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Flowing through the cracks? Helium release from bedrock zircon

Birk, P, Härtel,
Akeek, Maitra,
Eva, Enkelmann
Earth, Energy, and Environment, University of Calgary

Summary

Helium occurrences in hydrocarbon wells are receiving increasing attention for exploration. Isotopic analyses from He-rich wells in Precambrian basement (e.g., Combaudon et al., 2025), or intracratonic basins (e.g., Cheng et al., 2021; Xiong et al., 2024) show a significant radiogenic component (high ^{4}He, low R/Ra). It is commonly interpreted as an indicator of He influx from the basement. This begs the question how He is mobilized from basement lithologies. Uranium and thorium, the elements contributing most to radiogenic ^{4}He production occur in most igneous, metamorphic or siliciclastic sedimentary rocks as substituents in accessory heavy minerals, e.g., apatite, monazite, titanite, or zircon. Zircon stands out as a phase for He production and storage due to its high U and Th concentrations, and the relative immobility of helium in its crystal lattice at temperatures < 140 °C. Here, we study the possibility of He release through fractures in zircon grains, and compare this effect to diffusive He loss.

Theory / Method / Workflow

Zircon ($ZrSiO_4$) is a common accessory mineral in igneous, metamorphic and siliciclastic sedimentary rocks. Its most striking property is the incorporation of radioactive U and Th into its crystal lattice. With concentrations between 10^2 to 10^4 µg/g, these elements are about 10–1000 times enriched compared to the average upper continental crust (2.7 µg/g U, 10.5 µg/g Th; Rudnick and Gao, 2014). Zircon thus holds a significant amount of the U and Th budget of crustal rocks, despite its small share of the total rock volume. The α-decay of U, Th, and their radioactive daughter nuclides over geological timescales is the most important source of radiogenic ^{4}He. The higher a zircon's U and Th concentrations, and the longer the accumulation time, the more ^{4}He is produced

Besides producing ^{4}He, zircon is also a robust reservoir for crustal helium. It is chemically and mechanically stable and He diffusion in its crystal lattice is too slow for significant loss at temperatures ≤130 °C (Fig. 1b). This raises the question how helium is mobilized from zircon at shallow crustal depths (<5 km) to form economical viable reservoirs. One mechanism is enhanced He loss from old or U- and Th-rich zircon that suffered high doses of lattice damage from the α-self-irradiation (Fig. 1b; Hurley et al., 1956, Guenthner et al., 2013). Above an α-dose of about 200 10^{16} α/g, corresponding to a grain with 500 µg/g uranium accumulating damage for

approximately 1.3 Ga (purple line in Fig. 1b), the relationship of temperature and diffusive He-loss gradually shifts to shallower depths (Fig. 1a).

Alternatively, fractures in zircon (Figs. 1c, d) provide effective temperature-independent He-degassing pathways. The dominant mechanism for forming fractures in zircon is by differential expansion of zones during radiation-damage accumulation (Lee and Tromp, 1995). This leads to heterogeneous fracture densities by zone (Fig. 1c) and different fracture patterns in grain cores and rims (Fig. 1d).

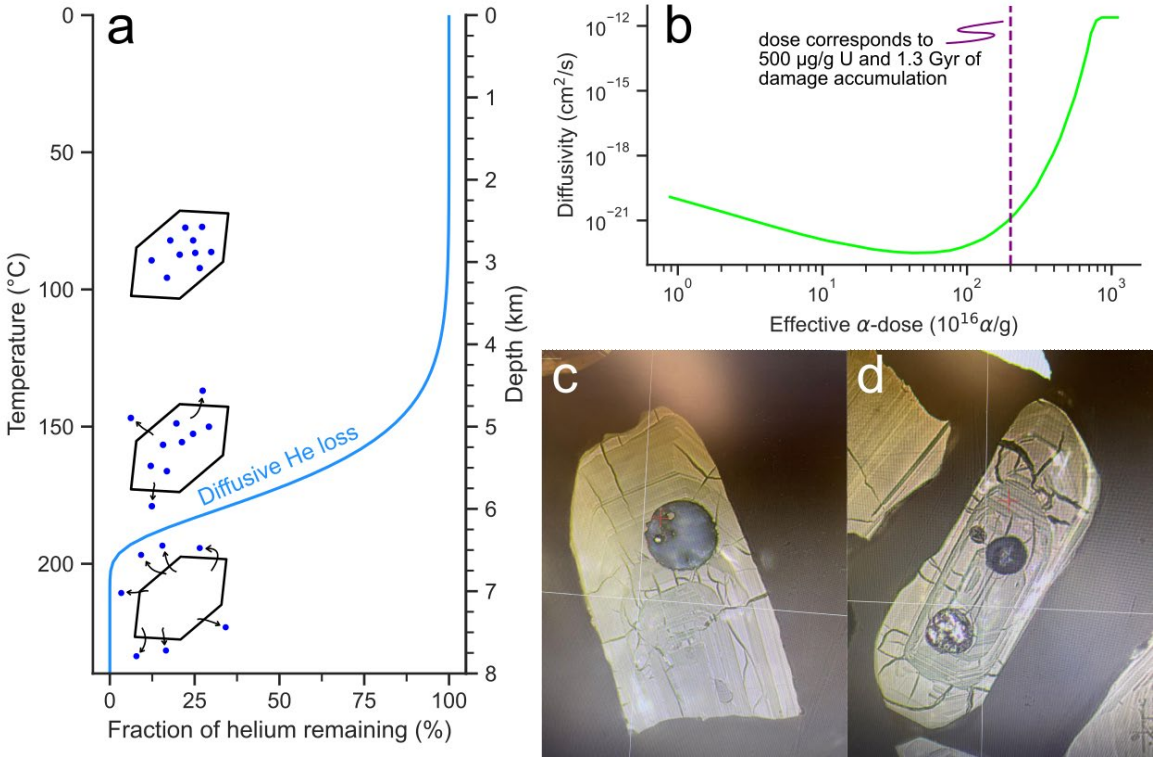


Figure 1. Overview of mechanisms for helium release from zircon. (a) Helium remaining in the zircon grain (%) as a function of temperature and depth (diffusion parameters of Reiners et al. (2004) for a grain with 60 µm radius). The inset figures illustrate diffusive helium loss. (b) Helium diffusivity in zircon (at 140 °C) as a function of radiation damage based on Guenthner et al. (2013). The purple line marks the approximate onset of enhanced He diffusivity. (c-d) Images of Paleoproterozoic zircon grains from the Western Canadian Shield with typical fracture patterns. The round laser-ablation spots have a diameter of 33 µm.

Our research focuses on the question if and how these fractures allow for a significant He loss from a zircon grain. We test this hypothesis by analyzing zircon grains with in-situ laser-ablation noble-gas mass spectrometry.

Results, Observations, Conclusions

We present maps of U-concentration-normalized helium concentrations for Paleo- to Mesoproterozoic basement zircon from the Canadian Shield and the Mid-Continent Rift. We compare the degrees of relative helium loss for grains with different fracture densities and patterns, as well as different levels of α-radiation damage.

This study adds to the growing research on understanding He occurrences in hydrocarbon wells by asking the question of how to effectively extract ^{4}He from zircon grains. Understanding the first step of He mobilization sets the foundation for understanding He-mobility and accumulation within geologic units for targeted exploration.

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