

Helium and heat distribution in western Anatolia, Turkey: Relationship to active extension and volcanism

Nilgün Güleç*

Department of Geological Engineering, Middle East Technical University, 06531 Ankara, Turkey

David R. Hilton*

*Geosciences Research Division, Scripps Institution of Oceanography,
La Jolla, California 92093-0244, USA*

ABSTRACT

Western Anatolia, one of the world's best-known extensional terrains, is characterized by the presence of several moderate- to high-enthalpy geothermal fields. Geothermal fluids have helium isotope compositions reflecting mixing between mantle and crustal helium components, the former ranging between 0.58% and 45% of the total helium in a given sample. Regarding the distribution of heat and mantle He and their correlation with tectonic structure and volcanism in western Anatolia, the prominent features are as follows: (1) the association between highest heat and highest ^3He lies along the eastern segment of the Büyük Menderes graben, (2) the high heat and high ^3He occur in the vicinity of the Quaternary Kula volcanism, (3) high-enthalpy fields exist in close vicinity to the young alkaline volcanics, (4) relatively high mantle He contributions occur in areas of not only the young alkaline, but also the old calc-alkaline volcanics, and (5) there is a lack of volcanic exposures along the Büyük Menderes graben (except at its western and southeastern terminations), where the highest values are recorded for both heat and helium. The first three features collectively suggest that the transfer mechanism for both heat and helium is probably mantle melting accompanying the current extension in western Anatolia, yet the latter two further indicate that this may be accomplished via subsurface plutonic activities. The large range observed in the helium isotope compositions may be linked with differential (local) extension rates and associated melt generation in the respective areas. This suggestion can be substantiated by He isotope data from more of the region.

Keywords: mantle He, heat, volcanism, extension, melt generation

INTRODUCTION

The presence of primordial or mantle-derived ^3He in the continental lithosphere is now well established, from xenolith studies of the lower crust (Porcelli et al., 1986, 1992) and from

groundwater and natural gas investigations in the uppermost crust (Oxburgh and O'Nions, 1987; O'Nions and Oxburgh, 1988). A general pattern has been established whereby mantle ^3He near the surface (identified by $^3\text{He}/^4\text{He}$ ratios greater than background crustal production values) is seen to accompany recent

*E-mails: Güleç—nilgun@metu.edu.tr; Hilton—drhilton@ucsd.edu.

volcanic activity and is found in areas of active or geologically recent continental extension (O'Nions and Oxburg, 1988). In most cases, the mechanism likely to have been responsible for the transfer of ^3He from the mantle into the lithosphere is melting. Because melts can freeze at different depths in the crust, it is unsurprising that ^3He anomalies at the surface are usually distributed over wider geographic areas than the surface volcanics themselves.

An important question has been just how long mantle ^3He may persist in the crust following a melting event. For example, in the lower part of the continental lithosphere, where ^3He may be trapped in CO_2 -bearing fluid inclusions (Porcelli et al., 1992), its diffusion rate is slow enough that it may remain intact for 10^8 to 10^9 yr (Kamensky et al., 1990; Tolstikhin et al., 1992). However, geological observation suggests that the survival times of ^3He in the crust may be more variable. For instance, melting occurred during the extension of the North Sea basin during the Late Jurassic, yet no ^3He signature remains in most parts of the basin (Hooker et al., 1985). On the other hand, melting has continued from the Miocene to the Quaternary in the Pannonian basin, and ^3He is still evidently distributed in surface fluids throughout the basin (Martel et al., 1989; Ballentine et al., 1991).

Yet another important geologic observation regarding the distribution of ^3He in the crust has been the positive correlation between the $^3\text{He}/^4\text{He}$ ratio and conductive heatflow worldwide (Polyak and Tolstikhin, 1985). However, the validity of this correlation has recently been questioned for Turkey (Güleç et al., 2002), where the highest (mantle) ^3He contribution is associated with the low- to moderate-enthalpy geothermal fields of eastern Anatolia, whereas the high-enthalpy fields of western Anatolia are characterized by a relatively low ^3He flux.

The present contribution is focused on western Turkey, a region of active extension since at least the late Miocene (Dewey and Şengör, 1979; Angelier et al., 1981; Seyitoğlu et al., 1992; Okay and Satır, 2000). The available $^3\text{He}/^4\text{He}$ ratios (Stone, 1986; Güleç, 1988; Ercan et al., 1995; Pfister et al., 1997; Güleç et al., 2002) and geothermometry data (Mutlu and Güleç, 1998) are examined in terms of their relationship to one other (i.e., $^3\text{He}/\text{heat}$ variations), as well as with respect to the distribution of major grabens in the region and the presence of Neogene–Quaternary volcanics.

TECTONISM

Western Anatolia comprises the eastern part of the Aegean province, which has experienced multiple microplate interactions within the complex convergent system of the Africa and Eurasia plates. The major features of the geodynamic history of this province have been (1) a prolonged north-northeast subduction since about the Late Cretaceous, in time retreating south-southwest to the present position of the Hellenic trench, and (2) the current north-south extension forming the most prominent neotectonic features, the grabens, of the so-called Aegean extensional province. Western Anatolia, the Aegean

Sea, central Greece, and parts of Albania, Macedonia, and Bulgaria are included in this extensional province, which is bounded to the south by the Hellenic trench and to the north by the North Anatolian fault and its seaward extension (Fig. 1A). Between these boundaries, the Aegean region is dominated by a tensional regime as evidenced by fault plane solutions and the presence of numerous normal faults (McKenzie, 1972, 1978; Dewey and Şengör, 1979; Angelier et al., 1981; Taymaz et al., 1990, 1991). While the faulting in the western part of the region is mostly extensional in nature, on normal faults trending northwest to WNW, the central and eastern Aegean along with northwest Turkey are dominated by distributed (mostly right lateral) strike-slip faulting with a northeast to ENE strike (Taymaz et al., 1991; Taymaz, 1996; Fig. 1A). Fault plane solutions and high seismicity indicate an active, rapid extension for the northern part of the Aegean. The level of seismicity is rather low in the southern parts and in the Peloponnesus, where few shocks occur at depths of 50 km or less. In the northwestern sector, most of the deformation is produced by normal faulting, except in western Greece and Albania, where both field studies and fault plane solutions indicate deformation by thrusting (McKenzie, 1978; Taymaz et al., 1990, 1991). In western Anatolia, the tectonic activity is concentrated in a number of approximately east-west-trending grabens and associated normal faults (Fig. 1B).

Subduction along the Hellenic trench is largely accepted to be the major driving mechanism of the current extension in the Aegean region (McKenzie, 1978; Taymaz et al., 1990). The presence of earthquakes to a depth of 150 km clearly indicates that subduction is taking place: active volcanism occurs where the subducting slab is between 100 and 150 km deep. As to western Anatolia, however, the mechanism, timing of initiation, and continuation of north-south extensional tectonics are currently debated issues. The mechanisms so far proposed for the extension in western Anatolia include: (1) the westward *tectonic escape* of the Anatolian landmass along the North and the East Anatolian fault zones since about the late Miocene (ca. 12 Ma; Dewey and Şengör, 1979; Şengör et al., 1985; Şengör, 1987; Taymaz et al., 1991), (2) *back-arc extension* associated with the southward-migrating Aegean subduction zone (McKenzie, 1978; Le Pichon and Angelier, 1979; Jackson and McKenzie, 1988; Taymaz et al., 1990; Okay and Satır, 2000) since about the late Oligocene, (3) *orogenic collapse* induced by the spreading and thinning of overthickened crust following the late Oligocene–early Miocene collision across the Neo-Tethys (Seyitoğlu et al., 1992; Seyitoğlu and Scott, 1996), (4) an episodic *two-stage extension* (Koçyiğit et al., 1999; Bozkurt, 2000, 2003; Bozkurt and Sözeri, 2004): Miocene–early Pliocene orogenic collapse and Plio-Quaternary tectonic escape, and (5) differential convergence rates between the northeastward-subducting Africa plate and the microplates in the Eurasian lithosphere, i.e., Greece advancing over Africa at a faster rate relative to Anatolia and Cyprus (Doglioni et al., 2002).

Topographic and geophysical data show that the crustal thickness is ~20–30 km in the Aegean, whereas it is ~30–40 km

