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The Problem of the Core–Cover Boundary of the Menderes Massif and an Emplacement Mechanism for Regionally Extensive Gneissic Granites, Western Anatolia (Turkey)

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Abstract: In previous studies, the stratigraphy of the Menderes Massif was divided into a Precambrian core and Mesozoic cover associations, the core consisting of gneissic granites and high-grade schists and the cover of mica schists and platform-type marbles. It has also been proposed that the two associations are separated by an unconformity although nowhere is this relation clearly observed.

In this study, the Bafa and Kavaklıdere areas in the southern part of the massif have been examined. In the Bafa area, Mesozoic mica schists with marble lenses occur in the lowermost parts of the sequence and are overlain, along a gradational boundary, by a Mesozoic carbonate succession. Gneissic granites cut the detrital parts of this Mesozoic succession and the boundary is clearly intrusive, characterised by enclaves of schist within the granite body and seams and veins of granite cutting the surrounding mica schists. In the Kavaklıdere area, Mesozoic metaclastics and platform marbles are underlain by the Permo-Carboniferous Göktepe Formation which consists of black marble, chert and quartz-mica schist intercalations. The gneissic granites in this region also have intrusive contact relations with surrounding rocks and cut the Göktepe Formation.

The granites were emplaced syntectonically during the main Menderes metamorphism which took place in Late Cretaceous–Early Cenozoic time and included strongly assimilated mica schist zones and patches. These granites are geochemically S-type, peraluminous and of syn-collisional character.

The subdivision of the stratigraphy of the massif into core and cover associations based on the position of the gneissic granites is incorrect. The Lycian Nappes were thrust northward coevally with the main Menderes metamorphism, and the Menderes platform was recumbently folded. Along the cores of these north-verging folds, granitic melts were emplaced syntectonically and strongly assimilated, and rejuvenated the lower parts of the platform sequence. Inversion of the metamorphic grade and vertical repetition of gneisses and mica schists in some areas are consequences of recumbent flow folding.

Key Words: gneissic granites, syntectonic granites, Menderes Massif, western Anatolia

Menderes Masifinde Çekirdek–Örtü Problemi ve Bölgesel Ölçekli Gnaysik Granitlerin Yerleşim Mekanizması

Özet: Menderes Masifi'nin stratigrafisi önceki çalışmalarda Prekambrien çekirdek ve Mesozoyik örtü toplulukları olmak üzere iki ana bölüme ayrılmış, çekirdek bölümünün gnaysik granitler ve yüksek dereceli şistler, örtü serilerinin ise şisler ve platform türü mermerlerden oluştuğu belirtilmiştir. Ayrıca, çekirdek ve örtü topluluklarının birbirlerinden açısal uyumsuz dokanak boyunca ayrıldığı ileri sürülmesine rağmen bu ilişki hiçbir yerde açık olarak gözlenememiştir.

Bu çalışmada Menderes Masifi'nin güney bölümünde bulunan Bafa ve Kavaklıdere alanları incelenmiştir. Bafa alanında mermer mercekleri içeren Mesozoyik yaşlı mika şistler stratigrafik olarak alt düzeyleri oluşturur ve üste doğru dereceli bir kuşak boyunca Mesozoyik karbonat istifine geçmektedir. Gnaysik granitler alttaki Mesozoyik kırıntılı düzeyleri kesmekte, dokanak ise intrüsif özelliktedir. Granitler içinde mika şist anklavları bulunurken, şistlerden oluşan çevre kayalarını kesen granit bant ve damarları dokanak boyunca yeralmaktadır. Kavaklıdere alanında Mesozoyik yaşlı metakırıntılı ve mermer istifinin altında siyah mermerler, çörtler ve kuvars mika şistlerden oluşan Permo-Karbonifer yaşlı Göktepe Formasyonu yeralır. Gnaysik granitler bu alanda da çevre kayalara sokulmuş, doğrudan Göktepe Formasyonu'nu kesmektedir.

Granitler sintektonik olarak yerleşmiş olup içirisinde ileri derecede yutulmuş mika şist zon ve yamaları bulunur. Jeokimyasal özellikleri güney Menderes Masifi'ndeki gnaysik granitlerin S-tipi, peraluminus ve çarpışma sırasında yerleşmiş granitler olduğuna işaret etmektedir. Granitler, Ana Menderes Metamorfizması sırasında Geç Kretase–Erken Senozoyik döneminde çevre kayalarını oluşturan şistlerin içerisine sintektonik olarak yerleşmişlerdir. Bu nedenle gnaysik granitlerin konumu esas alınarak yapılan çekirdek ve örtü sınıflaması yanlıştır. Likya napları, bu sırada kuzeye doğru itilmiş, buna bağlı olarak Menderes platformu bölgesel ölçekli kıvrımlarla deformasyon geçirmiştir. Granitik ergiyikler kuzeye devrik kıvrımların çekirdekleri boyunca yerleşmiş ve aynı zamanda platformun alt bölümlerini ergime ve yutmalar yoluyla mobilizasyona uğratmıştır.

Anahtar Sözcükler: gnaysik granitler, sintektonik granitler, Menderes Masifi, Batı Anadolu

Introduction

In the western part of Turkey, the Menderes Massif – with a regionally metamorphosed rock succession of gneissic granites, mica schists and massive marbles – forms the structurally lowest tectonic unit, upon which tectonic slices of mélange rocks of the İzmir-Ankara Zone in the north and the Lycian belt in the south lie as nappes (Figure 1).

In previous studies, the stratigraphy of the Menderes Massif has been considered to consist of two major rock associations; the lower part was named the "*core*" and the upper part the "*cover*" of the massif (Schuiling 1962; Dürr 1975; Dora *et al.* 1992). The core is considered Precambrian in age and the cover Palaeozoic, Mesozoic and Tertiary. The core comprises various types of gneisses and high-grade schists (Schuiling 1962) and the cover Palaeozoic and Mesozoic schists and marbles. The intrusion age of the orthogneisses of the core succession has been determined by radiometric methods to range from 570 to 520 Ma (Hetzel & Reischmann 1996; Loos & Reischmann 1999; Koralay *et al.* 2001) and 566 to 541 (Gessner *et al.* 2004).

Although the metamorphic rocks of the Menderes Massif crop out extensively in western Turkey, the boundary of the so-called core and cover associations has not been observed anywhere nor described unequivocally. In the Kavaklıdere area, the boundary was reported as an unconformity characterised by conglomerate horizons with clasts of leucocratic magmatic rocks which were interpreted to be derived from the underlying Precambrian granites (Konak *et al.* 1987). In the Selimiye region along the southern flank of the massif, the same boundary was described as a shear zone (Bozkurt 1994, 1996; Bozkurt & Park 1994, 1997a, 1997b, 1999, 2001; Hetzel & Reischmann 1996; Loos & Reischmann 1999; Bozkurt & Satır 2000; Bozkurt & Oberhänsli 2001; Lips *et al.* 2001; Whitney & Bozkurt 2002), and as an incipient detachment zone along which a young granite intruded by Bozkurt & Park (1994, 1997a, 1997b). There also claims that this contact is a south-facing thrust fault (Ring *et al.* 1999, 2001; Gessner *et al.* 2001a, 2001b, 2001c; Régnier *et al.* 2003). On the other hand, more recently it is suggested that the contact was contractional with top to the N–NNE sense of shearing, then inverted to extensional with top to the S–SSW sense of shearing during Eocene–Oligocene times (Lips *et al.* 2001; Whitney & Bozkurt 2002).

Boray *et al.* (1973), after mapping a large region between Milas and Tavas along the southern edge of the massif, pointed out that the contact relationship between the core and cover series could only be resolved after deciphering the origin of the core gneisses.

The stratigraphy of the upper parts of the massif, which is called the cover succession, is relatively better known (Figure 2). The cover series consists, in its lower half, of a very thick succession of mica schists, quartz-mica schists, quartzites, black cherts and lenses of dark grey marbles. Carboniferous and Permian ages have been determined from the fossil contents of marbles in the Kavaklıdere area (Önay 1949; Konak *et al.* 1987; Güngör & Erdoğan 2001). This Palaeozoic succession is unconformably overlain by a Mesozoic sequence (Konak *et al.* 1987) which starts at its base with purple to violet sandstones, conglomerates and phyllites (Figure 2). There are thin lenses of dolomitic limestones and mafic volcanic lenses (Güngör & Erdoğan 2001) in the upper parts of this detrital Triassic succession, which gradationally passes upward into a thick platform marble succession.

Around Milas, the detrital Triassic section includes lenses of quartz conglomerates (Konak *et al.* 1987) and, around Selçuk, dark gray thinly bedded cherts interbedded with phyllites, pelagic marbles and mafic volcanic intervals are present (Güngör & Erdoğan 2001).

The Mesozoic marbles in the southern part of the massif consist of gray and light grey dolomites and dolomitic marbles in the lower part and white to dark gray massive marbles in the upper part of the series (Boray *et al.* 1973; Dürr 1975; Konak *et al.* 1987; Özer

