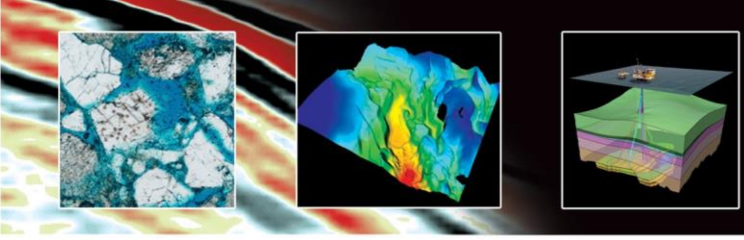

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Natural Hydrogen: A New Frontier for Energy Geoscience

A Geological Society Conference addressing the search for natural hydrogen

4th-5th July 2023

Hybrid Event -The Geological Society, Burlington House, Piccadilly London & Virtual

The Olympic Flame - said to originate from a 2,500 year old natural hydrogen seep

The quest for natural hydrogen is gathering momentum. Hydrogen exploration is currently active in Africa, South America, Australia, USA, France and Spain and a discovery of 'free' (gas-phase) hydrogen has been put into production in the Taoudeni Basin of Southern Mali (Prinzhofer et al. 2018). Although legislation is lagging behind, if significant volumes of gas-phase natural hydrogen can be proven in subsurface accumulations, it would naturally become the '**green' successor to petroleum and represent an exciting new frontier for exploration geoscience**.

This conference will address how geoscience can be applied to the exploration for Natural Hydrogen and will focus on developing the geological understanding and application towards exploiting Natural hydrogen. We invite abstracts for the following themes:

- Global Occurrences & Habitats of Natural Hydrogen
- Sources of Natural Hydrogen
- Migration & Alteration
- Trapping & retarding
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Natural Hydrogen: A New Frontier for Energy Geoscience

4-5th July 2023

The Geological Society (Burlington House, Piccadilly, London) & Virtual via Zoom

Provisional Programme

Day One	
08.30	**Registration**
08.50	**Welcome**
	Session One: Natural Hydrogen Exploration Plays
09.00	**KEYNOTE: Actively exploring the midcontinent rift natural hydrogen play in the central mid west, USA** Avon McIntyre, *HyTerra Ltd*
09.30	**The Natural Hydrogen System – how success can be achieved through the system and play approach** Owain Jackson, *H2Au Ltd*
09.55	**Natural Hydrogen Exploration Workflows: Insights from South Australia** Grant McMurtrie, *2H Resources Pty Ltd*
10.20	**Natural hydrogen in the Pyrenees and implications for exploration** Chris Atkinson, *Helios Aragon*
10.45	**BREAK**
11.10	**Why aren't there more native hydrogen accumulations?** Thomas Becker, *Astris Advisors*
11.35	**Defining an Architecture for Subsurface Hydrogen Play Concepts** Owen Sutcliffe, *Halliburton*
11.55	**DISCUSSION – What are the key geoscience knowledge gaps for Hydrogen Exploration?**
12.15	**LUNCH**
	Session Two: The Hydrogen System – Generation, Migration & Hosting
13.15	**KEYNOTE: Trapping processes of natural hydrogen in subsurface: The case of the emblematic H2 field of Bourakebougou (Mali)** Omar Maiga, *IFPEN*
13.45 Virtual	**Computation of vertical fluid mobility: Implications for hydrogen exploration and CO2 storage** Bhavik Lodhia, *CSIRO*
14.10	**Numerical Modelling of Hydrogen Migration and Trapping in Geological Settings: Comparisons between Natural Hydrogen and Petroleum Systems** Tiago Cunha, *MARUM - University of Bremen*

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14.35	**Heterogeneity of serpentinization through a km-size upper mantle body: The Turon de Técouère case (Pyrenees, France)** Loiseau Keanu, *LFCR*
15.00	**BREAK**
15.20	**KEYNOTE: How to quantify the initial and remaining potential of a H2 source rock?** Isabelle Moretti, *UPPA*
15.50	**A model of dynamic gas accumulation of hydrogen, helium, nitrogen and methane** Marie-Christine Cacas-Stentz, *IFPEN*
16.15	**Possible generation mechanisms for an organic hydrogen system** John Hansen, *Independent*
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17.00	**End of day one**
17.00 – 18.00	**Drinks Reception**

Day Two	
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08.50	**Welcome**
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09.00	**KEYNOTE: Exploring Natural H2 in the Balkans** Benoit Hauville, *45-8 Energy*
09.30 Pre-recorded	**Natural Hydrogen Exploration in South Australia** Elinor Alexander, *South Australia Department for Energy & Mining*
09.55 Virtual	**Natural hydrogen and helium occurrences of the Eastern Trans-Australian Corridor (Darling-Curnamonda-Delamerian) in New South Wales, Australia** Emma Black, *Geoscience Australia*
10.20 Virtual	**Anatomy of a Natural Hydrogen Seep: An Example from the Yilgarn Craton in Western Australia** Krista Davies, *Edith Cowan University*
10.45	**BREAK**
11.05 Virtual	**KEYNOTE: Identification of Hydrogen-Rich Zones as a First Step in Natural Hydrogen Exploration in China** Xueying Yin, *Beijing Santai-Tongdi Exploration Techhnologies Co. Ltd*
11.35	**Surface Circular Depressions: how are they forned? A Western Australian Example** Emanuelle Frery, *CSIRO Energy*
11.55	**DISCUSSION – Trap vs flux – how are surface expressions important for discovering commercial hydrogen?**
12.15	**LUNCH**
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13.15	**KEYNOTE: Natural hydrogen resource potential of the conterminous US** Geoffrey Ellis, *USGS*
13.45 Virtual	**Natural hydrogen – Estimating the resource, a case study from South Australia** Adam Craig, *RISC Advisory*
14.10 Virtual	**NATURAL HYDROGEN. Estimating the Resource: Flux vs. Accumulation, Tools for Evaluation and Analysis. Proposed Drilling Techniques Development** Vitaly Vidavsky, *Curtin University*
14.35	**A Mineral Systems Approach to Targeting Natural Hydrogen Deposits** David Tierney, *GETECH*
15.00	**BREAK**
15.25	**Early Exploration Services to aid in predicting the presence of Native Hydrogen at scale** Ranald Kelly, *CGG*
15.50	**A Statistical Approach as a tool for Native H2 Exploration: A Case Study in the Western Pyrenean Foothills (SW France)** Nicolas Lefeuvre, *CVA*
16.15	**Assessing hydrogen migration and accumulation potential: characterisation of the Adelaide Geosyncline basement structures and their mineral fills** Zak Milner, *Durham University*
16.40	**Natural Hydrogen Exploration: Risk Assessment** Gonzalo Zamora, *Repsol*
17.05	Conference Wrap Up
17.30	**End of Conference**

Posters
Biogeochemical hydrogen alteration of in hydrogen rich gas seeps from Italy Rebecca Tyne, *Woods Hole Oceanographic Institution*
Helium, Hydrogen and Hydrocarbon exploration in the Amadeus Basin, Central Australia– exploration strategies for understanding the similarities and differences in play models Julie Daws, *Mosman Oil and Gas Ltd*
The transport and accumulation of helium in a nitrogen-dominated reservoir Anran Cheng, *University of Oxford*
Reassessing the role of magnetite during natural H2 generation Ugo Geymond, *IPGP*
A multiscale petrology study on Fe-rich clays minerals in fayalite-bearing gabbros within the Kansas (USA) Precambrian basement: an attempt to quantify natural hydrogen generated Valentine Combaudon, *IFPEN*
Unlocking Tanzania's Helium Province Lorna Blaisse, *Helium One Global Ltd*
Advanced Gas Mud logging in Natural Hydrogen settings Caroline Magnier, *Abyssens*
New Approaches to Helium Exploration Field Gas Sampling for Helium and Hydrogen- a trial study Mick Small, *Devil Resources Ltd. / Global Oil and Gas*

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ORAL ABSTRACTS
(In Programme Order)

Session One - Natural Hydrogen Exploration Plays

Keynote – Avon McIntyre

Actively Exploring the Midcontinent Rift Natural Hydrogen Play In The Central Mid West, USA

Avon McIntyre, Jeff Goodall and Luke Velterop; *HyTerra Ltd.*

A working, subsurface, natural hydrogen system is recognised in the central Midwest states of the USA, where anomalous hydrogen (up to 92% by volume) has been observed in legacy oil and gas exploration wells. Sufficient data exists to map out the key geological elements for exploration purposes and the potential extent of the hydrogen system, using a play-based exploration approach similar, but not identical to that utilized in the petroleum industry.

Current natural hydrogen exploration is analogous to the early days of oil and gas exploration, in which geological rules are being tested and validated. A structured exploration approach is being developed in order to de-risk the exploration process and guide the acquisition of prospective acreage.

This presentation demonstrates how the targeted methodology for natural hydrogen exploration has moved from soil gas sampling of surface circular features to a more expansive predictive subsurface geological model which is currently being tested by new data acquired in the area.

The deliberate targeting of natural hydrogen resources in the Central Midwest of the USA is underway with a rapid ramp-up of exploration activity, including drilling and well testing by multiple companies. These data will help inform and refine our understanding of natural hydrogen system/s both in the Central Midwest and in other prospective locations globally.

The Natural Hydrogen System – how success can be achieved through the system and play approach

Owain Jackson, [1] Steve Lawrence, [1&2] Andy Stocks, [2] Andy Barnicoat, [2] Ian Hutchinson,
1 – H2Au Ltd
2 – Natural Hydrogen Study Group

Exploration success in the Petroleum industry has undoubtedly been realised through a science led understanding of the petroleum system and the development of plays; especially as exploration moved into more complex and costly settings. Prolific petroleum basins have also been defined based on the identification and mapping of the primary source rock and kitchen, rather than following secondary indications at surface.

The challenge faced by hydrogen explorers is to prove that meaningful reserves of hydrogen are possible. Looking for hydrogen with a focus on surface indications and seeps alone, without understanding the hydrogen system at work to explain the hydrogen, could lead to false starts, negative results, and an early loss of faith in natural hydrogen as an emerging resource. The play (genetic) approach overcomes this first challenge.

Based on first-hand experience in Mali, H2Au and the Natural Hydrogen Study Group (NHSG) have developed a hydrogen exploration model which can be used to explain the discovery of 98% hydrogen through drilling at Bourakebougou, Mali (Prinzhofer, 2018). This model proposes that the source of the natural hydrogen is serpentinization of ultramafic, Paleoproterozoic greenstone belts situated in the basement beneath the Taoudeni basin. Unlike other sources of hydrogen, Serpentinisation offers a rapid, focussed, and quantifiable source of hydrogen, which is well studied and proven in multiple geological settings such as mid ocean ridges (Merdith et al. 2020) and Ophiolites (Bachaud et al. 2017, Zgonnik 2019).

Once generated hydrogen migrates from the serpentinization reaction zone through a mix of advection and diffusion, largely along fracture systems and initially in solution before exsolving as free gas. Like petroleum gasses the hydrogen will eventually accumulate in traps where it meets sufficiently low permeability cap rocks and remains below the capillary and lithostatic entry pressure thresholds.

Within the model there are many challenges to be overcome: identifying the protolith (source) under a basin cover; availability of geophysical data and its interpretation in basement terrain; identifying active faults; integrating other disciplines like hydrogeology, metamorphic geology; understanding the flux, estimating the reserves (replenishable?); not to mention the production challenges, potential reservoir pressure issues and possible parallels to unconventionals. But unlike the early 20th century oil and gas pioneers, we have decades of applied, play based exploration techniques and technology at our disposal.

We present our hydrogen model, along with the similarities and key differences from the well understood petroleum system and illustrate the potential extent of the play across the Taoudeni basin.

Natural Hydrogen Exploration Workflows: Insights from South Australia

Grant McMurtrie[1], Frank Glass[1] and Harvey Keon[1]

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2H Resources has been identified as the preferred applicant for six South Australian petroleum exploration licences (PELs) for the purposes of natural hydrogen exploration. The granting of these licences is contingent on the execution of a valid land access agreement under the Native Title Act.

At the request of 2H Resources RISC Advisory has conducted an independent assessment of the potential natural hydrogen resources in the area under application. This assessment indicates that the area could contain between 49 million (risked 1U) and 1.3 billion (risked 3U) kilograms of hydrogen resources, with a risked prospective best estimate of 343 million kilograms.

