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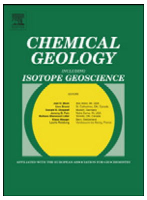

Noble gases in sulfide deposits of modern deep-sea hydrothermal systems: Implications for heat fluxes and hydrothermal fluid processes

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ABSTRACT

Studies of noble gases in seafloor sulfide deposits are an important tool for understanding the origin of ore-forming fluids, both enabling the determination of noble gas sources and revealing the degree of fluid–rock interaction and mantle degassing. The noble gas concentrations and isotopic compositions of 27 sulfide, 3 sulfate, and 2 opal mineral aggregate samples have been studied in different hydrothermal fields from the East Pacific Rise, Mid-Atlantic Ridge, Central Indian Ridge, Southwest Indian Ridge, and North Fiji Back-Arc Basin. The helium concentrations and isotopic ratios in the sulfide aggregate samples are variable (^{4}He 0.12 to 22 × 10^{-8} cm^3 STP/g; ^{3}He/^{4}He ~0.6 to 10.4 R_a), and most of the sulfide helium concentrations are higher than those in the opal mineral samples (^{4}He 0.017 and 0.028 × 10^{-8} cm^3 STP/g), suggesting that the low-temperature fluids have lost their mantle helium during cooling. The helium of high (>7 Ra), medium (1–7 Ra), and low (≈1 Ra) ^{3}He/^{4}He ratio samples is derived mainly from the MORB or OIB mantle by magma degassing, from mixing between hydrothermal fluid and seawater during ore-forming processes, and from ambient seawater, respectively. The high ^{3}He/^{4}He ratios (>7 Ra) of sulfides imply that high-temperature sulfides retain the helium isotopic compositions of the primary hydrothermal fluid, whereas low-temperature sulfides, sulfates, and opal minerals do not.

The neon, argon, krypton, and xenon concentrations in the sulfide aggregate samples are also variable; in most of the sulfide aggregates, they are significantly lower than in the sulfate and opal mineral samples. It is known that barite and opal minerals are characteristic of low-temperature (<200 °C) paragenetic associations, indicating that heavier noble gases (Ne, Ar, Kr and Xe) are enriched under low-temperature conditions. Most of the sulfide, sulfate and opal mineral aggregate samples possess heavy noble gas elemental abundances similar to those of air-saturated seawater and Ne, Ar, and Xe isotopic compositions that span narrow ranges around atmospheric values, an observation which is most easily explained by the dominance of a seawater-derived component.

In addition, based on the calculated helium/heat ratios, global helium and heat fluxes to high-temperature hydrothermal vents are approximately 0.05–6 × 10^4 kg per year and 0.1–12 × 10^{12} W, meaning that roughly 0.3% of ocean heat is supplied by seafloor high-temperature hydrothermal activity.

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1. Introduction

The study of noble gases in seafloor hydrothermal sulfides is key to revealing the evolution of seafloor hydrothermal systems. Such studies can be used to reconstruct fluid temporal variability and to extend our knowledge of the helium/heat ratio back into the geological record (e.g., Turner and Stuart, 1992; Stuart et al., 1994a, b; Jean-Baptiste and Fouquet, 1996; Zeng et al., 2001, 2004). To date, noble gas studies have been performed in sulfide deposits of modern seafloor hydrothermal fields in the Middle Valley of the northern Juan de Fuca Ridge (NJdFR) (Stuart et al., 1994a, b); in the Trans-Atlantic Geotraverse (TAG) and Snake Pit hydrothermal fields of the Mid-Atlantic Ridge (MAR) (Stuart et al., 1994b; Zeng et al., 2001); in the East Pacific Rise (EPR) near 13°N (Stuart et al., 1995; Jean-Baptiste and Fouquet, 1996) and 21°N (Turner and Stuart, 1992; Stuart et al., 1994b); in the JADE hydrothermal field of the Okinawa Trough (Zeng et al., 2004; Hou et al., 2005; Lüders and Niedermann, 2010); in the North Fiji Basin (NFB) (Lüders and Niedermann, 2010); and in the PACMANUS hydrothermal field of the Manus Basin in Papua New Guinea (Webber et al., 2011). The ^{3}He/^{4}He ratios of sulfide-, sulfate-, and opal-hosted fluid inclusions from the Middle Valley, the EPR near 13°N and 21°N, the TAG, Snake Pit, JADE, NFB, and PACMANUS hydrothermal fields range from 0.29 to 13.3 R_a (sulfide samples, n = 96; R_a is the atmospheric ^{3}He/^{4}He ratio of 1.39 × 10^{-6}) and from 2.6 to 12.4 R_a (sulfate and opal samples, n = 16), respectively (Turner and Stuart, 1992; Stuart et al., 1994a,

