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Geological Society, London, Special Publications 2009, v.311;
p213-233.
doi: 10.1144/SP311.8

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Notes

Geochemical and temporal evolution of Cenozoic magmatism in western Turkey: mantle response to collision, slab break-off, and lithospheric tearing in an orogenic belt

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Abstract: Post-collisional magmatism in western Anatolia began in the Eocene, and has occurred in discrete pulses throughout the Cenozoic as it propagated from north to south, producing volcano-plutonic associations with varying chemical compositions. This apparent SW migration of magmatism and accompanying extension through time was a result of the thermally induced collapse of the western Anatolian orogenic belt, which formed during the collision of the Sakarya and Tauride–Anatolide continental blocks in the late Paleocene. The thermal input and melt sources for this prolonged magmatism were provided first by slab break-off-generated aesthenospheric flow, then by lithospheric delamination-related aesthenospheric flow, followed by tectonic extension-driven upward aesthenospheric flow. The first magmatic episode is represented by Eocene granitoid plutons and their extrusive carapace that are linearly distributed along the Izmir–Ankara suture zone south of the Marmara Sea. These suites show moderately evolved compositions enriched in incompatible elements similar to subduction zone-influenced subalkaline magmas. Widespread Oligo-Miocene volcanic and plutonic rocks with medium- to high-K calc-alkaline compositions represent the next magmatic episode. Partial melting and assimilation-fractional crystallization of enriched subcontinental lithospheric mantle-derived magmas were important processes in the genesis and evolution of the parental magmas, which experienced decreasing subduction influence and increasing crustal contamination during the evolution of the Eocene and Oligo-Miocene volcano-plutonic rocks. Collision-induced lithospheric slab break-off provided an influx of aesthenospheric heat and melts that resulted in partial melting of the previously subduction-metasomatized mantle lithosphere beneath the suture zone, producing the Eocene and Oligo-Miocene igneous suites. The following magmatic phase during the middle Miocene (16–14 Ma) developed mildly alkaline bimodal volcanic rocks that show a decreasing amount of crustal contamination and subduction influence in time. Both melting of a subduction-modified lithospheric mantle and aesthenospheric mantle-derived melt contribution played a significant role in the generation of the magmas of these rocks. This magmatic episode was attended by region-wide extension that led to the formation of metamorphic core complexes and graben systems. Aesthenospheric upwelling caused by partial delamination of the lithospheric root beneath the western Anatolian orogenic belt was likely responsible for the melt evolution of these mildly alkaline volcanics. Lithospheric delamination may have been caused by ‘peeling off’ during slab rollback. The last major phase of magmatism in the region, starting *c.* 12 Ma, is represented by late Miocene to Quaternary alkaline to super-alkaline volcanic rocks that show OIB-like geochemical features with progressively more potassic compositions increasing toward south in time. These rocks are spatially associated with major extensional fault systems that acted as natural conduits for the transport of uncontaminated alkaline magmas to the surface. The melt source for this magmatic phase carried little or no subduction component and was produced by the decompressional melting of aesthenospheric mantle, which flowed in beneath the attenuated continental lithosphere in the Aegean extensional province. This time-progressive evolution of Cenozoic magmatism and extension in western Anatolia has been strongly controlled by the interplay between regional plate-tectonic events and the mantle dynamics, and provides a realistic template for post-collisional magmatism and crustal extension in many orogenic belts.

Western Anatolia (Turkey) is part of the Aegean extensional province, which is situated in an active convergent zone between the African and Eurasian Plates (Fig. 1a). One of the most seismically

active and rapidly deforming domains of the Alpine–Himalayan mountain belt, the Aegean province is also a site of widespread magmatism since the early Eocene (*c.* 54 Ma) although the tectonic

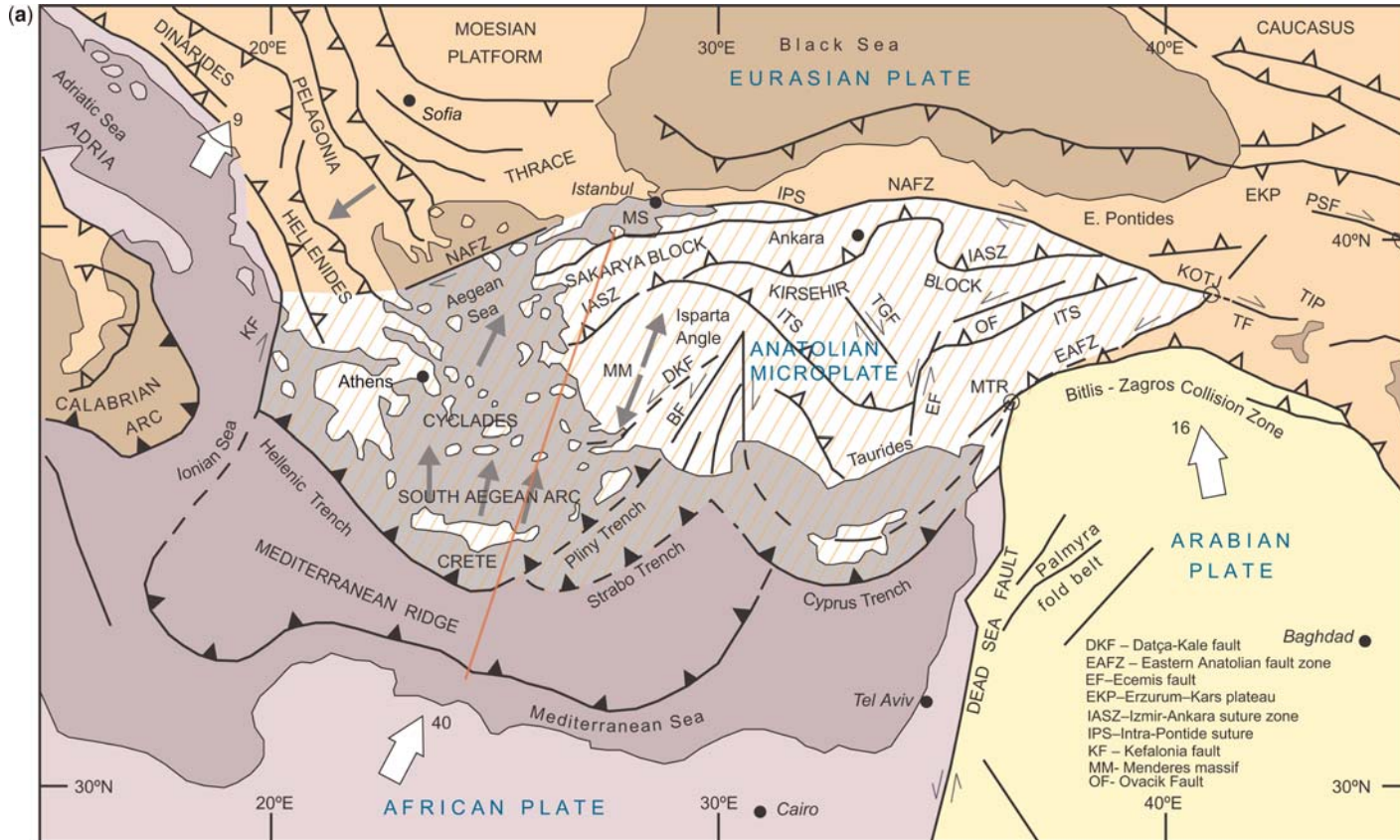


Fig. 1. (a) Tectonic map of the Aegean and eastern Mediterranean region, showing the main plate boundaries, major suture zones, and fault systems. Thick, white arrows depict the direction and magnitude (mm/a) of plate convergence; grey arrows mark the direction of extension (Miocene–Recent). Light-grey tone north of the North Anatolian Fault Zone (NAFZ) and west of the Calabrian Arc delineates Eurasian plate affinity, whereas the grey tones south of the Hellenic, Strabo and Cyprus Trenches delineate African plate affinity. KOTJ, Karliova triple junction; MS, Marmara Sea; MTR, Maras triple junction; NAFZ, North Anatolian fault zone; OF, Ovacik fault; PSF, Pampak-Sevan fault; TF, Tutak fault; TGF, Tuz Gölü fault; TIP, Turkish-Iranian plateau (modified from Dilek 2006).

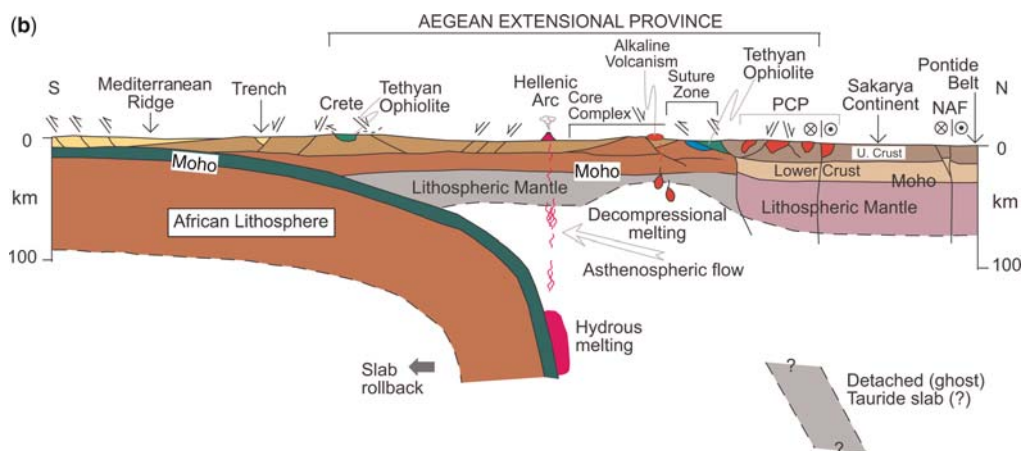


Fig. 1. (Continued) (b) Interpretative tectonic cross-section along a NNE-SSW-trending profile (straight line in 1a) through the Africa–Eurasia convergence zone and the Aegean extensional province. The Aegean extensional province straddles the Anatolide–Tauride and Sakarya continental blocks, which collided in the Paleocene. The Cretaceous Tethyan ophiolites and blueschist rocks are derived from the suture zone (Izmir–Ankara suture zone) between these two continental blocks. Eocene–Oligocene post-collisional plutons (PCP) north of this suture zone mark the oldest Cenozoic magmatic products in the region. Cenozoic magmatism appears to have migrated southward and to have changed from calc-alkaline to alkaline in composition. Lithospheric-scale necking and decompressional melting associated with asthenospheric upwelling may have been responsible for Quaternary alkaline volcanism (i.e. Kula region) in the south-central part of the Aegean extensional province.

settings and melt sources of this widespread magmatism appear to have varied through time. The geological record of the Cenozoic magmatic events in the Aegean province is perhaps most complete in western Anatolia, where both the modern landscape and surface rocks are predominantly volcanic (Fig. 1b). Therefore, a systematic documentation of the chronology and the chemical evolution of Cenozoic volcanism in western Anatolia should reveal significant information on the mantle dynamics and its response to lithospheric- and crustal-scale processes during the evolution of an orogenic belt.

