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# Geotectonic Setting and Origin of the Youngest Kula Volcanics (Western Anatolia), with a New Emplacement Model

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**Abstract:** The Quaternary Kula volcanics are Na-dominant in character while all the older volcanic rocks of western Anatolia are generally definitive K-dominant rocks. As a unique example in western Anatolia, the existence of a huge amount of plateau basalts at Kula indicates rapid uplift of mantle material, as confirmed by new geochemical data.

Based on our field observations, the oldest Kula volcanics are the plateau basalts with more than one main lava flow. At the beginning of volcanic activity (first-period plateau basalts), this plateau was vast. Subsequently, parts of the first-period plateau basalts were uplifted and partly eroded while other parts were covered by younger lavas, tephra and sediments. The horsts, covered by plateau basalts, are well protected because of their resistance to erosion. During extensional activity, the development of cinder cones continued without hiatus. During the last period of volcanic activity, the youngest craters once again produced lava flows to form the second-period plateau basalts. As a result, there are more than 80 cinder cones with quite different erosional stages between the first and second plateau-basalt periods.

The Kula basalts are the only example of rapid uplifting of asthenospheric material in western Anatolia, and are interpreted to form due to the opening of a horizontal slab window as a consequence of the more rapid southwestward movement of the Aegean microplate overriding Africa, with respect to the Anatolian plate.

**Key Words:** western Anatolia, extensional tectonics, Kula volcanics, geochemistry

## Genç Kula Volkaniklerinin Jeotektonik Konumu, Kökeni ve Yeni Yerleşim Modeli (Batı Anadolu)

**Özet:** Kuvaterner yaşlı Kula volkanikleri Na'ca baskın karakterde olmalarına karşın önceki diğer tüm Batı Anadolu volkanikleri K'ca egemen volkanik kayalardır. Batı Anadolu için tek bir örnek olan bu büyük miktardaki plato bazaltlarının varlığı jeokimya sonuçları ile de desteklenen hızlı bir manto materyalinin yükselimini işaret eder.

En yaşlı Kula volkanikleri, birden fazla lav akıntısından oluşan plato bazaltlarıdır. Volkanik aktivitenin başlangıcında geniş bir yayılım sunan bu plato bazaltları 1. evre plato bazaltları olarak adlanırlar. Birinci evre plato bazaltları kimi yerde yükselmiş kimi yerlerde aşınmış ve kimi yerde ise daha genç lavlar ve tortullarca örtülmüşlerdir. Plato bazaltları ile kaplı horstlar bazaltların dayanımlılığıdan dolayı cok iyi korunmuşlardır. Bölgedeki açılma dönemi süresince volkan konilerinin oluşumu kesintisiz devam etmiştir. Volkanik aktivitenin son döneminde en genç volkan konileri bir kez daha lav üreterek ikinci plato bazaltlarını oluşturmuşlardır. Bu iki plato bazalt evresi arasında farklı aşınma derecelerine sahip 80'den fazla volkan konisi vardır.

Kula bazaltları, Batı Anadolu'da astenosferik mantonun hızlı yükselmesine tek örnektir ve bu GB'ya hareket eden Ege mikroplakasının Afrika üzerine bindirme hızının, Anadolu plakasının Afrika üzerine bindirme hızından daha fazla olması sebebiyle açılmış olan bir çeşit yatay pencerenin varlığına bağlanabilir.

**Anahtar Sözcükler:** Batı Anadolu, genleşme tektoniği, Kula volkanikleri, jeokimya

## Introduction

The widely distributed small bodies of alkaline basalts occurring in all of the various sectors of the Aegean-Anatolian realm are derived from OIB-type rocks. The time-space distribution of volcanism in the Aegean and western Anatolia – with their main rock associations and the involved magma sources – definitely show a transition from calc-alkaline, mantle-wedge source rocks to alkaline, OIB-type mantle-source rocks. Southwestward migration of calc-alkaline, shoshonitic and lamproitic magmas in the hanging wall was accompanied by southwestward migration of the subduction hinge. With a higher enrichment of the more incompatible elements, the trace-element distribution is similar to OIB-type basalts as seen in the primordial-mantle (PM) normalized spider diagrams. The mainly potassic alkaline-basaltic magmatism, with its diverse geochemical compositions, reflects the extension-related activities prior to the Kula volcanism. The sodic – phonolitic plateau basalts, craters, and lava flows of the Kula volcanics are therefore products of the final activity where the mostly uncontaminated material of the Aegean mantle rapidly erupted as a new episode in a strongly extensional regime during the neotectonic period. The stretching between Greece and Anatolia, and the differential velocity of convergence with the underlying slabs, should have generated 'horizontal windows' both in the hanging wall and in the footwall of the subduction, allowing asthenospheric upwelling and consequently its partial melting. Thus, the OIB magmatism was generated after regular subduction/collision evolution. With this new model, it is much easier to explain the one-of-a-kind and characteristic evolution of the Quaternary Kula volcanics.

Kula is a small town on the main İzmir-Ankara road, which has a number of interesting volcanological aspects (Figure 1). The youngest volcanics of western Anatolia, with widespread plateau basalts and well-preserved craters and lava flows, are excellent examples of an alkali-basalt province in an area of active rifting. These volcanics have been investigated by several researchers from the nineteenth century to present.

The important tectonic, stratigraphic and sedimentologic characteristics of the Kula volcanics were reported previously by Hamilton & Strickland (1841). According to those authors, topographic inversion of the basalt stratigraphy within three periods is common in the Kula area. Philippson (1914) confirmed this classification with some remarks. Canet & Jaoul (1946) remarked that cinder cones in the area are roughly situated on two straight lines whose strikes are sub-parallel to the graben edge. This is also observable on the geological map of the area published by Hamilton & Strickland (1841).

Later researchers (Erinç 1970; Ercan 1981) made a similar classification of the basalts of the area with some insufficient criticism of Hamilton & Strickland (1841). Recent studies of the tectonic setting and volcanism of the Kula area have yielded diverse opinions. The most prominent neotectonic features of western Anatolia are E–W-, NE–SW- and NW–SE-trending grabens (e.g., Koçyiğit *et al.* 1999; Bozkurt 2000, 2001a, 2003; Bozkurt & Sözbilir 2004 and references there in). Shortly after the concentration of extension into two grabens ~ 2 Ma, the generation of alkali-basalt magmas was generated in Kula area (Richardson-Bunbury 1996). According to Gülen (1990), the Kula basalts contain mantle xenoliths and represent volatile-rich, metasomatised asthenospheric melts (the best representative mantle material in western Anatolia).

Besides the geotectonic setting and origin of the Kula volcanics, explanation of the evolution of the volcanism and the emplacement of volcanic rocks in the Kula area is possible with some modifications of Hamilton & Strickland's model – another aim of the present study.

The Kula volcanics are the youngest volcanic rocks of western Anatolia and, in contrast to the older volcanics of the area with their general potassic affinity, are mainly sodic and have geochemical and isotopic characteristics typical of OIB-type intraplate magmatism.

## Tectonic Framework of Western Anatolia

After the closure of N–dipping subduction zone between the Pontides to the NNW and the Anatolide Tauride platform to the SSE (Late Palaeocene to Early Eocene), the İzmir–Ankara suture zone was formed (Şengör 1979; Şengör & Yılmaz 1981).

According to a new tectonic model, developed in order to explain the Cenozoic magmatic activity of western Anatolia (Doglioni *et al.* 2002) as the most prominent geodynamic factor in shaping the area, the African plate (Cyprus-Aegean subduction zone) was subducted beneath the Greek and Anatolian microplates at different velocities, causing a diffuse extensional margin between

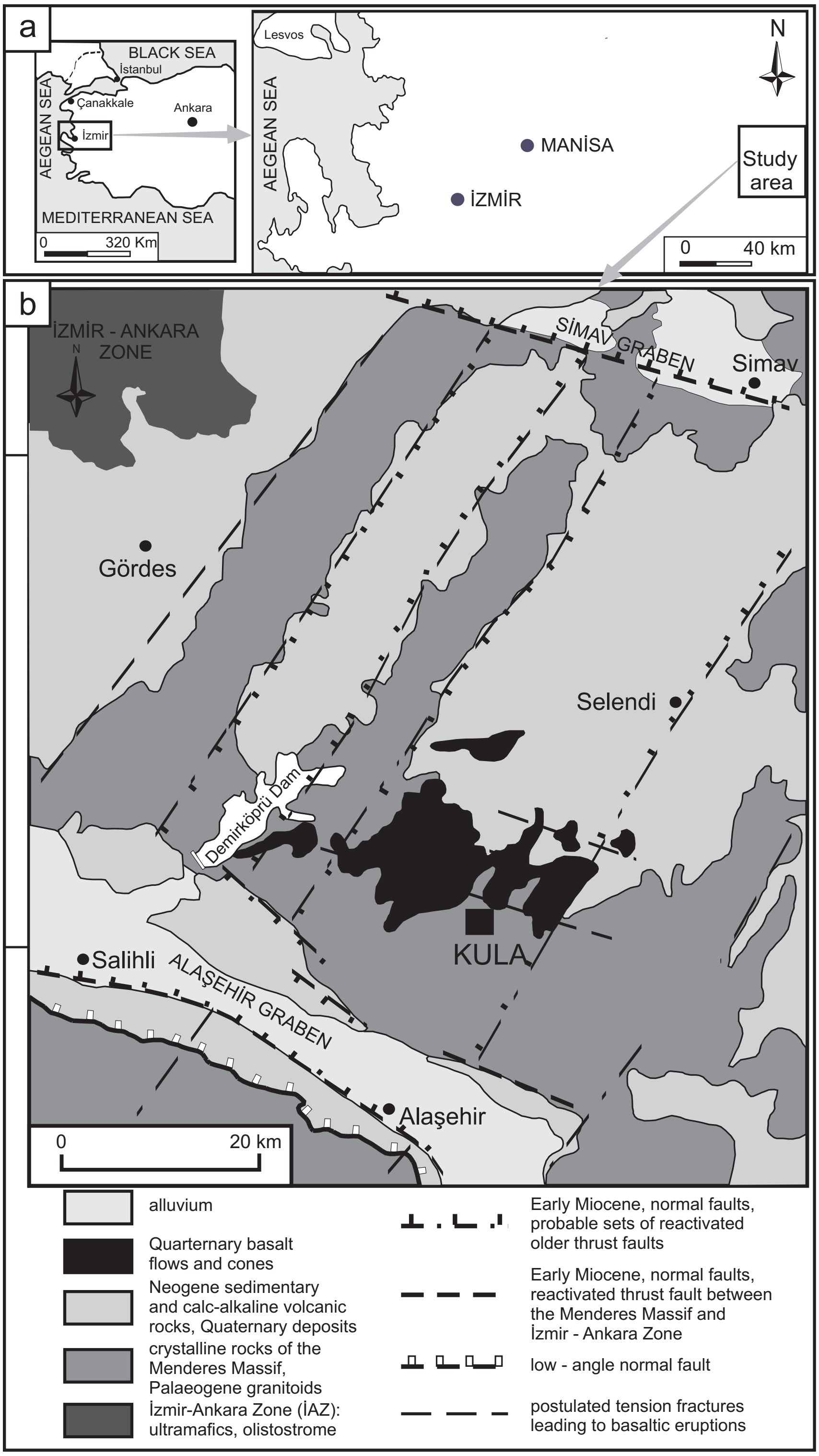

Figure 1. Location of study area (a) with generalized geological map of the Kula area (b) (taken from Savaşçın *et al.* 1999).

the Aegean Sea and western Anatolia (Doglioni *et al.* 2002); considering Africa as fixed, the faster southeastward motion of Greece relative to Cyprus-Anatolia determined the Aegean extension (Figure 2). In this point of view, at least from the Early Miocene, the previous horizontal NE–SW direction of the (–1) in the compressive stage become the trend of (–3), explaining the formation of NW–SE-trending normal faults and grabens, E–W-trending right–lateral transtensional faults and N–S- trending left-lateral transtensional faults (Figure 3).