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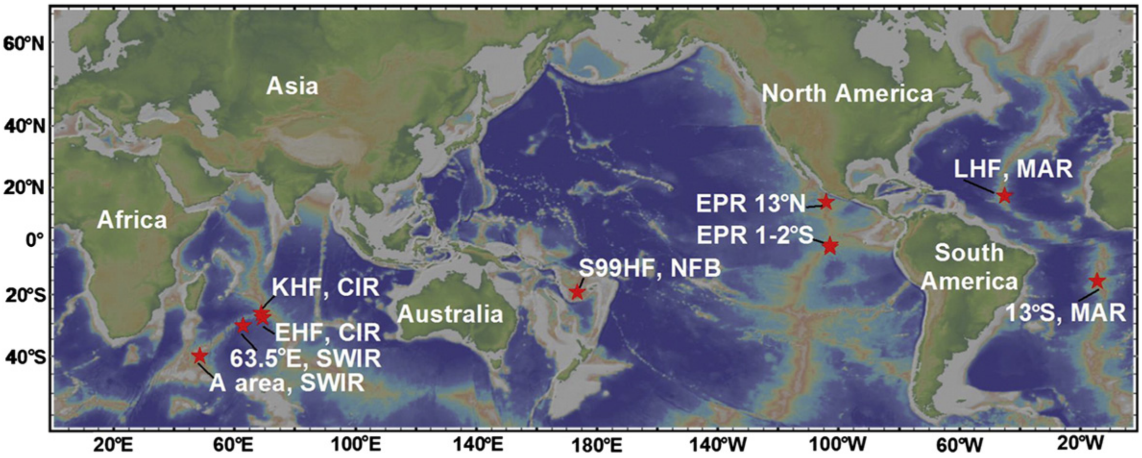

Fig. 1. Locations of seafloor hydrothermal sulfide samples from the deep-sea hydrothermal fields analyzed for noble gas concentrations and isotopic compositions in this study: KHF—Kairei hydrothermal field; EHF—Edmond hydrothermal field; CIR—Central Indian Ridge; SWIR—Southwest Indian Ridge; S99HF—Sonne 99 hydrothermal field; NFB—North Fiji Basin; EPR—East Pacific Rise; LHF—Logatchev hydrothermal field; MAR—Mid-Atlantic Ridge.

1994b, 1995; Jean-Baptiste and Fouquet, 1996; Zeng et al., 2001, 2004; Hou et al., 2005; Lüders and Niedermann, 2010; Webber et al., 2011). Most of these values are almost indistinguishable from the ^{3}He/^{4}He ratios of vent fluids (5.3–8.3 R_a) from these hydrothermal fields (e.g., Lupton et al., 1980; Craig and Lupton, 1981; Kim et al., 1984; Kennedy, 1988; Kodera et al., 1988; Jean-Baptiste et al., 1991; Rudnicki and Elderfield, 1992; Charlou et al., 1996) and of MOR basalts (6–11 R_a) (Kurz et al., 1982; Graham, 2002), suggesting that helium is predominantly derived from a magmatic source beneath the hydrothermal systems (Zeng et al., 2004; Hou et al., 2005; Lüders and Niedermann, 2010). This shows that the fluid inclusions of sulfides reliably record the helium isotope ratio of the original hydrothermal fluid (Lüders and Niedermann, 2010). In the Middle Valley, the ^{3}He/^{4}He ratios (5.8–7.1 R_a) of fluid inclusions in sulfide minerals are lower than those of typical MOR vent fluids (~8 R_a; e.g., Craig and Lupton, 1981; Kennedy, 1988; Kodera et al., 1988) and are closer to those of vent fluids from the sediment-covered Guaymas basin (7 R_a; Lupton, 1983), suggesting a contribution of radiogenic He derived either from sedimentary pore fluids or from aging of the magmatic system beneath the NJdFR (Stuart et al., 1994a). The fluid-inclusion ^{3}He/^{4}He ratios of sulfides reflect a mixture of basalt-derived He and radiogenic He acquired from pore fluids in the overlying Pleistocene turbidite sediments after seawater–basalt interaction, and the He isotopes can be used to distinguish pore fluids from seawater in seafloor hydrothermal systems (Stuart et al., 1994b). In another study, the helium isotopic compositions of fluid-inclusions in hydrothermal sulfides from the EPR near 13°N were measured using both crushing and heating techniques, and comparison of the two extraction methods suggests that both techniques give similar results (Jean-Baptiste and Fouquet, 1996).

