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Gas Geochemistry of Turkish Geothermal Fluids: He- and C-Isotope and Relative Abundance Studies

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ABSTRACT

We examine the He-isotope record of geothermal fluids from various neotectonic provinces of Turkey along with the results of a recent study concerned with the combined He-CO_2 characteristics of volatiles in the western Anatolian region. The distribution of mantle-He in Turkey has close connections with the distribution of heat and the age of tectono-magmatic activity. The mantle-He contribution is high (>50 % of total composition) in regions of historically-active volcanoes (eastern and central Anatolia) and most recent seismic activity (western central segment of the North Anatolian Fault Zone) where low-to moderate-enthalpy geothermal fields are located. In the high-enthalpy fields of western Anatolia, mantle-He contribution is relatively less. The negative correlation between ^3He and heat distribution in Turkey suggests different mechanisms for the transfer of heat and helium in different provinces. While recent and extensive volcanism in central and eastern Anatolia is consistent with the release of both helium and heat from cooling magmatic systems, the low ^3He/enthalpy ratio (1.7 x 10^6 atoms ^3He/J) in western Anatolia appears to result from lithospheric stretching which provides a regional and significant source of heat but comparatively low helium additions from localised magmatic activity. The western Anatolian fluids are characterized by $^3He/^4He$ ratios ranging from 0.27 to 1.67 R_A, $\delta^{13}C$ (CO_2) values between –8.04 and +0.35‰, and the $CO_2/^3He$ ratios varying from 1.6 x 10^9 to 2.3 x 10^{14}. Evaluation of He-C abundances indicates that degassing and calcite precipitation have significantly fractionated the elemental ratio ($CO_2/^3He$) in geothermal waters, while gas phase samples better represent the source characteristics of volatiles. Mixing between mantle and various crustal sources appears to be the main control on the observed He-C systematics, and crustal inputs dominate the CO_2 inventory. As to the He-inventory, the mantle-derived component is found to vary up to 21 % of the total He content and is probably transferred to the crust by fluids degassed from deep mantle melts generated in association with adiabatic melting accompanying current extension in the region.

1. INTRODUCTION

Volatile species have been widely used as geochemical tracers to study the interactions between terrestrial reservoirs and the physicochemical processes occurring in deep hydrothermal systems. Of these volatiles, CO_2 and He have wide isotopic and relative abundance contrast between potential volatile provenance and, hence, are particularly useful in identifying the source regions of gases. Being potential sources, the crust has $^3He/^4He$ ratio of 0.05 Ra (Ra: $^3He/^4He$ ratio of atmosphere= 1.39 x 10^{-6}), $CO_2/^3He$ ratio of 10^{12} and variable (both positive and negative) $\delta^{13}C$ values (Andrews, 1985; Sano and Marty, 1995). On the other hand, mantle has $^3He/^4He$ ratio of 8 Ra, $CO_2/^3He$ ratio about 10^9, and $\delta^{13}C$ value around -6.5 (Farley and Neroda, 1998; Sano and Marty, 1995).

The present contribution focuses on the helium isotope composition of the Turkish geothermal fluids in a geodynamic context, with further elaboration on the combined He-CO_2 characteristics of western Anatolian fluids. The objectives are to determine the distribution of mantle-He and heat in Turkey in relation to differing tectonic provinces, timing and distribution of volcanism, and the recent seismic activities, along with the effects of possible physicochemical processes in deep hydrothermal systems.

2. TURKEY: TECTONIC FRAMEWORK, VOLCANISM AND GEOTHERMAL ACTIVITY

Turkey comprises an integral segment of the Alpine-Mediterranean orogenic belt. The recent tectonic activity in Turkey has been governed by the convergence between the Arabian and the Eurasian plates, and is taken up by four major structures: Bitlis Suture Zone (BSZ), North Anatolian Fault Zone (NAFZ), East Anatolian Fault Zone (EAFZ), and Western Anatolian Graben System (WAGS) (Figure 1). Bounded by these structures, four main neotectonic provinces are recognized in Turkey (Şengör et al., 1985): (1) the East Anatolian contractional province, (2) the West Anatolian extensional province, (3) the Central Anatolian province where the compression in the east is transferred to extension in the west, and (4) the North Turkish province with strike-slip tectonics. Active tectonism in Turkey results in strong and frequent seismic activity, the most recent activities, with magnitude above 5, including the Izmit (with epicenters at Gölcük and Arifiye), Düzce and Orta earthquakes along the NAFZ (Figure 1).

