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Episodic, two-stage Neogene extension and short-term intervening compression in western Anatolia: field evidence from the Kiraz basin and Bozdağ Horst

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Abstract

Western Anatolia (Turkey) is a region of widespread active N-S continental extension that forms the eastern part of the Aegean extensional province. The extension in the region is expressed by two distinct/different structural styles, separated by a short-term gap: (1) rapid exhumation of metamorphic core complexes along presently low-angle ductile-brittle normal faults commenced by the latest Oligocene-Early Miocene period, and; (2) late stretching of crust and, consequent graben evolution along Plio-Quaternary high-angle normal faults, cross-cutting the pre-existing low angle normal faults. However, current understanding of the processes (tectonic quiescence vs N-S continental compression) operating during the short-time interval is incomplete. This paper therefore reports the results of recent field mapping and structural analysis from the NE of Küçük Menderes Graben—Kiraz Basin—that shed lights on the processes operating during this short-time interval. The data includes the thrusting of metamorphic rocks of the Menderes Massif over the Mio-Pliocene sediments along WNW-ESE-trending high-angle reverse fault and the development of compressional fabrics in the metamorphic rocks of the Menderes Massif. There, the metamorphic rocks display evidence for four distinct phases of deformation: (1) south-facing top-N ductile fabrics developed at relatively high-grade metamorphic conditions, possibly during the Eocene main Menderes metamorphism (amphibolite facies) associated with top-N thrust tectonics (D_1); (2) top-S and top-N ductile gentle-moderatley south-dipping extensional fabrics formed at relatively lower-grade metamorphic (possibly greenschist facies) conditions associated with the exhumation of Menderes Massif along presently low-angle normal fault plane that accompanied the first phase of extension (D_2); (3) moderately north-dipping top-S ductile-brittle fabrics, present configuration of which suggest a thrust-related compression (D_3); and (4) south-facing approximately E-W-trending brittle high-angle normal faults (D_4) that form the youngest structures in the region. It is interpreted that D_4 faults are time equivalent of graben-bounding major high-angle normal faults and they correspond to the second phase of extension in western Anatolia. The presence of thrust-related D_3 compressional fabrics suggests N-S compression during the time interval between the two phases of extension (D_2 and D_4). The results of the present study therefore support the episodic, two-stage extension model in western Anatolia and confirm that a short-time, intervening N-S compression separated the two distinct phases.

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Keywords: Continental extension; Detachment faults; Normal faulting; Thrust faulting; Exhumation; Menderes Massif; Western Anatolia

1. Introduction

Western Anatolia is the eastern continuation of Aegean extensional province on land and forms one of the best examples of natural laboratory to study active composite continental extension in the world. The region has been experiencing approximately N-S-directed late orogenic continental lithospheric extension since, at least, latest Oligocene-Early Miocene time, following crustal thickening across the closure of the northern Neotethyan ocean. The occurrence and epicentre distribution of earthquakes clearly shows that the extension is still active and widespread in the

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region. The rate of extension is rapid and claims range between > 60 mm a^{-1} (maybe as high as 110 mm a^{-1} [1]) and ~ 3-4 mm a^{-1} (e.g., [2-9]). The active subduction of the African plate beneath the southern margin of Anatolian plate along Mediterrenean-Cyprus subduction zone, and the slips along the dextral North Anatolian and sinistral East Anatolian fault systems effects current tectonics of the region (Fig. 1). The most prominent geomorphologic expression of N-S crustal extension in western Anatolia forms multi-directed, dominantly E-W-trending grabens (Fig. 1).

Although there is growing number of research in the region over the last three decades, the origin, cause and timing of crustal extension in western Anatolia is still controversial. The first approach to the origin of extension in the Aegean Region argues a typical back-arc extension model caused by inception of subduction rollback process and consequent southwestward migration of the southern Aegean Arc (*Back-arc spreading model*: [1, 10-16]). However, there is no consensus on the initiation age of subduction rollback process and the claims range from 60 Ma and 5 Ma. In addition, recent structural and isotopic evidence from extension-related metamorphism and magmatism both in the Aegean and western Anatolia confirms the role of southward migration of the southern Aegean Arc as the cause of Miocene phase of continental extension (e.g., [17-19] and references therein). Later, the extension in western Anatolia is attributed to the westward extrusion of the Anatolian block in response to the initiation of dextral motion along the North Anatolian Fault System (*Tectonic escape model*: [20-25]). This model is based on the age of extension-related sediments exposed on the shoulders of major grabens (e.g., Büyük Menderes and Gediz grabens). Latter, it is clearly documented that the age of these sediments is, based on biostratigraphic and isotopic dates, much older than it is thought (~ 20 Ma: Early Miocene). Accordingly, it is argued that the extension commenced much earlier (Early Miocene) as a result of spreading and thinning of overthickened crust immediately after the latest Paleogene collision across Neotethys [26, 27], following *orogenic collapse model* of Dewey [28]. This is inline with the recent studies where it is documented that the initiation age of dextral motion along the North Anatolian Fault System is much younger than previous thought and is latest Miocene and/or Pliocene (~ 5 Ma or ~ 7 Ma: e.g., [2, 29-37] and references therein). The last approach highlights the multistage nature of crustal extension in western Anatolia and considers the combined effect of two or more of the above mechanisms. The model argues for an *episodic, two-stage graben model* where the modern phase of Plio-Quaternary extension was preceded by an earlier phase during the Early-Middle Miocene orogenic collapse and/or back-arc extension [33, 36, 38-49]; these phases being separated by an interval of N-S crustal shortening during the Late Serravalian-late Early Pliocene times [38]. The later phase is related to the westward escape of the Anatolian block along with the initiation of the North Anatolian and East Anatolian fault systems during the latest Miocene and/or Pliocene. On the other hand, there are claims that the recent extension in the Aegean Sea and western Anatolia is dominated by mechanics of a continuous medium responding to contrasts in its gravitational potential energy rather than rigid plates [50]. More recently, the extension is ascribed to velocity differences between the overriding plates (Aegean and Anatolian plates) on African Plate [51, 52]. We believe that the tectonics of western Anatolia is more complex than it is envisaged and different causes described above are responsible for the extension and there are spatial and temporal interchanges between them.

It is now agreed that the Neogene continental extension in the western Anatolia is expressed by two distinct/different structural styles—core-complex vs rift modes: **(i)** the rapid exhumation of deep burial metamorphic rocks and associated granites of the Menderes and Kazdağ massifs along presently low-angle first ductile- then brittle-normal faults (detachment faults) related to orogenic collapse and/or back-arc extension commenced by the latest Oligocene-Early Miocene period (Menderes Massif: e.g., [36, 38, 39, 40, 42, 43, 53-81] and Kazdağ Massif: e.g., [19, 82]) and **(ii)** late stretching of crust and, consequent multi directed graben evolution along Plio-Quaternary high-angle normal faults (modern phase of extension) cross-cutting the presently low angle normal faults (e.g., [36, 38-49, 70, 71, 78, 83-98]). The Menderes Massif is a typical metamorphic core complex and comprises several sub-core complexes, each of which was exhumed at different times during the course of extension. It is geographically divided into three sub-massifs along active Gediz and Büyük Menderes grabens as northern, central and southern, respectively (Fig. 1). The low-angle vs high angle geometries for the origin of presently low-angle normal faults of the Menderes core complex form have been suggested by various scientists (e.g., [39, 40, 57, 61, 65, 78, 87, 97] and references therein).

2. The problem

Despite of this consensus over the two distinct styles of crustal extension in western Anatolia, it was highly debated if they represent a single continuous extensional tectonic regime from latest Oligocene-Early Miocene to present times, or they represent two different events, separated by a hiatus (e.g., [36, 38-49, 70, 71, 78, 84, 94-96, 98] and references therein). More recently, Bozkurt & Sözbilir [78] presented undoubtful field evidence from the southern margin of the Gediz Graben to the west of Alaşehir that the presently low-angle detachment fault is cut, chopped and displaced by graben-bounding high-angle normal faults where the displacement may reach up to 2 km, thus enabling an episodic two-stage extension model in western Anatolia. The recent field data emphasize that latest Oligocene-Early Miocene back arc extension and/or orogenic collapse cannot be responsible for the entire history of extensional tectonics and that continental extension in the region is not a continu-

