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Natural hydrogen: the race to discovery and concept demonstration

Natural hydrogen exploration is experiencing rapid growth. Philip J. Ball and Krystian Czado look at progress in understanding this little-understood resource

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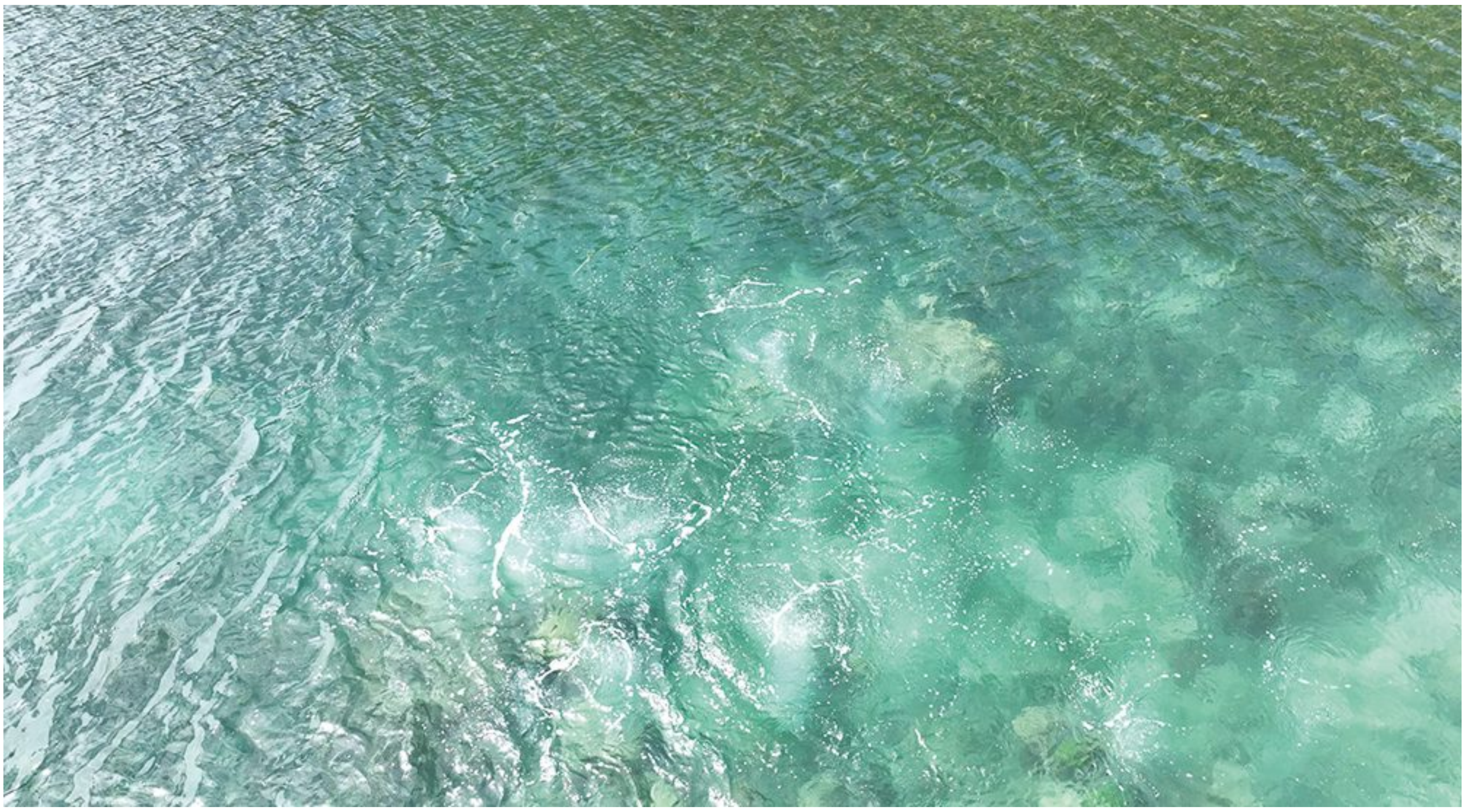

Offshore hydrogen seep, Indonesia (Credit: Indra Sanjaya, Ministry of Energy and Mineral Resources, Indonesia)

There is considerable excitement in the natural (or geologic) hydrogen community and beyond: the hypothesis that natural hydrogen can be found in nature, today is undisputed, with seeps being confirmed all over the world. The distributions of seeps, however, may not reflect geological conditions, rather locations that have received more research attention.