Neogene-Quaternary volcanism in Turkey (Figure 1) is closely associated with neotectonic evolution. Quaternary volcanism is confined to the Kula area in western Anatolia, whereas the recent volcanoes are more abundant in central and especially in eastern Anatolia where the latest eruptions took place at Nemrut volcanoe in about 14 hundred A.D. (Tchalenko, 1977).

The unique tectonic setting of Turkey in the Alpine-Mediterranean orogenic belt is marked by the presence of numerous hot springs which are manifested along the major structural zones, graben systems and Neogene - Quaternary volcanic regions. The results of our previous studies (Mutlu and Güleç, 1988) on thermal waters from various neotectonic provinces of Turkey revealed that most of the waters in these regions are of the Na-Ca-HCO_3 type, whereas coastal sites in western Anatolia and some inland areas of central Anatolia are characterized by Na-Cl waters. While this reflects sea water intrusion into the aquifers in western Anatolia, involvement of connate fossil waters in deep circulation is probably implied for central Anatolia. Again within the framework of this study (Mutlu and Güleç, 1998), chemical geothermometry applications yielded reservoir temperature estimates around 251 ºC for western Anatolia, 136 ºC for eastern Anatolia, 125 ºC for central Anatolia and 110 ºC for northern Anatolia. In this respect, the western Anatolian region, with a reservoir temperature of 251°C, has the highest geothermal potential in Turkey.

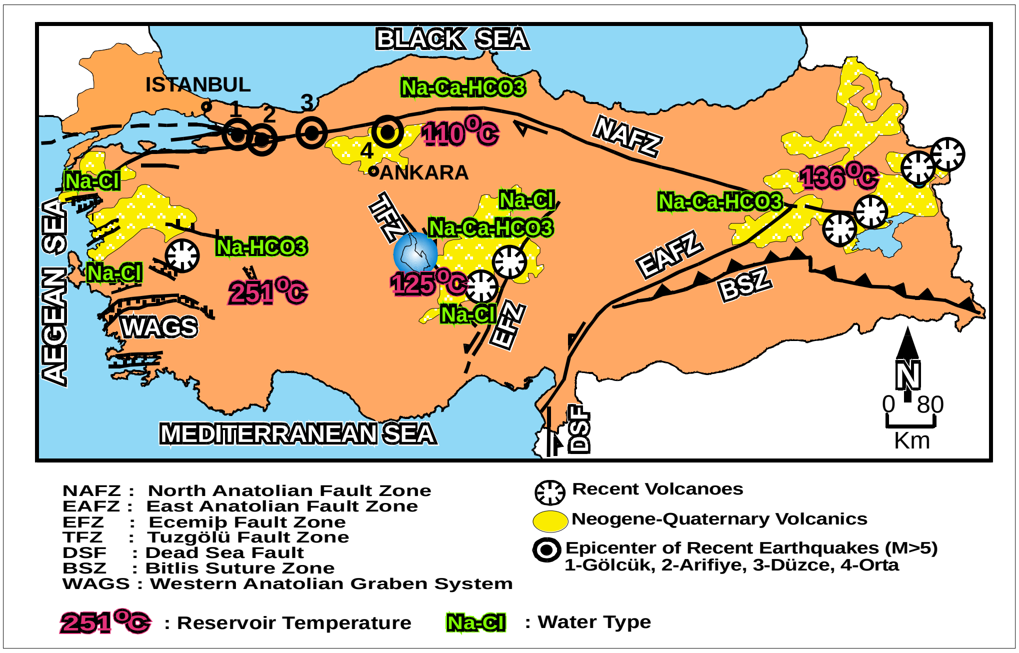

Figure 1. Distribution of neotectonic features, Neogene-Quaternary volcanics, water types and reservoir temperatures of geothermal systems in Turkey.

