Advances in Geo-Energy Research

Vol. 15, No. 2, p. 91-94, 2025

Perspective

Advances in global natural hydrogen research and exploration

Shuangbiao Han[1]*, Jie Huang[1], Alain Prinzhofer[2], Chengshan Wang[3]

[1] *College of Geoscience and Surveying Engineering, China University of Mining and Technology (Beijing), Beijing 100083, P. R. China*

[2] *GEO4U, Rio de Janeiro 22250-040, Brazil*

[3] *School of Earth Sciences and Resources, China University of Geosciences (Beijing), Beijing 100083, P. R. China*

Keywords:
Natural hydrogen
clean energy
hydrogen enrichment
hydrogen exploration

Cited as:
Han, S., Huang, J., Prinzhofer, A., Wang, C. Advances in global natural hydrogen research and exploration. Advances in Geo-Energy Research, 2025, 15(2): 91-94.
https://doi.org/10.46690/ager.2025.02.01

Abstract:
The development of natural hydrogen confronts numerous challenges. This paper summarizes the status of research and exploration in the natural hydrogen field and outlines future directions and trends. The accumulation of natural hydrogen is a dynamic process, and current research on its origins, migration pathways, reservoir and cap rocks, chemical and biological consumption and final occurrence state is still at the exploratory stage. This lack of comprehensive understanding hinders the exploration and commercial development of natural hydrogen. Due to the unique characteristics of natural hydrogen, there is currently a shortage of effective exploration technologies and commercial development cases for natural hydrogen. The dynamic enrichment process of natural hydrogen and the consumption reaction mechanisms during this process will be the main aspects of future theoretical research on natural hydrogen. Additionally, the exploration of natural hydrogen needs to be combined with more practical applications of theory to enrich experience. It is necessary to establish and standardize work processes for different geological environments to achieve commercial development of natural hydrogen.

1. Introduction

Natural hydrogen can effectively reduce global reliance on fossil fuels and thereby decrease carbon dioxide emissions. However, the development of this field confronts numerous challenges, mainly in the aspects of theoretical research on natural hydrogen generation, exploration and development techniques. Hydrogen has a higher calorific value when burned compared to traditional fossil fuels, and natural hydrogen is a genuinely Zero-Carbon clean energy source with great development prospects. It forms through various mechanisms and is widely distributed in multiple geological environments, including sedimentary basins, tectonic activity zones, geothermal areas, and volcanic rock regions (Milkov, 2022). In the context of pursuing a low-carbon economy, the discovery of natural hydrogen offers new possibilities for the global energy transition. With the advancement of science and technology, people's understanding of natural hydrogen is gradually deepening, and interest in its development and utilization is growing. After the successful exploration and commercial development of natural hydrogen in the Bourakebougou region of Mali, Africa, a wave of exploration for natural hydrogen has spread worldwide. Many countries have initiated a series of research and exploration projects aimed at exploring and assessing natural hydrogen resources, as well as studying their economic viability and commercial potential. Nevertheless, the large-scale commercial development of natural hydrogen is still in its early stages and confronts numerous challenges, such as research on accumulation theory and improvements in exploration and development technologies.

This paper summarizes and discusses current frontier issues in the development of natural hydrogen, including dynamic accumulation, origin and sources, occurrence mechanisms, distribution prediction, resource prospects, and exploration. It also looks ahead to the development trends and directions in

Yandy Scientific Press

*Corresponding author.
E-mail address: bjcuphan@163.com (S. Han); lukehuangjie@163.com (J. Huang); prinzhofer2@gmail.com (A. Prinzhofer); chshwang@cugb.edu.cn (C. Wang).

Received November 3, 2024; revised November 18, 2024; accepted November 29, 2024; available online December 1, 2024.

the field of natural hydrogen.