For the most part, three major geodynamic processes have been controlling the late Cenozoic evolution of the broader eastern Mediterranean region: subduction of the African/Arabian plate beneath Eurasia along the Hellenic and Cyprus trenches since the late Cretaceous (Westaway 1994; Kreemer *et al.* 2003 and the references therein; van Hinsbergen *et al.* 2005), continental collision of Arabia with Eurasia since the middle Miocene (McKenzie 1978), and the resulting westward escape of the Anatolian block along the North and East Anatolian fault zones away from the Arabia–Eurasia collision zone (Fig. 1; Dewey *et al.* 1986; Barka & Reilinger 1997). Subduction rollback processes along the Hellenic trench since 30 Ma (and potentially since the late Cretaceous) have resulted in upper-plate extension and the

gravitational collapse of the Tethyan orogenic crust (Meulenkamp *et al.* 1988; Jolivet 2001; Faccenna *et al.* 2003; van Hinsbergen *et al.* 2005). Both extension and attendant magmatism in the region date back to the late Oligocene (if not older), as evidenced by the existence of metamorphic core complexes (c. 26 Ma; Menderes and Kazdag massifs; Fig. 2; Bozkurt & Satir 2000; Okay & Satir 2000; Isik *et al.* 2004) and extensive calc-alkaline to alkaline volcanic rocks (Savaşçın & Oyman 1998; Aldanmaz *et al.* 2000, 2006; Alici *et al.* 2002; Altunkaynak & Dilek 2006, and references therein) in western Anatolia. How the extensional deformation and magmatism started and have varied in time, space, and magnitude since the beginning of the Neogene remain some of the most fundamental questions in the geodynamic evolution of the eastern Mediterranean region and in continental tectonics in general (Dilek 2006).

In this paper we review the nature and geochemical characteristics of Cenozoic magmatism in western Turkey within the framework of its regional tectonics and evaluate the mantle sources and melt evolution of this magmatism. We then discuss the potential links between regional plate-tectonic events and the mantle dynamics that appear to have strongly affected and controlled the evolution of the Cenozoic magmatism in the region. Our model for the western Anatolian Cenozoic tectonics may be applicable to many collisional orogens,

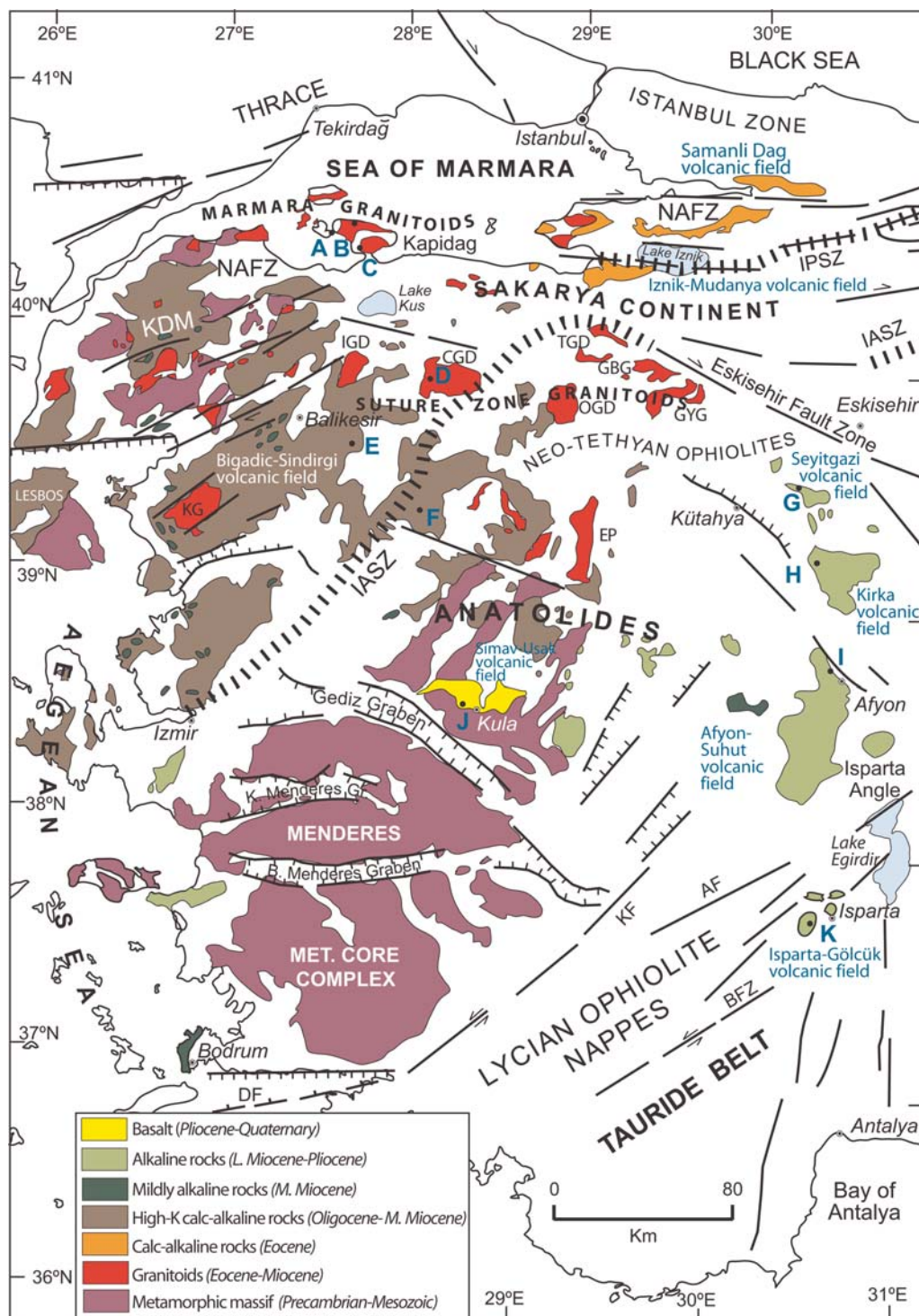


Fig. 2. Simplified geological map of western Anatolia and the eastern Aegean region, showing the distribution of major Cenozoic igneous provinces discussed in this paper and the salient fault systems. Menderes and Kazdag (KDM) massifs represent metamorphic core complexes with exhumed middle to lower continental crust. Izmir-Ankara suture

suggesting that the mode and tempo of post-collisional extension and magmatism in orogenic belts may have a common pathway.

Cenozoic geology and crustal make-up of western Anatolia

The present-day geodynamics of the eastern Mediterranean region is controlled by the relative motions of three major plates (Eurasia, Africa and Arabia) and much of deformation occurs at their boundaries (Fig. 1a; Westaway 1994; Doglioni *et al.* 2002; Dilek 2006). The convergence rate between Africa and Eurasia is greater than 40 mm/a across the Hellenic trench but decreases down to <10 mm/a across the Cyprus trench to the east (McClusky *et al.* 2000; Doglioni *et al.* 2002; Wdowski *et al.* 2006), most likely as a result of the attempted subduction of the Eratosthenes seamount beneath Cyprus (Robertson 1998). The Arabia–Eurasia convergence across the Bitlis–Zagros suture zone has been estimated to be *c.* 16 mm/a based on global positioning system measurements of present-day central movements in this collision zone (Reilinger *et al.* 1997). These differential northward motions of Africa (<10 mm/a) and Arabia (16 mm/a) with respect to Eurasia are accommodated along the sinistral Dead Sea fault zone (Fig. 1). The Anatolian microplate north of these convergent plate boundaries is moving toward West–SW (with respect to Eurasia) at *c.* 30 mm/a along the North and East Anatolian fault zones (Fig. 1a; Reilinger *et al.* 1997) and is undergoing complex internal deformation via mainly strike-slip and normal faulting. This deformation has resulted in the extensional collapse of the young orogenic crust, which has been developed during a series of collisional events in the region (Dewey *et al.* 1986; Dilek & Moores 1990; Yılmaz 1990), giving way to the formation of metamorphic core complexes and intracontinental basins (Bozkurt & Park 1994; Dilek & Whitney 2000; Jolivet & Faccenna, 2000; Okay & Satir 2000; Doglioni *et al.* 2002; Ring & Layer 2003).