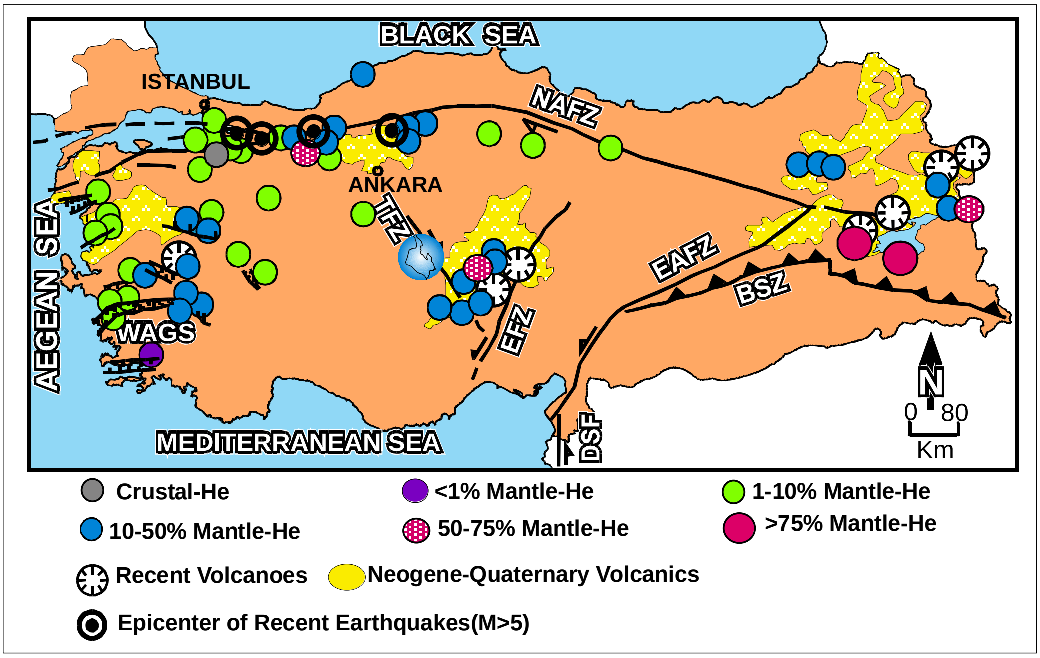

Figure 2. Distribution of mantle-He in Turkey (data sources: Stone 1986; Güleç, 1988; Nagao et al., 1989; Kipfer et al., 1994; Ercan et al., 1995; Pfister et al., 1997; Güleç et al., 2002; Güleç and Hilton, 2006; Mutlu et al., 2008).

3. HELIUM DISTRIBUTION

The distribution of He-isotope data in Turkey is depicted in Figure 2 in terms of the percentage of the mantle-He component. The data used in this figure covers the previously published data on a total of 76 sites, as well as the results of our He-surveys carried out i) along the North Anatolian Fault Zone after the devastating 1999 earthquakes (Güleç et al., 2002), and ii) in western Anatolia (Mutlu et al., 2008).

As can be seen from the map, He-isotope compositions in Turkey cover a wide range from values as low as those typical of crustal-He, to values exceeding 75% mantle-He characteristic of MORB-type samples.