The acreage under application by 2H Resources lies within the folded Neoproterozoic Adelaide Superbasin, bounded by Mesoproterozoic-Neoproterozoic cratonic terranes. The adjoining and underlying geology is consistent with generative mechanisms for natural hydrogen, contains significant subsurface discontinuities and has thin overlying regolith. The licences are geologically on trend with legacy natural hydrogen discoveries drilled in the 1920's and 1930's.

This presentation will discuss how 2H Resources consolidated a vast library of geological data over an area of ~30,000 square kilometers, approximately the size of Belgium. The database consists of petroleum, geothermal, mineral and water wells, potential fields data and detailed surface geology. Our challenge was to filter this dataset into meaningful subsets that could delineate prospects for the resource assessment and focus areas for natural hydrogen field measurements. This was achieved by adopting some of the principal tenants of petroleum play-based exploration (PBE) for natural hydrogen exploration.

Rather than adopting the classic PBE pyramid, a four-tiered framework for organizing data to understand the" natural hydrogen play" will be detailed:

- Underlying basement geology, tied to hydrogen generation processes.
- Conduits for migration
- Accumulation barriers and dams
- Surface features and gas anomalies

The presentation will discuss some of the challenges in defining plays when there is significant subsurface uncertainty of generative mechanisms and migration conduits.
We will also demonstrate the use of probability heat maps as an alternate approach to Common Risk Segment (CRS) mapping. Rather than a traditional bottoms-up approach, we propose to initially work top-down, from the surface where we have the highest data density, can physically measure seeps, then connect to potential migration paths and sources.

Natural hydrogen in the Pyrenees and implications for exploration

Christopher Atkinson, Sandra García-Curiel, Christopher Matchette-Downes and Ian Munro

Helios Aragon

Studies on each side of the Pyrenees have revealed the presence of natural free hydrogen and in Spain (Ebro Basin) helium is also present (Atkinson et al 2022 and Lefeuvre et al 2022). Lefeuvre’s paper describes the optimal geological, solubility and temperature requirements for the generation, accumulation, and preservation conditions for hydrogen from studies near Sauvete Béarn.

In our work in the Ebro Basin to the south, similar conditions are also observed, in fact free hydrogen has been recorded in well bores drilled in the 1960’s (e.g., Monzón-1). The location of these hydrogen gases is suggested to be related to underlying serpentinization of oceanic crust or upper mantle, with a contribution possibly derived from the radiolysis of Ordovician volcanoclastic marine shales. The latter are also thought to be the source of the helium found in soil gas samples collected in the Monzón and Barbastro permits in the first half of 2022.

The Monzón-Barbastro area also benefits from a thick salt and halite rich shale seal overlying several well-defined, structural closures at Triassic Bunter Sandstone level. An appraisal well is planned to be drilled in 2024 to test the commerciality of the natural hydrogen accumulation originally discovered in the Monzón-1 well.

Learnings from our studies in Spain can be applied to other prospective areas for natural hydrogen exploration.

Why aren't there more native hydrogen accumulations?

Thomas P. Becker and Gilles Pantanacce, Astris Advisors (UK) Limited, 8th Floor, 71 Queen Victoria Street, London, EC4V 4AY, UK

Travis Smithard, Rhino Resources, ICON Building, 24 Hans Strijdom Avenue, Foreshore, Cape Town, 8001 South Africa

Hydrogen is being explored as a future energy carrier, particularly for renewable energy applications, yet small seeps and accumulations of near-pure hydrogen hint at the possibility of subsurface resources that could also provide an extractable carbon-free fuel. Locations where native hydrogen has been found tend to be underlain by either ultramafic or Paleoproterozoic to Archean-age rocks, and mechanisms to explain these occurrences typically involve hydration of Fe-silicates and/or radiolysis: conditions that are found in many places on Earth. If creating free hydrogen is a relatively simple and common process, why hasn't more of it been encountered?

Given the extreme buoyancy of hydrogen, leakage to the atmosphere is casually cited as a reason that it might not be widespread (i.e., a seal failure). Capillary seal capacity is commonly used within the hydrocarbon industry to evaluate potential accumulation failure mechanisms, or test notional limits on column heights, and these same principles can be applied to hydrogen. Using temperature and pressure-dependent interfacial tension, contact angle measurements, and equations of state for hydrogen, it can be shown that typical mudstones should be able to retain a column. Increasing interfacial tension and decreasing contact angle with decreasing temperature and pressure indicate that the seal capacity increases in shallower depths as well. These relationships speak to so-called "fairy circles" as hydrogen-emission-related features, because if true they suggest either a lack of mudstones or a free hydrogen column that exceeds the seal capacity.

The existence of biogenic methane in low-porosity "basement" rocks and overlying strata also has a connection to geologically-produced hydrogen. In these locations, methane is a metabolic byproduct of hydrogenotrophic archaea. Their presence seems to prove a stable supply of free hydrogen, and moreover, open inquiries around biological cycling that may have obscured or consumed hydrogen before it could become an accumulation. Understanding the conditions for sustaining a habitat for methanogenic archaea is likely key to finding more hydrogen (and/or methane).

Defining an Architecture for Subsurface Hydrogen Play Concepts

Owen E. Sutcliffe
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Hydrogen (H_2) will be an increasingly important energy carrier in the future with large volumes created from the electrolysis of water or the breakdown of hydrocarbons. However, both processes require large amounts of energy. Therefore, the production of subsurface hydrogen may have the potential to remain a cheaper and less energy-intensive option at least locally.

Subsurface H_2 occurs as a free gas, in fluid inclusions or as an aqueous solution and has 28 non-anthropogenic generative processes. Once generated, H_2 reacts readily with oxidised elements, is highly mobile and is easily dissolved in fluids, all of which complicate the design of play concepts for H_2. Three different groups of play-concept are proposed:

- Structurally or stratigraphically retained, where H_2 has migrated away from its generative rock
- Mineralogically retained, where H_2 has only had negligible or minor migration and
- Engineered, where H_2 is created in-situ.

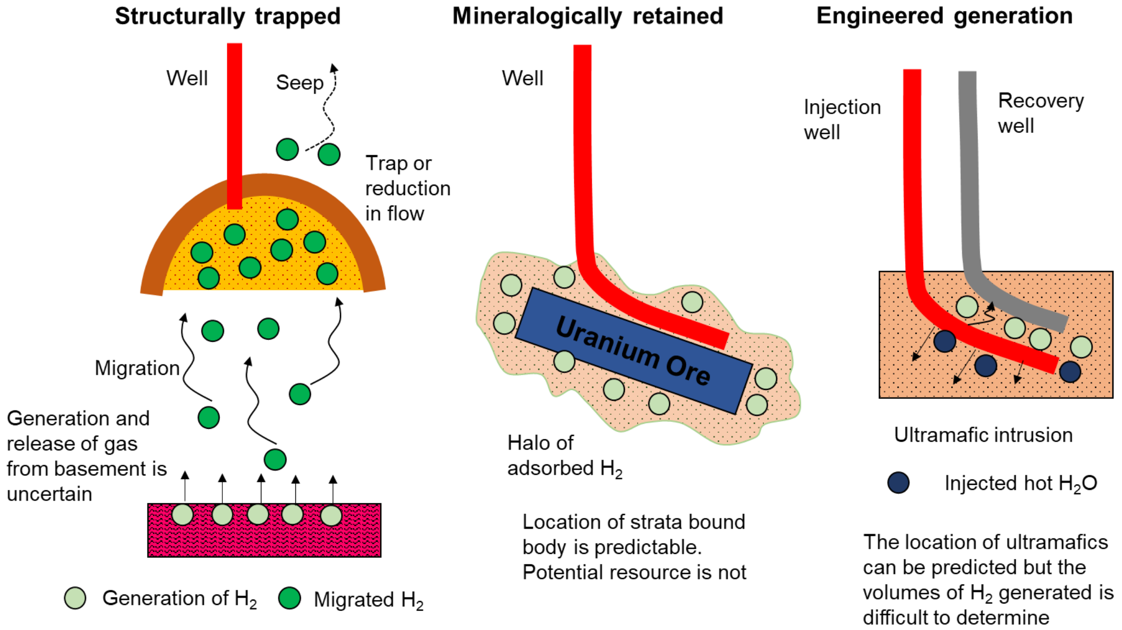

Figure 1. Schematic representation of the accumulations of hydrogen and its potential exploitation in the proposed three main groups of H_2 play concepts

A proven example of the first play concept includes the Bourakobougo Field, Taoudeni Basin, Mali. Here, the H_2 is 98% pure with the origin of the gas thought to derived from an active crustal source. However, it should be stated that H_2 concentrations at this level are incredibly anomalously irrespective of the setting the gas formed in.

When H_2 is generated from the radiolysis of water, the mineralogical retention of it is possible through adsorption onto clay minerals or by trapping within fluid inclusions. Fluid inclusions within the aqueous potassium-salt sylvite is common and in the Boulby Potash Mine, UK, the average concentration of H_2 in sylvite is up to 0.27%. Such potash deposits form extensive strata-bound layers. Similarly, in Athabasca, Alberta, H_2 is adsorbed onto clay minerals that surround a uranium ore body. Here, the Cigar Lake Ore Body is estimated to have 476t of H_2 and like shale-gas deposits, this H_2 can be thermally desorbed. These known occurrence of H_2 raises the question of whether they could generate an effective play for this resource but like other occurrences of H_2 the composition of the produced gas would be varied and includes He, CH_4 and CO_2.

Serpentinization of iron-rich rocks (e.g. ultramafic intrusions) is perhaps the most studied mechanism for generating subsurface H_2 and has the potential to form a play concept where H2 is effectively engineered. It is a process responsible for much of the H_2 in the crust today but the volumes of H_2 generated by serpentinization vary by 8 orders of magnitude due to pressure, temperature and mineralogy. However, up to 2-4 kg H_2/m^3 can form from an average peridotite.

In conclusion, the strategic search for subsurface H_2 has significant uncertainties but will provide an exciting challenge for the energy industry. The diverse origins for subsurface H_2 complicate the design of H_2 plays but three broad groups of play concepts are considered. In these, exploring for H_2 with concepts that compare with conventional petroleum systems (i.e. long-distance migration and trapping of the gas) will have higher risks than those where H_2 is retained or engineered in the subsurface. Focusing on the last two groupings will help the industry develop appropriate technology to recover H_2 and limit risks associated with migration to a trap. However, the potential for such “conventional” accumulations should not be discounted (at least locally).

Session Two: The Hydrogen System – Generation, Migration & Hosting

Keynote: Omar Maiga

Trapping processes of natural hydrogen in subsurface: The case of the emblematic H_2 field of Bourakebougou (Mali)

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Diallo, Aliou Boubacar[3] - *HYDROMA INC, Montréal, Québec, Canada*

Today, most of the discussions about natural hydrogen exploration focus on the world's surface hydrogen occurrences and its generation processes, while the trapping process remains the most important issue in allowing significant accumulation of hydrogen in the subsurface. The physicochemical properties of hydrogen (very small and highly mobile), as well as the number of hydrogen seeps (leakages) that have now been recorded worldwide confirm this fact. Thanks to the data provided by Hydroma, we were able to perform a detailed characterization of the caprocks that retain hydrogen in the Bourakebougou natural H_2 field. Clearly, the dolerite mega-sills that are widely present in this area play an important role in trapping H_2 within the main and shallower reservoir. Investigation on the sealing capacity of these dolerites reveals that not only the thickness of the dolerites is important but also the number of fractures and the degree of alteration of the dolerites. Another key player that has been identified is the retention role of an extensive aquifer in the area. Indeed, hydrogen being poorly soluble in water at low pressure conditions, it is less likely to diffuse easily to the surface at shallow depth. In addition, several barriers to H_2 migration to the surface are present below the shallower main reservoir. This study highlights that the exploration of H_2 fields should not only be established on the presence of a generation process but also on the presence of a very efficient accumulating system.