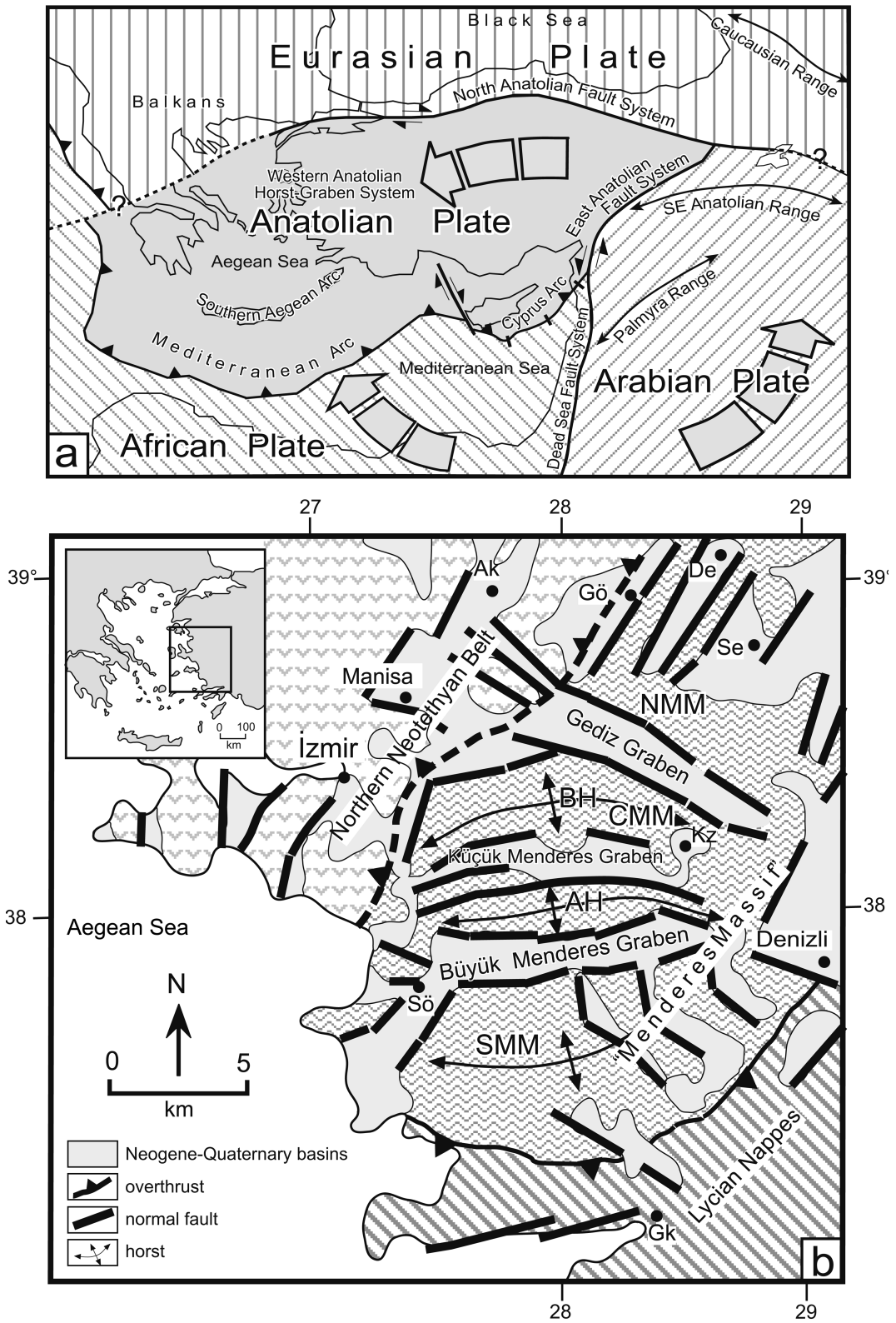

Fig. 1 **(a)** Neotectonic elements of the Eastern Mediterranean. Heavy lines with half arrows are strike-slip faults with arrows showing relative movement sense. Heavy lines with solid triangles indicate an active subduction zone, its polarity indicated by the tip of small triangles. Heavy lines with solid triangles and cross lines indicate a passive subduction zone. Bold open arrows indicate relative movement direction of African, Arabian and Anatolian plates. **(b)** Outline geological map of western Anatolia showing Neogene and Quaternary basins and subdivision of the Menderes Massif. Note that the sequences of Miocene and Pliocene age are not differentiated. BH- Bozdağ horst, AH- Aydın horst, CMM- Central Menderes Massif, NMM- Northern Menderes Massif, SMM- Southern Menderes Massif, Ak- Akhisar, Gö- Gördes, De- Demirci, Se- Selendi, Kz- Kiraz, Gk- Gökova, Sö- Söke.

ous event as previously suggested by Seyitoğlu *et al.* [87] but occurred in two stages separated by a short period lasting between ca. 7 Ma and 5 Ma; however, current understanding of the nature of process(es) operating during the short-time interval is incomplete (regional compression and/or tectonic quiescence: see [36, 38, 39, 42, 43, 70, 71, 78, 89, 90, 94, 97-99] and references therein for details).

We shall examine the style of deformation in the Miocene continental sediments, the nature of their faulted contacts with particularly the older rocks and, the number and relationships among different fabrics developed in the metamorphic rocks of the Menderes Massif to address the apparent paradox over the nature of short-time interval between two distinct styles of extension in western Anatolia. This paper therefore examines and reports the results of recent field geological mapping and structural analysis, for the first time, from two critical regions in western Anatolia to the NE of Küçük Menderes Graben (Figs 1, 2) that shed lights on the processes operating during this short-time interval. The possible implications of present study to the better understanding of the mechanisms of continental extensional deformation and its evolution in western Anatolia will be discussed.

3. Results of geological mapping

Geological mapping and structural analyses were undertaken **(i)** within the exhumed Miocene sedimentary association along the northern margin of the Kiraz Basin—a subsidiary to Küçük Menderes Graben and **(ii)** Bozdağ horst to the north of Kiraz (Figs 2, 3). The results of this work are described briefly below.

3.1. Kiraz Basin

The Kiraz Basin is a ~ 30-km-long, 1-15-km-wide structure with its long axis trending in NW-SE direction; it is located between the almost E-W-trending Küçük Menderes Graben in the west and NW-SE trending Gediz Graben in the north (Figs 1, 2). The basin is separated from the Küçük Menderes Graben in the west by a topographic high where the Kiraz basin is elevated with respect to the graben (Figs 2, 3); the Kiraz basin and Küçük Menderes graben floors lie at elevations of 250 m and 170 m above mean sea level, respectively. The basin is connected to the graben through N-S flowing narrow stream channel (Figs 2, 3). In this regard, the Kiraz basin can be considered as an actively growing isolated depression with active normal faults mainly located on the north-northeastern and southwestern margins (Fig. 3). The Kiraz basin is, based on the missing of bedded red Miocene clastics that are main elements of major grabens in western Anatolia, interpreted as a basin younger than other two Büyük Menderes and Gediz grabens [97, 100, 101]. Despite of its importance, geology of the Küçük Menderes Graben and the Kiraz basin have not been studied previously and there are a number of unpublished company reports that concerns with hydrogeology of the graben and basin (cf. [101-103]).

3.1.1. Stratigraphy

The Kiraz basin is developed above the metamorphic rocks of the Menderes Massif and is filled with the Neogene (Miocene-Quaternary) deposits and volcanics (Fig. 3). The rocks exposing in and around the basin can be grouped into four distinct rock units: (i) the metamorphic basement; (ii) Neogene volcanics; (iii) Neogene sediments and (iv) recent alluvium deposits (Fig. 3). The basement is composed mainly of schists, quartzites, phyllites, marbles and orthogneisses (traditionally known as augen gneisses) (see section 3.2. for further information). Neogene volcanics form isolated outcrops at two separate localities: Karaburç and Yenişehir areas (Fig. 3) and are composed of andesitic-dasitic and basaltic rocks. Similar volcanic rocks are exposed to the west of Küçük Menderes Graben where they are dated at 11.3-19.2 Ma [104-106]. Neogene sedimentary associations form widespread exposures along the margins of the Kiraz basin; they are exhumed with respect to the modern basin floor and mapped, based on their lithological characteristics, structure and colour (see below), into two distinct associations: relatively older beige-light green to grey-dirty white-light brown coloured well-bedded clastics and unconformably overlain by poorly bedded red clastics. The older sediments occur only along the northeastern margin of the basin while the younger is exposed along both margins (Fig. 3).

