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GEOLOGY OF THE EARLY MIOCENE ALAÇAMDAĞ (DURSUNBEY-BALIKESİR) MAGMATIC COMPLEX AND IMPLICATIONS FOR THE WESTERN ANATOLIAN EXTENSIONAL TECTONICS

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ABSTRACT.- Extensional regime in western Anatolia caused development of metamorphic core complexes, NE- and E-W-trending basins and emplacement of magmatic rocks since Late Oligocene and Early Miocene. The Alaçamdağ magmatic complex, which is located to the west of the Simav metamorphic core complex, includes significant data that highlight the style of extensional regime in western Turkey. It consists of Early Miocene granitic intrusions and volcanic rocks with variable compositions ranging from basalt to rhyolite. The granitic intrusions that were emplaced into the basement rocks of the Menderes Massive and İzmir-Ankara Zone are divided into two facies based on their lithological and textural characteristics: Musalar and Alaçam granites. The Musalar granite has typical holocystalline equigranular texture, while the Alaçam granite is characterised by its porphyritic texture defined by abundant K-feldspar megacrysts. Both granite units were locally transformed into mylonites along shear zones. Volcanic rocks consist of Sağırlar volcanic unit and felsic volcanic rocks. Sağırlar volcanic unit is made up of andesitic/dacitic intrusions, domes, lava flows, dykes and volcanogenic sedimentary rocks. The felsic volcanic rocks, which unconformably overlies the Sağırlar volcanic unit, consist of ignimbrite, dacite and rhyolite. These rocks have transitional contacts with alluvial/lacustrine sedimentary deposits. Ductile deformation on the granitic rocks, intra-basinal unconformities and syn-sedimentary deformational structures within the deposits are closely associated with the development of extensional regime during Early Miocene in western Turkey.

Key words: Stratigraphy, ductile deformation, extensional tectonics, volcano-sedimentary successions, north-western Anatolia.

INTRODUCTION

As one of the region experienced by extensional tectonics, the Aegean region has been subjected to crustal thickening related to the closure of the northern Neotethys, which continued from Early Cretaceous to Eocene times and led to the juxtaposition of various tectonic units in western Turkey (Şengör et al., 1984; Whitney and Bozkurt, 2002; Rimmele et al., 2003*a, b*; Bozkurt, 2004; Erdoğan and Güngör, 2004) (Figure 1a). Magmatic rocks with variable compositions were extensive over these tectonic units following the closure of the northern branch of the Neotethys. They extend along an E-W-trending zone of about 600 km long and 250 km wide (Figure 1a) (Borsi et al., 1972; Krushensky, 1976; Bingöl et al., 1982; Savaşcın and Güleç, 1990; Seyitoğlu and Scott, 1992; Seyitoğlu et al., 1997; Genç, 1998; Karacık and Yılmaz, 1998; Delaloye and Bingöl, 2000; Yılmaz et al., 2001). Recent research revealed that the extensional regime in western Turkey occurred since Late Oligocene-Early Miocene following the collisional events. However, some researchers suggest that the compressional period lasted until the end of Middle Miocene (Altunkaynak ve Yılmaz, 1998; Karacık ve Yılmaz, 1998; Westaway, 2006; Hasözbek et al., 2009, in press). Extensional tectonic regime caused the development of metamorphic core complexes, fault-controlled NE- and E-W-trending basins and emplacement of the magmatic rocks in western Turkey (Savaşcın and Güleç 1990; Seyitoğlu and Scott, 1992;

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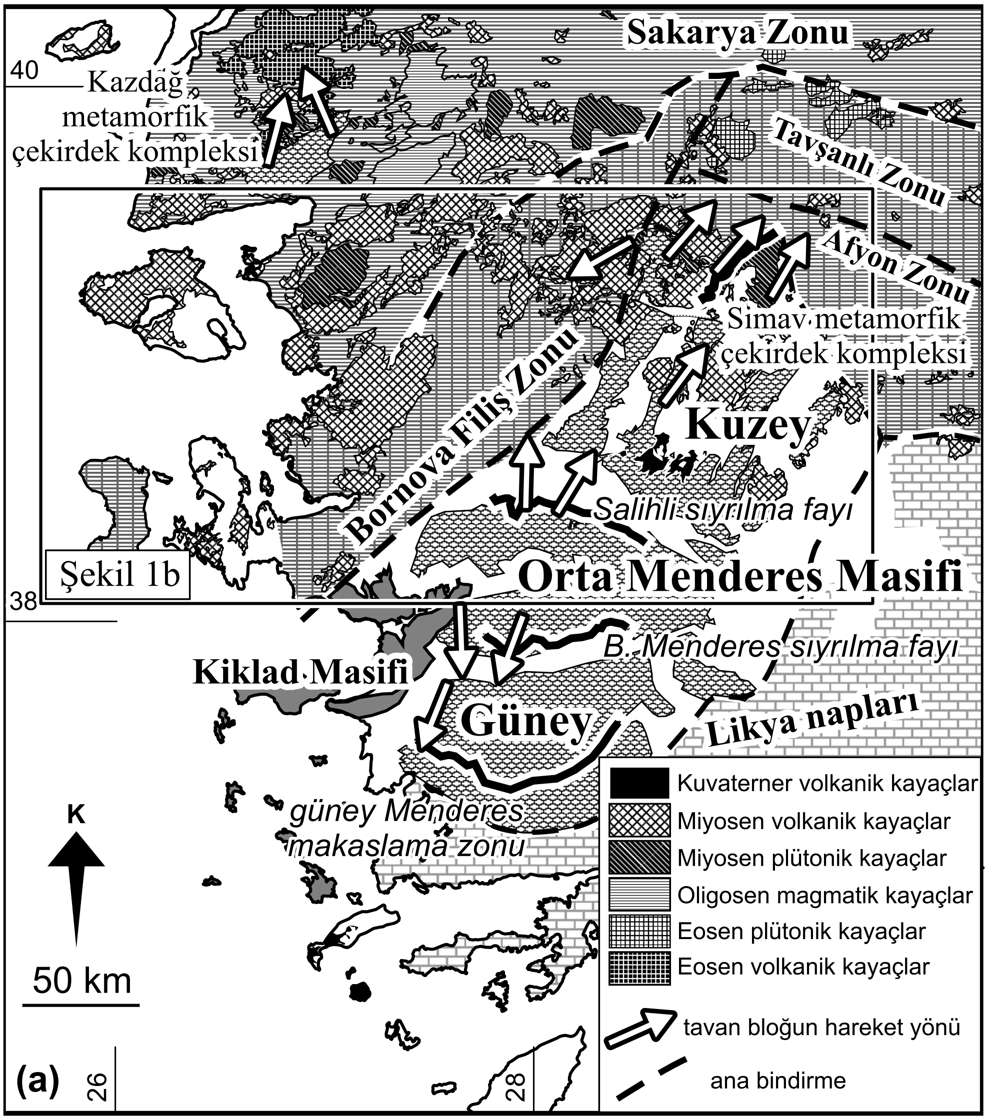

Figure 1a- A geological map showing major tectonic elements of the Aegean region (compiled from Hetzel et al., 1995*a,b*; Okay and Tüysüz, 1999; Ring et al., 1999; Ring and Collins, 2005; Okay and Satır, 2000).

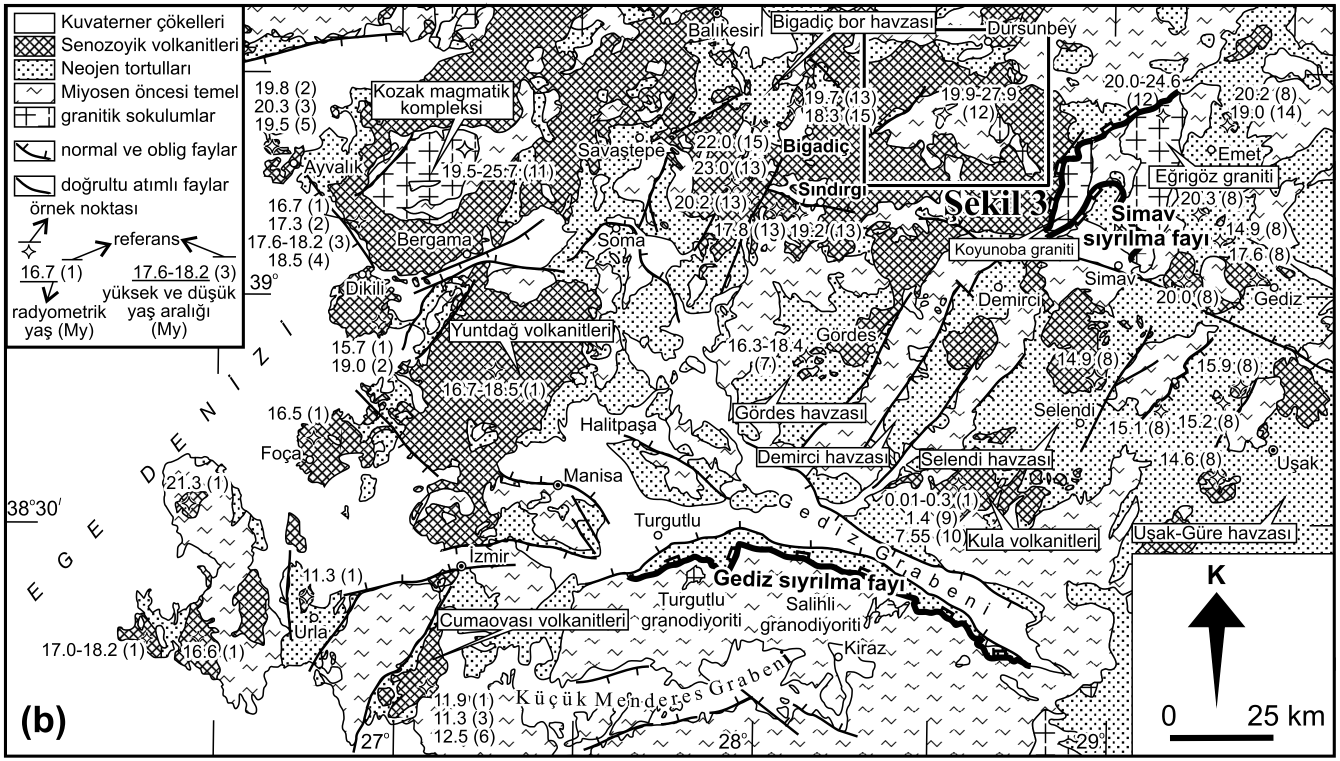

Figure 2b- Generalised geological map showing the distribution of Neogene to recent rocks, major tectonic lines and compiled radiometric age data (Bozkurt, 2000, 2001*a,b*, 2003; Yılmaz et al., 2000; Erkül et al., 2005*a*). Radiometric age data: (1) Borsi et al. (1972), (2) Ercan (1979), (3) Ercan et al. (1985), (4) Akyürek and Soysal (1982), (5) Krushensky (1976), (6) Innocenti and Mazzouli (1972), (7) Seyitoğlu and Scott (1992), (8) Seyitoğlu et al. (1997), (9) Ercan (1982), (10) Ercan and Öztunalı (1983), (11) Delaloye and Bingöl (2000), Ar-Ar data (12) Bingöl et al. (1982), (13) Erkül et al. (2005 *a,b*), (14) Helvacı and Alonso (2000), (15) Helvacı (1995).