Such a post-orogenic extension, caused by the hanging-wall plate overriding the slab (Doglioni *et al.* 2002), led to the coexistence of lacustrine sediments and coeval volcanic rocks overlying the basement (metamorphic rocks, ophiolitic nappes and flysch sediments) – a typical section of western Anatolia (Innocenti *et al.* 2005).

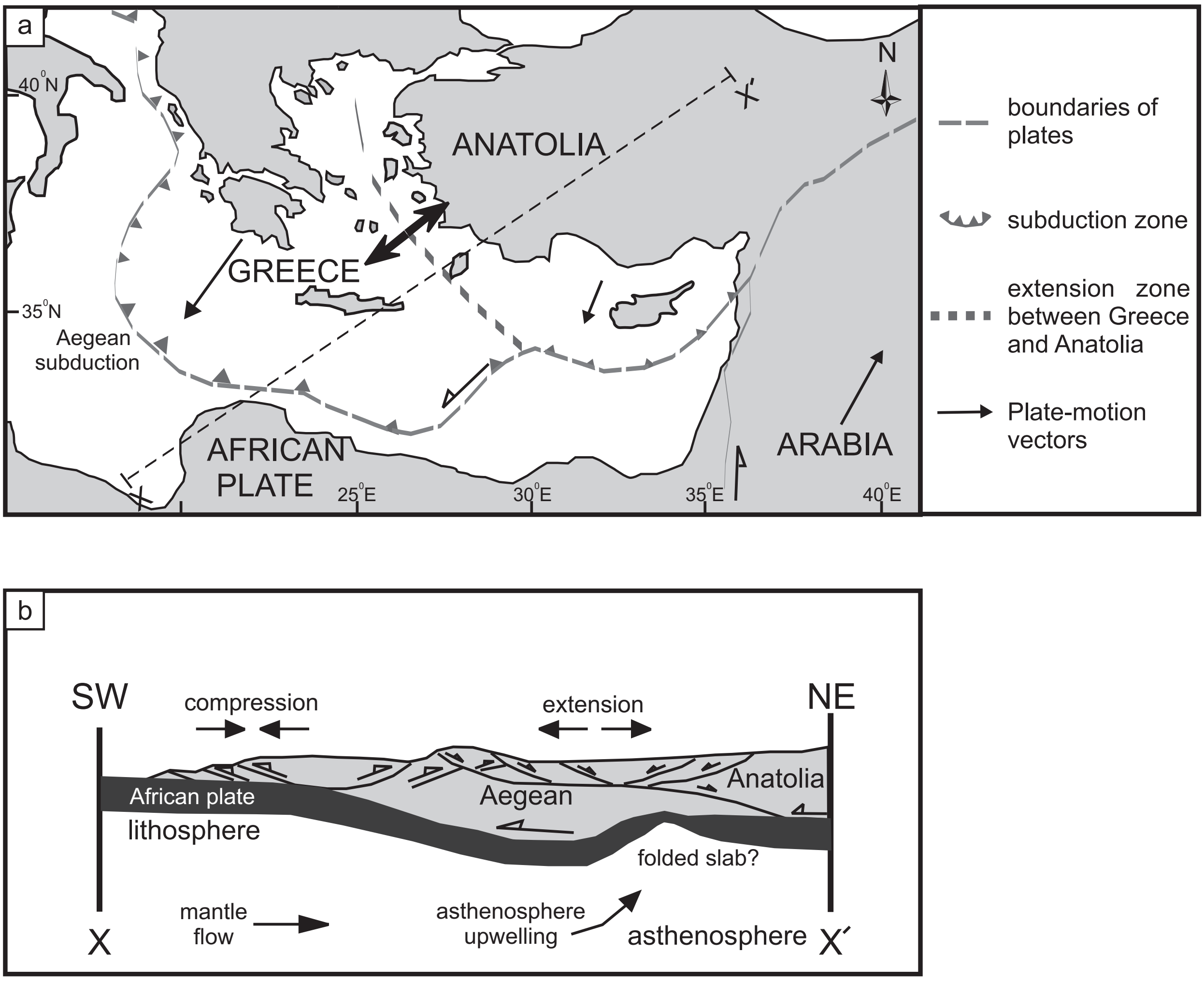

Figure 2. (a) Considering a fixed Africa, Greece is overriding Africa faster than Cyprus and Anatolia. This implies extension between Greece and Anatolia (thick double arrow). Thin arrows indicate present-day plate-motion vectors with respect to a fixed Africa, inferred from space geodesy (Doglioni *et al.* 2002), after NASA data base (from http://sideshow.jpl.nasa.gov/mbh/series.html); (b) Schematic cross-section of overriding western Anatolia and Greece to African Plate. African slab should be folded by isostatic uplift of the mantle in the rift. This should result in a sort of window in the hanging-wall lithosphere that is splitting apart into two independent plates, i.e., Greece and Anatolia. It would hypothetically be coupled with a sort of horizontal window in the underlying stretched slab, allowing melting and ascent of OIB basalts (Doglioni *et al.* 2002).

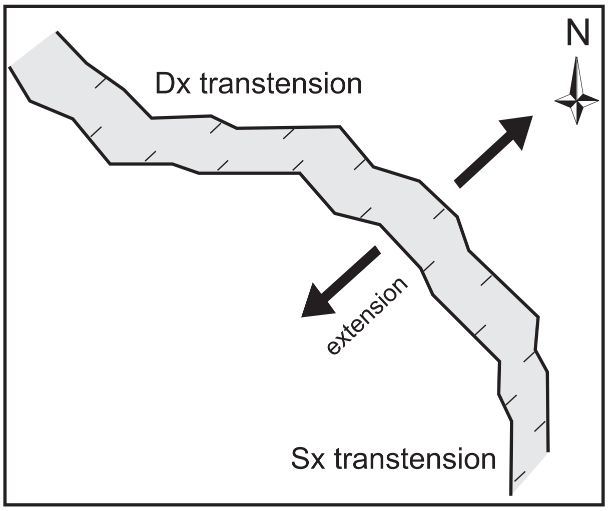

**Figure 3.** Main trends and tectonic implications of Miocene–Quaternary faults in the western Anatolia and Aegean areas (Doglioni *et al.* 2002).

The petrogenesis of the younger alkaline association and its relations with Neogene sedimentation and extensional tectonics are reviewed in this study within the framework of the relative movements of the Aegean-Anatolian, Eurasian and African plates.

## Cenozoic Volcanism in Western Anatolia

Early to Middle Miocene orogenic magmatism was followed by Late Miocene to Quaternary alkaline-basaltic volcanism (e.g., Francalanci *et al.* 1990; Savaşçın & Güleç 1990; Yılmaz *et al.* 2001).

The first calc-alkaline and shoshonitic rocks were characterized by stratostratovolcano-type occurrences and formed large centers with intercalated terrestrial sediments. Some investigators considered that these K-dominant, calc-alkaline to shoshonitic- type initial volcanics (23–15 Ma) were related to compressional (subduction) tectonism (Dora *et al.* 1987; Yılmaz 1989; Savaşçın & Güleç 1990; Savaşçın 1990), while others (Seyitoğlu & Scott 1992; Seyitoğlu *et al.* 1992) suggested that the entire Oligocene–Miocene volcanism of western Anatolia was related to the extensional tectonic regime.

Following the Middle Miocene, basins were enlarged and they accumulated still thicker deposits. The second phase was limited to the Middle Miocene–Early Pliocene and is characterized by the eruption of poorly evolved mildly alkaline rocks with mainly potassic (locally, also sodic) affinity, forming scattered outcrops in western Anatolia and Aegean Sea (e.g., Ezine, Urla, Foça, Bodrum, Karaburun, Uşak, Kütahya, Simav, Kaloyeri, Patmos). These products generally display a within-plate character, even if a slight subduction-related geochemical signature is also found locally. The radiometric ages from the second-stage alkaline volcanics (Borsi *et al.* 1972; Benda *et al.* 1974; Besang *et al.* 1976; Ercan *et al.* 1985, 1997; Seyitoğlu & Scott 1996; Innocenti *et al.* 2005) are consistent with those of the intercalating sediments.

Indeed, according to new radiometric age determinations (Ercan *et al.* 1997; Seyitoğlu *et al.* 1997; Innocenti *et al.* 2005) there is no significant time gap between the first-period volcanics of calc-alkaline to shoshonitic types and the succeeding ultrapotassic (U-K) and lamproitic types (Figure 4, columnar section). Some new ages of these ultrapotassic shoshonitic and lamproitic rocks indicate that these rocks cropped out locally before the end of the first orogenic period (Table 1).

As a third phase of volcanism, the Na-basaltic rocks of Kula cover an area over 350–400 $km^2$, and are located at the intersection of NE-trending tectonic lineaments with the youngest WNW-trending Alaşehir Graben (Figure 1b). This youngest volcanic field of western Anatolia comprises plateau basalts, several cinder and spatter cones dating back to prehistoric times (Ercan *et al.* 1985, 1997; Bunbury 1992; Richardson-Bunbury 1996; Savaşçın *et al.* 1999).

