Scientific Contributions Oil & Gas, Vol. 48. No. 1, April: 91 - 112

SCIENTIFIC CONTRIBUTIONS OIL AND GAS

Testing Center for Oil and Gas

LEMIGAS

Journal Homepage:http://www.journal.lemigas.esdm.go.id

ISSN: 2089-3361, e-ISSN: 2541-0520

The Emergence of Natural Hydrogen: Genesis and Current Perspectives

Himmat Singh

"G" CSIR-Indian Institute of Petroleum
Haridwar Rd, IIP, Mohkampur, Dehradun, Mohkam Pur Khurd, Uttarakhand 248005, India

R & D BPCL Mumbai & EX
13, Sewri Ft Rd, BPCL Complex, Sewri, Mumbai, Maharashtra 400015, India

Universities of Chandigarh, Mohali & UPES
Chandigarh University, NH-05, Ludhiana, Highway, Chandigarh State, Punjab 140413, India

Corresponding author: drhimmats@gmail.com

Manuscript received: November 07th, 2024; Revised: November 28th, 2024
Approved: January 16th, 2025; Available online: April 09th, 2025.

ABSTRACT - In recent years, natural hydrogen has emerged as a promising source in the future energy mix. Since its accidental discovery in Mali in 2012, global interest in this form of hydrogen—often called geological, white, or gold hydrogen—has surged. Generated primarily through serpentinization, a process where water reacts with iron-rich minerals, natural hydrogen can become trapped in reservoirs beneath impermeable rocks. Other natural processes also contribute to its formation. A recent discovery by French and Albanian scientists found a large natural source of hydrogen gas outgassing from the deep underground Bulqizë chromite mine having 85% purity with minimal methane contamination, resulting in a low carbon intensity of around 0.4 kg CO_2e per kg of hydrogen produced compared to black hydrogen (22-26 kg CO_2e/kg) and blue hydrogen (10-14 kg CO_2e/kg). According to Rystad Energy, white hydrogen could potentially transform the clean hydrogen sector, shifting it from an energy carrier to a primary energy source. Interest in natural hydrogen is growing rapidly, with the number of companies involved, increasing from 10 in 2020 to 40 by the end of last year. Exploration is underway in countries like Australia, the U.S., Spain, France, Albania, and Canada. Canada-based Hydroma, for instance, extracts white hydrogen at just $0.50 per kg, while projects in Spain and Australia aim for around $1 per kg. This suggests that natural hydrogen could offer a cost-effective, low-carbon energy alternative. Studies show far more natural hydrogen underground than believed, well-funded efforts to drill for the gas are underway around the globe. Boosters see a plentiful green replacement for fossil fuels, but few skeptics think otherwise. This article examines the potential of natural hydrogen that is expected to play, a key role in achieving a net-zero carbon future by exploring its science, economics, and ongoing global exploration efforts.

Keywords: natural hydrogen, gold and white hydrogen, geological hydrogen, serpentinization, radiolysis, exploitation of hydrogen reservoirs and subduction.

How to cite this article:

Himmat Singh, 2025, The Emergence of Natural Hydrogen: Genesis and Current Perspectives, Scientific Contributions Oil and Gas, 48 (1) pp. 91-112. DOI.org/10.29017/scog.v48i1.1691.

INTRODUCTION

Natural hydrogen (also referred to as gold, white, or geological hydrogen) is produced deep within the Earth that has been trapped by impermeable barriers on its way to the atmosphere, similar to the way petroleum was stored over time (Rubén Blay-Roger et al. 2024). This type of hydrogen can be extracted from wells in a similar manner as fossil fuels, such as oil and natural gas, (Gaucher Éric 2020; Hand Eric 2023). Natural hydrogen has been discussed in the geological literature for over 100 years. The German scientist Ernst Erdmann described in 1910, how he had detected an outflow of hydrogen at a salt mine and tracked it for four and a half years. But the possibility of widespread subterranean sources was still poorly understood, even into the 1980s, says Barbara Sherwood Lollar, a geologist at the University of Toronto (Chris Baraniuk 2022). She recalls surveying sites for gases back and realizing that significant volumes of hydrogen were present in the ground.

Naturally occurring molecular hydrogen is generated by a range of geological and biological processes which occur both shallow and deep within the Earth's crust. Some of the hydrogen produced can be detected when it seeps to the Earth's surface. For example, diffused flow of molecular hydrogen (H_2) through the Western Hajar mountains of Northern Oman (Viacheslav Zgonnik et al. 2019).

The term 'Gold hydrogen' is given specifically to hydrogen produced by microbial activities in depleted oil wells (IEC Editorial Team 2023). Cemvita Factory, a biotech firm in Texas says Gold Hydrogen' is an untapped resource in depleted oil wells (Chris Baraniuk 2022). It combines natural systems with technological innovations to convert leftover hydrocarbons from subsurface wells into usable hydrogen while capturing and storing CO_2.

There is currently a global rush for natural hydrogen-a previously underestimated resource, as advocates suggest. It could greatly aid in the transition away from fossil fuels. Scientists are looking to geological hydrogen as a promising avenue for clean energy. Rystad Energy (Sam Meredith 2024) attributes the excitement to the belief that this untapped resource could revolutionize the clean energy sector.

White and gold hydrogen offers significant cost and emissions advantages including lower carbon footprint relative to other means of hydrogen production. Producing green hydrogen requires significant amounts of renewable energy, potentially making it counterproductive for achieving decarbonization goals, while gold hydrogen bypasses the need for energy-intensive production processes.

White or Gold hydrogen, holds potential for various uses including power generation, transportation, heating, and industrial processes. Its storage capability also makes it suitable for off-grid power setups and facilitating rural electrification. The question on everyone's lips is whether this gas has a real future: Is it a viable alternative to producing hydrogen from fossil fuels or electrolysis. Discussions below present an update on the technological/scientific status of natural hydrogen and possible response to the above question.

METHODOLOGY

The methodology adopted to explain various elements concerning technological features of natural hydrogen, after a fairly detailed literature scan of recent publications/articles, is detailed below

Discovery, discoveries shaping into major projects, case studies and hot spots

The accidental discovery of geologic hydrogen occurred in 1987 in a small village, roughly 60 kilometers from Mali's capital of Bamako, west Africa. A failed attempt to drill for water by Canada's Hydroma, hit upon an abundance of odorless gas that was inadvertently found to be highly flammable. The well was plugged and aborted. But almost 20 years later, engineers on the hunt for fossil fuels confirmed the discovery: hundreds of feet below the arid earth and found geologic reservoirs containing nearly pure White hydrogen gas. Today, the resource is being used to provide power to the Malian village of Bourakébougou (Sam Meredith 2024).

In October 2023, researchers at the French National Centre of Scientific Research (CNRS) discovered a large reservoir of natural hydrogen in north eastern France's Lorraine coal basin. The reservoir may contain 250 million tons of naturally occurring hydrogen - enough to provide almost as much energy as the U.K's largest oil field (the Clair field, west of Shetland) (Sam Meredith 2024; Kheira Bettayeb 2023; The Conservation 2024). These deposits are considered to be the world's largest geologic hydrogen deposit to date.

A geologist team affiliated with a number of French institutions accompanied with two Albanian scientists have measured the biggest gold hydrogen flow ever found. According to the report, the team measured the gold hydrogen bubbling up through some of the chromium mine's liquid pools at multiple locations. They conducted an analysis of their measurements and produced an estimate of the total amount of H_2 escaping from under the mine. As per their findings every year, the mine allows about 200 metric tons of H_2 to escape, making it the largest natural hydrogen flow ever recorded (Bob yirka 2024).

This kind of hydrogen was previously dismissed as fictional at worst or untappable at best, but in the last few years "reservoirs" have been discovered in the United States, Canada, Finland, the Philippines, Australia, Brazil, Oman, Turkey, Mali and other European locations. The discovery of these multiple reservoirs has led the would-be gold hydrogen hunters to believe that there are numerous sources waiting to be discovered. An estimate published in Earth-Science Reviews back in 2020, indicates that the world could be extracting 23 million tons of hydrogen from the ground each and every year. And there's already a new wave of startups looking to do just that (Haley Zaremba 2024). Until recently, it was widely believed that natural hydrogen could not exist in a "free state" because it would quickly react with other molecules. However, recent scientific advancements have debunked this view. While there are still many unknowns regarding natural hydrogen and the scale of its potential commercialization, there is ample evidence to suggest that natural hydrogen merits attention and investment comparable to other "climate-saving" technologies.

The map (Figure 1) highlights all the locations where natural hydrogen has been accidentally discovered, typically during oil or water drilling operations. Primarily this includes locations in USA, western Europe - France & Spain, west Africa and two important locations in Australia which now have assumed the status of global natural hydrogen projects. However, the actual size of the reserves is still unknown, and challenges remain in the transportation and distribution of Hydrogen so produced.

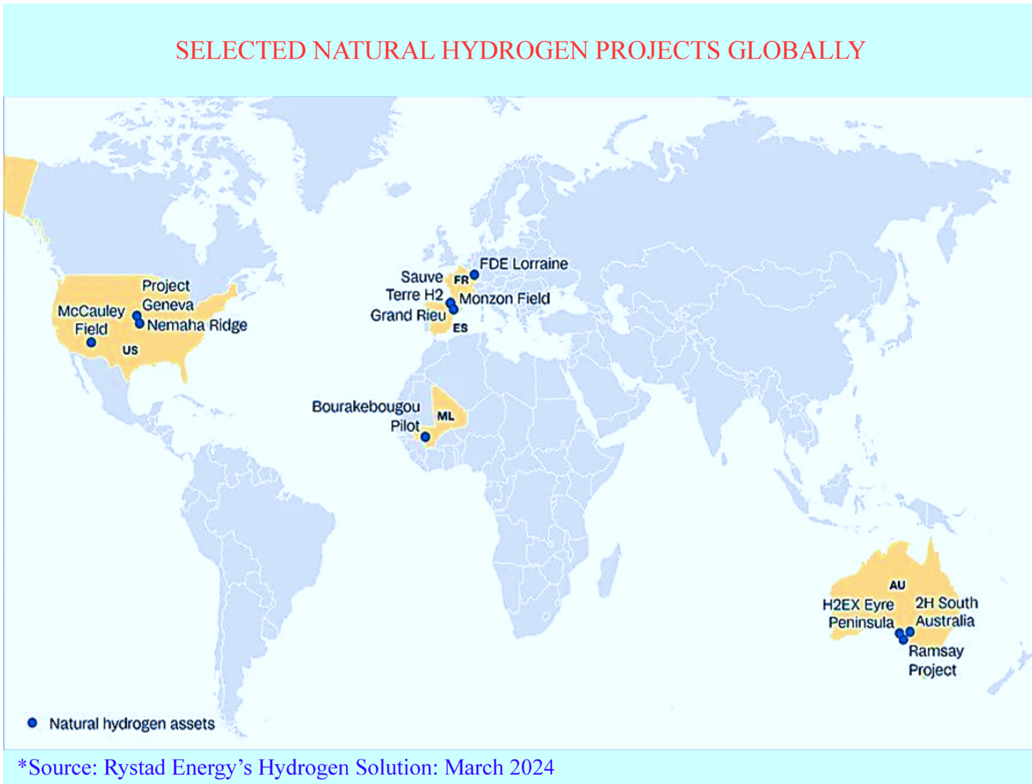


Figure 1
The map highlight's locations where natural hydrogen has been accidentally discovered and transforming into major Global projects (Green Review 2024).