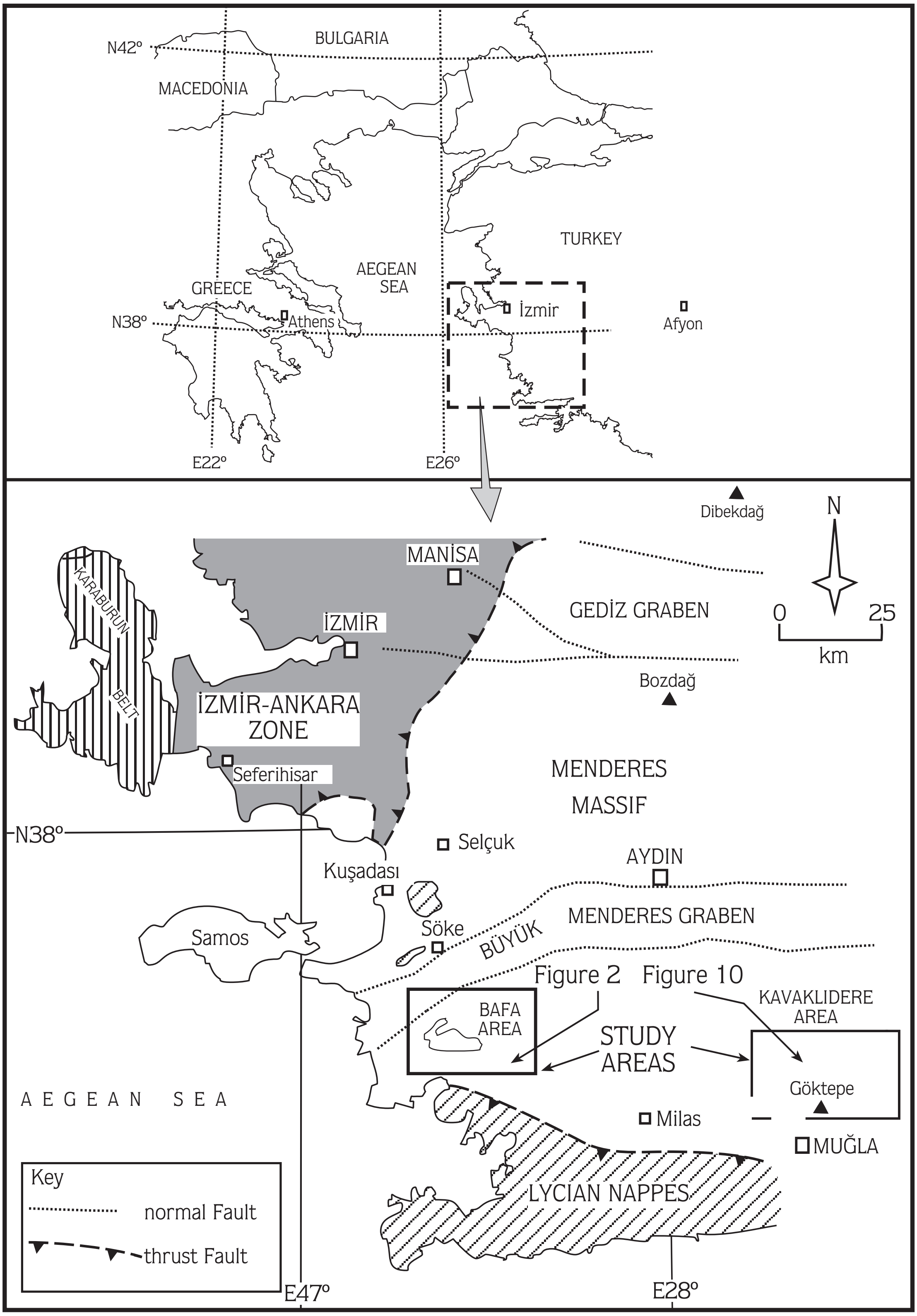

Figure 1. Map showing main tectonic belts of western Anatolia and the location of the study areas.

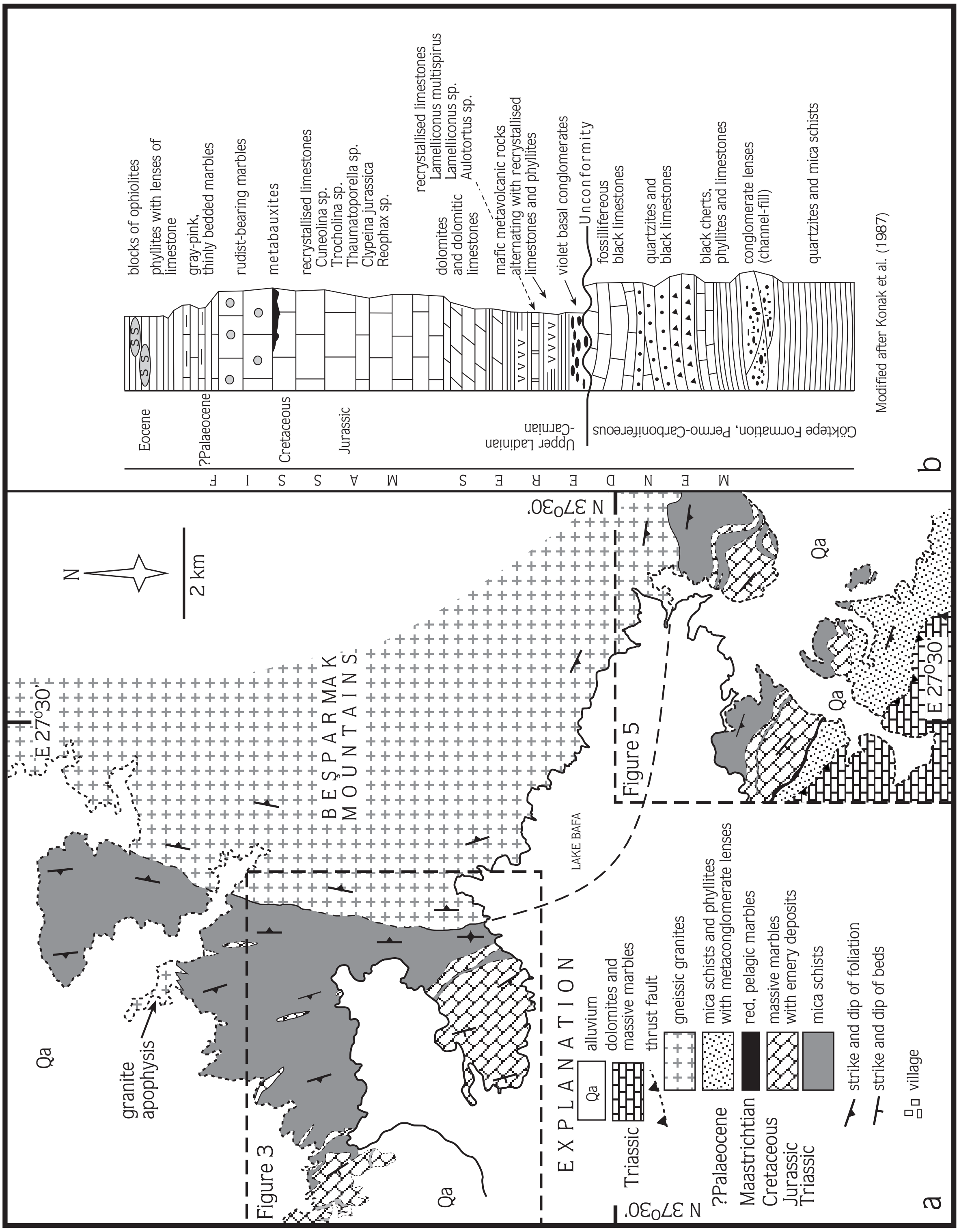

Figure 2. (a) Simplified geologic map of the Lake Bafa area and (b) generalised columnar section of the metasedimentary succession of the Menderes Massif.

1998; Özer *et al.* 2001). These upper sections include emery lenses which are interbedded with massive, Upper Cretaceous rudist-bearing marbles (Dürr 1975; Özer 1998). In the uppermost part of the platform-type marbles, there are bioclastic and intraformational limestone breccias that pass gradationally upward into red, green and grey, Campanian–Maastrichtian pelagic marbles (Dürr 1975; Konak *et al.* 1987; Özer 1998). The pelagic marbles grade into phyllites and schists with blocks of carbonate rocks, mafic volcanic rocks and peridotites (Konak *et al.* 1987; Güngör 1998; Güngör & Erdoğan 2001; Özer *et al.* 2001).

The regional metamorphism of the Menderes Massif is of the high temperature–medium pressure Barrovian type and is dominantly in the greenschist facies, but in extensive areas it reaches up to amphibolite facies, and is characterised by almandine-staurolite-sillimanite-kyanite mineral assemblages (Evirgen & Ataman 1982; Bozkurt 1996; Whitney & Bozkurt 2002; Régnier *et al.* 2003). The eclogite and granulite facies are also reported in close association with gneissic granites and gneisses, and these high-grade metamorphic events have been considered to be Precambrian (Candan 1994a, 1994b, 1995, 1996; Candan *et al.* 1998, 2001). It was previously suggested that the main metamorphism of the massif was related to collision in the Early Cenozoic which resulted in the burial of the Menderes platform beneath the load of the Lycian Nappes and the maximum depth of the burial was considered to be up to 15 km (Şengör & Yılmaz 1981). The massif was then later exhumed by detachment faults during Miocene time (Bozkurt & Park 1994, 1997a, 1997b, 1999; Emre & Sözbilir 1995; Hetzel *et al.* 1995a, 1995b, 1998; Koçyiğit *et al.* 1999; Bozkurt 2000, 2001a, 2001b, 2002, 2003; Seyitoğlu *et al.* 2000, 2002; Işık & Tekeli 2001; Gessner *et al.* 2001b; Işık *et al.* 2003; Özer & Sözbilir 2003; Rimmelé *et al.* 2003a, 2003b; Ring *et al.* 2003; Bozkurt & Sözbilir 2004). The E–W-trending graben systems of western Anatolia are thought to have been initiated in the Early Miocene and are still active (Seyitoğlu *et al.* 1992). But, recent works suggest that the grabens commenced to existance during the Pliocene and the extension in western Anatolia is expressed by two-stage episodic event (see Koçyiğit *et al.* 1999; Bozkurt 2000, 2001a, 2001b; Bozkurt & Sözbilir 2004 for further information).

In the present study, the stratigraphy of the core and cover series of the Menderes Massif was studied in the Bafa and Kavaklıdere areas (Figure 1), and the contact relations of these two successions were examined. In these two different areas, 1/25,000 scale geological mapping has been done. The so-called core rocks are typically gneissic granites in the Bafa area, forming the pronounced granitic topography of the Beşparmak Mountains. The contact of the gneissic granites is clearly observed and is traceable laterally for long distances. The map pattern and detailed characteristics of this boundary provide evidence that bears on the genesis and emplacement mechanism for granites in the massif. The Bafa area is also of particular interest because the gneissic granites and the stratigraphically well-known Mesozoic carbonate succession occur in close proximity to one another, and well-defined stromatolitic dolomites of the lower Triassic, and rudist-bearing middle and bioclastic and pelagic facies of the uppermost part of the carbonate succession are recognized in spite of metamorphism.

In the Kavaklıdere area, our mapping began in the vicinity of Göktepe (Figure 1), where the cover series has been dated palaeontologically in some detail (Önay 1949; Konak *et al.* 1987). In the present study, the rock units cropping out near Göktepe were traced toward the granite contact. Although the metamorphic grade increases and fossils are not preserved near the granite body, the units are still recognisable on the basis of lithological and facies characteristics.