The oldest light coloured sequence is composed mainly of alternation of graded-bedded conglomerates, sandstones with cross-bedded layers and mudstone intercalations (Fig. 4a, b). Conglomerates are typically thick bedded, poorly sorted, clast-supported, coarse-grained (pebble to boulder), polygenetic, and contain subrounded-subangular clasts (of marble, schist, orthogneiss and gneiss derived from the metamorphic rocks) within a well-cemented matrix of sand, silt and mud. Where channellized (occasional), polygenic conglomerates are characterized by scour-and-fill bottom structures and contain sporadic sandstone lenses. Sandstones display well-preserved medium- to thick-bedding and are composed of well sorted and well-rounded metamorphic clasts within a muddy matrix. They are typically white to grey and fine to medium grained, but local pebble-rich horizons also occur (Fig. 4b-d). Sporadic beige-cream to yellowish lacustrine limestone and clayey limestone intercalations form other characteristic features of this sequence. The above-mentioned lithologies show rapid lateral and vertical transitions from one to another. Cross-bedding, pebble imbrication and graded bedding are common syn-sedimentary structures (Fig. 4a-c). The unit is interpreted to represent the deposits of alluvial to lacustrine setting with ephemeral channels. The sediments are deformed and tilted steeply to the north or south; locally

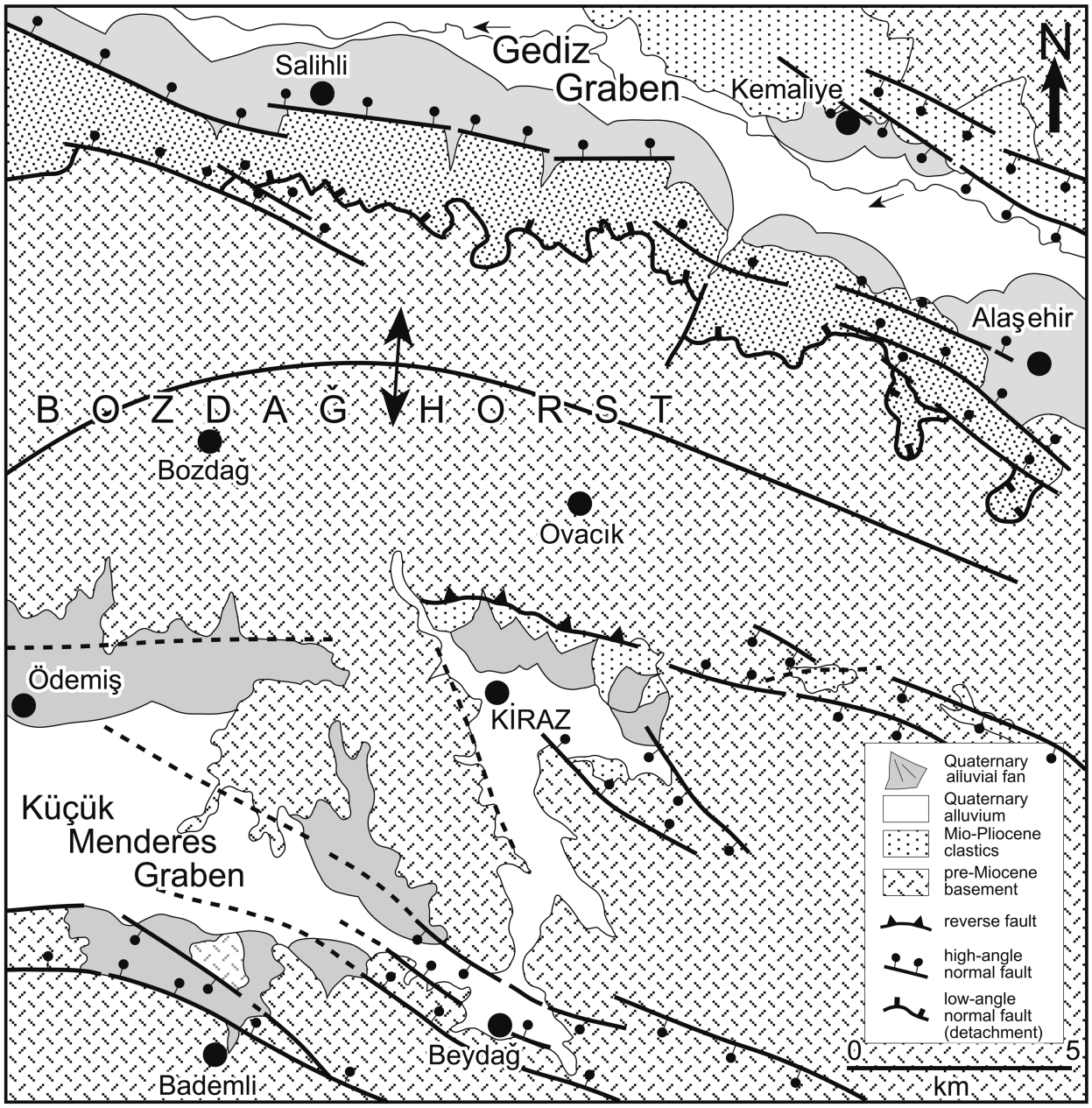

Fig. 2 Simplified geological map of the Bozdağ Horst in the area between Gediz Graben in the north and Küçük Menderes Graben in the south, showing the location of Kiraz Basin.

along their faulted contact with metamorphic rocks they become almost vertical and overturned (Fig. 4b, c). The dip amounts range between 40° and 89°. There is no direct evidence about the age of the sequence associated in the study area but it is interpreted as lithologically time-equivalent of various lithologies cropped out in the Kemalpaşa-Torbalı basin [107]; accordingly the age of these sediments is loosely assigned as Early Miocene-Early Pliocene.

Younger red coloured Neogene sequences are made up of poorly bedded, semi-lithified conglomerate, sandstone and claystone alternation; coarse clastics contain abundant andesitic volcanic fragments derived from the Neogene volcanics in the Kiraz basin (Fig. 4d). They are heavily dissected by river incision and interpreted as older alluvial fan deposits elevated with respect to the basin floor. These clastic rocks overlie unconformably the metamorphics, Neogene volcanic rocks and light coloured older clastic rocks with a pronounced angular difference. They show no sign of deformation as indicated by their gentle or horizontal attitudes. A Pliocene age is therefore assigned to this unit.

The fourth and the youngest rock association comprises recent (Quaternary) alluvium deposits and is represented by numerous diverse size, coalesced, actively developing alluvial marginal fans aligned along the margins of the Kiraz

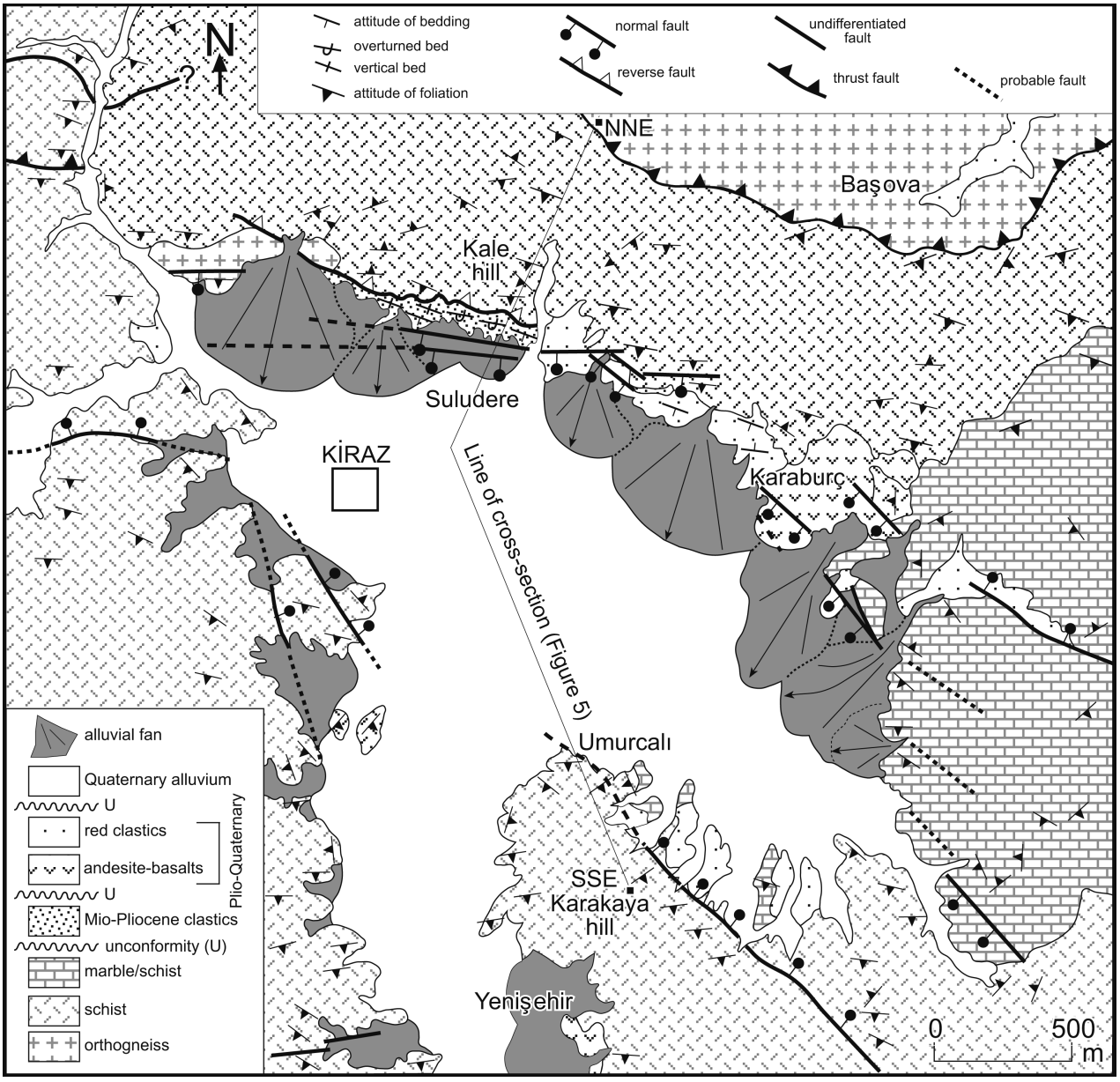

Fig. 3 Simplified geological map of the Kiraz Basin (partially modified from Toprak *et al.* [101]).

basin (Fig. 3). The fans occur in the downthrown blocks of neotectonic faults, indicating uplifted margins of the faulted basin and grade into fine-grained basin floor sediments (Fig. 3).