Natural hydrogen is gaining global momentum as a potential gamechanger in the search for cost-effective, low-carbon energy sources. Rystad Energy research shows (RYSTAD 2024) that at the end of last year, 40 companies were searching for natural hydrogen deposits, up from just 10 in 2020. Currently, exploratory efforts are underway in Australia, the US, Spain, France, Albania, Colombia, South Korea and Canada.

Although natural hydrogen exploitation is still in its early stages, the number of boreholes, potential deposits, and companies involved is increasing rapidly. Identifying the optimal sites for exploration requires a multidisciplinary approach that integrates geology, multi-physical imaging and seismic interpretation. Though numerous global research projects are investigating natural hydrogen resources, specifics regarding quantities, costs, and exact locations often remain confidential. Researchers have noted that certain scientific indicators may predict white hydrogen sources. On land, "fairy circles" often signify potential deposits, while underwater subduction zones - where continuous water supply and exposure to iron occur due to plate movements—are also conducive to natural hydrogen production (Guillaume 2024; Moretti 2023). Other promising targets for hydrogen prospecting include fossil oceanic spreading centers (ophiolites) and suture zones, which mark the collision and complete subduction of ocean basins between continents (Merdith AS et al. 2023; Liu.Z et al. 2023).

Frery E. et al. report an increasing number of natural hydrogen seeps being documented worldwide, often linked to circular or sub-circular depressions known as 'fairy circles'. (Zgonnik V. 2015; Larin N. 2015; Moretti 2021; Prinzhofer A 2018). In areas lacking soil, H_2 emanations have been observed in rivers and lakes, where bubbling can indicate hydrogen presence, such as in New Caledonia (E. Deville & Alain Prinzhofe 2016). Figure 2 illustrates fairy circles across different locations globally.

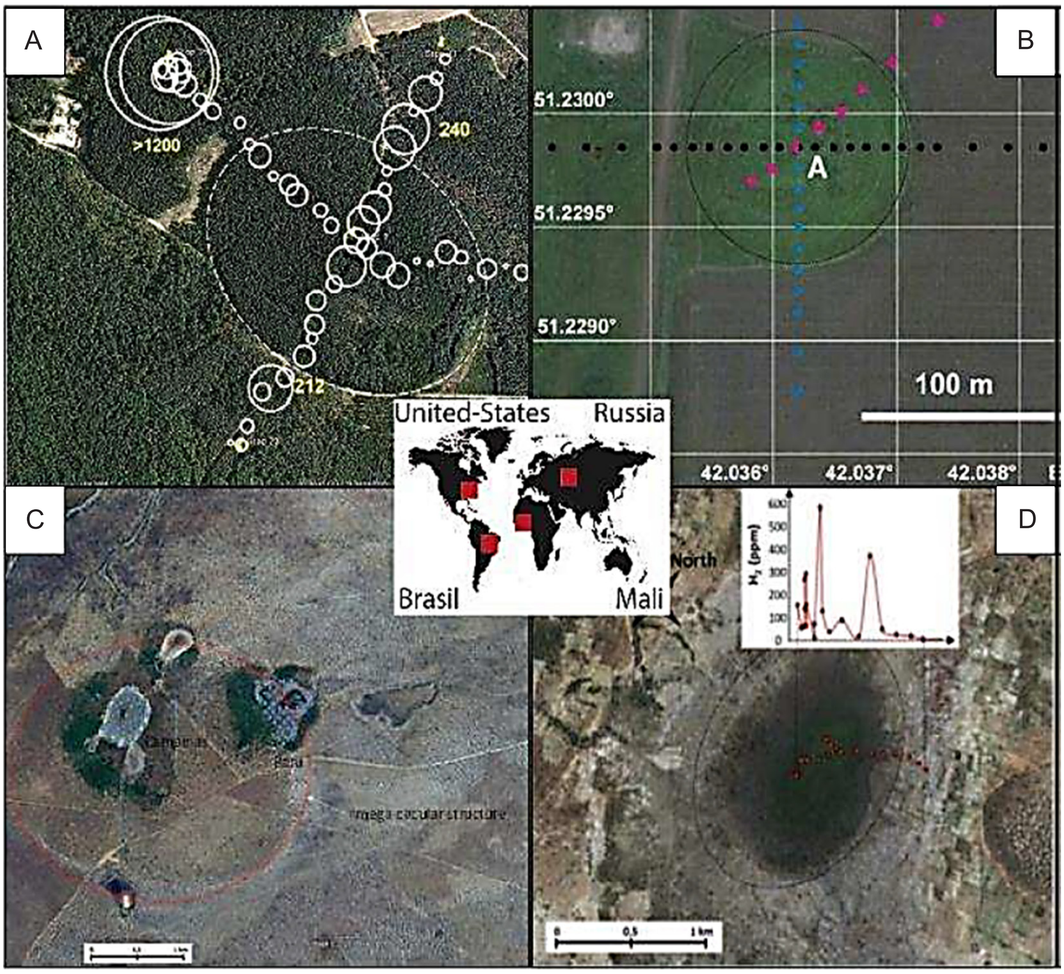


Figure 2
Fairy circles accross the globe (Zgonnik V. 2015; Larin N. 2015; Moretti 2021; Prinzhofer A. 2018)

Part A: In North Carolina, USA, a study of soil gases detected significant molecular hydrogen concentrations around morphological depressions, suggested to be surface expressions of fluid pathways for hydrogen gas moving from depth (Zgonnik V. 2015); Part B: In Central Russia, analysis of subsoil gas in subcircular morphological depressions revealed high molecular hydrogen levels in the soil, accompanied by small amounts of methane (Larin N. 2015).

Part C: In Brazil's São Francisco Basin (Minas Gerais), monitoring detected pulses of H_2 content in soil near fairy circles, interpreted as deep hydrogen flux leaking from an underlying reservoir or degassing aquifer (Moretti 2021). This geological setting resembles the intra-cratonic sedimentary basins in Australia's Northern Territory and Western Australia; Part D: In Mali, geochemical soil monitoring revealed notable hydrogen concentrations around a circular structure, with hydrogen exudations also recorded in another area to the east (Prinzhofer A. 2018).

Case Studies: Two case studies, one each pertaining to fairy Circles in Australia and another one relating to underwater subduction zone, in Bolivia are described below in relation to natural hydrogen production.

In Australia, many circular surface features, often referred to as salt lakes or swamps, are visible from above. Soil-gas analysis has shown consistent hydrogen concentrations around the outer ring of these circular depressions, which follow the Darling Fault - a significant crustal boundary dividing the granitic, mafic, and ultramafic rocks of the Yilgarn Craton from the sedimentary formations of the Perth Basin. This evidence supports the presence of "fairy circles," structures that emit hydrogen, in Australia, suggesting new opportunities for exploration (Frery E et al. 2021).

Neil McDonald (2023) reports a practical study, pertaining to Gold Hydrogen Ltd, an Australian company associated with Gold / White hydrogen. The study traces its history back to the 1920s and 1930s, when natural hydrogen occurrences were detected in the PEL 687 project during unsuccessful oil explorations. Gases from the Ramsay Oil Bore, collected by the State of South Australia and analyzed in a lab, showed high natural hydrogen concentrations between 66% and 89% (adjusted for air content). In October 2023, Gold Hydrogen successfully re-drilled the Ramsay Oil Bore (Ramsay 1) and drilled Ramsay 2, with results revealing up to 86% hydrogen and 6.8% helium concentrations.

In a subduction setting, slab dehydration, NH_4 destabilization, and hydration of the mantle wedge above the subducting lithosphere may lead to H_2 generation. Moretti I. et al. (2023) compiled data on gases in the central Pacific subduction and reported initial H_2 measurements taken across Bolivia, from La Paz to South Lipez. The study analyzed several areas: the emer$_2$ging thrust faults along the western border of the Eastern Cordillera, the Sajama region in the western volcanic zone near the Chilean border, north of Uyuni Salar, and the Altiplano-Puna Volcanic Complex in South Lipez. In the Cordillera's western margin, δC13 isotope values range from -5 to -13‰, aligning with volcanic gases and asthenospheric CO_2. Methane content is minimal, reaching 1% at only a few sites, and isotope values of -1‰ suggest an abiotic origin, indicating deep H_2 presence. High steam flow and H_2 content in South Lipez geothermal areas result in an estimated daily release of at least 1 ton of H_2 per well, warranting assessment for economic feasibility.

The hot spots: USA & Canada

In October 2023, the US Geological Survey reported that Earth's hydrogen reserves are likely to be much larger than previously estimated. Other geologists also see potential untapped hydrogen reserves across the US, Australia, and parts of Europe. This has sparked increased interest and the U.S. Department of Energy (DOE) has committed up to $20 million in funding for research into geologic hydrogen (Christian Robles 2024). "The potential is huge," said USGS geologist Geoffrey Ellis, noting that the estimated global supply of gold hydrogen is about 5 million megatons. Extracting just 2% could provide enough hydrogen for 200 years to meet net-zero emissions goals. Gold Hydrogen proposes extraction via drilling, akin to oil and natural gas. Meanwhile, startups are advancing projects, including Australia's HyTerra, which plans to drill for hydrogen in Kansas. Koloma - backed by Bill Gates' Breakthrough Energy, is exploring U.S. sites for gold hydrogen drilling (Christian Robles 2024).

Canada - another hotspot, has significant potential for natural hydrogen due to its vast land area and rock types, as highlighted by Omid Ardakani, a research scientist with the Geological Survey of Canada. Over 50% of Canada is covered by rocks that could potentially generate hydrogen. However, Ardakani notes that commercializing natural hydrogen will require extensive research, technological advancements, and regulatory support (Kyle Bakx;2024). Calgary-based petrophysicist Brière, vice-president at Chapman Hydrogen and Petroleum Engineering, plans to begin hydrogen exploration and drilling in northern Ontario this summer. The Geological Survey of Canada is also investigating, across the country, hydrogen storage in salt deposits and caverns. particularly in helium-rich areas of Saskatchewan and Alberta and seismic zones in British Columbia, drilling and testing for underground hydrogen are already underway in Ontario, with expansion plans for British Columbia (Resource Works; 2024).