Computation of vertical fluid mobility: Implications for hydrogen exploration and CO2 storage

Bhavik Lodhia, *CSIRO*

Over the last decade, there has been an irreversible shift from hydrocarbon exploration towards carbon storage, low- carbon energy generation and hydrogen exploration. Whilst basin modelling techniques may be used to predict the migration of hydrocarbons through sedimentary basins on geological timescales, there remains little understanding of how fluids behave at the basin scale on present-day timescales. We apply the Darcy flow equation to present an algorithm that calculates vertical fluid velocities for CO2, methane, and hydrogen as a function of depth in sandstones and carbonates. This allows for calculation of vertical fluid velocities ($v$max) on human timescales and on the basin scale. $v$max for CO2 and methane are on scales of m/year. Our results also indicate that the fluid mobility of subsurface CO2 may be sensitive to surface and near-surface temperature variations. CO2 stability may be affected by surface or near-surface temperature variations caused by long-term climate change or urbanisation. CO2 storage in geological media may be more efficient in regions of low surface temperature, away from sources of heat and beneath a minimum depth of ~ 0.6 km. $v$max for hydrogen is approximately 2 – 10 times greater than those for hydrocarbons at the same depth. This is important for determining the migration of hydrogen through geological media for both storage and exploration assessment. The increased vertical velocities must also be considered if applying conventional basin modelling software to model hydrogen migration.

Box-Size Numerical Modelling of Hydrogen Migration and Trapping: Testing the Geological Setting and Analogies with the Petroleum Systems

Javier García-Pintado[1], Marta Pérez-Gussinyé[1], Tiago Abreu Cunha[2], Marianne Nuzzo[2], Steve Lawrence[3], Owain Jackson[3], Andy Stocks[3], Andy Barnicoat[3], Ian Hutchinson[3]

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3. *Natural Hydrogen Study Group (NHSG), SRC Chiltern House, 45 Station Road, Henley-on- Thames, Oxfordshire RG9 1AT*

There is widespread evidence that hydrogen is naturally generated from a number of processes in the crust and mantle, namely from hydrothermal alteration of iron-rich rocks in the lower crust and upper mantle, water radiolysis within the lower crust, mechano-radical processes in active faults, and possibly also from the de-degassing of primordial hydrogen.

There is, however, only sparse evidence of high hydrogen concentrations in sediments, and we have limited knowledge on the processes that control hydrogen migration and trapping in sedimentary basins. The three most paradigmatic cases for known and/or potential hydrogen accumulations are, arguably:

1) The Cigar-Lake uranium-rich deposits in Athabasca (Canada), where significant amounts of hydrogen are found adsorbed to water-saturated, clay minerals (mainly illite, chlorite and kaolinite), in (very) high concentrations. According to Truche et al. (2018), 4-17% of the molecular hydrogen (H_2) produced by water radiolysis over a 1.4- Ga-lifetime is still trapped in alteration clays surrounding the uranium ore deposits; a very long-term geological storage.
2) The hydrogen field in the Taoudeni Basin (Mali), where H_2 in concentrations of up to 98% is stored in multi-layered sedimentary rocks (mainly carbonates). The traps are both doleritic sills and aquifers, which represent high permeability barriers due to the very low solubility of hydrogen in water at shallow depths. The artesian activity recorded in some wells, and presence of carbon monoxide, virtually absent in natural gases, indicate recent charges with high pressures sustained over 10 years. They are characteristic of a renewable source with a low- to medium- to (potentially) long-term geological storage with ongoing re-charge.
3) The Amadeus Basin in central Australia, where gas rich in CH_4, He and H_2 has been flown from sandstone and fractured basement reservoirs in two different wells, trapped under a laterally (very) extensive Neoproterozoic salt seal (Johns *et al.*, 2017). A similar play is envisaged in other basins of southern and western Australia and, taking advantage of favourable legislation, six companies have applied and/or been granted for 18 natural hydrogen exploration licenses covering an area of approximately one-third of South Australia (570,000 km^2).

In this study, we use box-size numerical models of miscible multiphase flow to support our understanding on the main factors controlling the migration and trapping of hydrogen in sedimentary basins. The setup involves an injection zone and a low-permeability (clay-like) trap at the top boundary. Hydrogen is injected as a source, as expected from generation by hydrolysis or from serpentinization reactions. The equation of state (EOS) for the liquid phase is pure water, and the EOS for the gas phase is pure hydrogen.

We evaluate the relative impact of geological layering and lithological/capillary contrasts, P-T effects, hydrogen diffusivity, temporal variability in the hydrogen sources, H_2 adsorption to clay particles, and the impact of biogenic sinks.

Initially, and at depth, the injected hydrogen is dissolved in the liquid phase (water), and migrates mainly as dissolved within the liquid phase. Further injection leads to free gas, with a much faster upward migration controlled by the corresponding phase relative permeability. Towards the surface, decreasing pressures lead to further degassing, with a positive feedback on gas mobility. The relation between injection rates (hydrogen generation) and the development of a positive capillary pressure and dominance of the free trapped gas phase is controlled by the retarding capability of the clay layer.

The rationale for modelling the hydrogen system is based on analogies with the gas-prone petroleum systems, including generation, migration, trapping and losses. The analogy becomes even more striking for the Cratonic Greenstone Model, where the serpentinization of mafic and ultramafic rocks takes place within an optimal temperature zone (broadly 200-300°C). In this presentation we show the details of the numerical experiments, which are planned to support the analysis of more complex geological settings, and where processes are modelled at prospect-play-basin scales.

Heterogeneity of serpentinization through a km-size upper mantle body: The Turon de Técouère case (Pyrenees, France)

Loiseau Keanu1,2,* ; Aubourg Charles1; Hoareau Guilhem1 ; Petit Valentin1 ; Bordes Sébastien1; Dupuy Johann2 ; Thomas Eric2 ; Lefeuvre Nicolas2 ; Rigollet Christophe2 ; Moretti Isabelle1

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** : kloiseau@univ-pau.fr*

The generation of oil and gas requires organic-rich, sedimentary source rocks. It is mainly temperature dependent (so rather homogeneous). In contrast, the generation of natural hydrogen by water rock interaction commonly occurs at various temperatures and depths. In addition, such source rocks can reveal strong heterogeneities at different scales, that are still to be fully characterized (Fig 1). We will present evidence of these heterogeneities and discuss the complexity to quantify the H2 generation due to serpentinization, on a mantle outcrop, the Turon de Técouère (TT) located in the Pyrenees (France),.

Several mantle bodies outcrop along the retro wedge of the Pyrenees, such as the Lhers massif on its eastern part or the TT massif on its western part. These bodies have been exhumed during an Albo-Cenomanian hyperextension phase. It is believed that during subsequent compression, the TT massif was embedded as a raft within Triassic salt, and exhumed to its present-day location. Such outcrop can be studied as a proxy of the underlying mantle wedge, considered as the potential source rocks for a hydrogen play in the Pyrenees. Previous studies in this orogen, including soil gas sampling, have shown H2 seepages along the deep-rooted faults such as North Pyrenean Frontal Thrust (NPFT). The H2 soil gas anomalies obtained In the TT can reach more than 1000 ppmv.

Since magnetite is a co-product of serpentinization, magnetic properties can be used to determine the homogeneity of this km-scale body. The TT was characterized by in situ measurements of the magnetic susceptibility and its local magnetic field. These data were correlated to describe the degree of serpentinization. Additional lab measurements (microscopy, rock magnetism and X-ray micro-tomography) have also been performed.

Figure 1: Different scales of serpentinization heterogeneity A) Magnetic susceptibility map of the whole peridotite body, high values are located to the north-east; B) Magnetic susceptibility of a meter-size block, where highest values are located along the fracture network; C) Thin section of the TT lherzolite. Opx: Orthopyroxene, Cpx: Clinopyroxene, Ol: Olivine, Sp: Spinel, Matrix: Minerals in fine-grained matrix, Serpentine (Serp) in mesh structure olivine.

Magnetic susceptibility ranges from 1.10-6 to 2.10-2 SI, where 92% of data are below 10-3 SI. Magnetite is firmly identified with its typical Verwey transition at -150°C and Curie temperature at 580°C. Intensity of magnetic field ranges from 46.02 to 47.60 µT. At km scale (Fig 1 A), serpentinization is localized in the NE part of the body whereas at meter scale (Fig 1 B), it is localized along the fracture network, consistent with the water circulation model.

This work is a first step to better quantify the level of serpentinization in a peridotite body, and hence the remanent potential of further serpentinization. Using magnetic properties of the peridotites, measured on the field, aims to find a new and fast proxy for these heterogeneities.

How to quantify the initial and remaining potential of a H_2 source rock?

Isabelle Moretti[1], Ugo Geymond[2], Nicolas bouton[3], Jérémie Ammounial[3]

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After years of trials and errors, the O&G world converged on the concept of petroleum system. Source rocks, maturation, expulsion, migration, accumulation are understood, maybe not perfectly but well enough to allow the development of powerful basin modeling tools, such as Petromod or Temisflow, that do useful predictions. Concerning the source rocks, pyrolizers are daily used to quantify the TOC, Tmax, HI and other characteristics of the organic rich material and the Arrhenius law that link maturation rate and temperature is the cornerstone. The success of these concepts was so high that the geologists even disregarded for couple of year alternative sources of HC such as biogenic and abiotic. The landscape is changing. The exploration of H_2 allows to revisit the idea of an abiotic origin of some CH_4 accumulations. Concerning the organic source rock evolution, the role of water and the pertinence of open versus closed system analyses remain question of debate but the results of the modeling done with the parameters deduced from the R&E analysis was good enough to find accumulations, and even to predict the fluid characteristics. So, the long and fastidious close system analyses in gold tubes have been abandoned in the daily life of the industry.

For the characterization of the H_2 source rocks the workflow is not yet so clear. In case of late maturation of organic rich source rocks, as published by B Horzfield and coauthors (2022), a H_2 detector at the exit of a R&E Pyrolizer allows quantifying the H_2 generation. But what about the quantification when the H_2 is due to the water reduction? Do we need thin section observations, major and minor element quantification, Fe2+/Fe3+ values …i.e. months of work? (Geymond et al., 2022). Do we really know the main reactions? Do we have the right kinetics? Is the temperature the key point? or the water/rock ratio? or something else… Today in the laboratories, we are working on all these topics but the H_2 E&P industry is growing and will need rather quick, but also systematic, quantification.

In this presentation, we will discuss how far we are for a simple and fast measurement, that will maybe simplify the problem, but which could be robust enough to allow us quantifying how many H_2 has been already produced and how may remain to be produced by a given H_2 source rock. The ideal tools will characterize the mineral and not, or not only, its organic content. In other words, how far are we from a H_2 RockEval?

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A model of dynamic gas accumulation of hydrogen, helium, nitrogen and methane

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Understanding the various processes that control the development of subsurface accumulations of hydrogen-enriched gas is key to the potential future exploration of natural hydrogen reserves. The experience gained in the exploration of hydrocarbon reservoirs is not sufficient to meet this new challenge, as other processes must now be considered, including hydrogen migration as a solute, high geochemical reactivity, and very high mobility due to the low density of the gas phase and high molecular diffusion as a solute.

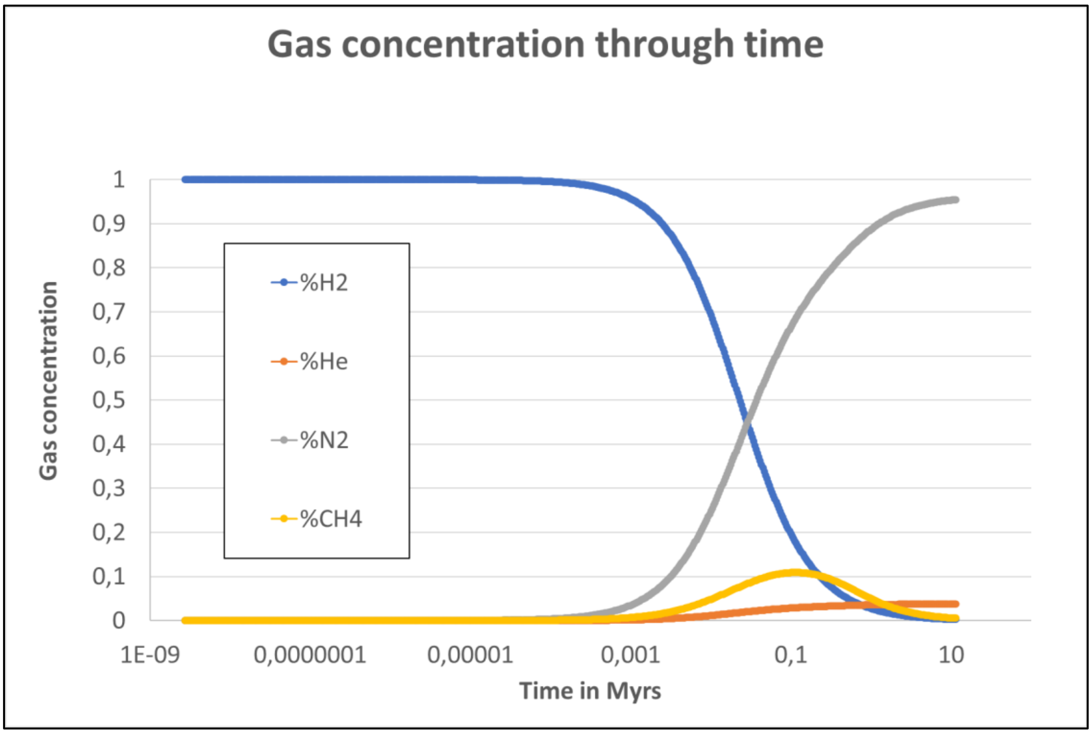
In addition to these new processes, we also observe that hydrogen-enriched gas accumulations are always associated with variable amounts of other gas compounds, such as nitrogen, methane and helium. The ability to simultaneously model the evolution of the gas accumulation and the chemical composition of the gas mixture gives us hope that we will be able to better understand the relative control exerted by the different geological, physical and chemical processes involved.