The most prominent feature from Figure 2 is that the samples dominated by a mantle-He component (i.e. more than 50 % mantle-He) are associated with regions of historically active volcanoes (eastern and central Anatolia) and the most recent seismic activity (western central segment of NAFZ). The mantle-He contribution is relatively low (less than 50%) in the western Anatolian extensional province, the highest values being recorded again from the historically active Kula volcano and from the Denizli area which has been a site of frequent seismic activities since 2000. Figure 3 shows, in more detail, the results of the He-survey along the NAFZ. Sampling localities spanned a west-to-east transect of about 800 km, from Yalova on the Sea of Marmara to Resadiye in central Anatolia. The results of this survey, are presented in Figure 3 both as the percentage of the mantle-He component and as the $^3He/^4He$ ratios normalized to the atmospheric ratio (R/Ra values). These results reveal the presence of mantle-derived helium throughout the fault zone and the maximum proportion of mantle-derived helium is obtained from Mudurnu as 27 %.

What is apparent from Figure 3 is that although variations exist among different localities, the highest mantle-He contributions are recorded from the seismically active Düzce area, and the ratios shows a systematic decrease to the east of Kurşunlu away from the seismically active region. The variations in the mantle-helium contributions, recorded from different localities of the seismically active region, are likely to reflect the subsurface processes within the local hydrogeologic systems and/or the mechanism and the related surface geometry of faulting along NAFZ associated with the recent earthquakes. With regard to the latter, for example, it is worth noting that Yalova with a low R/R_a ratio does not lie on the surface rupture associated with the recent earthquakes.

4. CORELATION OF HEAT AND HELIUM DISTRIBUTION

When the distribution of mantle-He in Turkey is considered together with the reservoir temperatures estimated for differing tectonic provinces, the striking feature is the association of the relatively high mantle-He contributions with the low- to moderate- enthalpy fields (Figure 4). For example, the highest mantle-He contribution is recorded in moderate-enthalpy fields of eastern Anatolia. Likewise, relatively high mantle-He contributions in central and northern Anatolia are associated with moderate- to low-enthalpy fields. The high-enthalpy fields of western Anatolian extensional province, on the other hand, have rather low mantle-He contributions. This is contrary to the generally observed positive correlation between the ^3He- and the heat-flux worldwide.

Estimates of the average ^3He/enthalpy ratios for different neotectonic provinces yield a value of $1.7x\ 10^6$ ^3He atoms/joule for high enthalpy fields of western Anatolia which is lower by a factor of about 2 than that of moderate-enthalpy fields of eastern Anatolia, and by a factor of about 1.5 than that of low-enthalpy fields of northern Anatolia. This negative correlation between ^3He and heat flux in Turkey suggests different mechanisms for the transfer of heat and helium in the various regions. The recent and widespread volcanic activity in regions of eastern and central Anatolia is consistent with the release of both He and heat from cooling magmatic systems, the ratio decreasing with aging of the magmatic activity. However, higher enthalpy values for western Anatolia appear to result essentially from lithospheric stretching which provides a regional and significant source of heat associated with mantle upwelling and the rise of geotherm, and comparatively low helium additions from localised intrusive activity. Another important point to note here is the considerably high ^3He-flux in northern Anatolia. Since there is no evidence of a recent volcanic activity associated with strike-slip motion along NAFZ, it remains to be seen whether the mantle-He inputs in this region are indicative of subsurface magmatic activities associated with pull-apart basins, or if they reflect transport of mantle volatiles with CO_2-rich fluids.

