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Helium and carbon isotope composition of gas discharges in the Simav Geothermal Field, Turkey: Implications for the heat source

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ABSTRACT

Helium and $^{13}C(CO_2)$ isotope compositions of gas discharges are used in conjunction with ^3He/enthalpy ratios to identify major heat sources of the Simav Geothermal Field, located on one of the major active graben system in western Anatolia (Turkey). The air-corrected $^3He/^4He$ ratios, $\delta^{13}C(CO_2)$ values, and $CO_2/^3He$ ratios of gas samples collected at the wellheads range from 1.36 R_A to 1.57 R_A (where R_A is the atmospheric $^3He/^4He$ ratio), −1.47‰ VPDB to −4.01‰ VPDB, and 4.66×10^9 to 11.4×10^9, respectively. The air-corrected helium ratios indicate a dominant crustal source for helium with significant mantle-derived helium contributions (up to 19.4%) to the total helium contents. Additionally, the combined $CO_2/^3He$ ratios and $\delta^{13}C$ (CO_2) values reveal that while the principal CO_2 contribution was from decomposition of marine carbonates, mantle-derived CO_2 contributions to the total CO_2 contents of the geothermal fluids can reach up to ~32%. The ^3He/enthalpy ratios were calculated in range from 0.016×10^{-12} cm^3 STP/J to 0.275×10^{-12} cm^3 STP/J, and are generally comparable to the theoretical ^3He/heat production ratio of the upper mantle. On the basis of ^3He/enthalpy ratios, the maximum magmatic heat contribution in the field was estimated as ~55% which is consistent with the average surface heat flow estimates for western Anatolia implying that at least half of the heat input to the overall heat budget of the Simav Geothermal System originating from a magmatic source. Finally, because there is no evidence of any active or recent volcanism in the region, mantle volatiles and magmatic heat contribution were attributed to the extension-related mantle melt generation providing mantle heat and volatile input beneath the crust.

1. Introduction

Most of continental geothermal systems developed in high heat flow regions are associated with either young igneous activity or active extensional tectonism characterized by numerous normal faults. Fluids in geothermal systems developed in young igneous environments derive their heat from intruding and cooling magma remains in the upper crust. These types of geothermal systems are generally high-temperature (≤370 °C) steam-dominated systems, and their reservoir depths are commonly ≤1.5 km (Goff and Janik, 2000). On the other hand, the majority of convective systems developed in non-volcanic regions of active extension derive their heat mostly from a crustal (radiogenic) source associated with decay of heat-producing radioactive elements (e.g., ^{238}U, ^{232}Th, ^{40}K) which release alpha (^4He), beta and gamma particles. The maximum reservoir temperatures of these types of geothermal systems are controlled by the circulation depth of meteoric waters and the presence of cap rock preventing heat loss from the system.

Western Anatolia (Turkey) hosts some of best examples of convective geothermal systems developed on the active margins of the large-scale E-to-W trending graben systems (Fig. 1a). The maximum bottom hole temperature (287 °C) in the region was recorded in a deep well (2750 m) located at Alaşehir-Gediz Graben (AGG). However, most of the productive geothermal reservoirs in terms of power generation, such as Kızıldere (245 °C), Germencik (239 °C), and Salavatlı (172 °C), are aligned on the northern margin of the Büyük Menderes Graben (BMG). The current geothermal power plant capacity in western Anatolia is approximately 400 MW, which is almost the total installed geothermal power plant capacity of Turkey. The driving heat source of these western Anatolia geothermal systems is still a matter of debate. Pliocene or younger volcanic activity that could serve as the heat source of the geothermal systems in the region is volumetrically minor and has limited extent.

Helium isotopic composition of geothermal fluids may provide critical constraints for the heat sources of geothermal systems due to: (1) distinctive isotope composition of helium in the mantle and

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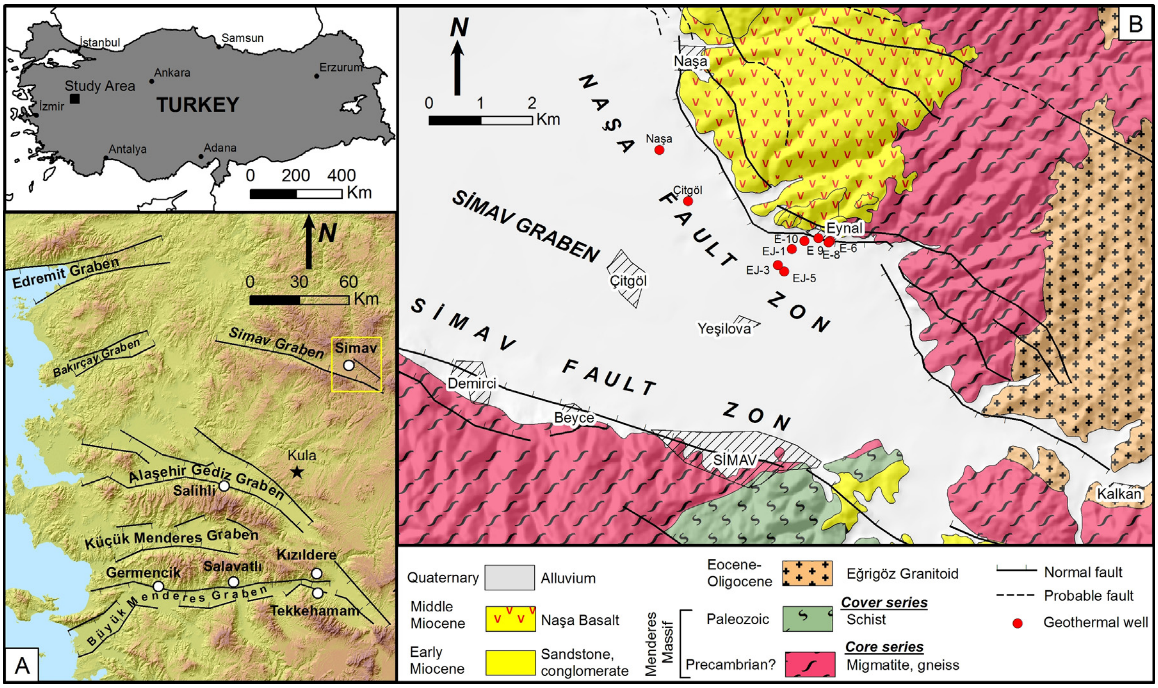