Seyitoğlu et al., 1997; Altunkaynak and Yılmaz, 1998; Genç, 1998; Aldanmaz, 2000; Delaloye and Bingöl, 2000; Pe-Piper and Piper, 1989, 2001; Yılmaz et al., 2001; Işık et al., 2004; Altunkaynak and Dilek, 2006; Dilek and Altunkaynak, 2007).

Radiometric dating of syn-tectonic granitoids and detachment-related fault rocks indicate that the central Menderes, Kazdağ and Simav metamorphic core complexes occurred during Early and Middle Miocene (Hetzel et al., 1995*a,b*; Bozkurt and Park, 1997*a,b*; Okay and Satır, 2000; Ring et al., 2003; Işık et al., 2004; Ring and Collins, 2005; Glodny and Hetzel, 2007). Studies on the Koyunoba and Eğrigöz plutons which are located in the east of the Alaçamdağ magmatic complex indicate that the plutonism in the region is closely associated with detachment faulting (Işık and Tekeli, 2001; Işık et al., 2003, 2004; Ring and Collins, 2005). Ar-Ar cooling ages from the detachment-related fault rocks and syn-extensional plutons range between 23 and 20 Ma (Işık et al., 2004).

Exhumation of the Menderes Massif along extensional detachment faults was accompanied by the emplacement of numerous volcano-sedimentary basins in western Turkey (Figure 1b) (Bozkurt and Park, 1994; Koçyiğit et al., 1999; Yılmaz et al., 2000; Bozkurt, 2000, 2001*a,b*, 2003; Sözbilir, 2001, 2002*a,b*; Seyitoğlu et al., 2002; Bozkurt and Sözbilir, 2004; Işık et al., 2003, 2004; Purvis and Robertson, 2004). The NE - trending basins, Soma, Bigadiç, Demirci, Gördes and Selendi basins, were formed during the extensional period around the Alaçamdağ region (Figure 2). These basins, which rest on the pre-Miocene basement, are characterized by lacustrine/fluvial sedimentary deposits, interbedded lavas and volcaniclastic rocks that were extruded along the NE-trending volcanic edifices. Radiometric dating of the basaltic to rhyolitic volcanic rocks indicates that the NE-trending basins were formed during Early-Middle Miocene. These volcano-sedimentary successions commonly include intra-basinal unconformities.

The Alaçamdağ region, which is located on the various tectonic units, is one of the least studied regions in western Turkey (Akdeniz and Konak, 1979; Erkül et al., 2009*a,b*; Hasözbek et al., in press). Recent structural and geochronological studies provide a convincing evidence for the syn-extensional ductile deformation of the Alaçamdağ granites (Erkül, 2010). However, role of ductile deformation in the volcanism and co-eval basins remains unclear. In this paper, we aimed to described geology of the magmatic rocks in the Alaçamdağ region and to discuss structural data from the deformed granites in the framework of western Anatolian extensional province.

STRATIGRAPHY

The Alaçamdağ region is underlain by the Miocene-Quaternary magmatic and sedimentary rocks that rest on the basement rocks of the Menderes Massif and the İzmir-Ankara Zone (Figure 3). Rock units are, from bottom to top, Menderes Massif, İzmir-Ankara Zone, Alaçamdağ granites, Sağırlar volcanic unit, fluvial/lacustrine sedimentary deposits, felsic volcanic rocks, continental deposits, alluvium and scree deposits (Figure 4).

Menderes Massif

Menderes Massif is formed by a NE-trending, dome-shaped outcrop with length of 250 km and width of 150 km. It consists of orthogneiss, schist, phyllite, quartzite amphibolite and marbles (Akdeniz and Konak, 1979; Bozkurt and Oberhänslı, 2001; Gessner et al., 2001; Işık et al., 2004), which is widely exposed in the west of the Alaçam village (Figure 3). Phyllites are defined by typical cream and grey colours and distinct cleavage seams. Mica schists are mainly composed of biotite, muscovite and quartz. Quartzite bands are up to 1-meter-thick structures within the mica schists. Menderes Massif is tectonically overlain by the İzmir-Ankara Zone (Erdoğan 1990*a,b*). Metamorphic rocks of the

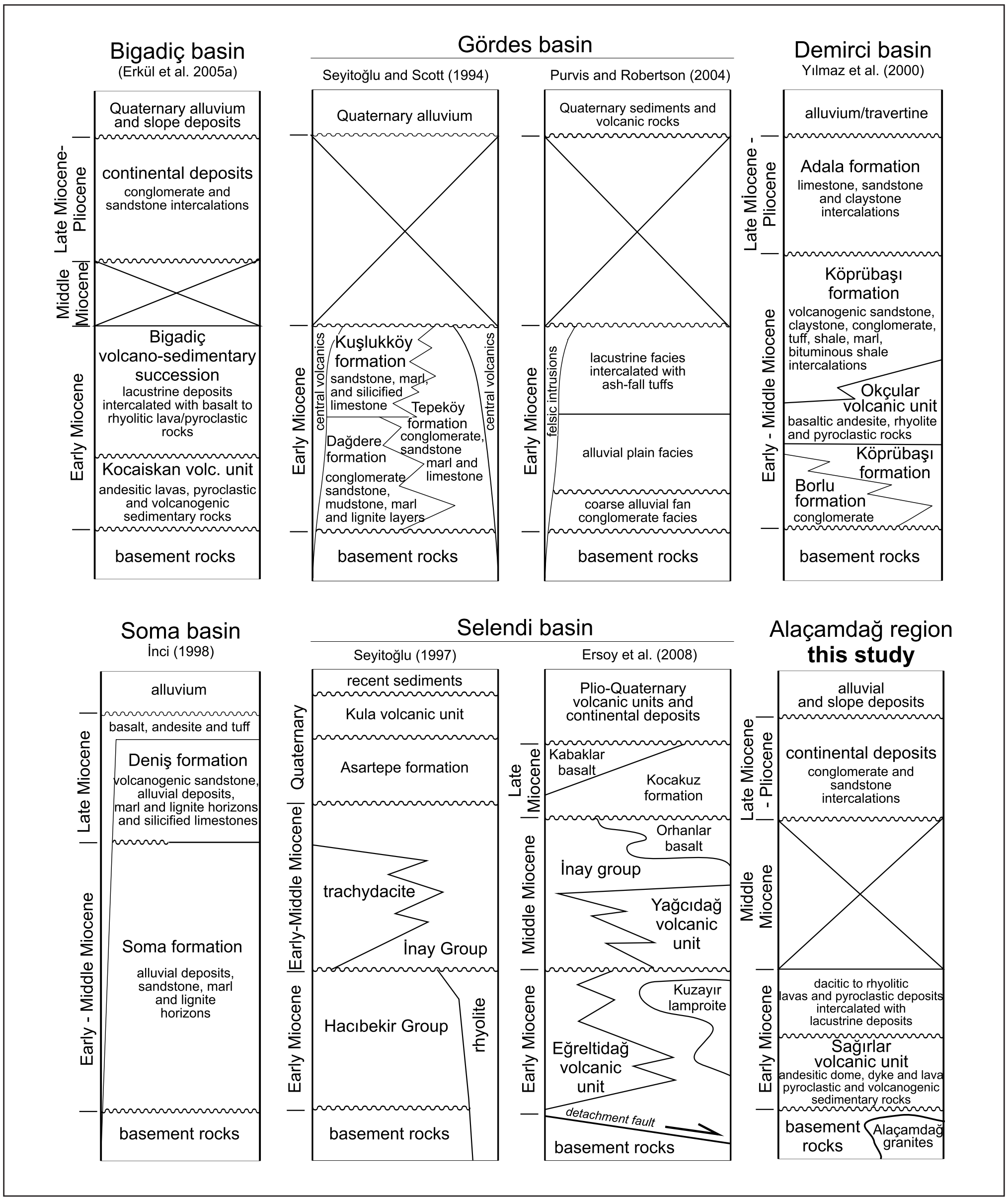

Figure 2- Stratigraphic correlation of the NE-trending Neogene basins located around the Alaçamdağ region.

Menderes Massif are juxtaposed with the re-crystallized limestone and flysch-type sediments of the İzmir-Ankara Zone along a steeply dipping contact that is distingusihed as a ductile shear zone in the west of the Alaçamdağ region.

İzmir-Ankara Zone

The İzmir-Ankara Zone is a NE-trending melange zone between Menderes Massif and the Sakarya Zone. It consists of olistostomes and ophiolite slices within a sheared matrix of flysch-type sediments (Erdoğan, 1990*a,b*; Okay ve Siyako, 1993). The İzmir-Ankara Zone is divided into the NE-trending Bornova Flysch Zone and the E-W-trending Afyon Zone in the Alaçamdağ region. These zones have similar lithological features to each other in the western part of the Alaçamdağ region. The Bornova Flysch Zone consists of greyish recrystallized limestone olistoliths and serpentinite (formerly gabbro) slices surrounded by a sheared, claret red to greyish matrix of sandstone and shale intercalations. The matrix locally includes limestone lenses. The Afyon Zone is located in the north of the Alaçamdağ region and characterized by detrital sedimentary rocks, olistrostromal limestones and ophiolitic slices with local low-grade metamorphic overprints.

