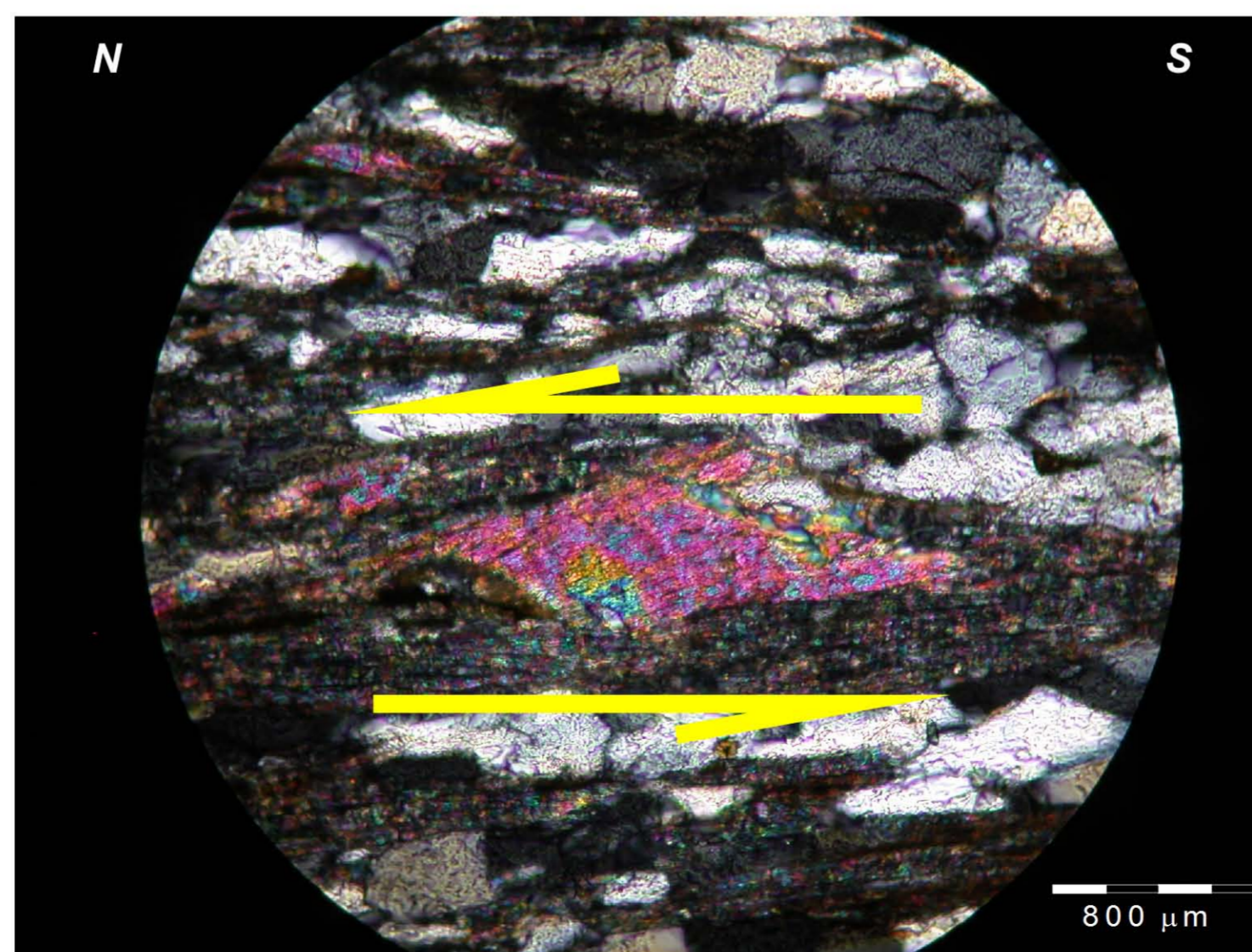
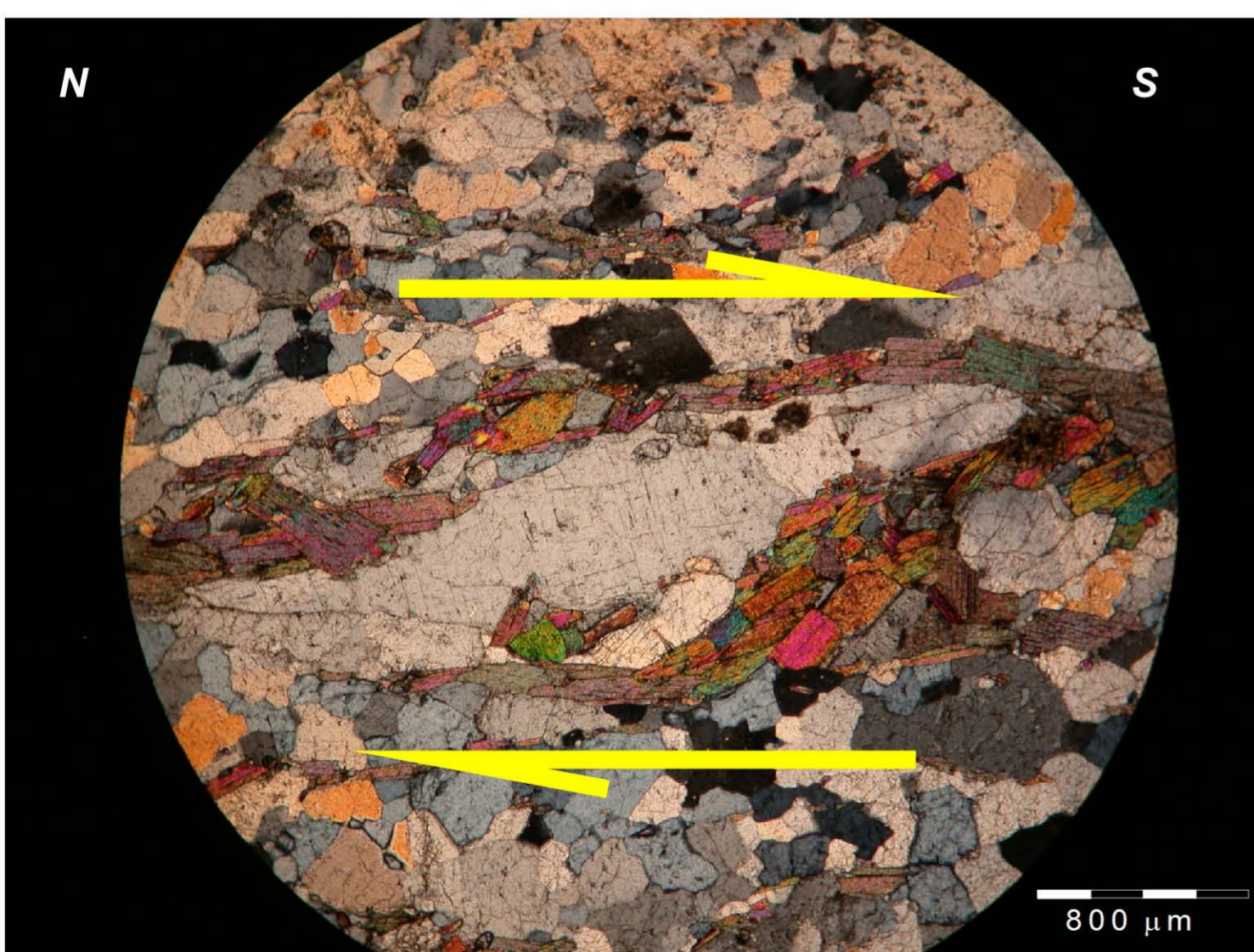