How natural hydrogen is generated-mechanisms

Our understanding of natural hydrogen is evolving quickly, but we still lack a complete explanation of how it is formed, accumulates and is stored in subsurface environments. Evidence of natural hydrogen appears as both diffused seepages and subsurface reservoirs encountered through drilling, found across varied geological settings, suggesting there may be a variety of mechanisms generating natural hydrogen. Five recent studies (Rubén Blay-Rogeret et al. 2024; Betina Bendall 2022; Q. Tian et al. 2022, Morita RY. 1999; Philip & Krystian 2024) have explored subsurface hydrogen generation mechanisms, mostly with common principles. Betina Bendall (2022) proposed six mechanisms, while (Morita RY 1999; Philip & Krystian 2024) highlight two dominant regenerative mechanisms for natural hydrogen: (1) serpentinization of ultramafic and mafic rocks (e.g., peridotite) when interacting with subsurface water, and (2) water radiolysis, where water is split by radiation from radioactive minerals. Q. Tian (2022) classified natural hydrogen origins into two main types: Abiotic, which includes deep-seated hydrogen, water-rock interactions, and water radiolysis and Biogenic which involves anaerobic decomposition of organic matter, fermentation, and nitrogen-fixing bacteria. Additional potential sources include the degassing of primordial hydrogen from the Earth's mantle or crust, overmature source rocks, and biological activity.

Rubén Blay-Roger et al. (2024) visually represented the origins of natural hydrogen through eight hypotheses (Viacheslav Zgonnik 2020; Chas Newkey-Burden 2024) practically summarizing all the above thoughts, as shown in Figure 3 below. Though abiotic processes appear to dominate natural hydrogen formation, other hypotheses involving biological processes (e.g., decomposition of organic matter, fermentation) and abiotic processes (e.g., radiolysis, direct reduction of H_2O) are being considered, with serpentinization recognized as the most significant abiotic mechanism (Liu Z. 2023; Milkov A. 2022).

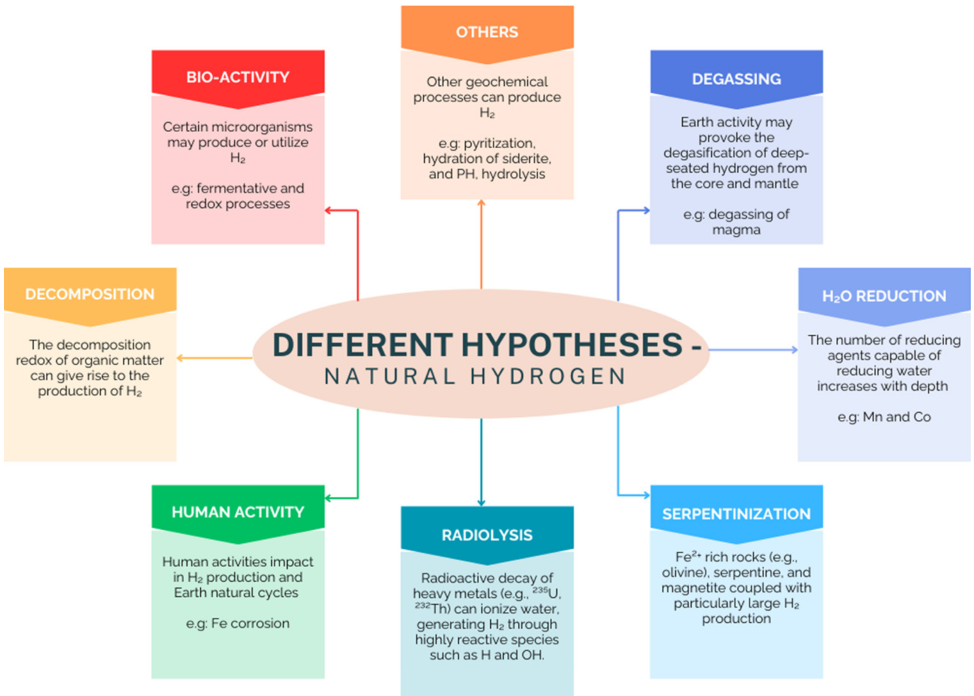


Figure 3
Different hypotheses about the origin of natural hydrogen deposits (Rubén Blay-Roger et al. 2024) Modified.

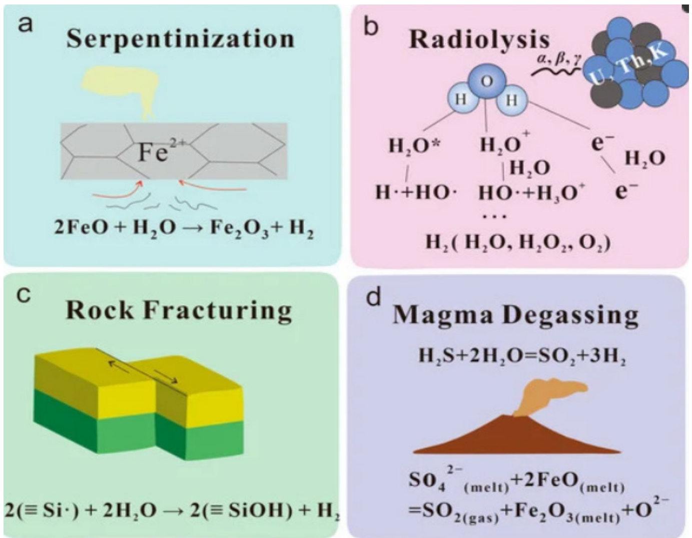


Figure 4
The primary hydrogen sources: alteration in fe(II)-containing rocks ,the radiolysis of water due to the radioactive decay of uranium, thorium, and potassium; degassed magma; and the reaction of water and surface-free radicals during mechanical fracturing of silica-containing rocks (Wang L. et al. 2023).

Wang L. et al. (2023) also presented pictorially four primary sources of natural hydrogen as shown in Figure 4 below: (a) serpentinization, where hydrogen is generated through water reduction during the oxidation of ferrous to ferric iron; (b) radiolysis, where radioactive decay splits water to produce hydrogen; (c) rock fracturing, which generates hydrogen on wet surfaces of active faults; and (d) volcanic degassing, where hydrogen is emitted from SO_2 at low pressures.

In nutshell although natural hydrogen primarily forms via two, dominant naturally regenerative mechanisms: (1) the serpentinization; and (2) water radiolysis, there are other equally significant mechanisms as well.

Summarizing the information reported in recent publications as discussed above; it is possible to state: subsurface natural hydrogen generation/formation mechanisms include (but are not limited to) following six regenerative mechanisms; 1). Reaction of water with ultrabasic rocks – serpentinization; 2). Water radiolysis, radioactive-rich rocks split water into its component atoms; 3). Degassing of magmas and deep-seated hydrogen from the earth core and mantle; 4). Biotic and Abiotic decomposition of organic matter; 5). Simulated /Engineered generation of natural hydrogen; 6). Mechanical and Medical Hydrogen generation.

Brief details of each mechanism are elaborated in the text below.

Serpentinization - reaction of water with ultrabasic rocks

Serpentinization is a geological process in which ultramafic rocks, rich in magnesium and iron (such as olivine and pyroxene), undergo transformation through their interaction with water, resulting in the formation of serpentine minerals and the release of hydrogen (H_2) and low-molecular-weight hydrocarbons like methane (CH_4). These by-products can potentially fuel microbial life in ecosystems lacking other energy sources.

Chemically, serpentinization (Antony Joseph 2023) involves the hydration and transformation of ferromagnesian minerals like olivine ($(Mg,Fe)_2SiO_4$) and orthopyroxene ($(Mg,Fe,Ca)(Mg,Fe,Al)(Si,Al)_2O_6$)). These minerals react with water to produce hydrogen-rich fluids and secondary minerals such as serpentine, magnetite, and brucite. An important aspect of serpentinization is the release of hydrogen, which can then react with carbon compounds like CO_2 and CO, leading to the formation of methane and other hydrocarbons through Fischer-Tropsch-type (FTT) synthesis.

Key hydrogen-producing reactions during serpentinization include:

Hydrolysis of olivine (serpentinization of olivine):

$$(Mg,Fe)2SiO4+H_2O \rightarrow serpentine+H_2 \quad (1)$$

Hydrolysis of pyroxene (serpentinization of pyroxene):

(Mg,Fe)SiO3+H2O→serpentine+H2+other secondary minerals (2)

Fischer-tropsch-type synthesis (methanogenesis):

$$CO_2+4H_2 \rightarrow CH_4+2H_2O$$
$$CO+3H_2 \rightarrow CH_4+H_2O \quad (3)$$

These reactions occur within a temperature range of 150°C to 400°C, typically found in environments like mid-ocean ridges, subduction zones, and tectonically active areas. The hydrogen produced can support microbial ecosystems in regions lacking sunlight or organic matter.

The key reactions involved in hydrogen formation during the serpentinization process as per Rubén Blay-Roger et.al, 2024 are shown below:

Research by Rubén Blay-Roger et al. (2024) and others have highlighted that molecular hydrogen (H_2) generated during the serpentinization of mantle rocks is a key energy source for chemosynthetic organisms. A study by Albers E. et al. (2021) on "Serpentinization-driven H_2 Production from Continental Break-up" offers insights into the geochemical processes within serpentinites peridotites at the West Iberia margin, presenting these main findings:

Rock composition and serpentinization

Samples taken from exhumed peridotites (specifically lherzolites) show extensive transformation into serpentine minerals, including an iron-rich type of serpentine with an XMg value (ratio of Mg to (Mg + Fe)) below 0.8, indicating a shift toward the cronstedtite variety.

Ferric iron content

Both bulk rock and silicate portions exhibit high Fe(III)/∑Fe ratios, ranging from 0.6 to 0.92, suggesting Fe(III)-rich serpentine plays a key role in the system's redox state and its potential for hydrogen production.

Hydrogen production

Initial serpentinization resulted in significant hydrogen generation—between 120 and over 300 mmol of H_2 per kg of rock. This production continued even during cold, late-stage weathering at the seafloor, leading to additional H_2 formation.

Geological evolution and H_2 Generation

The study suggests that H_2 production evolves with tectonic changes, from continental break-up to ultraslow and slow mid-ocean ridge (MOR) spreading. Variations in the mineral phases across these environments influence hydrogen yields during serpentinization, indicating that hydrogen production capacity adapts to geological conditions, which may have implications for potential energy sources for subsurface microbial ecosystems.

In summary, serpentinization, particularly in continental break-up and oceanic settings, is a dynamic, long-lasting hydrogen-generating process. The rock's mineral composition, especially iron content and minerology, is a critical factor influencing H_2 production, which can sustain microbial life in subsurface environments. Baptiste Debret et al. (2024) suggest that the geodynamical settings influence Fe oxidation processes and, therefore, H_2 production at mid-oceanic ridges. Iron oxidation state in abyssal serpentinites is primarily distributed along a serpentinization gradient affecting the oceanic lithosphere with depth.