5. COMBINED HE-CO_2 SYSTEMATICS: WESTERN ANATOLIA

The distribution of helium in Turkey is further evaluated in terms of combined He-CO_2 systematics of western Anatolian fluids. The western Anatolian fluids are characterized by $^3He/^4He$ ratios ranging from 0.27 to 1.67 R_A, $\delta^{13}C$ (CO_2) values between –8.04 and +0.35‰, and the $CO_2/^3He$ ratios varying from 1.6×10^9 to 2.3×10^{14}. He-CO_2 characteristics of the fluids are depicted in Figure 5 in terms of a ternary diagram where CO_2, ^3He and ^4He comprise the three end-members. Also shown in the diagram are i) the field characteristic for crustal fluids, and ii) the area of mixing between mantle-He and pure CO_2. In the diagram, symbols filled with white and black represent samples collected as free gas phase from bubbling pools/springs, and as dissolved gases in water phase, respectively. The samples collected from the northern part of the region (in close proximity to the western extension of the NAFZ) are denoted by square symbols, whereas those from the southern-central part (dominated by graben tectonics) are shown by circles. As can be seen from the diagram all the samples plot to the right of the mixing line between mantle-He and pure CO_2 suggesting significant addition of radiogenic helium or crustal contamination in all samples. With the exception of two samples plotting close to the CO_2 apex, water samples have comparatively lower $CO_2/^3He$ ratios than the gas samples pointing to the effects of physicochemical processes occurring in deep hydrothermal system. While the samples plotting close to the CO_2 apex appear to represent (residual) water phases after degassing (which will remove helium preferentially into the vapour phase), the composition of the other samples seem to be compatible with a processes of preferential CO_2 loss, possibly associated with calcite precipitation - a phenomenon common to most of the geothermal fields in western Anatolia as manifested by travertine deposition around natural springs and calcite scaling in production wells.

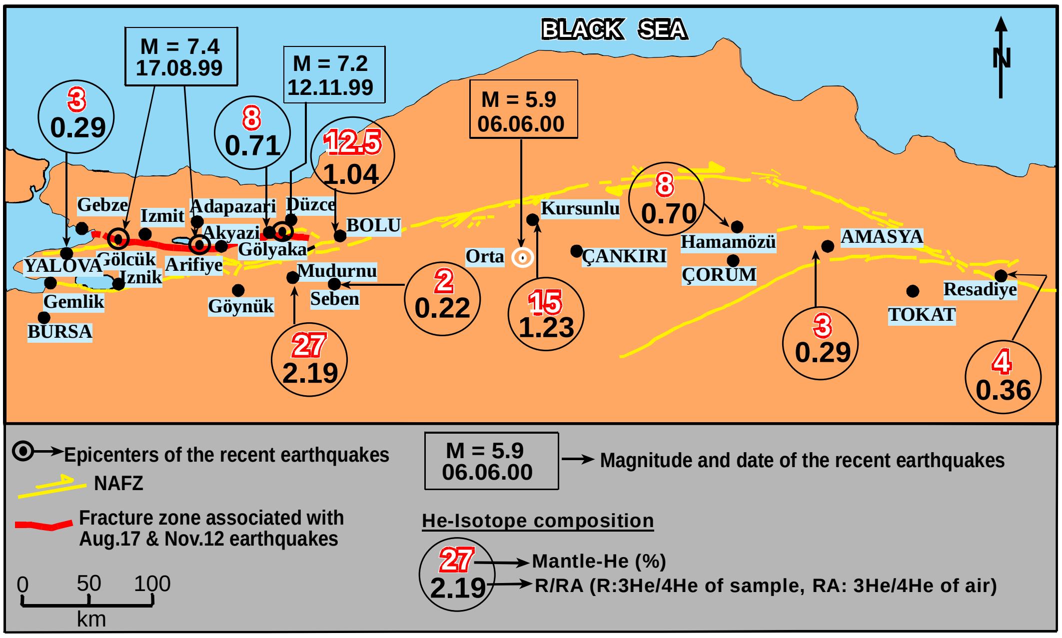

Figure 3. Results of He-survey along the North Anatolian Fault Zone.