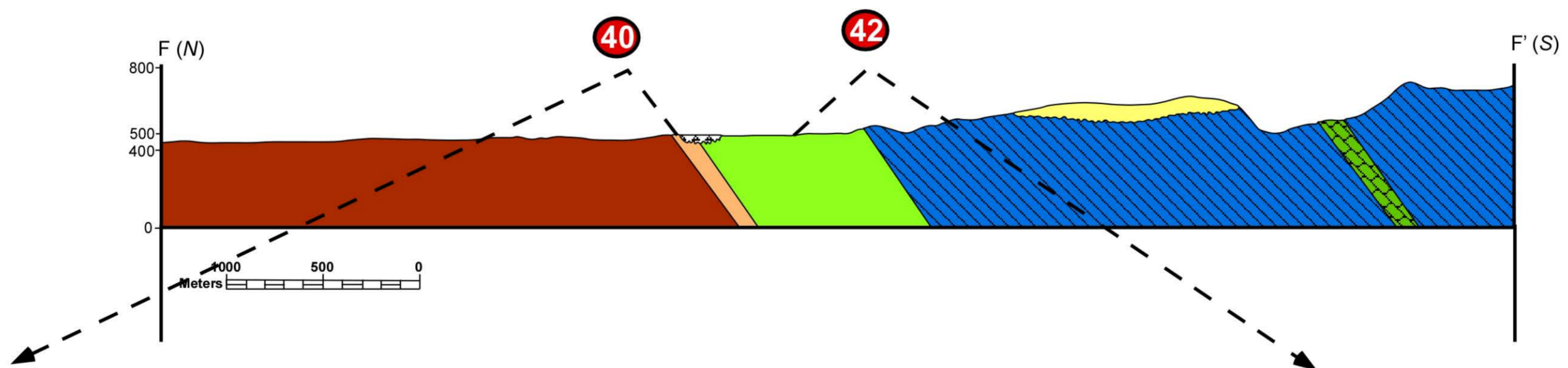
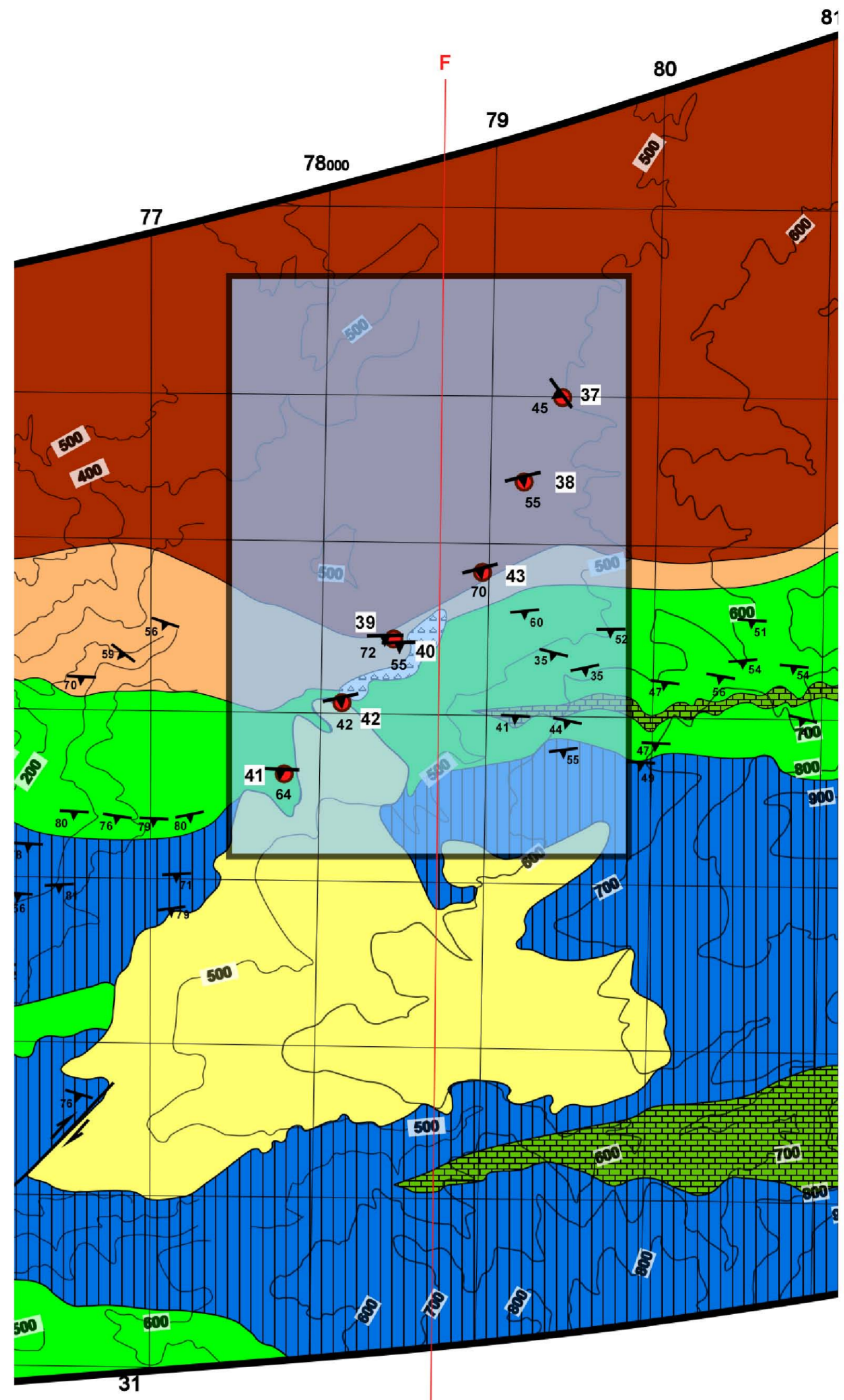