In this study, we also collected 18 relatively homogeneous samples from the gneissic granites in the Bafa area and analysed them geochemically to elucidate their tectonic settings.

Bafa Area

The Bafa area is located in the southwestern part of the Menderes Massif (Figures 1 & 2). The northern part of the study area is underlain by gneissic granites and, in the southern and western parts of the area, a thick succession of mica schists and marbles crops out (Figures 3 & 4).

Metasedimentary Succession

Along the Zobran Peninsula (Figure 3), a nearly complete Mesozoic carbonate succession is present. The lower parts of this succession consist of yellowish-grey dolomite, green calc-schist and grey mica schist, and this intercalation passes gradationally downward into mica

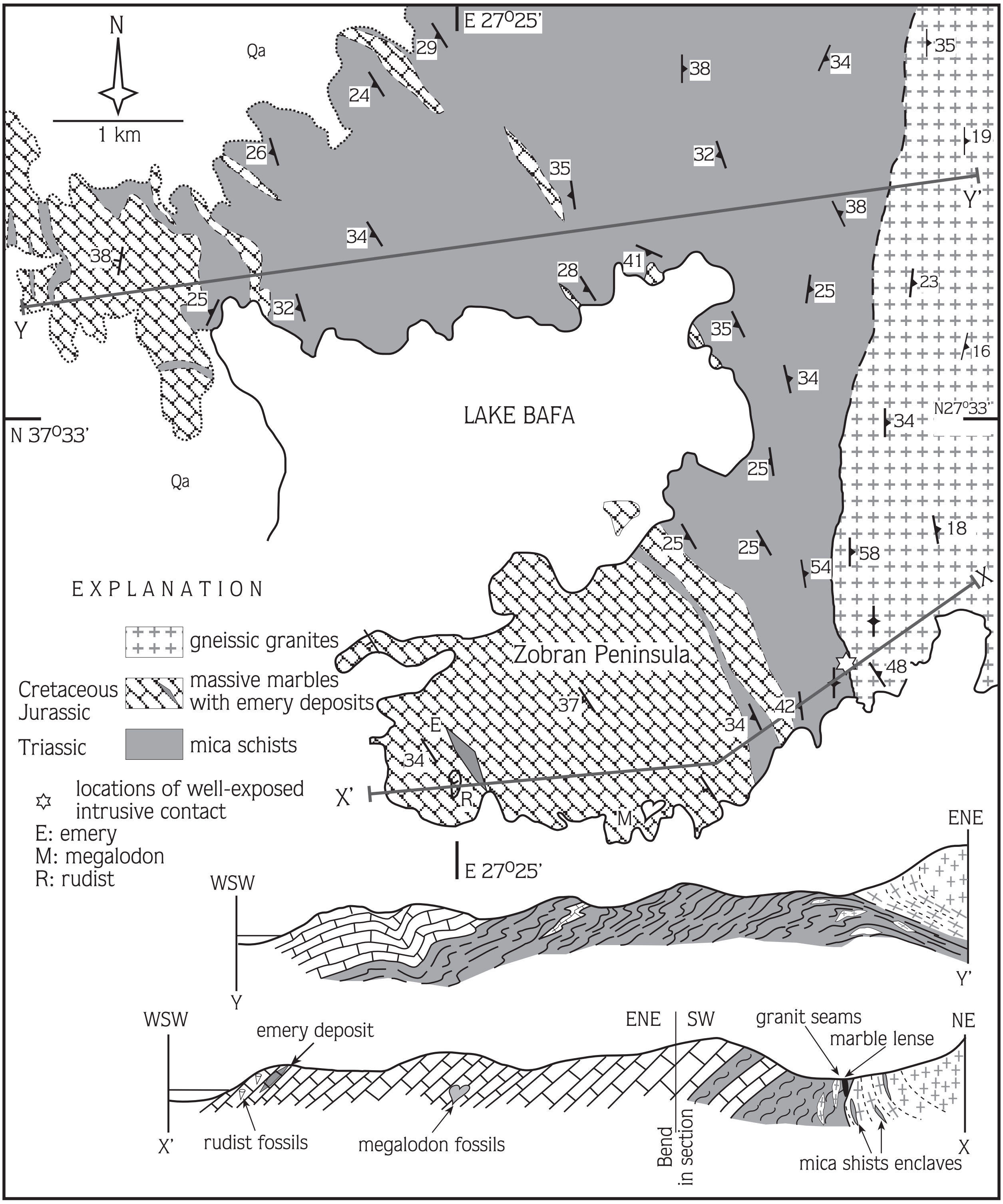

Figure 3. Geologic map and cross sections for the northern margin of the Lake Bafa area. See Figure 2 for location.

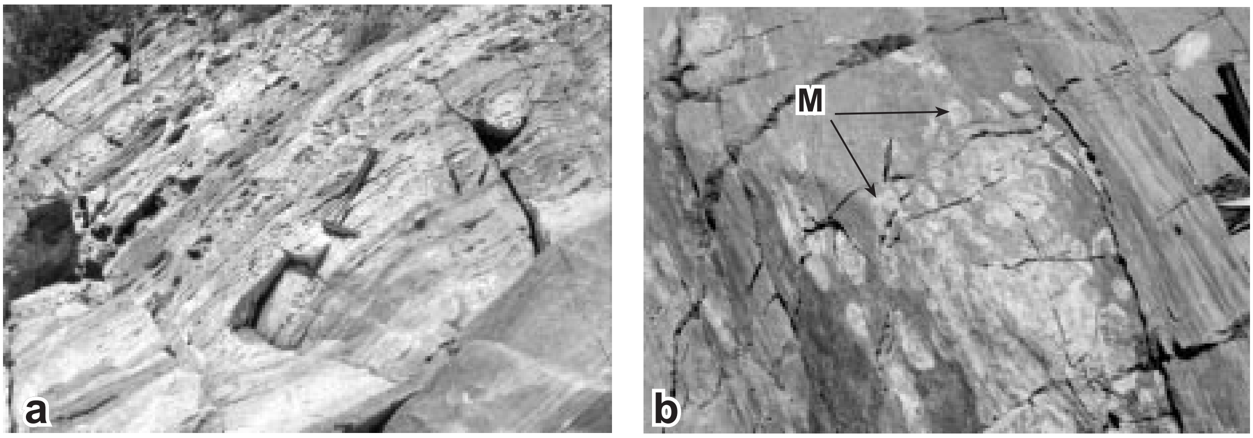

Figure 4. Photographs of the (a) primary structures in the carbonate section of the Menderes Massif and (b) megalodon fossils (M) (Zobran Peninsula). Hammer in (a) is 33-cm long; pencil in (b) is 13-cm long.

schist and quartz-mica schist with scarce lenses of yellow marble (section X–X' in Figure 3). There the lowermost mica schists of the platform sequence are cut by the gneissic granites. This crosscutting relationship will be described below. Overlying this lower metaclastic succession are light grey dolomites and laminated dolomitic marbles. Primary stromatolitic laminations are still recognisable in the dolomitic horizon (Figure 4a). The stromatolitic dolomite horizon contains massive light-grey marble beds. From one of these massive marble beds we have collected thick-shelled bivalve fossils, probably *Megalodon* sp. (Figure 4b), which may indicate a Late Triassic–Jurassic age. The upper parts of the succession consist of grey and dark-grey massive marbles with poorly preserved rudist remains (section X–X' in Figure 3). Interbedded with massive marbles is a 20-m-thick emery lens that extends laterally for 300 m. This part of the carbonates resembles the Upper Cretaceous zone of the Mesozoic Menderes platform (Figure 2). The uppermost part of the Mesozoic carbonates is shown in Figure 5, in which massive grey marbles host an emery lens and contain poorly preserved rudists. These marbles are overlain by intraformational limestone conglomerates which pass gradationally upward into pink pelagic marbles. This uppermost section of the Mesozoic carbonate platform is typical in the Menderes Massif, and the red limestones yield Maastrichtian foraminifers and nannoplankton (Özer *et al.* 2001). In the map area, the red and pink pelagic limestones are overlain by green mica schists with quartz conglomerate lenses which resemble the Selçuk Formation of Late Cretaceous-?Palaeocene age (Erdoğan & Güngör 1992; Güngör 1998). Above these Upper Cretaceous mica schists is a carbonate nappe, in the lateral continuation of which many emery lenses have been excavated. This is a good example of imbrication within the carbonate section of the Menderes platform along its southern border.

Within the lower parts of the Mesozoic carbonates, there is a mafic volcanic lens (Figure 5), and this horizon was reported to be Late Triassic in age in the Kavaklıdere area by Güngör & Erdoğan (2001). The Mesozoic carbonates vary in thickness laterally and interfinger with mica schists along strike as shown in Figures 3 & 5.

Gneissic Granites

Gneissic granites crop out to the north and northeast of Lake Bafa (Figure 2). The granites are homogeneous and spheroidally weathered; ~N–S-trending vertical cross joints are recognisable at long distances and form the most diagnostic structure of the gneissic granites. Planar and linear fabrics are present in every outcrop and the same penetrative foliation and lineation are observed in all road cuts within the Beşparmak Mountains. The intensity of deformation is uniform throughout the gneissic gneisses, from the border zone to areas many kilometres within the granite body. Deformation of the granites was described by Bozkurt & Park (1997b) and Gessner *et al.* (2001a).

The granites preserve holocrystalline texture with large K-feldspar porphyroclasts and slightly deformed megacrysts (up to 5 cm in length) (Figure 6a, b). These rocks are two-mica granites and are generally leucocratic. In places, biotite content increases and, thus, the granitic rocks become melanocratic. The compositional changes are diffuse and are not related to different phases of magma emplacement. In the contact zone and within the granite body, widespread engulfment and resorption of the mica schists (country rocks) are observed. The mica schists are strongly melted and digested by the granites, and constitute more than 50 volume percent of the outcrops of the granitic mass in the Çine region. Along the contact zone of the granites in the Zobran Peninsula, resorbed mica-schist enclaves are characteristic (Figure 7a, b). Near the resorbed zone, the granite is melanocratic because of high biotite content, and becomes leucocratic away from the resorption zones, indicating strong digestion of the country rocks by the granitic melts.