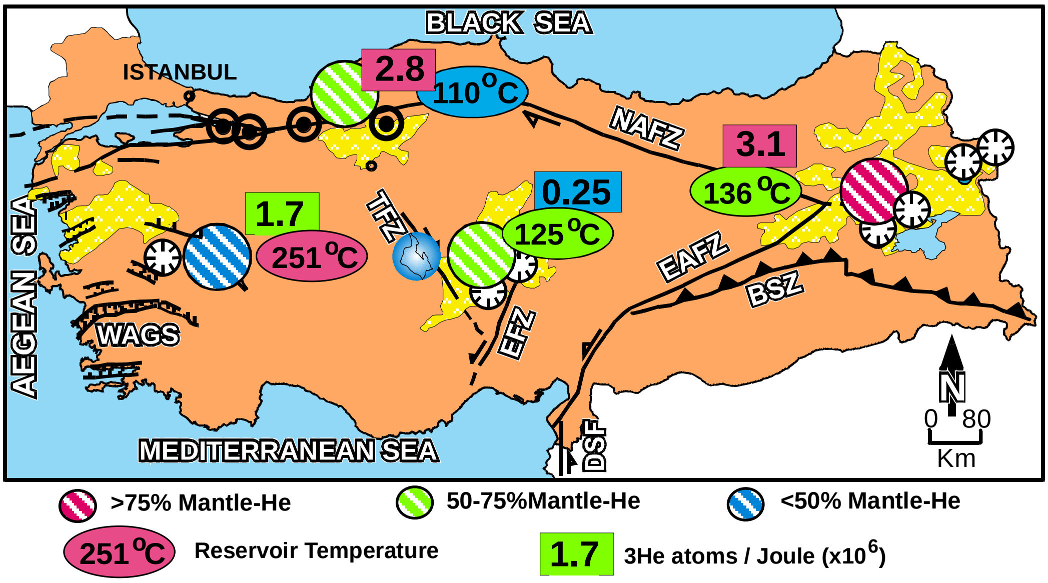

Figure 4. Heat and helium distribution and the average ^{3}He/enthalpy ratios in different neotectonic provinces of Turkey.

For the investigation of relative contributions from possible volatile sources, $\delta^{13}C$ values of the gas samples are plotted against their $CO_2/^3He$ ratios (Figure 6) together with the compositions of potential end-members, namely, mantle, limestone and sedimentary organic carbon components. The selection of samples for source evaluation assumes that gas phase samples better represent the source He-CO_2 characteristics (as hydrothermal degassing and calcite precipitation significantly fractionate the elemental $CO_2/^3He$ ratio in geothermal waters but do not affect gas phase samples to anywhere near the same extent). In Figure 6, the relative contributions from mantle and crust are essentially defined by $CO_2/^3He$ ratios, whereas those from different crustal sources (carbonate vs. sedimenatry organic carbon) are defined by $\delta^{13}C$ values. The positions of sample points on the diagram suggest that the source of CO_2 is dominantly crustal carbonates. A quantitative assessment of the various contributions to the volatile inventory in western Anatolia (Mutlu et al., 2008) reveal that > 72% of the total carbon budget is provided by crustal marine limestone, whereas the mantle-He component ranges up to 21 % of the total He content. Mantle-He is probably transfered to the crust by fluids degassed from deep mantle melts generated in association with adiabatic melting accompanying current extension in the region.

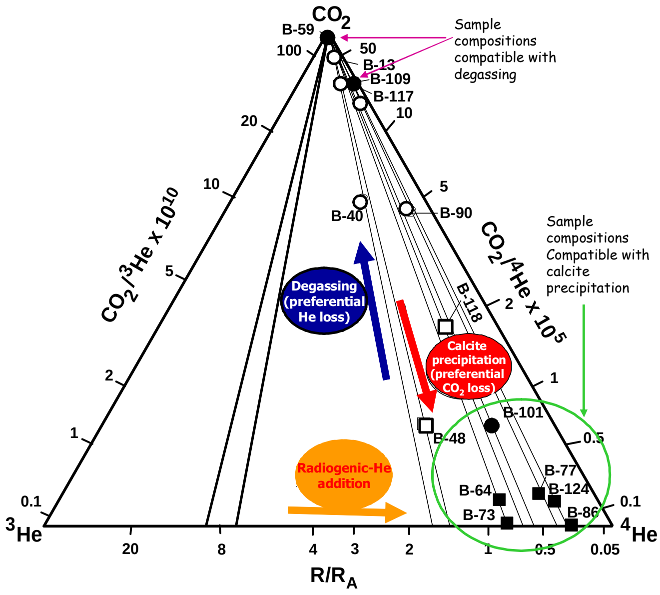

Figure 5. CO_2-^3He-^4He ternary diagram for the western Anatolian fluids (squares: samples from northern part, circles: samples from southern-central part of the region; black symbols: water samples, white symbols: gas samples; letters-numbers associated with symbols are sample numbers).