3.1.2. Structures

There are three distinct structures shape and control the evolution of the Kiraz basin (Fig. 3). The first and may be the most important structure in the view of the purpose of present paper is a WNW-ESE-trending, north-facing high-angle oblique-slip reverse fault that exposes just to the north of Suludere village, about 1 km north of Kiraz town (Fig. 3). It is marked with the juxtaposition of underlying overturned northward dipping Mio-Pliocene sequence and overlying metamorphic rocks of the Menderes Massif along the north-eastern margin of the basin (Figs 3, 5). The field relations clearly document that the metamorphics are thrust onto the sediments. We are able to trace the fault for about 1.5 km in approximately E-W direction, and then it is buried beneath the Pliocene sediments to the east (Fig. 3). The westward extension of the fault within the metamorphics is difficult to follow. The rocks immediate to the fault show evidence for intense brittle deformation as manifested by the development of brecciated-dismembered rocks. Similarly, the effect of reverse faulting is obvious by sudden increase in dip amounts up to 89° and northward dipping of the Mio-Pliocene sequence, and by the overturned nature of sandstone beds (deduced by syn-sedimentary structures, such as cross- and graded-bedding) (Figs 4b, c, 5). Where exposed the fault

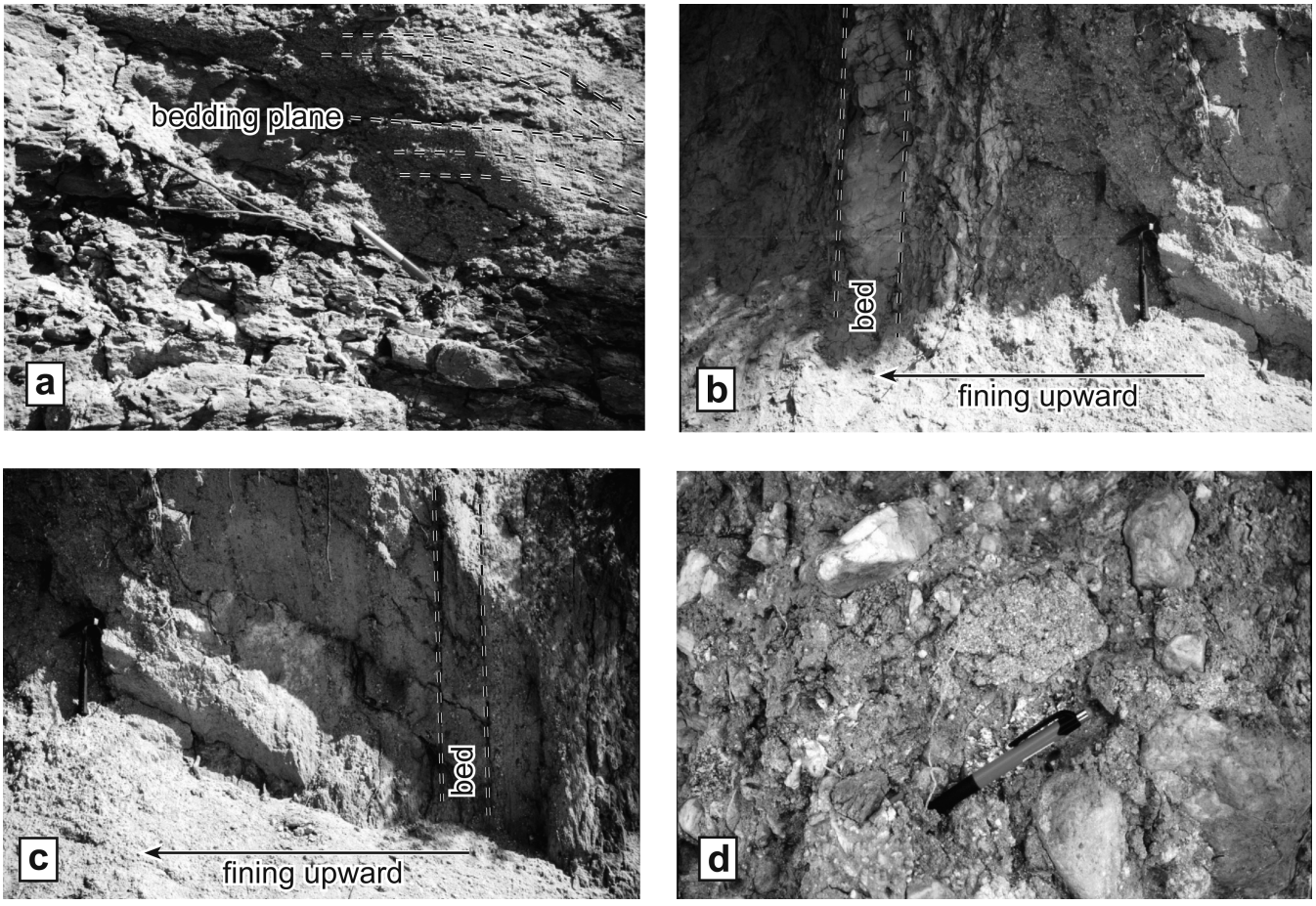

Fig. 4 Field photographs from the sedimentary rocks exposing to the north of Kiraz. **(a)** Gently dipping horizons of the Mio-Pliocene sediments. The cross-bedding in the pebbly sandstone levels indicate that the sequence is overturned (pencil is 14.5 cm long); **(b, c)** alternation of sandstone and pebbly sandstone horizons. Note that the beds are almost vertical, revealing the effect of bounding reverse fault. Note also the alternation of reddish muddy, whitish limy and greyish sandy beds (hammer is 33 cm long), **(d)** a close-up view from the Pliocene conglomerates, showing angular to subrounded volcanic rock fragment (pencil is 13 cm long).

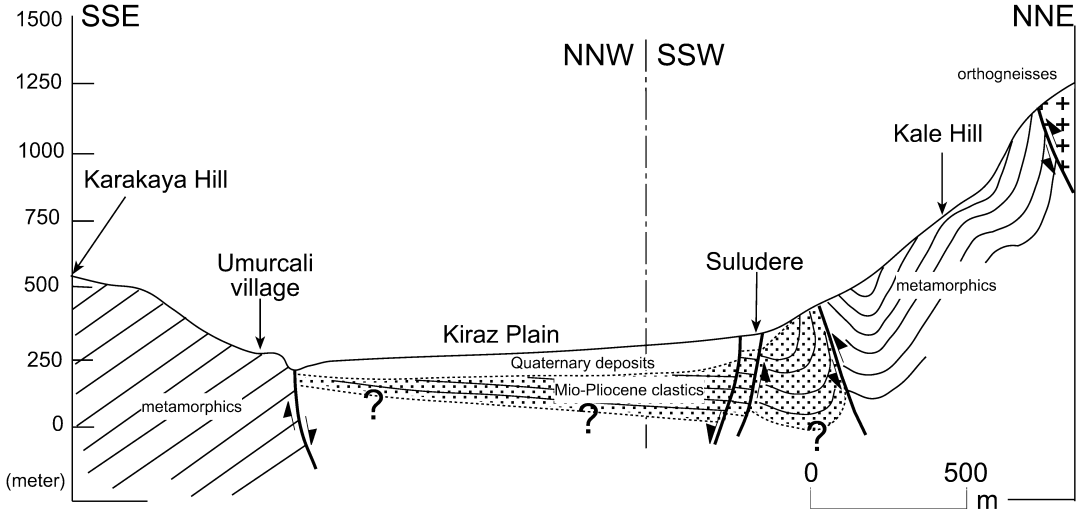

Fig. 5 Cross-section showing the relationship between Mio-Pliocene sediments and the metamorphic rocks of the Menderes Massif across the reverse fault. See Figure 4 for location.

plane is degraded but we are able to observe the slip plane with well-preserved striations at one locality where the fault has an attitude of N73°W/72°N with a rake of 55W°. This information suggests that the fault is an oblique-slip reverse fault with a considerable amount of dextral component.