These temporal variations in volcanic phases are interpreted to have resulted from changing the geochemical features of the magma sources from supra-subduction (calc-alkaline to lamproitic associations) to sub-slab mantle (Agostini *et al.* 2003a, b). (1) In the orogenic calc-alkaline and shoshonitic associations (mantle wedge metasomatized by subduction-related components), $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ isotopic ratios and trace–element variations suggest that interaction with the crust was moderate, so that the geochemistry of these rocks is considered to reflect mainly the heterogeneous chemical nature of their mantle source. (2) The ultrapotassic and lamproitic rocks are characterized by a high $^{87}Sr/^{86}Sr$ and low $^{143}Nd/^{144}Nd$ isotopic ratios and are strongly enriched in K and Rb with respect to Ba, indicating a phlogopite-bearing lithospheric source. (3) The low $^{87}Sr/^{86}Sr$ and high $^{143}Nd/^{144}Nd$ isotopic ratios, together with low LILE/HFSE ratios, reveal an OIB-type

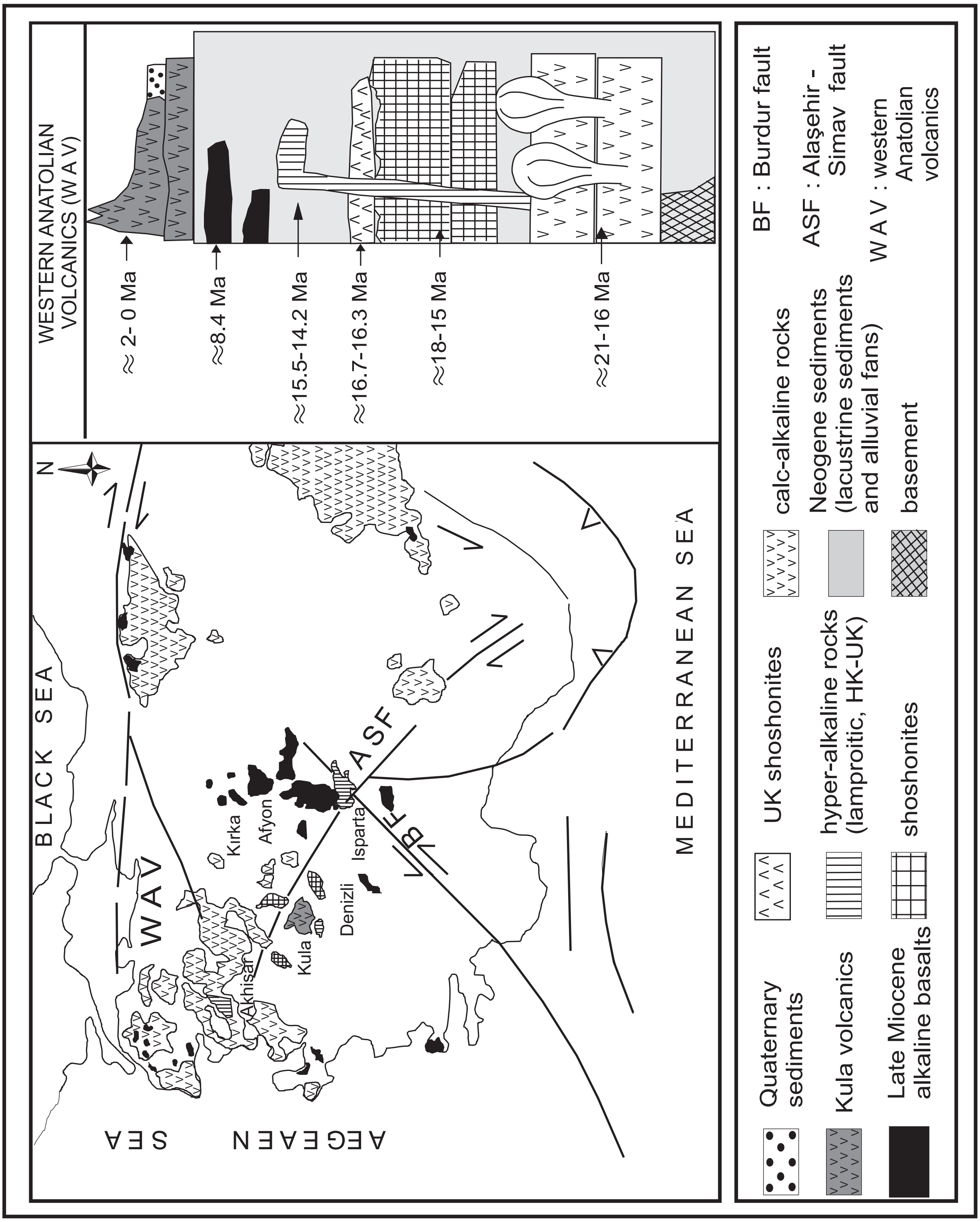

Figure 4. Distribution of Miocene volcanic rocks in western Anatolia with characteristic columnar sections (radiometric ages have been taken from Agostini 2004).

Table 1. Some new age determinations from alkaline and hyper-alkaline rocks.

| Locality | Rock Type | Age (Ma) | Data Source |
|---|---|---|---|
| Akhisar | UK-latite | 16.9±0.3 | Ercan *et al.* (1997) |
| Akhisar | UK-latite | 16.72±0.15 | Innocenti *et al.* (2005) |
| Simav-Naşa | alkali basalt | 15.2±0.3 | |
| | | 15.8±0.3 | Ercan *et al.* (1997) |
| Selendi | UK-rock | 15.5±0.4 | Seyitoğlu *et al.* (1997) |
| Güre | lamproite | 14.20±0.12 | Innocenti *et al.* (2005) |
| Ilıcaksu | lamproite | 15.87±0.13 | Innocenti *et al.* (2005) |

nature for the Kula volcanics, which originated from a sub-slab asthenospheric mantle (Agostini *et al.* 2003a, b; Innocenti *et al.* 2005). Furthermore, ultrapotassic shoshonites and Upper Miocene basalts have been generated by interactions of source (1) with sources (2) and (3), respectively (Agostini *et al.* 2003a).

## Geology of the Kula Region

### *Stratigraphy and Tectonics*

The WNW-trending Simav and Alaşehir grabens (Seyitoğlu 1997; Bozkurt 2001a, 2003; Seyitoğlu *et al.* 2004 and references therein), filled from Pleistocene to present, are well represented by gravity anomalies (Savaşçın *et al.* 1999) and bound the study area to the north and south, respectively (Figure 1b). Kula is located on a block of crystalline rocks of the Menderes Massif (e.g., Bozkurt 2001b; Bozkurt & Oberhänsli 2001; Erdoğan & Güngör 2004; Koralay *et al.* 2004; Seyitoğlu *et al.* 2004 and references therein), which is delimited by a southward-tilted footwall block of the Simav Graben or a southward-tilted hanging-wall block of the Alaşehir graben (Figure 5). The readers are referred to recent literature about the continental extensional tectonics in western Turkey and the Menderes Massif (Bozkurt 2001b, 2003, 2004; Bozkurt & Oberhänsli 2001; Seyitoğlu *et al.* 2002, 2004; Akal 2003; Altunel *et al.* 2003; England 2003; Işık *et al.* 2003, 2004; Karamanderesi & Helvacı 2003; Koçyiğit & Özacar 2003; Lenk *et al.* 2003; Westaway 2003; Bozkurt & Sözbilir 2004; Erdoğan & Güngör 2004; Kaya *et al.* 2004; Koralay *et al.* 2004 and references therein).

Two different generalized stratigraphic columnar sections from Kula and surrounding area are given in Figure 6a (Bunbury 1992) and Figure 6b (Kaya; an unpublished report for the Municipality of Kula). Regionally metamorphosed units of the Menderes crystalline rocks include gneiss, schist and marble (Brinkmann 1966; Dora *et al.* 1987). This metamorphic basement is poorly exposed only in the southern part of the study area (W and E of Kula and Demirköprü Dam), and is covered by listwaenite as relicts of the ophiolitic nappes (Kaya; an unpublished report for the Municipality of Kula), Neogene sediments and Kula volcanics. Seismotectonic data indicate that the tilted Kula block comprises up to 10–15 km of crystalline rocks from the upper crust (Eyidoğan 1988; Taymaz *et al.* 1991).

Following tilting and uplifting of the Menderes Massif assemblage, there was a a period of erosion in Kula (Richardson-Bunbury 1996; Tokçaer 2000). Small hills were formed in the peneplain. Fluviatile and overlying lacustrine sediments of Neogene age include conglomerate, sandstone, limestone and marl.

The Kula area is characterized tectonically by regularly ordered NE-trending normal faults that separate the crystalline rocks, the Neogene sediments and the volcanics from one another. According to Savaşçın *et al.* (1999), they acted as growth faults during the Miocene. NE-trending gravitational anomalies coincide in most places with these NE-trending fault blocks (Savaşçın *et al.* 1999). This NE-trending fault system reflected an older graben–horst structure with older Neogene sediments and, in the Kula region, have been partially reactivated in the Quaternary. To the NE of the study area, NE-trending