2. Theoretical study on natural hydrogen enrichment

The study of natural hydrogen accumulation demands a comprehensive consideration of four aspects: "hydrogen source", "migration pathways", "reservoirs" and "cap rocks or barriers" .Furthermore, the consumption, the phase occurrence of natural hydrogen during its generation, migration, and accumulation are also important research topics. Due to the characteristics of hydrogen, such as its small molecular size, its rapid diffusion rate, and its extremely reactive chemical properties, it undergoes varying degrees of migration, diffusion, and consumption even as it is generated. Therefore, unlike conventional oil and gas, the accumulation of natural hydrogen is a dynamic process with short residence time scales compared to hydrocarbon ones. When the amount of natural hydrogen generated far exceeds the amounts diffused and consumed, the hydrogen migrates through faults or fracture systems to rocks with reservoir and cap rock properties, where it can exist in various forms such as free, adsorbed, and dissolved states. As natural hydrogen is continuously generated with large flux and migrates into the reservoir system, it eventually accumulates to form high-concentration natural hydrogen reservoirs.

The causes and source rock types of natural hydrogen are diverse, ensuring the generation of large amounts of natural hydrogen. These can be broadly classified into organic and inorganic types. Organic natural hydrogen is mainly produced through the thermal decomposition of organic matter at high thermal stress and microbial activity. Most discovered natural hydrogen is of inorganic origin, mainly through the water-rock reactions represented by serpentinization (or more generally chemical water reduction through the oxidation of ferrous iron into ferric iron), which may be the primary global source of natural hydrogen. Organic-rich mudstones and coal rocks generate a certain amount of hydrogen during their thermal evolution, making them potential source rocks for organically derived natural hydrogen. Currently, the main methods for identifying the origin of hydrogen involve the use of hydrogen isotopes and the study of associated gases such as noble gases. However, the mechanisms of hydrogen production vary in different geological environments, and there is no clear method to definitively determine the source of natural hydrogen.

A large number of studies have demonstrated that after natural hydrogen is generated, it migrates and diffuses through faults and fractures developed underground. These large-scale fracture-dominated fault structures may be the primary migration pathways for hydrogen. After natural hydrogen is formed, as it moves along its migration path, the hydrogenation of rocks can form various compounds, including water, hydrocarbons, and acids, all of which can be easily mobilized and transported out of the reaction zone. During this process, the vertical migration of hydrogen gas may cause an increase in rock porosity, thereby forming its own vertical migration channels. "Fairy circles" are manifestations of underground hydrogen gas migrating to the surface. If the hydrogen migration paths can be inferred from the relationship between "fairy circles". and the underground fracture system, it might provide more reliable guidance for the exploration of natural hydrogen.

The reservoirs containing natural hydrogen exhibit a diverse range of lithologies, including shale, coal, sandstone, kimberlite, evaporites, and various metal deposits. Due to the small molecular weight of hydrogen, it has a stronger diffusion capability compared to gases like methane, thus requiring more stringent conditions for storage and sealing. One of the most typical examples of natural hydrogen reservoirs is found in Mali, where carbonate rocks with an average porosity of 4.27% and sandstones with an average porosity of 5.50% serve as the reservoirs, while diabase acts as the main cap rocks (Maiga et al., 2023). Sedimentary rocks, because of their higher porosity and permeability, make it easier for hydrogen to escape; however, adsorption experiments have indicated that clay minerals and organic-rich clastic rocks can significantly adsorb hydrogen.

The significant differences in hydrogen content under various geological conditions are not only related to the hydrogen generation capacity of hydrogen sources but may also be influenced by consumption reactions occurring among inorganic minerals, formation water, and organic matter with natural hydrogen in the subsurface environment. The consumption pathways of natural hydrogen can be classified into inorganic and organic ones. Organic consumption mainly involves the catalytic effects on the evolution of organic matter structure and microbial consumption; while inorganic consumption typically presents as reactions between hydrogen and minerals or other gases in the subsurface environment, resulting in the formation of new substances. This complex series of interactions collectively determine the distribution characteristics and content variations of natural hydrogen in different geological environments. However, research on the reaction and consumption processes of natural hydrogen from its generation to enrichment is still poorly quantified.