Water radiolysis

The next mechanism proposed for the generation of natural hydrogen involves the breakdown of water into its constituent elements, hydrogen (H_2) and oxygen (O_2). Water is the most prevalent fluid found within inclusions in subsurface minerals, making it the dominant liquid in the upper crust.

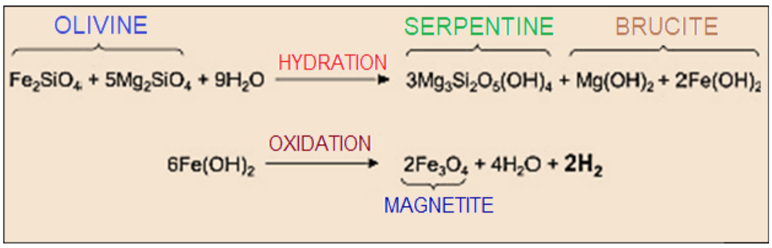


Figure 5
Key reactions in the formation of hydrogen during serpentinization process (Rubén Blay-Roger et al. 2024)

This crust also contains radioactive elements like uranium, thorium, and potassium, which emit α, β, and γ radiation as they decay over time. These radiation particles can disrupt the chemical bonds in water molecules found within these inclusions. The products of water radiolysis can include hydrogen, oxygen, peroxides, and hydroxyl radicals (Henry Moise 2024; Sherwood Lollar B et al. 2014; Parnell J & Blamey N. 2017; Warr 2019), as shown in Figure 6.

Porosity is vital in determining how much water can be exposed to the radioactive materials, while permeability affects the ability of a rock formation to transmit fluids through its pores. If porosity decreases, hydrogen production may also decrease due to a reduction in the available water, although an increase in irradiating material (which is inversely related to porosity) would enhance the total energy flux emitted. This implies that there is an optimal level of porosity that maximizes hydrogen production, which could help in identifying potential sites for hydrogen reservoirs (Henry Moise 2024).

Water radiolysis process may be expressed by the following equation:

$$H_2O \text{---} IonizingRadiation e^-aq, HO\bullet, H\bullet, HO\bullet 2, H3O+, OH-, H2O2, H2 \quad (4)$$

The $HO\bullet_2$ radical is a minor by-product in this reaction and is generally considered negligible under low-LET radiation conditions. It is noteworthy that dioxygen (O_2) is also not a primary product formed during the radiolysis of water.

Typically, the radiolytic process occurs in three main stages, each unfolding over different time scales, as illustrated in Figure 7.

Physical stage (∼1 femtosecond)

This stage involves the initial interaction of ionizing radiation with matter, resulting in energy deposition and rapid relaxation processes. It produces ionized water molecules (H_2O^+), excited water molecules (H_2O^*), and sub-excitation electrons (e^-).

Physico Chemical Change (10^{-15}–10^{-12} seconds)

During this stage, several processes occur, including: 1). Ion-molecule reactions (e.g., $H_2O^+ + H_2O \rightarrow H_3O^+ + HO\bullet$); 2). Dissociative relaxation (e.g., $H_2O^* \rightarrow HO\bullet + H\bullet$); 3). Autoionization of excited states; 4). Electron thermalization and solvation ($e^- \rightarrow e^-_aq$) Additionally, hole diffusion and other interactions contribute to this stage.

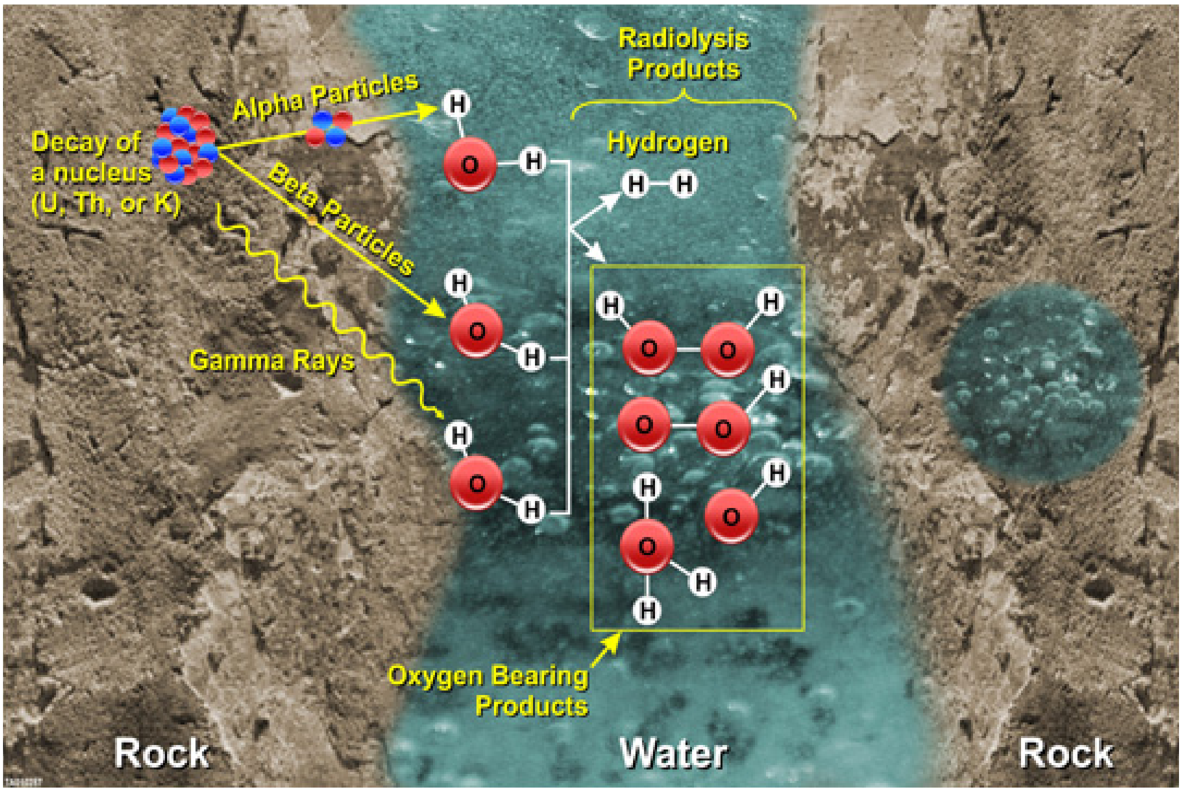


Figure 6
Summary of the process of water radiolysis by radionuclides. The radiolysis products are the result of several physico-chemical steps that follow the excitation/ionization of water by radiation (Bouquet et al. 2017, Sophie Le Caër 2011).

Chemical Stage (10^{-12}–10^{-6} seconds)

Species formed in the previous stages undergo chemical reactions within the particle tracks and diffuse into the solution. These reactions occur among the species themselves and with surrounding molecules. As radicals diffuse and react, the particle track expands.

The radiolytic yields of the different products obtained are a function of the type of radiation and the pH. Gamma radiation and accelerated electrons have a LET value of 0.2–0.3 keV μm^{-1}, whereas in the case of 5.3 MeV alpha particles (^{210}Po) the LET value is 140 keV μm^{-1}.Typical Radiolytic yields (in $\mu mol\ J^{-1}$) reported by (Ferradini & Gerin 2000) are shown in Table 1 below.

Degassing of magmas and deep-seated hydrogen from the earth core and mantle

The formation of a natural hydrogen (H_2) system necessitates the interaction of three key components: hydrogen resources, migration conditions, and storage environments with seals (Jiayi Liu et al. 2023). Hydrogen is present in carbon–oxygen–hydrogen (COH) magma systems, represented by the reaction $2H_2O + CH_4 = 4H_2 + CO_2$ at magmatic temperatures of around 1200 °C. This equilibrium favors the production of hydrogen, suggesting it may be an integral component of the magma (Wang L. et al 2023; Apps J.A. et al. 1993). Crustal weathering is another significant source of hydrogen. Studies from deep-sea and offshore drilling indicate that this weathering process continues in ejecta until the oceanic crust reaches an age of approximately 10 to 20 million years. As seawater cools and ages, the oceanic crust undergoes transformations at lower temperatures (less than 250 °C), leading to reactions (Wang L. et al. 2023; Bach W. & Edwards K.J. 2003) such as:

$$2(FeO)_{rock} + 4H_2O \rightarrow 2Fe(OH)_3 + H_2,$$
$$2(FeO)_{rock} + 2H_2O \rightarrow 2FeOOH + H_2, \text{ and} \quad (5)$$
$$2(FeO)_{rock} + H_2O \rightarrow Fe_2O_3 + H_2$$

Due to its light molecular weight, hydrogen possesses high mobility and readily reacts with oxidants, making it challenging for hydrogen to be preserved and accumulated. However, regions like New Guinea in Australia have reported hydrogen concentrations exceeding 10% (Woolnough W .G. 1934), while certain sedimentary basins in the United States (R.B. Newcombe 1935) and Poland (W. Meincke 1967) also exhibit elevated hydrogen levels. These findings indicate that hydrogen can accumulate in deposited strata within sedimentary basins.

The timeframe for hydrogen migration through the Earth can span from billions of years to just days, influenced by various geological and environmental factors (Lodhia B. et al. 2024). Key factors affecting hydrogen diffusivity in both crystalline and sedimentary rocks include grain size, temperature, and fluid salinity. Hydrogen migration via diffusion and advection operates on different scales: diffusion typically occurs over distances of less than 0.5 cm to several meters per year, while advection can extend over 1,000 meters per year. The flow of fluids along faults and fractures is governed by the rock's properties, subsurface stress conditions, and groundwater characteristics (Lodhia B. et al. 2024).

Table 1
Typical radiolytic yields (in μmol J−1) obtained as a function of the type of radiation and the p.
(Ferradini C. & Jay-Gerin J.P. 2000)

Radiation	$e^o aq$	^oOH	H^o	H_2	H_2O_2	HO_2^o
Y Electrons (0.1-10 Mev) pH=3-11	0.28	0.28	0.06	0.047	0.073	0.0027
Y Electrons (0.1-10 Mev) pH=0.5	0	0.301	0.378	0.041	0.081	0.0008
5.3 Mev a particles (^{210}Po) pH=0.5	0	0.052	0.062	0.163	0.150	0.011

Biotic and abiotic decomposition of organic matter

The formation of natural hydrogen involves three-stages as illustrated in Figure 7 which can encompass various hypotheses and mechanisms (Rubén Blay-Roger et al. 2024). In the subsurface, both biotic and abiotic processes contribute to the generation and consumption of hydrogen, although the exact contributions of these processes are often unclear. Abiotic hydrogen production within the Earth's crust occurs across a broad range of temperatures (exceeding 600 °C), while biotic processes are restricted to cooler environments that are more conducive to life. Three key abiotic processes for hydrogen generation include serpentinization, water radiolysis, reactions involving dissolved magmatic gases as elaborated above and the fourth one is cataclasis (hydrogen generation in fault zones) (Simon P. Gregory 2019). In cataclasis process, the hydromechanical reactions break chemical bonds, forming radicals that interact with groundwater to generate hydrogen. Another potential mechanism for hydrogen release in this context is the reduction of water through reactions with ferrous iron minerals found in silicate minerals within crushed rock. This mechanism has been reported to generate up to 0.22 moles of hydrogen per cubic meter of andesite (Kita I. et al.1982).