We have developed a model of gas accumulation that is assumed to occur in a reservoir rock which is capped by a low permeability geological formation. We focus on four gas compounds: N_2, H_2 and He, which are known to migrate from the deep subsurface, and CH_4, which is assumed to be produced in situ by hydrogen decomposition into methane. Deep water degassing can form a vapour phase that accumulates in the reservoir rock. We model this accumulation zone as a column of gas-saturated porous medium whose height varies with time as a result of gas input, possible chemical degradation and leakage. In the accumulation zone we assume that helium and nitrogen are inert and do not undergo chemical degradation. Hydrogen, on the other hand, is highly reactive and, depending on the availability of carbon in the system, can be decomposed as H^+ (then re-equilibrating with water) or produce methane via the Sabatier reaction. The reservoir is then filled with 4 gaseous compounds, which can leak out of the reservoir at their own rate, either by advective leakage in a vapour phase, or by diffusive leakage after solubilisation in the caprock water.

An analytical and a numerical solution of the problem with different levels of simplification of the physics are proposed. A numerical application, using parameters taken from various sources in the literature, shows that the chemical composition of the gas changes over geological time, with a high concentration of hydrogen at the beginning, followed by a predominance of nitrogen and varying non-negligible proportions of helium, hydrogen and methane. This is shown in the following figure.

Comparison of these results with gas compositions measured in several accumulations around the world and modelled at different hydrogen alteration rates demonstrates the credibility of these results and allows approximate ages to be assigned to these accumulations, ranging from 500 years in Mali to 1 million years.

These results confirm the model of dynamic gas accumulations in which hydrogen flows in and degrades at very high rates, while the proportions of non-reactive helium and nitrogen increase progressively with time. The model can also be used to quantify the relative contribution of the parameters controlling diffusive and advective leakage to the development of hydrogen-enriched natural gas accumulations.



Possible generation mechanisms for an organic hydrogen system.

J. Hanson *(Independent)* and H. Hanson *(Brighton University)*

ABSTRACT

The opportunity exists for organic natural hydrogen generation to be considered as part of the hydrocarbon generation system. Within this framework ideas are proposed for the generation mechanisms of organic hydrogen viewed through the lens of nanoscale low conversion rate matrix reactions which may or may not reach equilibrium. It is proposed that the current knowledge on the pyrolysis of organic matter needs to be reviewed recognizing that hydrogen is produced in high volumes at the endpoint of hydrocarbon generation and that this may be considered as a series of thermo-catalytic reactions.

It is shown that smectite to illite conversion releases hydrogen in the form of hydronium enhancing clay catalysis by Whitmore reaction type cracking of alkanes. Simultaneously Whitmore polymerization reactions of alkenes developed during cracking occur. These are instrumental in eventually creating amorphous carbon as a biproduct of the cracking process. Clay catalysis switches off due to the conversion of smectite to illite preventing hydronium release as the smectite structure collapses and illite traps hydronium in its lattice. Illite starts its transformation towards chlorite.

Amorphous carbon replaces clay as the primary catalyst for the reactions at higher temperatures due to increase in pH on difficult to crack smaller chain length alkanes. The control of hydrocarbon and hydrogen generation shifts from cation clay catalysis to radical reaction amorphous carbon catalysis at temperatures of around 2-250 ^{0}C evolving diatomic hydrogen and shorter chained alkanes. This is a thermo-catalytic reaction with low yielding slow rate catalysis which can be observed at comparable activation temperatures between lab and subsurface. Although the process is slow and low yielding vast reaction times are possible in the subsurface. A simplified reaction pathway for the complex surface reactions of amorphous carbon decomposing alkanes and being rejuvenated is proposed. The end of the hydrogen production process occurs post the dry gas window due to a combination of exhaustion of adsorbed reactive products, annealing causing deactivation of amorphous carbon to carbon black, but also due to illite to chlorite authigenesis. Phyllosilicate production incorporates water into its lattice prohibiting rejuvenation of the carbon catalyst.

The process is switched back on again as the critical point of water is reached at around 370 ^{0}C, which dehydrates chlorite and releases free water beginning during garnet creation. The resulting supercritical water acts as a non-polar solvent decomposing hydrocarbon residue left after oil and gas generation to create a new dry gas peak. The super critical water also rejuvenates the annealed surface of carbon black, which acts as catalyst for the process of decomposition of alkanes to diatomic hydrogen once more. This process continues until reactants and water are fully utilized resulting in diatomic hydrogen and graphite due to annealing of carbon black. This is then seen to mirror the process of volatiles elimination during the graphitization of anthracitic coals. Biotite being favoured over garnet production mops up water from the system and stops the reaction. Similar results from analysis of residual gases in shales and metapelites appear to confirm this model.

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Session Three: Global Occurrences & Habitats of Natural Hydrogen

Keynote: Benoit Hauville
Exploring natural H_2 in the Balkans

Benoît Hauville[1], J. David Macareno Quiroz[1], Molly Boka-Mene[1], Dan Lévy[2].

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Natural hydrogen (H_2), naturally produced by subsurface processes, is known since a long time but was mainly thought to be a geological curiosity encountered in very specific areas such as black smokers in medio-oceanic ridges. The impressive emergence of H_2 in the energy transition enabled a significant focus on it and many other natural occurrences in diversified geological contexts were since discovered and are still be reported every day by the scientific community.

At present, the best-known mechanism for explaining the formation of natural hydrogen is serpentinization. This is a geological process in which predominantly ultrabasic rocks are oxidized by water to form serpentine group minerals by producing hydrogen and enhancing the pH of the fluids which become hyperalkaline due to the formation of OH^- ions during the reaction (SUZUKI et al., 2015; VACQUAND et al., 2018; ZGONNIK, 2020).

Increasingly studied in recent years, the serpentinization process is reported to be at the origin of several hydrogen-rich seeps mainly located on ophiolitic belts that have been obducted and some of which are now outcropping in orogenic chains such as the Dinarides in the Balkan Peninsula. In this region, H_2-rich gas seeps of up to 84% have been identified in peridotite massifs in Serbia (RANDAZZO et al. (2021)) and Bosnia-Herzegovina (ETIOPE et al. (2017)).

Based on these hydrogen encouraging results, 45-8 ENERGY together with Pau University have conducted a regional geochemical tactical survey targeting key sites such as natural springs or boreholes in the territories of Albania and Kosovo where the ophiolitic massifs of the Vardar zone extends.

About 20 sites were studied and free gas sampled whenever possible to perform compositional and isotopic analyses. One of these sites exhibited 19% free hydrogen (H_2) in association with nitrogen (N_2) and methane (CH_4).

More focused work was carried out to study the local geological and tectonic setting, thus confirming the potential of the area and allowing further geochemical and petrological analyses. Isotopic results showed that methane has an abiotic origin, supporting the hypothesis that it is also a product of the serpentinization process.

Current understanding of the geological system suggests that H_2 is generated by serpentinization occurring at the basal levels of the ophiolitic massif where a rubble zone is likely to have formed as a result of seafloor obduction, therefore facilitating water circulation. Produced hydrogen can migrate to surface through tectonic pathways, but could also potentially be stored within the ophiolite massif in peripheral fractured zones confined by the untectonised rock acting as a seal.

With the purpose of better understanding the hydrogen geological system and modelling it in order to define and quantify its economic potential prior to a possible production phase, 45-8 ENERGY has applied for an exploration license, currently under review by the regulator, which will allow an ambitious exploration programme to be carried-out, while expecting that at its completion, a first exploitation of natural hydrogen will be born on the European continent.

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Natural hydrogen exploration in South Australia

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South Australia took the lead nationally in enabling exploration licences for natural hydrogen on 11 February 2021 when amendments to the *Petroleum and Geothermal Energy Regulations 2013* declared hydrogen, hydrogen compounds and by-products from hydrogen production ‘regulated substances’ under the *Petroleum and Geothermal Energy Act 2000*. Companies are now able to apply to explore for natural hydrogen via a Petroleum Exploration Licence (PEL) and the transmission of hydrogen or compounds of hydrogen via a Pipeline Licence is now permissible.

Since February 2021, seven companies have lodged 40 applications for PELs targeting natural hydrogen over the State’s basins and crystalline basement provinces (Fig. 1). The first of these (PEL 687) over Kangaroo Island and southern Yorke Peninsula was granted to Gold Hydrogen Pty Ltd in July 2021 and field work including soil gas sampling and airborne geophysics followed by drilling will commence following community engagement in 2023. The second licence (PEL 691) was granted to H2EX in June 2022 on Eyre Peninsula.

As well as issuing exploration licences, the South Australian Department for Energy and Mining provides access to comprehensive geoscientific data submitted by mineral and petroleum explorers and departmental geoscientists since the State was founded in 1836. Access to old 1920s and 1930s reports indicating anomalous hydrogen contents in gas samples, together with modern geophysical and well data have stimulated the current interest in natural hydrogen exploration.

Why the interest? Zgonnik (2020) first drew attention to anomalous hydrogen contents in gas samples taken from South Australian oil bores. 50-80% hydrogen content was measured in 1931 by the Mines Department in gas samples taken by the Chief Government Geologist - potential evidence that natural hydrogen has been generated (e.g. Ward, 1932). Gas samples from Robe 1 (drilled in 1915, Otway Basin) recorded 25% hydrogen, American Beach Oil 1 (drilled in 1921, Kangaroo Island) 51-68% hydrogen and the Ramsay Oil Bore 1 (drilled in 1931, Yorke Peninsula) 60-84% hydrogen. Salt lakes on Yorke Peninsula and Kangaroo Island have been interpreted as potential ‘fairy circles’ by Moretti *et al.* (2021), however this remains to be tested by soil gas sampling.

Boreham et al. (2021) and Bendall (2022) have reviewed potential hydrogen generation systems in Australia. The department has conducted high level desktop screening of the State’s basins and provinces. Iron-rich cratons and uranium-rich basement (also a target for geothermal energy explorers) occur in the Archaean-Mesoproterozoic Gawler Craton, Curnamona and Musgrave provinces which are in places fractured and seismically active with deep-seated faults - South Australia has potential natural hydrogen source rocks and migration pathways. Sedimentary cover ranges from Neoproterozoic-Recent in age, with thick clastic, carbonate and coal measure successions in hydrocarbon prospective basins and, in places, occurrences of mafic intrusives and extrusives, iron stones, salt and anhydrite which could form potential seals for natural hydrogen accumulations.

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Natural hydrogen and helium occurrences of the Eastern Trans-Australian Corridor (Darling-Curnamonda-Delamerian) in New South Wales, Australia

Emma Black1, Christopher Boreham1, Krystian Czado2, Ross von Spulak1, Grant Taylor2, and Andrew Feitz1

1 Geoscience Australia

2 Geological Survey of New South Wales

Australia is considered to be one of the most prospective locations for natural hydrogen due to our ancient geology and our established oil and gas exploration industry. A recent review of natural hydrogen and helium occurrences found high concentrations of both gases present in central New South Wales (NSW), Australia. Here we present early work and establishing methodologies that aim to further support the exploration of natural hydrogen under different geological conditions. Our field survey programs and proceeding laboratory studies will assess the potential for hydrogen and helium gas above known mineral prospects and other potential prospective geologic sites around NSW.