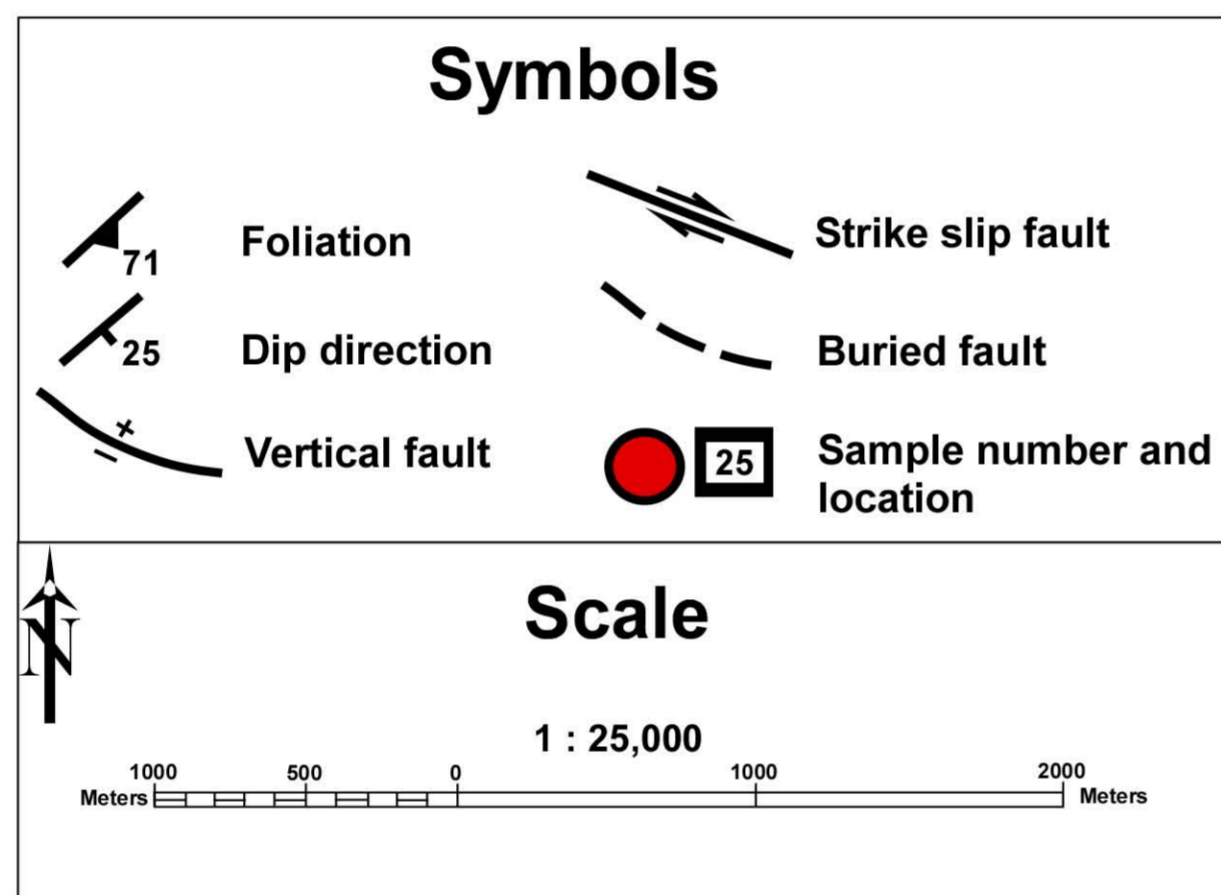
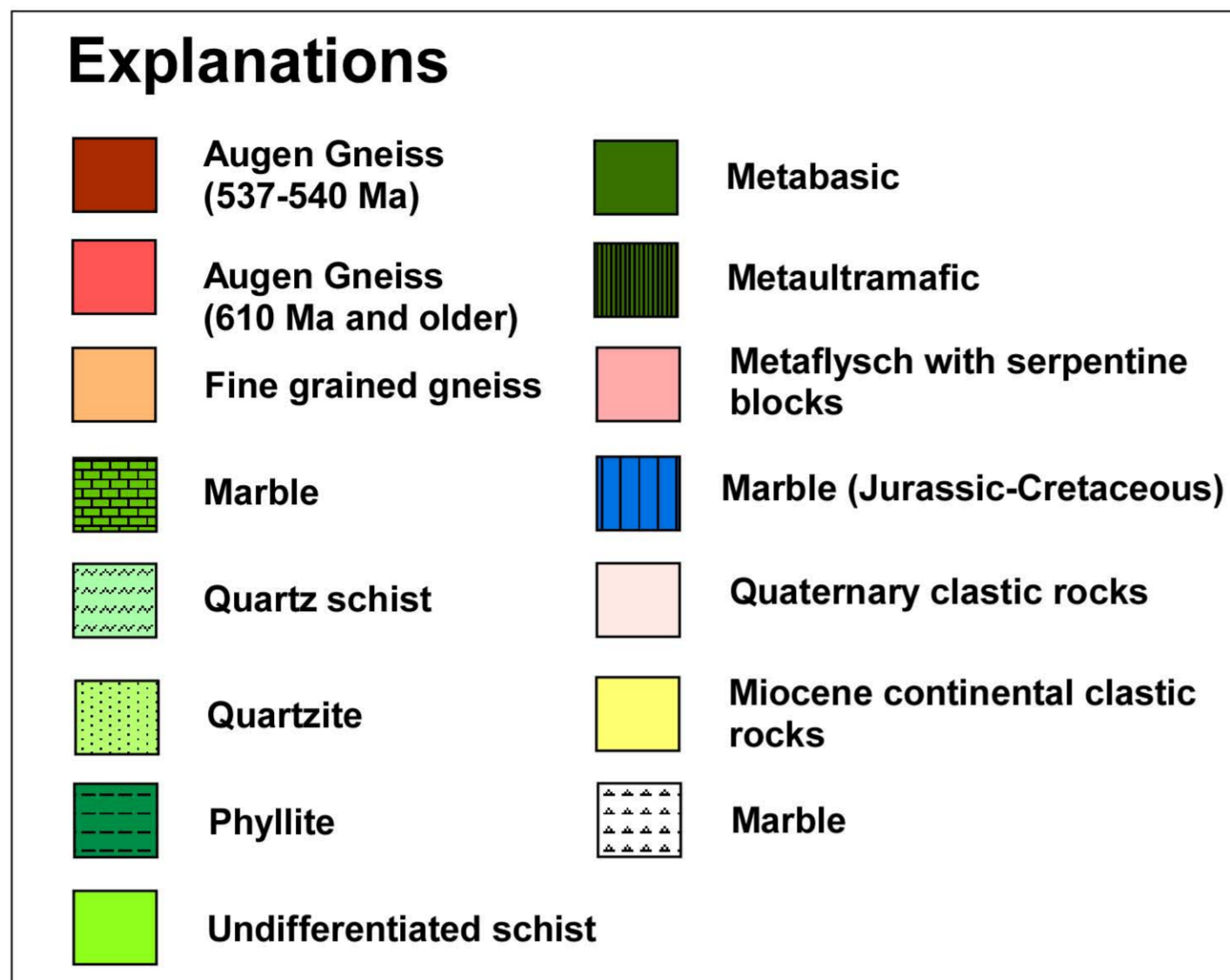