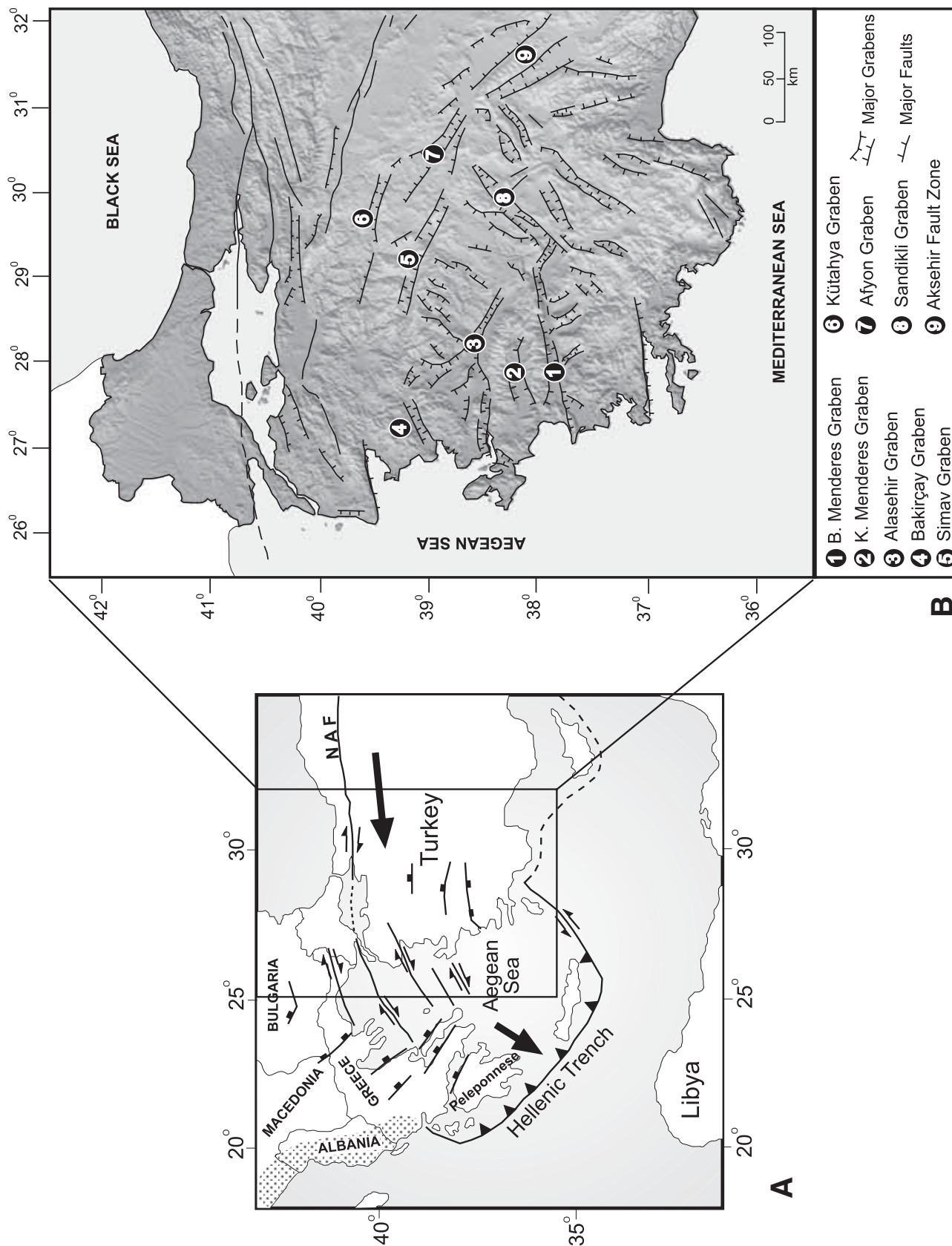


Figure 1. (A) Tectonic setting of the Aegean extensional province (from Taymaz et al., 1991). Predominantly normal faults have blocks in their hangingwalls. Predominantly strike-slip faults are marked by arrows. The Hellenic trench has filled triangles on the overriding plate. The hatched area in the northwest is the region of crustal shortening and thrusting. The large arrows show the motions of Turkey and the southern Aegean. NAF—North Anatolian fault. (B) Major structural features of western Anatolia (from Bozkurt, 2001).

beneath western Anatolia, suggesting a decrease in extension from the center part of the Aegean (with a β value of ~ 2) to western Anatolia (with a β value of ~ 1.2 – 1.3 ; Makris and Stobbe, 1984; Patton, 1992; Taymaz, 1996; Tsokas and Hansen, 1997; Saunders et al., 1998). The reported extension rates across the Aegean range from >100 mm/yr to 3–4 mm/yr (Jackson and McKenzie, 1988; Westaway, 1994a,b; McClusky et al., 2000, 2003; Papadimitriou and Sykes, 2001).

VOLCANISM

Volcanism in the Aegean and western Anatolia has accompanied the geodynamic evolution of this province, generating products with distinct petrogenetic affinities. Except in the northernmost part of the province, where upper Eocene–upper Oligocene volcanics cover large areas in the Rhodope–Thrace segment (Fytikas et al., 1984), most of the magmatic activity in western Anatolia developed during the Miocene and has continued, with a decrease in intensity, up to recent times. Three different associations are identified as to the nature of the western Anatolian volcanics, although they display some temporal and spatial overlap: (1) lower–upper Miocene calc-alkaline, (2) middle Miocene–Pliocene ultrapotassic-potassic, and (3) upper Miocene–Quaternary sodic alkaline (Fig. 2).

Lower–upper Miocene calc-alkaline volcanics form an east-west-trending belt (Fig. 2), extending from the vicinity of Afyon in the east through Gediz, Simav, Bergama, and Dikili to the northern and central Aegean islands in the west. The reported geochronological data yield an age range between 23 Ma (Edremit area; Seyitoğlu and Scott, 1992) and 6.99 Ma (Söke area; Ercan et al., 1985). Lava flows, domes, agglomerates, tuffs, and ignimbrites comprise the products of this association, ranging in composition from basaltic andesites to rhyolites but dominated by andesites and dacites (Innocenti et al., 1982; Fytikas et al., 1984; Ercan et al., 1985; Savaşçın and Güleç, 1990; Yılmaz, 1990; Güleç, 1991; Seyitoğlu and Scott, 1992; Ercan et al., 1996; Seyitoğlu et al., 1997; Aldanmaz et al., 2000).

Middle Miocene–Pliocene ultrapotassic-potassic associations are shoshonitic to alkaline in nature and are confined to the Afyon, Isparta, Denizli, and Bodrum areas (Fig. 2). The reported ages range from 14.8 Ma (Afyon area; Francalanci et al., 2000) to 4.07 Ma (Isparta area; Lefevre et al., 1983). These volcanics consist of lava flows, domes, and ignimbrites, the latter covering extensive areas particularly in the Afyon area. The compositions range from trachytic basalts and trachytes in silica-saturated potassics to lamproites and phonolitic leucites in silica-undersaturated ultrapotassic varieties (Robert and Cantagrel, 1977; Ercan, 1981; Innocenti et al., 1982; Pe-Piper and Piper, 1989; Güleç, 1991; Montigny and Robert, 1991; Robert et al., 1992; Francalanci et al., 2000; Ulusoy et al., 2004).

Upper Miocene–Quaternary sodic alkaline associations occur in the Urla, Ezine–Ayvacık, and Kula areas (Fig. 2). The reported radiometric ages are 11.3 Ma for Urla (Borsi et al., 1972), 9.7 Ma for Ezine (Borsi et al., 1972), 8.32 Ma for

Ayvacık (Aldanmaz et al., 2000), and 1.94–0.13 Ma for Kula (Borsi et al., 1972; Richardson-Bunbury, 1996). These volcanics are typically silica-undersaturated, Ne-normative alkaline basalts, basanites, tephrites, and phonolites (Yılmaz, 1990; Güleç, 1991; Aldanmaz et al., 2000; Aldanmaz, 2002; Alıcı et al., 2002). Although they cover a considerable area in Kula, the alkaline rock associations comprise only minute fractions of the volcanic rocks exposed in Urla and Ezine.

Regarding the genesis of the western Anatolian volcanics, although the evolution in time from early calc-alkaline to late alkaline activity is widely accepted, the source regions and the mechanisms of magma generation are controversial in many respects. The calc-alkaline volcanics have petrogenetic affinities resembling those from orogenic suites, and hence imply a close connection to a subduction process, or at least derivation from a subduction-modified lithospheric mantle (Innocenti et al., 1982; Fytikas et al., 1984; Güleç, 1991; Seyitoğlu et al., 1997; Aldanmaz et al., 2000; Yılmaz et al., 2001). However, whether this subduction component has links (1) with an old Tethyan closure (the volcanics representing the postcollisional products; e.g., Yılmaz et al., 2001) or (2) with the present Hellenic subduction (e.g., Gülen, 1990) is a contentious issue, as is the development of this phase of volcanism in association with either compression (Güleç, 1991; Yılmaz et al., 2001) or extension (Seyitoğlu and Scott, 1992) tectonic regimes. The current debates about the origin of calc-alkaline volcanics essentially stem from the controversy over the initiation ages for extension in the Aegean province.

The potassic-ultrapotassic associations show both orogenic and within-plate affinities (Francalanci et al., 2000), whereas the sodic alkaline associations have typical within-plate characteristics (Güleç, 1991; Aldanmaz et al., 2000; Aldanmaz, 2002; Alıcı et al., 2002). The origin of the sodic alkaline phase of volcanism is less debatable, because it has clear connections to the presently active extension. The currently proposed models commonly accept the involvement of asthenospheric melts in the generation of the alkaline volcanics in association with adiabatic melting during extension (Aldanmaz et al., 2000; Aldanmaz, 2002; Alıcı et al., 2002). The potassic-ultrapotassic associations apparently represent the transitional products, with the involvement of both subduction-modified and asthenospheric mantle components in the generation of the volcanics (Francalanci et al., 2000).