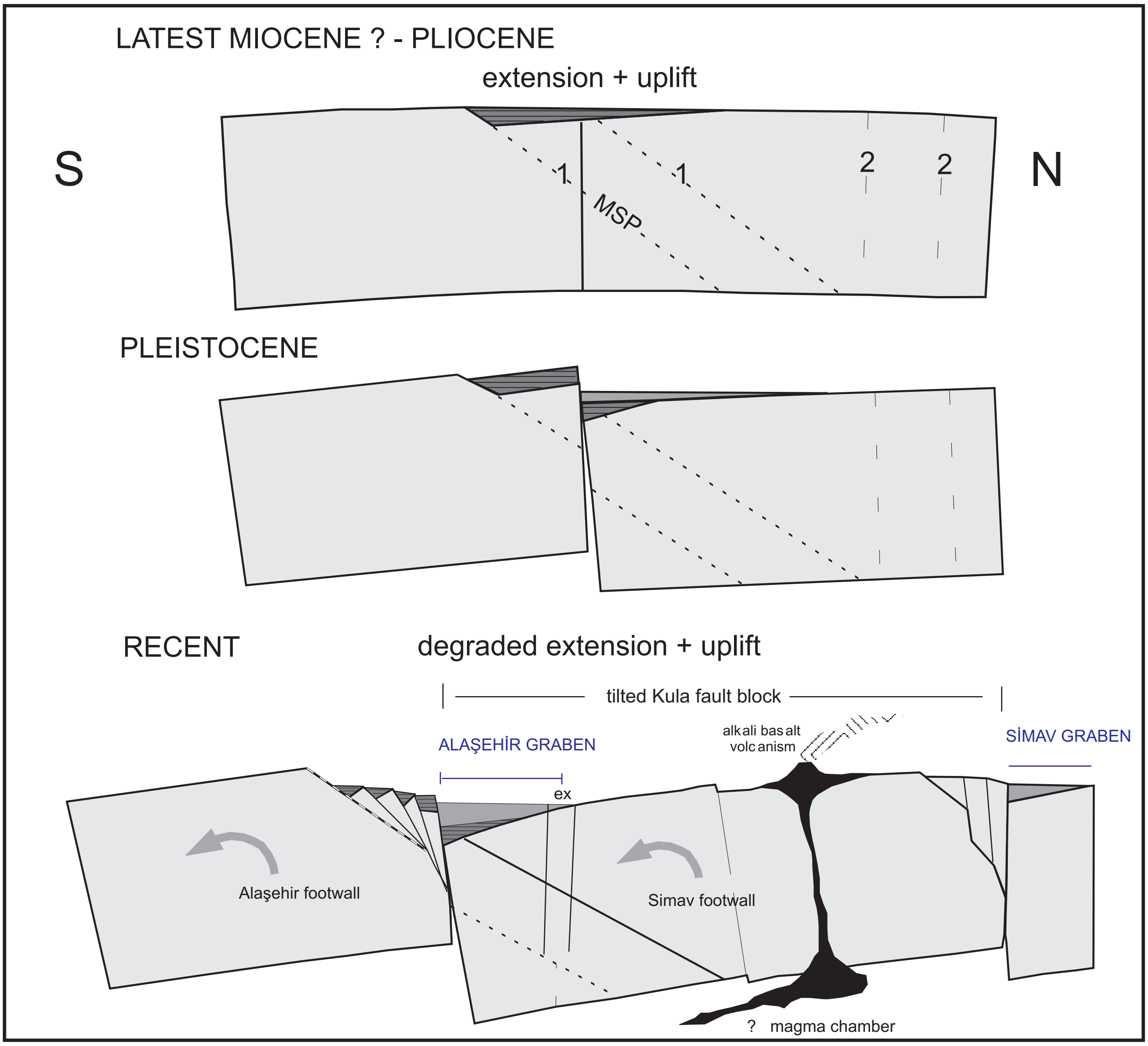

**Figure 5.** An alternative model for the latest Miocene–Pliocene to recent structural development of the Kula area (Savaşçın *et al.* 1999). 1– master share plane (MSP), reactivated older weakness zone; 2– tension fracture as the product of regional updoming, or reactivated older strike-slip fault along with regional updoming; ex– prominent exhumation in the north.

faults also cut the first-period plateau basalts of Kula (Figure 7).

### *Volcanics of Kula*

In western Anatolia, during three distinct phases, the volcanism changed from orogenic to K-alkaline and finally to sodic alkaline (Pliocene to Quaternary Kula volcanics; Richardson-Bunbury 1996). As the youngest volcanic rocks of western Anatolia, the Kula volcanics are Na-dominant in character while all of the older volcanic series of western Anatolia are generally K-dominant rocks.

The Kula volcanic field is a rectangular area about 15 km N–S by 40 km E–W. The volcanic rocks consist of lavas and tephra originating from ~ 80 small cinder cones (Richardson-Bunbury 1996).

Basaltic cinder cones are commonly small compared to other types of volcanic edifices, e.g., they are orders of magnitude smaller than those of the Andes (Bunbury

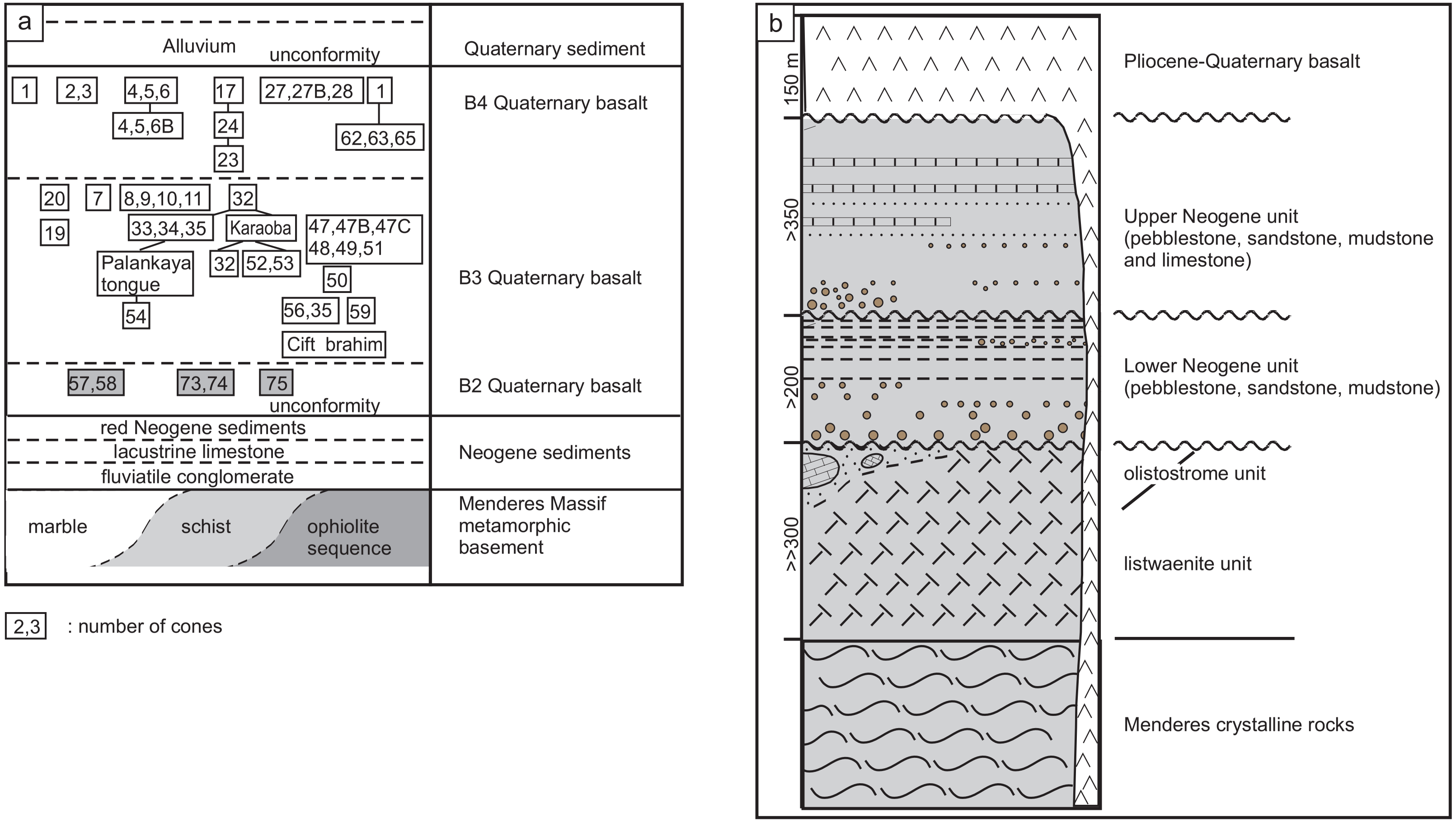

Figure 6. Two generalized stratigraphic columnar sections from Kula and environs from Bunbury (1992) (a) and Kaya (unpublished report) (b).

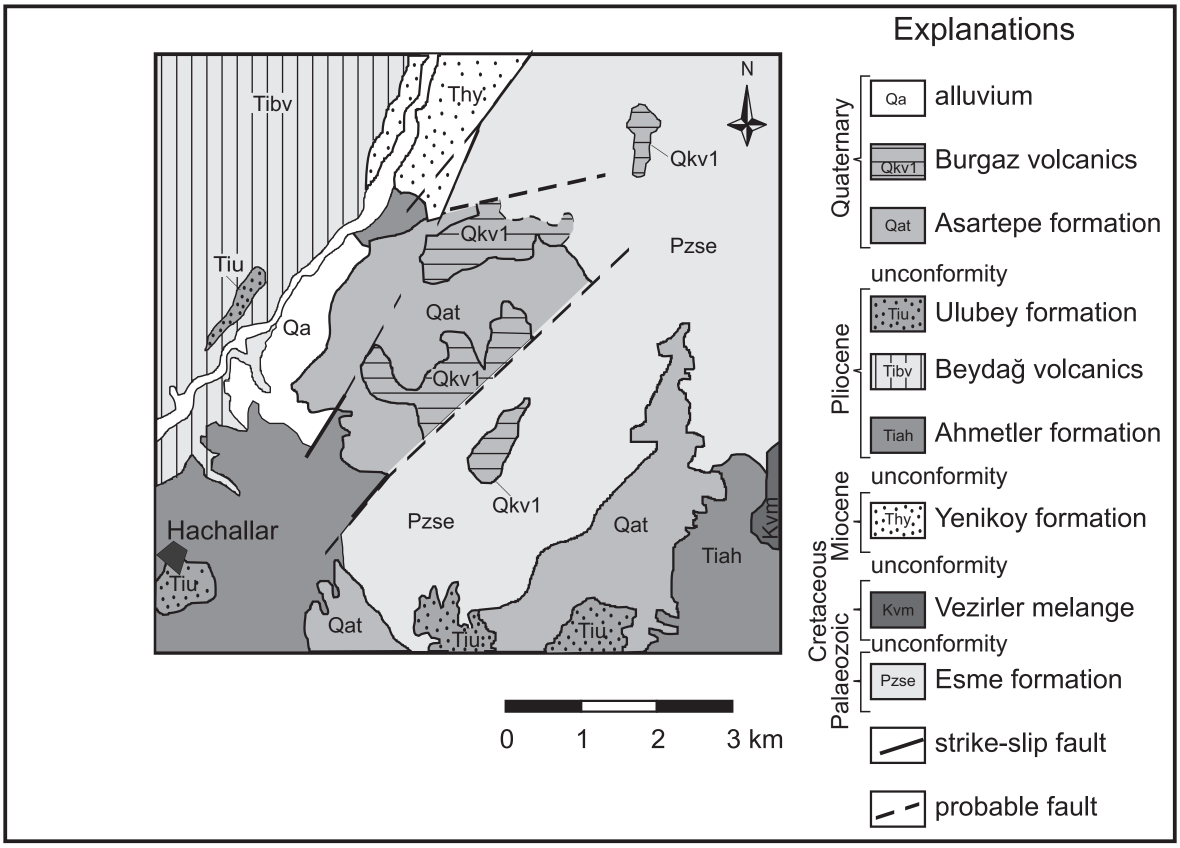

**Figure 7.** Reactivation of older NE-trending faults (modified from MTA map of the Kula area). Explanation from the MTA map (not our own).