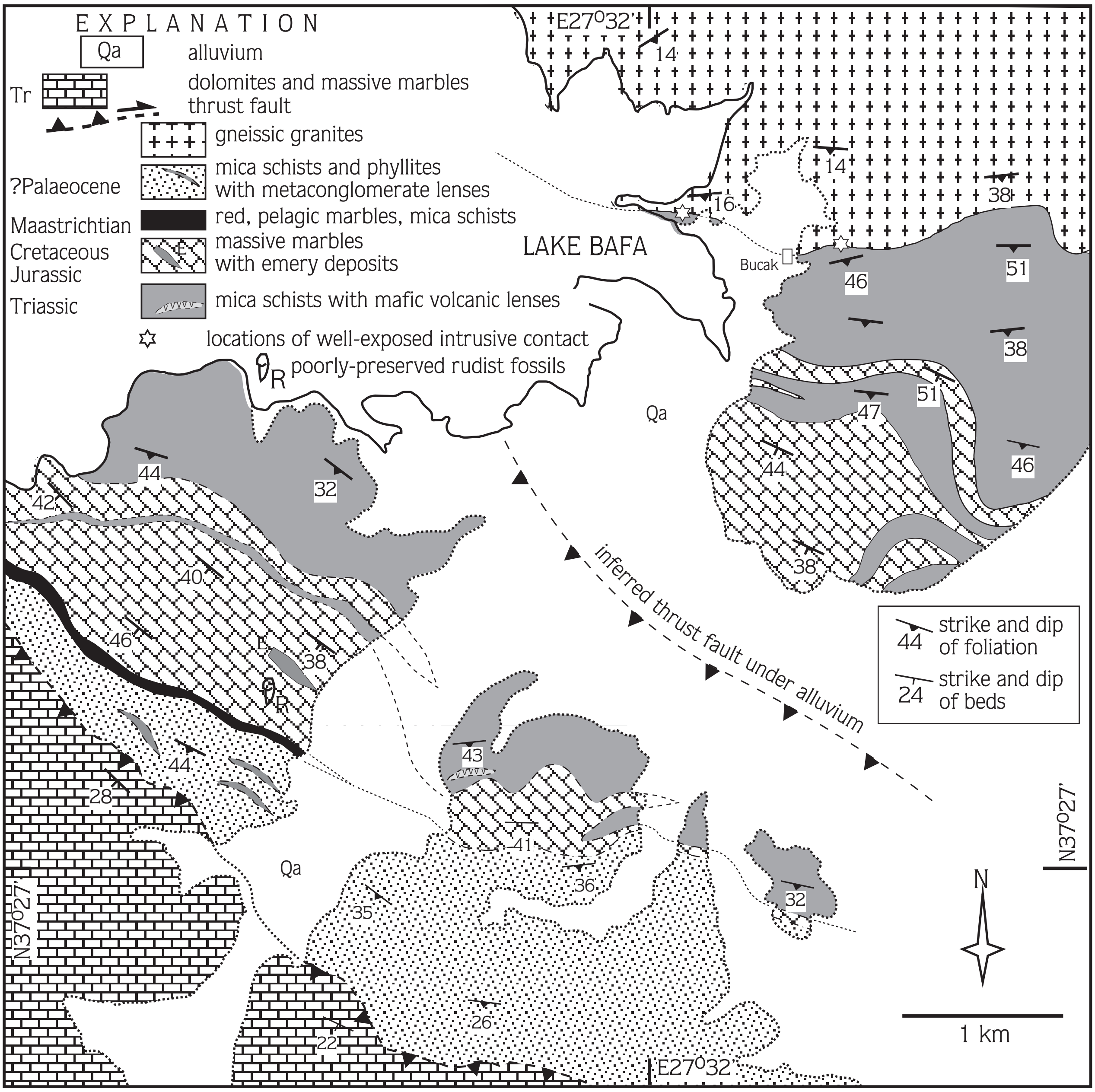

Figure 5. Geologic map of the eastern margin of the Lake Bafa area. See Figure 2 for location.

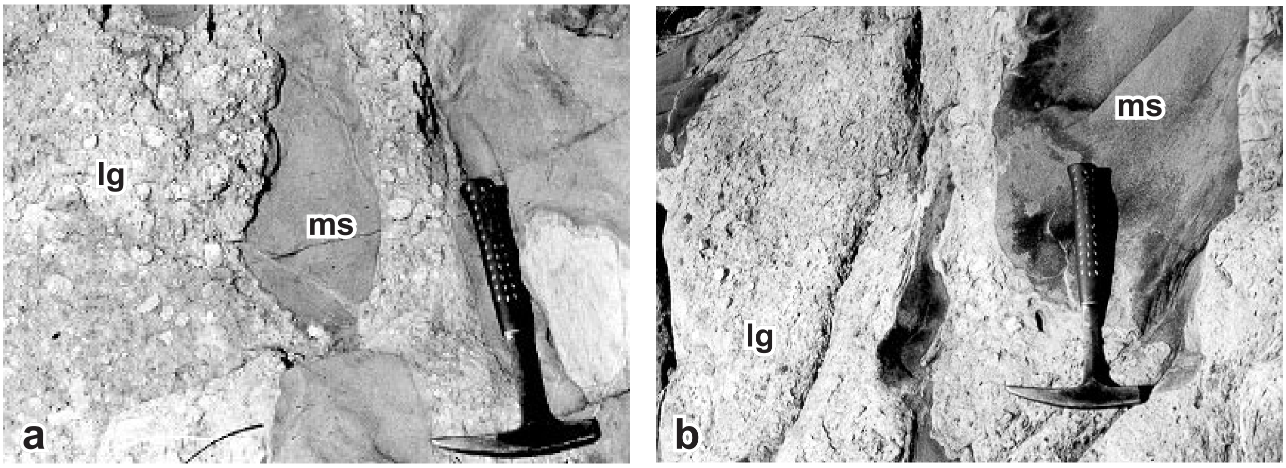

Figure 6. Photographs of mica-schist enclaves (ms) within coarse-grained leucocratic granite (lg). Note the large feldspar porphyroclasts in the leucogranites. Hammer is 33-cm long.

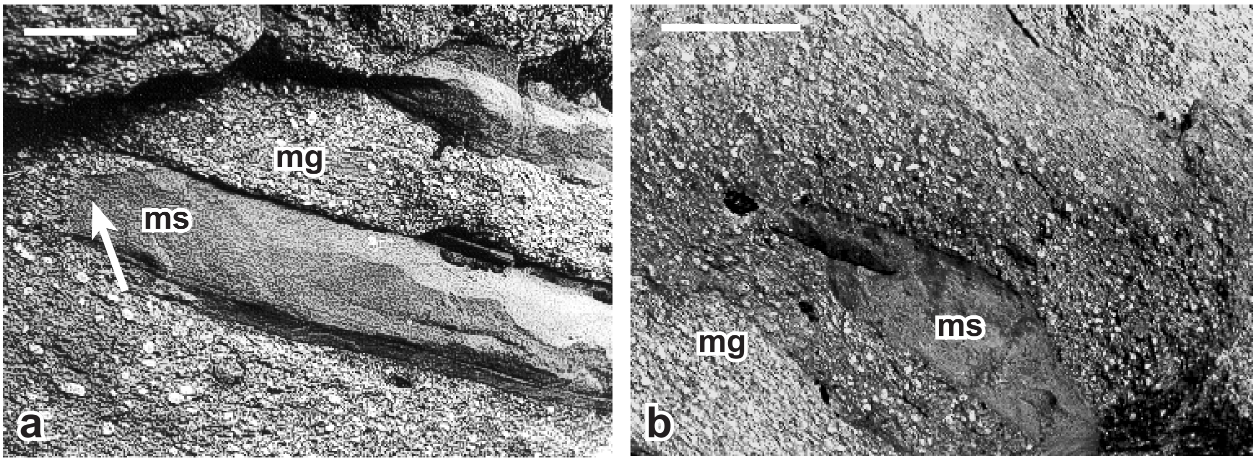

Figure 7. Photographs of partly digested mica-schist enclaves (ms) within melanocratic granite (mg). The scale bar is 15-cm long.

Although the contact zone of the granite is ill-preserved, there are areas where intrusive and crosscutting relations are clearly observed (locations marked with stars on Figures 3 & 5). The granites intrude and cut the surrounding mica schists; they also include schist enclaves of variable sizes (Figure 8a). Some enclaves have sharp boundaries (Figure 8b) where most are consumed by the granites (Figure 8c). As seen in Figure 8d, enclaves of mica schist are also cut by thin granitic veins.

Within the country-rock mica schists, there are fine-grained, leucocratic granitic seams, and toward the granite contact the frequency of these seams increases, as is seen to the NW of Bucak village (Figure 5).

The contact along the Zobran Peninsula is intrusive and is characterised by abundant enclaves of schist. At this location, a yellow dolomitic marble lens is cut and engulfed by the granite at the contact (Figure 4a). These mica schists and yellow marble lenses pass gradationally upward into Mesozoic platform-type marbles suggesting a Triassic or Jurassic age for this metaclastic succession. The granites cut these metaclastic rocks and were emplaced syntectonically during metamorphism and deformation. The fold vergence of granitic seams

