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Helium isotopes in Dead Sea Transform waters

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ABSTRACT

The concentrations and isotopic compositions of helium, and relative abundances of CO_2, were studied in brines and freshwater springs, groundwater wells, and gas bubbles, in and around the Dead Sea Transform (DST) fault system. The latter forms part of the plate boundary between the African and Arabian plates along which intensive tectonic and volcanic activity occurred and where a range of freshwater to hypersaline water bodies percolate.

The atmosphere-normalized $^3He/^4He$ ratios (R/R_a) show a distinct geographic gradient, whereby fluids in the north part of the DST, near Lake Kinneret, are characterized by $R/R_a \approx 2$. These values decrease gradually southward until the Arava Valley, where they are approximately 0.15, reflecting a corresponding decrease in the mantle-derived He fraction, from about ~30% in the north, to a few percent in the south. Freshwater springs outside the DST, in the Galilee and Judea Mountains, are characterized by R/R_a ratios close to unity, reflecting the dominance of atmosphere-derived helium, although they still contain a few percent of a mantle component.

The spatial pattern of change in R/R_a ratios is independent of regional tectonic activity (rifting), which is similar around the Lake Kinneret basin and the Dead Sea, and a correlation does not exist between such activity and He concentrations and $CO_2/^3He$ ratios. In contrast, helium concentrations, and to a lesser extent CO_2/He ratios, correlate with temperatures of the sampled fluids, reflecting a dilution process of a deep, hot mantle component as it percolates upwards toward the surface. The preferential injection of a mantle He toward the surface in the north DST is facilitated by deep faults and a shallower Moho boundary, which are also associated with enhanced volcanism in the north DST, and is superimposed over a regionally scaled mantle background value. Regionally, the observations reflect a transition from a domination of a dilute mantle end member in the north, which itself is the product of a mixture between mantle and crustal helium, to a dominant crustal (radiogenic) end member in the south.

The R/R_a ratio in basaltic olivines and diopside from the Golan is on average 6.6 ± 0.7, lower than typical mantle values (~8) but corresponding to comparable sub-continental mantle compositions.

1. Introduction

Helium and other gases are often found in groundwaters and water bodies on continents, recording continuing escape of gases from the Earth's interior to the atmosphere (Oxburgh and O'Nions, 1987). Variable, but sometimes considerable He fluxes derived from the continental crust are found in regions with no, or hardly any, tectonic activity (e.g. the Canadian shield; Greene et al., 2008), while He derived from the mantle is most conspicuous in extensional basins, and active extensional rift zones in particular, which tunnel deep-rising fluids and gases escaping the mantle (Oxburgh et al., 1986; O'Nions and Oxburgh, 1988; Ballentine et al., 2002; Kipfer et al., 2002; Torgersen, 2010). Significant fluxes of He from the mantle occur also along strike slip fault zones where there is no (or hardly any) crustal extension, or even transpression, such as the San Andreas and North Anatolia fault zones (e.g., Kennedy et al., 1997; Gulec et al., 2002). Mantle-derived He is also enhanced in areas experiencing active or recent volcanism along rifts and also where faulting is minimal, but in detail the relations between the extent and age of volcanism and He composition are quite loose (Matthews et al., 1987; Poreda et al., 1988; Greisshaber et al., 1992; Allard et al., 1997; Kennedy et al., 1997; Ballentine et al., 2002; Gulec et al., 2002; Kulongoski et al., 2005; Kennedy and van Soest, 2007; Torgersen, 2010), and in some cases, elevated mantle-derived He reflect various combinations of the above processes (e.g., Kennedy and van Soest, 2007; Wiersberg and Erzinger, 2007; Dogan et al., 2009; de Leeuw

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et al., 2010; Kulongoski et al., 2013), resulting in major challenges in the deconvolution of the degassing processes.

The typically elongated and subsided structure of rift zones serves as host of volatile-bearing groundwater and trapped fluids, whose He content may record their hydrological history, and therefore the provenance of He reflects the temporal and spatial interplay between tectonic and volcanic activity and brine geochemical evolution (e.g., Oxburgh and O'Nions, 1987; Marty et al., 1989; Hilton, 1996; Allard et al., 1997; Polyak et al., 2000; Ballentine et al., 2002; Kipfer et al., 2002; Pik and Marty, 2009; Fourré et al., 2011; Burnard et al., 2012).

Helium isotope ratios are a sensitive tracer of gas provenance due to the three orders of magnitude difference between the main reservoirs on Earth; crustal $^3He/^4He$ ratios (R) are ~0.04 those of the atmosphere (the atmospheric $^3He/^4He$ ratio (R_a) is $1.384 \cdot 10^{-6}$; Clarke et al., 1976), upper mantle values are characterized by $R/R_a = 6–10$, with even higher ratios of approximately $R/R_a = 15–50$ associated with mantle plumes (Craig and Lupton, 1976; Lupton, 1983; Oxburgh et al., 1986; Ballentine and Burnard, 2002; Graham, 2002; Georgen et al., 2003). The ratio between the two isotopes of He (^3He and ^4He) imposes two distinct geochemical "fingerprints" of their source: the more abundant helium isotope, ^4He, is produced in the crust as α particles during the decay of uranium and thorium series, whereas helium of mantle origin is labeled by a considerably higher relative content of the non-radiogenic, primordial ^3He component (Craig and Lupton, 1976; Tolstikhin, 1978; Mamyrin and Tolstikhin, 1984). Thus, helium concentrations and isotopic compositions in crustal and surface fluids reflect the mixing proportions of radiogenic, mantle and atmospheric He. The isotopic composition of crustal He depends on the ratio between crystalline and sedimentary rocks, as well as on the interaction between the sediment matrix (grains, cement, porosity), where (radiogenic) ^4He is produced, and the surrounding fluids which are also the carrier phase of magmatic helium. Other reactive gases, such as carbon dioxide, whose relationship with He has been widely studied in crustal and volcanic gases (Marty and Jambon, 1987; Matthews et al., 1987; Giggenbach et al., 1991; Griesshaber et al., 1992), can be used to scale helium contents and identify chemical fractionation processes. A characteristic mantle $CO_2/^3He$ ratio of $2 \cdot 10^9$ provides a useful constraint on the provenance of gas and fluids in various tectonic settings (Marty et al., 1989; Poreda et al., 1988; Hilton, 1996) although this ratio might be strongly influenced, typically toward higher values, by water–rock interaction in carbonate-underlain terrains.