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Energy Geoscience, held at the Geological Society of London in July 2023.

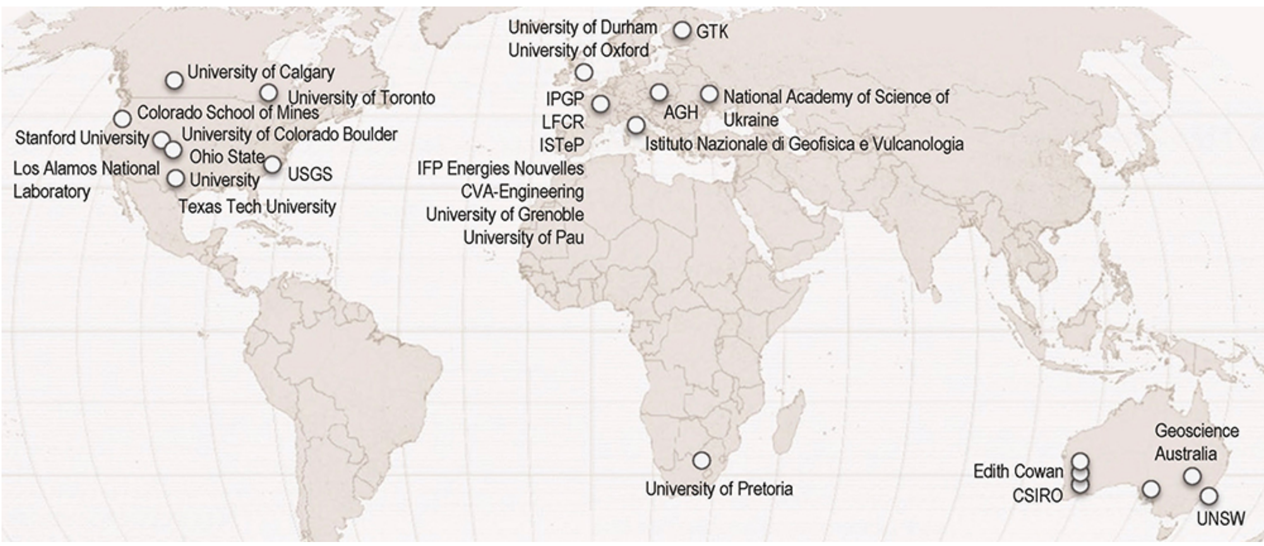

Figure 1: Active natural hydrogen research groups (locations approximate)

Interest and investment

The growing interest in natural hydrogen is reflected in the rise of mainstream media outlets, including *The Wall Street Journal*, *The Guardian*, *Reuters*, and *Forbes*, reporting on this emerging sector in 2023 (see Geoscientist.Online for a comprehensive list of news articles).

Not only is natural hydrogen in the news, but it is also increasingly attracting investors who are driven by the promise of an abundant, low-carbon energy source that is not reliant on renewable energy in the conversion process. (While green hydrogen, which is produced by using renewable energy to split water via electrolysis, offers the opportunity to electrolyse seawater, the challenges associated with scaling up green hydrogen to meet energy demands are intricate and expensive.) This investment has triggered a proliferation of research projects across the globe (**Fig. 1**). Researchers well-acquainted with the origins of natural hydrogen are currently forging partnerships with a multitude of emerging start-ups or recently established natural hydrogen companies (**Fig. 2**), 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.

In 2023, the US-based company Koloma secured an impressive $96.3 million in funding, supported by notable figures such as Bill Gates

Many of these start-up companies are private enterprises, and several of them have successfully secured substantial funding. For example, in 2023, the US-based company Koloma secured an impressive $96.3 million in funding, supported by notable figures such as Bill Gates from Breakthrough Energy Ventures. Other companies have also secured financing and made offerings on the stock markets. For instance, the France-based company Energy 45-8 raised $29.05 million (Nordic, 2023), and the Australian-based Hytera secured AU$5.8 million ($3.9 million) through a public offering on the Australian stock exchange (ASX; ListCorp, 2022), while Gold Hydrogen obtained AU$20 million ($13.5 million) through an IPO on the ASX in January 2023, and raised an additional AU$14.8 million ($9.9 million) following its recent drilling campaign.