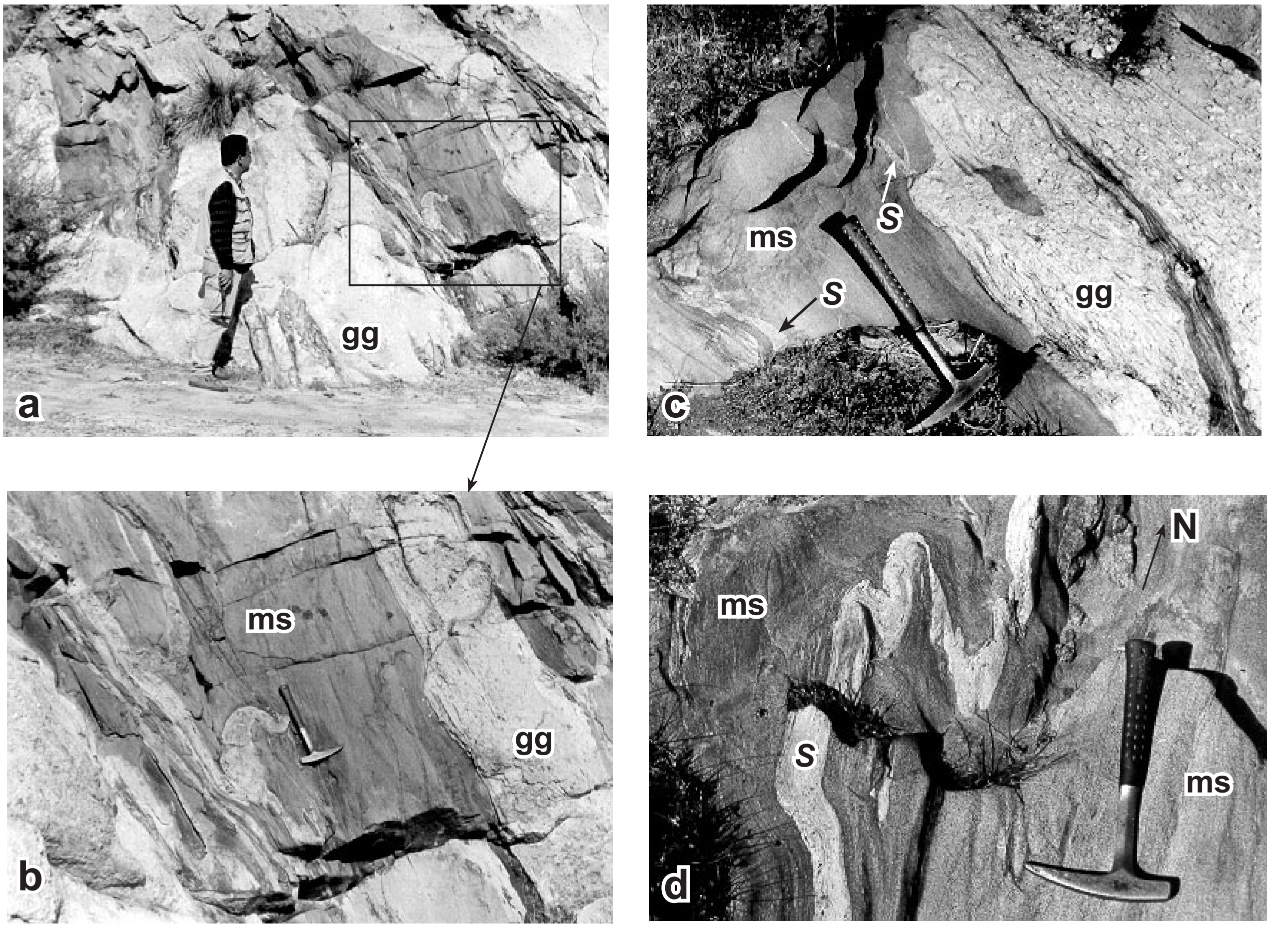

Figure 8. Close-up views from the gneissic granite and mica schist contact in the Lake Bafa area. (a) Igneous contact between gneissic leucocratic granites (gg) and the country-rock mica schists. The granites crosscut the main foliation in the schists; (b) leucocratic metagranites (gg) also occur as vein-like bodies intrusive into mica-schist enclave (ms); (c) a close-up view of the intrusive relationship between coarse-grained leucocratic granite and mica schist. Note local occurrence of thin granite seams (S, arrowed) crosscutting the main foliation in the schists; (d) a sill-like leucocratic granite seam oriented parallel to the foliation in the schist. The field relations are consistent with syntectonic emplacement. The folded structure is obvious; it is asymmetric with northern limbs thinned, indicating northward tectonic movement. Man in (a) is 1.70-m tall and hammer in (b-d) is 33-cm long.

indicates northward tectonic transport, and the northern limbs of mesoscopic folds are strongly attenuated (Figure 8d).

The contact between the granite and the structurally overlying mica schists dips 40º–50º southward near Bucak (Figure 5), whereas it dips eastward or is nearly vertical in the Zobran Peninsula; farther north the same boundary is vertical or overturned (Figure 3). Along the overturned boundary, the granite is intrusive into the mica schists and leucocratic aplitic veinlets occur characteristically in the mica schists. Similar relationships have also been documented by Mittwede *et al.* (1995a, 1995b, 1997). Also, about 5 km away from the granite contact, a leucocratic granite apophysis is intrusive into the schists containing a lense-shaped marble (Figure 2). The marble-bearing schists, at this location, are similar to marble-schist intercalations of the Mesozoic association.

Toward the contact of the granitic body in the Bafa area the grade of metamorphism increases most notably in the mica schists (Başarır 1970). The schists are typically rich in pink almandine and contain coarse mica minerals (biotite and muscovite) within a 300 m-wide zone along the granite contact. The index of crystallinity in the mica schists is markedly high. Close to the granite contact there are garnet felses (Figure 9), which are mica schists with red almandine crystals up to 8 mm in diameter; garnets make up 40–60% of the rock. The garnet felses are exposed along the entire boundary of the gneissic granites along the southern flank of the Menderes Massif; they are formed in association with the intrusive body. Both biotite-rich mica schists with abundant granite veinlets/lenses, and red almandine-bearing garnet-mica schists typically occur near the granite contact. Granite lenses (10–20 cm in diameter) first appear in the mica schists within a 300-m-wide zone along the granite contact and become abundant towards the granite.

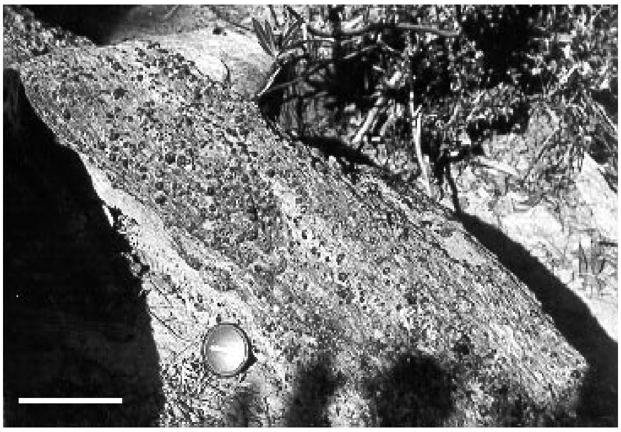

Figure 9. Close-up view of garnet-fels along the contact between gneissic granite and mica schist to the north of Irmadan village (Figure 10). Diameter of lens cap is 5 cm.

Another characteristic feature of the contact zone is that the boundary is nowhere sharp, but rather irregular with mica-schist patches/zones interfingering with granites at all scales. Within such zones, aplitic veins, granitic veinlets concordant with foliation in the schists and crosscutting granitic veins are common all along the gneissic granite–mica schist contact with no exception.

Both the granites and surrounding mica schists are foliated, but the boundary zone preserves its primary intrusive nature, and no sheared zones are present as suggested by Bozkurt & Park (1994), who proposed that this zone corresponds to a south-facing extensional shear zone and that the southern Menderes Massif is an incipient core complex. In the area between Lake Bafa and Bağarası, the boundary between the schists and the gneissic granite is not only diffuse and gradational, but also trends NNE and become vertical and is overturned locally (Figure 3); this observation is not consistent with the geometry of a proposed south-dipping detachment.

Kavaklıdere Area

In the Kavaklıdere area (Figure 1), a geological map of the Göktepe area (about 25 km east of Kavaklıdere outside of the map area shown in Figure 10) and its close vicinity was prepared. In the Göktepe area, Menderes Massif comprises low-grade metamorphic (lower greenschist facies) rocks; the metamorphic grade is so low that fossils are preserved and can be observed easily on weathered surfaces. The metamorphic sequence commences with black limestones, phyllites, cherts and pink-grey quartzites that make up the fusulinid-bearing Permo-Carboniferous Göktepe Formation (Figure 2). Black limestones that form the uppermost part of the Göktepe Formation, just below the overlying Mesozoic succession, yielded *Epimastopora* sp., *Gymnocodium bellerophontis, Gymnocodium* sp., *Globivalvulina* sp., *Mizzia velebitana, Protonodosaria* sp., *Pacyphloia ovata, Stafella* sp., *Nankonella* sp., *Baisalina* sp., *Hemigordius* sp., *Agathammina parilla*, *Dagmarita chanakchiensis, Dackeralla* sp. *Frondina permica* fossils which are consistent with a latest Permian age. The crystalline limestones, however, contain coral, fusulinid and crinoid remains of possibly Carbonifereous–Permian age (Önay 1949; Konak *et al.* 1987). The black cherts are thinly bedded, and are interbedded with phyllites and limestones. The unit is overlain by Upper Triassic violet sandstones, quartz conglomerates and phyllites that grade upward into a thick platform-type dolomitic limestone succession. In the lowermost part of the dolomitic limestones, there is a mafic volcanic horizon where volcanic rocks are intercalated with thinly bedded yellow limestones (Güngör & Erdoğan 2001). The limestone intercalations yielded *Lamelliconus multispirus*, *Lamelliconus* sp., and *Aulotortus* sp. fossils that suggest a Late Triassic age. The platform carbonates host emery lenses, and are interbedded with rudist-bearing Upper Cretaceous limestones (Özer *et al.* 2001). Atop the carbonate succession, there are thinly bedded pelagic marbles and mica schists with mafic volcanic and metaserpentinite blocks (Konak *et al.* 1987). This unit comprises the uppermost part of the Menderes platform and is of Late Cretaceous age (Konak *et al.* 1987; Erdoğan & Güngör 1992; Özer 1998). The fossiliferous Palaeozoic units in the Göktepe region continue laterally