HEAT DISTRIBUTION

Owing to its setting in an extensional basin, the Aegean province is characterized by high heatflow. The measurements reported for the Aegean Sea (Jongsma, 1974; Erickson et al., 1976) show a range between 1.01 heat flow units (HFU) and 2.12 HFU, decreasing from a mean of 2.08 HFU in the northern and central parts to 1.6–1.0 HFU in the southern part (Jongsma, 1974). The data available for western Anatolia cover a relatively limited area. Included in these are the estimates by Tezcan

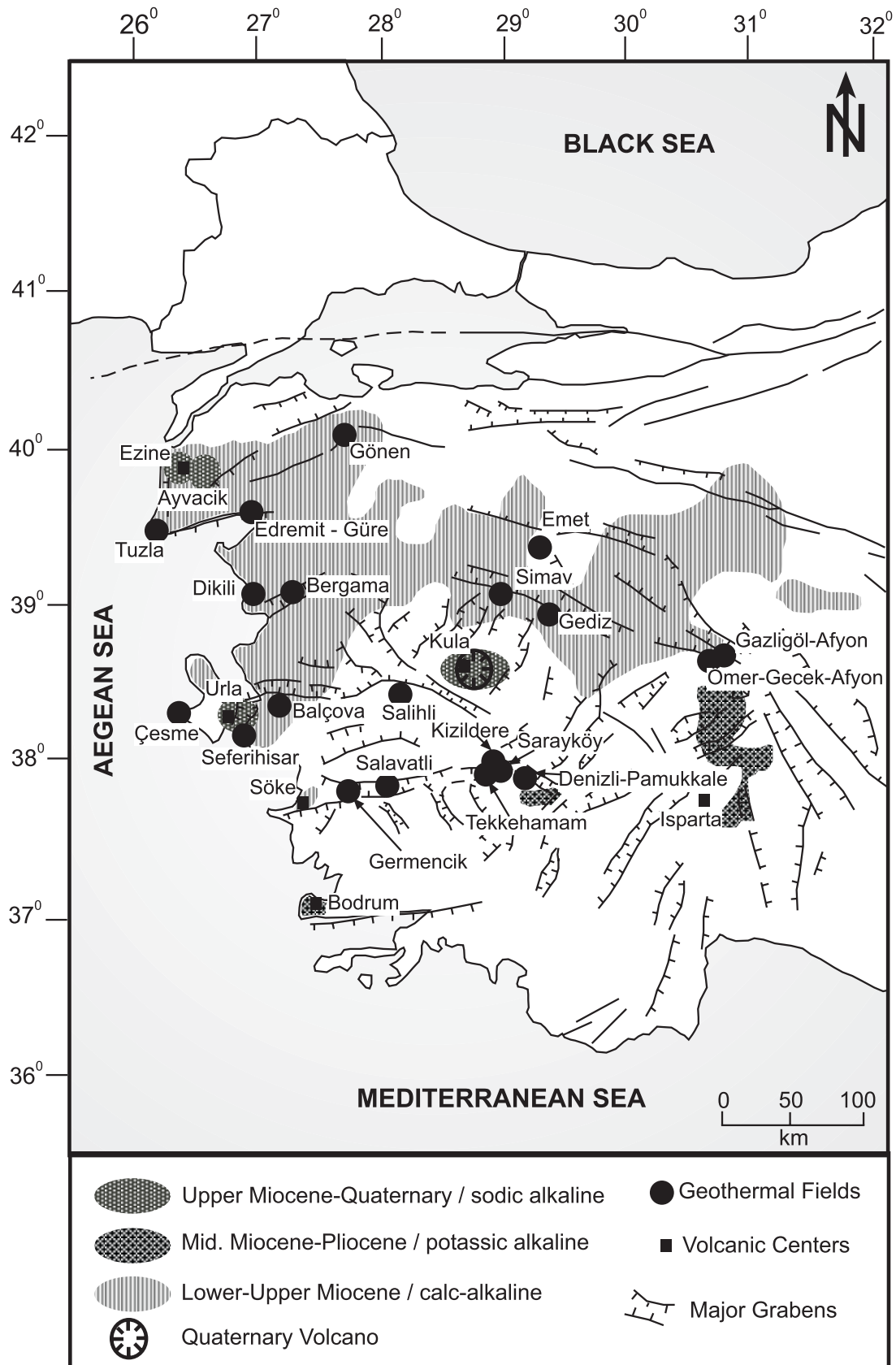


Figure 2. Distribution of major grabens, Neogene–Quaternary volcanics, and major geothermal fields in western Anatolia.

(1979), who used geothermal gradient measurements in geothermal exploration wells, assuming a constant thermal conductivity of $2.1 \text{ Wm}^{-1}\text{K}^{-1}$, which is typical of the clayey sediments filling the major grabens in the region. His study revealed a close spatial connection between heatflow anomalies and the main grabens in western Anatolia, as did the studies by Koçak (1990) and İlkışık (1995), who used reservoir temperature estimates based on silica geothermometers. İlkışık (1995) calculated a mean value of $\sim 107 \pm 45 \text{ mWm}^{-2}$ (2.6 HFU) for the regional heatflow in western Anatolia, with the highest value (247 mWm^{-2}) recorded in the Gediz (Alaşehir) graben; he reported a close connection between areas of high heatflow and the areas of Tertiary and younger volcanism. Most recently, Göktürkler et al. (2003) performed two-dimensional steady-state heatflow modeling along two profiles: one is a northeast-southwest-trending line passing through the Büyük Menderes-Gediz (Alaşehir)–Simav grabens, and the other trends north-south, passing through the central parts of the Büyük Menderes and Gediz (Alaşehir) grabens. Their results confirmed the findings of the previous studies that the temperatures in the grabens are higher than those in the surrounding regions. They attributed the difference in temperature to the effect of sedimentary fill in the grabens, because these sediments have thermal conductivities as low as $2.1 \text{ Wm}^{-1}\text{K}^{-1}$.

The high heatflow in western Anatolia is associated with widespread geothermal activity manifesting itself as numerous hot springs, fumaroles, and areas of recent mineralization. Geothermal exploration surveys implemented by the General Directorate of the Turkish Mineral Research and Exploration in the 1960s have revealed the presence of several moderate- and high-enthalpy geothermal fields in western Anatolia (Fig. 2) comprising $\sim 79\%$ of the total geothermal potential of Turkey.

The distribution of the major geothermal fields in western Anatolia is shown in Figure 3, together with the reservoir temperatures, which are either (1) recorded in drilling wells as bottom-hole temperatures (available for the Germencik, Salavatlı, Kızıldere, Tuzla, Simav, Seferihisar, and Balçova fields; Mertoğlu, 2005) or (2) estimated from hot spring or well-head samples via chemical geothermometry (Mutlu and Güleç, 1998). Concerning the latter, the temperatures used in Figure 3 are the best estimates selected from those reported in Mutlu and Güleç (1998) and represent either the K-Mg or the chalcedony geothermometry results for fields with temperatures below 150°C , along with the quartz geothermometry results for those fields with temperatures above 150°C .

As can be seen from Figure 3, geothermal fields are spatially associated with the major grabens, in agreement with the heatflow estimates hitherto reported (e.g., by Tezcan, 1979; İlkışık, 1995; Göktürkler et al., 2003). Note, however, that the high-enthalpy geothermal fields (with the highest reservoir temperatures of 232°C and 242°C) are concentrated along the Büyük Menderes graben rather than in the Gediz (Alaşehir) graben, which is reported by İlkışık (1995) as having the highest heatflow in the region. Regarding a correlation with the dis-

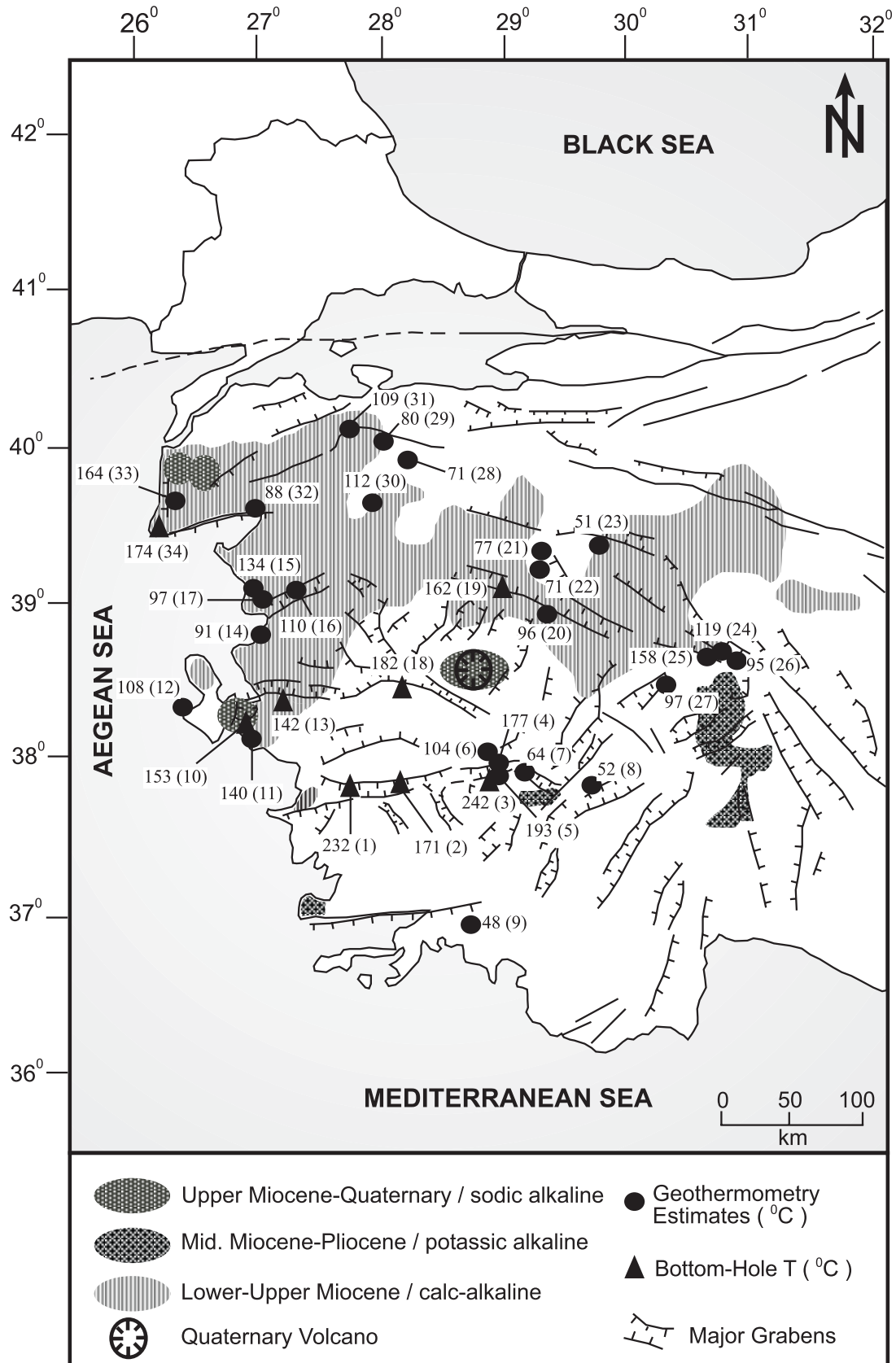
tribution of volcanics, on the other hand, an important observation is the lack of volcanic activity in the Büyük Menderes graben, where the fields with the highest enthalpy are located. The only exceptions are the rather small exposures of middle Miocene–Pliocene Denizli volcanics on the southeastern end of the graben and the upper Miocene Söke volcanics on the western end. Interestingly, however, the Afyon, Seferihisar, Balçova, Salihli, and the Tuzla geothermal fields, which also have relatively high enthalpy, are in close proximity to young volcanics: the middle Miocene–Pliocene potassic-alkaline associations of Afyon and the upper Miocene–Quaternary sodic-alkaline associations of Urla (for the Seferihisar and Balçova fields), Kula (for the Salihli field), and Ezine (for the Tuzla field).