Fig. 1. Location of the stud area. (a) Main high-temperature (>150 °C) geothermal fields of western Anatolia. (b) General geologic map of the Simav Geothermal field (modified from Akdeniz and Konak, 1979; Yücel et al., 1983).

crustal reservoirs, (2) contemporary release of heat and helium from a magmatic mass or from decay of unstable elements in the crust, (3) upward transport of mantle and crustal helium with the accompanying transport of heat within the crust. The first feature relate with the relative abundances of ^{3}He and ^{4}He in the volatile provenances. Mid-ocean ridge basalts (MORB), which represent the convecting upper mantle (Graham, 2002), bear imprints of primordial ^{3}He component by an average ^{3}He/^{4}He ratio of 8 R_A ±1 (Farley and Neroda, 1998), where R_A is the ^{3}He/^{4}He ratio of air (1.384×10^{-6}; Clarke et al., 1976). In contrast, crustal fluids are significantly enriched in ^{4}He due to decay of U and Th series radioactive elements in the crust and display lower ^{3}He/^{4}He ratios of 0.005–0.02 R_A (Lupton, 1983). Given the ^{3}He abundance (or ^{3}He/^{4}He ratio) in the MORB that is 2–3 orders magnitude higher than that of crust, the second feature suggests that the ^{3}He/heat production ratio of the upper mantle is much larger than that of crustal reservoirs. Based on the average ^{3}He/^{4}He ratio observed in MORB ($\sim 1.1 \times 10^{-5}$, 8 R_A), Elderfield and Schultz (1996), and Lupton et al. (1989) calculated the theoretical ^{3}He/heat production ratio in the upper mantle as $\sim 0.5 \times 10^{-12}$ cm^3 STP/J. In crustal regimes, far removed from volcanic processes, helium in fluids is dominated by radiogenic ^{4}He and characterized by a ^{3}He/heat ratio of $\sim 1 \times 10^{-15}$ cm^3 STP/J, almost three orders of magnitude lower than the expected mantle value (Kennedy et al., 2000). Therefore, ^{3}He/^{4}He and ^{3}He/heat ratios provide a useful tool to predict heat sources of the geothermal systems. Furthermore, because the CO_2 is the major volatile carrier phase that transport of ^{3}He (O'Nions and Oxburgh, 1988), $CO_2/^3$He ratios, alone or coupled with δ^{13}C, may be used another indicator of mantle volatiles. Mantle-derived fluids have a uniform $CO_2/^3$He ratio of 2×10^9 (Marty and Jambon, 1987). In contrast, $CO_2/^3$He ratios of gases in continental settings vary widely from 10^8 to 10^{14} (O'Nions and Oxburgh, 1988), reflecting dilution with or addition of crustal-CO_2 produced by decomposition of carbon bearing minerals (O'Nions and Oxburgh, 1988; Sherwood Lollar et al., 1997).

In this contribution, we report helium and ^{13}C (CO_2) isotope composition of gas discharges in the Simav Geothermal Field (SGF) located in one of the major active graben systems in western Anatolia (Turkey). Detailed geochemical studies dealing with water–rock interaction processes and reservoir temperature estimation in the field were conducted previously (e.g., Gemici and Tarcan, 2002; Bayram and Şimşek, 2005; Palabiyik and Serpen, 2008). However, no concrete evidence on the heat source of the field has been yet put forward. With this contribution, the general geochemical features and reservoir temperature conditions of the Simav geothermal field were evaluated. Then, helium and carbon isotope systematics were employed to determine the probable heat sources of the SGF. Finally, on the basis of the ^{3}He/heat ratios mantle and crustal heat contributions to the SGF were estimated.

2. Regional settings

The SGF is located at the northern margin of the Simav Graben (SG), an extensional feature developed in a greater tectonic domain referred as the Western Anatolian Extensional Province. The WNW-ESE trending SG is an asymmetric graben extending from an elevation of 780 m to 820 m asl. The southern margin of the graben is bordered by its active north-dipping Simav Fault, which has a listric nature flattening out at a depth of approximately 9 km (Seyitoğlu, 1997). Basement rocks in the area are Precambrian–Paleozoic metamorphic rocks of the Menderes Massif, comprised from two sequences of rock assemblages: core and cover series (Fig. 1b). While the core series is composed of high-grade metamorphic rocks, mainly migmatite, and biotite-bearing gneiss dated back to Precambrian age, the cover series is composed of Paleozoic schist and marble (Akdeniz and Konak, 1979).

The eastern part of the graben is confined by the N–S trending dome-shaped the Eğrigöz Granitoid, which intruded into the metamorphic rock assemblage at the basement. Based on K–Ar radiometric-age determination on biotite and orthoclase, Bingöl et al. (1982) estimated the cooling ages of the Eğrigoz Granitoid in the range of 20.0 ± 0.7–20.4 ± 0.6 Ma and 21.2 ± 1.8–24.6 ± 1.4 Ma, respectively.