The Aegean province is situated in the upper plate of a north-dipping subduction zone at the Hellenic trench (Fig. 1b) and is considered to have evolved as a backarc environment above this subduction zone (Le Pichon & Angelier 1979; Jolivet

2001; Faccenna *et al.* 2003; van Hinsbergen *et al.* 2005). The slab retreat rate of the subducting African lithosphere has been larger than the absolute velocity of the Eurasian upper plate, causing net north–south extension in the Aegean region since the early Miocene (Fig. 1b; Jolivet *et al.* 1994; Jolivet & Faccenna 2000; Faccenna *et al.* 2003; Ring & Layer 2003). The thrust front associated with this subduction zone and its slab retreat has also migrated from the Hellenic trench (south of Crete) to the south of the Mediterranean Ridge since then (Jolivet & Faccenna 2000; Le Pichon *et al.* 2003). The backarc extension in the Aegean region thus appears to have started *c.* 25 Ma, long before the onset of the Arabian collision-driven southwestward displacement of the Anatolian microplate in the late Miocene (Barka & Reilinger 1997; Jolivet & Faccenna 2000).

Timing of the onset, the causes, and the nature of extensional tectonics in western Anatolia are controversial (Seyitoğlu & Scott 1996; Gautier *et al.* 1999; Bozkurt & Satir 2000; Bozkurt 2003; Ring *et al.* 2003; Purvis & Robertson 2004; Catlos & Çemen 2005), although it is commonly accepted that the orogenic crust in western Anatolia and the Aegean area was already thinned significantly by the middle Miocene (Jolivet *et al.* 1994; Ring & Layer 2003, and references therein). Based on zircon fission track ages and radiometric dates from synkinematic granodioritic plutons (i.e. Eğriğöz and Koyunoba plutons), some researchers have suggested that tectonic extension and magmatism were synchronous events starting around 25–24 Ma (Isik *et al.* 2004; Ring *et al.* 2003; Thomson & Ring 2006). In addition to slab rollback induced extensional deformation above the Hellenic subduction zone, widespread latest Oligocene–early Miocene magmatism in the region may have been partially responsible for thermally weakening the crust and hence facilitating orogen-wide extension (Thomson & Ring 2006). The timing and the causes of the initial Cenozoic magmatism in western Anatolia have, therefore, significant implications for extensional tectonism and the geodynamic evolution of the region during the late Cenozoic.

The crustal thickness in the Aegean province ranges from *c.* 16 km in the Crete Sea to 25–35 km in the Cyclades and SW Turkey (Makris & Stobbe 1984; Doglioni *et al.* 2002; Faccenna *et al.* 2003; Tirel *et al.* 2004; Zhu *et al.* 2006). These variations

Fig. 2. (Continued) zone (IASZ) marks the collision front between the Sakarya continental block to the north and the Anatolide-Tauride block to the south. The Eocene granitoids (shown in red) straddling this suture zone represent the first products of post-collisional magmatism in the region. Much of western Anatolia is covered by Cenozoic volcanic rocks intercalated with terrestrial deposits. Letters A through K mark the type localities of major Cenozoic igneous provinces shown in Figure 3. AF, Acigöl fault; BFZ, Burdur fault zone; DF, Datça fault; IASZ, Izmir-Ankara suture zone; KDM, Kazdag metamorphic massif; KF, Kale fault; NAFZ, North Anatolian fault zone.

in crustal thickness may indicate that extensional thinning has not been uniform in the general north–south direction, assuming that the initial crustal thickness was consistent throughout the region. Recent seismic experiment studies in the region have shown that significant amount of crustal attenuation appears to coincide with the occurrence of the metamorphic core complexes (i.e. Menderes and Cycladic massifs; Figs 1 & 2), in which high-grade intermediate to lower-crustal rocks have been exhumed in the footwalls of large-scale, low-angle detachment surfaces and in the rift shoulders of mostly east–west-trending major grabens (Lister *et al.* 1984; Avigad & Garfunkel 1991; Gautier *et al.* 1999; Bozkurt & Satir 2000; Yılmaz *et al.* 2000; Keay *et al.* 2002; Ring & Layer 2003).

The continental crust making up the upper plate of the Hellenic subduction zone south of the North Anatolian fault is composed of the Sakarya continent and the Anatolide and Tauride blocks (Fig. 2). The Sakarya continent consists of a Palaeozoic crystalline basement with its Permo-Carboniferous sedimentary cover and Permo-Triassic ophiolitic and rift or accretionary-type *mélange* units (Karakaya complex) that collectively form a composite continental block (Tekeli 1981; Okay *et al.* 1996). These Sakarya continental rocks and the ophiolitic units of the Izmir-Ankara suture zone (IASZ) are intruded by a series of east–west trending Eocene and Oligo-Miocene granitoid plutons (Fig. 2; Altunkaynak 2007). The Kazdag massif within the western part of the Sakarya continent (KDM in Fig. 2) represents a metamorphic core complex, which is inferred to have been exhumed starting at *c.* 24 Ma from a depth of *c.* 14 km along a north-dipping mylonitic shear zone (Okay & Satir 2000).

The western Anatolian orogenic belt consists of, from north to south, two tectonic zones: (1) the Izmir-Ankara suture zone (IASZ); and (2) the Menderes metamorphic core complex. The Menderes metamorphic massif and the IASZ rocks collectively constitute the Anatolide block in western Turkey. The IASZ south of the Sakarya continent includes dismembered Tethyan ophiolites, high-pressure low-temperature (HP/LT) blueschist-bearing rocks, and flysch deposits mainly occurring in south-directed thrust sheets (Figs 1b, 2; Önen & Hall 1993; Okay *et al.* 1998; Sherlock *et al.* 1999). Late-stage diabasic dykes crosscutting the ophiolitic units in the Kütahya area are dated at *c.* 92–90 Ma ($^{40}\text{Ar}/^{39}\text{Ar}$ hornblende ages; Önen 2003) indicating a minimum late Cretaceous igneous age of the ophiolites, whereas the blueschist rocks along the suture zone in the Tavsanli area have revealed $^{40}\text{Ar}/^{39}\text{Ar}$ cooling ages (phengite crystallization during exhumation) of 79.7 ± 1.6 – 82.8 ± 1.7 Ma (Sherlock *et al.* 1999) suggesting a latest Cretaceous timing of the

HP/LT metamorphism in the region. The Lycian nappes, including the ophiolites, structurally overlie the platform carbonates of the Tauride block farther south (Figs 1b & 2; Collins & Robertson 1999; Ring & Layer 2003) and represent the tectonic outliers of the Cretaceous oceanic crust derived from the IASZ. These Lycian nappes are inferred to have once covered the Menderes metamorphic massif, and then to have been removed due to the tectonic uplift and erosion associated with the exhumation of the Menderes core complex during the late Cenozoic (Ring & Layer 2003; Thomson & Ring 2006).

The Menderes core complex comprises several nappe systems composed of high-grade metamorphic rocks of Pan-African affinity that are intruded by synkinematic granitoid plutons (Hetzl & Reischmann 1996; Bozkurt & Satir 2000; Bozkurt 2004; Gessner *et al.* 2004). Rimmelé *et al.* (2003) estimated the *P-T* conditions of the metamorphic peak for the Menderes massif rocks at >10 kbar and >440 °C. The main episode of metamorphism is inferred to have resulted from the burial regime associated with the emplacement of the Lycian nappes and ophiolitic thrust sheets (Yılmaz 2002). Imbricate stacking of the Menderes nappes beneath the Lycian nappes and ophiolitic thrust sheets appears to have migrated southwards throughout the Paleocene – middle Eocene (Özer *et al.* 2001; Candan *et al.* 2005). The unroofing and exhumation of the Menderes massif may have started as early as in the Oligocene (25–21 Ma) as constrained by the cooling ages of the syn-extensional granitoid intrusions crosscutting the metamorphic rocks (Ring & Collins 2005; Thomson & Ring 2006; Bozkurt & Satir 2000; Catlos *et al.* 2002). This timing may signal the onset of the initial post-collisional tectonic extension in the Aegean region.

The Tauride block to the south consists of Precambrian–Ordovician to Lower Cretaceous carbonate rocks intercalated with volcano-sedimentary and epiclastic rocks (Ricou *et al.* 1975; Demirtasli *et al.* 1984; Özgül 1984; Gürsu *et al.* 2004) that are tectonically overlain by the Tethyan ophiolites (i.e. Lycian, Beyşehir-Hoyran, Alihoca and Aladag ophiolites) along south-directed thrust sheets (Collins & Robertson 2003; Dilek *et al.* 1999a; Elitok & Drüppel 2008). Underthrusting of the Tauride carbonate platform beneath the Tethyan oceanic crust and its partial subduction at a north-dipping subduction zone in the Inner-Tauride ocean resulted in high-*P*/low-*T* metamorphism (Dilek & Whitney 1997; Okay *et al.* 1998). Continued convergence caused crustal imbrication and thickening within the platform and resulted in the development of several major overthrusts throughout the Tauride block (Demirtasli *et al.* 1984;

Dilek *et al.* 1999b). The buoyancy of the Tauride continental crust in the lower plate eventually arrested the subduction process and caused the isostatic rebound of the partially subducted platform edge, leading to block-fault uplifting of the Taurides during the latest Cenozoic (Dilek & Whitney 1997, 2000).

Cenozoic magmatism: distribution and geochemistry

The post-collisional Cenozoic magmatism in western Anatolia started after the collision of the Sakarya and Anatolide–Tauride continental blocks in the late Paleocene (Okay *et al.* 1998). The collisional front is today marked by the IASZ (Fig. 2), along which the Upper Cretaceous ophiolites tectonically overlie the high-grade metamorphic rocks of the Anatolides. The earliest products of this post-collisional magmatism are represented by I-type calc-alkaline granitoids that are linearly distributed (*c.* east–west) in a narrow belt along the IASZ. These plutons are intrusive into the Cretaceous ophiolites, the blueschist rock assemblages and the basement rocks of the Sakarya continent and are plastically to brittlely deformed by extensional shear zones and normal faults (*i.e.* Kapıdag and Çataldag plutons; Fig. 3a–d). Those plutons closer to the IASZ (the suture zone granitoids, SZG, of Altunkaynak 2007) range in composition from diorite, quartz diorite, and granodiorite to syenite (Orhaneli, Topuk, Gürgenyayla and Göynükbelen plutons) and have ages around 54–48 Ma (Ataman 1972; Bingöl *et al.* 1982, 1994; Harris *et al.* 1994; Delaloye & Bingöl 2000; Yılmaz *et al.* 2001). The plutons farther north along the Marmara Sea (Marma granitoids, MG, of Altunkaynak 2007) are composed of monzogranite, granodiorite and granite (Armutlu, Lapseki and Kapıdag plutons) and have ages around 48–34 Ma (Bingöl *et al.* 1994; Harris *et al.* 1994; Ercan *et al.* 1985; Genç & Yılmaz 1997; Delaloye & Bingöl 2000; Köprübasi *et al.* 2000; Köprübasi & Aldanmaz 2004), slightly younger than the SZGs. Volcanic equivalents of these Marmara granitoids are locally represented by basaltic to andesitic lavas and pyroclastic rocks (Genç & Yılmaz 1997).