Early field trials have focussed on understanding methodology parameters and limitations by obtaining soil gas samples from different prospective geologically relevant sites. These trials involved deploying stainless steel Geoprobe soil vapour implants at 1 metre soil depth across a transect that followed a historical seismic line in the Tumut region in central NSW. Geological sites that were assessed and sampled for soil gas included metamorphosed and deformed diorites, mafic-ultramafic intrusives, serpentinites and granites. Laboratory analysis determined the soil gas composition and isotopic compositions of the soil gas components. Further soil gas field survey programs are planned to occur throughout NSW, including regions in far western NSW, designed to assess areas with potential circular depressions or ‘fairy circles’ and known iron ore rich areas. Through these field and laboratory studies we present a comprehensive assessment of geologic hydrogen and helium with the aim to provide an initial pathway for future exploration of these two crucial gas commodities within NSW.

Anatomy of a natural hydrogen seep: An example from the Yilgarn Craton in Western Australia

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Exploration for natural hydrogen has gained interest among the global geological community in recent years as a response to the need for a transition to lower carbon emitting fuel sources. If natural hydrogen fields can be discovered and produced, this could potentially provide the cleanest and most economical form of hydrogen and accelerate global targets to a lower carbon future.

Soil gas sampling may be an important tool for the exploration of this new resource, but natural soil gas flux of hydrogen understanding is currently in its infancy and requires significantly more research to enable us to understand the implications of our field results.

A natural hydrogen surface seep, site FF4, was sampled on the Yilgarn Craton in Western Australia during a soil gas sampling campaign in 2022 (Figure 1). The seep was sampled over time and under variable climatic conditions to determine the consistency and seasonal variation in the natural hydrogen flux and its interaction with other gases and climatic conditions, with the results compared with previously published examples.

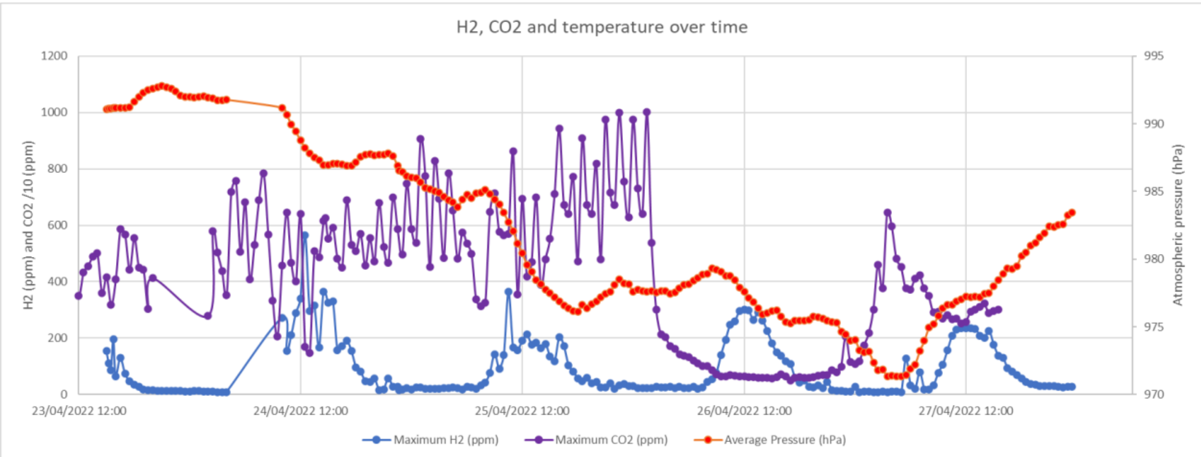

Figure 1: Autonomous log of H2, CO2/10 and atmospheric pressure at site FF4H.

The natural hydrogen flux in each shallow borehole at site FF4, which is located at the edge of a salt pan, was found to decline over time as water inundated the bores, even during the dry summer season. The water table was found to be shallow, at less than 1m below surface in some boreholes.

A sampling strategy was utilised to test the impact of water inundation on the shallow boreholes and the associated hydrogen flux, and to determine if the presence of shallow groundwater inhibits the hydrogen soil flux to surface. Headspace gas analysis using both manual and autonomous pumping processes showed elevated hydrogen in groundwaters associated with the natural hydrogen seep. Autonomous sampling methods at the same location using pumped water management vs passive measurement clearly demonstrate an inhibition of the natural hydrogen flux, with the results reviewed in a global context. This research has significant implications for the future approach to natural hydrogen exploration, particularly in areas of high rainfall or surrounding water bodies such as salt lakes

Keynote: Xueying Yin

Identification of Hydrogen-Rich Zones as A First Step In Natural Hydrogen Exploration in China

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Global interest in hydrogen as a clean, renewable energy source rises rapidly. China has seen a major political push for transitioning into green energy and is now the world's largest consumer of hydrogen. Natural hydrogen exploration has the potential of providing clean, low-cost, carbon-free hydrogen. Being the forerunner in assessing China's potential for natural hydrogen, we have launched China's first-ever natural hydrogen exploration campaign starting in 2022.

Here we present results from the first stage of our campaign with primary focuses on identifying hydrogen-rich zones. Among our study sites we chose Shangdu and Zhangbei in the same faulted basin where drilling wells with hydrogen concentrations (in mud samples) up to 2% were discovered in 2008. Situated towards the western end of the active seismic Wulanhada-Gaowusu deep fault system. the basin is characterized by late Variscan-early Yanshanian intermediate to acidic intrusions which are primarily acidic granites and Cenozoic basalts. Preliminary logging data indicated that hydrogen coexisted with water and isotopic analyses implied a deep-seated source of hydrogen. In fall of 2022, we set a total of 17 transects and collected over 1700 soil gas samples at an interval of 40 meters and a depth of 1m in the Shangdu-Zhangbei basin. We used portable sensors to measure H2 and CO2 concentrations in situ. Several areas of high H2 and CO2 concentrations were identified with H2 and CO2 concentrations exceeding 1000 ppm and 3%vol, respectively. These H2 hot spots were located closely to the NWW-trending group of faults in the basin. We believe that hydrogen together with other fluids migrated upwards along the active seismic Wulanhada-Gaowusu deep fault system and accumulated in the shallow reservoirs in the basin. Well-developed Neogene and Paleogene reservoir-cap assemblages in the basin with mudstone as cap and sedimentary fluvial facies as reservoirs serve as traps for hydrogen. For the next stage of hydrogen exploration in the Shangdu-Zhangbei basin we are set to conduct magnetotelluric soundings and seismic surveys to better characterize the hydrogen trap system in the area. Our work in the Shangdu-Zhangbei basin lay the foundation for understanding natural hydrogen systems in China and showed potential for hydrogen extraction in the near future.

Surface circular depressions: how are they formed? A western Australian example

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Natural hydrogen seeps so-called "fairy circles" have been identified worldwide in intracratonic settings with common features such as a green vegetation surrounding the feature, specific shapes and density across a region and sustained long-term episodic hydrogen emissions above 100 ppm. In Australia, studies identified hydrogen concentrations from soil-gas measurements along targeted surface circular depressions. However, circular surface depressions are widespread in semi-arid climates and their formation can be triggered by numerous parameters such as the erosion of paleo-rivers and anthropogenic modifications of the landscape such as land clearing for intensive agriculture.

The southern part of the Yilgarn craton in Western Australia presents a unique opportunity to unravel those parameters by the join occurrence of numerous types of surface circular depressions and historical data on farming. Field soil gas sampling recording hydrogen measurements have been acquired along a transect going from the Darling Fault, western limit of the Yilgarn Craton with the Perth Basin, to Beaumont, located northeast of Esperance and at the southern limit of the Yilgarn craton with the Fraser range orogeny.

Here, we propose to classify the different types of surface circular depressions according to the results from a soil-gas sampling survey, the geological and geophysical dataset, the past and present seismology and a bibliographical review of the geomorphologic data and historical records of satellite data recording the potential impact of agriculture to separate anthropogenic impacts and to understand formation of hydrogen in natural environments.

Keynote: Geoffrey Ellis

Natural hydrogen resource potential of the conterminous US

Geoffrey S. Ellis

U.S. Geological Survey, Denver, CO USA

Although the presence of natural hydrogen in the subsurface of the Earth is well documented in a variety of geologic environments, economic accumulations of natural hydrogen have generally been assumed to be non-existent. Recent discoveries in Africa and elsewhere have challenged this notion, and there is a growing acknowledgement that geoscientists have not looked for natural hydrogen in the right places with the right tools. While much is known about the occurrence of subsurface hydrogen (e.g., generation mechanisms, consumptive processes, etc.), there is currently a lack of understanding of the processes and settings that are most conducive to the formation of significant accumulations of hydrogen. To develop effective strategies for exploration and assessment of geologic hydrogen resources, a comprehensive framework is required that could lead to the discovery of economic hydrogen accumulations.

The U.S. Geological Survey has developed a preliminary “hydrogen system” model for understanding the potential generation of economic accumulations of hydrogen resources in the Earth’s subsurface based on the “petroleum systems” concept. The essential components that make up the models (e.g., source, migration pathway, reservoir, seals, etc.) are the same but the details of each of the components vary and may not be directly comparable. For example, thermal maturation of organic-rich rocks is well understood to be the primary mechanism for petroleum generation, whereas serpentinization of ultramafic rocks is generally recognized as a major pathway for hydrogen generation in geologic environments. Although thermal maturity (i.e., time and temperature) and content of reactant materials (i.e., organic carbon in the case of petroleum source rocks or iron content for hydrogen generation) are factors that are common to both systems, the hydrogen system may also be critically dependent on the water-rock contact area and time. Such distinctions have important implications for understanding resource potential and designing exploration strategies.

Given our nascent understanding of geologic hydrogen, many components of the hydrogen system are highly uncertain. However, the uncertainty associated with each of the essential components of the hydrogen system can be estimated and used to assign risk. A workflow has been developed for mapping the individual components of the hydrogen system and the associated uncertainty on a regional scale. This approach has been used to provide a preliminary estimate of the most prospective regions for discovery of geologic hydrogen resources in the conterminous U.S. This presentation will discuss the details of the workflow used for mapping hydrogen prospectivity on a regional scale as well as the requisite datasets. Details of ongoing research to further refine the hydrogen system model, to improve geologic hydrogen prospectivity mapping capabilities, and to reduce the associated uncertainty (i.e., risk) will be presented.

Natural hydrogen – Estimating the resource, a case study from South Australia

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Naturally occurring hydrogen exploration is garnering quite a lot of interest globally with research and literature ever increasing, public and private companies established to undertake hydrogen exploration and exploitation, and leases or permits granted for hydrogen exploration. Given this, analogies can be drawn with the early days of oil exploration and exploitation.

The 'natural hydrogen system', unlike the widely recognised and adopted 'petroleum system' of the petroleum industry is immature and not well characterised. In particular it is the 'source' components of generation, migration and entrapment of naturally occurring hydrogen that is poorly understood. There is much conjecture regarding flux versus accumulation for source and migration in 'natural hydrogen systems'.

The Petroleum Resources Management System ('PRMS')[1] is a system developed for consistent and reliable definition, classification and estimation of hydrocarbon (petroleum) resources, originally published in 2007 and subsequently updated in 2018 with application guidelines published in 2011 and most recently in November 2022.

Through the application of the PRMS consistent reporting of reserves and resources is possible and underpins the value and access to capital of those exploration, development and exploitation enterprises.

According to the PRMS, substances such as naturally occurring hydrogen (and helium) are considered non-hydrocarbon components. It is stated in the PRMS that such substances cannot be included in Reserves or Resources assessments and statements.

However, given the global interest in the exploration for and exploitation naturally occurring substances other than hydrocarbons, the SPE Oil and Gas Reserves Committee ('OGRC') advised in August 2022 that the principles of the PRMS can be extended to naturally occurring substances other than hydrocarbons, including the gaseous extraction of carbon dioxide, helium and hydrogen[2].

The OGRC advised that there is a reasonable foundation for the application of PRMS principles to situations such as the gaseous extraction of naturally occurring substances considering the similarities in exploration, evaluation, and exploitation processes.