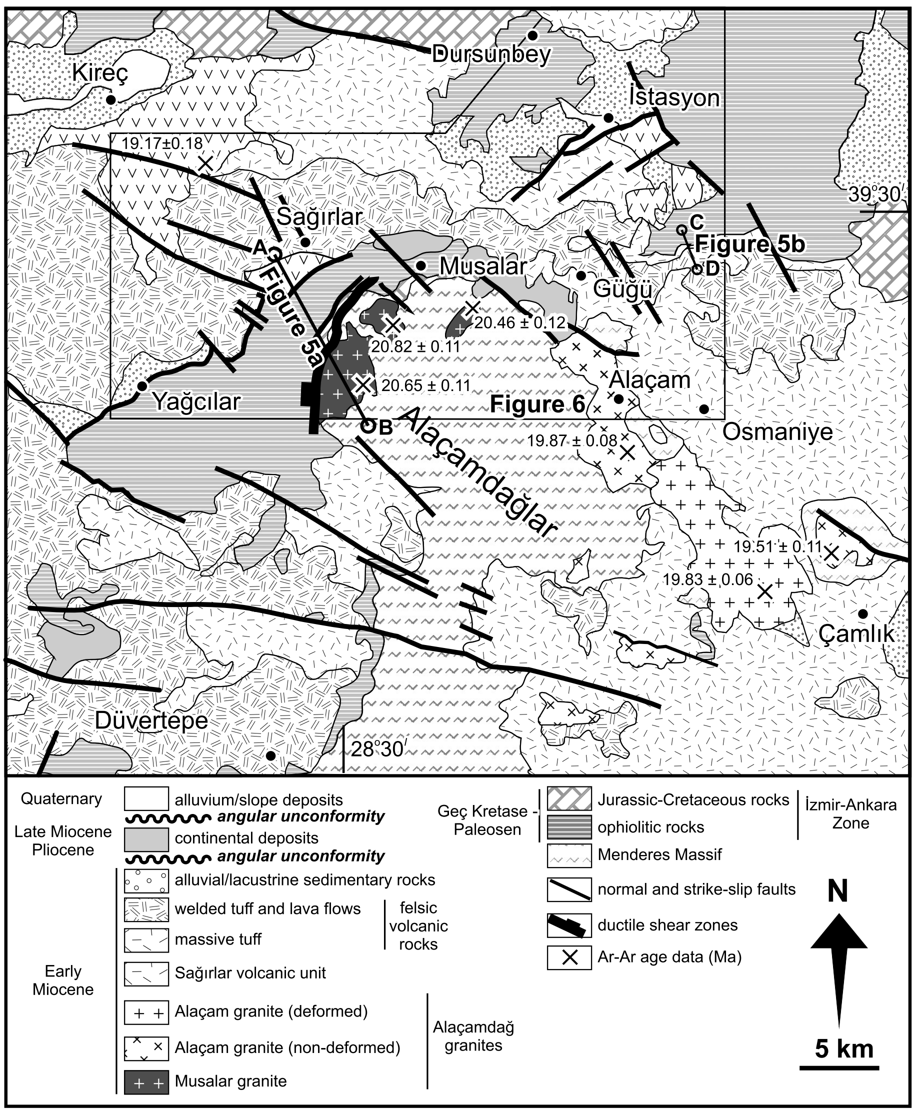

Figure 3- Geological map of the Alaçamdağ region (lithological boundaries were modified from Akdeniz and Konak (1979) and Ar-Ar ages of granites are from).

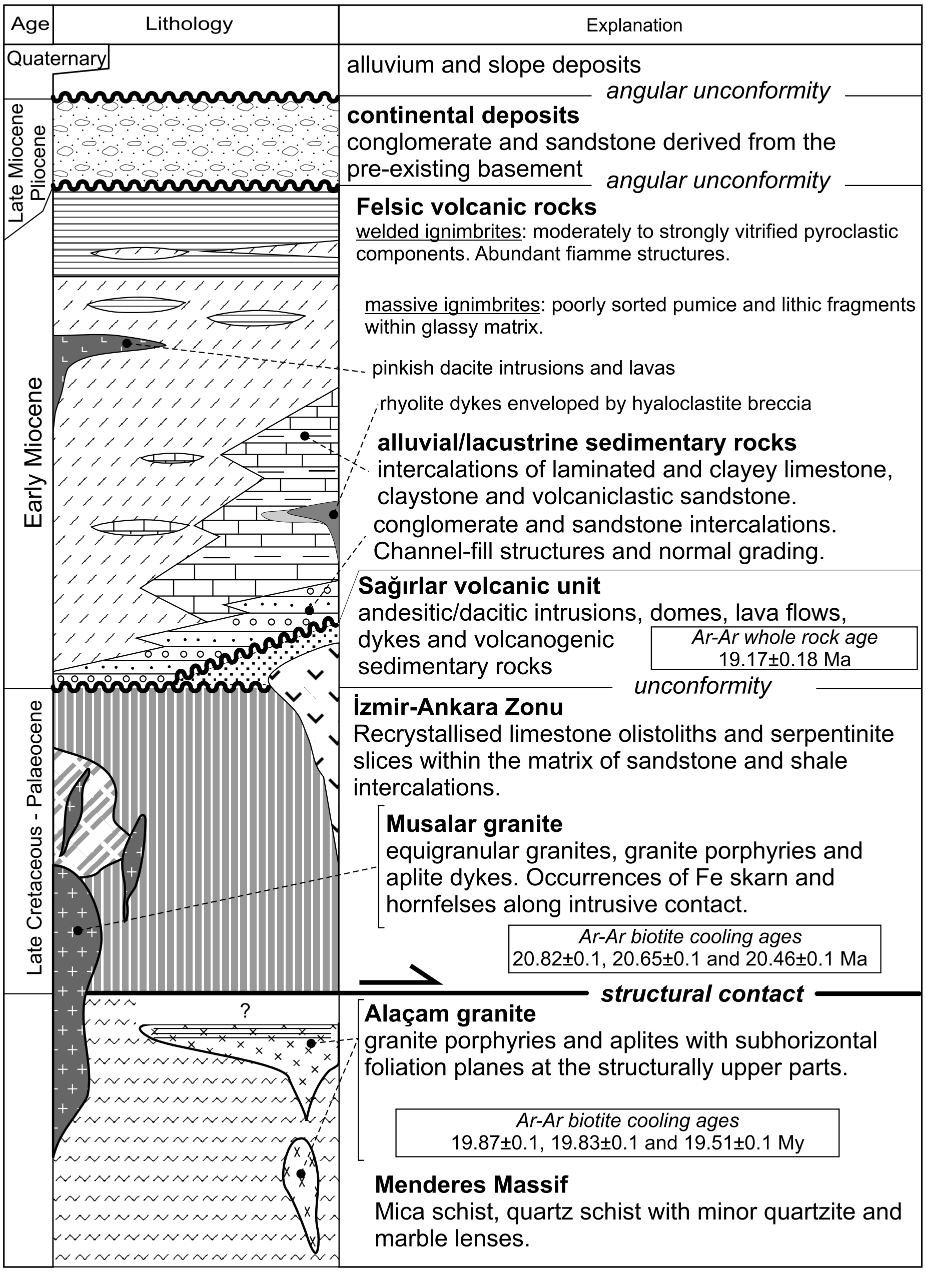

Figure 4- Generalised stratigraphic columnar section of the Alaçamdağ region.

Alaçamdağ granites

The Alaçamdağ granites crop out in an area of 30 km² within an arc-shaped zone (Figure 3). Granitic rocks of the Alaçamdağ magmatic complex are divided into two facies: Musalar and Alaçam granites (Table 1).

Musalar granite.- Musalar granite is exposed in an area of about 16 km² around Aşağımusalar

Table 1- General characteristics of the Musalar and Alaçam granites

Unit	**Musalar granite**	**Alaçam granite**
Texture	equigranular	porphyritic
Megacryst	minor K-feldspar megacrysts	relatively abundant K-feldspar megacrysts
Mafic microgranular enclaves (MME)	present	present
Hypabyssal equivalents	granite porphyries and aplites	aplites
Name of rock	granite	granite
Major mineralogical constituents	quartz, plagioclase, orthoclase, biotite and hornblende	quartz, plagioclase, orthoclase, biotite and hornblende
Deformation	a high-angle ductile shear zone along the western margin of the Musalar granite.	a shear zone formed by subhorizontal foliation surfaces within the southern part of the largest, NW-trending stock.
Ductile deformation structures within the granites	ultramylonites are common • dynamic recrystallisation of quartz • ondulatory extinction in quartz and biotite • Asymmetrical quartz porphyroclasts • Microfaults cutting the pre-existing foliation planes	protomylonites are common. • C' shear bands • Syn-tectonic deformation of aplitic dykes • Dynamic recrystallisation of quartz • asymmetrical mica-fish structure • ondulatory extinction in K-feldspars

and Yukarımusalar villages. Each granite stock, which covers an area up to 11 km^2, has commonly elliptical, rhomb-shaped and circular plan views. Elliptical and rhomb-shaped stocks extends NE-SW and N-S in direction. Musalar granites are characterized by equigranular granites, granite porphyries and aplitic dykes. Equigranular granites are distinguished by their typical spherical wheathering in the field. Foliation planes also occur within the Musalar granites that are locally affected by ductile deformation along their margins. Equigranular Musalar granite is composed of orthoclase, quartz, plagioclase, biotite and hornblende. It also contain centimeter to decimeter-sized mafic microgranular enclaves, indicating magma mingling processes. Granite porphyries are usually known as having relatively small megacrysts of orthoclase within the fine-grained matrix of rock-forming minerals. They are greyish coloured in the field, have a dyke morphology, extending in a NE direction and include minor amount of mafic minerals. Aplitic dykes are recognized by their microcrystalline texture. They are composed of quartz, plagioclase, orthoclase and minor biotite. Musalar granite intrudes the Menderes Massif and the Bornova Flysch Zone to the west of the Alaçamdağ region (Figure 5a). The intrusive contact of the Musalar granite with the Bornova Flysch Zone is characterized by an iron skarn zone between recrystallized limestone and N-S-trending granite stock. This relationship is well exposed around the Geyiktepe vicinity (Figure 5a). A skarn zone is made up a few meters around it which consists of garnet, diopside, epidote, actinolite, tremolite, chlorite and pyrite. It is also recognized by iron disseminations within the recrystallized limestones. The intrusive contact of the Musalar granite with the Menderes Massif is defined by hornfelsic rocks within mica schists and quartzites. Hornfelsic rocks are a few meters wide and are recognized by their gray-green clours. Clastic sedimentary rocks and recrystallized limestones are intruded by a few meter wide granite porphyry dykes (Figure 5a). Aplitic dykes cut the recrystallized limestone, metamorphic rocks and Musalar granite. The Musalar granite has cooling ages between 20.17 and 20.82 Ma while U-Pb zircon crystallization age is 20.3 Ma (Table 2).