1992). The diminutive size of the Kula cinder cones is probably a result of a very low flow rate of magma to the surface (Richardson-Bunbury 1996).

Basaltic eruption in the Kula area started 1.6 Ma ago (Richardson-Bunbury 1996) and continued up to the recent. These volcanics developed in more than three phases, or perhaps their evolution was without hiatus. Age determinations of the Kula lavas gleaned from various publications (and also from different periods) are illustrated in Figure 8.

The important tectonic, stratigraphic and sedimentological characteristics of the Kula volcanics were reported previously by Hamilton & Strickland (1841). According to those authors, topographic inversion of the basalt stratigraphy is widespread in the Kula area. 'It occurs where lava flows onto a plain, or into a valley of material more easily eroded than the basalt. Following erosion the flow leaves as a topographic height (plateau or hilltop) around which flowing later the younger lavas' (Hamilton & Strickland 1841). The geological map of Kula made by Hamilton & Strickland (1841) clearly illustrates the important role of NE–SW- and WNW–ESE-trending lineaments in the development of the cinder cones and on lava flow directions. According to those authors, the development of the Kula volcanics occured in three periods: (1) plateau basalts with more than one flow, (2) subsequent erosional valleys and eroded cinder cones with vegetation, (3) fresh non-eroded cinder cone without vegetation.

Philippson (1914) confirmed this classification with some remarks. According to him, the time interval between the second and third periods was not short. Rather, it was long, and there were also cinder-cone phases between the second and third periods.

Canet & Jaoul (1946) remarked that the cinder cones in the area are situated along two straight lines whose

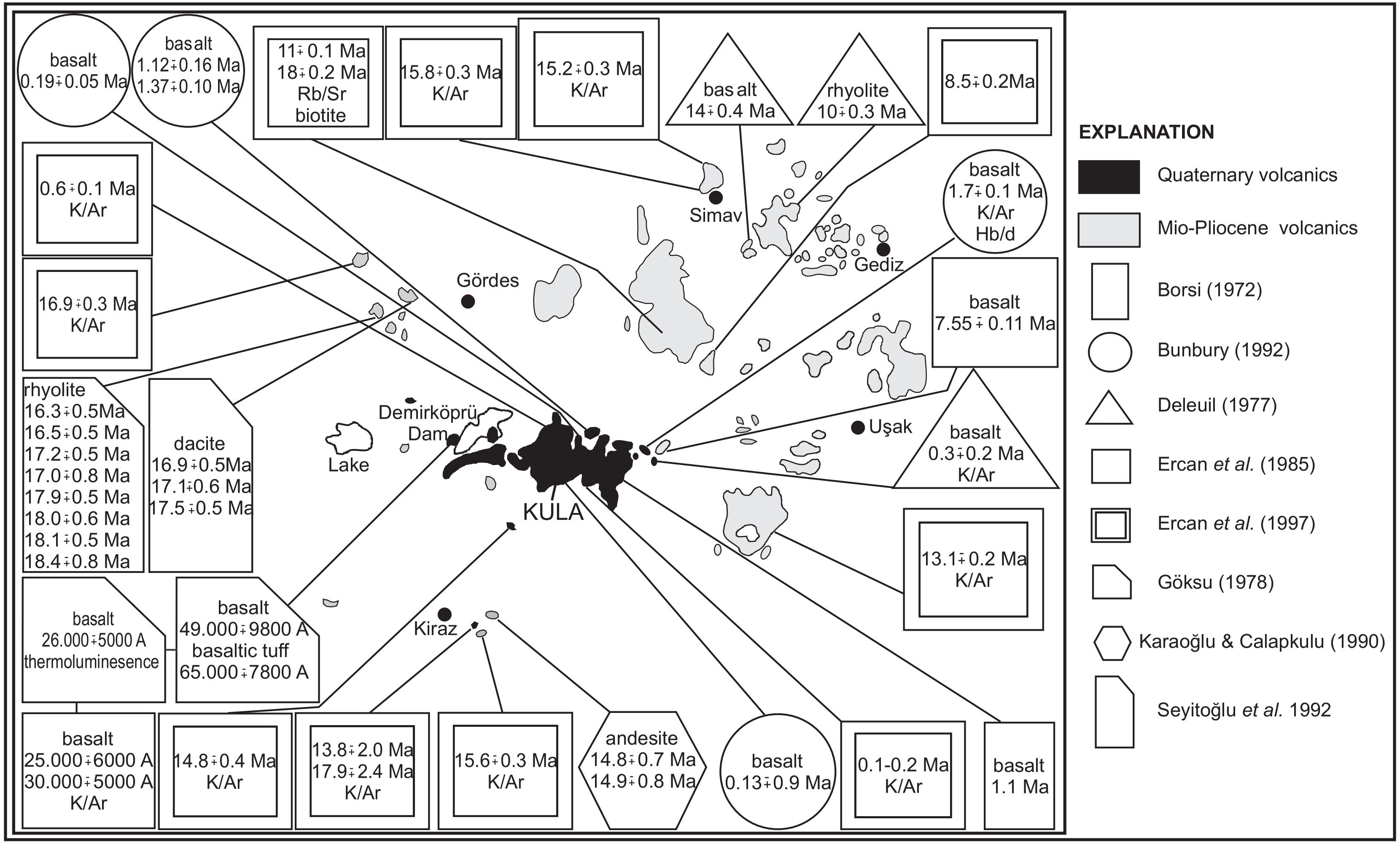

Figure 8. Age determinations for the Kula lavas (modified after Ercan *et al.* 1997).

strike is sub-parallel to the graben orientations. These occurrences are observable on the geological map of Hamilton & Strickland (1841). The geological map of the region made by Erinç (1970) also divided the basalts of the area, as Hamilton and Strickland, into three groups on the basis of stratigraphic position: (i) an early group of plateau basalts in the Sarnıç and Burgaz area; (ii) an intermediate group, which incorporated all of the remaining volcanic rocks; (iii) a late group of fresh-looking cinder cones and lavas. Ercan (1981) also used the same classification for the basalts of the area.

Based on our field observations, the oldest Kula volcanics are the plateau basalts with more than one main lava flow. At the beginning of the volcanic activity (first-period plateau basalts), this plateau was widespread (Figure 9). The first-period plateau basalts of Kula have an areal distribution of at least 330–400 km$^2$. This plateau, which was initially a unique block, overlies the Neogene sedimentary succession with locally variable ages (Late Miocene–Pliocene), related to the structural pattern that preceded volcanism. Subsequent to the first episode, tilting continued in the area and led to uplift along old and new fractures in relation to graben structures. Meanwhile, the underlying, poorly indurated sediments underwent rapid erosion (Figures 9 & 10).

During the development of younger grabens (Alaşehir-Salihli and Simav grabens), both older (NE) and younger (WNW) tectonic lineaments were reactivated alternately. Parts of the first-period plateau basalts were then uplifted and partly eroded while other parts were covered by younger lavas, tephra and sediments (Tokçaer 2000). The horsts covered by plateau basalts are well protected because of their resistance to erosion. During extensional activity, the development of cinder cones continued without hiatus. During the last period of volcanic activity, the youngest craters once again produced lava flows to form the second plateau basalt (Tokçaer 2000).

As a result, there are more than 80 cinder cones characterized by quite different erosional stages between first and second plateau basalt periods. In other words, the youngest volcanic activity of the Kula area represents the beginning of the second plateau formation (again the lava flows) along the main fault systems (Figure 10). The existence of a huge volume of plateau basalts indicates a rapid uplift of mantle material, a scenario confirmed by our geochemical results.

## Petrography and Geochemistry

More than 50 samples of lava and scoria from several locations and different phases of activity of the Kula volcanics were collected for petrographic and geochemical investigation.

Figure 9. Primary spreading of the 1st plateau basalt, cinder cone and 2nd plateau basalt episodes (the border between the metamorphic rocks and sediments is modified from the MTA map of the Kula area).