The second type of structure is an overturned syncline with an almost WNW-ESE-trending fold axis paralleling the reverse fault in the north and the graben-bounding high-angle normal faults in the south (Fig. 5). We interpret the overturned syncline as a fault-forced structure, with northern limb overturned.

Margin-bounding high-angle (≥40°) faults of diverse size form the other conspicuous features of the Kiraz basin (Fig. 3). Most are traced on the basis of their topographic expression and define a characteristic step-like pattern, particularly along the northern margin of the basin. In many cases, within the limits of the study area, fault planes are degraded due to extensive erosion, but we are able to observe fault planes and related features (slip lines) in a number of localities. The fault slip data is analysed and computed in order to determine the kinematic framework of normal faulting in the Kiraz basin, using the stress inversion method of Angelier [108-110] and the software (TENSOR; version 5.42) developed by Hardcastle & Hills [111]. The method is based on the assumption that the slip on each fault surface has the same direction and sense as the maximum shear stress resolved on the fault surface from the regional stress field (cf. [108-110, 112-122]). There are also claims that this assumption has some limitations (e.g., [123, 124]). The estimated maximum principal stress axis, s1, is plunging steeply at 58° and trends in 279°. The calculated attitudes of intermediate and minimum principal stress axes, σ_2 and σ_3, are 31°/091° and 03°/182°, respectively (Fig. 6). These results suggest oblique-slip normal faulting in a N-S-trending extensional tectonic environment; a result consistent with regional constraints. The calculated ϕ value [$\phi = (\sigma_2 - \sigma_3)/(\sigma_1 - \sigma_3)$] of 0.170 indicates that the magnitude of σ_1 is much higher than σ_2 and is consistent with the extension. However, σ_3 direction is not in a soundness attitude due to ϕ value far away from 0.2 (0.179 here) that prevent us to interpret the exact extension orientation in the study area.

3.2. *Bozdağ Horst*

The topographic high located between the Gediz Graben in the north and the Küçük Menderes Graben in the south is known as the Bozdağ horst (Figs 1, 2). It is a typical continental-ribbon bounded by north- and south-dipping conjugate normal faults. The area is characterized by widespread exposures of metamorphic rocks belonging to the Menderes Massif; there are patchy exposures of Plio-Quaternary fluvial clastic rocks preserved here and there higher-up in the topography (see Toprak *et al.* [101] for details). Menderes Massif is an approximately NE-SW-trending crustal-scale metamorphic culmination that covers vast areas in, and has key role in the better understanding of the geological evolution of, western Anatolia (see Bozkurt & Oberhänsli [63, 64] and references therein). It comprises there submassifs—northern (NMM), central (CMM) and southern (SMM)—separated by the active Gediz and Büyük Menderes grabens and each is interpreted as core complexes exhumed at different types (e.g., [36, 39, 40, 42, 43, 53-59, 62-67, 69, 73-76, 78-80, 97, 125, 126] and references therein; Fig. 1). The characteristics of different rock units of the Menderes Massif exposed in the Bozdağ horst and their structural characteristics will be given in the following sections.

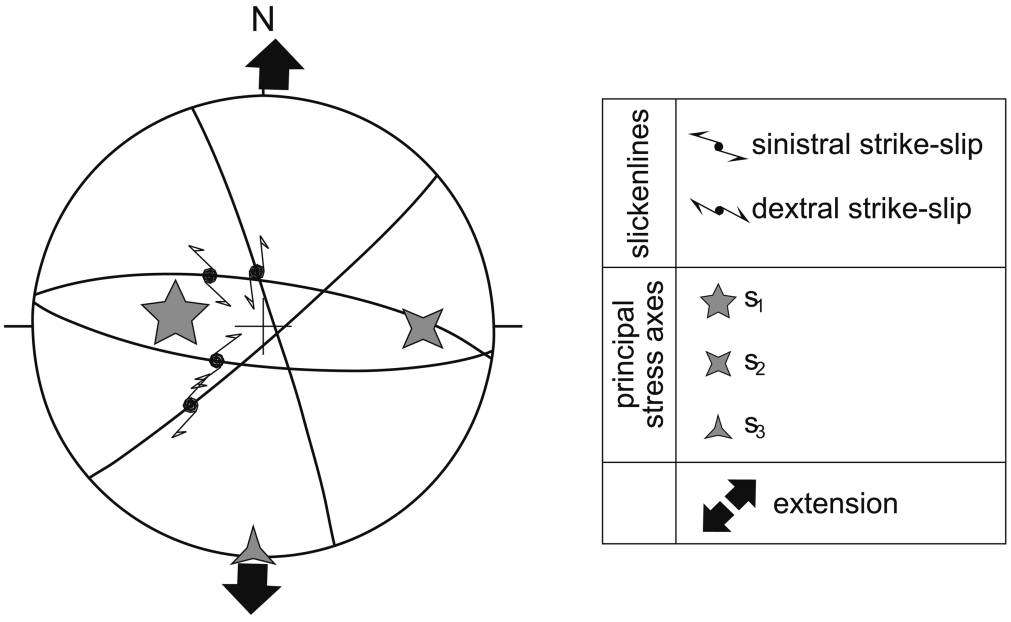

Fig. 6 Schmidth lower hemisphere equal-area projections of slip data from the high-angle normal faults. Great circles are fault surfaces, the arrows are striations.

3.2.1. Rock units

The metamorphic rocks exposing in the Bozdağ horst (including the study area) is comprised mainly of two distinct lithologies: metasediments and orthogneisses. Metasediments are represented by locally migmatitized paragneisses, high-grade schists (kyanite-staurolite mica, garnet mica, biotite-muscovite and muscovite-biotite-quartz [psammitic] schists), low- to medium-grade mica schists, graphitic phyllites—with grey/marble intercalations and/or lenses—quartzites and marbles with metapelite intercalations (phyllites or schists, depending on the metamorphic grade). This sequence also includes pods-boundinaged sill-like and/or stock-like bodies of metagabbros with eclogite relics and metabasics mainly in form of garnet amphibolites ([58] and references therein). Orthogneisses, traditionally known as augen gneisses, form the other conspicuous rock unit of the metamorphic rocks all along the Menderes Massif. They are typical blastomylonitic rocks characterized by large retort-shaped feldspar porphyroclasts (augen) within a more ductile wrapping matrix of biotite-muscovite-feldspar-quartz. The presence of eclogite relics in the metagabbros suggest an early phase of HP metamorphism prior to the major Eocene high-grade metamorphic phase (amphibolite facies), known as the main Menderes metamorphism.

3.2.2. Structure

The detail structural analysis of the metamorphic rocks exposed in the Bozdağ horst shows that these rocks have experienced, at least, four distinct phases of deformation (D_1-D_4) that occurred at different metamorphic conditions. The metamorphic rocks are typical L-S tectonites characterized by two sets of foliation (S_1 and S_2) and invariably associated approximately N-S-trending mineral stretching lineation ($L_{1/2}$). Penetratively developed regional pervasive S_1 foliation forms the most spectacular structure of the metamorphic rocks. It is more pronounced in pelitic rocks than the marbles, psammites and orthogneisses (augen gneisses). S1 in the metasediments is defined mostly by the preferred parallel alignment of micas and quartz grains. The growth of synkinematic mica and garnet within the limits of the present area is obvious, event at the outcrop scale, but there is well-documented evidence for synkinematic staurolite, kyanite and sillimanite in similar rocks exposing in close vicinity [56-58, 127-131]. Where garnet present, it occurs as poikioblastic porphyroblasts, with spiral-shaped inclusion trails, around which the matrix foliation wraps. The orthogneisses are blastomylonitic rocks with large feldspar porphyroclasts (augen) within a more ductile fine-grained matrix of mica, quartz and dynamically recrystallized feldspars. The S_1 foliation is defined by strongly elongated and flattened feldspar porphyroclasts, dynamically recrystallized quartz ribbons and preferably parallel aligned micas. The spacing of the foliation is variable across the study area and depends on the intensity of the deformation and the lithology (rheology). This is evident in the various lithologies of the metasediments: where foliation spacing in pelitic rocks is so small suggesting a continuous fabric but foliation in psammites and marbles display a more spaced character (cf. [132]); in these lithologies foliation planes is marked with the abundance of parallel-aligned micas. Similarly, the spacing of foliation in the orthogneisses varies depending on the intensity of deformation: in high strain areas, it is in the orders of millimetres since almost all feldspar porphyroclasts are elongated/flattened and dynamically recrystallized into smaller new grains. On the other hand, in low-strain areas where deformation is relatively less the rock exhibits a typical blastomylonitic texture with large feldspar porphyroclasts, reaching up-to a few centimetres along their long axes, within a fine-grained matrix foliation that wraps around the porphyroclasts; the porphyroclasts and their recrystallized tails display a stair-stepping geometry similar to s-type porphyroclasts defined by Passchier & Simpson [133]. Although, in general, the S1 foliation strikes in approximately WNW-ESE direction and dips to the south at variable angles ranging between ~ 20-80°, their attitudes and distribution define a series of folds with axes trending WNW-ESE in the area to the north of Kiraz (Fig. 3). Some of these folds occur as mappable structures but many are typical meso-scale intrafolial structures. Relatively large-scale folds are associated with crenulation cleavage development where S_1 foliation is readily recognized between cleavage domains. Similar, crenulation fabrics were described in other parts of the central Menderes Massif along the margins of the Küçük Menderes Graben [57, 58].