Alaçam granite.- Alaçam granite crop out in an area of about 65 km^2 around the Alaçam and Çamlık districts and has NW-SE- and NE-SW-trending exposures. Largest granite outcrop is about 19 km long and 3 km wide. Alaçam granite consists of porphyritic granites and aplitic dykes. Porphyritic granites are defined by large megacrysts of orthoclase surrounded by plagioclase, quartz, biotite and hornblende. Length of the individual megacryst reaches up to 5 cm. The Alaçam granite contains mafic microgranular enclaves and xenoliths near the contact zone. The enclaves, up to a decimeter long, are dioritic composition. Aplitic dykes are usually a few to locally 50 centimeter wide, which intrude marginal parts of the granites and metamorphic host rock. The Alaçam granite cuts mica schists of the Menderes Massif and includes metamorphic xenoliths around contact zone. Intrusive contact relationships are well exposed around Alaçam village. The intrusive contact of the granite with mica schists is sharp and is characterized by the aplitic dykes that occurs in a 100 metres wide zone. The aplitic dykes also cross-cut the mica-schist foliation within the zone. Alaçam granite is also unconformably overlain by Early Miocene ignimbrites that have crude stratification and poorly sorted pumice clasts. No deformational features are exposed within the ignimbrites. Cooling ages of the Alaçam granites range between 20.01 and 19.51 Ma while their U-Pb crystallization age is 20 Ma (Table 2).

Sağırlar volcanic unit

Sağırlar volcanic unit consists of andesitic/dacitic intrusions, domes, lava flows, dykes and volcanogenic sedimentary rocks. The unit is exposed in an area of about a few tens of km^2 in the south of Sağırlar and southeast of Dursunbey (Figure 6). Intrusions are located in the east of Yağcılar and south of Değirmenciler. They have circular plan views and their diametre is up to 300 metre. Andesitic/dacitic intrusions are massive and locally display radial cooling joints. In a hand specimen, andesites and dacites are made up of feldspar, biotite and minor quartz phenocrysts within pink and grey coloured matrix. Intrusions cut the clastic sediments of the İzmir-Ankara Zone. Domes consist of grey and pink coloured dacite and andesite. They are exposed in the west of Sağırlar and south of Beyel. Domes around Sağırlar are distinguished by their massive appearence. Domes are usually surrounded by andesite/dacite breccia and cut by late-stage faults. They display similar lithologies to those exposed in the south of Beyel. The dome, up to 200 metre high, contains radial cooling joints and is surronded by monomictic breccia (Figure 7a). Andesitic/dacitic lavas are typically distinguished by their pink colours and porphyritic textures that are defined by plagioclase, biotite, hornblende and minor quartz phenocrysts within the hyalopilitic matrix. They include flow foliation and minor vesicles. Dykes of the Sağırlar volcanic unit are only exposed around Kürsü district. They are a few tens of metres long and are up to 10 metres wide. Dip of dykes is nearly vertical and strike is N10-40°E. Andesitic dykes intrude the polymictic andesite breccia (Figure 7b). Andesitic dykes are distinguished with their brown and dark pink colours and include a few cm thick flow bands that have oriented phenocrysts. Volcanogenic sedimentary rocks consist of volcanic sandstone, breccia and conglomerates. Main components of the volcanogenic sedimentary rocks are polymictic, poorly sorted, angular and subrounded andesite and dacite clasts within a sand-size matrix

Table 2- Geochronological data from the magmatic rocks of the Alaçamdağ area

Location	Methods	Rock dated	Mineral dated	Age (Ma)	Reference
Alaçamdağ granites (undifferentiated)	K-Ar	Granite	biotite	20.3±0.6	Bingöl et al. (1982)
			potassium feldspar	20.0±0.8	
				19.9±0.7	
				20.6±0.8	
				20.9±0.5	
	Ar-Ar		biotite	20.6±0.8	Delaloye and Bingöl (2000)
				20.9±0.5	
	U-Pb		zircon	20.7±1.1	Hasözbek et al. (2009)
Alaçamdağ granites - west	U-Pb		zircon	20.3 ± 3.3	Hasözbek et al. (in press)
Alaçamdağ granites - east				20.0 ± 1.4	
Alaçamdağ granites - west	Rb-Sr		biotite	20.17 ± 0.2	
Alaçamdağ granites - east				20.01 ± 0.2	
Musalar granite UTM coordinates (zone 35; longitude/latitude)					Erkül (2010)
630390 4364466	Ar-Ar	Granite-equigranular	biotite	20.65±0.11	
631542 4367877				20.82±0.11	
636084 4368640				20.46±0.12	
Alaçam granite					
644773 4360962	Ar-Ar	Porphyritic granite	biotite	19.87±0.08	
651000 4353500		Granite-protomylonitic		19.83±0.06	
655413 4355019		Granite-porphyritic		19.51±0.11	
Sağırlar volcanic unit					
620822 4375278	Ar-Ar	andesite	whole rock	19.17±0.18	this study

(Figure 7c). Clasts may occur clast- or matrix-supported and are locally stained by iron oxides.

Intrusive rocks of the Sağırlar volcanic unit cut the clastic sediments of the İzmir-Ankara Zone. Lava flows and volcanogenic sedimentary rocks are interfingered unconformably overlie the rocks of the İzmir-Ankara Zone (Figure 7d). The Sağırlar volcanic unit is unconformably overlain by the alluvial/lacustrine sedimentary deposits and felsic volcanic rocks in Kürsü and south of Dursunbey. Ar-Ar cooling age measured from the andesite lava of the Sağırlar volcanic unit is 19.17±0.18 Ma (Table 2).

Alluvial/lacustrine sedimentary rocks

Alluvial/lacustrine sedimentary rocks are located in Yağcılar, Kürsü and south of Dursunbey. They consist of conglomerate, sandstone, claystone, volcanic sandstone and laminated/clayey limestone intercalations. Largest exposures are located in the south of Dursunbey, covering an area of about 40 km^2. Conglomerates consist of basement-derived, subrounded to rounded clasts of andesite, recrystallized limestone, sandstone and shale within a sand-size matrix at the basal part of the succession. Proximity of the basement rocks defines abundance