The elemental abundances of Ne, Ar, Kr, and Xe in fluid inclusions of sulfide samples from the JADE hydrothermal field and NFB suggest that the heavier noble gases are derived from ambient seawater (Zeng et al., 2004; Lüders and Niedermann, 2010). The Ar, Kr, and Xe concentrations of Middle Valley sulfides are 10 to 50 times higher than those of sulfides from the EPR near 21°N, and the Ar and Xe isotopic ratios of sulfides from both settings are indistinguishable from atmospheric values (Turner and Stuart, 1992). The argon isotopic ratios in fluid inclusions of sulfides from the TAG (^{40}Ar/^{36}Ar 287–359; Zeng et al., 2001) and the PACMANUS hydrothermal field (^{40}Ar/^{36}Ar 295–310; Webber et al., 2011) are somewhat more variable, but still close to the atmospheric ratio (295.5 after Nier, 1950; 298.56 after Lee et al., 2006; Mark et al., 2011). This also indicates that most of the heavier noble gases come from seawater (Turner and Stuart, 1992; Zeng et al., 2001; Webber et al., 2011). Likewise, ^{40}Ar excesses of up to 2.6% relative to atmospheric Ar (i.e., ^{40}Ar/^{36}Ar up to 303) are present in fluid inclusions of sulfide samples from the EPR near 13°N. Fluid-inclusion ^{3}He/^{4}He ratios of 7.3–9.3 R_a in the same samples are typical for mid-ocean ridge hydrothermal fluids and imply a mantle origin for the ^{40}Ar excess also (Stuart and Turner, 1998).

Although noble gases in seafloor hydrothermal sulfides can provide important information on fluid sources, fluid flux changes (e.g., Turner and Stuart, 1992), and hydrothermal processes (e.g., Stuart et al., 1994a, b), noble gas composition data for fluid inclusions in sulfide, sulfate, and opal samples from seafloor hydrothermal systems in mid-ocean ridge (MOR) and back-arc basin (BAB) settings are still scarce; in particular, Ne, Ar, Kr, and Xe data for modern seafloor sulfide deposits are lacking. In this study, noble gas concentrations and isotopic compositions have been measured, for the first time, in seafloor hydrothermal sulfide deposits from the EPR near 1–2°S, the Logatchev hydrothermal field (LHF) in the MAR near 15°N, the MAR near 13°S, the Central Indian Ridge (CIR), and the Southwest Indian Ridge (SWIR) (Fig. 1). The characteristics of noble gas concentrations and isotopic compositions in sulfide, sulfate, and opal mineral aggregates are described, seawater and magmatic noble gas contributions are characterized, the implications for fluid–rock interaction and fluid–seawater mixing are explored, and helium and heat fluxes from hydrothermal fluids to seafloor hydrothermal sulfide deposits are evaluated.

2. Sampling and methods

Seafloor hydrothermal sulfide samples were recovered by TV-grab samplers from the fast-spreading EPR near 13°N, the ultra-fast spreading EPR near 1–2°S, the Kairei hydrothermal field (KHF) and the Edmond hydrothermal field (EHF) on the intermediate-spreading CIR near 25°S, the slow-spreading MAR near 13°S and at the LHF (15°N), and the ultra-slow spreading SWIR near 63.5°E and in the "A" area (49°E) in 2005, 2007, 2008, 2009, and 2010 during the DY105-17, DY115-19, DY115-20, and DY115-21 cruises of R/V "Dayang Yihao". Sulfide samples from the Sonne 99 hydrothermal field (S99HF) in the back-arc North Fiji Basin (NFB) were collected in 1998 during the SO134 cruise of HYFIFLUX II (Fig. 1).

At the EPR near 13°N and 1–2°S, the KHF, the EHF, the MAR near 13°S, the A area, the SWIR near 63.5°E, and the S99HF, the seafloor hydrothermal sulfides are hosted by mid-ocean ridge basalt (MORB) (e.g., Zeng et al., 2010, 2014). The KHF is situated on basaltic rocks but the hydrothermal fluids also interact with and circulate through ultramafic rocks (Nakamura et al., 2009). In the LHF, the hydrothermal sulfide deposit is associated with ultramafic rocks located in a debris flow consisting of heterogeneous ultramafic and mafic intrusive rocks, including serpentinized harzburgite, serpentinized dunite, gabbronorite,

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