Based on the analysis of typical examples of high-content natural hydrogen discoveries worldwide, the occurrence states of natural hydrogen can mainly be classified into four types: free state, dissolved state, inclusion state, and adsorbed state. Moreover, metal hydrides generated under high-temperature and high-pressure conditions underground can also be considered as another form of natural hydrogen occurrence. The different occurrence states of natural hydrogen gas can transform into one another due to changes in external conditions such as temperature and pressure, similar to the dynamic process of natural hydrogen accumulation. Free-state natural hydrogen gas is considered the main form of natural hydrogen occurrence. Natural hydrogen seepage points discovered at the surface in countries like Turkey and Oman are all in the free state (Etiope, 2023; Leong et al., 2023). In Mali, naturally occurring hydrogen generated deep underground rapidly fills the voids created by extraction in its free state. A considerable amount of natural hydrogen dissolved in groundwater is gradually released and replenished as temperature and pressure conditions change (Maiga et al., 2023).

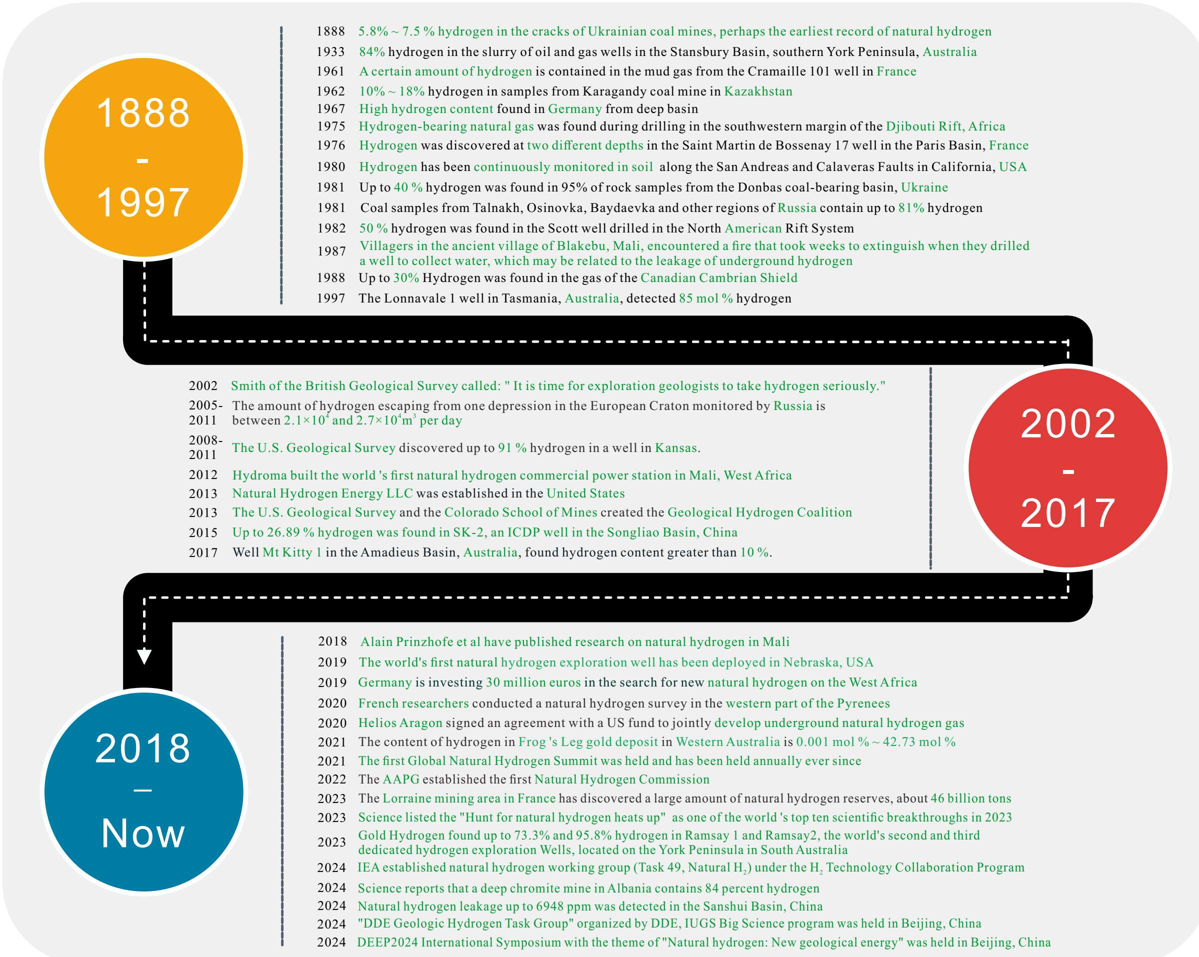

Fig. 1. Global natural hydrogen exploration and development history.

3. Natural hydrogen exploration and technology

According to historical records, the existence of natural hydrogen gas has been documented since 1888 (Zgonnik, 2020). Up to now, human research and exploration in the field of natural hydrogen can be divided into three main phases (Fig. 1): initial discovery (1888-1997), preliminary exploration (2002-2017), and rapid development and theoretical exploration (2018 to Now).

Although there might have been records of natural hydrogen as early as 1888, scholars truly recognized its importance and began exploration or research only after 2018. In 2012, Hydroma, a Canadian company, established a commercial power station for natural hydrogen in Mali, making Mali's natural hydrogen the first and only one globally to achieve commercial development. The publication of research on the commercial development of Mali's natural hydrogen (Prinzhofer et al., 2018) provided some theoretical guidance for finding natural hydrogen, leading to a significant increase in the number of explorations and studies related to natural hydrogen. The enthusiasm for exploring natural hydrogen continued through 2023, and the "Hunt for natural hydrogen heats up" was listed by Science as one of the top ten scientific breakthroughs of 2023. Scholars also published research articles on natural hydrogen in Science (Couzin-Frankel et al., 2023; Truche et al., 2024). It was also in 2023 that the dedicated natural hydrogen exploration wells Ramsay1 and Ramsay2, drilled by Gold Hydrogen, an Australian company, in the York Peninsula of Australia obtained natural hydrogen with