Although the geochemical features of the SZG and MG plutons show some similarities, their magmas may have undergone different magnitudes of fractional crystallization and crustal contamination. Both the SZGs and MGs show medium- to high-K calc-alkaline characteristics with their silica contents ranging from *c.* 76 to 64 wt.% (Altunkaynak 2007). Their trace-element abundances exhibit large variations (*e.g.* Ba: 57–1150 ppm; Th: 2–13 ppm; La: 2.01–57.1 ppm), suggesting

that these rocks were moderately enriched in incompatible elements and that their melts were moderately evolved (Pearce 1982). They display enrichment in large ion lithophile elements (LILEs; K, Rb, Ba, Th) over light rare earth elements (LREEs) and medium REEs, and depletion in high field strength elements (Zr, Nb, Ti and P) with respect to the adjacent LILE on MORB-normalized multi-element variation diagrams. Whereas the SZGs show no distinct Eu anomalies (with $\text{Eu}^*/\text{Eu} = 0.89\text{--}0.98$), the MGs display negative Eu anomalies, the magnitude of which increases with increasing SiO_2 contents; the concave upward REE patterns also become more prominent with increasing SiO_2 contents from the SZGs in the south to the MGs in the north, indicating strongly fractionated REE patterns regardless of rock type (Altunkaynak 2007). Stronger depletion of the MG rocks in Eu, Ba, Sr, and P and their higher contents of Pb, K, Ni, and SiO_2 in comparison to the SZG rocks suggest greater amounts of crustal contamination during the ascent of their magmas through the Sakarya continental crust.

The next magmatic pulse in the region is represented by Oligo-Miocene granitoid plutons and volcanic units (ranging from andesite to dacite, rhyodacite and rhyolite) that are overlain by ignimbrite flows, pumiceous air-fall, and mudflow deposits, intercalated with lower to middle Miocene lacustrine rocks and coal seams (Fig. 3e–f; Bingöl *et al.* 1982, 1994; Erkül *et al.* 2005; Yücel-Öztürk *et al.* 2005). These Oligo-Miocene volcanoplutonic complexes have silica contents ranging from 63 to 48 wt.%, medium to high Al_2O_3 abundances, and very low TiO_2 (<1 wt.%), with their MgO contents slightly higher than those of the Eocene volcanoplutonic assemblages. They are made of shoshonitic to high-K calc-alkaline rocks, showing enrichment in the most incompatible elements (Ba, Rb, Th, K, La, Ce) and depletion in Nb, Ta, P, and Ti on MORB-normalized multi-element diagrams (Altunkaynak & Dilek 2006). These features, combined with their LREE enrichment and relatively flat HREE patterns, and minor Eu anomalies ($\text{Eu}^*/\text{Eu} = 0.75\text{--}0.91$) on chondrite-normalized REE diagrams, collectively suggest derivation of their magmas from moderately to strongly evolved melts (Frey *et al.* 1978) with subduction zone geochemical signatures (Thirwall *et al.* 1994; Pearce & Peate 1995).

The ensuing middle Miocene volcanism produced mildly alkaline lavas that are spatially associated with NNE-trending transtensional fault systems (Fig. 2). Volcanic rocks of this phase consist of andesitic, trachy-andesitic and pyroclastic rocks intercalated with mildly alkaline basaltic lavas and have no plutonic equivalents exposed at the surface in the region (Akay & Erdogan 2004). The SiO_2

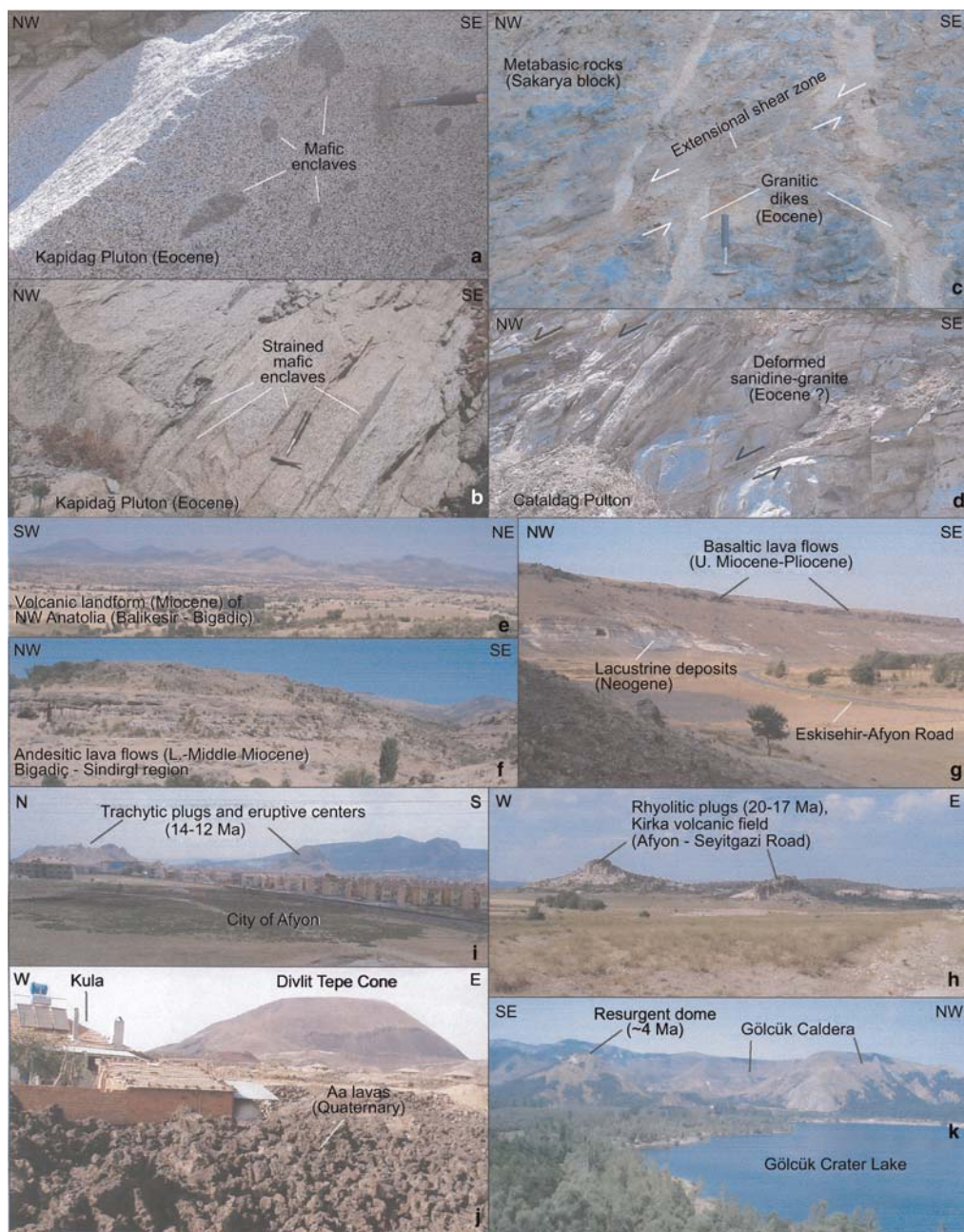


Fig. 3. Products of post-collisional Cenozoic magmatism in western Anatolia as seen in the field (see Fig. 2 for locations). (a) Undeformed Eocene Kapıdağ pluton (with mafic enclaves) as part of the Marmara granitoids in NW Turkey. (b) Deformed Kapıdağ pluton showing L-S tectonite fabric. Highly strained mafic enclaves define a WNW-dipping foliation. (c) Eocene granitic-granodioritic dikes intruding the metabasic basement rocks of the Sakarya block displaced along NW-dipping extensional shear zones. (d) Eocene Çataldağ pluton, a Suture Zone granitoid near the IASZ, showing pervasive brittle-ductile deformation along NW-dipping, subparallel low-angle shear zones. (e) Volcanic landform of the Bigadiç-Sındırgı area, consisting mainly of Miocene high-K, calc-alkaline volcanic rocks. (f) Lower middle Miocene andesitic lava flows in the Bigadiç-Sındırgı volcanic field. (g) Upper Miocene – Pliocene basaltic lava flows and the underlying Neogene lacustrine deposits of the Seyitgazi volcanic field, south of the Eskişehir

contents of these volcanic rocks range from 60 to 46 wt.% (mildly silica-undersaturated), and have moderate to high Al_2O_3 (14.26–19.30 wt.%) and TiO_2 (0.76–2.90 wt.%), and relatively high K_2O and $\text{Na}_2\text{O} + \text{K}_2\text{O}$ values for lower SiO_2 contents. These mildly alkaline rocks display less pronounced enrichment trends in Ba, Th, K and weaker Nb and P anomalies on MORB-normalized multi-element diagrams, and lower LREE enrichment patterns on chondrite-normalized REE diagrams, in comparison to the Eocene and Oligo-Miocene igneous assemblages in western Anatolia.