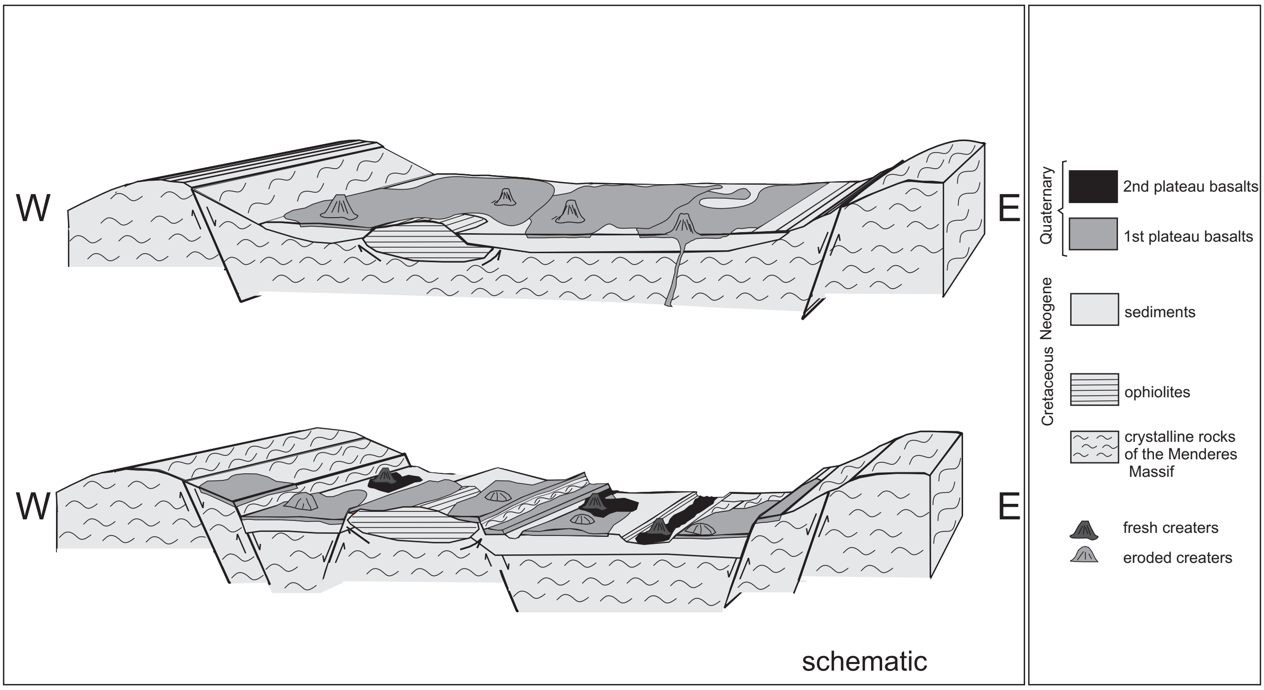

**Figure 10.** Volcano-tectonic model for the development of the Kula basalts (modified after Tokçaer 2000).

Major- and trace-element data were carried out at the Dipartimento di Scienze della Terra, Università di Pisa. Rock powders were prepared, after crushing, by grinding in an agate mill. Major elements were determined by XRF (Philips PW1480) on fused disks and FeO by titration. Loss-on-ignition was measured by gravimetry at 1000° C after pre-heating at 110° C. Trace elements were determined by XRF on pressed pellets following a full-matrix correction procedure after Leoni & Saitta (1976). The contents of 30 trace elements were determined by ICP-MS (Fisons PQ2 Plus®) at the Dipartimento di Scienze della Terra, Università di Pisa. Analytical precisions, evaluated by repeated analyses of the in-house standard HE-1 (Mt. Etna hawaiite), are generally between 2 and 5% RSD, except for Gd (6%), Tm (7%), Pb and Sc (8%). Detection limits are in the range 0.002–0.02 ng ml$^{-1}$ in the solution for all elements, except for Ba, Pb and Sr (0.1–0.2) (D'Orazio 1995). The results of the chemical analyses are given in Tables 2 & 3 (more data are available in Agostini 2004).

Representative samples, selected for major-element determination, do not show (i) evident macroscopic and/or microscopic alteration or (ii) xenolith contamination.

According to the TAS classification (Le Maitre 1989), the Kula volcanics exhibit an alkaline, mainly sodic, character and fall in the basanite, trachybasalt (hawaiite) and phonolitic tephrite fields (Figure 11).

### *Petrography*

The Kula volcanic rocks are porphyritic in character. The lavas generally are massive and have hypocrystalline groundmass, while the scoriae are vesiculated and glassy, and may be subaphyric. The phenocryst assemblage is generally made up of clinopyroxene, olivine and amphibole, in some places together with plagioclase, while the groundmass usually contains variable quantities of glass and plagioclase, clinopyroxene, amphibole, olivine, feldspathoids (nepheline and probably leucite), and magnetite; ilmenite is quite scarce and confined to basanites. Mineralogical compositions are given in Table 4.

The groundmasses of the Kula rocks vary from hypohyaline and vesicle-rich in scoriaceous samples, to holocrystalline and vesicle-free in some massive lavas: generally they are hypocrystalline, and contain microcrystals (10–50 µm sized) or microlites of sialic,

**Table 2.** Selected major-element analyses and CIPW norms for the Kula volcanics.

| Sample | IZ 73 | IZ 78 | K 99/5 | IZ 98 | IZ 83 | IZ 87 | IZ 94 | IZ 95 | IZ 96 | 99/12 |
|---|---|---|---|---|---|---|---|---|---|---|
| *Major Elements (wt %)** | | | | | | | | | | |
| $SiO_2$ | 46.26 | 47.80 | 47.25 | 45.96 | 49.43 | 47.17 | 47.57 | 48.17 | 48.92 | 50.72 |
| $TiO_2$ | 2.15 | 2.06 | 1.93 | 2.10 | 1.68 | 2.01 | 2.18 | 1.89 | 2.04 | 2.02 |
| $Al_2O_3$ | 17.24 | 17.36 | 19.47 | 17.16 | 19.43 | 18.24 | 16.15 | 18.76 | 19.63 | 19.68 |
| $Fe_2O_3$ | 4.49 | 2.97 | 3.36 | 2.71 | 4.83 | 2.61 | 4.14 | 3.64 | 3.59 | 2.43 |
| FeO | 4.58 | 5.23 | 5.01 | 5.82 | 2.41 | 5.10 | 5.01 | 4.53 | 5.19 | 5.15 |
| MnO | 0.16 | 0.13 | 0.16 | 0.15 | 0.16 | 0.14 | 0.16 | 0.15 | 0.16 | 0.13 |
| MgO | 6.99 | 7.44 | 4.99 | 6.94 | 3.90 | 6.16 | 4.49 | 7.46 | 3.96 | 4.94 |
| CaO | 9.78 | 9.60 | 8.62 | 9.59 | 6.73 | 8.65 | 11.35 | 8.31 | 9.09 | 7.79 |
| $Na_2O$ | 6.28 | 4.43 | 5.46 | 5.23 | 6.65 | 5.65 | 5.75 | 5.08 | 4.73 | 5.23 |
| $K_2O$ | 1.00 | 2.42 | 2.40 | 3.31 | 4.21 | 3.53 | 2.57 | 1.32 | 1.74 | 1.23 |
| $P_2O_5$ | 1.06 | 0.56 | 1.34 | 1.02 | 0.57 | 0.75 | 0.62 | 0.69 | 0.96 | 0.68 |
| FeO* | 8.62 | 7.90 | 8.04 | 8.27 | 6.76 | 7.44 | 8.74 | 7.81 | 8.42 | 7.34 |
| L.O.I. | 1.96 | 1.85 | 1.25 | 0.94 | 1.10 | 0.99 | 1.19 | 2.88 | 2.41 | 2.12 |
| Mg# | 64.76 | 68.05 | 58.44 | 65.51 | 57.47 | 65.97 | 54.66 | 68.39 | 51.54 | 61.23 |
| *CIPW Norm (mol %)* | | | | | | | | | | |
| or | 5.9 | 14.3 | 14.2 | 19.6 | 24.9 | 20.8 | 15.2 | 7.8 | 10.3 | 7.2 |
| ab | 17.7 | 14.0 | 19.2 | 3.5 | 12.0 | 6.6 | 7.8 | 25.3 | 28.2 | 37.1 |
| an | 15.9 | 20.3 | 21.5 | 13.6 | 10.7 | 14.0 | 10.7 | 24.5 | 27.2 | 26.6 |
| ne | 19.2 | 12.7 | 14.6 | 22.1 | 24.0 | 22.3 | 22.1 | 9.6 | 6.4 | 3.9 |
| di | 20.8 | 19.0 | 10.1 | 22.0 | 15.4 | 19.3 | 33.9 | 9.8 | 9.6 | 6.1 |
| hy | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| ol | 10.8 | 11.6 | 10.7 | 10.0 | 5.6 | 8.5 | 1.2 | 15.0 | 9.2 | 10.8 |
| mt | 3.0 | 2.7 | 2.8 | 2.8 | 2.6 | 2.9 | 3.4 | 2.7 | 2.9 | 2.8 |
| il | 4.1 | 3.9 | 3.7 | 4.0 | 3.2 | 3.8 | 4.1 | 3.6 | 3.9 | 3.8 |
| ap | 2.4 | 1.3 | 3.1 | 2.4 | 1.3 | 1.7 | 1.4 | 1.6 | 2.2 | 1.6 |
| SUM | 99.8 | 99.9 | 99.9 | 99.9 | 99.7 | 99.9 | 99.8 | 99.8 | 99.8 | 100.0 |
| Rock type | Basan. | Basan. | Basan. | Tep. | Ph. Tep. | Ph. Tep. | Ph. Tep. | Haw. | Haw. | Mug. |

Basan. – basanites; Tep. – tephra; Ph. Tep. – phonolitic tephrite; Haw. – hawaiites; Mug. – mugearite

femic and opaque phases. Typical mineral assemblage of groundmass is consisted by plagioclase (generally the most abundant phase in the groundmass), clinopyroxene (ubiquitous, and more abundant in basanites), olivine and Ti-magnetite. Kaersutite microcrystals are typical in hawaiites and may be abundant in phonolitic tephrites, and small quantities of feldspathoids (nepheline, in somes cases with leucite) can occur in all of the rock types. Ilmenite occurs ssparsely in some basanites.

## *Major Elements, Trace Elements and Isotope Geochemistry*

The Kula volcanics are alkaline and dominantly sodic in character; they are $SiO_2$ poor ($SiO_2$ ranges from 45.6 and 50.8 wt%, recalculated anhydrous), and generally alkali and Mg-rich: Mg and Mg# lie in the range 9.1–3.9 wt% and 75–52, respectively. $Na_2O$ (3.9–6.7 wt%) is abundant in all Kula rocks, while $K_2O$ contents are more

Table 3. Selected trace-element analyses for the Kula volcanics.

| Sample | IZ 78 | *K 99/5* | IZ 98 | IZ 83 | IZ 87 | IZ 94 |
|---|---|---|---|---|---|---|
| *Trace Elements (ppm)* | | | | | | |
| Li | 12.1 | | 8.2 | 11.7 | 10.3 | 12.0 |
| Be | 1.90 | | 2.48 | 2.84 | 2.29 | 2.66 |
| Sc | 24 | | 18 | 10 | 17 | 13 |
| V | 198 | *226* | 181 | 108 | 165 | 136 |
| Cr | 187 | *26* | 96 | 34 | 64 | 42 |
| Co | 33 | *30* | 30 | 20 | 28 | 23 |
| Ni | 66 | *13* | 73 | 34 | 61 | 31 |
| Rb | 63.8 | *61* | 68.7 | 102.2 | 75.8 | 80.2 |
| Sr | 777 | *1672* | 1112 | 867 | 911 | 856 |
| Y | 23.7 | *27* | 28.4 | 26.4 | 25.0 | 26.9 |
| Zr | 178 | *269* | 237 | 268 | 214 | 268 |
| Nb | 61.9 | *125* | 98.6 | 99.8 | 86.8 | 90.6 |
| Mo | 3.53 | | 6.93 | 6.48 | 5.28 | 6.36 |
| Cs | 1.03 | | 1.30 | 1.35 | 1.34 | 1.38 |
| Ba | 613 | *1359* | 967 | 873 | 887 | 816 |
| La | 37.8 | *110* | 62.5 | 56.7 | 48.6 | 50.1 |
| Ce | 71 | *189* | 113 | 98 | 86 | 89 |
| Pr | 8.4 | | 12.8 | 10.7 | 9.5 | 10.1 |
| Nd | 32.0 | | 47.1 | 38.3 | 35.4 | 37.7 |
| Sm | 6.2 | | 8.2 | 6.5 | 6.4 | 6.8 |
| Eu | 1.94 | | 2.48 | 2.02 | 1.95 | 2.13 |
| Gd | 5.6 | | 6.7 | 5.5 | 5.7 | 6.0 |
| Tb | 0.78 | | 1.00 | 0.84 | 0.82 | 0.87 |
| Dy | 4.5 | | 5.3 | 4.8 | 4.6 | 5.0 |
| Ho | 0.87 | | 1.01 | 0.90 | 0.88 | 0.92 |
| Er | 2.14 | | 2.56 | 2.48 | 2.29 | 2.54 |
| Tm | 0.32 | | 0.39 | 0.37 | 0.35 | 0.38 |
| Yb | 1.79 | | 2.22 | 2.23 | 2.04 | 2.21 |
| Lu | 0.25 | | 0.32 | 0.33 | 0.29 | 0.32 |
| Hf | 3.9 | | 4.9 | 5.2 | 4.4 | 5.5 |
| Ta | 3.44 | | 5.56 | 6.18 | 4.87 | 5.45 |
| Tl | 0.10 | | 0.10 | 0.15 | 0.09 | 0.13 |
| Pb | 3.74 | | 4.86 | 4.70 | 4.34 | 4.33 |
| Th | 5.6 | | 8.2 | 8.0 | 7.4 | 8.1 |
| U | 1.6 | | 2.3 | 2.4 | 2.2 | 2.3 |