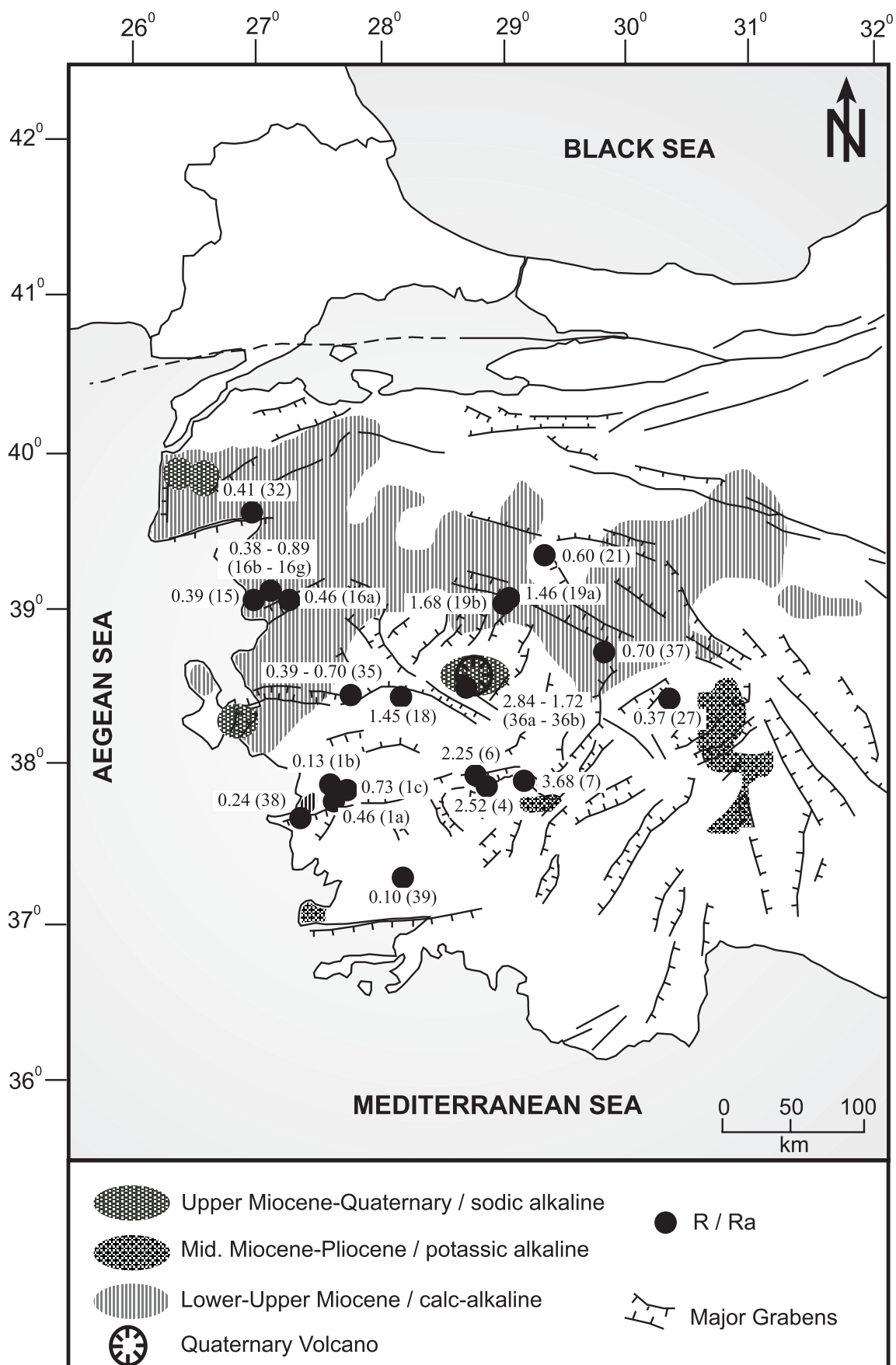
HELIUM DISTRIBUTION

The distribution of helium associated with geothermal fluids in western Anatolia is shown in Figure 4 as $^3\text{He}/^4\text{He}$ ratios (R) normalized to the atmospheric $^3\text{He}/^4\text{He}$ ratio ($R_A = 1.39 \cdot 10^{-6}$). The data used in the figure are taken from the previously published He isotope compilation of Güleç et al. (2002). The R/R_A ratios represent measurements of water and/or gas phases bubbling through the water and are all corrected for possible air contamination by assuming that the measured Ne in these samples is of atmospheric origin.

The air-corrected R/R_A values in western Anatolia cover a large range, from 0.10 to 3.68. A comparison with the values characteristic of mantle He, typified by samples from mid-ocean ridges (average $R/R_A = 8$; Farley and Neroda, 1998), and crustal-He, characterized by radiogenic production ratio (average $R/R_A = 0.02$; Morrison and Pine, 1955), reveals both crustal and mantle He components in the samples. Although ^3He is essentially primordial and has been trapped in the mantle since the formation of the Earth (whereas ^4He is produced by the radioactive decay of U and Th concentrated in the crust), tritogenic ^3He (produced by the radioactive decay of tritium) can also be a possible source of ^3He in geothermal fluids. Given, however, that the water samples in western Turkey have lower He contents than gas samples at the same localities, but similar

Figure 3. Distribution of reservoir temperatures of geothermal fields in western Anatolia. The triangles represent the bottom-hole temperatures reported in Mertoğlu (2005); the circles represent the best estimates from chemical geothermometers reported in Mutlu and Güleç (1998); the numbers before the parentheses represent reservoir temperatures in $^\circ\text{C}$; the numbers in parentheses represent the geothermal fields: 1—Germencik; 2—Salavatlı; 3—Kızıldere; 4—Tekkehamam; 5—Sarayköy; 6—Buldan; 7—Pamukkale; 8—Çardak; 9—Köyceğiz; 10—Seferihisar; 11—Doğanbey; 12—Çeşme; 13—Balçova; 14—Aliağa; 15—Dikili-Kaynarca; 16—Bergama-Dübek; 17—Dikili-Kocaoba; 18—Salihli; 19—Simav; 20—Gediz; 21—Emet; 22—Hisarcık; 23—Yoncalı; 24—Gazlıgöl; 25—Ömer-Gecek; 26—Heybeli; 27—Sandıklı; 28—Susurluk; 29—Manyas; 30—Pamukçu; 31—Gönen; 32—Edremit-Güre; 33—Kestanbol; 34—Tuzla.





$^3\text{He}/^4\text{He}$ ratios (Güleç, 1988), it is unlikely that tritiogenic ^3He is a contributor to measured $^3\text{He}/^4\text{He}$ ratios in western Turkey, because it would affect He-poor waters preferentially, leading to higher values in the water phase. This is not observed, and both gas and water samples at various locations throughout the region have similar $^3\text{He}/^4\text{He}$ ratios. In this respect, the recorded R/R_A values can be regarded as reflecting the mixture of mantle and crustal He components.

The distribution of ^3He in western Anatolia does not show a simple correlation with tectonic structure. For example, the samples associated with the Büyük Menderes graben in the south have R/R_A ratios ranging from as low as 0.13 in the western segment to as high as 3.68 in the eastern segment. Likewise, the ratios are not well correlated with the distribution of volcanics: the ratios obtained in the vicinity of the Quaternary Kula volcanics are relatively high (up to 2.84), yet the highest ratios recorded from the eastern segment of the Büyük Menderes graben do not occur in the immediate vicinity of the Denizli volcanics.

DISCUSSION

Correlation of Mantle He and Heat Distribution

The distribution of helium and heat in western Anatolia is depicted in Figure 5 (A and B) in terms of the relative percentage of the mantle—derived He component and the enthalpies of the geothermal fields, respectively. Following the argument presented in the preceding section (that the recorded R/R_A values in western Anatolia can be regarded as reflecting the mixture of mantle and crustal He components), the relative percentage of mantle He is calculated using $R/R_A = 8$ for the mantle He (Farley and Neroda, 1998) and $R/R_A = 0.02$ for the crustal He (Morrison and Pine, 1955) components. Calculations reveal that the mantle He component covers a wide range, from 0.58% up to ~45% of the total He in a single sample. The enthalpy values are taken from Henley et al. (1984) and represent those corresponding to the reservoir temperatures.