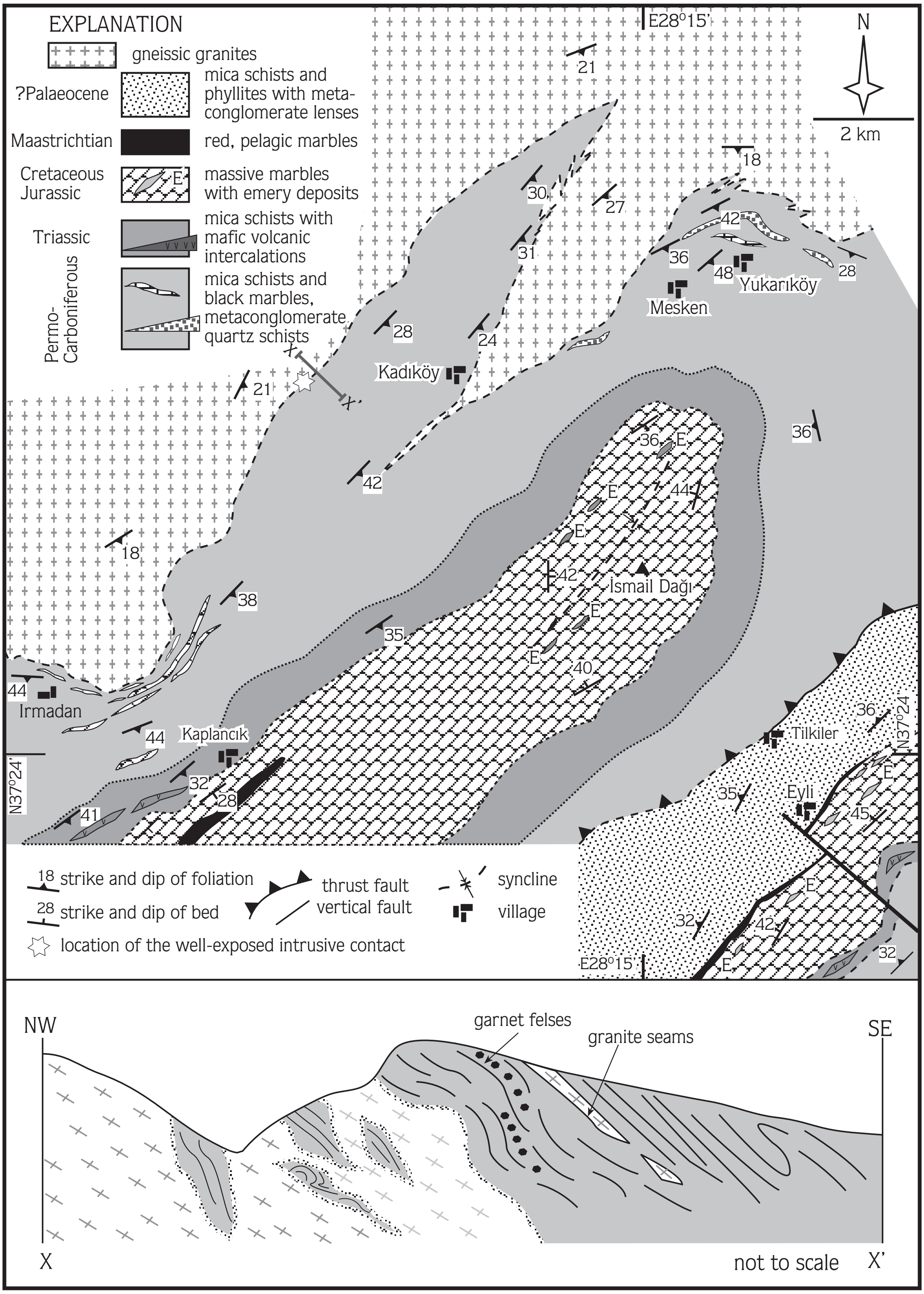

Figure 10. Geologic map of the Kavaklıdere area.

toward the granite contact (Figure 10). Near the gneissic granite, the metamorphic grade increases dramatically and there are no reported fossils; nevertheless, their facies and stratigraphic order are easily recognised.

In the map area (Figure 10), İsmail Dağı is underlain by Mesozoic marbles, the upper parts of which contain emery zones. Atop these carbonates, pink pelagic marbles and metaserpentinite-bearing Late Cretaceous mica schists are present. West of Kaplancık village (Figure 10) below the Mesozoic carbonates, there are mafic volcanic lenses within the metaclastic rocks, which resemble the Upper Triassic detrital unit of the Göktepe area (Güngör & Erdoğan 2001). Below the metaclastic rocks lie black limestones, black cherts, dark-grey mica schists and quartzite intercalations – typical facies of the Permo-Carboniferous Göktepe Formation. In this area, limestones are recrystallised.

At the base of the Göktepe Formation, there are conglomerate horizons around Mesken and Yukarıköy villages (Figure 10), which were interpreted, by Konak *et al.* (1987), as basal conglomerates of the cover series. However, these conglomerate horizons are laterally discontinuous and lensoidal in shape, pinching out in the quartz-mica schists of the study area. The discontinuous conglomerate lenses are repeated both vertically and laterally and they are not confined to a distinct horizon. They appear to be formed as channel-fills in the quartz-mica schist matrix and do not resemble a basal conglomerate. These metaconglomerates include light-grey, elongate and deformed blocks and clasts (Figure 11a). Original textures are still preserved in the deformed particles (Fig 11b) and thin-section study shows that they are porphyritic-volcanic rock fragments. Phenocrysts of easily recognisable euhedral feldspar and quartz grains are set in a light-grey matrix. The pebbles display typical volcanic texture (Figure 11b), and the rocks are identified as porphyritic rhyolites. We speculate that these pebbles are similar to rhyolitic volcanic rocks of the Lower Cambrian succession known as the Sandıklı porphyroids (Erdoğan *et al.* 1997, 2000, 2001) in the Sandıklı area of the Afyon province which lies in Taurus Mountain Range (Gutnic *et al.* 1979). The conglomerates are polygenic and comprise dark grey chert and quartzite clasts in addition to the leucocratic rhyolites. (there are also quartz-tourmaline [probably tourmalinite] pebbles!)

The quartz-mica schists continue stratigraphically downward until the gneissic granites, where the granites are intrusive. Along the contact, the granites contain abundant enclaves of metaclastic rocks. To the west, the granite cuts the conglomerate horizons and intrudes the Permo-Carboniferous Göktepe Formation. For example, along the old Çine-Yatağan road, the granite intrudes the black chert, phyllite and limestone intercalations of the Permo-Carboniferous Göktepe Formation.

The contact zone of the gneissic granites is best observed along a section shown in Figure 10. Thick

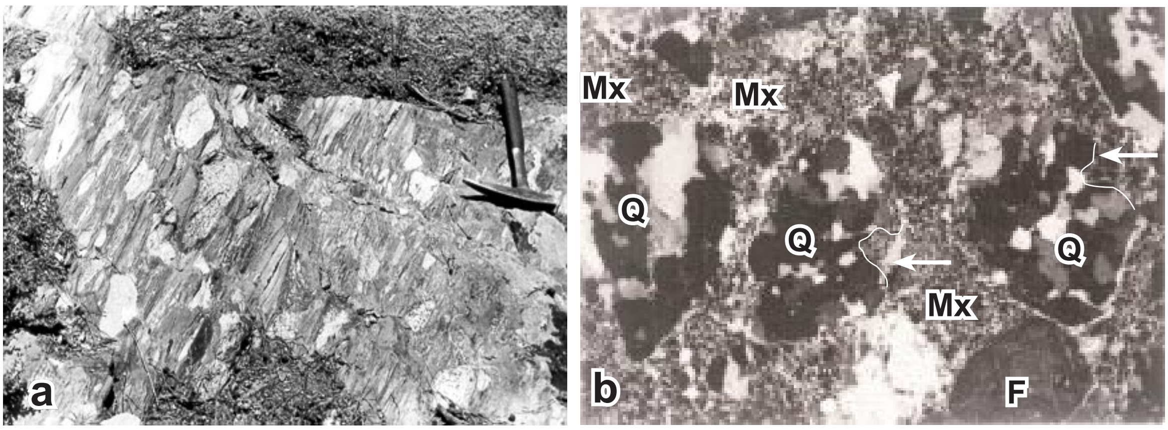

Figure 11. (a) A close-up view of metaconglomerates in the metasedimentary sequence of the Menderes Massif in the Kavaklıdere area (hammer is 33-cm long); and (b) photomicrograph showing porphyritic texture of the felsic metavolcanic pebbles in the metaconglomerates. Please note that quartz (Q) and feldspar phenocrysts (F) are surrounded by a microcrystalline matrix (Mx), and a large quartz phenocryst in the central part of the photograph is resorbed (arrowed). Original undeformed matrix of the volcanic rock is preserved in this embayed area (see arrow). Width of photo is 2 mm.

quartz-mica schists below the Göktepe Formation are exposed at this location. Toward the contact zone, seams of leucocratic gneissic granite appear in the schists and their frequency increases toward the granite; finally, at the contact, large enclaves of mica schist occur in the granite. Crosscutting relationships are clearly seen along the contact where granitic veins are common and intrude both the enclaves and the country rocks. As in the Bafa area, garnet felses are present in the contact zone. Foliation is characteristic both in the contact zone and within the granite body. The granites are of the two-mica type and the relative amounts of white and black micas varies over short distances so that the colour of the granite changes from light grey to dark grey. These changes are seen even around engulfed enclaves with diffuse boundaries.

Geochemistry of the Gneissic Granites

Eighteen samples of granitic rocks from the Bafa area were analysed (Table 1). Homogeneous granitic outcrops away from assimilated mica-schist zones were chosen for sampling. Three samples were collected from the aplitic phases of the granites that occur in the contact zone and within the country-rock mica schists. Two samples were taken from the typical augen gneisses, 2 km away from the contact zone within the granite body. Five samples of grey and four samples of leucocratic granite were collected along a traverse that began at the contact zone and continued 10 km into the granitic body. An additional three samples from tourmaline-bearing, muscovite-rich and biotite-rich granites were collected.

The major-oxide analyses were made by atomic absorption spectrophotometry, and the trace elements were analysed by X-ray fluorescence in the geochemistry laboratory of the Geological Engineering Department of Dokuz Eylül University.

In the nomenclatural diagram of Debon & Le Fort (1983) that uses normative values of Si, Ca and alkali components, two aplite samples are defined as tonalite, and the rest (including the third aplite) cluster within the granite field (Figure 12a). In the diagram of Maniar & Piccoli (1984) which uses major-oxide contents, all of the samples plot as peraluminous granites (Figure 12b).

The tectonic setting of the samples appears to be syn-collisional based on their major-and trace-element contents (Figure 12c, d). The major-oxide compositions of the samples support an S-type classification of the granites (Figure 12e) on the diagram of Chappell & White (1974) in agreement with the results of Bozkurt *et al.* (1992, 1993, 1995).

In both the nomenclature and tectonic-discrimination diagrams, the granite samples cluster together and do not show pronounced scatter, indicating close geochemical affinity and genetic relationships, as indicated also by field studies.