Biotic decomposition of organic matter occurs in intricate chemical and biological settings. Microorganisms can produce hydrogen through several processes, including fermentation, nitrogen fixation, anaerobic oxidation of carbon monoxide, and phosphite oxidation (Schwartz E et al. 2013; Sipma J. et al. 2006). The enzyme hydrogenase plays a critical role in these processes, catalyzing the following reaction:

$$H_{2\,(g)} \leftrightarrows H^- + H^+ \leftrightarrows 2H^+ + 2e^- \quad (6)$$

Hydrogen production is primarily associated with [FeFe]-hydrogenases, which are commonly found in anaerobic bacteria and some eukaryotic organisms. Microorganisms generate hydrogen through fermentation and nitrogen fixation as part of their metabolic processes, which can be harnessed for the development of hydrogen-producing bioreactors (Chang J. 2002; Nandi & Sengupta 1998). Nevertheless, the role of biological activity in the natural production of hydrogen in subsurface environments is not yet fully understood.

Fermentation of organic matter is particularly significant in subsurface settings where organic carbon is abundant, either naturally or through human intervention. Conversely, in environments such as crystalline basins, fermentation may play a lesser role due to the scarcity of organic carbon sources (Lin L.H. et al. 2006).

Simulated/engineered generation of natural hydrogen.

The growing recognition of natural hydrogen as a crucial climate-friendly energy source underscores its importance. However, the natural process of serpentinization that produces hydrogen occurs at an exceedingly slow pace, potentially requiring millions of years to yield sufficient quantities, especially if temperatures are low (Sherwood Lollar B. et al. 2014). Therefore, it is essential to stimulate and accelerate the rate of 'natural' hydrogen generation by several orders of magnitude to establish it as a viable and sustainable energy source within a timeframe relevant to human activities (Wanambwa Silagi & Yuan Qingwang 2023].

As per Mengli & Yaoguo (2024) Stimulated hydrogen is produced artificially by applying chemical and physical stimulations to source rocks under controlled conditions. Osselin et al. (2022) propose method, which involves adjusting factors such as temperature, pressure, water pH, source-rock composition, and rock-water ratio to generate hydrogen directly from source rocks without the need for a separate reservoir.

In natural hydrogen systems, the processes of generation and accumulation occur independently. In contrast, in stimulated hydrogen systems, generation and accumulation overlap in time and space, requiring simultaneous consideration of both the source rocks and the reservoir. The process begins with hydrogen generation in the source rocks, followed by extraction, either within a short timeframe or concurrently with the stimulation activities.

To ensure efficient and sustainable production of stimulated hydrogen, it is important to: 1). Continuously monitor the hydrogen generation process, such as serpentinization, to maintain its effectiveness; 2). Track changes in fluid composition and rock properties over time during hydrogen extraction to optimize production and prevent system degradation.

Simon P. Gregory et al. (2009) offer a different perspective, suggesting that in engineered subsurface environments, hydrogen levels can be artificially increased through activities such as hydrogen storage for fuel, the presence of hydrogen as an impurity in the storage of other gases, or its generation via the corrosion of steel infrastructure. This elevated hydrogen serves as a potential energy source for microbial processes, which can influence corrosion dynamics and the production or consumption of gases in these systems.

Mechanical and medical hydrogen generation

Wang L. et al. (2023) examines the mechanical and medical production of hydrogen, which can occur extensively in geological fault zones. These faults are typically located in orogenic belts, subduction zones, continental rifts, passive margins, spreading centers, transition faults, and other fault areas. Hydrogen generation is generally associated with active faulting; creeping faults may produce hydrogen continuously, while locked faults might generate it intermittently during slip events. This process occurs whenever silicate rocks are crushed. A prime example is the crushing of subglacial bedrock, where hydrogen production can support microbial ecosystems at temperatures near the freezing point of water, potentially sustaining life even during global glaciation events.

Several factors can lead to rock rupture or fragmentation, including freezing and salt wedging, thermal contraction during cooling, thermal expansion during heating, sandblasting by wind, erosion from rivers and coastal areas, landslides, rockfalls, meteorite impacts, and fractures driven by chemical reactions. When rocks break apart, the disruption of chemical bonds produces free radicals that react with water to generate hydrogen, represented by the reaction:

$$2(\equiv Si\cdot) + 2H_2O \rightarrow 2(\equiv SiOH) + H_2 \tag{7}$$

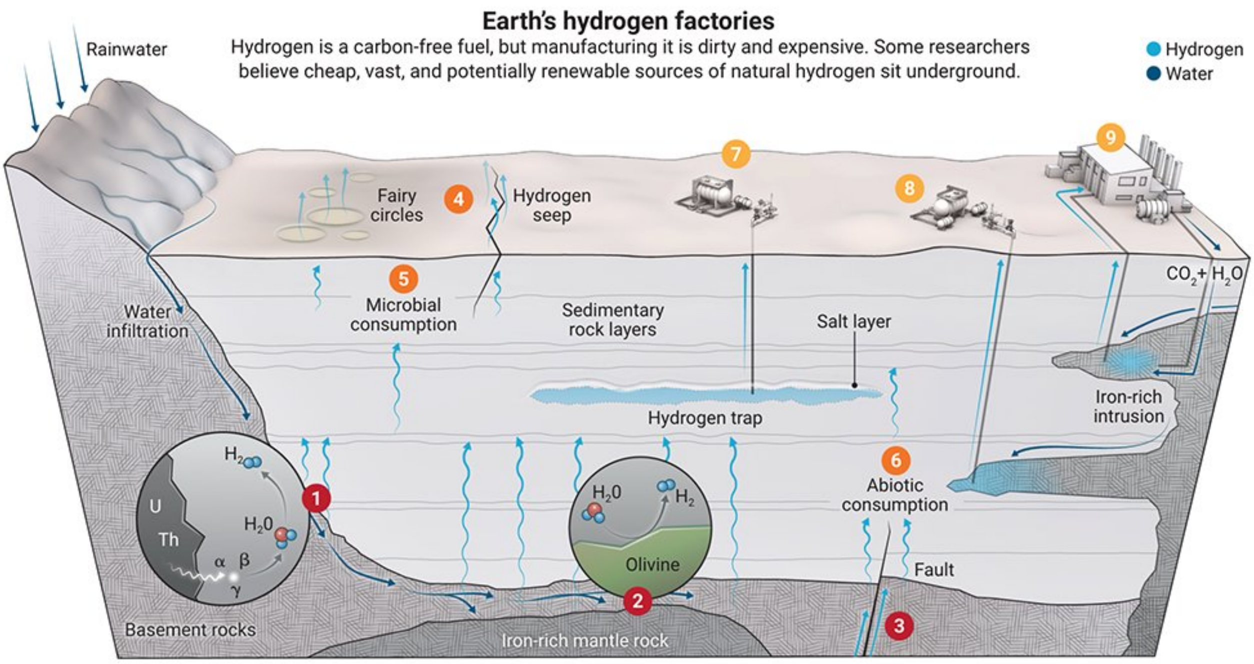
(Figure 4c) (Kita I. et al. 1982; Hirose T. et al. 2011). The high hydrogen concentrations found in soil gases near tectonic faults are attributed to fault movements, which crush rocks and produce free radicals (Sato M. 1986).

Mechanical stress can break covalent Si–O bonds in silicate minerals, resulting in the formation of surface free radicals such as ≡Si· and ≡SiO· (homolytic) or charged surface radicals like ≡Si+ and −O--Si≡ (heterolytic). Once these surfaces are exposed, they may either recombine to form siloxane bonds (Si–O–Si) or react with water in the reaction Si· + H_2O → SiOH + H·, leading to the release of hydrogen as a by-product: H· + H· → H_2.

Proximity with prms

Dove (2024) summarized the entire natural hydrogen system, as being similar to petroleum system in his presentation as seen in Figure 8 along with the following observations:

Natural hydrogen exploration is being established globally and continues to grow. The system is viewed as being similar to the petroleum, containing genetic elements: Source– Reservoir– Seal and the processes of generation migration trap formation accumulation (including preservation). Geological risk elements of preservation are greater than compared to a petroleum system. In August 2022 the SPE Oil and Gas Reserves Committee ('OGRC') advised that the principles of the PRMS can be applied to natural hydrogen due similarities in methods of exploration, evaluation and exploitation. How ever resource estimation for flux systems requires further quantification before any resource estimates can be ascribed. System can be extended to substances other than hydrocarbons, including the gaseous extraction of carbon dioxide, helium and hydrogen.



Generation

1 Radiolysis
Trace radioactive elements in rocks emit radiation that can split water. The process is slow, so ancient rocks are most likely to generate hydrogen.

2 Serpentinization
At high temperatures, water reacts with iron-rich rocks to make hydrogen. The fast and renewable reactions, called serpentinization, may drive most production.

3 Deep-seated
Streams of hydrogen from Earth's core or mantle may rise along tectonic plate boundaries and faults. But the theory of these vast, deep stores is controversial.

Loss mechanisms

4 Seeps
Hydrogen travels quickly through faults and fractures. It can also diffuse through rocks. Weak seeps might explain shallow depressions sometimes called fairy circles.

5 Microbes
In shallower layers of soil and rock, microbes consume hydrogen for energy, often producing methane.

6 Abiotic reactions
At deeper levels, hydrogen reacts withrocks and gases to form water, methane, and mineral compounds.

Extraction

7 Traps
Hydrogen might be tapped like oil and gas—by drilling into reservoirs trapped in porous rocks below salt deposits or other impermeable rock layers.

8 Direct
It might also be possible to tap the iron-rich source rocks directly, if they're shallow and fractured enough to allow hydrogen to be collected.

9 Enhanced
Hydrogen production might be stimulated by pumping water into iron-rich rocks. Adding carbon dioxide would sequester it from the atmosphere, slowing climate change.

Source: https://www.science.org/content/article/hidden-hydrogen-earth-may-hold-vast-stores-renewable-carbon-free-fuel

Figure 8
The natural hydrogen system and its related elements (Devex 2024)

RESULT AND DISCUSSION

The information surfaced from the study of mechanisms has been applied to preliminary attempts at exploration, research to find new ways to generate natural hydrogen under softer conditions and encourage more businesses to get involved in this new emerging energy source.