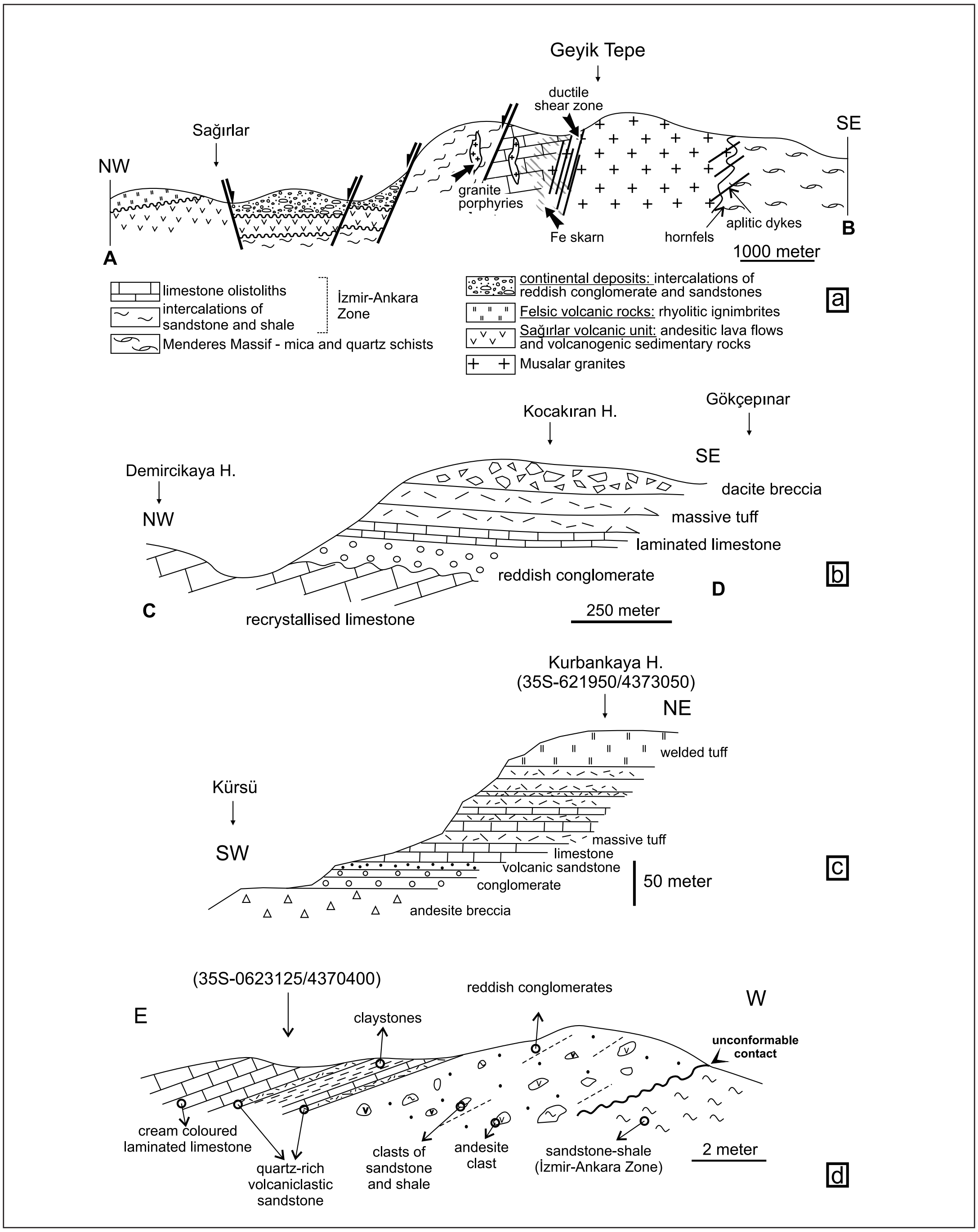

Figure 5- (a) Geological cross section along Sağırlar and Geyiktepe districts. (b) Geological cross-section along Gökçepınar. (c) Geological cross-section displaying lithologies and contact relationship of the alluvial/lacustrine sedimentary deposits on the volcanic breccia of the Sağırlar volcanic unit. (d) Unconformable contact relationship between the alluvial/lacustrine sedimentary rocks and the İzmir-Ankara Zone in the west of the Sağırlar district. Location of figures 5a and 5b is shown in figure 3.

of clast type in the unit. Sandstones display limited extent above conglomerates as lenses. Thickness of sandstone and conglomerate intercalations may locally reach up to 80 meter. Volcanic sandstones are recognized by their grey to cream colours and include quartz, feldspar and biotite crystals. Thickness of the volcanic sandstones may reach up to a few metres. Uppermost part of the unit consists of laminated, well stratified and clayey limestones; they are distinguished by typical yellow to cream colours.

Alluvial/lacustrine sedimentary rocks are unconformably overlies the İzmir-Ankara Zone, while they are conformably overlain by volcaniclastic rocks of the felsic volcanic unit. Unconformable contacts are well exposed around Değirmenciler, Kürsü, Sağırlar and Saçayak districts. In the Değirmencikaya district, recrystallized limestones are overlain by 20 meter thick reddish conglomerates. Conglomerates are overlain by laminated limestone, massive ignimbrites and dacite breccia from lower to upper parts of succession (Figure 5b). Andesite breccia is overlain by the basement-derived, well rounded and oxide stained conglomerates, volcanic sandstones, felsic tuffs and cream limestone. These rocks are conformably overlain by welded ignimbrites (Figure 5c). In the Sağırlar area, a 5-6-meter thick conglomerate overlies the sandstone and shale intercalations of the İzmir-Ankara Zone. Conglomerate comprises well-rounded andesite and sandstone/shale intercalation. Conglomerate is conformably overlain by quartz-rich volcanic sandstone, claystone and cream coloured, laminated lacustrine limestones (Figure 5d). In the Saçayak district, lava flows of the Sağırlar volcanic unit is covered by bedded sandstones (Figure 8). Bedded sandstones commonly have cross-stratification. They are overlain by massive conglomerates that occur as channel-fill deposits at the basal parts. Massive conglomerates also display clast imbrication and cross stratification. They gradually pass upward into the bedded sandstones that include channel-fills and lenses of conglomerates. This sequence is covered by chaotic claystone layers that have syn-sedimentary deformational patterns and conglomerate/clayey limestone lenses. The chaotic layers are covered by pebbly sandstones that have channel-fill structures and clayey limestone intercalations. They pass upward into the conglomerates with an erosinal basal contact and comprise andesite boulders up to 1 meter long within a matrix of pebbly sandstones. Intrabasinal unconformities are very common within the alluvial/lacustrine sedimentary deposits (Figure 9). Layers with dips about 35°, which consist of claystone, sandstone and clayey limestone intercalations, are overlain by nearly flat-lying beds of sandstone and conglomerate along an erosive contact. Clayey limestones transgressively overlie the İzmir-Ankara Zone at some localities.

Alluvial/lacustrine sedimentary deposits occur as lenses within the welded ignimbrites of felsic volcanic rocks around Çatalçam district. Age of these deposits are accepted Early Miocene owing to correlation and radiometric dating of felsic volcanic rocks in the surrounding regions.

Felsic volcanic rocks

Felsic volcanic rocks around Alaçamdağ region cover hundreds of km^2 from Bigadiç to Simav and from Dursunbey to Düvertepe districts (Figures 3 and 6). They consist of dacites, rhyolites and ignimbrites. Ignimbrites are the most voluminous deposits in the Alaçamdağ region and their thickness may reach up to 350-400 meters. They are recognized by pumice and lithic fragments together with basement-derived accidental clasts enclosed by an ash-size matrix. Columnar joints are common within ignimbrites. Ignimbrites are usually grey and brown coloured, but locally greenish owing to alteration of pumice fragments (Figure 10a). Textural characteriztics are usually defined by the degree of welding in ignimbrites. Flattened and virtrified pumice clasts, which form a typical fiammes, were locally transformed into volcanic glass (Figure 10b).

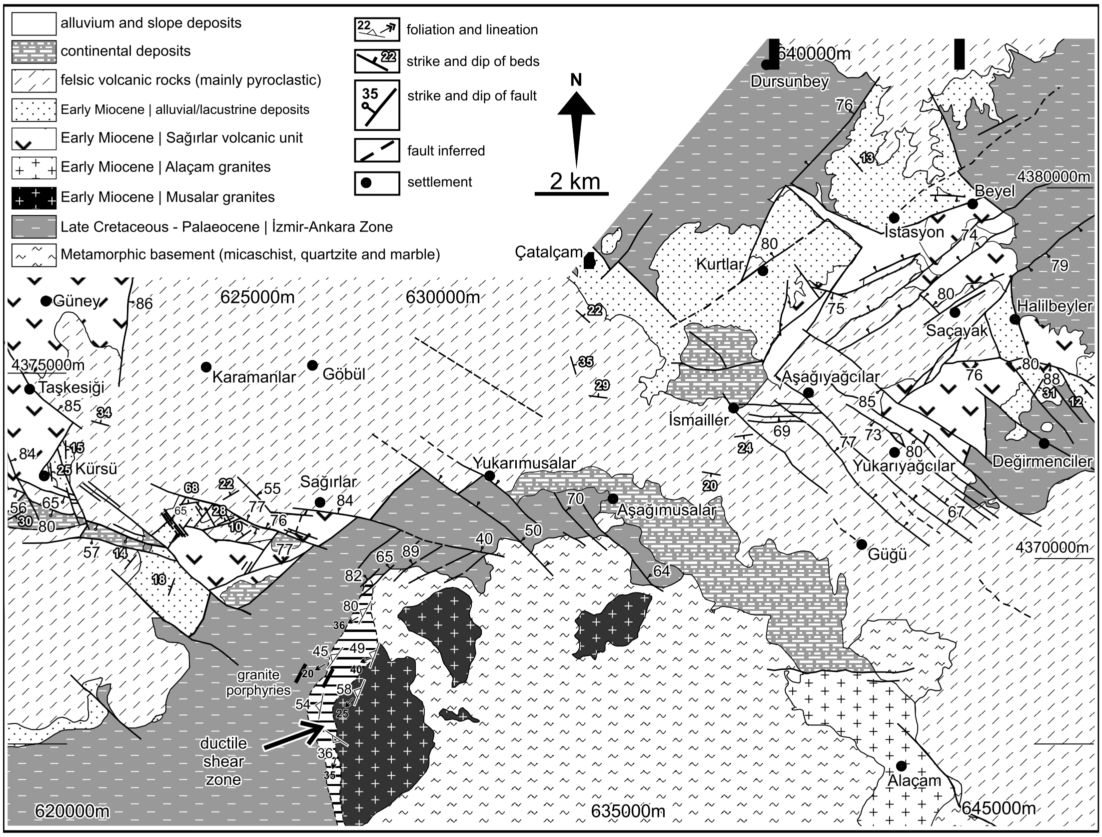

Figure 6- Geological map of the Alaçamdağ region. Map coordinates: UTM - zone 35.

Dacites crop out in the Güğü area and are recognized by phenocrysts of quartz, plagioclase, biotite and hornblende within a grey and pink coloured matrix.

Rhyolites, which cover an area up to a few km², are characterized by typical flow foliations and quartz phenocrysts within a cream coloured matrix in a hand specimen. They are associated with hyaloclastite breccias in the north of Kürsü, suggesting a subaqueous emplacement. Hyaloclastite breccias surround rhyolitic dykes that are defined by subvertical distinct flow foliations. Dykes are up to about 10 metres wide and 100 metres long. Hyaloclastite breccias are recognized by its perlitic clasts that display a typical jig-saw fit texture (Figure 10c). Rhyolite dykes intrude alluvial/lacustrine sedimentary deposits.