A well-developed mineral stretching lineation forms the other most important, penetrative and striking structure of the metamorphic rocks. It is mostly defined by the parallel alignment of micas and elongated quartz grains in the metasediments and smeared out micas, stretched and dynamically recrystallized quartz grains (quartz ribbons), elongated/flattened feldspars porphyroclasts and recrystallized tails of asymmetric feldspar porphyroclasts in the orthogneisses. It trends in approximately NNE-SSW direction and plunges to the south. The close association of mineral lineation with both sets of foliation (S_1 and S_2) suggests that the general orientation of stretching lineation did not change during the formation of two distinct fabrics; for this reason the mineral stretching lineation is denoted as $L_{1/2}$.

The metamorphic rocks of the present area exhibit abundant kinematic indicators; they include C-type shear band foliation (extensional crenulation cleavage; Platt & Vissers [134]), S-C fabrics, mica fish, strain shadows around garnet prophyroblasts, asymmetric carbonate and quartz boudins in the metasediments and σ-type feldspar porphyroclasts, S-C mica fabrics, mica fish, and oblique quartz grain-shape fabrics in the orthogneisses. These fabrics demonstrate a top-to-the-NNE bulk shear sense during a non-coaxial deformation—up-dip direction with respect to the present configuration of S1 regional foliation, thus indicating a compressional deformation.

The regional S_1 foliation is overprinted by a well-developed, relatively low-grade (possibly greenschist-facies facies) shear band foliation (S_2). The latter is relatively less pervasive when compared to the former and commonly occurs around contacts between various lithologies of the Menderes Massif, particularly at orthogneiss-schist contact. The S_1 foliation is readily preserved as curved (lazy S- and or Z-shaped) and/or inclined structure between the adjacent shear bands along which retrogressive process are characteristic (Fig. 7). Many lack lineation, but brittle striations and

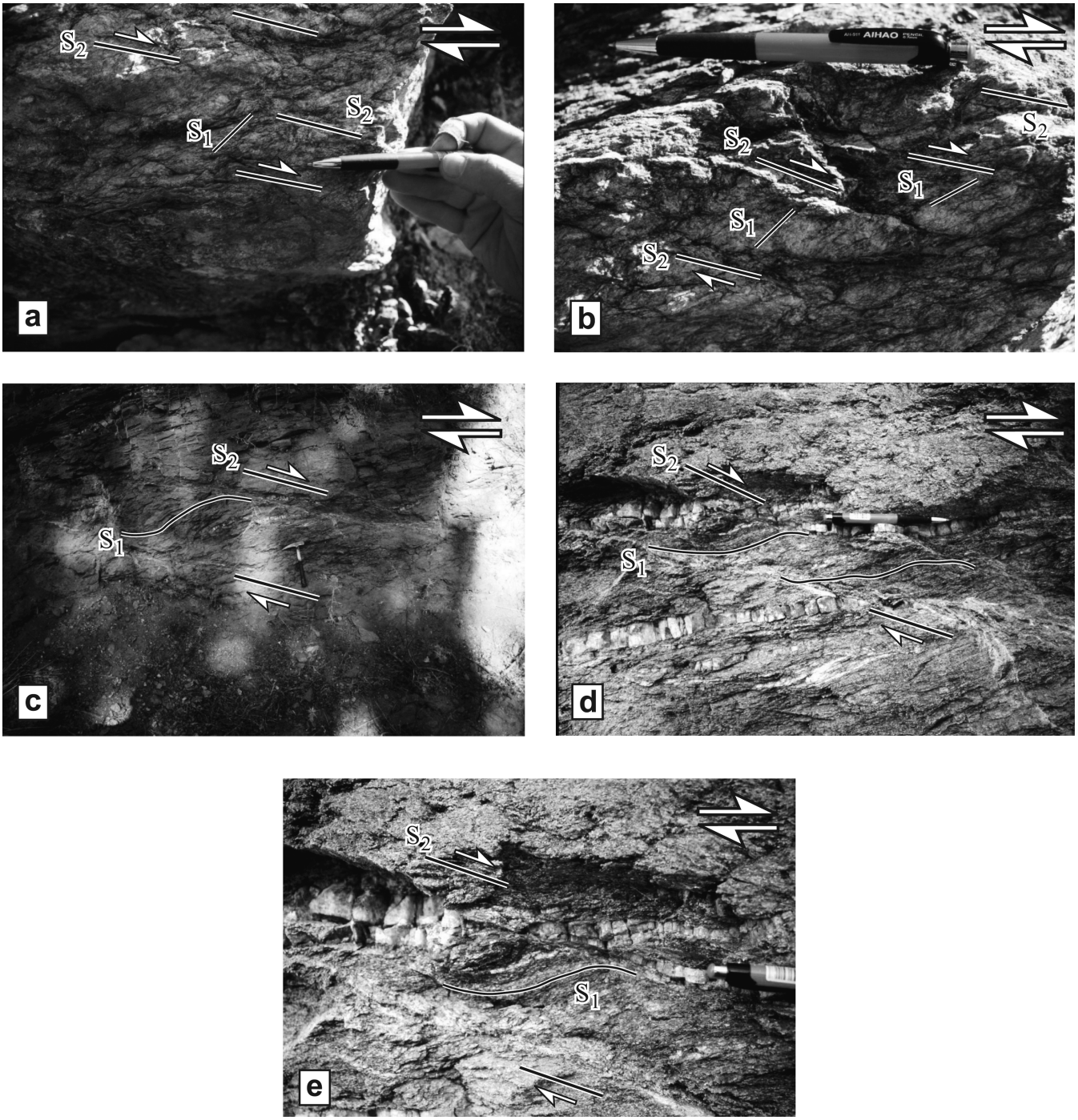

Fig. 7 Typical field views of shear band foliation (S_2) overprinting the main fabric (S_1 foliation) in the orthogneisses and schists of the Bozdağ horst during the D_2 Alpine extensional deformation. The rocks are characterized by two distinct fabrics with gently-moderately dipping shear band foliation (S_2) (south-dipping in the orthogneisses **[a, b]** and to the north in the metasediments **[d-e]**) and a S_1 foliation preserved within the microlithons between the adjacent shear bands. Note that the oblique S_1 foliation has a tendency to bend and curve into the S_2 shear band foliation. Intense deformation and alteration (mainly chloritization, dark to brown in colour) concentrated within narrow zones along shear bands are characteristic. Note also the brittle normal offset of quartz-rich horizon in **(d, e)**. The hammer and pencil are 33 cm and 13 cm long, respectively; pencil points north in each case.

extensive chloritization are characteristic; this suggests declining P-T conditions during their formation. The S_2 shear band foliation trends approximately WNW-ESE but dips gently-moderately (~ 10-40°) to the south or north. This could be interpreted as conjugate sets of fabric generation during D_2 deformation but we have not observed the two sets cross-cutting each other within the limits of the present area. The curved geometry of S_1 foliation preserved between the microlithons of adjacent shear band fabrics indicate both S-SSW (along south-dipping S_1) and N-NNE (along north-dipping S_1) shearing (Fig. 7), parallel to the mineral stretching lineation ($L_{1/2}$), thus suggesting a coaxial deformation during D_2. The down-dip sense of shearing associated with S_2 suggests an extensional deformation.

The third set of fabrics (S_3) is relatively less common when compared to S_1 and S_2 foliations. This is because of the nature of D_3 deformation and relatively scarcity of suitable exposures since they commonly occur at or near contacts among various lithological associations. It is more brittle as marked with brecciation along them. S_1 is readily recognizable in-between adjacent S_3 surfaces and display a typical curved pattern, suggesting a top-to-the-south deformation; this direction is up-dip relative to the present configuration of the S_3 thus confirming a more thrust faulting along these surfaces.

Brittle normal faults of variable scale (outcrop-scale to kilometers) form the youngest structural elements affecting and deforming the metamorphic rocks (D_4). They occur as approximately E-W-striking, north- or south-dipping structures cutting and displacing the older fabrics. Typical brecciation is common style of deformation along these faults.