Attempts at exploration, new researches and major players

Naturally occurring hydrogen, has been detected in several locations worldwide. If successfully harnessed, this resource could play a critical role in the energy transition and decarbonization efforts due to its extremely low carbon emissions and the significantly lower production costs compared to other forms of clean hydrogen. However, not all types of natural hydrogens are economically viable. Of the three primary forms of naturally occurring hydrogen dissolved gas, gas in inclusions and free gas only the latter presents potential for commercial extraction. The other two forms, being either adsorbed or dissolved, indicate hydrogen trapped during mineral formation or found in concentrations too low for cost-effective separation using current technology (The Oxford Institute of Energy studies 2024).

Exploring natural hydrogen resources is expected to follow similar strategies to those used in petroleum exploration, incorporating elements from mineral and geothermal resource studies. The exploration process for commercially viable hydrogen generally involves several broad steps:

Identifying potential locations

Modern scientific techniques play a crucial role in identifying regions with high natural hydrogen potential. For instance, the United States Geological Survey (USGS) has a specialized team that uses a hydrogen system model to map and assess the distribution of key components, offering preliminary estimates of hydrogen potential across the United States (Communications & Publishing 2023).

Advancements in fields like artificial intelligence (AI) are also transforming hydrogen exploration. Researchers at Ohio State University have developed a deep-learning algorithm capable of analyzing the earth's surface and subsurface to detect hydrogen presence. This algorithm has identified specific surface features, such as ovoids and semicircular depressions, often linked to "gold hydrogen" deposits, proving itself as a valuable tool for locating potential hydrogen reservoirs (Ibtisam Abbasi 2024).

Additionally, Getech (2020) has pioneered a workflow model based on Mineral Systems Analysis to forecast natural hydrogen deposits, treating them in a manner similar to mineral and hydrocarbon deposits. This approach generates favorability maps, much like those used in hydrocarbon exploration, to pinpoint areas warranting further investigation. The model focuses on three primary hydrogen sources: serpentinization (hydration of iron-rich rocks/minerals), radiolysis (water molecule splitting through radioactive decay), and organic matter decay (David Tierney & Howard Golden 2023; Himmat S. 2024).

New research

Researchers at The University of Texas at Austin are studying a group of natural catalysts that could enable hydrogen production from iron-rich rocks without emitting carbon dioxide. This work has the potential to launch a new "geologic hydrogen" industry. The catalysts being investigated are designed to speed up "serpentinization," a natural process where chemical reactions cause iron-rich rocks to release hydrogen as a byproduct. While serpentinization usually requires high temperatures, the team is exploring the use of natural catalysts, such as nickel and other platinum group elements, to activate this process at lower temperatures. By making hydrogen production possible from iron-rich rocks accessible with current technology, this research could significantly increase global hydrogen supply. This project is part of broader initiatives at the Bureau of Economic Geology focused on the role of the subsurface in hydrogen generation and storage, supporting the energy transition [UT News; 2024].

Play-based exploration

Serpentinization, a key process in hydrogen generation, is being used to develop play models that guide exploration in specific geotectonic settings like continental cratons, ophiolites

and convergent margins. This approach is aimed at creating models for areas that are accessible and viable for future hydrogen extraction. Three important models (Owain Jackson 2024) include:

Cratonic greenstone exploration model

This model involves hydrogen generation through the serpentinization of ultramafic rocks found in Precambrian greenstone belts. Groundwater, fault systems, and cratonic basin sediment cover are required to host hydrogen accumulations (Hutchinson I.P. 2024).

Cordilleran forearc basin exploration model

Based on the Sandino fore-arc basin offshore Nicaragua, this model suggests that subduction-related dehydration fluids interacting with ultramafic rocks beneath the basin generate hydrogen. The supra-subduction basement is composed of dense oceanic crustal rocks or mantle wedge (Walther C.H. 2000 & Sallarès V. 2013).

Tethyan ophiolite exploration model

The Semail Ophiolite in Oman and the UAE is an active site for hydrogen seepage, either as a free gas or evolving from spring water. Hydrogen in this area is primarily generated by low-temperature serpentinization of groundwater, although high-temperature processes are also possible (Leong J.A. 2023 & Ellison E.T. 2021).

Preliminary exploration attempts

Betina Bendall (2022) provides a recent overview of the geology of natural hydrogen occurrences and exploration methodologies. Using this approach, exploration for natural hydrogen has been conducted in countries such as Mali, Australia, the United States, Brazil, and several European nations, resulting in the discovery of numerous areas with natural hydrogen potential. In Mali, natural hydrogen has been harnessed for power generation in nearby villages. The Mali natural hydrogen field has proven, for the first time, the feasibility of drilling and extracting natural hydrogen directly from the subsurface, giving confidence for future exploration and development of hydrogen as a standalone energy source (Q Tian et al. 2022).

Dan Lévy & his team (2023) in their study of natural hydrogen (H_2) exploration, share their experience in characterizing H_2 plays based exploration efforts carried out in many countries in Europe, North and South America, Africa, and Oceania between 2017 and 2023. The study focusses on onshore exploration where three main reactions are generating H_2: (i) redox reactions between Fe^{2+} and H_2O, (ii) radiolysis of water and (iii) organic late maturation where H_2 comes from hydrocarbons. This study led to classifying the H_2 generating rocks into four types that seem more likely to be of economic interest: basic and ultrabasic rocks of oceanic/mantellic affinity, iron-rich bearing sedimentary and intrusive rocks, radioactive continental rocks and organic matter-rich rocks which could be targeted as new promising areas for H_2 exploration as a preliminary exploration guide.

V Roche et al (2024) present structural evidence that reported H_2 emissions from Waterberg Basin, Namibia are associated with underlying Neoproterozoic banded iron formations the Chuos formation. Magnetite, a known H_2-generating mineral, is ubiquitous and accompanied by other suspected H_2-generating minerals (biotite and siderite) in Chuos formation

In united states, the first natural hydrogen well was drilled in Kansas at the end of 2019 (Moretti I. & Webber ME. 2021). One well in this area was sampled from 2008 to 2011. The well drilled through about 424 m of the Paleozoic sedimentary strata and about 90 m of the underlying Precambrian basement, where the highest hydrogen content reached about 91% (Guélard J et al. 2017)

In Australia, a comprehensive assessment was conducted, and licenses were issued for natural hydrogen exploration. Geoscience Australia in 2021 analyzed a large number of wells for hydrogen composition and isotopic content and estimated hydrogen production from radiolysis and serpentinization. The results suggest that hydrogen resources at depths less than 1 km range from approximately 1.6×10^6 m³/a to 58×10^6 m³/a. Additionally, the South Australian Department for Energy and Mines (DEM) granted exploration permits to Golden Hydrogen, established in 2021, after the company demonstrated the presence of up to 90% purity natural hydrogen on Kangaroo Island and the southern York Peninsula (Q Tian et al. 2022).

Similar exploration efforts are ongoing in Europe, Russia, and China.

Major players

Currently, only one company is actively producing energy from natural hydrogen. Hydroma-a Canadian company, supplies free electricity to the inhabitants of Bourakébougou, a village in Mali located near a hydrogen deposit.

Several energy and oil & gas industry groups, including Buru Energy, Total Energies, and Engie, are beginning to invest in natural hydrogen projects. However, these companies are still in the early stages of development, primarily obtaining exploration permits to evaluate the size of potential deposits and conducting research on scaling up production for industrial use.

Numerous new startups are also emerging in this sector, particularly in France with companies like 45-8 Energy and TB-H_2 Aquitaine, and in Australia with Gold Hydrogen and H_2EX. Australia is highly active in this space, with over 35 exploration permits already issued in the southern part of the country (Guillaume et al. 2024). Philip J. Ball & Krystian; (2024) report that several oil and gas companies, including Shell, BP, Repsol, OMV, Chevron, Petrobras, Ecopetrol, and Saudi Aramco, are indicating a clear shift by participating in recent natural hydrogen conferences.

Researchers well-acquainted with the origins of natural hydrogen are currently forging partnerships with a multitude of recently established natural hydrogen companies, which are spearheading the testing and development of exploration concepts. The coming years are poised to be marked by a surge of activities as these groups shift from the conceptual stage to the fieldwork planning and drilling phases.

As per Energy Institute (2024) Natural hydrogen, is increasingly recognized as a potential gamechanger in the energy sector. Unlike "green hydrogen" (produced via electrolysis using renewable energy) or "blue hydrogen" (produced from natural gas with carbon capture), natural hydrogen occurs naturally in the earth's crust and is non reliant on renewable energy. Extracting it can be more cost-effective and environmentally friendly, as it avoids the energy-intensive production processes of other types.

Preliminary estimates and cost benefits

Geoffrey Ellis, a geoscientist at the US Geological Survey Denver, through his early calculations suggest that there may be something like 10 trillion tons of natural, or "geologic" hydrogen buried underground worldwide. Many reserves will be too deep or remote to tap easily around hydrothermal vents in the deep ocean, for instance. And just a small fraction of the buried hydrogen could meet the world's needs for centuries (Fred Pearce 2024; Chas Newkey-Burden 2024).

Viacheslav Zgonnik, a researcher who has been exploring the potential of white hydrogen for the last decade and managing a start-up in the field since 2013, says that preliminary estimates show natural hydrogen may be the cheapest alternative of the gas at $0.1 to $1 per Kg even cheaper than currently dominant grey hydrogen (Goda Naujokaitytė 2022).

Abdul' Aziz Aliu (2024) report, if economically viable methods for harnessing natural hydrogen are developed, it could significantly reduce the reliance on clean water currently required for green hydrogen production, where approximately 20 kg of tap water is consumed to produce 1 kg of hydrogen (IEAGHG). Additionally, it could eliminate the need for carbon capture and storage (CCS) abated blue hydrogen production.

Stakeholders such as Michael Levy (Aqius/Hynat, Switzerland), Alain Prinzhofer (HYNAT, Brazil), and Viacheslav Zgonnik (Natural Hydrogen Energy LLC, USA) estimate that natural hydrogen production costs could range between USD 0.5 and USD 1.0 per kg. For comparison, hydrogen production costs via steam methane reforming (SMR) with CCS in the Netherlands in 2020 were USD 2.84 per kg (IEAGHG April 2022) and steam naphtha reforming (SNR) in the UAE cost USD 4.42 per kg [IEAGHG.March 2022] Hydrogen production using renewable electricity ranges from USD 3 to USD 8 per kg (IEA 2021)

Natural hydrogen exhibits a low greenhouse gas (GHG) intensity at the site boundary (~0.4 kg CO_2-eq/kg), assuming a composition of 85 mol% H_2, 12% N_2, and 1.5% CH_4 [Brandt et al.2023]. In contrast, the GHG intensity of unabated SMR hydrogen is 10.13 kg CO_2-eq/kg, while CCS-abated SMR hydrogen (90% capture) produces 2.45 kg CO_2-eq/kg. Hydrogen produced through electrolysis using renewable electricity has near-zero GHG emissions at the production site (IEA 2023).

Canada-based producer Hydroma, at present extracts white hydrogen at an estimated cost of $0.5 per kg. Depending on the deposit's depth and purity. Projects in Spain and Australia aim for a cost of about $1 per kg, solidifying white hydrogen's price competitiveness (Dale Granger 2024).