The OGRC endorsed the application of the PRMS to these situations as long as it is made clear that while such application is outside the scope of the PRMS, PRMS principles have been followed and applied as though the extracted resources were considered as petroleum.

However, the application of the PRMS requires that the naturally occurring substance to be an accumulation and there by implication must have a reservoir and seal. Application of the PRMS to flux in 'natural hydrogen systems' is therefore difficult if not impossible.

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[1] Petroleum Resources Management System ('PRMS'), prepared by the Oil and Gas Reserves Committee ('OGRC') of the Society of Petroleum Engineers ('SPE') and reviewed and jointly sponsored by the American Association of Petroleum Geologists ('AAPG'), World Petroleum Council ('WPC'), Society of Petroleum Evaluation Engineers ('SPEE'), Society of Exploration Geophysicists ('SEG') and approved by the Board of the SPE in March 2007. The PRMS was subsequently updated in June 2018.

[2] https://www.spe.org/en/industry/reserves/non-hydrocarbons/

In this case study, which may have a working ‘natural hydrogen system’, we have applied the principles of the PRMS and estimated the natural hydrogen Prospective Resources through volumetric analysis and estimation of its uncertainties and risk.

NATURAL HYDROGEN - Estimating the Resource: Flux vs. Accumulation, Tools for Evaluation and Analysis

Proposed Drilling Techniques Development

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The global energy marketplace is being moved towards the new commodities, and hydrogen is entering this stage as a new player in a fast pace. Out of existing "ways" to supply hydrogen on industrial scale, only natural hydrogen offers economical yet carbon-free solution.

New models and scenarios call for new concepts. The first and the most comprehensive attempt was first made by Dr. V. Larin in early-mid 1970s[i], now called the Primordially Hydridic Earth concept[ii]. Currently, this concept is being confirmed by numerous results of fundamental research[iii iv], as well as by the field data documented from the soil gas detection campaigns.

Dr. V. Larin originally suggested drilling for natural deep-seated hydrogen as early as in 1990s, first documented in 2008:

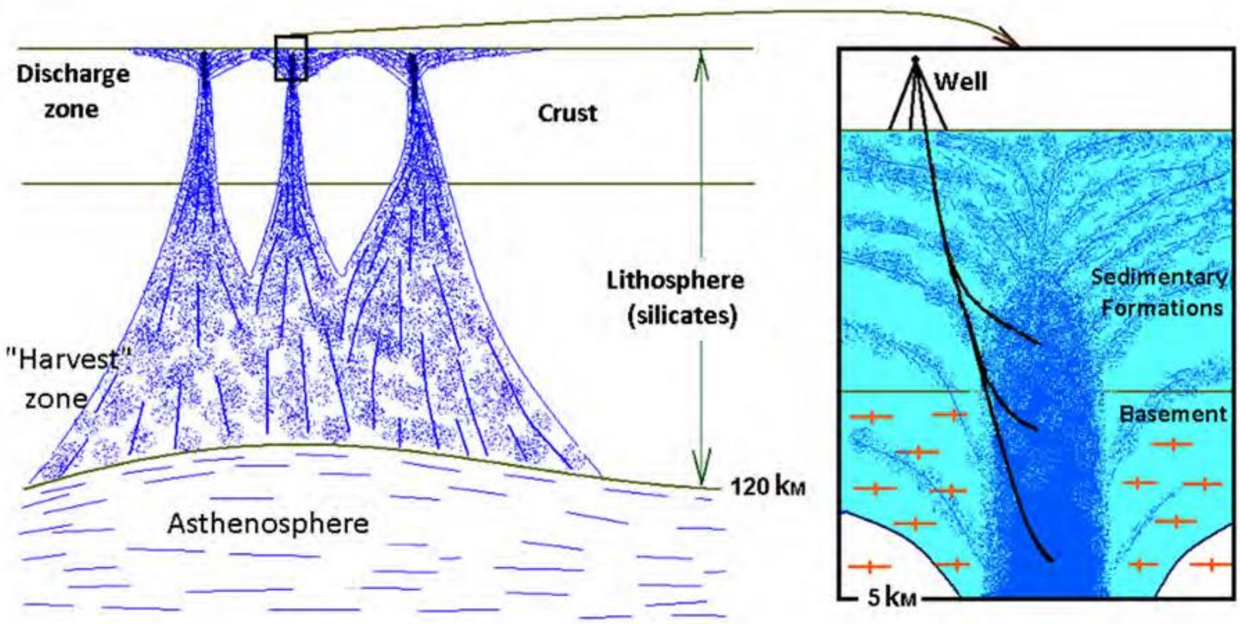

Fig. 1. Hydrogen De-Gassing Structures and their Development Proposed Schematics. *Modified from* V. Larin, N. Larin, 2008. Hydrogen De-Gassing on Russian Platform: Pluses and Minuses, [***https://hydrogen-future.com/list-c-phenomen/4-page-id-18.html***](https://hydrogen-future.com/list-c-phenomen/4-page-id-18.html)

Currently, there are two plausible scenarios for natural hydrogen drilling:
1. "*Nebraska Case"*: Deep wells targeting major hydrogen conduits, a.k.a. "chimneys", suggested by Dr. V. Larin in 2000[v] (Fig 1).

It is proposed to penetrate hydrogen productive structures conducting this gas to the surface. Indeed, these structures have to be explored and appraised prior to spudding the well, which the authors of this Abstract have a very good understanding hereof[vi vii].

It is crucial to drill right into the core of such structure, below the depth of hydrogen stream dissemination, while lithostatic pressure still keeps such degassing structure in un-dispersed state.

For this scenario, the existing drilling and completions technologies are very likely to be suitable for natural hydrogen extraction from the Earth. However, certain adjustments may need to be made, such as:

- Since hydrogen bearing "chimneys" possess (sub-)vertical shape, long departure lateral wells are unlikely to be needed. The emphasis may be shifted towards multilateral – crowfoot, fishbone - wells
- Schematics of completions, especially lower, may need to be modified, since the lithology and petrophysical properties of "productive zone" (e.g., granites, gneisses, etc.) are likely to be quite different from those typical for Oil and Gas industry
- Well exploitation lifespan may be surprisingly long, since there is no such thing as "depleted deposit" when it comes to the deep-seated primordial hydrogen – these resources are constantly replenished by permanent deep-seated hydrogen de-gassing activity. This resource is likely to be available for production from the same wells for many decades to come, interrupted by periodic well servicing campaigns, only.

2. "*Mali Case*": Grid/s of shallow - several hundred meters – wells for development of temporary hydrogen accumulations close to the surface, e.g. below semi-circular structures demonstrating elevated concentrations of hydrogen from the top soil layers. This scenario shall work very well for autonomous power supply situations, when consumers are located far away from the grids and/or power plants, and the supply from the solar and wind sources cannot be maintained steadily.

Summarizing, the future for natural hydrogen drilling looks quite positive, especially if the Oil and Gas industry accepts the de-carbonization trend and provides its technology and vast expertize to this new trade.

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A Mineral Systems Approach to Targeting Natural Hydrogen Deposits

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Introduction

The mineral systems approach to mining exploration has gained industry-wide acceptance in recent years (McCuaig et al. 2018). A similar play-element approach has been employed in the hydrocarbon exploration industry at least since 1974 (Hageman et al. 2016). We have successfully employed such an approach globally for decades and have recently repurposed hydrocarbon systems techniques for application to critical minerals and natural hydrogen exploration. The deep understanding of earth systems required to find a viable petroleum accumulation with its source, migration, reservoir, seal and structure is equally applicable to the search for natural hydrogen occurrences, even though there are some notable differences.

The approach we have taken to natural hydrogen exploration is grounded in the best current understanding of its genetic system and a unique geologic database that includes global gravity and magnetic data, stage-level palaeogeographical reconstructions from present day to Devonian, heat flow calculations, palaeoclimatic data, global geological compilations, mineral occurrence databases, and hundreds more categories of data through geological time.

Source

Ultramafic rocks are significant producers of H_2 during processes including serpentinization, hydrothermal hydration, and water hydrolysis (Milkov, 2022). These processes are better understood and more amenable to exploration strategies than H_2 sources such as radiolysis and deep-seated generation. Consequently, building a mineral systems model for hydrogen begins with locating all known ultramafic rocks in their present-day locations using geological databases. It is also important to predict where such rocks could be present in the subsurface using geophysical data (made possible by their high densities and susceptibilities) and palaeo-reconstructions of ophiolitic tectonic settings rotated to their present-day locations. Next, the temperature for reactions releasing H_2 can be predicted using a combination of potential field data, Curie depth calculations, thermal conductivity and radiogenic-heat predictions to find areas near surface with temperatures appropriate for hydration reactions, which are believed to be $< 300°C$ (Zgonnik, 2020, and personal communication).

Migration

Vaquand (2011) determined through field measurements and laboratory experiments that H_2 is highly diffusible, but no more or less so than CH_4, with the resulting conclusion that migration and reservoirs for H_2 could be similar to those of hydrocarbons. This conclusion then leads to adding the criterion of permeable media such as sandstones overlying ultramafics for migration (vertically) and storage of H_2 in a gaseous state or dissolved in water.

Reservoir

Potential reservoirs for hydrogen accumulations above ultramafic rocks should resemble those of oil and gas reservoirs. We use our global database of present-day geological maps, as well as palaeogeographic reconstructions, to infer the presence of permissive hydrogen reservoirs.

Seal

There is considerable academic debate about what types of overlying lithologies are the best and most likely seals for hydrogen reservoirs. Ball and Czado (2022) note in their review that "While the jury is still out on whether or not hydrogen is stored over geological timescales, salt or halite are recognised as viable sealing lithologies, and it is possible that igneous rocks (like diorite in Mali) could also work as seals. Clay-rich rocks could also act as barriers to hydrogen migration." Mudstones suitable for sealing hydrocarbons or sequestered CO_2 should work equally well for H_2; their presence can also be predicted with paleo-geographic and -oceanographic proxies (Jonk et al. 2022).

Structure

Numerous authors (including Rogozhin et al., 2010) have noted the correlation between gasses, including H_2, and structures. Given the obvious transport provided by structures, faults active syn- and post-deposition of ultramafic rocks provide a characteristic that can also predict the favourable genetic context for transport and accumulation of hydrogen in a reservoir. There is, of course, a caveat that structures that penetrate above a gas reservoir can allow the gas to permeate upward and become simply a leak with no subsurface accumulation. Structures and stress fields throughout geological time can be incorporated using interpreted plate-motion vectors and the global coverage of potential field geophysical measurements included in our database.

All these disparate genetic criteria can be brought together in a 'play-based' manner using analytical software to predict the environments favourable for the accumulation of natural hydrogen. To further support the prediction of H_2 'sweetspots', potential natural hydrogen anomalies can be detected by repurposing advanced image recognition analytics of satellite imaging to identify fairy circles (Frery et al., 2021) in areas identified through the mineral systems approach as being of high interest.

Finally, any potential natural hydrogen occurrence must also be placed in a commercial context; hence, understanding the above ground geospatial setting is a critical additional consideration. Inputs such as distances to infrastructure, transport, processing facilities, power, and end users are included in the Getech database routinely used for hydrocarbon and geothermal studies and can be applied equally to hydrogen exploration.

Conclusion

Putting all the complex data of the above criteria systematically together to produce a robust play map to discover new search spaces for natural hydrogen exploration is a critical artery in the roadmap to carbon neutral energy production. This presentation will detail the datasets used for the mineral systems approach to hydrogen exploration and demonstrate the progress to date in assembling play maps which reflect the co-location of the criteria in space and time.

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Early exploration services to aid in predicting the presence of native hydrogen at scale

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Native hydrogen (H_2) is considered as a possible alternative energy resource for the decarbonisation of society. While native H_2 has been confirmed at several sites through surface emanations (typically called 'fairy circles') and in numerous oil and gas wells, the potential volume ranges, spatial distributions, flux rates and temporal evolution remain unclear. As a first step to investigate these aspects, two approaches have been developed which utilise bespoke machine learning techniques integrated with remote sensing, data science and geological data.

