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Gas chemistry of the Dallol region of the Danakil Depression in the Afar region of the northern-most East African Rift

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ABSTRACT

A combination of noble and major gas composition and isotope geochemistry provides a window into the source of volatiles and the mechanisms of transport associated with a series of hot springs located near the Dallol volcano within the Danakil Depression along the Red Sea arm of the Afar triple junction. The helium isotopic composition of these gases range up to 11.9 times the atmospheric ratio (11.9 R/Ra), which suggests that the Afar plume interacts with the Afar depression across at least the 300 km transect from Tendaho-Gabo basin to Dallol within the Danakil Depression. The $^4He/^{40}Ar^*$ of ~14 in the mantle-rich end-member at Dallol indicates significant degassing prior to emplacement at Dallol either during basaltic dyke intrusions beneath the Danakil Depression or during the release and transport of fluids from a degassed subsolidus source in the upper mantle along high permeability fracture zones. The $CO_2/^3He$ of the magmatic end-member is ~2× higher (7.7×10^9) and more positive $\delta^{13}C$ (CO_2) (−2.1‰) than other archetypal plumes (e.g. Hawaii, Iceland, etc.). The Dallol composition is consistent with a hypothetical model that assumes a plume-type starting composition and experiences ~92% degassing (where helium is preferentially degassed with respect to CO_2) and the addition of CO_2 from the thermal degradation of carbonate. Non-atmospheric excess N_2 with a $\delta^{15}N$ (N_2) of +3.5 to +4‰ dominates the Dallol volatiles and suggests interaction between mantle fluids and Proterozoic meta-sediments. By comparing and modeling the range in atmospherically (e.g. ^{20}Ne, ^{36}Ar, ^{84}Kr) and mantle-derived (e.g. $^4He/^{40}Ar^*$ and $CO_2/^3He$) components in Dallol volatiles, we propose that the coherent variations in these gases result from mixing of magmatic volatiles with extremely degassed remnant fluids present within the hydrothermal reservoir.

1. Introduction

Volatile geochemistry plays a fundamental role in constraining the source and dynamic processes that generate the fluids brought to the Earth's surface during volcanic, magmatic, and hydrothermal activity. The inert nature, low terrestrial abundance, and well characterized isotopic composition of each of the major terrestrial reservoirs of noble gases (i.e. mantle, crust, hydrosphere, and atmosphere) make these geochemical tracers exceptionally useful for evaluating the evolution of magmatic bodies, understanding the chemical heterogeneities within the mantle, as well as distinguishing the source, mixtures, and sub-surface crustal interactions of mantle-derived fluids (e.g. Craig and Lupton, 1976; Mamyrin and Tolstikhin, 1984; Poreda and Craig, 1989; Kurz, 1993; Lollar et al., 1997; Hilton et al., 1999; Ballentine et al., 2001; Fischer et al., 2009; Zhou et al., 2012). Paired noble gas and volatile isotope chemistry provide insights into the source, character, and mixing relationships of mantle and crustal fluids both globally and at locations along the geologically and tectonically complex East African Rift, including some areas within the Afar triple junction (i.e. Tendaho Basin) (Marty et al., 1996; Scarsi and Craig, 1996; Pik et al., 2006; Montagner et al., 2007; Fischer et al., 2009; Tassi et al., 2009; Tedesco et al., 2010; Hilton et al., 2011). Nonetheless, there is paucity of noble gas isotope and volatile geochemical data for several magmatic segments with recent historical activity, including the peculiar and picturesque Dallol hot springs in the Danakil Depression (Fig. 1).