The features readily apparent from Figure 5 are: (1) the association of the highest mantle helium with the highest enthalpy values along the eastern segment of the Büyük Menderes graben, (2) the high mantle He contribution in the vicinity of the

Quaternary Kula volcano, where there are no enthalpy data to correlate the heat and helium relationship (note, however, that the high-enthalpy Salihli field is at a distance of ~60 km to the west of Kula), (3) the occurrence of relatively low mantle He contributions along the western segment of the Büyük Menderes graben, where some of the highest-enthalpy fields of western Anatolia are located, and (4) the lack of He data in the north-western part of the region and in the coastal areas where young alkaline volcanics are exposed. The first two observations noted suggest a positive correlation between the distribution of heat and that of helium in western Anatolia, yet the latter two features fail to fully substantiate this relationship.

Although it is contrary to the overall heat-helium distribution pattern in Turkey (Güleç et al., 2002), the positive correlation between heat and helium in western Anatolia is in agreement with the worldwide trend (Polyak and Tolstikhin, 1985) and suggests similar mechanisms for the transfer of heat and helium. Given (1) the association of high heat with high mantle He in the vicinity of the Quaternary Kula volcanism and (2) the occurrence of moderate- to high-enthalpy fields (Seferihisar, Afyon, and Tuzla) in the vicinity of the young alkaline volcanics (Figs. 2, 3, and 5), it can be argued that the transfer mechanism is most probably mantle melting accompanying extension in western Anatolia. The localization of the highest heat and highest mantle He along the eastern segment of the Büyük Menderes graben, where there is no evidence of surface volcanism, further suggests that the transfer of heat and helium is accomplished by volcanic activities or by plutonic activities with no surface equivalents. Whether this magmatic activity is contemporaneous or the fluids are scavenging long-stored mantle He introduced into the crust by older (e.g., Miocene) magmatic activities is an issue to be resolved. Because ^3He (following its introduction via mantle melting) may persist in the crust for timescales of $\sim 10^8$ yr (Kamensky et al., 1990), the latter alternative seems possible. In this case, a mantle He component would be expected to be more pronounced in the vicinity of younger as opposed to older volcanics. An examination of Figures 4 and 5, however, reveals that although the values obtained in the vicinity of the Quaternary Kula volcanics are among the highest reported for western Anatolia, high R/R_A ratios are not consistently associated with young volcanics. For instance, R/R_A ratios as high as 1.68 (20% mantle He) are recorded in the Simav geothermal field (Fig. 4), which is spatially associated with the old calc-alkaline volcanics. This observation, together with the fact that the occurrence of high ^3He in the eastern segment of Büyük Menderes graben is accompanied by frequent and recent seismic activity (particularly in the Denizli area, with $M_S = 4-5$), favors the former possibility, which is further supported by the high enthalpy in this region, implying a currently active or recently dormant magmatic system.

On the other hand, the significance of the observation of relatively low ^3He accompanied by high enthalpy in the western segment of the Büyük Menderes graben remains to be explained. Given that the helium isotope data come from point

Figure 4. Distribution of ^3He in western Anatolia. The numbers before the parentheses are the air-corrected R/R_A ratios, where $R = ^3\text{He}/^4\text{He}$ in the sample and $R_A = ^3\text{He}/^4\text{He}$ in the atmosphere. The numbers in parentheses represent the geothermal fields: 1a—Bozköy-Germencik; 1b—Ömerbeyli-Germencik; 1c—Çamur-Germencik; 4—Tekkehamam; 6—Çubukdağ-Tekkeköy; 7—Pamukkale; 15—Dikili; 16a—Bergama; 16b to 16g—Paşalıda, Geyikli, Kaynarca, Nebiler, Mentese, and Bademli; 18—Salihli; 19a—İhıcalar-Simav; 19b—Eynal-Simav; 21—Emet; 27—Sandıklı; 32—Edremit-Güre; 35—Turgutlu-Urganlı; 36a—Kula-madensu; 36b—Kula-Emir; 37—Banaz-Uak; 38—Şöke-Davutlar; 39—Yatağan-Bozhöyük. The R/R_A values are from Güleç et al. (2002) and references therein.

samples representative of tens of kilometers, this may be an artifact of sampling. Another possible explanation may be loss of the mantle He signal by crustal production of ^4He , which may be linked with the local geology and/or the thickness of graben-filling sediments. This suggestion needs to be supported by further studies, however.

A final presentation of the distribution of heat and helium anomalies in western Anatolia is given in Figure 6 in the form of thematic maps based on the enthalpy values and the relative mantle He percentages. Note that the eastern segment of the Büyük Menderes graben has striking anomalies in both ^3He and heat. This area clearly represents a target locality for further studies from various disciplines concerned with active tectonics.

Implications for Active Extension and Melting

From the previous discussion, it appears that mantle He is widely distributed in western Anatolia in relation to regions of current extension and associated magmatism. Although the overall extension factor (β) in western Anatolia is not likely to exceed 1.5, as determined from the tectonic analyses of data in tilted faulted blocks and the modeling of gravity values (Angelier et al., 1981; McKenzie and Yılmaz, 1991; Patton, 1992), the rather large range observed in the relative percentage of the mantle He component throughout the region may have links with the (differential) local extension rates and the volume of associated melts in the respective areas. Given the occurrence of the highest heat and the highest mantle He anomalies along the eastern segment of the Büyük Menderes graben, and relatively lower anomalies in the Alaşehir graben (Kula area; Fig. 6), this argument appears to be supported by the slip rates estimated on the basis of GPS data by Nyst and Thatcher (2004) as 19–23 mm/yr and 10 mm/yr for the fault segments along the respective grabens.

From the general consideration of crustal extension and thinning and their relationship to melting (McKenzie, 1984; McKenzie and Bickle, 1988), however, it appears that the extension factor reported for western Anatolia is not likely to produce substantial amounts of melt (McKenzie and Yılmaz, 1991). In fact, the thickness of lava flows exposed in the Kula area, measured as 10 m by Richardson-Bunbury (1996), is in agreement with a β of ~ 1.3 . Given age constraints that the Kula volcanics were generated within the last 2 Ma, this thickness implies the generation of melt ~ 5 m thick per m.y.

Taking the Kula area as a reference, an estimate of the amount of melt necessary to produce the observed R/R_A values in the eastern segment of the Büyük Menderes graben is made here using the relationship between He flux and melting that follows.

$$(^3\text{He}/^4\text{He})_{\text{total}} = (^3\text{He}/^4\text{He})_{\text{mantle}} F_{\text{mantle}} + (^3\text{He}/^4\text{He})_{\text{crust}} F_{\text{rad.}}$$

where

$(^3\text{He}/^4\text{He})$ = the max. ratio in the area concerned
(3.92×10^{-6} for Kula and 5.05×10^{-6} for Büyük Menderes graben),

$(^3\text{He}/^4\text{He})_{\text{mantle}} = 10^{-5}$ (typical of MORB),

$(^3\text{He}/^4\text{He})_{\text{rad.}} = 1.5 \times 10^{-8}$ (radiogenic He production ratio in normal crust and mantle lithologies [Andrews, 1985]),

F_{total} = total He flux = $F_{\text{mantle}} + F_{\text{rad.}}$,

F_{mantle} = mantle He flux in the concerned area, and
 $F_{\text{rad.}}$ = radiogenic He flux = 2.8×10^{10} atoms $\text{m}^{-2} \text{s}^{-1}$
(based on the assumption that average crust contains 6 ppm U over the upper 8 km;

Th/U = 3.8 [O'Nions and Oxburgh, 1983]).

Inserting these values into the previous equation yields 1.79×10^{10} atoms $\text{m}^{-2} \text{s}^{-1}$ and 2.85×10^{10} atoms $\text{m}^{-2} \text{s}^{-1}$ for the mantle He fluxes in Kula and the Büyük Menderes graben, respectively.

Because the mantle He flux in Kula is essentially produced by the generation of 5 m-thick melt per m.y. over an area of ~ 300 km^2 , simple mathematics suggest that the melt thickness required to satisfy the He flux in the Büyük Menderes graben is not likely to have exceeded 8 m/m.y. over the same area. In turn, this suggests that differences in the rates of extension are not significant.