concentrations of 73.3% and 95.8%, respectively. To date, countries such as Australia, France, Brazil and China have conducted surface seepage detection and other exploration activities for natural hydrogen and have discovered high-concentration natural hydrogen. In China, high-concentration natural hydrogen has been identified in various geological environments and stratum, showing widespread distribution and broad prospects for exploration and development (Han et al., 2022; Jin et al., 2024). Additionally, many countries and regions worldwide have formulated policies and plans for the exploration and development of natural hydrogen, considering it a crucial support for future energy transitions. Considering that the enrichment of natural hydrogen reservoirs requires consideration of multiple factors such as hydrogen sources, reservoirs, migration pathways, and cap rocks, the core areas of ancient continental cratons, with their unique and rich geological conditions, can be considered as one of the main target regions for future natural hydrogen exploration.

The exploration and development technology for natural hydrogen is significantly different from conventional and unconventional oil and gas. It requires the use of multiple methods such as remote sensing, aeromagnetic surveys, field gas component detection, and seismic techniques to identify areas of natural hydrogen leakage, such as "fairy circles" or reactivated faults. These methods help analyze the characteristics of large rock bodies and structures involved in the generation and migration of natural hydrogen, preliminarily determining the location of natural hydrogen sources and their relationships with ophiolites, faults, and special mineral resources. Based on this understanding, dedicated exploration wells for natural hydrogen can be arranged. High-precision logging techniques can accurately analyze the depth and reservoir characteristics of natural hydrogen enrichment, aiming to discover high-concentration natural hydrogen indicators, ultimately leading to commercial development. However, currently, only natural hydrogen in Mali has been commercially developed (for a pilote power generation in small towns). Although high-concentration natural hydrogen has been discovered in the York Peninsula of Australia, it is still in its early stages and has not yet entered commercial development. There are no excellent examples available for global reference in the exploration and commercial development of natural hydrogen. The occurrence patterns of natural hydrogen in different geological environments are complex, and there is currently no fully established and unified workflow. Further exploration and potential assessment of natural hydrogen resources require the integrated application of multiple geophysical and geochemical exploration methods and drilling, not limited to soil and existing well gas measurements.