Sample ED-9: Rotated garnet porphyroblast showing top-to-the north sense of shear



Sample ED-35: Biotite fish surrounded by a fine grained matrix showing top-to-the south sense of shear

TRANSECT 6 (F-F')



Sample ED-40: Quartz mylonite showing top-to-the south sense of shear.

Sample ED-42: σ -type porphyroblast of feldspar showing top-to-the north sense of shear.

Sample ED-42: Fragmented quartz mylonite showing top-to-the south sense of shear. The top-to-the south shear sense has been overprinted by brittle deformation.

TRANSECT 7 (G-G')

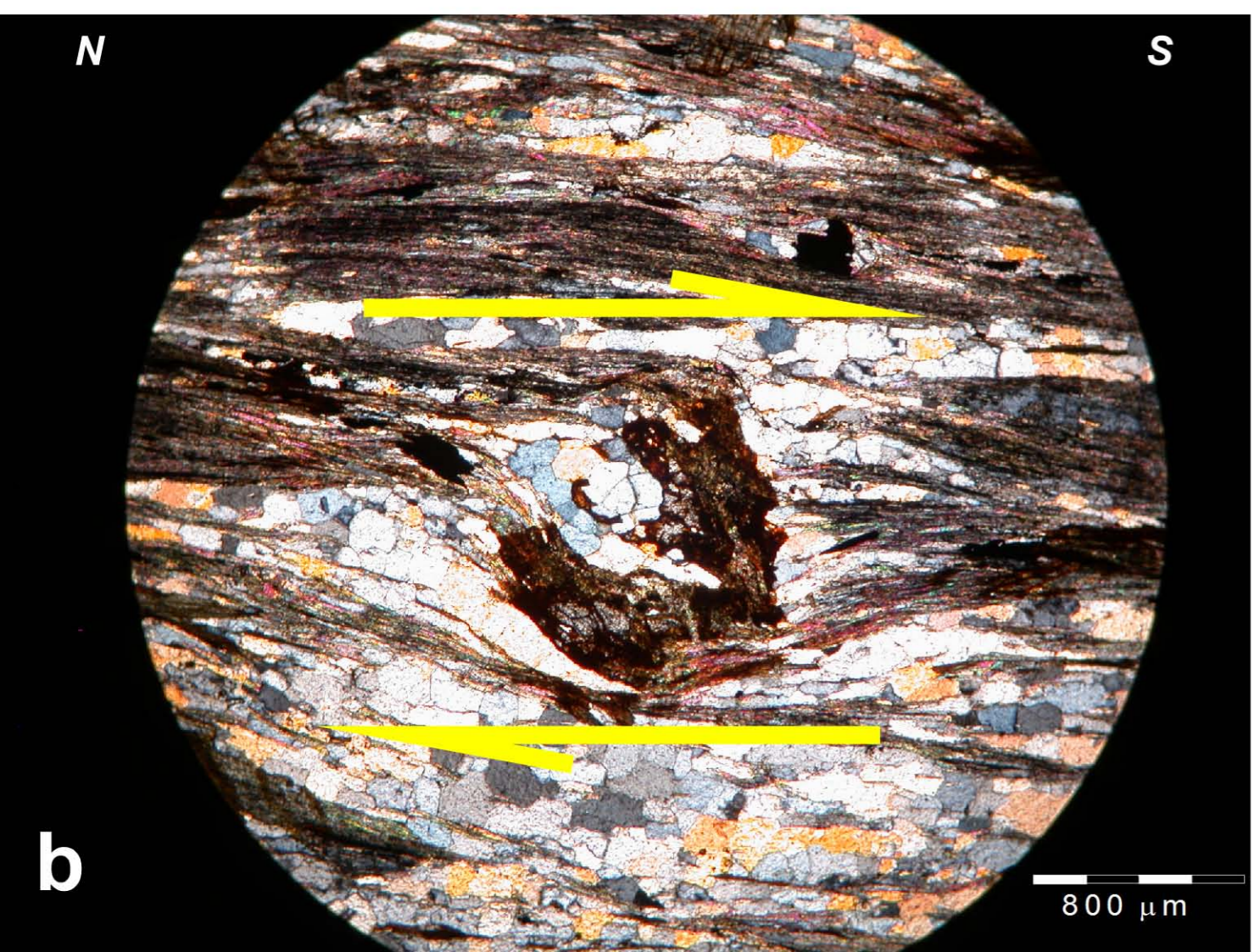
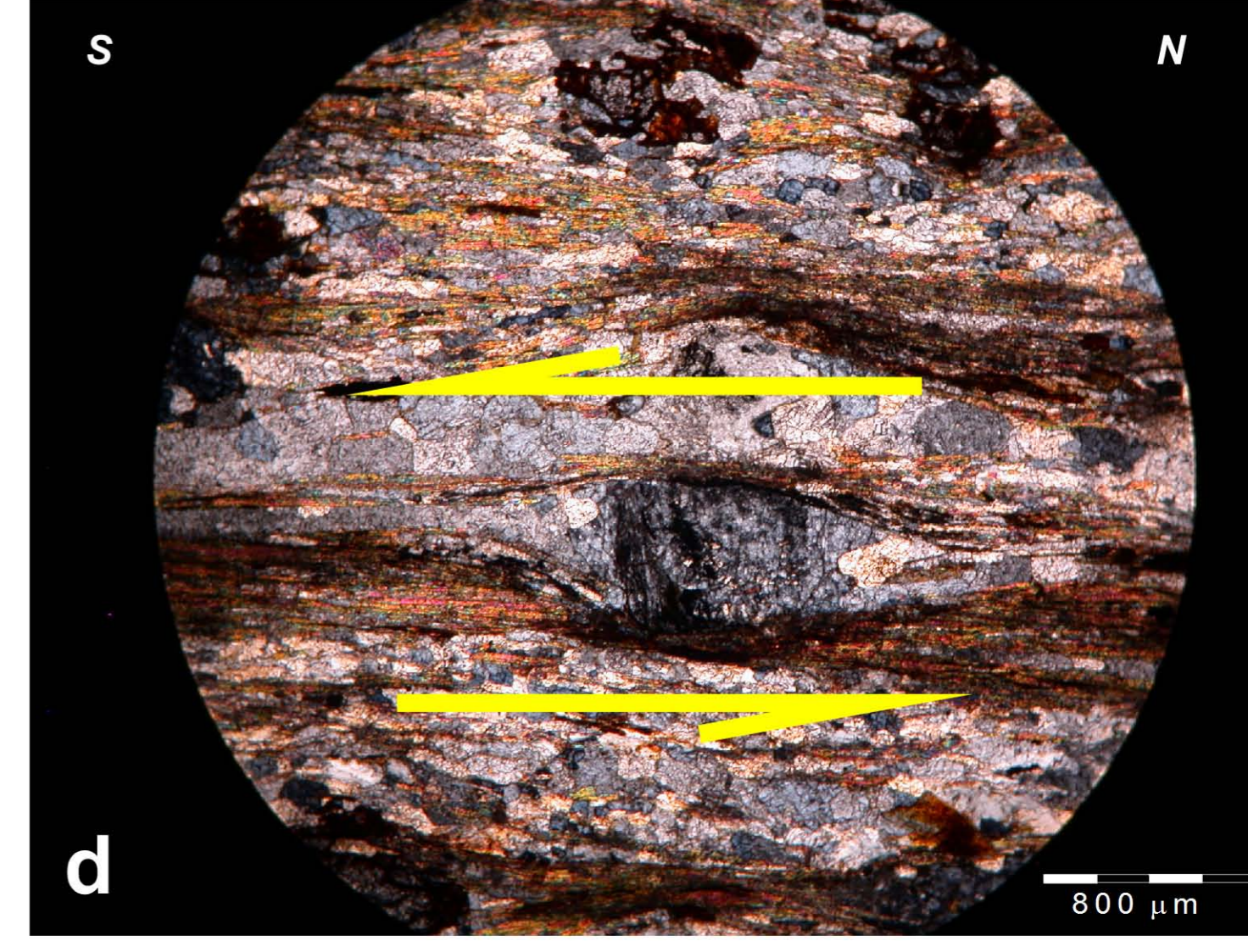
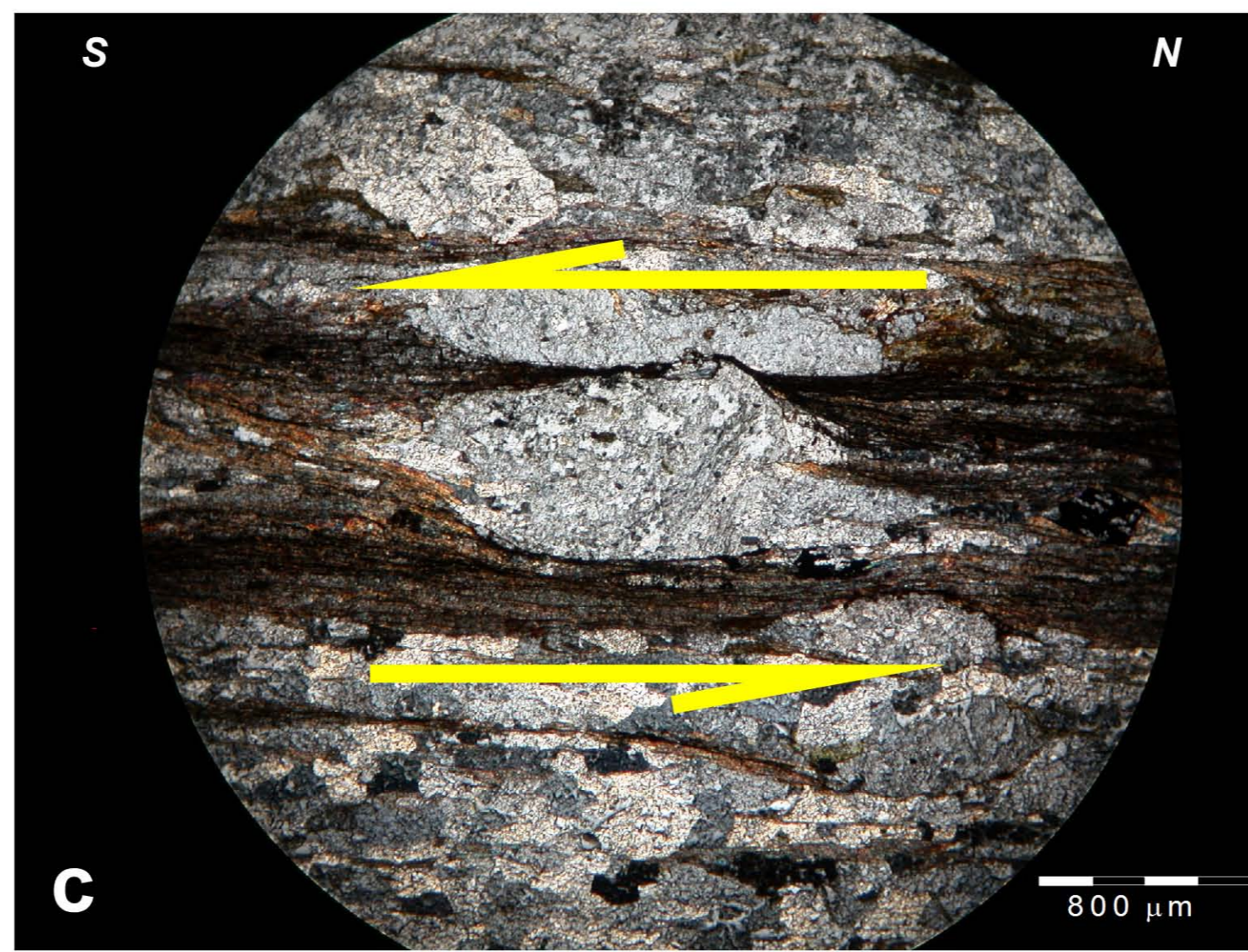