Felsic volcanic rocks rest on the Menderes Massif, İzmir-Ankara Zone, Alaçam granite and Sağırlar volcanic unit. They have vertically and horizontally transitional contacts with alluvial/lacustrine sedimentary deposits (Figure 10d). Ignimbrites unconformably overlies the Menderes Massif and Alaçam granite. Foliated granites are covered with pumice-rich massive ignimbrites along a sharp contact. Lithic-rich ignimbrites unconformably overlies the İzmir-Ankara Zone in the south of Dursunbey and southeast of Yukarıyağcılar areas (Figure 10e). Massive and welded ignimbrites, which are transitional to alluvial/lacustrine sedimentary deposits, unconformably overlie the andesite breccia of the Sağırlar volcanic unit around Sağırlar and Kürsü. Massive ignimbrites rest directly on the andesitic

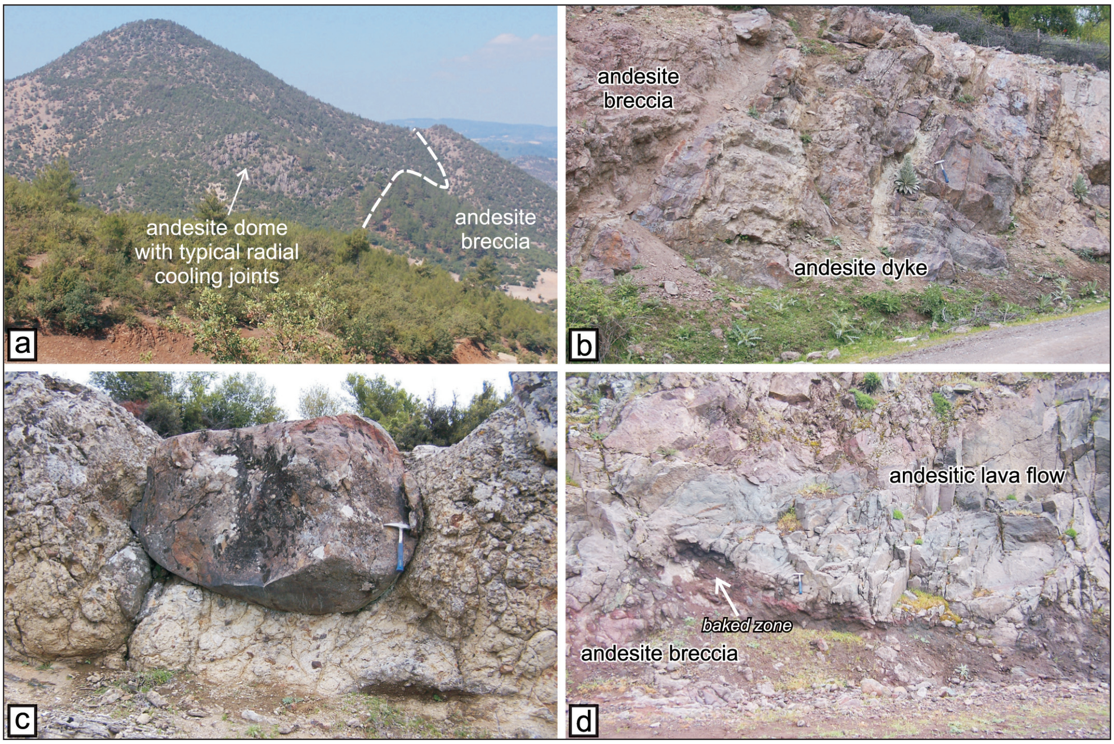

Figure 7- (a) An andesite dome surrounded by andesite breccia in the south of Beyel, Dedetepe. Field of view is about 800 metres wide. (b) an andesite dyke that intrudes the polymictic andesite breccia. The dyke trends in N10°E. Width of view is about 10 metres (35S-620385/4371955). (c) A large, rounded andesite clast within the lacustrine deposits (35S-620700/4371800). (d) basal conformable contact of the lava flows overlying the polymictic andesite breccias (35S-620262/4373555).

lava flows of the Sağırlar volcanic unit around Sağırlar area. The contact zone between these lithologies is represented by oxidation zone and a-few-decimetre-thick palaeosoil occurrences (Figure 10f). Felsic volcanic rocks radiometrically dated in the Bigadiç borate basin can be correlated with Early Miocene felsic volcanic units (Erkül et al., 2005*b*).

Continental deposits

Continental deposits crop out in an area of about 40 km^2 in the north of Alaçamdağ region. They have variable clast types defined by basement source. Components are recognized by cream, brown and red colours in the south of Kürsü, Aşağımusalar, Yukarımusalar and İsmailler areas (Figure 6).

In the Kürsü area, continental deposits are up to 200 metres thick and consist of subrounded welded ignimbrite boulders and cobbles within a loose matrix of sand and gravel. They display crude stratification and overlie the welded ignimbrites. In the Yukarımusalar area, continental deposits are composed of well rounded and poorly sorted clasts of granites and rocks of the İzmir-Ankara Zone. In the Aşağımusalar area, they reach at their maximum thickness which is around 300 metres.

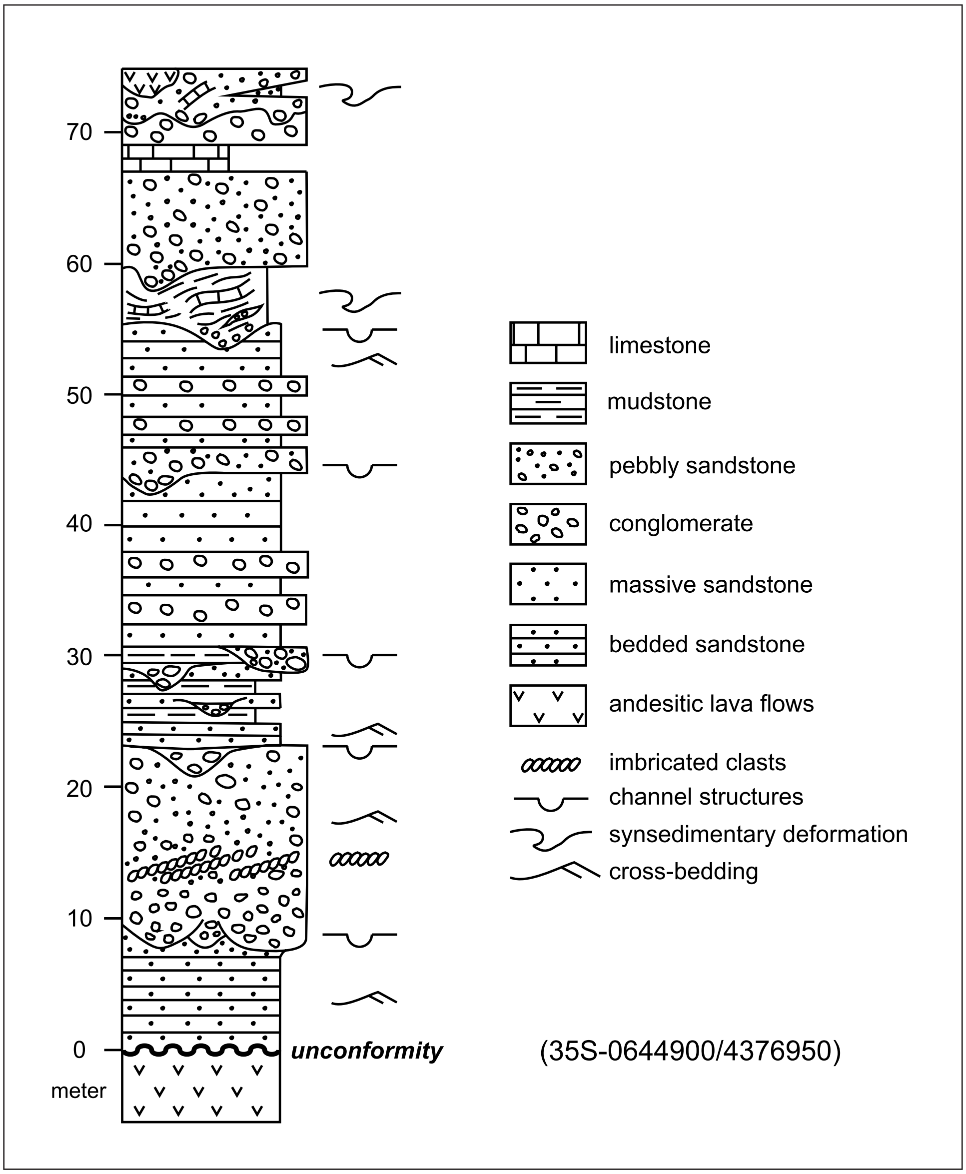

Figure 8- Measured stratigraphic log showing the contact zone between the Sağırlar volcanic unit and the overlying alluvial/lacustrine sedimentary deposits.

Alluvium and scree deposits

Alluvial deposits are exposed in recent river beds and alluvial plains, which are commonly around Dursunbey area. Alluvial plains are generally surrounded by prominent topographic highs. Slope deposits are represented by unconsolidated and poorly sorted clasts, which were formed by rapid uplift and erosion processes.

GEOCHRONOLOGY

Granitic and volcanic rocks of the Alaçamdağ magmatic complex were analysed by using Ar-Ar

Figure 9- Field appearance of an unconformity within the alluvial/lacustrine sedimentary deposits (Dursunbey - Gökçepınar road-cut; 35S-0645855/4376435)

furnace step heating method in order to have cooling ages (Erkül, 2010). Analytical methods and ages of the Alaçamdağ magmatic complex are summarized in table 2. In this study, Ar-Ar age of andesites of the Sağırlar volcanic unit is presented.

The dated andesite sample consists of phenocrysts of plagioclase, biotite, hornblende and kersutite within a hyalopilitic matrix. Biotite and honblendes are commonly altered into opaque phases, forming pseudomorphs. Subhedral and anhedral phenocrysts of plagioclase contain tiny matrix inclusions.

Andesite sample of the Sağırlar volcanic unit were run as conventional furnace step heating analyses. U-shaped age spectra are commonly associated with excess argon (the first few and final few steps often have lower radiogenic yields, thus apparent ages calculated for these steps are effected more by any excess argon present), and this is often verified by isochron analysis, which utilizes the analytical data generated during the step heating run, but makes no assumption regarding the composition of the non-radiogenic argon. Thus, isochrons can verify (or rule out) excess argon, and isochron ages are usually preferred if a statistically valid regression is obtained (as evidenced by an acceptably low MSWD value). If a sample yields no reliable isochron, the best estimate of the age is that the minimum on the age spectrum is a maximum age for the sample (it could be affected by excess argon, the extent depending on the radiogenic yield). $^{40}Ar/^{39}Ar$ total gas ages are equivalent to K/Ar ages. Plateau ages are sometimes found, these are simply a segment of the age spectrum which consists of 3 or more steps, comprising >50% of the total gas released. Such ages are preferred to total gas or maximum ages if obtained. However, in general an isochron age is the best estimate of the age of a sample, even if a plateau age is obtained.