Located in one of the most remote, inhospitable (temperatures routinely exceed 40 °C), and seldom studied locations in the world, the Dallol hot springs are an important local economic resource (i.e. rock salt, potash, manganese deposit mining and tourism),

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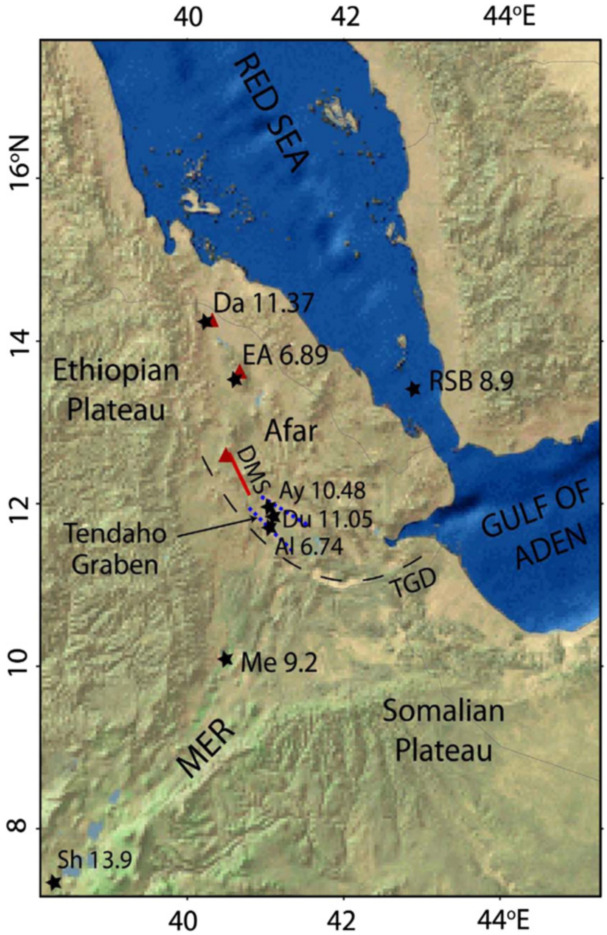

Fig. 1. The Afar depression and active volcanoes, near the triple junction of the actively spreading Red Sea and Gulf of Aden, and magmatically rifting Main Ethiopian Rift (MER). The Tendaho graben (containing the Ayrobera (Ay), Dubti/Tendaho (Du), and Alalobeda (Al) hot springs) is located near the triple junction along the Tendaho-Gabaad (Gabo) Discontinuity. The TGD is along-strike of the recently active Dabbahu Magmatic segment (DMS) (erupted in 2005 and 2007; Wright et al., 2006; Ayele et al., 2007) and Danakil Depression, which contains the Erta 'Ale (EA) and Dallol (DA) volcanoes and the nearby Dallol hot spring area. The $^3He/^4He$ ratios are shown for each hot spring–fumarole for comparison. The Red Sea brine $^3He/^4He$ was reported in Lupton et al. (1977).