CONCLUSIONS

We emphasize the following points:

1. Western Anatolia has a high geothermal potential, with several moderate- to high-enthalpy fields located along the major grabens and their boundary faults.
2. The He isotope composition of geothermal fluids reveals mixing between mantle and crustal He components, the former ranging up to 45% of the total helium in any single sample.
3. High heat values tend to be associated with high mantle He contributions, with the highest values for both recorded along the eastern segment of the Büyük Menderes graben.
4. Except along the Büyük Menderes graben, where there is no surface volcanism, high-enthalpy fields are spatially associated with the young alkaline volcanics.
5. The distribution of mantle He does not display a simple relationship to the spatial and/or temporal distribution of the volcanics. Although the $^3\text{He}/^4\text{He}$ value in the vicinity of the Quaternary Kula volcanics is among the highest reported for western Anatolia, high $^3\text{He}/^4\text{He}$ values are not consistently associated with young volcanics. Along the eastern segment of the Büyük Menderes graben, where the highest

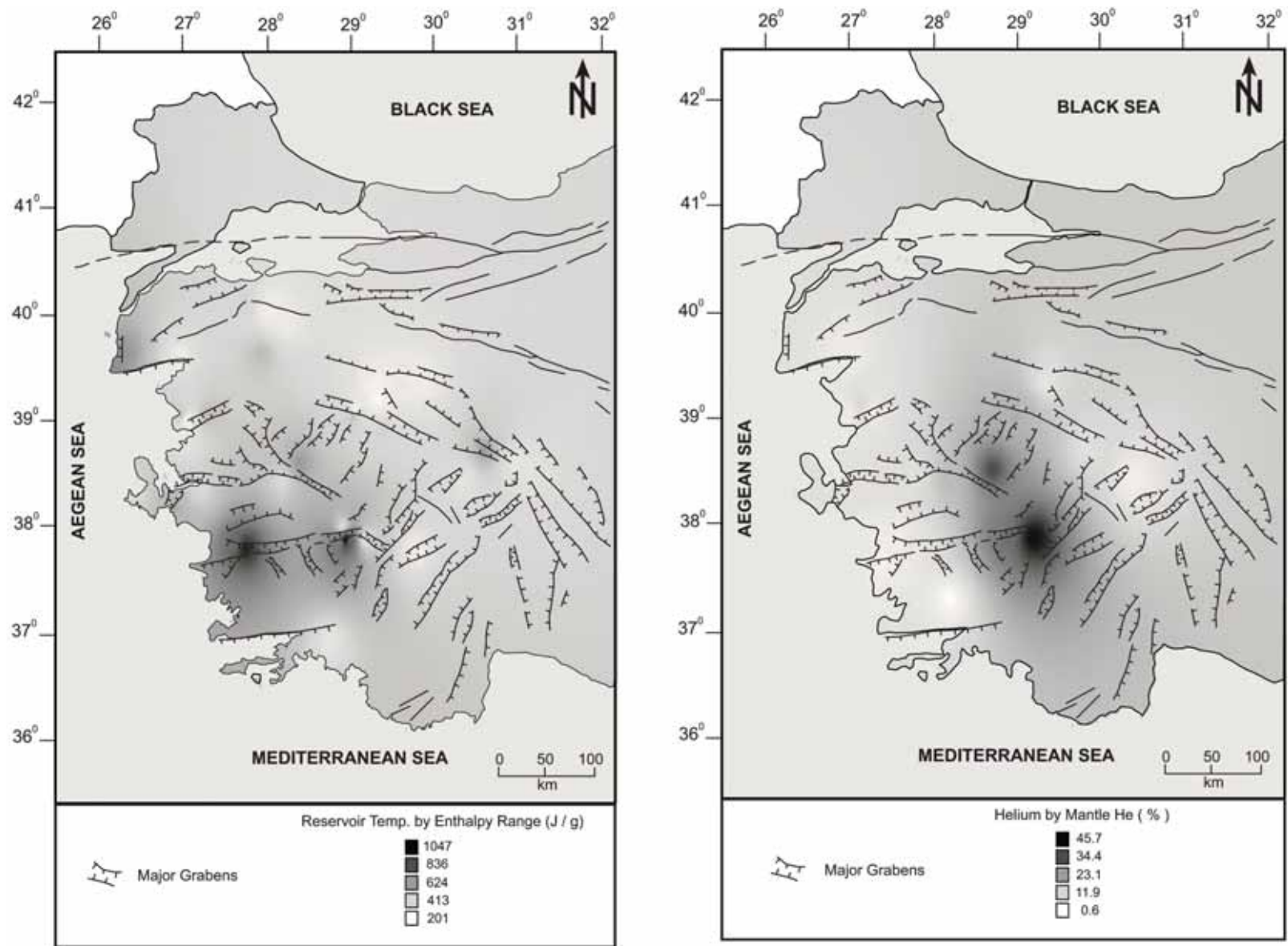


Figure 6. Thematic maps showing the heat and the mantle helium anomalies in western Anatolia in relation to the distribution of major grabens and the Neogene–Quaternary volcanics.

- $^3\text{He}/^4\text{He}$ is recorded, there is no evidence of surface volcanism except at the southeastern end (Denizli volcanics).
- The previously stated features collectively suggest that the transfer of both heat and helium occurs via mantle melting accompanying the current extension in western Anatolia: either the melts are transported to the surface forming the volcanics or they are emplaced at crustal levels with no surface (volcanic) equivalents.
 - The large range of He isotope compositions (0.58% to 45% mantle He component) observed in the region can be linked with the differential (local) extension rates and the associated melt generation.
 - Based on the previously reported thickness of lava flows in Kula, which suggests a 5 m-thick melt generation per m.y. over an area of $\sim 300 \text{ km}^2$, the estimated melt thickness required to satisfy the mantle He flux in the eastern segment of the Büyük Menderes graben is not likely to exceed 8 m/m.y. over the same area. This indicates that the differences in the rates of extension are not significant; they are in the range of the overall extension factor ($\beta = 1.2\text{--}1.3$) reported for western Anatolia.
 - Validation of the aforementioned statements requires He isotope data from a greater part of the region

ACKNOWLEDGMENTS

NG expresses her gratitude to R.K. O’Nions, who gave her the inspiration for this article long ago when she was his student. The support of TÜBİTAK (YDABAG-100Y097) and NSF (EAR-0229508) is gratefully acknowledged in initiating our continuing studies on helium in Turkey. Special thanks go to Nesrin Tüfekçi for the time and effort she dedicated to the preparation of the figures in this article. Reviews by A.I. Okay and T. Taymaz proved very helpful.

REFERENCES CITED

- Aldanmaz, E., 2002, Mantle source characteristics of alkali basalts and basanites in an extensional intracontinental plate setting, western Anatolia, Turkey: Implications for multi-stage melting: *International Geology Review*, v. 44, p. 440–457.
- Aldanmaz, E., Pearce, J.A., Thirlwall, M.F., and Mitchell, J.G., 2000, Petrogenetic evolution of late Cenozoic volcanism in western Anatolia, Turkey: *Journal of Volcanology and Geothermal Research*, v. 102, p. 67–95, doi: 10.1016/S0377-0273(00)00182-7.
- Alici, P., Temel, A., and Gourgaud, A., 2002, Pb-Nd-Sr isotope and trace element geochemistry of Quaternary extension-related alkaline volcanism: A case study of Kula region (western Anatolia, Turkey): *Journal of Volcanology and Geothermal Research*, v. 115, p. 487–510, doi: 10.1016/S0377-0273(01)00328-6.
- Andrews, J.N., 1985, The isotopic composition of radiogenic He and its use to study groundwater movement in confined aquifer: *Chemical Geology*, v. 49, p. 339–351, doi: 10.1016/0009-2541(85)90166-4.
- Angelier, J., Dumont, J.F., Karamandereci, H., Poisson, A., Şimşek, Ş., and Uysal, S., 1981, Analyses of fault mechanisms and expansion of south-western Anatolia since the Late Miocene: *Tectonophysics*, v. 75, p. T1–T9, doi: 10.1016/0040-1951(81)90271-7.
- Ballentine, C.J., O’Nions, R.K., Oxburgh, E.R., Horvath, F., and Deak, J., 1991, Rare gas constraints on hydrocarbon accumulation, crustal degassing and groundwater flow in the Pannonian Basin: *Earth and Planetary Science Letters*, v. 105, p. 229–246, doi: 10.1016/0012-821X(91)90133-3.
- Borsi, S., Ferrara, G., Innocenti, F., and Mazzuoli, R., 1972, Geochronology and petrology of recent volcanism in the Eastern Aegean Sea (West Anatolia and Lesbos Island): *Bulletin of Volcanology*, v. 36, p. 473–496.
- Bozkurt, E., 2000, Timing of extension on the Büyük Menderes graben, western Turkey, and its tectonic implications, *in* Bozkurt, E., et al., eds., *Tectonics and magmatism in Turkey and the surrounding area: Geological Society of London Special Publication 173*, p. 385–403.
- Bozkurt, E., 2001, Neotectonics of Turkey: A synthesis: *Geodinamica Acta*, v. 14, p. 3–30, doi: 10.1016/S0985-3111(01)01066-X.
- Bozkurt, E., 2003, Origin of NE trending basins in western Turkey: *Geodinamica Acta*, v. 16, p. 61–81, doi: 10.1016/S0985-3111(03)00002-0.
- Bozkurt, E., and Sözeri, H., 2004, Tectonic evolution of the Gediz Graben: Field evidence for an episodic, two-stage extension in western Turkey: *Geological Magazine*, v. 141, p. 63–79, doi: 10.1017/S0016756803008379.
- Dewey, J.F., and Şengör, A.M.C., 1979, Aegean and surrounding regions: Complex multiplate and continuum tectonics in a convergent zone: *Geological Society of America Bulletin*, v. 90, p. 84–92.
- Dogliani, C., Agostini, S., Crespi, M., Innocenti, F., Manetti, P., Riguzzi, F., and Savaşçın, Y., 2002, On the extension in western Anatolia and the Aegean sea: *Journal of the Virtual Explorer*, v. 7, p. 117–131.
- Ercan, T., 1981, Batı Anadolu Tersiyer volkanitleri ve Bodrum yarımadasındaki volkanizmanın durumu: *Istanbul Yerbilimleri Dergisi*, v. 2, no. 3–4, p. 263–281.
- Ercan, T., Satır, M., Kreuzer, H., Türkecan, A., and Günay, E., Çevikbaş, A., Ateş, M., and Can, B., 1985, Batı Anadolu Senozoyik volkanitlerine ait yeni kimyasal, izotopik ve radyometrik verilerin yorumu: *Türkiye Jeoloji Kurumu Bülteni*, v. 28, p. 121–136.
- Ercan, T., Matsuda, J.I., Nagao, K., and Kita, I., 1995, Noble gas isotopic compositions in gas and water samples from Anatolia, *in* Erlar, A., et al., eds., *Proceedings, International Symposium on the Geology of the Black Sea Region, Ankara, Turkey*, p. 197–206.
- Ercan, T., Satır, M., Sevin, D., and Türkecan, A., 1996, Batı Anadolu’daki Tersiyer ve Kuvaterner yaşlı volkanik kayalarda yeni yapılan radyometrik yaş ölçümlerinin yorumu: *Maden Tetkik ve Arama Dergisi*, v. 119, p. 103–112.
- Erickson, A.J., Simmons, G., and Ryan, W.B.F., 1976, Review of heatflow data from the Mediterranean and Aegean Seas, *in* Biju-Duval, B., and Montadert, L., eds., *Proceedings, International Symposium on the Structural History of the Mediterranean Basins, Yugoslavia*, p. 263–280.
- Farley, K.A., and Neroda, E., 1998, Noble gases in the Earth’s mantle: *Annual Review of Earth and Planetary Sciences*, v. 26, p. 189–218, doi: 10.1146/annurev.earth.26.1.189.
- Francalanci, L., Innocenti, F., Manetti, P., and Savaşçın, M.Y., 2000, Neogene alkaline volcanism of the Afyon-Isparta area, Turkey: Petrogenesis and geodynamic implications: *Mineralogy and Petrology*, v. 70, p. 285–312, doi: 10.1007/s007100070007.
- Fytikas, M., Innocenti, F., Manetti, P., Mazzuoli, R., Peccerillo, A., and Villari, L., 1984, Tertiary to Quaternary evolution of volcanism in the Aegean region, *in* Dixon, J.E., and Robertson, A.H.F., eds., *The geological evolution of the Eastern Mediterranean: Geological Society of London Publication 17*, p. 687–699.
- Göktürkler, G., Şalk, M., and Sarı, C., 2003, Numerical modeling of the conductive heat transfer in western Anatolia: *Journal of the Balkan Geophysical Society*, v. 6, p. 1–15.
- Güleç, N., 1988, He-3 distribution in western Turkey: *Maden Tetkik ve Arama Dergisi*, v. 108, p. 35–42.
- Güleç, N., 1991, Crust-mantle interaction in western Turkey: Implications from Sr and Nd isotope geochemistry of Tertiary and Quaternary volcanics: *Geological Magazine*, v. 125, p. 417–435.
- Güleç, N., Hilton, D.R., and Mutlu, H., 2002, Helium and heat distribution in Turkey: Relations to tectonic provinces, volcanism and recent seismic ac-