The age spectrum for an andesite sample is very strongly U-shaped (Figure 11). Initial ages are very old, ranging up to ~429 Ma, in comparison to the minimum ages which are ~21 Ma. This is a very clear indication of excess argon and with no other information one would simply use the minimum age of ~21.3 Ma as a maximum age for the sample. The total gas age of 42.8 ± 0.2 Ma is very likely to be anomalously old. There was no plateau age defined for this sample. Isochron analysis reveals that 3 steps (6-8) define an age of 19.2 ± 0.2 Ma and suggest excess argon is present (initial $^{40}Ar/^{36}Ar$ = 338.0 ± 1.9). This isochron is defined by the minimum number of data points allowable (n = 3) and comprises 42% of the total gas released. In this case, the isochron indicates excess argon and this is also indicated by the U-shaped age spectrum. The isochron indicates an age less than the minimum on the age spectrum and this is what would be expected if excess argon is present. For these reasons, this particular isochron age of 19.2 ± 0.2 Ma can be accepted.

STRUCTURAL GEOLOGY

Ductile deformation in the Alaçamdağ granites

Patterns of ductile deformation were observed in the Musalar and Alaçam granites. Ductile deformation within the Musalar granite is

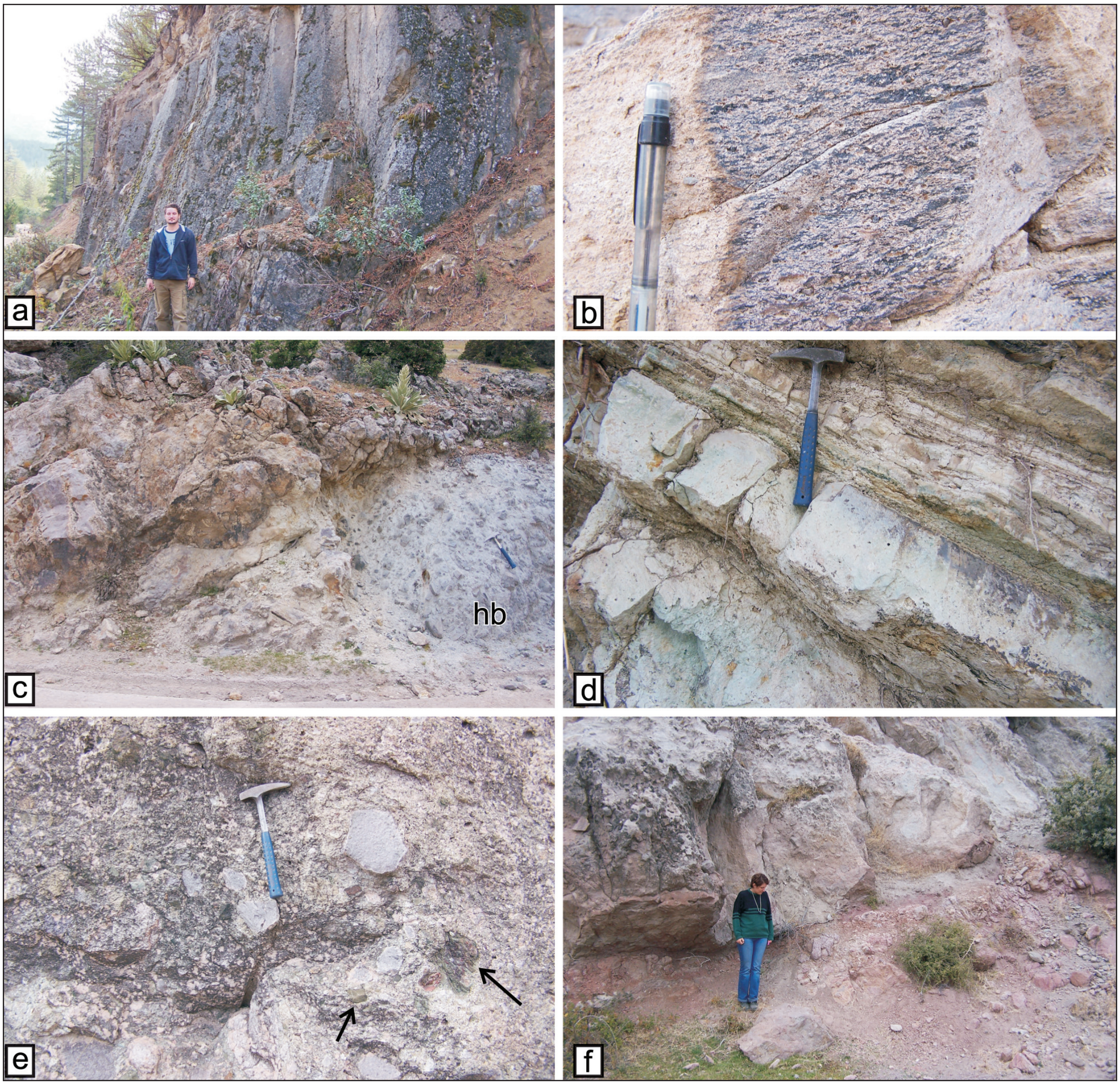

Figure 10- (a) Columnar-jointed ignimbrites on the clastic sediments of the İzmir-Ankara Zone is up to 400 metres thick. (b) welded ignimbrites on the massive ignimbrites. Pumice clasts were entirely transformed into fiamme (35S-0625325/4370650). (c) hyaloclastite breccias (hb) surrounding rhyolitic dykes in the Kürsü area (35S-0620580/4372100). (d) greenish massive ignimbrites intercalated with laminated limestones and claystones (35S-0618350/4366225). (e) lithic-rich ignimbrites on the İzmir-Ankara Zone. Volcanic clasts are angular and monomictic. Sandstone, shale and serpentinite clasts are shown by arrows (35S-0625200/4358000). (f) the contact relationship between breccias of the Sağırlar volcanic unit and the overlying massive ignimbrites (south of Sağırlar, 35S-0626398/4370750). The contact is represented by an up-to-50 cm-thick palaeosoil.

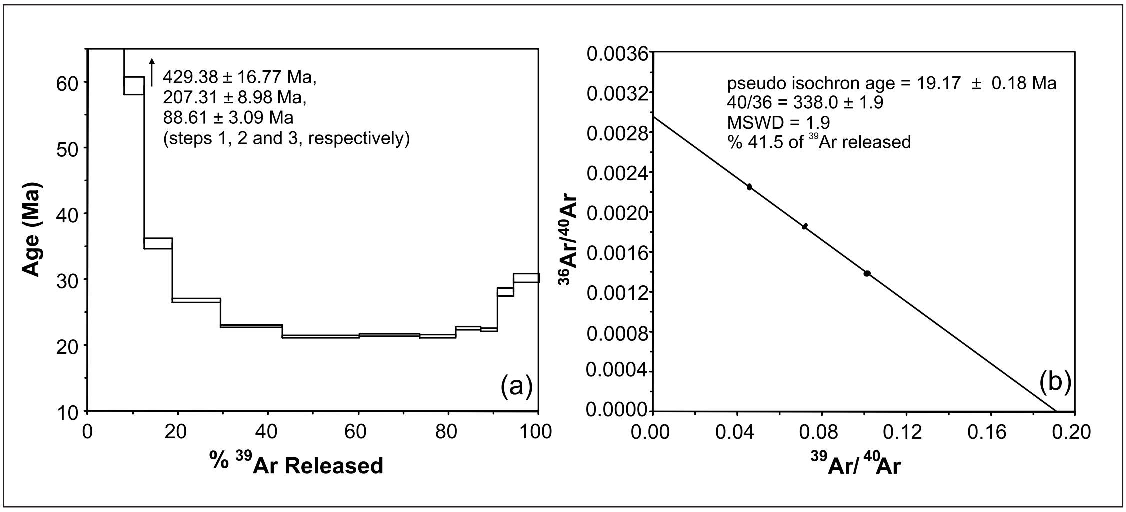

Figure 11- (a) apparent age spectrum and (b) isochron for andesite sample of the Sağırlar volcanic unit.

located along a western margin of a rhomb-shaped stock (Figure 6). The contact between schists of the Menderes Massif and izmir-Ankara Zone is more or less vertical, defined by cm-thick foliation and lineation patterns. Undeformed granites have sharp contact with deformed, fo-liated granites (Figure 12a). Deformed gra-nites display increasing deformation patterns and thinner foliation planes towards the marginal parts (Figure 12b). Deformation zone, the shear zone, usually consists of microcrystalline quartz, sericite and minor biotite crystals. Mafic minerals are less abundant in the shear zone with respect to those in the undeformed granites. Strike of foliation is variable, ranging between N45°E and N45°W. Dip of foliation is relatively low, ranging between 35 and 85 and plunging towards west. Lineation completely plunges towards the south-west with angles of between 2 and 56°.

Petrographic studies show that mylonitic rocks associated with Musalar granites consist of quartz, sericite, hornblende, biotite and minor potassium feldspar. These rocks are classified as ultramylonites based on abundance of matrix, which are by parallel microfaults (Figure 12c). These microfaults indicate a top-to-the-SW sense of shear. Quartz grains typically display oblique grain-shape foliation (Figure 12d) and occurs between foliation surfaces mainly defined by biotite crystals. Undulatory extinction and microfractures are common in large quartz grains. Sericites, which are after feldspars, become predominant towards the marginal parts of stocks.

Mylonitic foliation within the Alaçam granite is exposed in the southeastern and structurally upper parts of the NW-trending granite stock. In the northwestern part, porphyritic granites are completely undeformed (Figure 12e). Foliation planes are defined by lineation and quartzite bands formed by microcrystalline quartz grains (Figure 12f). Strike of foliation is variable and dip is relatively low angle ranging between 8 and 54°. Steeply dipping foliation is commonly exposed in the southern parts of the region. Lineation plunges toward NE and SW at an angle of 1-36°. Deformed Alaçam granites, which can be classified as protomylonites, are locally cut by C' shear bands. These shear bands indicate a top-to-the-NE sense of shear. At a mesoscopic scale, deformed granites are composed of quartz, plagioclase, potassium feldspar and biotite. They are also associated with aplites and mafic microgranular enclaves, which display ductile deformation patterns such as sword-like intrusions of aplites and flattened enclaves.