The first approach focuses on the recognition and classification of fairy circles at terrain, basin and play scales. One of the key challenges associated with fairy circle identification is that not all elliptical topographic features are associated with H_2 leakage, many other processes may be taking place. Another key challenge is recognising and classifying fairy circle arrays at scales attractive to operators and explorers. To address these challenges, a classification scheme has been developed which attempts to distinguish H_2 surface seeps based on analysis of satellite-derived images, integrated with more conventional geological base mapping. Classification utilises data enhancement to distinguish the presence of H_2 versus other gasses and 'active' versus 'inactive' sites. The key aim is to provide high graded sites to confirm both the presence of native H_2 and, more critically, provide limits on flux rates and possible sub-surface volume ranges for economic considerations.

The second approach focuses on the concept that significant H_2 volumes may have already occurred in oil and gas wells, and the cryptic evidence for this missed H_2 pay has been retained in corporate data bases as part of the post-well archive. While detecting 'gas' is standard in drilling operations, recognising H_2 is not. To recognise missed H_2 pay, a bespoke machine learning approach has been developed. It is based on both standard text-based parameters from well reports and tables, coupled with sophisticated recognition of missed pay using density and pressure related responses acquired during drilling operations and logging.

Taken together and integrated with more conventional geological mapping approaches including multi-physics, these methodologies represent early but effective exploration approaches designed to aid and guide H_2 exploration at scale.

A Statistical Approach as tool for native H2 exploration: a case study in the Western Pyrenean foothills (SW France)

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Molecular hydrogen (H2) is now considered as an energy resource for the development of a low carbon society. Since few decades, numerous H2-bearing seepages have been discovered throughout the world and continue to be discovered nowadays (e.g. Australia, Africa, France, South America, Spain, USA …). But to date, neither exploration workflow nor resource evaluation exist as practical guidelines for hydrogen targeting. Here, we set up a new geochemical approach dedicated to H2 targeting using soil gas analysis and statistical treatment. The North Pyrenean Foreland Basin was selected as a suitable geological setting for hydrogen (H2) exploration because some key pathfinders that define a fertile geological environment for H2 have been identified. Indeed, the North-Western Pyrenean foreland and especially the Mauléon Basin are characterized by the presence of a massive mantle body located under favorable P-T conditions (< 10km depth) for serpentinization to occur. The crustal-scale architecture is also prone to drain deep-seated fluids along major faults as suggested by geophysical data. Hydrogen traps remain poorly understood, but the presence of salt-related structures (fomes and diapirs) could play this role and appear to be at a suitable temperature (100 to 200°C) to preserve trapped hydrogen (Fig.1).

We will show how the statistical processing (e.g. QQ-plot) of more than 1100 in situ soil gas analysis (H2, CO2, O2) at the regional scale (8000 km2) can help to discriminate between biological and deep-seated hydrogen. I) The QQ-plot showed an anomaly in soil gas concentration for H2 and CO2 with values above 74 ppmv over 19 localities and 3%v over 29 localities, respectively. ii) The CO2 vs. O2 plot identified 22 localities where the origin of CO2 was attributed to an exogenous deep leakage input. Comparing results from these two methods allows to identify 4 locations where the H2 is likely to be of deep origin and located along major faults well-known in the Western Pyrenees. Further investigations are now needded, to better document bacterial activities in the near surface and gas migration at depth. Finally, this surface sampling will be complemented by an evaluation of subsurface resource capacity. In a probabilistic approach, trap pore volume and amounts of possibly accumulated or transiting H2 will be assessed to quantify the economic feasibility of those subsurface H2 prospects. The investigations are continuing within the framework of the collaborative project H2NA financed by the regional council of Nouvelle Aquitaine (France), whose objective is to identify hydrogen economic prospects.

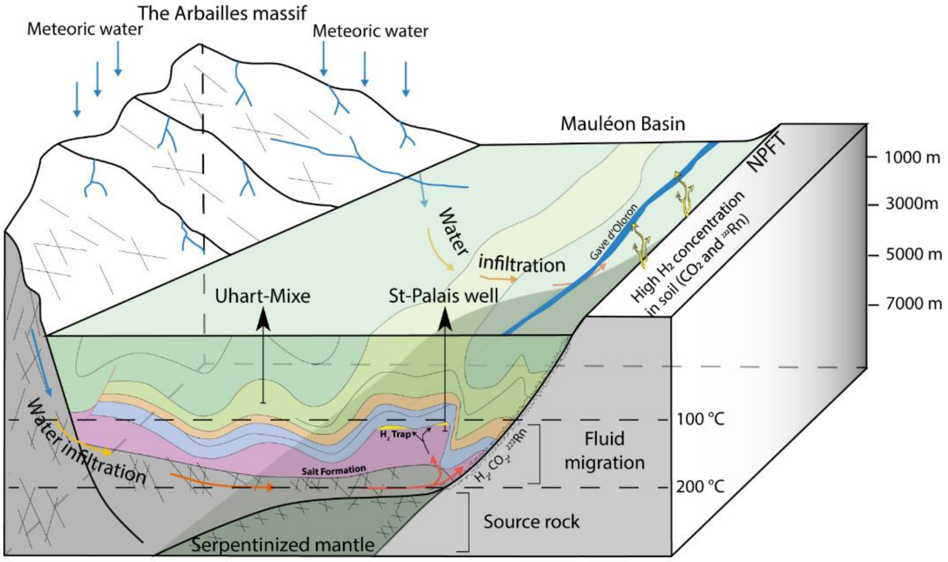

Figure 1: 3D bloc diagram illustrating a potentially fertile H2 system beneath the Mauléon Basin with the location of the recharge zone and deep fluid circulation (Modified from Lefeuvre et al., 2022)

Assessing hydrogen migration and accumulation potential: characterisation of the Adelaide Geosyncline basement structures and their mineral fills

Zak Milner, Jon Gluyas, Ken Mccaffrey, Chris Ballentine, Bob Holdsworth

Releasing only heat and water vapour when burnt, demand for hydrogen (H2) is expected to increase eight-fold by 2050, driven by growth sectors such as transportation and industrial energy. Natural or gold H2 is often produced in the lithosphere via water radiolysis in U- and Th-rich Precambrian basement and serpentinization in mafic-ultramafic rocks. Migration can occur through open faults and fractures acting as fluid conduits, whilst evaporites and fissure fills can minimise diffusive loss and trap H2 in accumulations.

U- and Th-rich Precambrian basement underlies much of South Australia, where H2 discoveries are of global significance (up to 84% H2 Ramsay Oil Bore). The structural network within these rocks, however, and their associated fissure fill petrologies are yet to be characterised. Mid-Proterozoic crystalline basement outcrops towards the north-east of the Adelaide Geosyncline therefore this region provides an excellent geographical focus to further understand H2 migration and accumulation within these structures.

Here we show the results of our remote sensing work, which integrates regional satellite imagery, geological maps, digital elevation models (DEMs) and aeromagnetic data to interpret the spatial distribution of basement structures. Subsequent slip and dilational tendency analysis and fault topology analysis are used to predict structures bearing high H2 migration and accumulation potential.

Although yet to be tested in the field, we provide here a workflow in which structural geology can be used to assess migration and accumulation potential and ultimately aid natural hydrogen exploration efforts.

Natural Hydrogen Exploration: Risk Assessment

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The growth of energy demand, and therefore the continuous emissions of greenhouse gases, has triggered the need to look for alternative and cleaner energy sources. In this sense, hydrogen, with a specific energy greater than hydrocarbons and no residues in its combustion, has attracted the interested of the society as a candidate to decarbonize the economy. At present, 100% of the H2 used has to be manufactured, which either has an environmental impact (grey H2) or the cost is still very high (blue or green H2 among others). In all these cases, the process has a negative energy balance, which implies more energy is expended than what will be obtained later. In that frame, the possibility to find and produce natural H2 appears to be a promising alternative, where the exploration industry can apply the knowledge obtained in more than a century. Production of natural H2 will not only reduce considerable the final cost, but also will convert H2 in an energy resource instead of an energy vector.

The scientific community has done a great effort in understanding the geological sources and reactions behind natural hydrogen. Among the several geological sources prone to generate natural hydrogen, serpentinization is being considered the most promising to generate hydrogen at large scale. These efforts have ended in the discovery of hundreds of hydrogen seeps in a large variety of geological settings from mid continental ridges to passive margins, cratonic areas and fold and thrust belts. However, there is still a large uncertainty in the migration, the reservoir that can storage a commercial accumulation, the sealing and very important the preservation of this gas in volumes that might be considered for exploitation. Therefore, when thinking in an exploration project, which implies large inversions with high risk, an exercise to estimate the probability of success is needed to properly evaluate the chances of finding both a technical and commercial success.

The goal of this communication is to identify the knows and unknowns in a hydrogen system and evaluate, in a conceptual way, the chance of success of hydrogen exploration leads according to their location. This analysis will help to focus future works on decreasing the risk of these projects.

Our analysis covers the regions from the internal part of a fold and thrust belt to the undeformed zone (craton) passing through the foreland basin. In this sense, although there are several known hydrogen seeps in in the internal part of the fold and thrust belts, where mafic and ultramafic rocks are structured and either outcrop or are close to the surface, we don´t believe they are the most promising areas for exploration due to the lack of reservoirs and seals. We consider similar situation in the shallower part of the foreland basin, where the lack of good sealing formations for hydrogen and/or the presence of bacteria may compromise any project. However, the deeper part of the foreland basin, under the basal detachment, too deep for bacteria, and still having chance for having reservoirs and seals might be the most prospective areas at present time.

POSTER ABSTRACTS

Biogeochemical hydrogen alteration of in hydrogen rich gas seeps from Italy

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Many national Net-Zero strategies (where CO2 removal matches emission rates) involve a "hydrogen economy" where hydrogen (H2) replaces fossil fuels as a carbon free alternative. Naturally occurring H2 from geological formations represents an ideal source of H2, as it does not result in CO2 emissions or require significant energy inputs. Hydrogen concentrations up to 98% have been measured in the subsurface (Prinzhofer et al 2018), demonstrating the promise of extracting H2 from natural sources. Hydrogen can be found in a large range of geological settings including in oceanic and continental crust, volcanic gases, and hydrothermal systems. Hydrogen is most likely formed via the hydration of mafic/ultramafic rocks (e.g., serpentinization) or via radiolysis. However, to find commercially viable natural accumulations, a better understanding of generation mechanisms, migration pathways and associated subsurface processes is required.

Hydrogen is not conservative, and can be consumed and converted to CH4 or H2S over time in the subsurface - either microbially or abiotically (e.g., Sherwood Lollar et al., 2002, Warr et al., 2020). In addition, during H2 geological storage, subsurface microbial processes utilise H2 and could affect the storage efficiency. Therefore, identifying the role that biogeochemistry plays in regulating natural H2 accumulations will aid in developing exploration strategies for naturally occurring H2 resources.

We investigate geochemical and biological alteration of H2 from thirteen H2 rich gas seeps in Italy using an integrated biogeochemical approach. This includes gas chemistry (bulk composition, clumped, stable and noble gas isotopes), water chemistry (dissolved gas composition, pH and major and trace ions) and microbial sequencing. Measurement of clumped methane isotopologues (Δ13CH3D and Δ12CH2D2) are used to determine whether CH4 is in thermodynamic isotopic equilibrium (e.g., thermogenically or abiotically produced) or in disequilibrium (i.e., microbially produced by methanogenesis).

Here, we present geochemical (water and gas phase) and microbial data from Italy. This integrated approach allows us to place constraints on both the physical and biogeochemical processes altering H2 in the subsurface. In particular, we focus on the conversion of H2 to methane and determine the different methane production pathways (a potential by-product of H2 alteration/microbial consumption) using clumped methane isotopologues, combined with stable C isotopes of CH4 and microbial sequencing. Where CH4 isotopologues are in disequilibrium, it suggests there is a shallow conversion and thus H2 could still exist at depth. In contrast, if the system is in thermodynamic equilibrium, conversion at depth is likely and therefore there is a lower probability of H2 accumulation. We also identify H2S formation in 9 seeps, with 7 seeps recording high dissolved sulphide concentrations (> 1 mg/l), and potential water-rock interactions. We then compare the data from Italy with H_2/CH_4 rich gas seeps collected in New Zealand and the Yellowstone hotspot track (USA). We use these results to try to understand the physiochemical conditions conducive for H_2 alteration, which will be important for identifying possible H_2 accumulations where minimal H_2 conversion to other species (e.g., CH_4 and H_2S) has occurred.