The Dead Sea Transform (DST) forms part of the plate boundary between the African and Arabian plates (Fig. 1). A large volcanic province is exposed in the northern part of the study area (the Galilee and Golan) and basalts occur sporadically also along its southern part. To the south of the DST, in the center of the Red Sea, He isotope ratios are characterized by relatively high values ($R/R_a > 8$ Ra) reflecting several mantle sources, including a mantle hotspot (Moreira et al., 1996).

Radium and radon are the decay products of U and Th (and their progenies) and are typically associated with a crustal component. Previous efforts have documented their characteristics in groundwater and lakes along the DST (Mazor, 1962; Stiller and Chung, 1984; Chan and Chung, 1987; Somayajulu and Rengarajan, 1987; Moise et al., 2000), where both display relatively elevated concentrations that vary with time and show a correlation to seismic activity (Steinitz et al., 2003). Hence, it might be expected that similar patterns exist in the He concentration and isotopic compositions along the DST and it is of relevance to determine whether the isotope composition of He in water and gases from springs and wells along the DST is controlled by a radiogenic-crustal or a mantle-like end member, similarly to other rift zones. To date, only limited and sporadic $^3He/^4He$ data in the DST were reported prior to the present study (Gat et al., 1979; Moise et al., 1998; Bergelson et al., 1999; Lange et al., 2008).

Here, we investigate the spatial patterns of helium concentrations and isotopic compositions and examine the association between recent volcanism and mantle degassing. The findings are discussed in the context of the different fluid types and geographic gradients in and around the DST based on measurements of helium, neon and carbon dioxide.

2. Background

2.1. Geology and tectonics

The DST is a fracture zone about 1000 km long, extending from the Red Sea in the south along the Gulf of Aqaba, the Arava Valley, the Dead Sea, the Jordan Valley, and through Lebanon to the Taurus Mountains in the north (Fig. 1). A continental breakup phase, beginning at about 30–25 Ma, led to the detachment of Arabia from Africa, which became two distinct plates, whose ongoing divergence is responsible for the formation and spreading of the Red Sea. North of the Red Sea, the Arabian–African plate motion was mostly taken up by the DST, but a part of the motion was accommodated by opening of the Suez rift (Freund, 1965; McKenzie et al., 1970; Joffe and Garfunkel, 1987).

The areas bordering the transform were uplifted to different degrees, from about 1 km to >10 km (Garfunkel and Ben Avraham, 1996). At present, the DSTs floor is mostly below sea level, usually, 5–15 km wide, and it is generally delimited by narrow zones of normal faults and a left lateral displacement of ~105 km (Quenell, 1956; Freund, 1965). The part of the transform south of Lebanon is characterized as "leaky" (Garfunkel, 1981), as its flanks often diverge slightly, but the divergence decreases northward; north and south of Lake Kinneret, and in Lebanon, transpression takes place (Garfunkel, 1981; Rotstein et al., 1992; Weinberger et al., 2009, 2011). The geometry of the left stepping arrangement of the main strike slip fault strands along this part of the DST results in a series of pull-apart basins, the largest among them being the Dead Sea, Lake Kinneret, the Hula Valley and several basins in the Gulf of Aqaba. This string of basins is flanked by normal faults that produce the transform valley (Garfunkel, 1981; Garfunkel and Ben-Avraham, 2001). Since their inception in the Neogene, the pull-apart basins have been filled by thick sedimentary sequences dominated by clastic rocks (the Hazeva Formation of Miocene age), evaporites (the Sedom Formation), and Pliocene to recent fluviatile and lacustrine sediments (Neev and Emery, 1967; Zak, 1967; Marcus and Slager, 1986; Hurwitz et al., 2002). The combined thickness of these and older sedimentary and volcanic sequences, is ~4–6 km in the northern part of the region, overlaying crystalline basement rocks. Southwards, the top of the crystalline basement rises gradually until its exposure in the southern part of the Arava Valley, near the Gulf of Aqaba (Rybakov and Segev, 2004).

The crust on both sides of the Dead Sea basin and the nearby parts of the transform is ~25–35 km thick, exhibiting a small gradient over distances larger than ~50 km of spatial thinning toward West (Ginzburg et al., 1979a,b; Weber et al., 2012). On a north–south axis, the depth of the Moho was inferred to be in the range of ~25–35 km, reaching its shallowest point in the northern part of the studied area, beneath northern Israel and Lebanon (Segev et al., 2006; DESERT Group et al., 2004.

2.2. Hydrology

Water bodies in and around the DST vary in their origin and can be divided into three main groups based on their salinity and geochemical properties:

(1) Saline surface and groundwaters in the DST are dominated by a characteristic Ca-chloride composition and are present in two areas along the DST (Fig. 1): Lake Kinneret in the north, and the Dead Sea in the south. The Ca-chloride brines were formed by evaporation of seawater in paleo-lakes, followed by interaction with local bedrock and ancient lake sediments (Zak, 1967; Starinsky, 1974). They are characterized by a Na/Cl ratio lower