Petrographic observations indicate the presence of some intense shear bands. Recrystallized quartz grains occur as clusters within asymmetrical shear bands (Figure 12g). Biotites within protomylonites display mica fish structures (Figure 12h). Potassium feldspars are subhedral to unhedral, brittlely fractures and display ondulose extinction. Recrystallized quartz grains, shear bands, asymmetric potassium feldspar porphyroclasts and mica fish structures indicate a top-to-the NE displacement within the Alaçam granites.

DISCUSSION

Geological mapping studies in the Alaçamdağ region pointed out two volcanic episodes in the region. These episodes comprise Sağırlar volcanic unit and felsic volcanic rocks, which are separated by an unconformity. Unconformable contact zones, which are characterized by palaeosoil occurrences and angular unconformities, indicate fast erosion and hiatus after emplacement of the Sağırlar volcanic unit. Intrabasinal unconformities within the Early Miocene alluvial/lacustrine sedimentary/volcanic deposits together with extensive syn-sedimentary deformation suggest an active tectonic environment during sedimentation and volcanism in the Alaçamdağ region.

Ignimbrites, which have transitional contacts with alluvial/lacustrine sedimentary deposits, unconformably overlie mylonites of the Alaçam granites. Similar contact relationship was already described in the Koyunoba granites (Işık et al., 2004; Ring and Collins, 2005). Ductilely deformed Koyunoba granites are unconformably overlain by massive ignimbrites. Apatite fission track and U-Pb zircon ages from the Koyunoba ve Eğrigöz granites indicate that uplift of granites and their exhumation were associated with Simav detachment fault that was active during 25 to 19 Ma (Thomson and Ring, 2006; Ring and Collins, 2005; Hasözbek et al., 2009).

Thomson and Ring (2006) pointed out that erosional processes had a significant contribution to granite exhumation. Erkül (in press) provides convincing evidence for syn-extensional ductile deformation during emplacement of the Alaçam granite. The Alaçam granite includes a gently-dipping shear zone that is exposed in the structurally upper levels. Ar-Ar cooling ages of between 19.8 and 19.5 Ma were obtained from the deformed and undeformed granites, supporting the syn-tectonic emplacement of the Alaçam granite. These granites were probably exhumed by extensional shear zones that caused rapid uplift and erosion. Erosional processes operated after the emplacement of the Sağırlar volcanic unit during 19.2 Ma.

Another important point is the time and space relationships between the Alaçamdağ granites and the overlying felsic volcanic rocks. This study demonstrates that the felsic volcanic rocks intercalated with alluvial/lacustrine deposits emplaced after the cooling of the Alaçamdağ granites. This suggests that the felsic volcanic rocks are not directly associated with exhumed Alaçamdağ granites and that younger and unexposed granite intrusions occurred following the exhumation processes in the Alaçamdağ region. Therefore, felsic volcanic rocks are not spatially and temporally associated with the Alaçamdağ granites.

Geological relationships among volcanism, plutonism and extensional tectonic patterns in the Alaçamdağ region strongly resemble to those of metamorphic core complexes exposed in the northwest Turkey. Early Miocene metamorphic core complexes were described in the northern Menderes and Kazdağ Massifs (Okay and Satır, 2000; Işık and Tekeli 2001; Işık et al., 2004; Ring and Collins 2005). Evidence from these massifs indicate that extensional regime commenced during about 20 Ma. This age correspods to

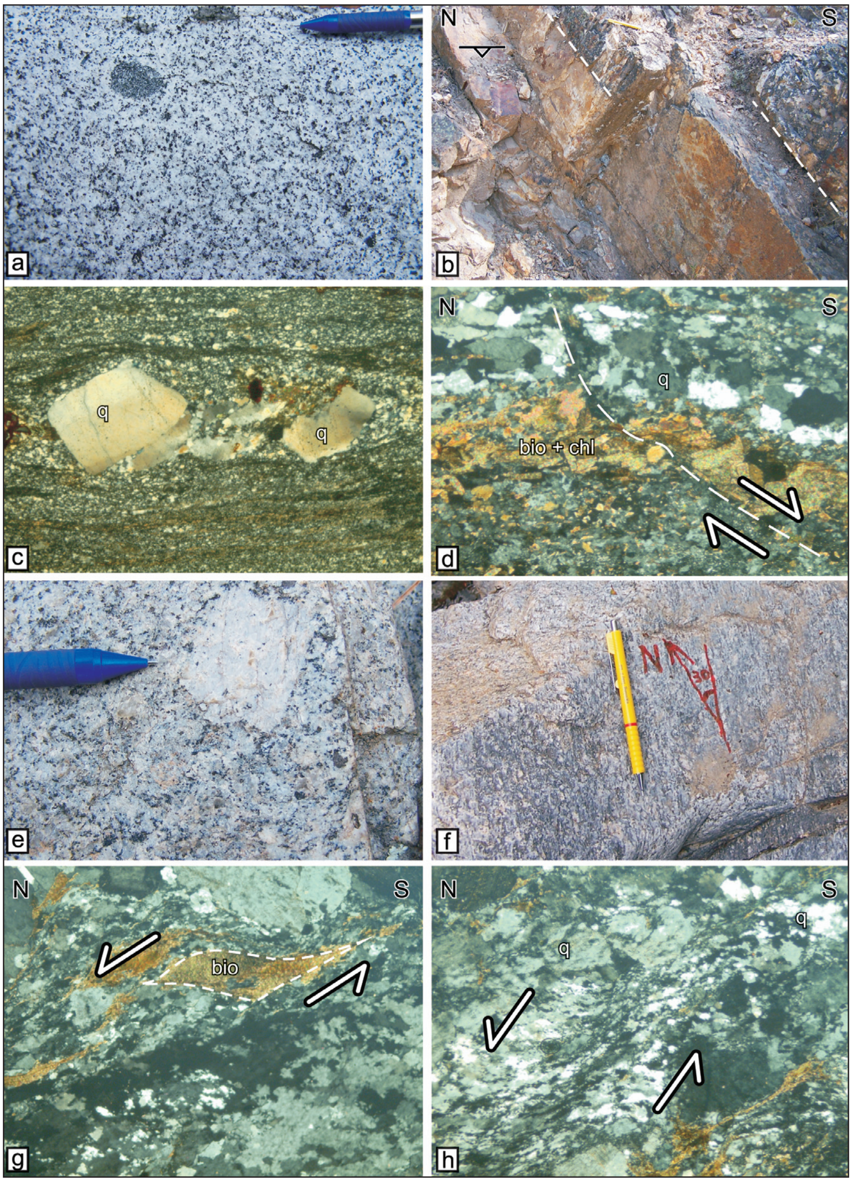

Figure 12 - Petrographic and structural characteristics of the Musalar (a-d) and Alaçam granites (e-h). (a) mafic microgranular enclaves within the equigranular Musalar granite. (b) mesoscopic appearance of shear-related foliation planes within the Musalar granite. Foliation dips towards southwest. (c) photomicrograph of domino-type structures in quartz grains within the sericite-rich ultramylonites. Dynamically recrystallised quartz grains display ondulatory extinction and microfractures. (d) photomicrograph of chlorite-filled microfaults cutting the quartz-rich ultramylonites Microfaults indicate a top-to-the southwest sense of shear. (e) orthoclase megacrysts in the porphyritic Alaçam granite. (f) mineral lineation on the protomylonitic granites. Pen is 15 cm long. (g) mica-fish structure within protomylonites. Kinematic data indicate a top-to-the northeast sense of shear. (h) shear bands formed by dynamically recrystallised quartz grains in the protomylonites. q: quartz, chl: chlorite, bio: biotite. Width of view in microphotographs is 3 millimetres.

emplacement and cooling ages of the Alaçamdağ granites. Streching lineations from the ductile shear zones occurred in the Alaçamdağ granites indicate that the hanging-wall rocks, the İzmir-Ankara Zone, displaced in different directions. Streching lineations within shear zones in the Alaçam granites show top-to-the-NE displacement of hanging-wall rocks, while shear zones within the Musalar granite indicate a top-to-the-SW displacement of the Bornova Flysch Zone. Ductile shear zones within the Musalar granite suggest the presence of a high-angle sinistral displacement between the juxtaposed rocks of the Menderes Massif to the west and the Bornova Flysch Zone to the east. Shear zones in the Alaçam granites are gently dipping and have streching lineations indicating top-to-the NE sense of shear. These kinematic indicators in the Alaçam granites are consistent with those measured in the Kazdağ and Simav metamorphic core complexes. All kinematic data from the metamorphic core complexes suggest that northwestern Turkey experienced a NE-SW-directed extension during at least Early to Middle Miocene times.

Stratigraphy of the Alaçamdağ region is similar to that of the NE-trending basins in western Turkey. Volcanism accompanied the deposition of alluvial and lucustrine sedimentary deposits in the NE-trending Bigadiç, Gördes, Demirci and Soma basins during Early Miocene. Unconformities observed in volcanic and sedimentary successions appear to be associated with the regional-scale detachment faults and extensional shear zones occurred in western Turkey.

CONLCUSION

The Alaçamdağ region has been subjected to the rapid uplift and erosional processes owing to activity of steeply and gently dipping shear zones during Early Miocene. Evidence for operation of these processes were recorded in the Early Miocene volcano-sedimentary successions in the Alaçamdağ region: (1) angular unconformities between the Sağırlar volcanic unit and the overlying alluvial/lacustrine sedimentary and felsic volcanic rocks, (2) intrabasinal unconformities and syn-sedimentary deformation structures within the alluvial/lacustrine sedimentary deposits, and (4) felsic volcanic rocks overlying the mylonitised Alaçam granites.

Streching lineations and kinematic indicators associated with the Alaçam granites are consistent with shear sense recorded from other metamorphic core complexes in western Turkey. These data indicate that the western Anatolia experienced NE-SW-directed extension during Early Miocene.

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