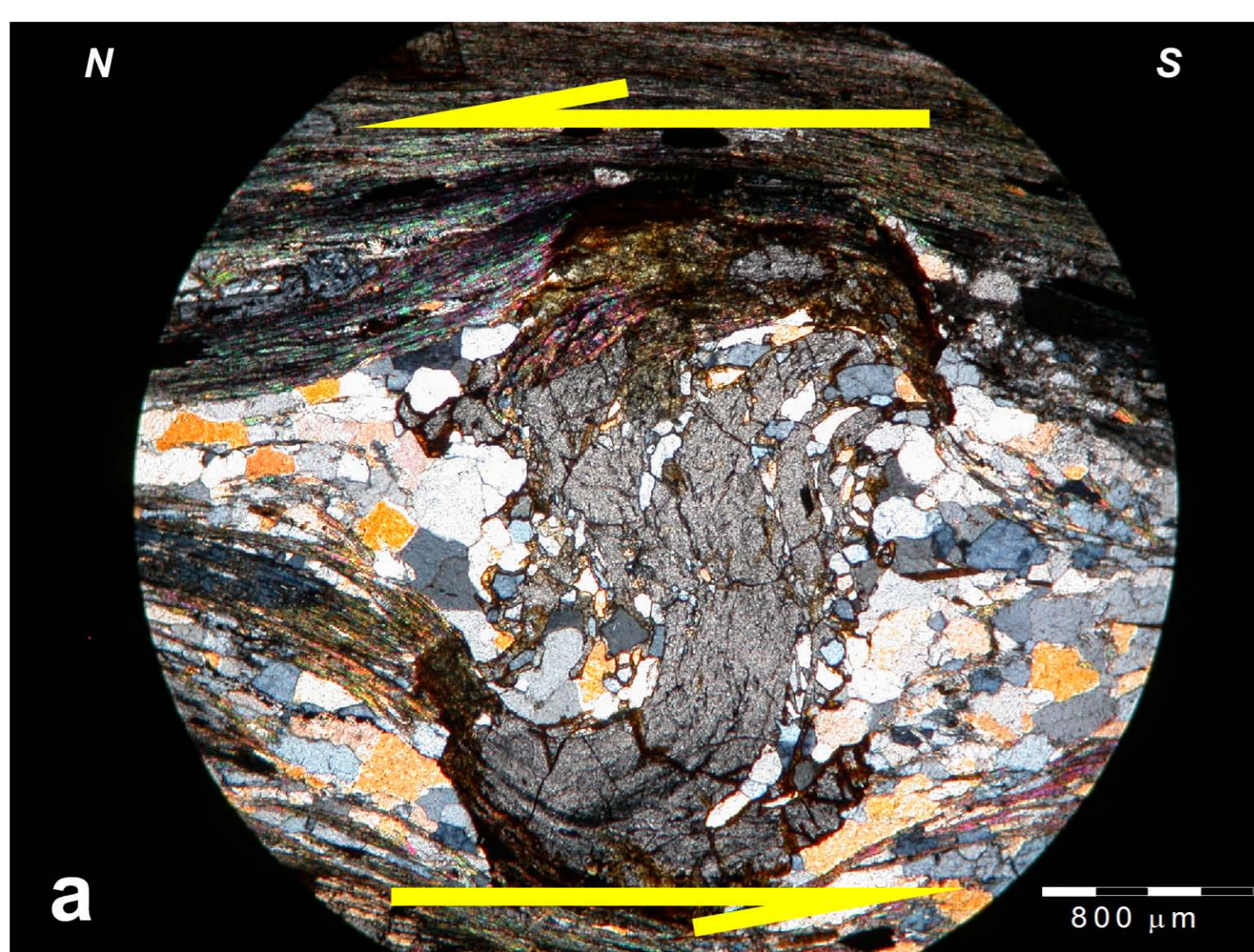
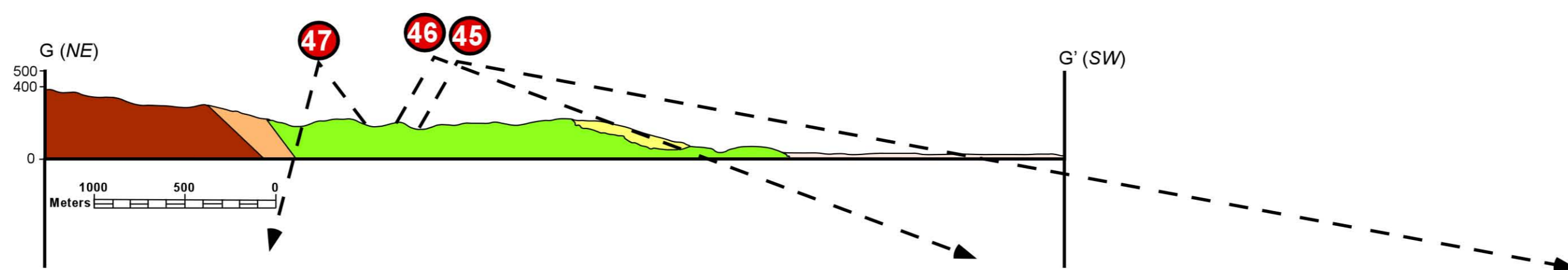
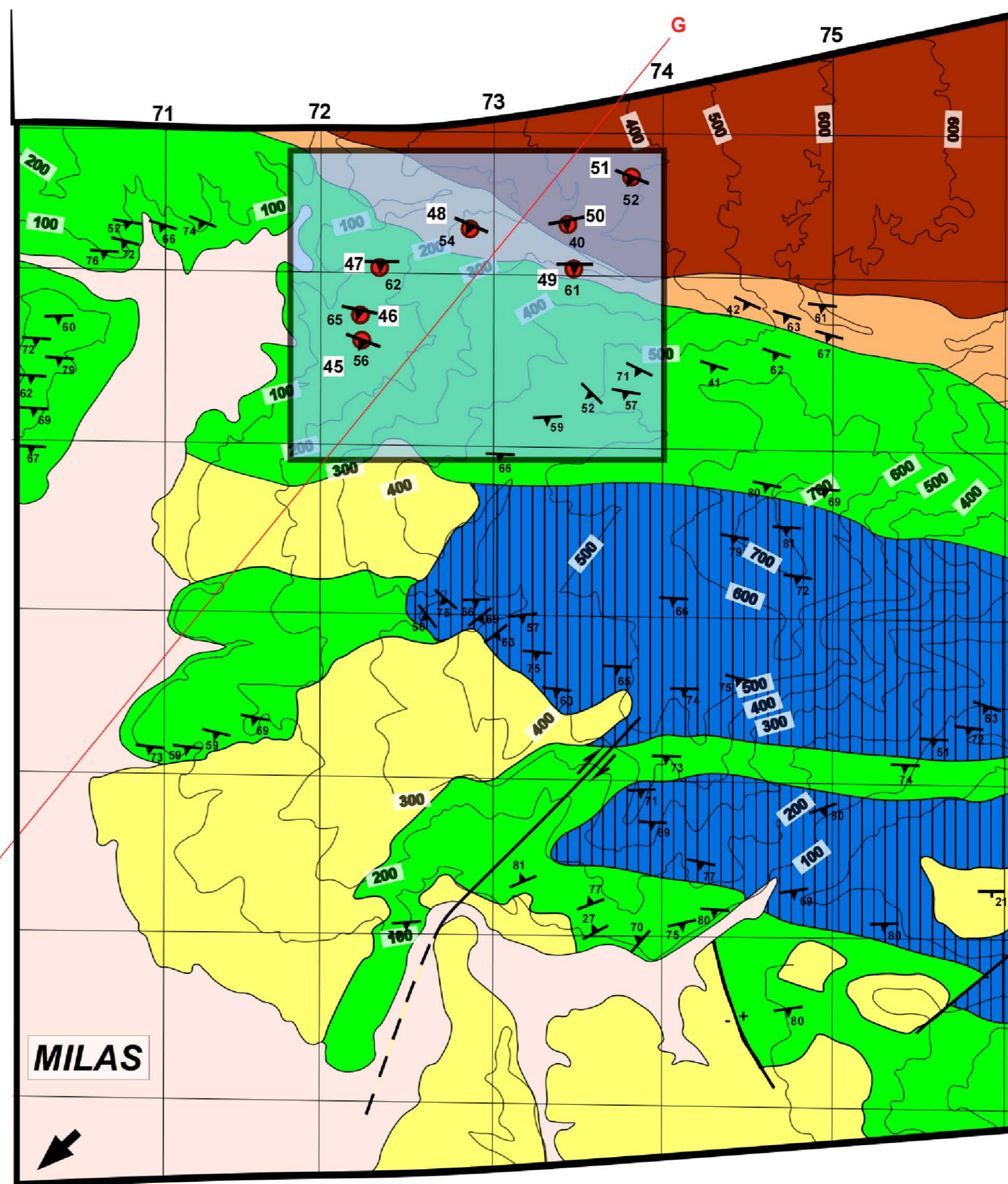
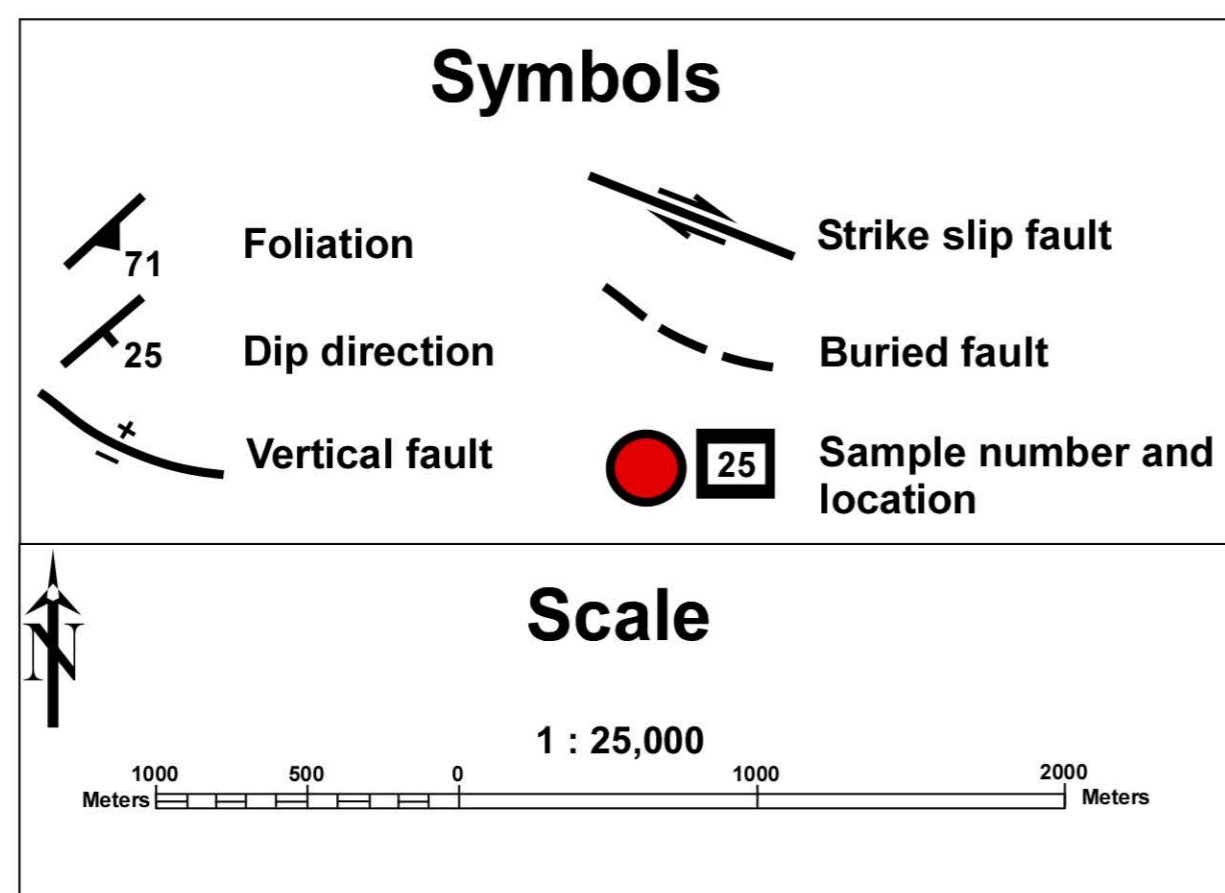
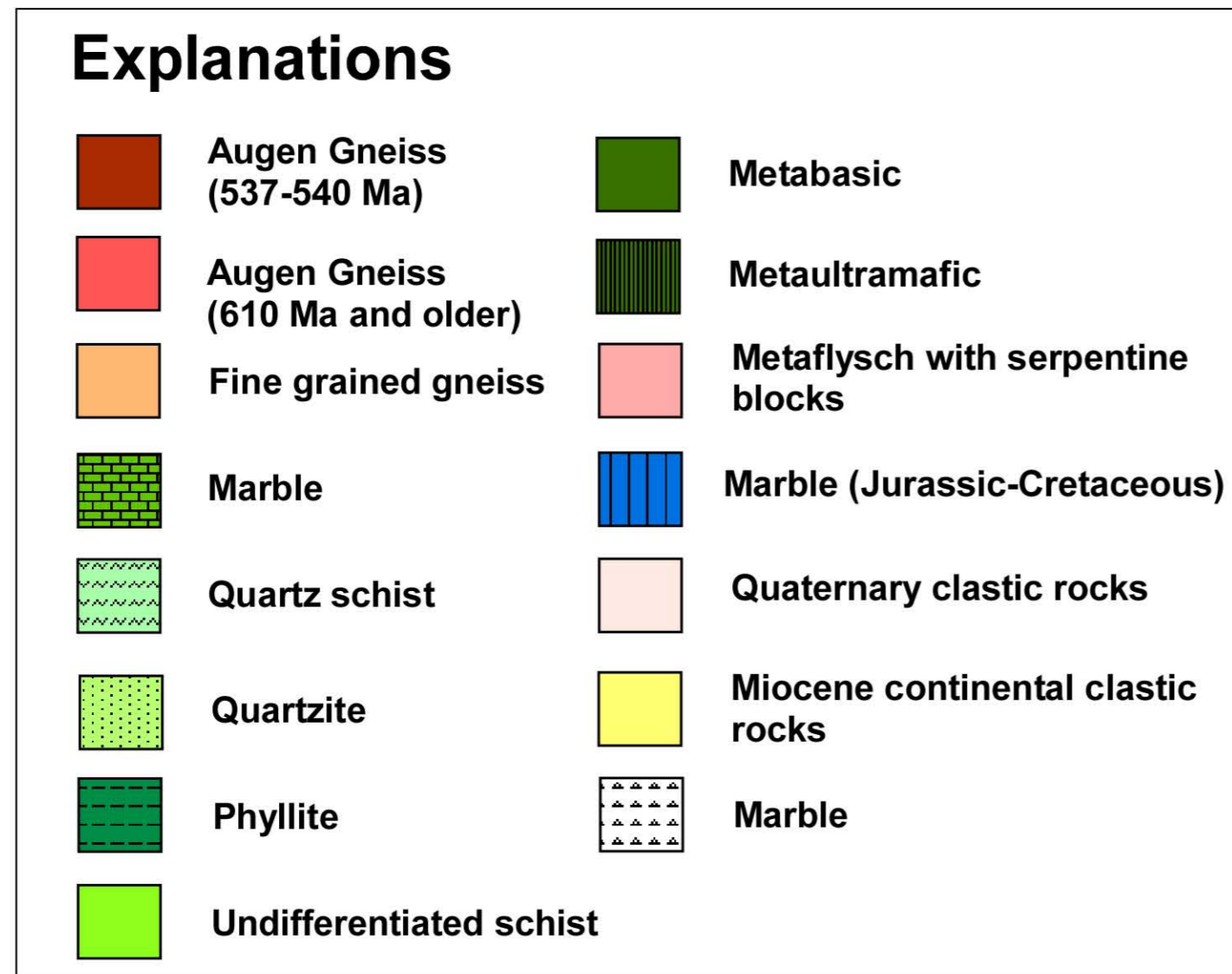