Raghunandan of News click says some "Optimists "estimate that there could be tens of billions of tons of hydrogen worldwide. Much of this may be from very small deposits. But if even a small percentage is available in commercially viable quantities, it could be far more than the 100 million tons a year of quiet energy- produced or the 500 million tons annually projected to be produced by 2050. Further, going by experience in Mali and test bores elsewhere, white hydrogen could be produced at $1/kg compared to about $6/kg for "green hydrogen," produced using solar energy or other renewables (Raghunandan D. 2023).

CONCLUSION

Historically, hydrogen exploration was largely overlooked due to the widespread belief that natural hydrogen was rare in the Earth's crust. This misconception persisted despite geoscientists documenting occurrences of natural hydrogen in both sedimentary and igneous geological formations since the early 20th century.

While natural hydrogen holds significant potential, its exploration and exploitation come with numerous challenges. Currently, hydrogen exploration is still in its infancy, with scientists now intensifying efforts to study its formation, migration, and viability for commercial production. Major oil companies have adopted a cautious "wait-and-watch" strategy, leaving independent explorers to undertake the initial high-risk exploration efforts.

Preliminary simulation models (Abdul Aziz 2024) estimate that approximately 10 trillion tons of natural hydrogen could be stored underground globally. However, much of this resource may remain inaccessible due to factors like depth, offshore locations, or low concentrations that make extraction impractical. If only 1% of this hydrogen were recoverable, it could meet the world's energy needs for over 200 years, even with a projected surge in hydrogen demand, as noted by Geoffrey Ellis, a geoscientist at the USGS.

The potential of natural hydrogen remains largely untapped but could become a critical component of the sustainable energy landscape. As technological advancements continue and interest grows, natural hydrogen may shift from relative obscurity to the forefront of renewable energy solutions.

Currently, around 40 companies worldwide are evaluating natural hydrogen resources, though no commercially viable reserves have yet been confirmed. In 2023, geologists announced a significant discovery in northern France, identifying what could be the largest known deposit of natural hydrogen an estimated 250 million tons with 98% purity.

Optimism in the market is expected to drive innovation in clean energy technologies, fostering research and development to enhance the efficiency of natural hydrogen production and utilization. This burgeoning interest in "white hydrogen" could mark a pivotal shift toward environmental sustainability, paving the way for a greener, more resilient energy future (PRNewswire 2024).

Addressing the question of whether natural hydrogen has a viable future, Phillip and Czado (2022) argue that "natural hydrogen is clearly more abundant than previously assumed." With numerous documented instances of natural hydrogen worldwide, it seems statistically unlikely that fields like Bourakébougou are unique.

ACKNOWLEDGEMENT

Author greatly appreciates the computer related support provided by my daughter / granddaughters in the preparation of this complete manuscript.

REFERENCES

Abdul' Aziz Aliyu, 2024, Gold, Geologic, White, Native, Hidden, Natural Hydrogen: Does Earth hold extensive stores of untapped, carbon-free fuel? IEAGHG,26th June.

Albers E. et al., 2021, Serpentinization-Driven H_2 Production from Continental Break-Up to Mid Ocean Ridge Spreading: Unexpected High Rates at the West Iberia Margin. Front. Earth Sci. V.9 .22nd June Doi: 10.3389/feart.2021.673063.

Antony Joseph, 2023, Serpentinization implications for the search for biosignatures, in Water Worlds in the Solar System , Elsevier, Chap 4.Biosignatures.

Apps J.A. et al., 1993, Energy gases of abiogenic origin in the Earth's crust Journal Article January, United States Geological Survey, Professional Paper; (United States) OSTI ID:6779771.

Bach W. & Edwards K.J., 2003, Iron and sulfide oxidation within the basaltic ocean crust: Implications for chemolithoautotrophic microbial biomass production. Geochim. Et Cosmochim. Acta 67, 3871–3887.

Baptiste Debret et al., 2024, A review of abyssal serpentinite geochemistry and geodynamics. Earth-Science Reviews. Volume 258, November, 104910.https://doi.org/10.1016/j.earscirev.2024.104910.

Betina Bendall, 2022, Current perspectives on natural hydrogen: a synopsis; MESA Journal 96, (37–46).

Bob Yirka, 2024, Largest flow of natural hydrogen gas ever found measured in Albanian chromium mine. Phy Org . Feb 9th.

Bouquet A. et al., 2017, “Alternative Energy: Production of H_2 by Radiolysis of Water in the Rocky Cores of Icy Bodies,» Astrophys. J. Lett. 840, L8.

Brandt et al., Joule, Brandt et al., Joule, Greenhouse gas intensity of natural hydrogen produced from subsurface geologic accumulations, Volume 7, Issue 8, 16 August 2023, Pages 1818-1831, July 2023.

Chang J., 2002, Biohydrogen production with fixed-bed bioreactors. Int J Hydrogen Energy, Nov;27 (11–12):1167–74.

Chas Newkey-Burden, 2024, Gold hydrogen: a near limitless supply of clean fuel? The Week UK, FEBRUARY 20th.https://theweek.com/environment/gold-hydrogen-a-near-limitless-supply-of-clean-fuel.

Chris Baraniuk, 2022, ‘Gold Hydrogen” is an untapped resource in depleted oil wells. Science, Nov,24, https://www.wired.com/story/gold-hydrogen/.

Christian Robles, 2024, Gold Hydrogen: The next clean fuel, Energy wire,5th Feb..https://www.eenews.net/articles/gold-hydrogen-the-next-clean-fuel/.

Communications and Publishing, 2023, The potential for natural hydrogen for next generation energy-Featured Story. April 13. https://www.usgs.gov/news/featured-story/potential-geologic-hydrogen-next-generation-energy.

David Tierney and Howard Golden; 2023, A Mineral Systems Approach to Targeting Natural Hydrogen Deposits. Getech: 6th August. https://getech.com/blog/hydrogen/a-mineral-systems-approach-to-targeting-natural-hydrogen deposits.

Devex, 2024, Natural hydrogen exploration Leveraging existing skillsets and technologies, some case studies. RISC ,28-29th May. file:///D:/1435_-DEVEX-Natural-H2-expl-and-estimating-the-resource.pdf.

E.Deville &Alain Prinzhofer, 2016, The origin of N2-H2-CH4-rich natural gas seepages in ophiolitic context: A major and noble gases study of fluid seepages in New Caledonia .Chemical Geology Volume 440, 15th November, PP 139-147.

Ellison ET. et al. 2021, Low-temperature hydrogen formation during aqueous alteration of serpentinized peridotite in the samail ophiolite. Journal of Geophysical Research: Solid Earth.126. .https://doi.org/10.1029/2021jb021981.

Energy Institute, 2024, The white gold rush: 40 companies now in pursuit of natural hydrogen. March. https://knowledge.energyinst.org/new-energy-world/article?id=138647.

Fred Pearce, 2024, Natural Hydrogen: A Potential Clean Energy Source Beneath Our Feet. Yale Environment 360, January 25th.

Frery E. et al., 2021, Natural hydrogen seeps identified in the North Perth basin, western Australia. Int J Hydrogen Energy;46(7): DOI:10.1016/j.ijhydene.2021.07.023.

Gaucher Éric C., 2020, New Perspectives in the Industrial Exploration for Native Hydrogen». Elements: An International Magazine of Mineralogy, Geochemistry, and Petrology. 16 (1): 8-9. Bibcode:2020 Eleme.168G. Doi:10.2138/gselements.16.1.8.

Goda Naujokaitytė, 2022, Hydrogen could be taken straight from the ground. Science Business. News 06 Jan. https://sciencebusiness.net/news/hydrogen-could-be-taken-straight-ground#:~:text=Na 209ref).

Green Review, 2024, The emergence of natural hydrogen — a gamechanger in energy March. https://greenreview.com.au/resources/the-emergence-of-natural-hydrogen-a-gamechanger-in-energy/.

Guélard J. et al., 2017, Natural H_2 in Kansas: Deep or shallow origin? Geochemistry, Geophysics, Geosystems, 18 (5). pp. 1841-1865 doi:10.1002/2016GC006544.

Guillaume et al. 2024, The industrial exploitation of white hydrogen, myth or reality? Energy-Environment-Mobility, 12th January. https://www.alcimed.com/en/insights/white-hydrogen/.

Haley Zaremba, 2024, Tapping into Earth’s Natural Hydrogen Reserves. Oilprice.Febuary,8th https://markets.businessinsider.com/news/stocks/tapping-into-earths-natural-hydrogen-reserves-

1033048484#:~:text.

Hand Eric, 2023, "Hidden hydrogen". Science.16th Feb https://www.science.org/content/article/hidden-hydrogen-earth-may-hold-vast-stores-renewable-carbon-free-fuel.

Henry Moise, 2024, Radiolysis in Natural Hydrogen, Stanford University. March 7th. http://large.stanford.edu/courses/2024/ph241/moise2/.

Himmat Singh, 2024, Potential of natural hydrogen in the energy transition. Decarbonization technology. August. PP 49-52.

Hirose T. et al., 2011, Mechano radical H_2 generation during simulated faulting: Implications for an earthquake-driven subsurface biosphere. Geophys. Res. Lett, 38(17). DOI:10.1029/2011GL048850. https://news.utexas.edu/2024/03/04/producing-hydrogen-from-rocks-gains-steam-as-scientists-advance-new-methods/.

Hutchinson, I.P., et al., 2024, Greenstones as a source of hydrogen in cratonic sedimentary basins. Geological Society London, Special publication,547,Issue 1. https://doi.org/10.1144/SP547-2023-39.

Ibtisam Abbasi, 2024, Tapping Into Earth's Natural Hydrogen Sources; Azo Tech editorial feature, Feb 11th. https://www.azocleantech.com/article.aspx?ArticleID=1792.

IEA, Towards hydrogen definitions based on their emissions intensity- 13 Apr 2023.

IEAGHG, Comparative analysis of electrolytic hydrogen pathways with CCS-abated hydrogen. Ongoing study.

IEAGHG, "Blue Hydrogen: Global Roadmap", 2022-07, April 2022.

IEAGHG, "Blue Hydrogen: Beyond the Plant Gate", 2022-06, March 2022.

IEC editorial team, 2023, International Electrotechnical Commission. Could white and gold hydrogen be clean fuel options? 7th Nov. https://www.iec.ch › blog › could-white-and-gold-hydr.

J. Hanson & H. Hanson, 2023, Hydrogen's organic genesis. Unconventional resources 4, 100057; Doi.org/10.1016/j.uncres.2023.07.003

Jiayi Liu et.al;2023. Genesis and energy significance of natural hydrogen. Unconventional Resources Volume 3, 2023, Pages 176-182. https://doi.org/10.1016/j.uncres.2023.01.002.

