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Natural Hydrogen and Helium Systems of Canada: Geological Controls and Exploration Implications

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Summary

Hydrogen (H_2) is continuously generated within Earth continental crust through a range of geological processes (Ballentine et al., 2025; Sherwood Lollar et al., 2014), yet it is still unclear what range of environments support the best chance for free hydrogen gas of economic potential. Natural H_2 is commonly associated with specific geological settings, including ultramafic rocks undergoing serpentinization, hydrothermal systems, and fractures in crystalline basement rocks. Helium (He), an inert noble gas, is generated naturally with H_2 during the radiogenic decay of U, Th, and K in continental crust (Ballentine and Burnard, 2002; Sherwood Lollar et al., 2014). The H_2 generation rates in continental settings (radiolysis and serpentinization) are generally slow, favoring long-term accumulation models analogues to natural gas systems (Ballentine et al., 2025; Etiope et al., 2026). This shared origin links the generation, migration, and accumulation of H_2 and He, making their combined assessment particularly relevant for energy transition and critical mineral strategies.

Canada provides a particularly favorable geological setting for assessing these resources. Canada is underlain by extensive Precambrian crystalline basement, representing some of the oldest continental crust on Earth, and it is overlain by multiple large sedimentary basins containing thick succession of reservoir and sealing intervals. Together these features provide the fundamental components for H_2 and He generation, migration, and potential accumulation. Despite this favorable geological context, Canada's natural H_2 potential has not previously assessed in a systematic, national scale framework as was recently done for the United Kingdom (The Royal Society, 2025).

This study presents the first Canada-wide synthesis of natural H_2 and He systems using both integrated data from geological and geochemical studies, and a modeling approach. A source-reservoir-seal framework adapted from petroleum system analysis and recent natural hydrogen system concepts (Ballentine et al., 2025) was applied to Canadian geology. Publicly available gas compositions from industry, government open-file reports, and peer-reviewed studies were compiled into a unified database. These datasets were harmonized, quality checked and evaluated alongside lithogeochemical and petrological information from both exposed and buried basement domains.

First-order numerical models (Sherwood Lollar et al., 2014; Warr et al., 2023) were used to estimate H_2 and He generation by radiolysis and serpentinization across representative Canadian lithologies. Results indicate that H_2 and He generation potential varies strongly with rock type, age, mineralogy, ferrous iron (Fe^{2+}) content, and concentration of radiogenic elements. While H_2 and He generation is widespread in Precambrian crust, the likelihood of accumulation depends

on structural pathways, basin architecture, and presence of effective caprocks such as evaporite, shales, tight carbonates units. Key controls on H_2 accumulation are also exerted by the depth of penetration of recharging groundwater and blooms of H_2-utilizing microbial activity that such water infiltration sustains (Sherwood Lollar et al., 2024, 2014; Song et al., 2024).

Major Canadian sedimentary basins – including the Western Canada Sedimentary Basin, Williston Basin, Michigan and Appalachian basins – exhibit geological conditions favorable for trapping basement-derived H_2 and He (Cheng et al., 2023). Helium serves as a particularly robust tracer of deep radiogenic gas generation and long-term retention, providing an important tool for evaluation of H_2 systems. The H_2 and He distribution maps generated from legacy data reveal regional H_2 and He anomalies; however, these patterns require cautious interpretation due to variable sampling methodologies, analytical limitations, and the potential influence of non-geological (largely microbial) H_2 sources.

Occurrence of H_2-rich gases documented in deep mines within the Canadian Shield (Sherwood Lollar et al., 2014; Warr et al., 2019) demonstrate that H_2 is actively generated and retained within fractures in crystalline rocks. Nevertheless, the potential for such basement domains to function as source-reservoir systems, particularly when coupled with He co-production, remains largely unexplored in Canada. The H_2 and He distribution maps reflect historical exploration focus rather than intrinsic geological potential. This synthesis provides a national framework for identifying priority research directions, targeted data acquisition, and future exploration in Canada.

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