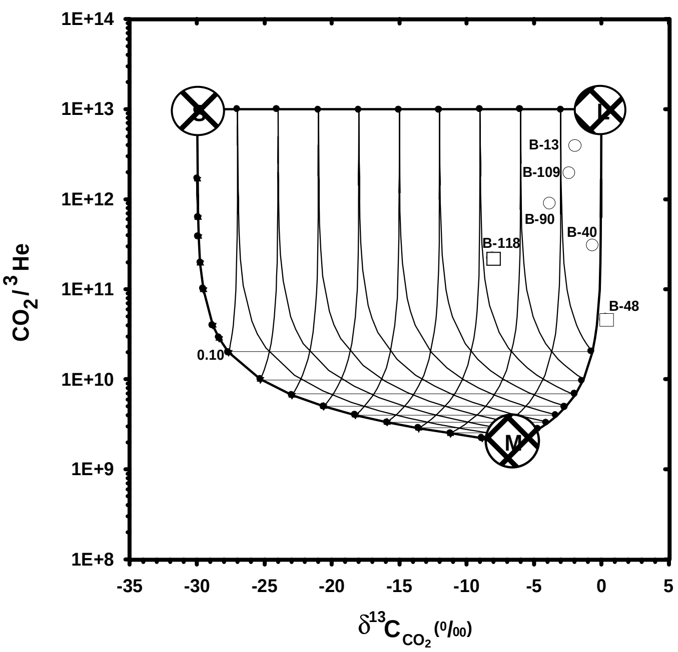

Figure 6. $CO_2/^3He$ vs. $\delta^{13}C$ (CO_2) plot for the western Anatolian gas samples. The end-member compositions for sedimentary organic carbon (S), mantle carbon (M) and limestones (L) are $\delta^{13}C$ (CO_2) = –30, –6.5 and 0‰; and $CO_2/^3He$ = 1x10^{13}, 2x10^9 and 1x10^{13}, respectively (Sano and Marty, 1995) (squares: samples from northern part, circles: samples from southern-central part of the region).

6. CONCLUSIONS

1. The overall distribution of mantle-He in Turkey reveals a close association with the age of tectono-magmatic activity, the highest mantle-He contributions being found in regions of historically active volcanoes (eastern and central Anatolia) and regions with the most recent seismic activity (western-central segment of NAFZ). In western Anatolia, mantle-He contribution is relatively less, the highest values being recorded from historically active Kula volcanoe and from Denizli area which has been a site of frequent seismic activities in recent years.

2. The distribution of heat and mantle-He correlates negatively, suggesting different mechanisms for the transfer of heat and helium in different provinces.

3. Recent and extensive volcanism in central and eastern Anatolia is consistent with the release of both helium and heat from cooling magmatic systems.

4. High ^3He / low enthalpy values of northern Anatolian fluids deserve particular attention as there is no evidence of recent volcanism associated with NAFZ.

5. Low ^3He/enthalpy ratio in western Anatolia seems to result from lithospheric stretching which provides a regional and significant source of heat but comparatively low helium additions from localised intrusive activity.

6. He-CO_2 characteristics of western Anatolian fluids suggest degassing and calcite precipitation (controlled probably by adiabatic cooling due to degassing) as the major processes affecting the composition of the geothermal fluids.

7. Inputs from crustal carbonates dominate the CO_2 inventory in western Anatolia; mantle contribution to the He inventory ranges up to 21% of the total He content. The transfer of mantle-He to the crust is probably accomplished by adiabatic melting associated with the current extension in the province. The fault systems appear to have acted as conduits for the geothermal fluids to carry the mantle-He to the surface.

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