Extensional tectonism was well established in western Anatolia by late Miocene and was accompanied by alkaline magmatism (Dilek & Altunkaynak 2007, and references therein). Mainly basaltic volcanism of this phase with progressively more potassic compositions increased toward south in time (G through K in Figs 2 & 3; Seyitoğlu & Scott 1992; Alici *et al.* 1998, 2002; Savaşçin & Oyman 1998; Aldanmaz *et al.* 2000; Innocenti *et al.* 2005; Çoban & Flower 2006). Late Miocene–Pliocene to Quaternary volcanism produced basalts, basanites, and phonotephrites with potassic to ultrapotassic compositions (Richardson-Bunbury 1996; Seyitoğlu *et al.* 1997; Aldanmaz *et al.* 2000; Alici *et al.* 2002; Savaşçin & Oyman 1998; Francalanci *et al.* 2000; Innocenti *et al.* 2005) that are commonly spatially associated with major extensional fault systems. Major eruption centers of these potassic-ultrapotassic lavas include the Afyon, Kula, and Isparta-Gölcük volcanic fields in SW Turkey (i, j and k, respectively, in Figs 2 & 3). These alkaline rocks range in age from 8.4 Ma to 0.13 ± 0.005 Ma (Richardson-Bunbury 1996; Aldanmaz *et al.* 2000; Alici *et al.* 2002; Savaşçin & Oyman 1998) and have silica-undersaturated (48–41 wt.% SiO_2) compositions with higher Mg numbers (#51–84) and TiO_2 (1.80–3.22 wt.%) contents in comparison to the rocks of the subalkaline and mildly alkaline groups. The potassic-ultrapotassic lavas of the Kula volcanic field (Fig. 3j) have, for example, multi-element patterns similar to those of ocean-island basalts (OIB) with maximum enrichment in the more incompatible elements (from Nd to Cs), and display LILE enrichment (e.g. in Ba and Rb) and HREE depletion relative to the N-MORB (Innocenti *et al.* 2005). They also show LREE enrichment relative to chondrites.

The Isparta–Gölcük volcanic field farther south in the Isparta Angle region (Figs 2 & 3k) contains

potassic-ultrapotassic rocks (tephriphonolite, trachyandesite, andesite) with olivine, plagioclase, clinopyroxene, biotite, amphibole and phlogopite phenocryst phases (Alici *et al.* 1998; Çoban & Flower 2006; Kumral *et al.* 2006). These rocks have very low SiO_2 (46.8–49.2 wt.%) and high MgO (10.4–11.6 wt.%) contents and lamproitic affinity, and show high LILE (Ba, Sr, Rb, K) and LREE compared to HFSE. Their depletions in Nb and Ta and high Ba/Nb (>28) ratios are characteristic of subduction zone magmas, and low Sr and high Nd isotopic compositions indicate relatively low degrees of crustal contamination.

The Cenozoic magmatism in western Anatolia appears to have swept across the region, getting younger from north to south and changing its character from calc-alkaline to alkaline over time. We evaluate below first the changing mantle sources and melt evolution of this magmatism in the region, and then the potential links between the regional plate-tectonic events and the mantle dynamics that appear to have strongly affected and controlled this evolutionary path of the Cenozoic magmatism in the region.

Mantle sources and melt evolution

Time-progressive evolution of the Cenozoic magmatism in western Anatolia closely follows the aesthenospheric – lithospheric melting array depicted on the $\epsilon\text{Nd}_{(t)}$ vs. $^{87}\text{Sr}/^{86}\text{Sr}_{(t)}$ diagram in Figure 4. Eocene volcanoplutonic complexes, upper Oligocene – lower Miocene high-K calc-alkaline to shoshonitic rocks, and middle Miocene mildly alkaline volcanics fall between the MORB and the crustal (Aegean Sea sediments and Aegean metamorphic basement) fields along this array indicating their hybrid compositions. Trace-element and rare-earth element chemistry of these hybrid rocks suggest that the metasomatized lithospheric mantle source contribution to their melt evolution was significant, and that this enriched mantle source was subduction-influenced (Altunkaynak & Dilek 2006, and references therein). The subduction component to the source mantle was most likely introduced by the late Cretaceous subduction of the Neo-Tethyan oceanic lithosphere beneath the Sakarya Continent, as well as by the ongoing subduction at the Hellenic trench in the late Oligocene and later times (van Hinsbergen *et al.* 2005). Earlier Palaeo-Tethyan subduction events affecting the

Fig. 3. (Continued) fault zone. (h) Lower Miocene rhyolitic plugs in the Kirka volcanic field (Afyon-Seyitgazi Road). (i) Middle Miocene trachytic plugs and eruptive centers in and around the City of Afyon in the Afyon-Suhut volcanic field. (j) Quaternary basaltic Aa lava flows and a cinder cone in the Kula volcanic field. (k) Ignimbrites and a resurgent dome (c. 4 Ma) within the Gölcük caldera in the highly alkaline Isparta-Gölcük volcanic field.

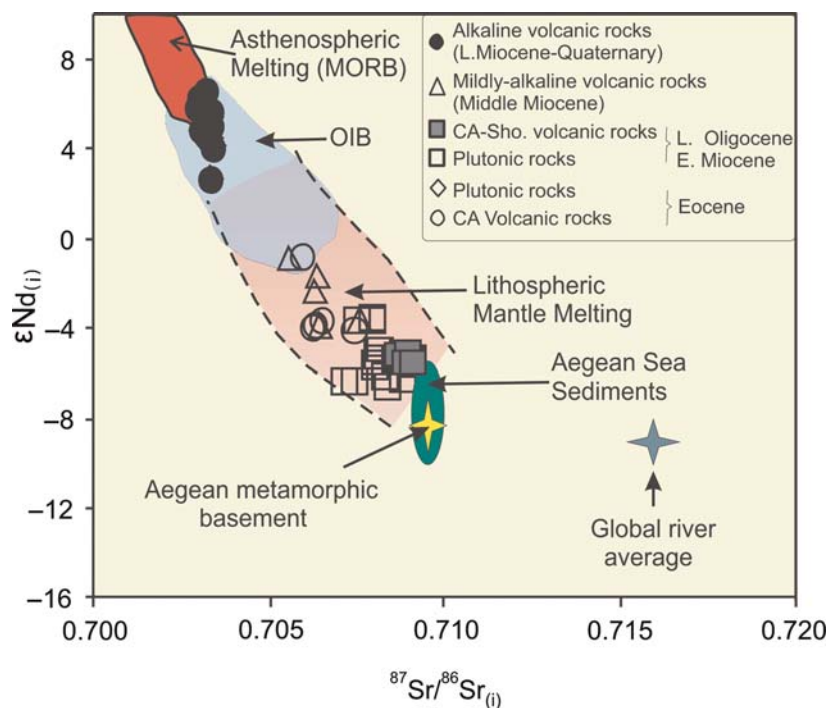


Fig. 4. Epsilon- $Nd_{(i)}$ versus $^{87}Sr/^{86}Sr_{(i)}$ diagram for the Cenozoic magmatic rocks in western Anatolia. Data for asthenospheric and lithospheric mantle melting array from Davis & Blanckenburg (1995), for Aegean metamorphic basement from Briquieu *et al.* (1986), for Aegean Sea sediments from Altherr *et al.* (1988), and for Global river average from Goldstein & Jacobsen (1988). Modified from Altunkaynak & Dilek (2006).

geodynamic evolution of the Vardar Ocean farther north (Dilek & Thy 2006; Stampfli *et al.* 2001; Okay *et al.* 1996) may have also contributed to the metasomatization and heterogeneity of the continental mantle beneath NW Anatolia.

Geochemical features of the middle Miocene (16–14 Ma) volcanic assemblages in western Anatolia point out a major shift in the nature of the Cenozoic magmatism in the region during this time. Although the negative Ta and Nb anomalies, enriched LREE, and low Rb/Sr ratios of the mildly alkaline middle Miocene volcanic rocks indicate the involvement of a subduction-influenced and incompatible element-enriched mantle source in their magma evolution, their significantly lower La/Nb, Zr/Nb, and $^{87}Sr/^{86}Sr$ ratios, and higher $^{143}Nd/^{144}Nd$ ratios in comparison to the Eocene and Oligo-Miocene igneous assemblages suggest a diminishing effect of subduction influence and possibly a considerable influence of incoming asthenospheric melts. The $\epsilon Nd_{(i)}$ vs. $^{87}Sr/^{86}Sr_{(i)}$ values of these middle Miocene volcanics plot in the middle part of the lithospheric-aesthenospheric mantle melting array (Fig. 4) supporting this interpretation.

The upper Miocene–Quaternary alkaline rocks (Fig. 2) plot mainly in the OIB field and partly straddle the MORB–OIB fields (Fig. 4), suggesting an asthenospheric mantle source for their origin (Aldanmaz *et al.* 2000, 2006; Alici *et al.* 2002; Altunkaynak & Dilek 2006). The lack of negative Ta and Nb anomalies in their trace element patterns and an increase of the Rb/Nb and Ba/Nb ratios with decreasing $^{87}Sr/^{86}Sr$ ratios indicate that subduction contribution to their melt source was non-existent. However, the systematic variation of their ϵNd values and of Sr–Nd isotope ratios (Fig. 4) suggests a small-scale geochemical heterogeneity in their mantle source.