variable, from 1.0 to 4.2 wt%. Consequently, $Na_2O/K_2O$ ratios range between 1.4 and 6.2, and the Kula rocks may display either sodic or potassic affinities: sodic rocks strongly prevail, with 64% of collected samples having $Na_2O–2>K_2O$, about 20% having $Na_2O–2\approx K_2O$, and only the remaining 16% displaying mildly potassic affinity. $TiO_2$ and $Al_2O_3$ contents vary between 1.6 and 2.3 and from 16.1 to 20.0 wt%, respectively.

Basanitic rocks generally display the lowest $SiO_2$, the highest MgO, and the highest $Na_2O/K_2O$ ratios (up to 6.2); they are all strongly undersaturated, with normative nepheline ranging between 10 and 22%. Hawaiitic samples are mildly silica-undersaturated (normative nepheline from 4 to 11%), showing the lowest alkali contents ($Na_2O+K_2O \approx 6.0$-6.8 wt%) and higher $SiO_2$ values (up to 50.8 wt%). Phonolitic tephrites are strongly alkaline and undersaturated ($Na_2O+K_2O$ from 11 to 24 wt% and ne-norm ≈ 11-24%), and are characterized by the lowest $Na_2O/K_2O$ ratios (from 1.4 and 2.2), and display high values for MgO and Mg# (from 3.9 to 9.0 wt% and 55–76, respectively).

With regard to trace elements, the Kula volcanics – despite their primitive character – do not have very high compatible-element contents; Cr does not exceed 187 ppm and Ni does not exceed 92 ppm. The abundance and distribution of incompatible elements is characterized by enrichment in both LILE and HFSE (e.g., Th/Ta≈1.3-1.9). Spider diagrams (Figure 12a) show that the Kula rocks have patterns strongly resembling the OIB of Sun & McDonough (1989) and are more enriched in most incompatible elements (from Cs to K). Their REE distribution patterns are characterized by evident LREE fractionation (Figure 12b), with $La^N/Sm^N \approx 3.8$–5.5, minor fractionation for HREE ($Gd^N/Yb^N \approx 2.0$–2.5), and a negligible Eu anomaly ($Eu^N/Eu^* \approx 0.94$–1.02).

The $^{87}Sr/^{86}Sr$ and $^{134}Nd/^{144}Nd$ isotope ratios for the Kula volcanics have narrow ranges, 0.703087–0.703273 and 0.512924–0.512952, respectively. Such values fall in the depleted quadrant of the $^{87}Sr/^{86}Sr$ vs. $^{134}Nd/^{144}Nd$ isotope diagram, between the MORB field and bulk silicate earth (BSE). Thus, the isotopic compositions of the Kula magmas have values typical of OIB-type, intra-plate magmatism (Figure 13) (Agostini 2004).

In summary, all of the geochemical and isotopic data point to an asthenospheric mantle source for the Kula volcanics, without any subduction-related contamination. Little fractionation of the HREE may be indicative of no residual garnet in the source. Thus, the Kula alkaline magmas were probably derived by small degrees of melting of a spinel lherzolite mantle. Variation in Mg and alkali contents – without coincident variation in Sr and Nd isotopic ratios – as well as trace-element distributions, indicate that crystal fractionation played a role in the differentiation of the Kula volcanics, with no crustal assimilation.

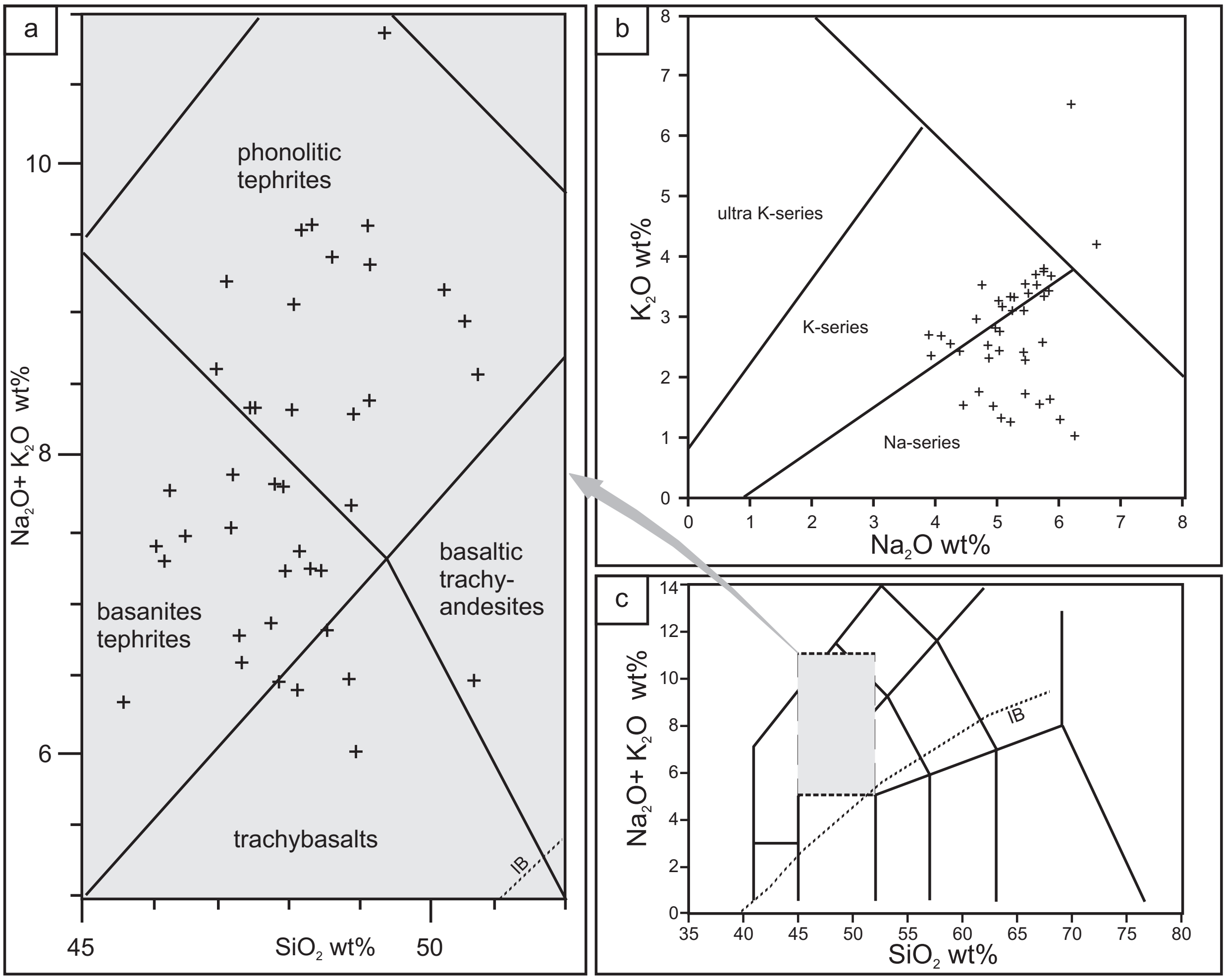

Figure 11. (a, c) TAS, total alkali versus silica (Le Maitre 1989) diagram. Shaded box in (c) is enlarged in (a) where the Kula volcanics are plotted. IB, dividing line between alkaline and subalkaline fields from Irvine & Baragar (1971); (b) $Na_2O$ vs $K_2O$ diagram for the Kula volcanics: dividing lines between sodic, potassic and ultrapotassic series are from Middlemost (1975).

## Discussion and Conclusion

Several granites and rhyolites in the Attic-Cycladic and Menderes massifs with dominant crustal signatures were emplaced during the Middle–Late Miocene in relation to a regional-scale extensional phase that formed the Aegean basins (e.g., Hetzel *et al.* 1995; Delaloye & Bingöl 2000; Pe-Piper 2000; Pe-Piper *et al.* 2002; Keay *et al.* 2001; Altherr & Siebel 2002; Doglioni *et al.* 2002; Bozkurt 2004; Işık *et al.* 2003, 2004 and references therein). The second-period volcanics in western Anatolia are, in general, poorly evolved (alkali basalts being the most widespread) and generally display a slight potassic affinity. The subduction-related geochemical signature of these products is generally slight.