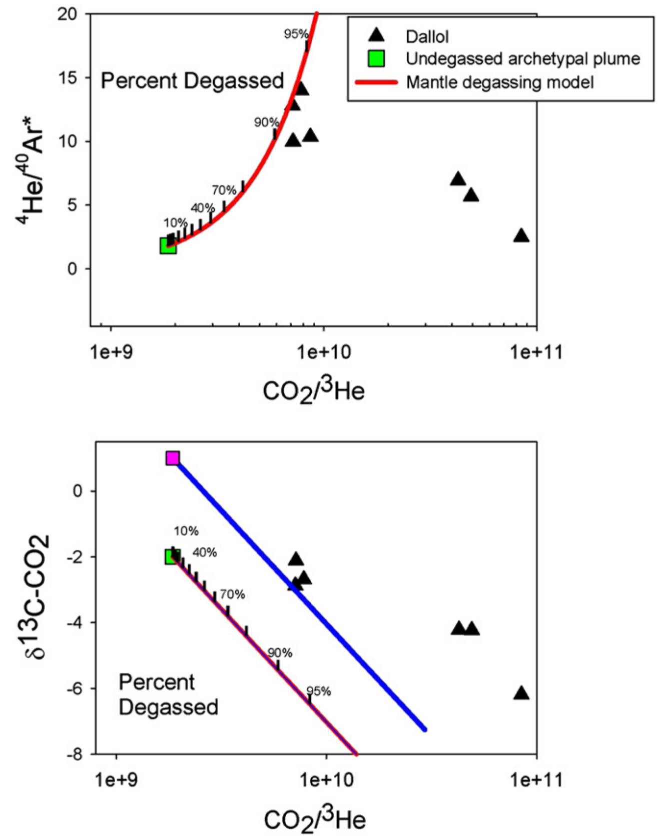

Fig. 2. Evolution of $\delta^{13}C–CO_2$, $CO_2/^3He$, and $^4He/^{40}Ar^*$ calculated for the gas phase of degassing archetypal plume magmatic body (green box) (Poreda et al., 1992; Giggenbach and Poreda, 1993) (model following Ballentine et al., 2002). The model assumes an initial starting composition of $\delta^{13}C–CO_2 = -2$‰, $CO_2/^3He = 2 \times 10^9$ and bulk earth $^4He/^{40}Ar^* = 1.8$. These end-members are within the ranges observed for other plume environments and alkaline-rich magmatic end-members. Note that even by using favorable end-member compositions the mantle gases must have degassed to approximately 92% before being entrained in the hydrothermal system. The degassing model cannot account for the extent of $\delta^{13}C–CO_2$ and $CO_2/^3He$ enrichment suggesting additional sources of CO_2 in the mantle end-member. We also model a degassing trend for a hypothetical plume gas component that has an initial $\delta^{13}C–CO_2 = +1$‰, $CO_2/^3He = 3 \times 10^9$. The validity of this end-member composition is suspect, but consistent with the Dallol mantle-derived end-member.

while the associated 'boinas' (i.e. the Afari name for hot springs) are commonly necessary for human and animal drinking water consumption (Holwerda and Hutchinson, 1968). The limited amount of published data for volatile chemistry within the Erta 'Ale volcanic complex of the Danakil Depression focuses on major species (e.g. CO_2, S_2O, H_2, H_2S), acidic gases (e.g. HF, HCl), and water (H_2O) (Tazieff et al., 1972; LeGuern et al., 1975; Giggenbach and LeGuern, 1976; Oppenheimer and Francis, 1997; Sawyer et al., 2008). The Dallol hot springs offer a unique window into the interrelation between Afar plume mantle processes and the transport of volatiles to the surface within the complex geological environment of active extension and crustal formation along an active rift segment. Additionally, these data represent the first noble gas or major gas data for this active magmatic segment within this Red Sea arm of the Afar triple junction.

2. Geological setting

The East African Rift System (EARS) constitutes the classic example of active continental rifting that continues to split Africa from Arabia (e.g. Wright et al., 2006; Ebinger et al., 2008). Today, active rifting and volcanism span the distance from the Afar triple junction as far south as Mozambique (e.g. Hayward and Ebinger, 1996; Furman, 2007) (Fig. 2). The first recorded volcanism along the EARS began ~45 Ma in southern Ethiopia, while the largest volume of lava erupted further north toward Afar. The most voluminous eruptions occurred when the Ethiopian traps, still observable today as the ~2000 m high Ethiopian plateau, were emplaced as flood basalts in about 1 Myr at ~30 Ma (Ebinger and Sleep, 1998; George et al., 1998; Pik et al., 1998; Courtillot et al., 1999; Kieffer et al., 2004). The onset of the Ethiopian flood basalts at ~30 Ma is unambiguously linked to the deep mantle Afar plume, whose thermal and seismic anomalies persist to the present day (Lupton et al., 1977; Hayward and Ebinger, 1996; Marty et al., 1996; Scarsi and Craig, 1996; Bastow et al., 2005; Benoit et al., 2006a, 2006b; Pik et al., 2006). The flood basalt sequence is contemporaneous with the initiation of rifting of the southern Red Sea and is likely responsible for stimulating the seafloor spreading in the Gulf of Aden and the Red Sea (e.g. Courtillot et al., 1999; Lahitte et al., 2003; Kendall et al., 2005). The evolution of this rift is responsible for the formation of the 300-km wide Afar depression (Afar triple junction), located at the intersection of the Red Sea, Gulf of Aden, and East African Rift, throughout the last ~30 Myr (predominantly the last 10 Myr) (e.g. White and McKenzie, 1989; Hayward and Ebinger, 1996; Wright et al., 2006; Ayele et al., 2007).

During the last ~2–4 Myr, the northern Afar depression has experienced increased seismic, tectonic, and volcanic activity along localized magmatic segments that erupt dominantly basaltic volcanics