In line with this evolutionary trend of the mantle melt sources and the diminishing effect of subduction influence, we also see a progressive decrease in the degree of crustal contamination going from calc-alkaline to alkaline compositions starting around 22 Ma (Fig. 5). The lower to middle Miocene (*c.* 22–16 Ma) subalkaline rocks display higher $^{87}Sr/^{86}Sr_{(i)}$ ratios in comparison to the Eocene and Oligo-Miocene subalkaline groups, despite their other geochemical features in common. Therefore, we think of a common melt source for all these

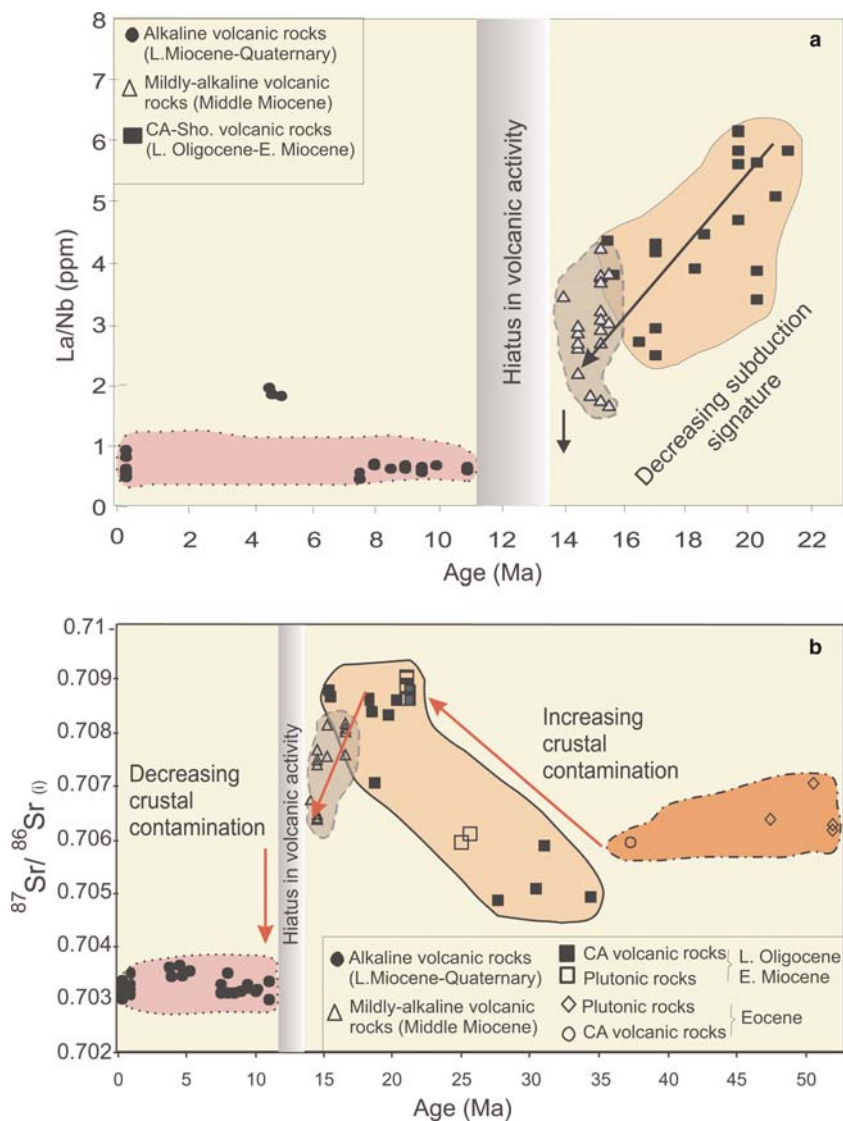


Fig. 5. (a) La/Nb versus Age (Ma) diagram, and (b) $^{87}\text{Sr}/^{86}\text{Sr}_{(i)}$ versus Age (Ma) diagram for the Cenozoic magmatic rocks in western Anatolia. See text for discussion.

subalkaline igneous groups but interpret increasing amounts of crustal contamination of the ascending magmas during the period of 22 to 16 Ma, because of their longer residence time in the crust prior to the onset of widespread extensional tectonics in the region. The degree of crustal contamination appears to have decreased rapidly with the eruption of the mildly alkaline lavas during 16–14 Ma (Fig. 5), overlapping with the influence of incoming asthenospheric melts during their magmatic evolution and with the establishment of the whole-sale lithospheric extension in the region (Ring *et al.*

2003; Çemen *et al.* 2006; Dilek 2006; Dilek & Altunkaynak 2007).

The subsequent apparent abrupt drop in the degree of crustal contamination seems to have coincided with a short hiatus in widespread volcanism in western Anatolia during *c.* 14–11 Ma (Fig. 5). The upper Miocene–Quaternary alkaline lavas have consistently low $^{87}\text{Sr}/^{86}\text{Sr}$ (0.70302–0.70349) ratios, OIB-like trace-element patterns, high LILE abundances, and high MREE/HREE ratios, characteristic of a garnet-bearing lherzolitic asthenosphere mantle source (Aldanmaz *et al.*

2000, 2006; Alici *et al.* 2002) for their magmas. Agostini *et al.* (2007) have suggested in the case of the Kula lavas (area j in Figs 2 & 3) the possibility of mixing two isotopically distinct end members of melt sources. The first of these sources is characterized by high $^{143}\text{Na}/^{144}\text{Nd}$, low $^{87}\text{Sr}/^{86}\text{Sr}$ ratios, MORB-like Pb isotopic compositions, and low Sr and Nd contents, analogous to the typical geochemical features of a DMM mantle reservoir. The less-depleted second source is characterized by lower $^{143}\text{Nd}/^{144}\text{Nd}$ and higher $^{87}\text{Sr}/^{86}\text{Sr}$, Sr and Nd abundances. In the absence of any subduction component in the origin of these melt sources, Innocenti *et al.* (2005) and Agostini *et al.* (2007) have proposed that the Kula lavas were generated from melts that were derived from a heterogeneous, sub-slab mantle source in an intra-plate setting. The geochemical features of the Isparta–Gölcük volcanic rocks in the Isparta Angle area suggest that their magmas were originated from a metasomatized or enriched (in LREE, Ba, Sr) mantle source (Alici *et al.* 1998). The silica-poor leucite lamproites here were likely derived from magmas originated by partial melting of phlogopite-bearing refractory peridotite (spinel-garnet lherzolite transition); aesthenospheric upwelling, as inferred from melt segregation pressures consistent with shallow aesthenospheric sources, may also have provided additional heat and melt to this process (Çoban & Flower 2006).

Linking Cenozoic plate-tectonics and mantle dynamics

The apparent causes and mechanisms of the southward propagation of the Cenozoic volcanism in western Anatolia, the changes in its chemical character through time, and the inferred shifts in the mantle source domains (from lithospheric to aesthenospheric domains) are significant questions regarding the Cenozoic chemical geodynamics of the entire Aegean province. We think that the first major post-collisional magmatic pulses in western Anatolia with calc-alkaline geochemical signatures during the Eocene and Oligo-Miocene had a subduction-influenced, lithospheric mantle source. Slab break-off-induced aesthenospheric upwelling was responsible for partial melting of the previously subduction-metasomatized mantle lithosphere beneath the orogenic belt (Figs 6 & 7). The impingement of the upwelling hot aesthenosphere on the overlying metasomatized mantle lithosphere caused its partial melting, producing potassic, calc-alkaline magmas that in turn formed the granitoids and shoshonitic volcanic series (Fig. 6). Geochemical characteristics of the Eocene granitoids and volcanic associations in NW Anatolia are similar to those of

other well-documented slab break-off-related igneous suites in various collision zones (von Blanckenburg *et al.* 1992; von Blanckenburg & Davies 1995; Atherton & Ghani 2002). The geological evidence in support of this inferred slab break-off magmatism includes: (1) a linear distribution of the plutons in a narrow belt straddling the IASZ, where ophiolitic and high-P blueschist rocks are exposed (Fig. 7). This spatial pattern suggests focused heat source, limited in space and intensity, that was likely derived from an aesthenospheric window; and (2) continental subduction, evidenced by the latest Cretaceous blueschist rocks of the Tavsanli zone. This attempted subduction of the Anatolide–Tauride continental crust to a depth of ≥ 80 km (Okay *et al.* 1998) is likely to have clogged the subduction zone and caused the detachment of the sinking Tethyan oceanic lithosphere (Fig. 7).

The continued collision of the Sakarya and Anatolide–Tauride continental blocks led into the development of thick orogenic crust, orogen-wide burial metamorphism, and anatectic melting of the lower crust (*c.* 25 Ma, Fig. 7). This episode coincides with bimodal volcanism and widespread ignimbrite flare-up in western Anatolia (Balıkesir–Bigadiç, Bigadiç–Sindirgi volcanic fields; e and f in Fig. 3). It was this phase of the post-collisional magmatism that caused thermal weakening of the crust in the western Anatolian orogenic belt leading into its extensional collapse. The Kazdag core complex in NW Anatolia (Fig. 2) began its initial exhumation in the latest Oligocene–early Miocene (Okay & Satir 2000) and the Menderes core complex in Central Western Anatolia (Fig. 2) underwent its exhumation in the earliest Miocene (Fig. 6; Isik *et al.* 2004; Thomson & Ring 2006; Bozkurt 2007). Some of the collision-generated thrust faults may have been reactivated during this time as crustal-scale low-angle detachment faults, (*i.e.* Simav detachment fault, SW Anatolian shear zone) facilitating the region-wide extension (Thomson & Ring 2006; Çemen *et al.* 2006). In general, tectonic extension also appears to have migrated southward in time; following the exhumation of the Kazdag and Menderes metamorphic core complexes in the Oligo-Miocene, the Tauride block in SW Anatolia was uplifted (Dilek *et al.* 1999b) and the blueschist rocks in Crete and the Cyclades in the South Aegean region (Ring & Layer 2003) were exhumed in the Miocene and onwards (Fig. 6).