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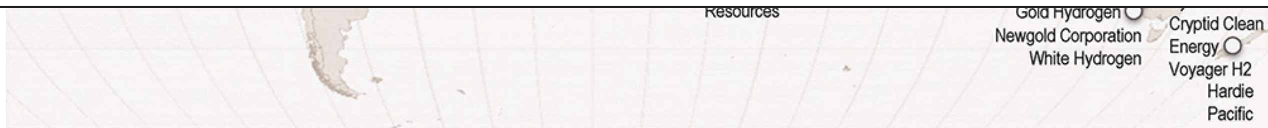

Figure 2: Countries with natural hydrogen exploration companies established, or companies with official activities (locations approximate). Notably, since 2021, a significant number of new natural hydrogen exploration ventures have been established.

Government, philanthropic, and industry support

Private investment in natural hydrogen has also been complemented by a series of government, industry, and philanthropic grants. For example, in the US in 2023, the company Advanced Research Projects Agency-Energy announced a $20 million initiative to explore for geologic hydrogen (ARPA-E, 2023), the USGS and the Colorado School of Mines announced a joint industry project looking at natural hydrogen and exploration technologies with eight companies signed up (Zhang, 2023, pers. Comm.), while the University of Colorado secured a Grantham Foundation grant to study the stimulation of hydrogen from peridotites. International collaboration is also growing, with US-based Eden GeoPower signing a Memorandum of Understanding with Oman for the study of simulated or 'engineered' hydrogen from peridotites (BW, 2023).

In Australia, the government has embraced natural hydrogen, promoting its exploration by amending relevant legislation. For example, the company H2EX received AU$863,000 ($585,600) from federal government grant funding, while the government of New South Wales has allowed for hydrogen to be regulated under the Mining Act 1992 (although the exploration areas have not yet been released).

Institutions representing geologic hydrogen explorers have started to form (e.g., the Natural Hydrogen Association of Australia), and exploration is gaining pace, with efforts concentrated in the state of South Australia, where Gold Hydrogen has conducted drilling for two exploration wildcats. Meanwhile, other states are gearing up for acreage releases for hydrogen exploration scheduled for 2024.

The national government organisation Geoscience Australia recently completed an extensive desktop study, followed by several soil gas sampling expeditions in western New South Wales (the findings of which are set for publication in 2024). Simultaneously, the geologic hydrogen team at the Commonwealth Scientific and Industrial Research Organisation (CSIRO) has been actively involved in advancing exploration efforts. They are working on the development of new exploration hardware, exploring hydrogen migration and containment, and offering valuable support to explorers in South Australia by conducting soil gas surveys. Furthermore, the Geological Survey of Western Australia has conducted thorough reviews of legacy data and initiated soil gas sampling activities in regions historically associated with hydrogen shows.

> French law has officially recognised natural hydrogen as a resource

In France, since April 2022, French law has officially recognised natural hydrogen as a resource. The presence of natural hydrogen has been confirmed in various regions of the country, notably in the Pyrenean foreland, the Jura, and Lorraine. Companies interested in exploration can choose to apply for either an Exclusive Research Permit (PER in French) or an Exploration company reported the €12 million appraisal well would drill in late 2024, with production due to begin in 2029. In Poland, an amendment to the Geological and Mining Law (published on 27 September 2023) provides the legal framework for the exploration and recognition of natural hydrogen fields in Poland. In terms of regulation, some approaches are, however, strangely contrasting. For instance, in the US, the Inflation Reduction Act offers a $3 per kg premium on low-carbon hydrogen production, while in Western and South Australia, a 10% royalty (i.e. a tax), has been proposed on hydrogen extracted from underground formations (Peakock, 2023).

Despite growing exploration activity in the US, Australia, France, Spain, Poland, Oman, and Africa (e.g. HyAfrica project), many governments and their associated geological surveys remain ill-informed and uneducated regarding natural hydrogen and have no national plan to exploit the potential resource.