4. Conclusions and prospects

Natural hydrogen is an important green and clean energy source. Research and exploration of natural hydrogen have become global hotspots, but they are still in the exploratory stage. The weak theoretical research on the enrichment mechanism of natural hydrogen has led to difficulties in exploration and development, while the lack of effective exploration techniques also hinders theoretical research. Currently, the methods for studying the accumulations of natural hydrogen are relatively simple, and mainly rely on the experimental methods of classical oil and gas reservoir systems. Due to the unique physical and chemical properties of natural hydrogen, these methods are not entirely applicable, and there is an urgent need to explore innovative experimental equipment and methods specifically designed for natural hydrogen research. In the future, research priorities should gradually shift to the dynamic mechanisms of diffusion, migration, and occurrence during the formation of natural hydrogen reservoirs, as well as the consumption processes that occur when natural hydrogen interacts with minerals, water, microorganisms, and organic matter, whether in situ or during migration. For the exploration of natural hydrogen, continued geological surveys of natural hydrogen resources by countries around the world are needed to gradually accumulate experience and establish high-precision surface detection and source identification techniques. Ultimately, this will help clarify the workflow for natural hydrogen resource exploration. The integration of interdisciplinary approaches in natural hydrogen exploration will be a future trend, providing strong support for the exploration, development, and theoretical research of natural hydrogen reservoirs.

Acknowledgements

This research was supported by the National Natural Science Foundation of China (No. 42072168).

Conflict of interest

The authors declare no competing interest.

References

Couzin-Frankel, J., Hand, E., Langin, K., et al. 2023 Breakthrough of the Year. Science, 2023, 382(6676): 1228-1233.

Etiope, G. Massive release of natural hydrogen from a geological seep (Chimaera, Turkey): Gas advection as a proxy of subsurface gas migration and pressurised accumulations. International Journal of Hydrogen Energy, 2023, 48(25): 9172-9184.

Han, S., Tang, Z., Wang, C., et al. Hydrogen-rich gas discovery in continental scientific drilling project of Songliao Basin, Northeast China: New insights into deep Earth exploration. Science Bulletin, 2022, 67(10): 1003-1006.

Jin, Z., Zhang, P., Liu, R., et al. Discovery of anomalous hydrogen leakage sites in the Sanshui Basin, South China. Science Bulletin, 2024, 69(9): 1217-1220.

Leong, J.A., Nielsen, M., McQueen, N., et al. H_2 and CH_4 outgassing rates in the Samail ophiolite, Oman, Implications for low-temperature, continental serpentinization rates. Earth and Planetary Science Letters, 2023, 347: 1-15.

Maiga, O., Deville, E., Laval, J., et al. Characterization of the spontaneously recharging natural hydrogen reservoirs of Bourakebougou in Mali. Scientific Reports, 2023, 13: 11876.

Milkov, A.V. Molecular hydrogen in surface and subsurface natural gases: Abundance, origins and ideas for deliberate exploration. Earth-Science Reviews, 2022, 230: 104063.

Prinzhofer, A., Tahara Cissé, C.S., Diallo, A.B. Discovery of a large accumulation of natural hydrogen in Bourakebougou (Mali). International Journal of Hydrogen Energy, 2018, 43: 19315-19326.

Truche, L., Donz, F-V., Goskolli, E., et al. A deep reservoir for hydrogen drives intense degassing in the Bulqizë ophiolite. Science, 2024, 383(6683): 618-621.

Zgonnik, V. The occurrence and geoscience of natural hydrogen: A comprehensive review. Earth-Science Reviews, 2020, 203: 103140.