Starting in the middle Miocene, both lithospheric and aesthenospheric mantle melts were involved in the evolution of bimodal volcanic rocks in western Anatolia with the lithospheric input diminishing in time. This timing coincides with widespread lower crustal exhumation and tectonic extension across the Aegean region (Fig. 6). This extensional phase and the attendant mildly alkaline volcanism were

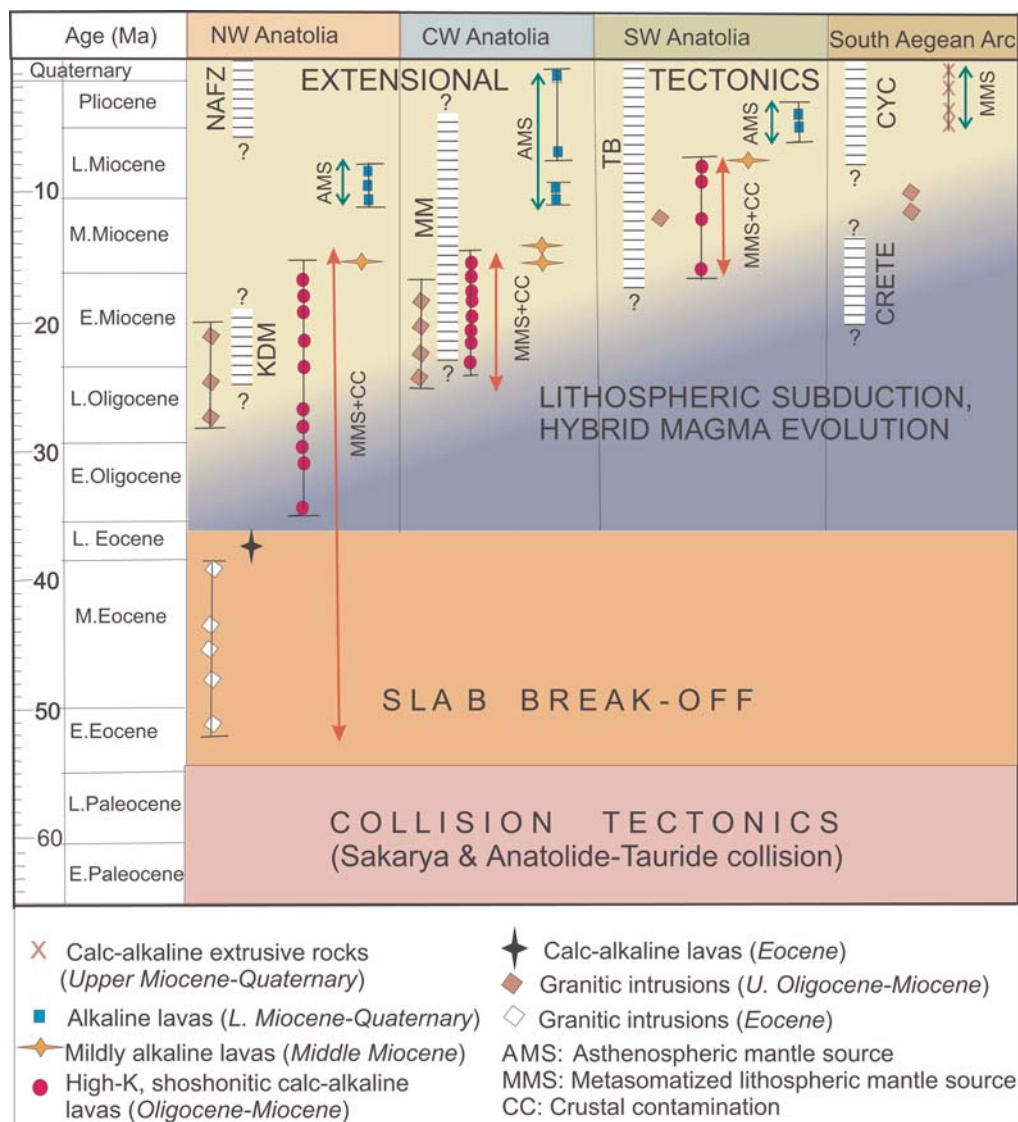


Fig. 6. Geochronology of the Cenozoic tectonomagmatic evolution of western Anatolia and the Southern Aegean Arc. CYC, Cyclades; KDM, Kazdag metamorphic massif; MM, Menderes metamorphic massif; NAFZ, North Anatolian fault zone; TB, Tauride block. See text for discussion.

caused by thermal relaxation associated with possible delamination of the subcontinental lithospheric mantle beneath the northwestern Anatolian orogenic belt (Fig. 7; Altunkaynak & Dilek 2006; Dilek & Altunkaynak 2007, and references therein). Lithospheric delamination might have been triggered by peeling of the base of the subcontinental lithosphere as a result of slab rollback at the Hellenic trench (*c.* 14 Ma in Fig. 7).

Regional graben systems (i.e. Gediz, Büyük Menderes, Fig. 2) developed during the advanced

stages of extensional tectonism throughout the late Miocene–Quaternary and further attenuated the continental lithosphere beneath the region (Fig. 7). This extensional phase was accompanied by upwelling of the asthenospheric mantle and its decompressional melting (Fig. 7). Lithospheric-scale extensional fault systems acted as natural conduits for the transport of uncontaminated alkaline magmas to the surface. The late Miocene and younger (<10 Ma) asthenospheric flow in the region may also have been driven in part by the extrusion

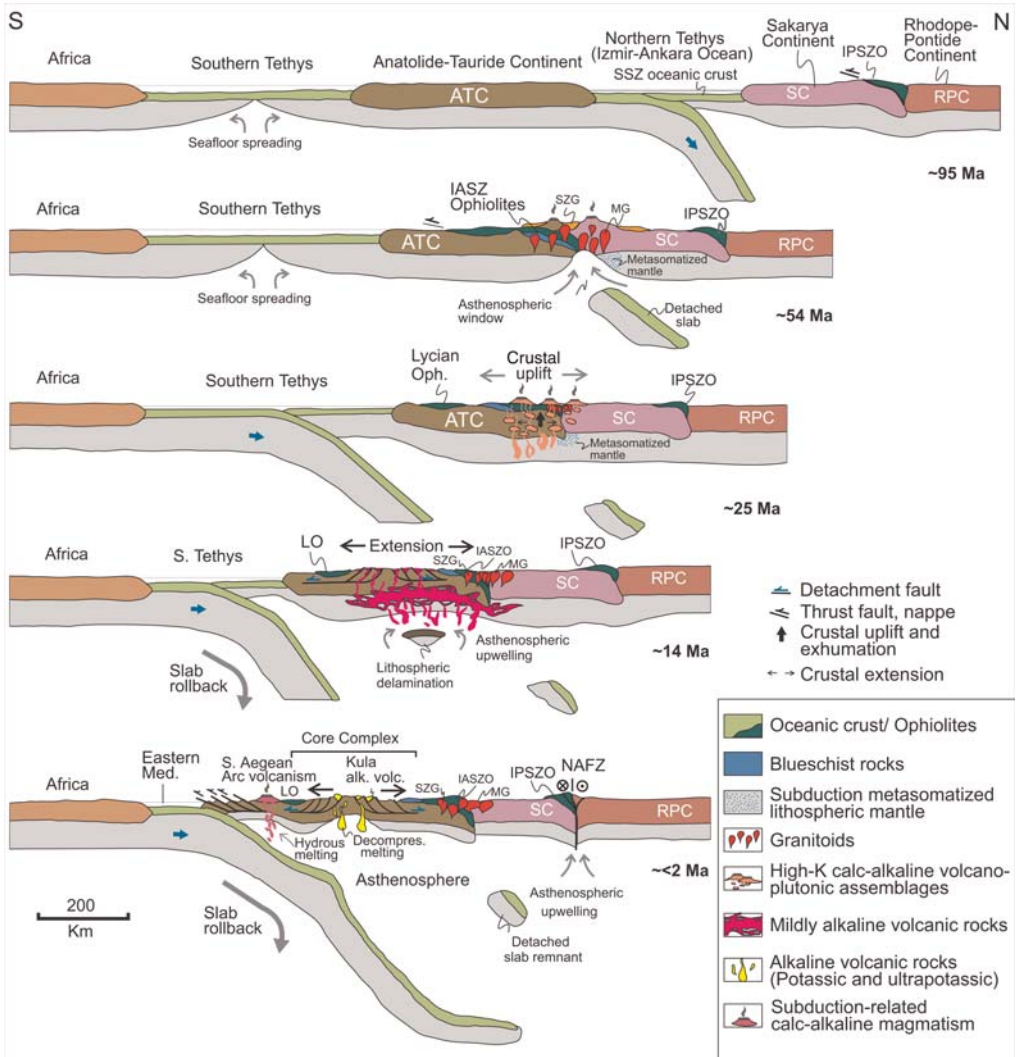


Fig. 7. Late Mesozoic–Cenozoic geodynamic evolution of the western Anatolian orogenic belt through collisional and extensional processes in the upper plate of north-dipping subduction zone(s) within the Tethyan realm. See text for discussion.

tectonics caused by the Arabian collision in the east, as observed by the SW-oriented shear wave splitting fast polarization direction in the mantle parallel to the motion of the Anatolian plate (Sandvol *et al.* 2003; Russo *et al.* 2001). This SW-directed lower mantle flow beneath Anatolia may have played a significant role in triggering intra-plate deformation via extension and strike-slip faulting parallel to the flow direction and horizontal mantle thermal anomalies, which may have facilitated melting and associated basaltic volcanism. This lateral asthenospheric flow might also have resulted in the interaction of different compositional end-members

contributing to the mantle heterogeneity beneath western Anatolia. Similarly, lateral displacement of the asthenosphere due to the extrusion of collision-entrapped ductile mantle beneath Asia and SE Asia has been suggested to have caused post-collisional high-K volcanism in Tibet and Indo-China during the late Cenozoic (Liu *et al.* 2004; Williams *et al.* 2004; Mo *et al.* 2006).