Discussion and Conclusions

In the Kavaklıdere area, the lowermost part of the Menderes metamorphic rocks consists of a very thick quartzite and mica schist intercalation. There are lensoidal channel-fill conglomerate horizons in the upper part of this detrital succession. The conglomerates include abundant rhyolite pebbles which were probably derived from Lower Cambrian units of the Taurus Range (Erdoğan *et al.* 1997, 2000, 2001). Although the rhyolite clasts are deformed, they still display preserved primary textures and there is no indication of an earlier high-grade metamorphism as envisaged for the so-called core association (Konak *et al.* 1987; Candan 1994a, 1994b, 1995, 1996). Overlying the metaclastic sequence is an alternation of quartzites, mica schists, black marbles and black cherts belonging to the Late Palaeozoic Göktepe Formation. The Mesozoic succession overlies unconformably the Göktepe Formation and is represented by a sequence of detrital sediments and platform-type marbles. In the Bafa area, only the detrital and overlying carbonate rocks of the Mesozoic succession are present.

The gneissic granites syn-tectonically intruded the lower parts of the Triassic detrital sequence in the Bafa area and the Upper Palaeozoic sections of the Kavaklıdere area during the main Menderes metamorphism, which occurred in Late Cretaceous–Early Cenozoic time. The granites strongly assimilated the country-rock mica schists, and kilometers-long, strongly resorbed schist patches are abundant in the granite body. In most outcrops, it is quite difficult to estimate how much initial melt and how much country rock were involved in the production of the final granite bodies. The geochemical studies we have done, as well as earlier work (Bozkurt *et al.* 1993, 1995), indicate a peraluminous, S-type classification of the granites, suggesting an origin from a sedimentary source.

Table 1. Whole-rock analytical results of major oxides and trace elements of the gneissic granites in the Bafa area.

	augen gneiss		granite					biotite granite	leucocratic augen gneiss				muscovite granite	tourmaline granite		aplite		
	95-39	95-40c	95-43	95-67	95-64	95-61	95-43b	95-45	95-46	95-47	95-49	95-59	95-63	95-65	95-66	95-48	95-62	95-68
SiO_2	71.88	70.12	72.79	74.23	77.74	70.93	74.95	74.60	76.49	76.49	73.82	74.93	73.21	74.72	78.74	81.16	73.84	75.53
Al_2O_3	13.86	14.53	14.02	13.25	11.65	14.94	13.89	13.10	13.51	12.93	13.45	13.10	14.15	12.82	11.22	11.02	14.92	13.25
$Fe_2O_3^{(t)}$	3.46	3.53	1.69	1.51	1.39	1.80	1.00	2.08	1.30	2.08	1.47	1.59	1.03	1.33	0.94	n.d	0.64	0.82
MgO	1.10	1.06	0.43	0.25	0.23	0.31	0.66	0.36	0.38	0.44	0.44	0.30	0.36	0.15	0.10	n.d	0.28	0.14
CaO	0.17	0.22	0.34	0.44	0.39	0.73	0.26	0.45	0.25	0.48	0.32	0.31	0.27	0.45	0.32	0.20	0.60	0.27
Na_2O	2.46	3.69	3.09	3.26	2.83	3.07	3.89	2.87	3.69	2.66	3.14	2.87	3.43	3.00	2.58	6.16	6.77	3.52
K_2O	5.12	4.45	6.08	6.39	5.02	7.04	4.20	5.18	5.61	5.58	6.36	5.80	6.62	5.96	5.14	0.57	1.53	5.18
TiO_2	0.49	0.48	0.18	0.18	0.13	0.24	0.19	0.18	0.24	0.21	0.21	0.16	0.10	0.13	0.10	0.21	0.00	0..00
MnO	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	n.d	0.01	0.01
LOI	1.39	1.32	0.67	0.40	0.42	0.69	0.80	0.74	0.60	0.83	0.66	0.75	0.42	0.61	0.41	n.d	0.63	0.73
Total	99.94	99.41	99.3	99.92	99.81	99.76	99.85	99.57	102.8	101.78	99.88	99.82	99.6	99.18	99.56	99.32	99.22	99.45
Nb	17.4	19.1	11.9	7.9	12.9	13.6	17.8	12.0	16.7	12.3	9.8	11.3	17.4	20.4	12.5	10.7	22.4	16.1
Rb	159.4	142.6	184.0	227.6	269.7	230.1	152.6	327.1	163.3	177.3	165.2	250.3	327.1	362.9	327.9	3.5	50.7	352.3
Sr	47.8	64.5	73.7	57.7	29.7	79.3	55.0	54.6	82.2	62.0	79.9	56.5	50.0	38.4	27.2	65.4	98.9	30.2
Y	48.3	38.0	27.0	46.1	40.7	54.4	41.3	32.3	35.7	42.6	35.0	37.1	43.6	57.0	52.9	4.1	3.8	38.6
Zr	201.3	165.2	84.5	91.2	75.4	107.1	131.7	93.2	130.7	115.1	97.0	82.6	70.3	110.3	87.9	123.2	42.2	49.2
Ba	594.2	574.6	346.1	244.2	132.4	535.3	295.5	326.1	367.1	347.7	502.0	291.7	301.3	168.1	94.2	-	487.7	29.0
U	2.3	14.7	11.7	12.5	13.2	-	15.5	40.1	9.5	4.4	11.6	11.0	40.1	4.2	3.6	6.4	26.4	15.0
Th	-	-	-	-	-	-	6.2	4.1	-	-	9.3	8.9	4.1	-	-	10.4	-	7.5
Ga	21.2	19.0	34.7	20.0	17.5	20.8	18.5	19.4	21.2	15.6	13.8	20.1	22.9	19.4	12.6	17.9	17.9	23.5

Note: $Fe_2O_3^{(t)}$ = Total iron

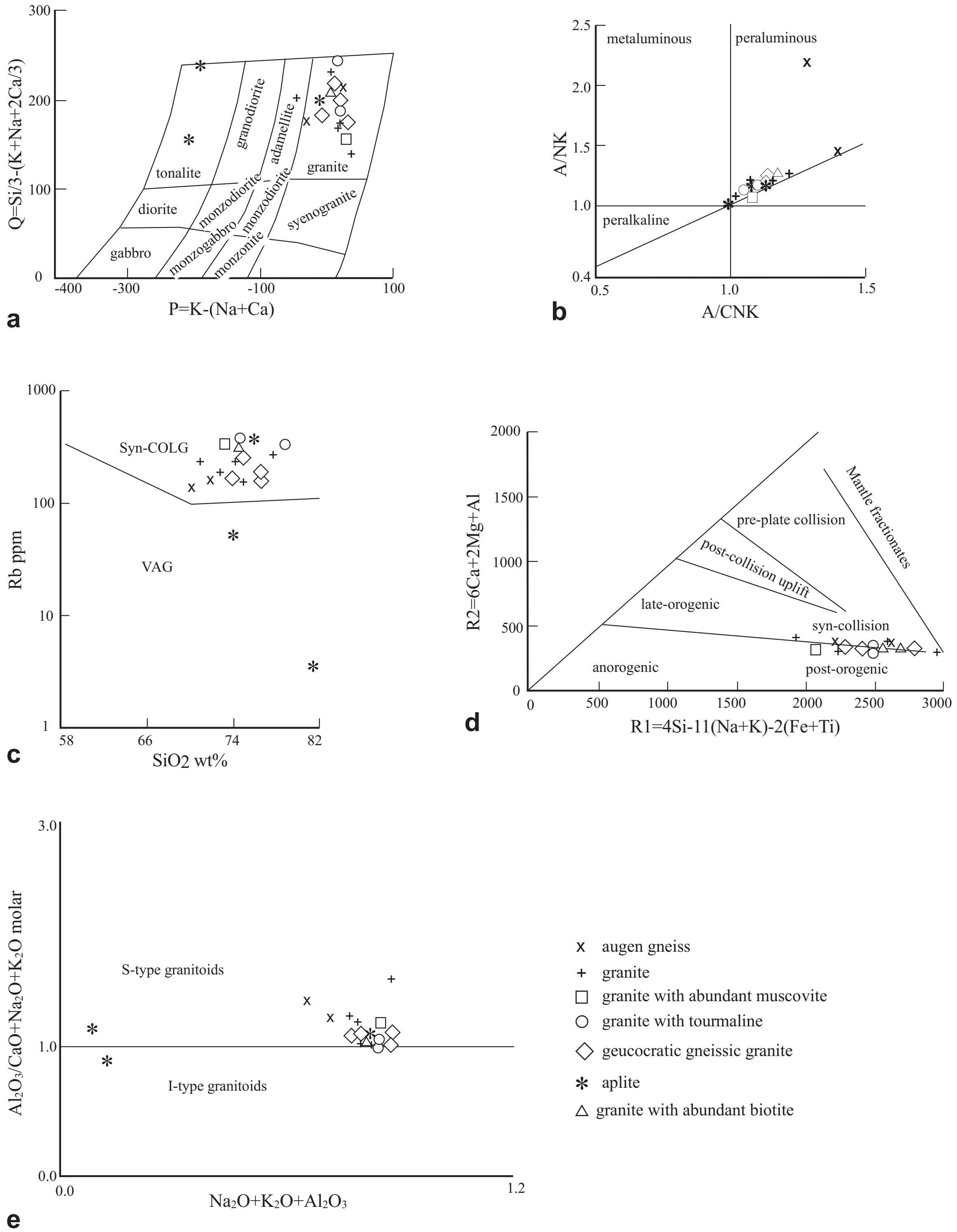

Figure 12. Geochemical discrimination diagrams for Menderes granites based on major- and trace-element contents. (a) Q vs P discrimination diagram after Debon & Le Fort (1983); (b) Maniar & Piccoli (1989); (c) Rb vs SiO_2 diagram after Pearce *et al.* (1984); (d) tectonic discrimination diagram after Batchelor & Bowden (1985); (e) total alkali diagram after Chappell & White (1974).