In polydeformed metamorphic terrains it is unlikely to observe fabrics of different deformational phases preserved. This is because partly that the earlier fabrics are commonly obliterated by subsequent phases or that the exposures are scarce. On the other hand, in this particular locality in the Bozdağ horst within the orthogneisses, we are lucky to observe four sets of fabrics in a single exposure with preserved relationships; the exposure is so clear that a relative chronology is well established (Fig. 8). The related fabrics, based on overprinting field relations, are: (1) south-facing steep top-north ductile fabrics (074°/77°N; D_1); (2) top-S ductile moderately south-dipping fabrics (137°/37°S; D_2). D_1 structures are scarce and preserved within the microlithons of D_2 fabrics; (3) moderately north-dipping top-S ductile-brittle fabrics (084°/41°N; D_3); and (4) south-facing approximately E-W-trending brittle high-angle normal faults (090°/76°S; D_4) that form the youngest structures in the exposure (Figs 8, 9).

4. Discussion and Conclusion

In the study area, four distinct phases of Alpine deformation (D_1-D_4) have been defined. There is evidence for a pre-Alpine deformation and metamorphism (granulite- and amphibolite-facies) preserved within the metagabbro lenses in the augen gneisses (e.g., [135] and references therein). The related fabrics, based on overprinting field relations, are: **(1)** south-facing top-N ductile fabrics (regional penetrative S_1 foliation) developed at relatively high-grade metamorphic conditions, possibly during the amphibolite facies Eocene Main Menderes Mtamorphism (MMM) associated with thrust tectonics (D_1), which is attributed to the top-NNE backthrusting of Lycian Nappes over the Menderes Massif [125, 136]. This event has resulted in imbrication and internal stacking of the Menderes Massif and consequent crustal thickening in the massif area. The top-north deformation is also supported by well-documented inverted metamorphism [58, 129]. The formation of Bozdağ anticline forms the latest structure formed during D_1 deformation [58]. The evidence suggest that the D_1 deformation is represented by the structures of three distinct progressive increments: (i) formation of S1 regional foliation, (ii) post peak-MMM ductile northward thrusting and consequent inverted metamorphic sequence where higher grade rocks are emplaced over lower-grade ones and (ii) formation of a large Bozdağ anticlinorium with curvilinear axis trending almost E-W.

(2) D_2 deformation is characterized by ductile gentle-moderately south-dipping extensional fabrics (S_2 shear band foliation) formed at relatively lower-grade and decreasing metamorphic (possibly greenschist facies) conditions. S1 foliation is clearly overprinted and preserved as S-shaped foliation within the microlithons of S_2 fabrics. The relationship between S_1 and S_2 foliations are consisted with both top-SSW and top-NNE shearing along pronounced NNE-SSW-trending mineral stretching lineation (Figs 7-9). The dual shear sense during D_2 deformation has important implications and their distribution fall into two distinct domains. The fabrics suggest a top-SSW movement along the southern flank of the Bozdağ anticlinorium to the north of Kiraz. On the other hand, top-NNE fabrics begin to appear at topographically higher locations in areas close to the fold axis. These observations is consistent with that of Hetzel *et al.* [58] who documented similar results for the distribution of opposing shear sense indicators and suggested that Bozdağ anticlinorium fold axis has profound influence on the distribution of D_2 extensional fabrics. Both top-SSW and top-NNE down-dip shearing indicates that D_2 deformation around axial areas of Bozdağ anticlinorium is coaxial. On the other hand, on the scale of Bozdağ mountains, the D_2 fabrics are bivergent with top-SSW shearing in the south along the northern margin of the Küçük Menderes Graben and top-NNE shearing in the northern margin of the Gediz Graben (e.g., [40, 42, 56-58, 65, 66, 74, 78, 86] and references therein). Similarly, bivergent extension is valid for the scale of central Menderes Massif in the area between the Büyük Menderes and Gediz grabens (e.g., [63, 64] and references therein). This event is attributed to crustal thinning and consequent extensional exhumation of Menderes Massif

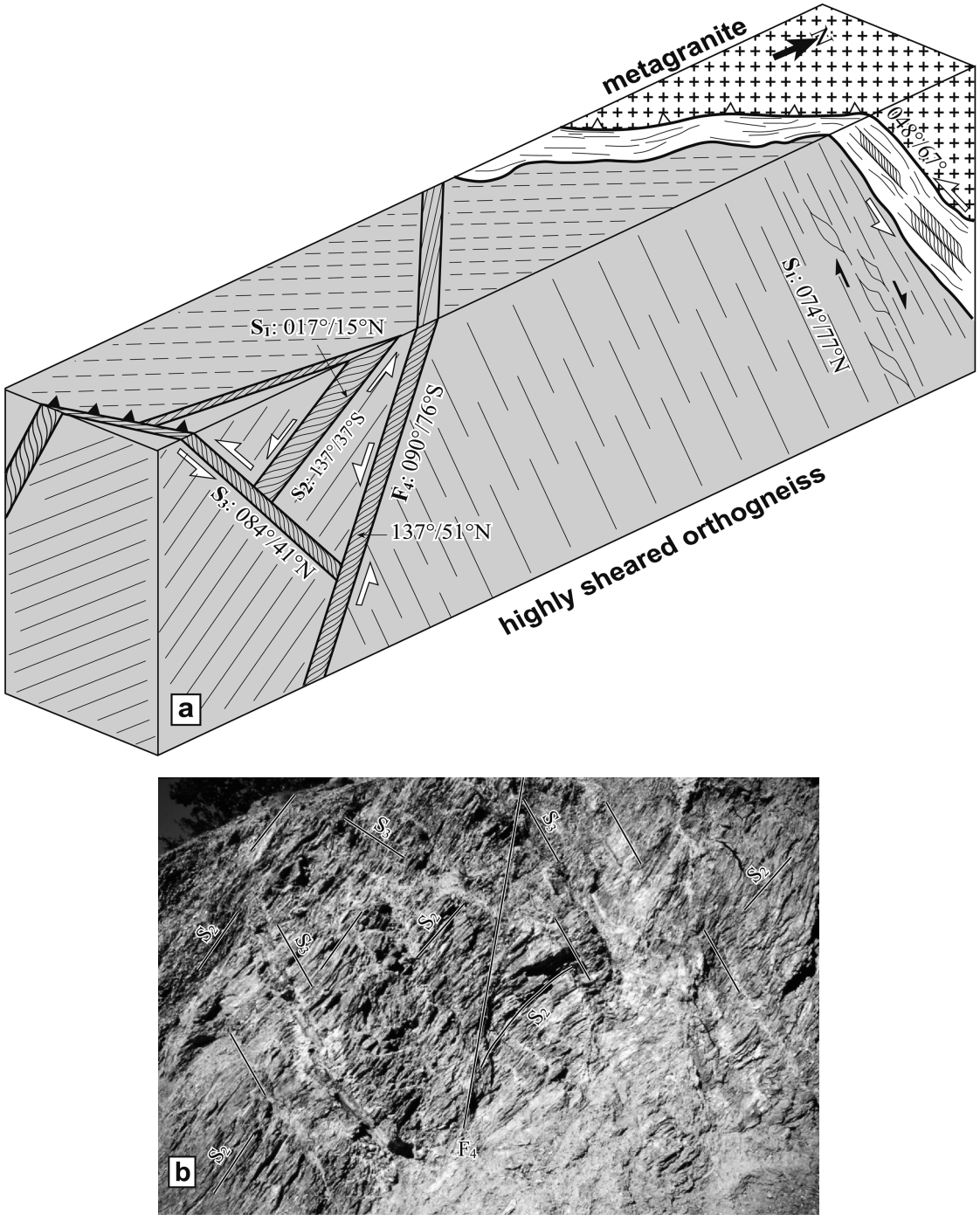

Fig. 8 **(a)** Sketch block diagram illustrating the four set of structures deforming the rocks of the Menderes Massif in the Bozdağ horst (D_1-D_4 deformations). Note that the contact between highly sheared orthogneisses and metagranite is a typical compressional shear zone with a top-to-the-SSW thrusting; **(b)** Field view from the block diagram area showing S_2 to S_4 fabrics. Pencil is 13 cm long. Please also note the overprinting relationships among S_1 to S_4 fabrics. See Figure 9 for detailed field views of these structures.

in the footwall of presently low-angle normal fault plane(s) (detachment faults) that accompanied the first phase of extension (D_2) due to the combined effect of southward Mediterranean-Cyprus subduction rollback processes and collapse of crust previously overthickened during D_1 deformation. The most recent literature agrees that this event commence by latest Oligocene-Early Miocene time. The detachment faults hosted the sedimentation of Miocene red clastic sequences on the hanging-walls.