Kheira Bettayeb, 2023, A gigantic hydrogen deposit in northeast France? CNRS News 26 july, https://news.cnrs.fr/articles/a-gigantic-hydrogen-deposit-in-northeast-france.

Kita I., et al., 1982, H_2 generation by reaction between H_2O and crushed rock: An experimental study on H_2 degassing from the active fault zone. J. Geophys. Res. Solid Earth; 87, 10789–10795.

Kyle Bakx, 2024, A new gold rush? The search for the natural hydrogen motherlode is coming to Canada; CBC News ·Jan 26, https://www.cbc.ca/news/canada/bakx-white-hydrogen-natural-Mali-1.7094645#:~:t.

Larin N. et al., 2015, Natural molecular hydrogen seepage associated with surficial, rounded depressions on the European craton in Russia.24(3),369-383.

Leong J.A., et al., 2023, H_2 and CH_4 outgassing rates in the Samail ophiolite, Oman: implications for low-temperature, continental serpentinization rates. Geochimica et Cosmochimica Acta, 347, 1–15. https://doi.org/10.1016/j.gca.2023.02.008.

Lin L.H., et al., 2006, Long-term sustainability of a high-energy, low-diversity crustal biome. Science. 314:479–482. Doi: 10.1126/science.1127376.

Liu Z., et al., 2023, Mantle serpentinization and associated hydrogen flux at North Atlantic magma-poor rifted margins. Geology March, 1;51(3):284–9.DOI 10.1130/G50722.1.

Lodhia B., et al., 2024, A review of the migration of hydrogen from the planetary to basin scale. Journal of Geophysical Research: Solid Earth, 129, e2024JB028715. https://doi.org/10.1029/2024JB028715.

Mengli Zhang, Yaoguo Li, 2024, The role of geophysics in geologic hydrogen resources, Journal of Geophysics and Engineering, Volume 21, Issue 4, August 2024, Pages 1242–1253, https://doi.org/10.1093/jge/gxae056.

Merdith AS. et al., 2020, Pulsated global hydrogen and methane flux at mid-ocean ridges driven by Pangea Breakup. Geochemistry, Geophysics, Geosystems Apr;21(4).: /doi/abs/10.1029/201

9GC008869.

Milkov A., 2022, Molecular hydrogen in surface and subsurface natural gases: abundance, origins and ideas for deliberate exploration. Earth Sci Rev Jul; 230:104063.

Moretti I., et al., 2021, Long-term monitoring of natural hydrogen superficial emissions in a Brazilian cratonic environment. Sporadic large pulses versus daily periodic emissions. International Journal of Hydrogen Energy. 46(5), 3615-3628. https://doi.org/10.1016/j.ijhydene.2020.11.026.

Moretti I., et al., 2023, Subduction and hydrogen release: the case of Bolivian altiplano. Geosciences 2023, Apr 4;13(4):109. https://doi.org/10.3390/geosciences13040109.

Morreti I. & Webber M., 2021, Natural hydrogen: a geological curiosity or the primary energy source for a low-carbon future? Renewable Matter (RM), , 34. hal-04686538.

Morita RY., 1999, Is H_2 the universal energy source for long-term survival? Microbial ecology, 38 (4) pp. 307-320.

Nandi R. & Sengupta S., 1998, Microbial production of hydrogen: an overview. Crit Rev Microbiol Jan.24 (1) pp 61–84.

Neil McDonald et al., 2023, Gold Hydrogen; Aiming to Discover and Develop Naturally Occurring Australian Hydrogen. AGM presentation, 03, Oct.

Osselin.E., et al. 2022.Orange hydrogen is the new green. Nature Geoscience volume 15, pages765–769. https://doi.org/10.1038/s41561-022-01043-9.

Owain Jackson et al., 2024, Natural hydrogen: sources, systems and exploration plays. Natural hydrogen: sources, systems and exploration plays, Geoenergy. 7th May, 2 (1): 2024-002. https://doi.org/10.1144/geoenergy2024-002.

Owen E., Sutcliffe, 2023, Defining an Architecture for Subsurface Hydrogen Play Concepts Natural Hydrogen: A New Frontier for Energy Geoscience 4-5th July. The Geological Society (Burlington House, Piccadilly, London) & Virtual via Zoom.

Parnell J. & Blamey N., 2017, Global hydrogen reservoirs in basement and basins. Geochemical Transactions 18(1), March. Doi:10.1186/s12932-017-0041-4.

Philip J. Ball & Krystian C. Zado, 2024, Natural hydrogen: the race to discovery and concept demonstration. Geoscientist (London) 28, February, https://geoscientist.online/sections/unearthed/natural-hydrogen-the-race-to-discovery-and-concept-demonstration.

Philip J. Ball and Krystian Czado, 2022, Natural hydrogen: the new frontier. Geoscientist, March 1st. https://geoscientist.online/sections/unearthed/natural-hydrogen-the-new-frontier/?utm_source=chatgpt.com.

Prinzhofer A., et al., 2018, Discovery of a large accumulation of natural hydrogen in Bourakebougou (Mali). International journal of hydrogen energy, 43(42), 19315-19326.

PRNewswire, 2024, The "White (Natural) Hydrogen Market: Focus on Exploration, Identified Deposits, and Future Scenarios", April 1st, https://www.prnewswire.com/news-releases/white-natural-hydrogen-industry-research-report-2024---focus-on-exploration-identified-deposits-and-future-scenarios-302103854.html.

Q Tian et al, 2022, Origin, discovery, exploration and development status and prospect of global natural hydrogen under the background of "carbon neutrality; China geology, V5,Issue 4, October.. PP 722-733, https://doi.org/10.31035/cg2022046.

R.B. Newcombe, 1935, Natural gas fields of Michigan,Geol.Natural Gas pp. 787-812.

Raghunandan. D., 2023, Climate Change is white hydrogen the new savior, News click 03 Nov.. https://www.newsclick.in/climate-change-white-hydrogen-new-saviour.

Resource works, 2024, Hydrogen is slowly emerging on Canada's horizon, March 21st. https://www.resourceworks.com/hydrogen-emerging-on-canada-horizon.

Rubén Blay-Roger et al., 2024, Natural hydrogen in the energy transition: Fundamentals, promise, and enigmas. Renewable and Sustainable Energy Reviews 189, 113888. DOI:10.1016/j.rser.2023.113888.

RYSTAD Oil Price, 2024, 40 Companies Join Race for Natural Hydrogen Deposits, March

13th https://markets.businessinsider.com/news/stocks/40-companies-join-race.

Sallarès V., et al., 2013, Overriding plate structure of the Nicaragua convergent margin: relationship to the seism genic zone of the 1992 tsunami earthquake. Geochemistry, Geophysics, Geosystems, 14, 3436–3461. https://doi.org/10.1002/ggge.20214.

Sam Meredith, 2024, A global gold rush for buried hydrogen is underway — as hype builds over its clean energy potential. SUSTAINABLE FUTURE: MAR 26th ,https://www.cnbc.com/2024/03/26/natural-hydrogen-a-new-gold-rush-for-a-potential-.

Sato M. et al., 1986, Monitoring of hydrogen along the San Andreas and Calaveras faults in central California in 1980–1984. J. Geophys. Res. Solid Earth, 91, pp12315–12326.

Schwartz E., et al., 2013, H_2 Metabolizing prokaryotes. In The Prokaryotes; Springer: Berlin/Heidelberg, Germany; pp. 119–199. ISBN 9783642301407.

Sherwood Lollar B., et al., 2014, The contribution of the Precambrian continental lithosphere to global H_2 production. Nature 516:379–382, Doi:10.1038/nature14017.

Simon P. Gregory et al., 2019.Subsurface Microbial Hydrogen Cycling: Natural Occurrence and Implications for Industry. Microorganisms, 7(2), https://doi.org/10.3390/microorganisms7020053.

Sipma J., et al., 2006, Microbial CO Conversions with Applications in Synthesis Gas Purification and Bio-Desulfurization. Crit. Rev. Biotechnol, 26, 41–65. DOI: 10.1080/07388550500513974.

Sophie Le Caër, 2011, Water Radiolysis: Influence of Oxide Surfaces on H_2 Production under Ionizing Radiation. Water 3, 235-253; Doi:10.3390/w3010235.

The Conversation, 2024, Gold-hydrogen-is-found-naturally-around-the-world-can-it-help-us-move-us-away-from-fossil fuels The IMPACT Jan 28th. https://www.fastcompany.com/91017369/gold-hydrogen-is-found-naturally-around-the-world-can-it-help-us-move-us-away-from-fossil-fuels.

The oxford Institute of Energy studies, 2024, Natural (geologic) hydrogen and its potential role in a net-zero carbon future: Is all that glitters gold? September: ISBN 978-1-78467-251-5,

UT NEWS, 2024, Producing Hydrogen From Rocks Gains Steam as Scientists Advance New Methods,https://news.utexas.edu/2024/03/04/producing-hydrogen-from-rocks-gains-steam-as-scientists-advance-new-methods/.

V Roche et al., 2024, A new continental hydrogen play in Damara Belt (Namibia). Scientific Reports volume 14, Article number: 11655. https://doi.org/10.1038/s41598-024-62538-6.

Viacheslav Zgonnik et al., 2019, Diffused flow of molecular hydrogen through the Western Hajar mountains, Northern Oman. Arabian Journal of Geosciences 12 (3), ttps://doi.org/10.1007/s12517-019-4242-2.

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

W. Meincke, 1967, Zur Herkunft des Wasserstoffs in Tiefenproben,Zeitschrift fur Angewandte Geologie, 13 (7) pp. 346-347.

Woolnough W.G., 1934, Natural gas in Australia and new Guinea, AAPG Bull., 18 (2). pp. 224-226.

Walther C.H., et al., 2000, Crustal structure across the Pacific margin of Nicaragua: evidence for ophiolitic basement and a shallow mantle sliver. Geophysical Journal International, 141, 759–77 . https://doi.org/10.1046/j.1365-246x.2000.00134.x.

Wanambwa Silagi & Yuan Qingwang, 2023, Stimulated mechanisms for engineered natural hydrogen production from ultramafic rock-water interactions, AGU Fall Meeting 2023, held in San Francisco, CA, 11-15 December 2023, Publication Date. December 2023, Bibcode: 2023AGUFMNS13C0531W.

Wang L., et al., 2023, The Origin and Occurrence of Natural Hydrogen, Energies, 16, 2400. https://doi.org/10.3390/en16052400.

Warr O., et al., 2019, Mechanisms and rates of 4_{He}, 40_{Ar}, and H_2 production and accumulation in fracture fluids in Precambrian Shield environments. October, Chemical Geology 530(41):119322. DOI:10.1016/j.chemgeo.2019.119322.

Zgonnik V., et al., 2015, Evidence for natural molecular hydrogen seepage associated with Carolina bays (surficial, ovoid depressions on the Atlantic Coastal Plain, Province of the USA). Progress in The Earth and Planetary Science, Article number: 31.