- tivities: *Chemical Geology*, v. 187, p. 129–142, doi: 10.1016/S0009-2541(02)00015-3.
- Gülen, L., 1990, Isotopic characterization of Aegean magmatism and geodynamic evolution of the Aegean subduction: Proceedings, International Earth Sciences Congress on Aegean Regions (IESCA 1990), v. 2, p. 143–166.
- Henley, R.W., Truesdell, A.H., Barton, J.R., and Whitney, J.A., 1984, Fluid-mineral equilibria in hydrothermal systems: *Reviews in Economic Geology*, v. 1, p. 245–252.
- Hooker, P.J., Bertrami, R., Lombardi, S., O’Nions, R.K., and Oxburgh, E.R., 1985, Helium-3 anomalies and crust-mantle interaction in Italy: *Geochimica et Cosmochimica Acta*, v. 49, p. 2505–2513, doi: 10.1016/0016-7037(85)90118-8.
- İlkışık, O.M., 1995, Regional heat flow in western Anatolia using silica temperature estimates from thermal springs: *Tectonophysics*, v. 244, p. 175–184, doi: 10.1016/0040-1951(94)00226-Y.
- Innocenti, F., Manetti, P., Mazzuoli, R., Pasquare, G., and Villari, L., 1982, Regional distribution and character of active andesite volcanism: Anatolia and northwestern Iran, in Thorpe, R.S., ed., *Orogenic andesites and related rocks*: New York, J. Wiley and Sons, p. 327–349.
- Jackson, J.A., and McKenzie, D.P., 1988, The relationship between plate motions and seismic moment tensors and rates of active deformation in the Mediterranean and Middle East: *Geophysical Journal*, v. 93, p. 45–73.
- Jongsma, D., 1974, Heat flow in the Aegean Sea: *Geophysical Journal of the Royal Astronomical Society*, v. 37, p. 337–346.
- Kamensky, I.L., Tolstikhin, I.N., and Vetrin, V.R., 1990, Juvenile helium in ancient rocks, I: ^3He excess in amphiboles from 2.8 Ga charnokite series: Crust-mantle fluid in intracrustal magmatic processes: *Geochimica et Cosmochimica Acta*, v. 54, p. 3115–3122, doi: 10.1016/0016-7037(90)90127-7.
- Koçak, A., 1990, An approach to occurrence of the geothermal systems in western Anatolia, in Savşaçın, M.Y., and Eronat, A.H., eds., *Proceedings, International Earth Science Congress on Aegean Regions*: IESCA Publication 2, p. 148–159.
- Koçyiğit, A., Yusufoglu, H., and Bozkurt, E., 1999, Evidence from the Gediz Graben for episodic two-stage extension in western Turkey: *Journal of the Geological Society of London*, v. 156, p. 605–616.
- Lefevre, C., Bellon, H., and Poisson, A., 1983, Présence de leucitites dans le volcanisme Pliocène de la région d’Isparta (Taurides Occidentales, Turquie): *CR Acad Sci Paris*, v. 297, p. 367–372.
- Le Pichon, X., and Angelier, J., 1979, The Aegean arc and trench system: A key to the neotectonic evolution of the Eastern Mediterranean area: *Tectonophysics*, v. 60, p. 1–42, doi: 10.1016/0040-1951(79)90131-8.
- Makris, J., and Stobbe, C., 1984, Physical properties and state of the crust and upper mantle of the eastern Mediterranean area: *Tectonophysics*, v. 60, p. 1–42.
- Martel, D.J., Deak, J., Dövényi, P., Horvath, F., O’Nions, R.K., Oxburgh, E.R., Stegena, L., and Stute, M., 1989, Leakage of helium from the Pannonian basin: *Nature*, v. 342, no. 6252, p. 908–912.
- McClusky, S., Balassanian, S., Barka, A., Demir, C., Ergintav, S., Georgiev, I., Gurkan, O., Hamburger, M., Hurst, K., Kahle, H., Kastens, K., Kekelidze, G., King, R., Kotzev, V., Lenk, O., Mahmoud, S., Mishin, A., Nadariya, M., Ouzounis, A., Paradissis, D., Peter, Y., Prilepin, M., Reilinger, R., Sanli, I., Seeger, H., Tealeb, A., Toksöz, M.N., and Vies, G., 2000, Global Positioning System constraints on plate kinematics and dynamics in the eastern Mediterranean and Caucasus: *Journal of Geophysical Research*, v. 105, no. B3, p. 5695–5719, doi: 10.1029/1999JB900351.
- McClusky, S., Reilinger, R., Mahmoud, S., Ben Sari, D., and Tealeb, A., 2003, GPS constraints on Africa (Nubia) and Arabia plate motions: *Geophysical Journal International*, v. 155, p. 126–138, doi: 10.1046/j.1365-246X.2003.02023.x.
- McKenzie, D.P., 1972, Active tectonics of the Mediterranean region: *Geophysical Journal of the Royal Astronomical Society*, v. 30, p. 109–185.
- McKenzie, D.P., 1978, Active tectonics of the Alpine-Himalayan belt: The Aegean and surrounding regions: *Geophysical Journal of the Royal Astronomical Society*, v. 55, p. 217–254.
- McKenzie, D., 1984, The generation and compaction of partially molten rock: *Journal of Petrology*, v. 25, p. 713–765.
- McKenzie, D., and Bickle, M.J., 1988, The volume and composition of melt generated by extension of the lithosphere: *Journal of Petrology*, v. 29, p. 625–679.
- McKenzie, D., and Yılmaz, Y., 1991, Deformation and volcanism in western Turkey and the Aegean: *Bulletin of the Technical University of Istanbul*, v. 44, p. 345–373.
- Mertoğlu, O., 2005, Geothermal applications in Turkey: Proceedings CD of the World Geothermal Congress 2005 (WGC 2005), 24–29 April 2005, Antalya, Turkey, paper no. 0014.
- Montigny, R., and Robert, U., 1991, $^{39}\text{Ar}/^{40}\text{Ar}$ dating on igneous rocks from the Bodrum volcanic complex (SW Turkey): *EUG IV Strasburg, Terra Abstracts*, v. 3, p. 500.
- Morrison, P., and Pine, J., 1955, Radiogenic origin of the helium isotopes in rocks: *Annals of the New York Academy of Sciences*, v. 62, p. 69–92.
- Mutlu, H., and Güleç, N., 1998, Hydrogeochemical outline of thermal waters and geothermometry applications in Anatolia (Turkey): *Journal of Volcanology and Geothermal Research*, v. 85, p. 495–515, doi: 10.1016/S0377-0273(98)00068-7.
- Nyst, M., and Thatcher, W., 2004, New constraints on the active tectonic deformation of the Aegean: *Journal of Geophysical Research*, v. 109, p. B11406, doi: 10.1029/2003JB002830.
- Okay, A.I., and Satır, M., 2000, Coeval plutonism and metamorphism in a latest Oligocene metamorphic core complex in northwest Turkey: *Geological Magazine*, v. 137, p. 495–516, doi: 10.1017/S0016756800004532.
- O’Nions, R.K., and Oxburgh, E.R., 1983, Heat and helium in the Earth: *Nature*, v. 306, p. 429–431, doi: 10.1038/306429a0.
- O’Nions, R.K., and Oxburgh, E.R., 1988, Helium, volatile fluxes and the development of continental crust: *Earth and Planetary Science Letters*, v. 90, p. 331–347, doi: 10.1016/0012-821X(88)90134-3.
- Oxburgh, E.R., and O’Nions, R.K., 1987, Helium loss, tectonics, and the terrestrial heat budget: *Science*, v. 237, p. 1583–1588.
- Papadimitriou, E.E., and Sykes, L.R., 2001, Evolution of the stress field in the northern Aegean Sea (Greece): *Geophysical Journal International*, v. 146, p. 747–759, doi: 10.1046/j.0956-540x.2001.01486.x.
- Patton, S., 1992, The relationship between extension and volcanism in western Turkey, the Aegean sea and central Greece [Ph.D. thesis]: University of Cambridge, 300 p.
- Pe-Piper, G., and Piper, D.J.W., 1989, Spatial and temporal variation in Late Cenozoic back-arc volcanic rocks, Aegean Sea region: *Tectonophysics*, v. 169, p. 113–134, doi: 10.1016/0040-1951(89)90186-8.
- Pfister, M., Balderer, W., Greber, E., Kahle, H.G., Mayer-Rosa, D., Mueller, S., Rybach, L., Schindler, C., Sellami, S., and Straub, C., 1997, Synthesis of the Marmara poly-project, in Schindler, C., and Pfister, M., eds., *Active tectonics of northwestern Anatolia: The Marmara poly-project*: Zurich, Vdf Hochschulverlag AG an der ETH, p. 539–565.
- Polyak, B.G., and Tolstikhin, I.N., 1985, Isotopic composition of the Earth’s helium and the problem of the motive forces of tectogenesis: *Chemical Geology*, v. 52, p. 9–33.
- Porcelli, D.R., O’Nions, R.K., and O’Reilly, S.Y., 1986, Helium and strontium isotopes in ultramafic xenoliths: *Chemical Geology*, v. 54, p. 237–249, doi: 10.1016/0009-2541(86)90139-7.
- Porcelli, D.R., O’Nions, R.K., Galer, S.J.G., Cohen, A.S., and Matthey, D.P., 1992, Isotopic relationships of volatile and lithophile trace elements in continental ultramafic xenoliths: *Contributions to Mineralogy and Petrology*, v. 110, p. 528–538, doi: 10.1007/BF00344086.
- Richardson-Bunbury, J.M., 1996, The Kula volcanic field, western Turkey: The development of a Holocene alkali basalt province and the adjacent normal-faulting graben: *Geological Magazine*, v. 133, p. 275–283.
- Robert, U., and Cantagrel, J.M., 1977, Le volcanisme basaltique dans le Sud-Est de la Mer Egée: Données géochronologiques et relation avec la tec-