(3) D_3 deformation is represented by two distinct structures within the study area. The first one is an oblique-slip reverse fault with a dextral component. This structure

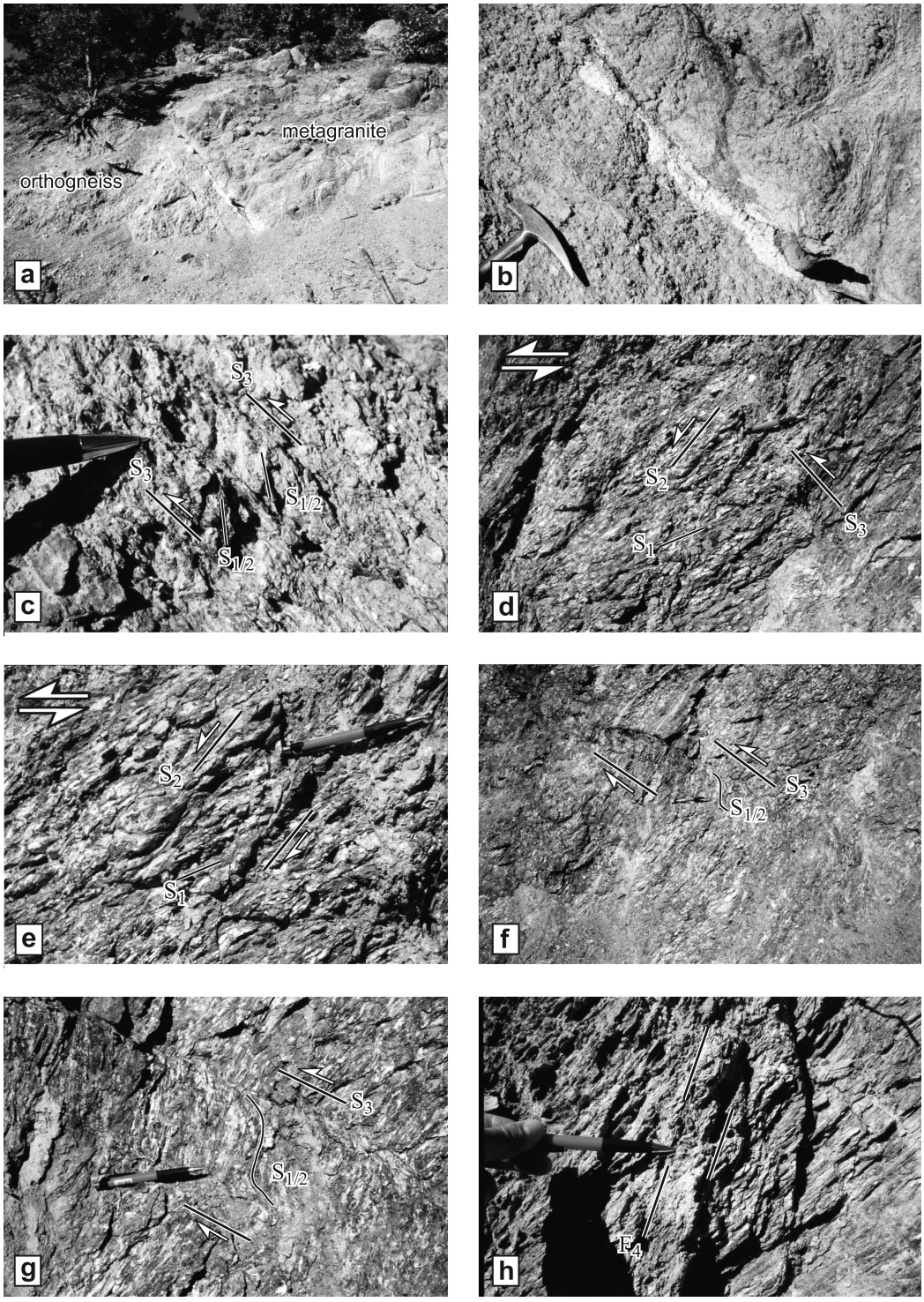

Fig. 9 Close-up field views from the area depicted in Figure 8b. (a, b) Views from the thrust fault contact between the highly sheared and relatively less deformed orthogneisses. Contrast in the intensity of deformation between the hanging-wall and footwall rocks is obvious with the former showing boulder appearance while the latter posses a penetrative fabric overprinted with relatively brittle deformation. Hammer is 33 cm long; **(c)** close-up view to the footwall rocks of this thrust fault. Note the development of top-to-the-SSW deformation where earlier fabrics (S_1 and/or S_2) are overprinted by a latter S_3 fabrics; **(d)** Typical view of penetrative moderately south-dipping shear band foliation (S_2) overprinting the main fabric (S_1 foliation) where S_1 foliation is preserved within the microlithons between the adjacent shear bands and has a tendency to bend and curve into the S_2 foliation. Alteration along S_2 foliation is reflected by brown colour. Note how S_3 fabrics oveprints the S_2 surfaces; **(e)** close up view to the S_2 surfaces in **(d)**, indicating top-to-the-SSW down-dip shearing; **(f, g)** views from the S_3 surfaces that develops over S_2 fabrics. When compared, the S_3 foliation is represented by discrete features. Note how earlier foliation ($S_{1/2}$) is preserved as S-sphaped fabrics within the microlithons of the S_3 and bends/curves into the S_3. The present configuration of S_3 surfaces is consistent with a top-to-the-south, up-dip shearing; **(h)** close-up view from a steeply south-dipping F_4 faults along which brittle deformation is pronounced. Pencil is 13 cm long and points north in each case.

emplaces metamorphic rocks of the Menderes Massif onto the Lower Miocene-Pliocene sequences along the northern margin of the Kiraz basin (Fig. 3). The field relations suggest that the age of faulting must be younger than Early Pliocene. Similar structures that emplace older basement rocks onto the Neogene sequences have been documented further to the north of study area around Manisa, Bigadiç basin and Gulf of Edremit (see [95, 96, 98, 137] for more information). The second of structures are moderately north-dipping top-S semi-brittle (?) fabrics, present configurations of which suggest a thrust-related compression (D_3) (Figs 8, 9). The clearly overprint and displace earlier S_1 and S_2 foliations, which are commonly preserved between S_3 fabrics. It is interpreted that D3 structures are thrust-related fabrics formed during an approximately N-S compression.

(4) Approximately E-W-trending high-angle normal faults (D4 deformation) form the youngest structures in the study area. There is overwhelming evidence that the faults cut and displace the earlier structures; they also have influenced and controlled the morphology in and around the Kiraz basin. It is interpreted that D_4 faults are time equivalent of graben-bounding major high-angle normal faults and they correspond to the second phase of extension in western Anatolia.

Western Anatolia forms a natural laboratory to examine extension following crustal thickening. It is a key locality to study the rapid extensional exhumation of deep burial metamorphic rocks and associated granites on the footwall of presently low-angle first ductile- then brittle-normal faults (detachment faults) and late stretching of crust and, consequent graben evolution along high-angle normal faults. The recent literature agrees, based on stratigraphy and structure of the graben fills and metamorphic rocks, that Neogene N-S crustal extensional tectonics in Western Anatolia is expressed by two distinct stages: there is a change in style of extension from Oligocene-Early Miocene core-complex evolution to the development of Plio-Quaternary horst-and-graben system (e.i. core-complex mode then wide-rift mode) (see Introduction for references).

On the other hand there is no consensus over the evolution of Neogene extensional tectonics in the region. There are claims that the two modes represent a *single continuous evolution* since the latest Oligocene-Early Miocene to Quaternary times (e.g., [87]). While others suggest that they represent two different events, separated by a hiatus (e.g., [36, 38-49, 70, 71, 78, 84, 94-96, 98, 99, 137] and references therein). The displacement of presently low-angle detachment fault along graben-bounding high-angle normal faults up to 2 km and angular unconformity between the syn-extensional Miocene sediments and Pliocene sediments [78] clearly demonstrate that there is a short time break between two styles of extension, thus supporting the episodic two-stage extension model of Koçyiğit *et al.* [38]. But it was yet not clear if the short-time interval corresponds to time of compression and/or quiescence (see [36, 38, 39, 42-44, 70, 71, 78, 89, 90, 92, 94] and references therein for details). Addition above mentioned proposed models the compressional period, dated as Early Quaternary, followed by a region-wide extension, was proposed in some early studies [138-140]. However, to conclude, the Early Quaternary age of the studied structures are not well constrained and also not in agreement with the stratigraphic records—existence of an unconformity bounded Neogene clastics between Late Miocene and Pliocene in the region. Therefore it would be wise to constrain the timing of compression to the hiatus between the Neogene continental sequences and unconformably overlying Pliocene clastics which possibly corresponds to late Serravalian-late Early Pliocene times as suggested by Koçyiğit *et al.* [38].

The above-mentioned short summary of field mapping and structural analysis along the northern margin of the Küçük Menderes Graben—Kiraz basin—supports the conclusion that that the area has experienced four distinct phases of deformation (D_1-D_4) during phases of compressional (D_1 and D_3) and extensional periods (D_2 and D_4). The evidence confirms the episodic, two-stage extension model in western Anatolia and that a short-time, intervening N-S compression separated the two distinct phases.

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