Industry pivot

Thought leaders from industry and research are actively exploring ways to align the emerging natural hydrogen industry with existing regulations for hydrocarbons. During the meeting at the Geological Society, Adam Craig (RISC Advisory) detailed efforts to find alignment with the Society of Petroleum Engineer's (SPE) Oil and Gas Reserves Committee (OGRC) and the application of the Petroleum Resources Management Systems (PRMS) to natural hydrogen. Regarding the flow and containment of hydrogen, two presentations explored this topic in detail comparing hydrogen with carbon dioxide or with methane (Bhavik Lodhia, CSIRO, and Javier Garcia-Pintado, University of Bremen). The move towards standardisation and characterisation of hydrogen reserves is matched by efforts of ArianeLogix, a software company that aims to provide a tool for the standardisation of subsurface asset evolution, similar to that used in oil and gas workflows, but with an emphasis on gas composition and pressure, volume and temperature.

Numerous petroleum and mineral exploration firms have incorporated natural hydrogen into their research portfolios

Geoscience technology and software companies are also devoting efforts to hydrogen exploration. CGG, Haliburton (Neftex) and GETECH have redirected their extensive geological databases towards hydrogen exploration. CGG has also utilised Machine Learning to develop 'at scale' screening approaches to the fundamentals of hydrogen exploration. Evidence of a discrete transition is notable across several oil and gas companies with representatives from major organisations including Shell, BP, Repsol, OMV Chevron, Petrobras, EcoPetrol and Saudi Aramco, participating in recent natural hydrogen conferences (including the Geological Society meeting). Furthermore, numerous petroleum and mineral exploration firms have incorporated natural hydrogen into their research portfolios, with some industry giants even advertising positions for geoscientists experienced in natural hydrogen.

Halliburton is exploring novel play concepts, including the engineered generation of hydrogen in ultramafic rocks, while EXLOG is developing an advanced mud-logging system that can distinguish between naturally occurring hydrogen and hydrogen generated during drilling. The multi-energy company Repsol is developing a risk-assessment approach that can be used to identify the chance of success of hydrogen exploration according to geological settings (as outlined by Gonzalo Zamora, Repsol). Interestingly, within the case study used to illustrate the subsurface producing a reaction between minerals like olivine, biotite and amphibole; and (2) water radiolysis, whereby radioactive-rich rocks split water into its component atoms. The hydrogen gas may then migrate to accumulate in traps similar to oil and natural gas systems, amass in rock fractures, or perhaps be mineralogically retained via adsorption onto clay minerals or within fluid inclusions – or a combination of these. Additional sources of hydrogen are also proposed such as the degassing of deep (primordial) hydrogen from Earth's mantle or crust (Vitaly Vidavsky, Curtin University), overmature source rocks (John Hanson, Independent), and biological activity.

Numerous presentations at the conference tackled natural hydrogen exploration by assuming a 'play-based approach' – modifying the traditional petroleum systems approach to become a hydrogen-systems approach. The most similar scenario to oil and gas is the case of a natural hydrogen accumulation that is structurally trapped. Target areas must have a source (in this case a mafic or radioactive rock with the presence of water), migration, reservoir, trap and seal (halite or clay-rich mudstone), as well as possibly the right preservation and timing characteristics.

A second resource type discussed at the meeting was natural generation, which involves targeting actively seeping systems. In this scenario, exploration of a dynamic seeping system is associated with considerable risk given there are no seals or traps or reservoir. To understand the economics, data are needed to determine whether the flux is steady state.

A third concept is stimulated or engineered generation of hydrogen, which only requires the presence of a source rock. Many conceptual plays were outlined, such as iron-rich mafic rocks or 'mineralogically retained hydrogen' (Owen E. Sutcliffe, Halliburton). Both play types would involve the drilling of horizontal and vertical wells to artificially stimulate hydrogen production, but there are some important differences. For the engineered generation of hydrogen, water is injected into ultramafic rocks to stimulate serpentinization and kickstart hydrogen production, potentially generating fresh hydrogen fast enough to become cost effective. The mineralogically retained concept is more complex – to recover this hydrogen requires an understanding of adsorption and desorption. Hydrogen generated via radiolysis of water can be retained within minerals as inclusions or via adsorption onto clay minerals. An example of such natural hydrogen trapping is the Lake Cigar Uranium deposit, where hydrogen is absorbed by clays that encapsulate the deposit (Owen E. Sutcliffe, Halliburton). John Hanson (Independent) noted that much needed research into over-mature coals, organic-rich shales, and uranium-enriched rocks is required for both natural and engineered hydrogen concepts.