From the Late Miocene up to the Quaternary, widely distributed small bodies of alkaline basalt with OIB-type source characteristics were erupted in all of the different sectors of the Aegean-Anatolian realm (Aldanmaz *et al.* 2000; Yılmaz *et al.* 2001; Wilson *et al.* 1997; Aydar *et al.* 1995; Doglioni *et al.* 2002; Alıcı *et al.* 2002; Innocenti *et al.* 2005). The time-space distribution of volcanism in the Aegean and western Anatolia, with their main rock associations and involved magma sources, show an apparent transition from orogenic (calc-alkaline: CA, shoshonitic: SHO, ultrapotassic-shoshonitic: UK-SHO, lamproitic), mantle-wedge source rocks to alkaline (K–Na alkali basalts to Na-alkali basalts), OIB-type mantle source rocks (Doglioni *et al.* 2002). According to those authors,

**Table 4.** Mineralogical composition of some Kula rocks (mineral chemistry is taken from Bunbury 1992).

| | Olivine | Clinopyroxene | Amphibole | Plagioclase |
|---|---|---|---|---|
| Size, form and alteration | may show iddingsitic and bowlingitic alteration | the largest phenocryst phase; can reach 10–15 mm in size | phenocrysts are generally smaller than pyroxene and in a few cases are larger than 4 mm; generally euhedral, prismatic; pleochroic under plane-polarized light, from brown through pale brown to brownish yellow | scarce, as small phenocrysts; can reach 0.5–3 mm in size |
| Composition and zoning | generally colorless, show high birefringence under crossed polars, and are directly zoned (e.g., $Fo_{84–68}$) | diopside in composition ($En_{46–49}$ $Wo_{42–46}$ $Fs_{7–9}$); pale green under plane-polarized light, and may show hour-glass zoning under crossed-polars | can be classified as kaersutite (Ti-rich hornblende); typically characterized by oxidation rims; in many cases partially or completely replaced by secondary alteration (opaque oxides and hydroxides) | labradorite-andesine in composition; show little direct zoning (e.g., $An_{51–45}$) |
| Abundance | ubiquitous in basanites and phonolitic tephrites; larger (up to ~5 mm) and more abundant in hawaiites | the most abundant and widespread mineral in all rock types of the Kula area | present both in basanites and hawaiites, but is abundant only in phonolitic tephrites and is often the main phenocryst phase | in basanites and hawaiites, whilst they occur and are the most abundant phase in two specimens of phonolitic tephrite |

the southwestward migration of calc-alkaline, shoshonitic and lamproitic magmas in the hanging wall was accompanied by the southwestward migration of the subduction hinge. These volcanic products were emplaced in an already extending area that eventually evolved in a more extreme setting of mantle upwelling, the source for the OIB basalts.

The widespread (330–400 km$^2$) plateau basalt of the first-period Kula volcanics (thickness 5 to 20 m) provides the only example during Miocene volcanic activity in western Anatolia. In addition to this, the rapid change in chemical composition also represented a new epoch for the western Anatolian volcanics. According to Gülen (1990), the mantle xenolith-bearing Kula alkaline basalts (<1 Ma), with their least contaminated Sr, Nd and Pb isotopic compositions, provide the best geochemical data for the Aegean mantle. With higher enrichments in the more incompatible elements (from Nd to Cs), the trace-element distribution is similar to that of OIB-type basalts as is evident in PM-normalized spider diagrams. The first products that show the influence of a OIB-type source are the Upper Miocene K-alkali basalts, erupted when extension was less developed. In this case, sodic – phonolitic plateau basalts, craters and lava flows of the Kula volcanics are products of the final activity where the mostly uncontaminated material of the Aegean mantle

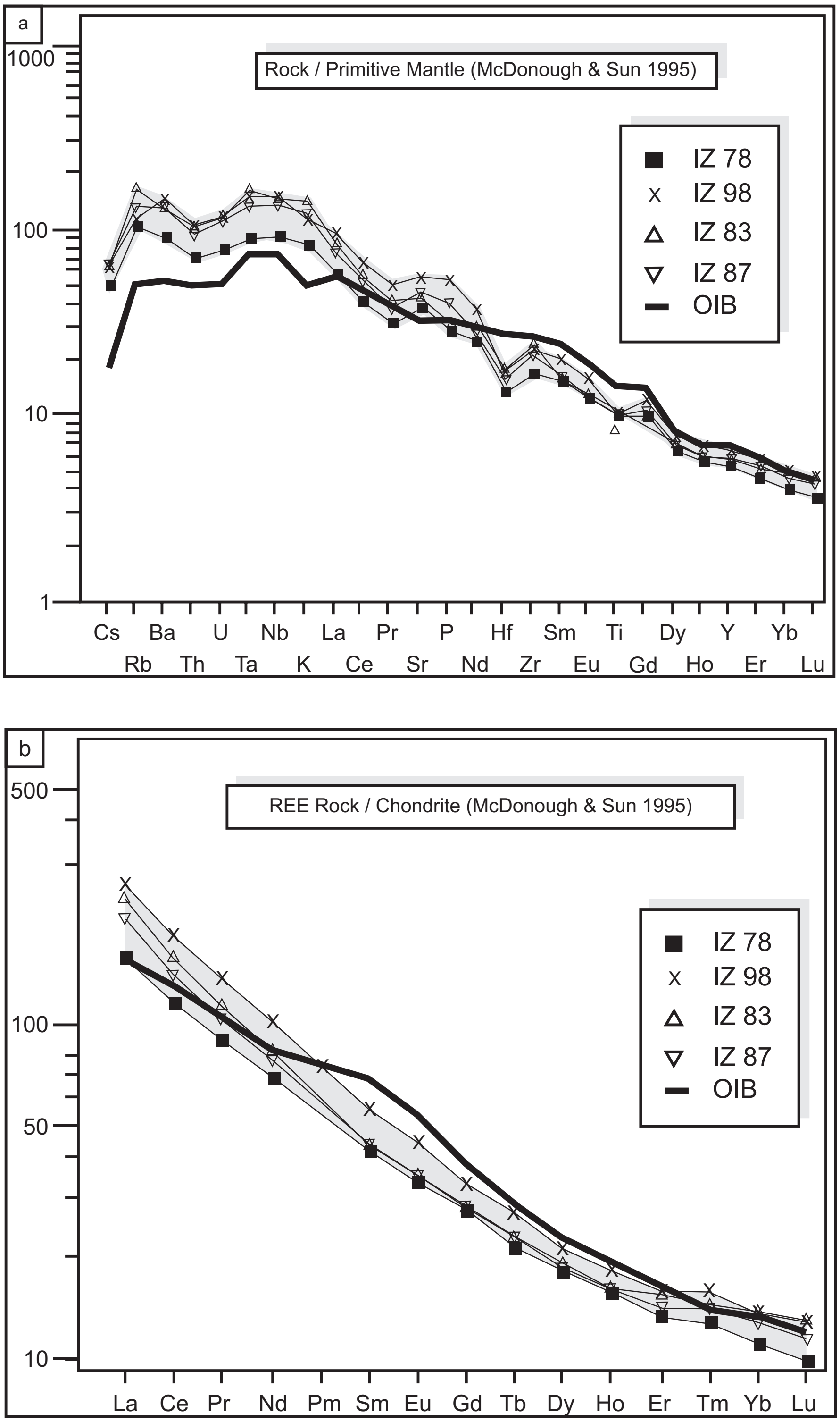

Figure 12. Incompatible trace-element (a) and rare-earth element (b) spider diagrams for the Kula volcanics: OIB of Sun & McDonough (1989) is plotted for comparison. Shaded areas represent the entire compositional range of the collected samples. Normalizing values: primitive mantle (a) and chondrite (b) after McDonough & Sun (1995).

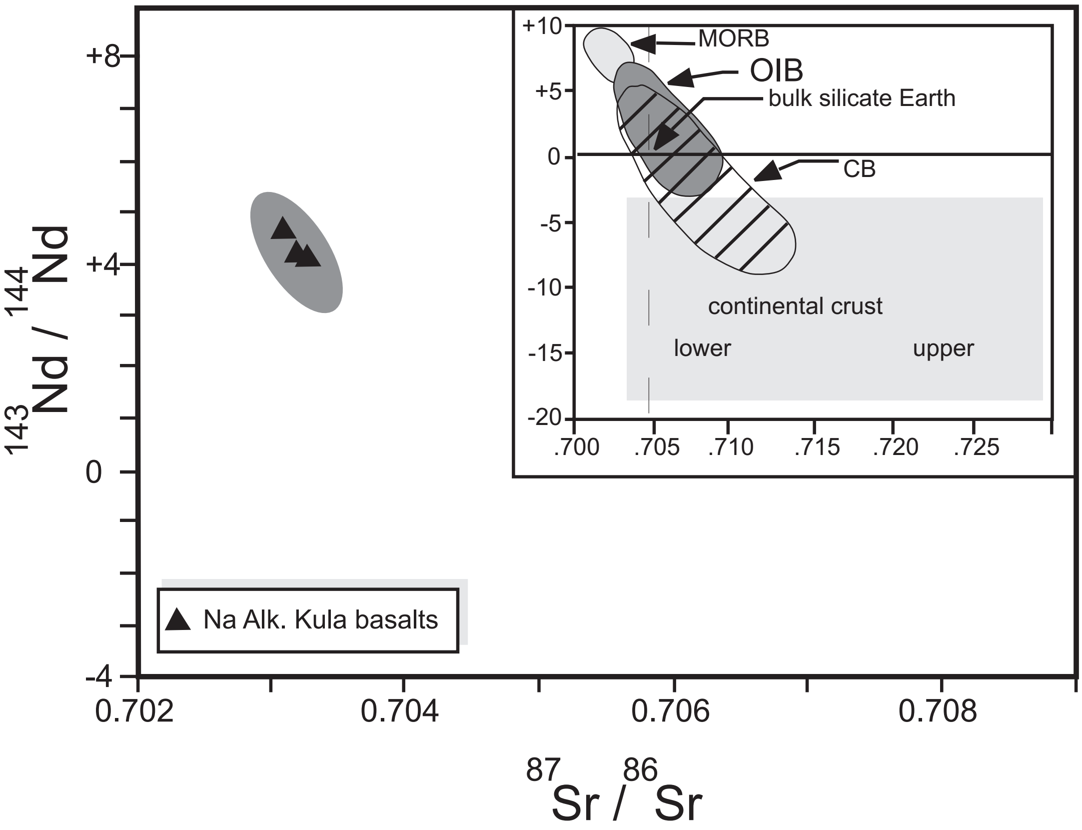

Figure 13. $^{143}$Nd/$^{144}$Nd versus $^{87}$Sr/$^{86}$Sr diagram. The variation field of the Kula Na-rocks is after Innocenti *et al.* (2005).

rapidly erupted as a new episode in the strong extensional regimes of the neotectonic period (rapid upwelling of mantle). According to Doglioni *et al.* (2002), the stretching between Greece and Anatolia, and the differential velocity of convergence with the underlying slabs, should have generated 'horizontal windows' both in the hanging wall and in the footwall of the subduction allowing melting of mantle, and generating the OIB magmatism after normal subduction/collision evolution. With this new model, it is much easier to explain the evolution of Quaternary Kula volcanics.

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