The apparent SW propagation of both the Cenozoic magmatism and tectonic extension through time was a combined result of the thermally induced collapse of the western Anatolian orogenic belt and the slab rollback associated with the

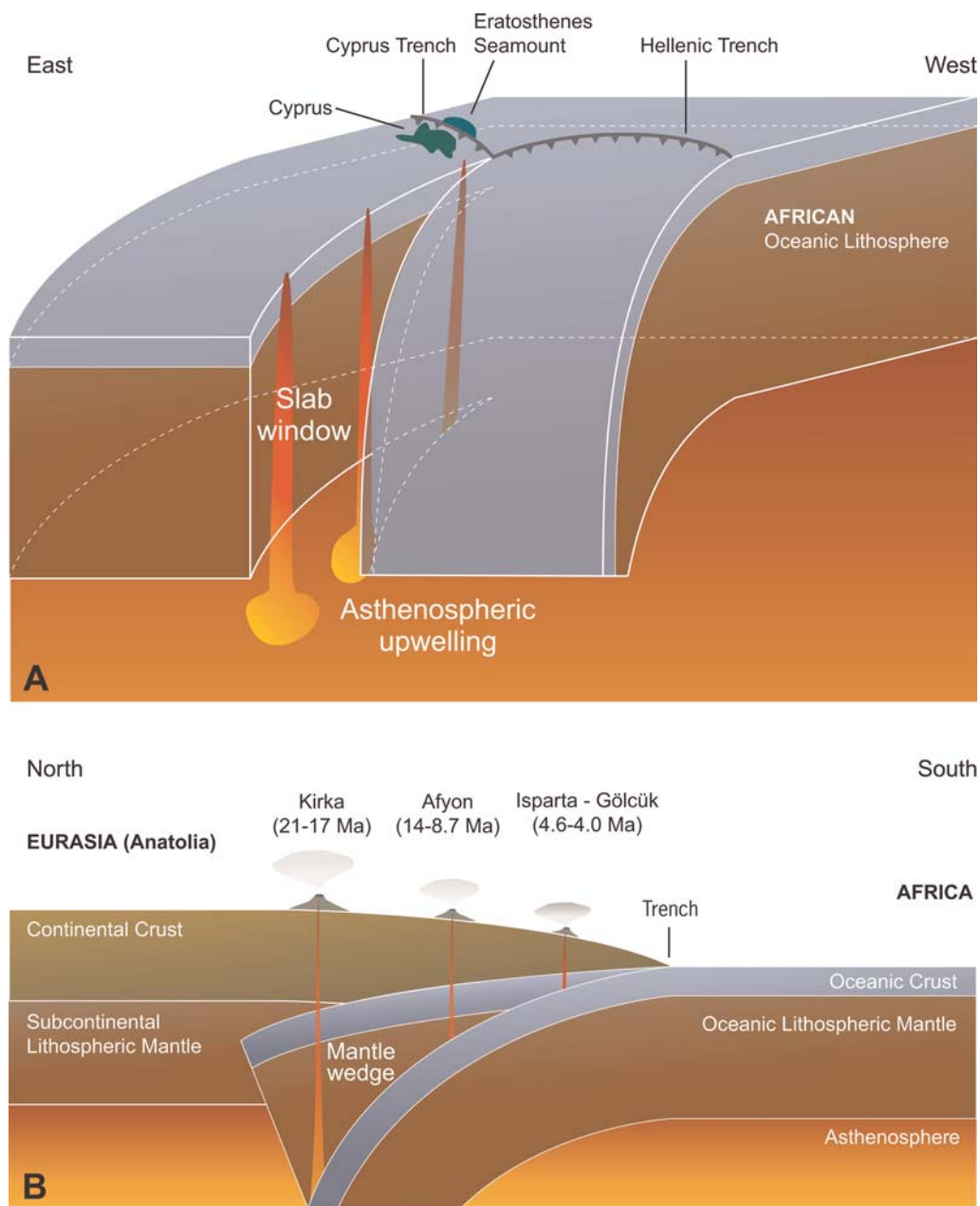


Fig. 8. An interpretive geodynamic model for the evolution of the north-south-trending alkaline volcanic field (from Kirka and Afyon-Suhut to Isparta-Gölcük) in western Anatolia along a Subduction-Transform Edge Propagator (STEP) fault zone, developed in a tear within the northward subducting African lithosphere. The collision of the Eratosthenes Seamount with the Cyprus trench has resulted in slowing down the Africa-Eurasia convergence to < 10 mm/a, whereas the convergence between these two plates across the Hellenic trench is $c. 40$ mm/a. This differential motion within the downgoing African plate is interpreted to be responsible for the lithospheric tear. The occurrence of this STEP fault zone coincides with the cusp between the Hellenic and Cyprus trenches.

subduction of the Southern Tethys ocean floor at the Hellenic trench (Figs 6 & 7). The thermal input and melt sources were provided first by slab break-off-generated aesthenospheric flow, then by lithospheric delamination-related aesthenospheric flow, followed by tectonic extension-driven upward aesthenospheric flow and collision-induced (Arabia–Eurasia collision) lateral (westward) mantle flow. The inferred lithospheric delamination around the middle Miocene may have been caused by slab rollback-induced peeling off of the lithospheric root beneath the orogenic belt. The Plio-Quaternary tectonic uplift, crustal exhumation, and young volcanism along the North Anatolian fault zone in the northern Aegean region (Figs 6 & 7; Agostini *et al.* 2007) are most likely associated with transform plate boundary processes and the related aesthenospheric flow.

The subduction zone magmatism related to the retreating Hellenic trench has been responsible for the progressive southward migration of the South Aegean Arc since the late Miocene (Figs 6 & 7; Pe-Piper & Piper 2006). The exhumation of high-P rocks in the Cyclades was likely driven by upper plate extension and channel flow associated with this subduction (Jolivet *et al.* 2003; Ring & Layer 2003). The sharp cusp between the Hellenic and Cyprus trenches (Fig. 1) and the significant differences in the convergence velocities of the African lithosphere at these trenches (*c.* 40 mm/a vs. <10 mm/a at the Hellenic and Cyprus trenches, respectively) are likely to have resulted in a lithospheric tear in the downgoing African plate that allowed the aesthenospheric mantle to rise beneath SW Anatolia (Fig. 8; Doglioni *et al.* 2002; Agostini *et al.* 2007). This scenario is analogous to lithospheric tearing at Subduction-Transform Edge Propagator (STEP) faults described by Govers & Wortel (2005) from the Ionian and Calabrian arcs, the New Hebrides trench, the southern edge of the Lesser Antilles trench, and the northern end of the South Sandwich trench. In all these cases, STEPs propagate in a direction opposite to the subduction direction, and aesthenospheric upwelling occurs behind and beneath their propagating tips. This upwelling induces decompressional melting of shallow aesthenosphere, leading to linearly distributed alkaline magmatism younging in the direction of tear propagation. The north–south-trending potassic and ultra-potassic volcanic fields stretching from the Kirka and Afyon–Suhut region in the north to the Isparta–Gölcük area in the south shows an age progression from 21–17 Ma to 4.6–4.0 Ma that is consistent with this pattern and supports a STEP model for their origin (Fig. 8). Aesthenospheric low velocities detected through Pn tomographic imaging in this region (Al-Lazki *et al.* 2004) support the existence of shallow

aesthenosphere beneath the Isparta Angle at present. We infer, therefore, that magmas of the Kirka, Afyon–Suhut, and Isparta–Gölcük fields were produced by melting of the sub-slab (aesthenospheric) mantle, which was metasomatized by recent subduction events in the region (Fig. 8). They were slightly contaminated during their ascent through the crust along the transtensional fault systems within the Kirka–Isparta STEP.

Discussion and conclusions

The geochemical and temporal evolution of the Cenozoic magmatism in western Anatolia clearly shows that plate-tectonic events, mantle dynamics and magmatism are closely linked during the late-stage evolution of orogenic belts. The mantle responds to collision-driven crustal thickening, slab break-off, delamination, and lithospheric tearing swiftly, within geologically short time scales (few million years). This results in lateral mantle flow, whole-sale extension and accompanying magmatism that in turn cause the collapse of tectonically and magmatically weakened orogenic crust. Initial stages of post-collisional magmatism thermally weaken the orogenic crust in continental collision zones giving way into large-scale extension and lower crustal exhumation via core complex formation. These cause-effect relations between magmatism and extension and between the crustal processes and mantle dynamics, and the temporal and chemical evolution of the post-collisional magmatism in western Anatolia, as documented in this study, are common to many orogenic belts (Dilek 2006; Dilek & Altunkaynak 2007, and references therein). This observation suggests to us that the mode and nature of post-collisional magmatism in mountain belts may follow a common pathway with some minor deviations. The existence of active lithospheric subduction and associated slab rollback processes play a significant role, however, in the mode and nature of deformation in orogenic belts that are situated in the upper plates of post-collisional subduction zones (Le Pichon *et al.* 2003).

Slab break-off appears to be the most common driving force for the early stages of post-collisional magmatism in many collisional orogenic belts (Wortel & Spakman 2000; Kohn & Parkinson 2002; Cloos *et al.* 2005). The rocks produced at this stage are represented by calc-alkaline to transitional (in composition) igneous suites. Subsequent lithospheric delamination or partial convective removal of the sub-continental lithospheric mantle in collision-induced, overthickened orogenic lithosphere causes decompressional melting of the upwelling aesthenosphere that in turn results in alkaline basaltic magmatism. Attendant crustal extension and widespread thinning

of the lithosphere facilitates rapid ascent of basaltic magmas without much residence time in the crust and hence the eruption of relatively uncontaminated, aesthenosphere-derived magmas at the surface (i.e. Kula lavas in SW Anatolia). Regional geodynamics and other plate boundary processes at work in the vicinity of the collision zones may strongly control, however, the mode and nature of slab break-off and lithospheric delamination events in orogenic belts and hence the suggested pathway of post-collisional magmatism.

This study was supported by research grants from the Scientific & Technical Research Council of Turkey (TUBITAK-CAYDAG-101Y006), Istanbul Technical University, and Miami University Committee on Faculty Research. Constructive and thorough reviews by C. Busby, G. Lister, P. A. Ustaömer, and D. van Hinsbergen helped us improve the paper greatly. We particularly acknowledge our lively discussions and exchange on the Cenozoic geodynamics of the Aegean region with Editor van Hinsbergen during the preparation of this paper.

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