- tonique, *in* Proceedings, VI. Colloquium on the Geology of the Aegean Region, Athens, v. III, p. 961–967.
- Robert, U., Foden, J., and Varne, R., 1992, The Dodecanese province, SE Aegean: A model for tectonic control on potassic magmatism: *Lithos*, v. 28, p. 241–260, doi: 10.1016/0024-4937(92)90009-N.
- Saunders, P., Priestley, K., and Taymaz, T., 1998, Variations in crustal structure beneath western Turkey: *Geophysical Journal International*, v. 134, p. 373–389, doi: 10.1046/j.1365-246x.1998.00571.x.
- Savaşçın, Y., and Güleç, N., 1990, Relationship between magmatic and tectonic activities in western Turkey: Geological and geochemical features with examples from the coastal section, *in* Proceedings, International Earth Sciences Congress on Aegean Regions (IESCA 1990), v. 2, p. 300–313.
- Şengör, A.M.C., 1987, Cross-faults and differential stretching of hanging walls in regions of low-angle normal faulting: Examples from western Turkey, *in* Coward, M.P., et al., eds., *Continental extensional tectonics*: Geological Society of London Special Publication 28, p. 575–589.
- Şengör, A.M.C., Görür, N., and Şaroğlu, F., 1985, Strike-slip faulting and related basin formation in zones of tectonic escape: Turkey as a case study: *Society of Economic Paleontologists and Mineralogists Special Publication* 37, p. 227–264.
- Seyitoğlu, G., and Scott, B.C., 1992, Late Cenozoic volcanic evolution of the northeastern Aegean region: *Journal of Volcanology and Geothermal Research*, v. 54, p. 157–176, doi: 10.1016/0377-0273(92)90121-S.
- Seyitoğlu, G., and Scott, B.C., 1996, The age of the Alaşehir graben (west Turkey) and its tectonic implications: *Geological Journal*, v. 31, p. 1–11, doi: 10.1002/(SICI)1099-1034(199603)31:1<1::AID-GJ688>3.0.CO;2-S.
- Seyitoğlu, G., Scott, B.C., and Rundle, C.C., 1992, Timing of Cenozoic extensional tectonics in west Turkey: *Journal of the Geological Society of London*, v. 149, p. 533–538.
- Seyitoğlu, G., Anderson, D., Nowell, G., and Scott, B., 1997, The evolution from Miocene to Quaternary sodic magmatism in western Turkey: Implications for enrichment process in the lithospheric mantle: *Journal of Volcanology and Geothermal Research*, v. 76, p. 127–147, doi: 10.1016/S0377-0273(96)00069-8.
- Stone, J.O.H.S., 1986, Helium isotopic tracing of fluids in the lithosphere [Ph.D. thesis]: University of Cambridge.
- Taymaz, T., 1996, S-P wave traveltimes residuals from earthquakes and lateral inhomogeneity in the upper mantle beneath the Aegean and the Hellenic Trench near Crete: *Geophysical Journal International*, v. 127, p. 545–558.
- Taymaz, T., Jackson, J., and McKenzie, D., 1990, Earthquake mechanisms in the Hellenic Trench near Crete: *Geophysical Journal International*, v. 102, p. 695–731.
- Taymaz, T., Jackson, J., and McKenzie, D., 1991, Active tectonics of the north and central Aegean Sea: *Geophysical Journal International*, v. 106, p. 433–490.
- Tezcan, A.K., 1979, Geothermal studies, their present status and contribution to heat flow contouring in Turkey, *in* Cermak, V., and Rybach, L., eds., *Terrrestrial heat flow in Europe*: Berlin, Springer, p. 283–292.
- Tolstikhin, I.N., Dokuchaeva, V.S., Kamensky, I.L., and Amelin, Y.U.V., 1992, Juvenile helium in ancient rocks, II: U-He, K-Ar, Sm-Nd, and Rb-Sr systematics in the Monche Pluton: $^3\text{He}/^4\text{He}$ ratios frozen in uranium-free ultramafic rocks: *Geochimica et Cosmochimica Acta*, v. 56, p. 987–999, doi: 10.1016/0016-7037(92)90042-H.
- Tsokas, G.N., and Hansen, R.O., 1997, Study of the crustal thickness and the subducting lithosphere in Greece from gravity data: *Journal of Geophysical Research*, v. 102, no. B9, p. 20,585–20,597, doi: 10.1029/97JB00730.
- Ulusoy, I., Çubukçu, E., Aydar, E., Labazuy, P., Gourgaud, A., and Vincent, P.M., 2004, Volcanic and deformation history of the Bodrum resurgent caldera system (southwestern Turkey): *Journal of Volcanology and Geothermal Research*, v. 136, p. 71–96, doi: 10.1016/j.jvolgeores.2004.03.016.
- Westaway, R., 1994a, Evidence for dynamic coupling of surface processes with isostatic compensation in the lower crust during active extension of western Turkey: *Journal of Geophysical Research*, v. 99, p. 20,203–20,223, doi: 10.1029/94JB01054.
- Westaway, R., 1994b, Present-day kinematics of the Middle East and the eastern Mediterranean: *Journal of Geophysical Research*, v. 99, p. 12,071–12,090, doi: 10.1029/94JB00335.
- Yılmaz, Y., 1990, Comparison of the young volcanic associations of the west and the east Anatolia under the compressional regime: A review: *Journal of Volcanology and Geothermal Research*, v. 44, p. 69–87, doi: 10.1016/0377-0273(90)90012-5.
- Yılmaz, Y., Genç, S.C., Karacık, Z., and Altunkaynak, Ş., 2001, Two contrasting magmatic associations of NW Anatolia and their tectonic significance: *Journal of Geodynamics*, v. 31, p. 243–271, doi: 10.1016/S0264-3707(01)00002-3.

MANUSCRIPT ACCEPTED BY THE SOCIETY 30 DECEMBER 2005

Geological Society of America Special Papers

Helium and heat distribution in western Anatolia, Turkey: Relationship to active extension and volcanism

Nilgün Güleç and David R. Hilton

Geological Society of America Special Papers 2006;409; 305-319
doi:10.1130/2006.2409(16)

E-mail alerting services click www.gsapubs.org/cgi/alerts to receive free e-mail alerts when new articles cite this article

Subscribe click www.gsapubs.org/subscriptions to subscribe to Geological Society of America Special Papers

Permission request click www.geosociety.org/pubs/copyrt.htm#gsa to contact GSA.

Copyright not claimed on content prepared wholly by U.S. government employees within scope of their employment. Individual scientists are hereby granted permission, without fees or further requests to GSA, to use a single figure, a single table, and/or a brief paragraph of text in subsequent works and to make unlimited copies of items in GSA's journals for noncommercial use in classrooms to further education and science. This file may not be posted to any Web site, but authors may post the abstracts only of their articles on their own or their organization's Web site providing the posting includes a reference to the article's full citation. GSA provides this and other forums for the presentation of diverse opinions and positions by scientists worldwide, regardless of their race, citizenship, gender, religion, or political viewpoint. Opinions presented in this publication do not reflect official positions of the Society.

Notes