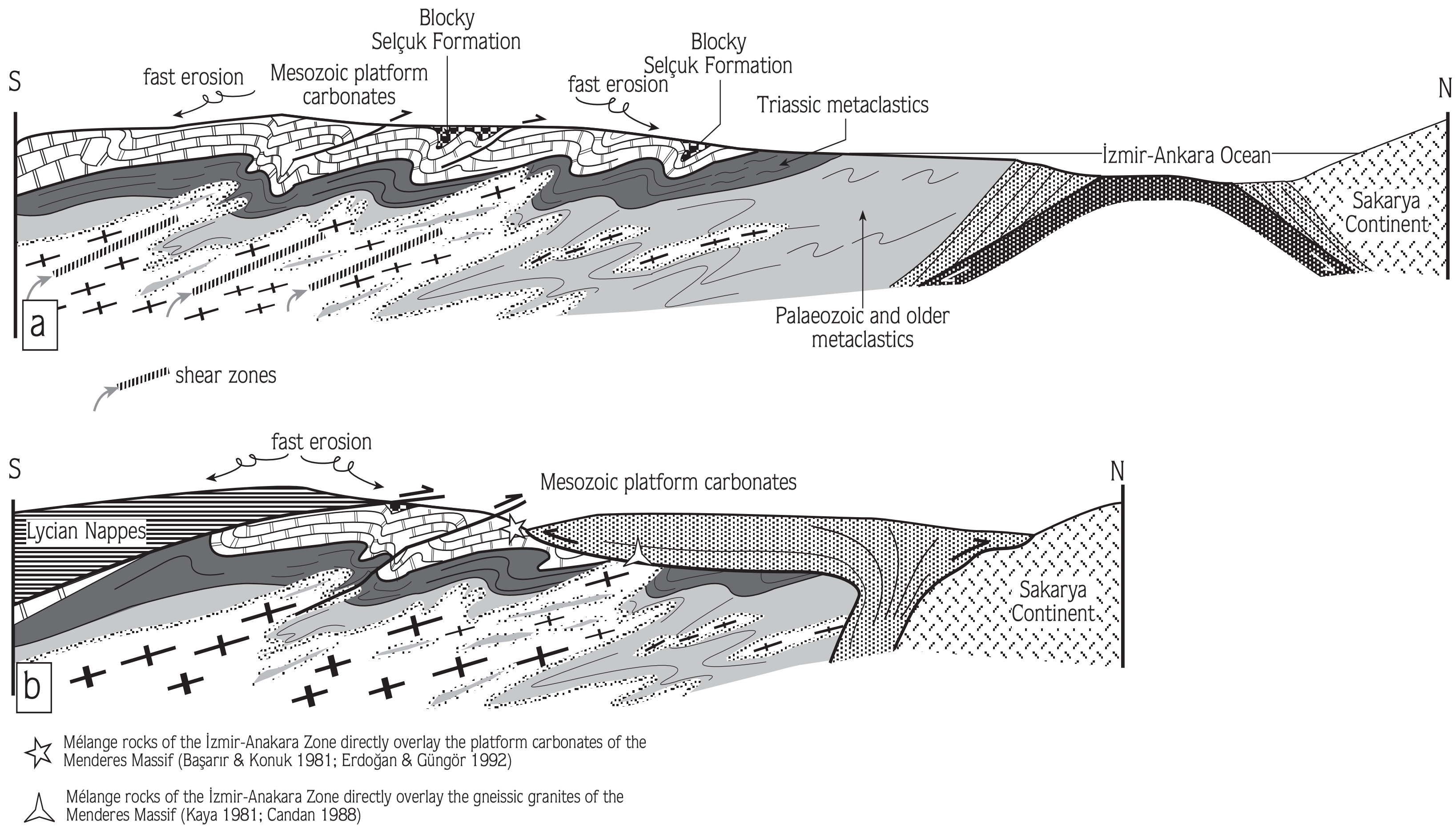

Figure 13. Schematic cross sections illustrating mechanism of granite emplacement in the Menderes Massif.

The southern flank of the Menderes Massif in the Muğla region is characterised by large-scale, north-vergent overturned folds in the Mesozoic succession (Boray *et al.* 1973; Konak *et al.* 1987; Bozkurt & Park 1997a, 1997b, 1999; Rimmelé *et al.* 2003b). Within the granitic body, the same kind of overturned flow folding has been deduced from our large-scale mapping, indicating that the mica schists and gneissic granites are intercalated at map scale. Okay (2001) also noted stratigraphic and metamorphic inversions in the central part of the massif around Aydın and interpreted the dominant structure as a regional overturned recumbent fold. To the north, in the vicinity of Demiköprü Dam near Dibekdağ (Figure 1), low-grade mica schists underlie the gneissic granites and their boundary is quite diffuse, characterised by abundant granitic seams in the country rock. The gradational boundary zone is 4–5 km in width. The same overturned relations are observed along Bozdağ Mountain north of Ödemiş (Figure 1); there the gneissic granites overlie the mica schists and the gradational boundary is 4–5 km wide. This last area, where gneisses are interlayered with mica schists, has been interpreted as thrust packages (Candan 1995; Koralay *et al.* 2001), although their boundaries always occur as wide diffuse zone. In all of these areas, however, the dominant structures are overturned flow folds. The granitic melts syn-tectonically intruded along the cores of antiforms (Figure 13). The emplacement of granitic magma, which was accompanied by crustal-scale penetrative deformation and medium- to high-grade regional metamorphism, was aided by zone-melting along flow folds and shear zones. Syn-tectonic intrusion, crustal-scale shearing and folding produced strong assimilation of the detrital country rocks.

In regions of magma emplacement, the grade of the regional metamorphism becomes higher, passing into a magmatic stage within the granitic bodies. Within the granitic bodies strongly assimilated mica-schist patches, engulfed diabase and spheroidal mafic bodies and scarce marble lenses that escaped digestion are preserved. From these partly resorbed mafic bodies, granulitic and eclogitic metamorphic facies have been described mostly as relict parageneses and have been attributed to Precambrian events (Candan *et al.* 2001). Any metamorphic facies or events described from the granitic-magma emplacement zones would be ill-advised, and the high-grade metamorphic events defined for the Menderes Massif inside the greissic granites would need careful reexamination.

In only a few areas, such as Lake Bafa and Kavaklıdere, the boundary between the granites and mica schists is as narrow as 300–500 m and crosscutting relationships are clearly observed. In other areas, this boundary is as wide as 5 km and is characterised by gradational zones with centimeters- to tens-of-meters thick granites seams which show increasing abundance toward nearby granitic bodies. In the Çine region, sillimanite-bearing brown rocks with pronounced polygonal texture (previously termed “leptites”; Dora *et al.* 1988) are abundant. In fact, they are migmatites that were nearly melted and crystallised with a polygonal texture. Zircons from these migmatites and from granites that clearly cut the same rocks yield nearly the same ages (~540 Ma), as reported by Hetzel & Reischmann (1996) and Reischmann *et al.* (2000); this situation is due to resorption and rejuvenation of the earlier detrital rocks by granite melt. The same age discrepancies are noted along the southern flank of the massif between the quartzites and the gneissic granites. They have yielded nearly the same ages, and Reischmann *et al.* (2001) have tended to interpret these discrepancies as an indication of an unconformity, meaning that the 540 Ma granites were eroded and the quartzites deposited unconformably above them. However neither in that area nor anywhere else in the Menderes Massif are any metaclastic rocks found overlying the gneissic granites along a stratigraphic boundary; rather, the boundaries are intrusive and granites always cut the surrounding schists. The close zircon ages between the granites and the adjacent quartz-mica schists are most probably due to assimilation of the detrital succession by granitic melt and rejuvenation of the country rocks. The strong assimilation of country rocks is clearly noted in the results of zircon-age studies (Koralay *et al.* 2001). In every sample of granite collected from contact zones or from far inside the granitic bodies, zircon ages always show pronounced scatter.

The oldest parts of the Menderes metamorphics should be studied in areas away from gneissic granite intrusions. One of the best areas is the Mahmut Dağı region (Erdoğan & Güngör 1992) where Mesozoic marbles form a huge E–W-trending anticline, in the core of which there is a detrital succession consisting of quartzites, mica schists, cherts, scarce grey marble lenses and mafic metavolcanics, together attaining a thickness of 3–4 km.

During the main Menderes metamorphism, tectonic transport along the southern flank of the massif was northward as the geometry of large-scale folds and kinematic studies of the sole of the Lycian Nappes indicate (Boray *et al.* 1973; Konak *et al.* 1987; Bozkurt & Park 1997a, 1999; Arslan 2001; Rimmelé *et al.* 2003b). During this folding, granitic melts intruded the cores of antiforms at deeper crustal levels where remobilisation of crustal rocks was taking place (Figure 13). Emplacement of granitic melts produced additional thermal fronts in the core zones of antiforms in addition to the overall regional metamorphism. Tectonic transport accompanied by magma injection produced intensive penetrative deformation and stretching lineations throughout the massif.

The gneissic granites underlie a vast area of the Menderes Massif, and we believe that production of such a large volume of granitic melt requires, besides rejuvenation, some kind of subduction below the Menderes platform. In the northern part of the Menderes Massif near Demirci and Akhisar, non-metamorphic ophiolitic mélanges lie directly on regionally metamorphosed rocks as klippen (Başarır & Konuk 1981; Kaya 1981; Candan 1988; Erdoğan & Güngör 1992). There probably was a south-dipping subduction zone along the northern border of the Menderes platform within Neotethys. As the Sakarya and Menderes platforms (lying on either side of this ocean) collided by subduction (probably both northward below the Sakarya Continent and southward below the Menderes platform), mélange prisms formed along the subduction zone and were thrust southward atop the relatively early-formed Menderes metamorphic rocks. Subduction along the northern border, accompanied by northward thrusting of the Lycian Nappes along the southern border, generated granite emplacement, regional Barrovian metamorphism and intense ductile deformation of the Menderes platform.

In the proposed subduction model of the metamorphic and deformational evolution of the Menderes Massif, there is no need for deep burial of the platform by the load of nappe packages. Thus, the exhumation of the Massif would be accomplished solely by erosion without extensive tectonic denudation envisaged in the earlier models (Hetzel *et al.* 1995a).

During subduction, strong erosion was taking place along the axis of the developing Menderes Mountains which striped off the uppermost structural successions (Figure 13). When the Sakarya Continent finally collided with the Menderes Platform, it was internally imbricated (Figure 13b) and parts of the Lycian Nappes were thrust farther to the north and came to overlie directly higher grade metamorphic successions, as observed on the Dilek Peninsula (Güngör 1998).

In this study, we have endeavored to document the geology of the southern part of the Menderes Massif in two critical areas and introduce a model which may fire new discussions on the tectonic evolution of this complex region.

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