In contrast to the hydrogen systems models, Howard Golden (GETECH) presented a hydrogen-exploration concept based on the 'mineral systems approach' adopted from McCuaig et al. (2018). This approach has notable differences: initially, petroleum systems involve a mass-trapping process with the transporting fluid serving as the commodity, whereas mineral systems engage in mass scrubbing processes. In mineral systems, the transporting fluid typically holds low concentrations of the commodity, necessitating increased fluid throughput. Secondly, mineral systems facilitate fault-controlled fluid flow. Thirdly, for petroleum systems, maintaining the entire system in a reduced state is crucial for sustaining high-quality hydrocarbons. Conversely, in numerous copper, lead-zinc, uranium, and hydrogen systems, conditions mandate that the systems remain oxidized until the point of deposition. In a mineral system, the metal is absorbed by the trapping formation from the metal-rich brine.

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Figure 3: ‘Fairy circles’ in Western Australia. Clusters of ‘fairy circles’ – circular depressions that seep hydrogen gas from around their perimeters – exist in the North Perth Basin near the town of Moora (urban area, lower right of the image). The clusters occur along the N-S-trending Darling Fault and are several hundred metres in diameter. The large orange circular depression towards the centre-left of the image is Lake Dalaroo. ‘Fairy circles’ have been found on multiple continents. (*Credit: NASA Earth Observatory image by Wanmei Liang, acquired on 27 June 2023 using Landsat data from the U.S. Geological Survey. Story by Lindsey Doermann.*)

Quest for a blueprint

The prevailing approach of the emerging hydrogen companies is top-down, to look for evidence of hydrogen seeps or circular depressions (e.g. fairy circles; **Fig. 3**) that may be located at the surface above a degassing natural-hydrogen accumulation. However, critics point out that circular depressions are absent in areas with well-documented hydrogen seepage. For example, the Tajung Api area of Central Sulawesi Province, Indonesia, is host to over 600 seeps (on and offshore), yet there are no fairy circles.

Exploration rooted in observation is natural for an emerging industry, as companies attempt to develop exploration concepts that can be standardised and replicated elsewhere. There will be failures, but the critical question remains: Can the natural hydrogen industry emerge with a blueprint for replication of concept demonstration?

Mali

A presentation on the discovery of natural hydrogen in Mali was keenly awaited since this remains the only ‘commercial’ hydrogen field. Discovered serendipitously in Mali in 1987 while drilling for water, this natural hydrogen field has been in production supplying the village of Bourakebougou with electricity since 2012. In a recent study, Maiga et al. (2023a) outlined the core sampling, logging, and geochemical studies conducted in the region. The primary reservoir, which is relatively shallow and contains the highest hydrogen content, is made of dolomitic carbonate, known as the Neoproterozoic cap carbonate. These carbonates exhibit extensive karstification and demonstrate significant heterogeneity in porosity ranging from 0.21% to 14.32%. An analysis of drilling imagery reveals that hydrogen accumulates within the karstic voids, representing secondary porosity within the rock matrix. These results, coupled with production data, enable the initial characterization of natural hydrogen reservoir systems.

Based on data provided by Hydroma, Omar Maiga (IFP Energies Nouvelles) and colleagues presented a new analysis of the trapping process of natural hydrogen in the Bourakebougou field, Mali (Maiga et al., 2023b). Their results indicate that the hydrogen trapping is complex. The field has a structural component: the accumulation is migrated into an anticlinal trap with an unfractured dolerite sill as the active seal. Maiga also noted there is a hydrodynamic trapping component, with shallow water playing the role of barrier. It was also revealed that the Bourakebougou area is not associated with a fairy circle, and that there was a correlation between the dolerite thickness and the wells and zones rich in hydrogen.

In summary, the two studies conducted on this initial ‘commercial’ hydrogen field have led to two noteworthy discoveries, notably the dynamics of natural hydrogen reservoirs (particularly,

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Geoscientist at the Geological Survey of New South Wales, Australia.

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