Figure a (Sample ED-47): Syn-kinematic rotated garnet porphyroblast showing top-to-the north sense of shear.

Figure b (Sample ED-47): δ - type garnet porphyroblast showing top-to-the south sense of shear.

Figure c (Sample ED-46): Γ - type feldspar porphyroblast showing top-to-the south sense of shear.

Figure d (Sample ED-45): Γ - type porphyroblast showing top-to-the south sense of shear.

VITA

Emre Diniz

Candidate for the Degree of

Master of Science

Thesis: STRUCTURAL EVOLUTION AND SIGNIFICANCE OF THE KAYABUKU SHEAR ZONE WITHIN A POST COLLISIONAL ALPINE METAMORPHIC CORE COMPLEX: MENDERES MASSIF, SW TURKEY

Major Field: Geology

Biographical:

Personal Data: Born in Ankara, TURKEY, on May 5, 1983, son of Faruk Riza Diniz and Sevda Diniz

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Experience: Geological Engineer Intern, Sureyyabey Dam Construction, Turkey, 2002; Teaching Assistant, School of Geology, Oklahoma State University, 2005-2007; Research Assistant, School of Geology, Oklahoma State University, 2005-2007.

Professional Memberships: Phi Kappa Phi, American Association of Petroleum Geologists (AAPG), Society of Exploration Geophysicists (SEG), Geological Society of America (GSA), American Geophysical Union (AGU).

Name: Emre Diniz

Date of Degree: May, 2007

Institution: Oklahoma State University

Location: Stillwater, Oklahoma

Title of Study: STRUCTURAL EVOLUTION OF THE KAYABUKU SHEAR ZONE,
SOUTHERN MENDERES MASSIF, WESTERN TURKEY

Pages in Study: 96

Candidate for the Degree of Master of Science

Major Field: Geology

Scope and Method of Study: This study is concerned with the geologic evolution of the Kayabuku (Selimiye) shear zone, Menderes Massif, Turkey. A geologic map between the towns of Milas and Yatagan was compiled from 1:25,000 scale previous geologic maps. 7 transects were made along the shear zone and 51 oriented rock samples were collected for microtectonic and petrographic analysis. Mesoscopic shear sense indicators were examined in the field.

Findings and Conclusions: The Kayabuku shear zone separates orthogneiss in its footwall from schist and marble in its hanging wall. The first developed ductile shearing is top-to-the north, overprinted by top-to-the south ductile shearing which, in turn, is overprinted by top-to-the south brittle deformation. The hanging wall of the shear zone is locally brittlely deformed by a south-dipping normal fault zone, discontinuously exposed between the schist and marble units. Therefore, the shear zone must have been subjected to at least two deformation phases; D₁: top-to-the north and D₂: top-to-the south.

ADVISER'S APPROVAL: _____ Dr. Ibrahim Cemen