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“Natural Hydrogen, Helium and hydrocarbon discoveries in the Amadeus Basin, Central Australia – exploration strategies for understanding play models”

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The Amadeus basin, Central Australia lies within the Proterozoic Centralian Superbasin, one of the most prospective areas globally for helium, hydrogen and hydrocarbons. The basin contains producing oil and gas fields together with world class helium and hydrogen discoveries. Mosman Oil and Gas operates 2 permits in the northern Amadeus basin, EP145 & EPA155 which lie on trend with major producing oil and gas fields. Exploration wells in both permits have flowed hydrocarbons in the relatively shallow Ordovician Larapinta play but the deeper Neoproterozoic targets for helium, hydrogen and hydrocarbons remain untested in this part of the basin. An exploration work program has been designed to address the similarities and differences in plays when exploring for these gases, and how to commercialise potential resources.

Recent high resolution SEEBASE® mapping over the entire Amadeus Basin has successfully identified extensive basement structures and integration of gravity, magnetics and seismic data has resulted in a detailed model of the basement. This technique provides a high level of understanding of basement tectonics and composition which are key pre-requisites in the exploration of helium and hydrogen. As in conventional hydrocarbon systems exploration activities need to address the components of potential helium and hydrogen prospects; trap, reservoir, source and seal. Discoveries of hydrogen and helium at Mt Kitty-1 and Magee-1 located in the southeast Amadeus basin demonstrate the presence and effectiveness of these play elements with recent exploration efforts in the basin focusing on the success of these wells. The NW-SE Walker Creek basement anticline in EP145 forms an extensive closure extending approximately 35km over the permit. It is bounded by a steeply dipping reactivated basement fault that acts as a conduit for helium and hydrogen migration from deep seated sources. The Gillen Fm, a thick sequence of evaporites and shales is interpreted across the permit and is a proven seal at Mt Kitty-1 and Magee-1. Basement modelling also supports the presence of large granitic intrusives within and adjacent to the Mosman acreage which have the potential to source significant quantities of both hydrogen and helium.

Early exploration in the basin focused primarily on hydrocarbons in Cambro Ordovician sandstone targets and helium and hydrogen were largely discovered by chance. Mosman’s exploration strategy is to investigate the play fairways for helium and hydrogen in the Neoproterozoic succession and understand the distribution of play elements across its permits. New seismic acquisition and drilling is planned within both of Mosman’s permits which may lead to the future development of subsalt helium and hydrogen resources.

The transport and accumulation of helium in a nitrogen-dominated reservoir

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Helium, a highly diffusive inert gas, is essential for scientific, medical and industrial applications and also an excellent natural tracer in understanding subsurface fluids transport and interactions. Helium is generated through radioactive decay of uranium and thorium. Even with low concentrations of the parent elements, continental crust is the predominant source rock due to the massive volume and millions to billions of years of production and accumulation. Once produced, helium is dissolved in porewater and can be transported diffusively or advectively.

An economically-favourable helium target requires a subsurface gas phase to focus dissolved helium from porewater. Helium concentration in groundwater is low compared to its solubility, and hard to form a gas phase on its own. Two of the most common gases observed that help form a gas phase are CH_4 and CO_2, which chain helium to a high carbon footprint. An alternative type of helium reservoir is nitrogen-dominated, and understanding such a system can significantly advance helium discovery while aligning with the Net Zero target.

Natural hydrogen has gained increasing global interest as an alternative green energy resource. A study found that continental crust produces a comparable amount of hydrogen to the marine system [1]. Sharing the same source rock, helium is, therefore, an invaluable analogue and tracer for quantifying hydrogen production and constructing a framework of subsurface physical processes, including migration, accumulation and fresh-water disruption.

To understand helium migration in sedimentary basin systems, we construct a numerical simulation of helium concentration in porewater that considers sediment deposition and compaction [2]. In some deep sedimentary units, groundwater can be stable over geological time, and dissolved gases are transported predominantly through diffusion. In such scenarios, subsurface temperature, porosity and thickness of sedimentary units are important factors controlling the accumulation and transport of helium in pore fluids proximal to the crystalline basement. To understand the formation of these low-carbon nitrogen-enriched helium reservoirs, we co-simulated the transport of basement nitrogen observed co-existing with helium [3]. While diffusing upwards through the sedimentary units following the same principles as helium, the higher nitrogen flux can result in its concentration exceeding solubility and form a gas phase, an essential component for forming a helium reservoir.

The model is able to simulate the formation of a gas phase and its gas composition of a nitrogen-dominated helium reservoir in the Williston Basin. Williston Basin is an intracratonic basin in North America overlying Archean basement rock with old basinal water that has not been disturbed by freshwater flushing. The basin has both source and time for the production and accumulation of helium in the basal sedimentary units. With a basement helium flux of $0.8\text{-}1.6\times10^{-6}$ mol $^4He/m^2$ yr and $N_2/^4He$ of 25-50, typical for continental settings, the model predicts gas phase helium concentrations and $N_2/^4He$ matching those observed in the Williston Basin nitrogen-dominated helium well. The gas phase can be formed as early as 140Ma at the Deadwood basal units, directly overlying the crystalline basin.

The gas phase acts as a bank of helium. In the Williston Basin Deadwood gas pool, 0.03 - 6 % of all helium from the continental crust could be stored in the nitrogen gas phase. Helium concentration in the porewater gradually reduces but is alternatively stored in the gas phase. This limits the cross-formational helium flux to shallower units and the atmosphere. Meanwhile, a series of sensitivity tests indicate that the basin could have a weak memory of gas formation histories. In the Williston Basin, the formation of a gas phase in the unit close to the basement is insensitive to hydrogeological events before 200Ma.

This new concept of gas field formation and its effect on helium budget and distributions broadened the understanding of subsurface gas/chemical transport. It expands not only the exploration strategy for helium but also basement-produced hydrogen, marking an exciting potential for a clean hydrogen source towards a net-zero society.

[1] Sherwood Lollar et al. (2002) Nature 416.6880 (2002): 522-524
[2] Cheng et al. (2021) EPSL 574: 117175.
[3] Cheng et al. (2023) Nature in press

Reassessing the role of magnetite during natural H2 generation

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Interactions between water and ferrous rocks are known to generate natural H_2 in oceanic and continental domains via the oxidation of iron. Such generation has been mainly investigated through the alteration of Fe^{2+}-silicate, and additionally some Fe^{2+}-carbonates. So far magnetite (α-Fe_3O_4) has never been considered as a potential source mineral for natural H_2 since it is considered as a by-product of every known chemical reaction leading to the formation of H_2, despite it bears 1/3 of Fe^{2+}. This iron oxide is rather seen as a good catalyst for the formation of H_2.
Recently, hydrogen emissions were observed in the surroundings of Banded Iron Formations (BIF) that are constituted, among other minerals, by magnetite. Thus, this work is an attempt to constrain the true potential of magnetite, by the mean of batch reactor experiments and additional thermodynamic calculations. It explores theoretical and practical reactivities of magnetite during water-rock interactions, focusing on low temperatures (T < 200°C). For the purpose of experiments, gold capsules filled with magnetite powders were run at 80°C and 200°C. Gas products were analyzed using gas chromatography (GC) while solid products were characterized by X-ray diffraction (XRD), Mössbauer spectroscopy and scanning electron microscopy (SEM). After experimental alteration, high amounts of H_2 were quantified while mineralogical transition were observed by SEM. It showed self-reorganization of the primary iron oxide resulting in sharp-edge and better crystalized secondary minerals. In parallel, XRD analyses showed tiny changes between the patterns of initial powder and solid products of reaction. Finally, Mössbauer spectroscopy revealed that the starting magnetite was partly converted to maghemite (γ-Fe_2O_3), a metastable Fe-oxide only containing Fe^{3+}. Major implications arise from these results. Concerning H_2 exploration, this work provide evidence that natural hydrogen can be generated at near-ambient temperature. It also infers that magnetite-rich lithologies such as BIF should be targeted while looking for H_2 source rocks. In addition, these outcomes could be of major interest for mining compagnies as it provides key elements to understand the formation of BIF-hosted iron ores.

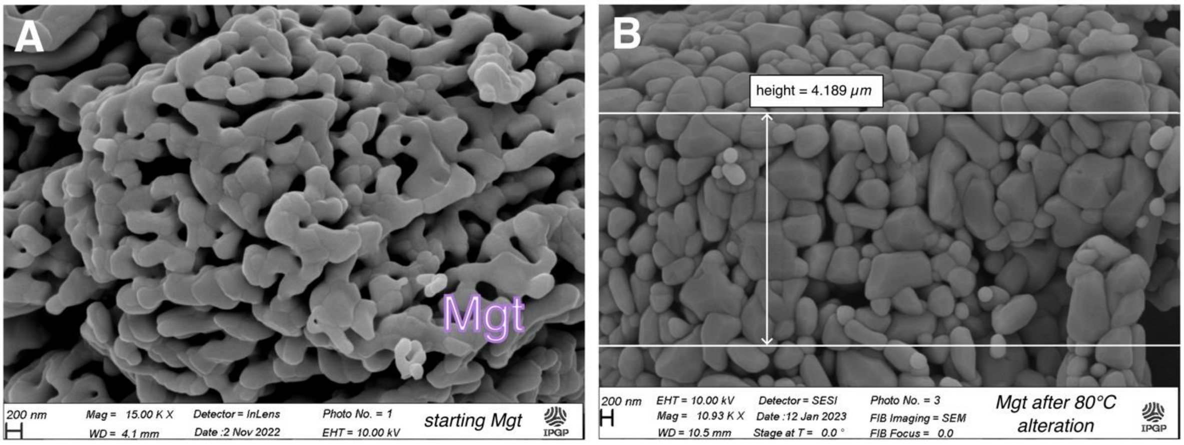

Figure 1: SEM images of ***(A)*** *the starting magnetite compared to* ***(B)*** *the magnetite after alteration at 80°C. Note the higher mineral density and better crystallization after alteration. Mgt refers to magnetite.*

A multiscale petrology study on Fe-rich clays minerals in fayalite-bearing gabbros within the Kansas (USA) Precambrian basement: an attempt to quantify natural hydrogen generated

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Natural hydrogen (H_2) generation has long been believed to only occur during the serpentinization of ultramafic to mafic rocks at mid-oceanic ridges. Nevertheless, several studies have shown that natural H_2 could also be generated within ancient cratonic basements located in the middle of continents. To date, the mechanisms, and quantities of H_2 generated within basements remain poorly understood. Here, we report the study of drill cores from the DR1-A well which reaches the Kansas (USA) Precambrian basement, where high concentrations of native H_2 emissions have been detected[1].

The studied area consists of iron-rich monzo-gabbro. A multi-scale petrological study, including SEM, TEM, and STXM-XANES performed on FIB-thin sections of two samples (K1, K2) shows that the DR1-A well reaches a part of the Mid-Rift System, a Precambrian aborted rift from 1.1 Ga. The monzo-gabbro is composed of feldspars, fayalite (the iron-rich end-member of olivine), ferrosilite (the iron-rich end-member of orthopyroxene), iron-rich amphiboles, and iron-rich clays minerals. This study has shown these clay minerals might have been formed during two distinct events: 1) a late magmatic event, a process called deuteric alteration, leading to the metasomatic replacement of fayalite by a first generation of clay minerals enriched in ferric iron, and 2) a post deuteric alteration at lower temperatures and new redox conditions leading to the formation of a second generation of clay minerals enriched in ferrous iron.

In order to establish a link between these clay minerals and the documented hydrogen emissions we performed quantitative compositional mapping of the K2 sample by EMPA. Data were processed using XMaptools 4.1[2,3]. The two primary iron-rich minerals are replaced specifically: (i) olivine by serpentine (ii) orthopyroxene by amphibole. For each reaction, respective mass transfer and associated solid volume variation were obtained to estimate element behavior and redox conditions. Results show that both reactions have similar redox conditions (Loss of Fe^{2+}, gains of Fe^{3+} and H_2O) and can be used to quantify the hydrogen produced within the Precambrian basement.

[1] Guélard et al (2017) G[3] **18(5)**, 1841-1865. [2] Lanari et al (2014) Comput Geosciences, **62**, 227-240. [3] Lanari et al (2019) Geological Society, London, **478(1)**, 39-63.

Unlocking Tanzania's Helium Province

Lorna Blaisse, Kai Gruschwitz, Colin Ivory, Owen Hughes, Michael Williams, Goldeni Mteri, Karim Mtili
Helium One Global Ltd

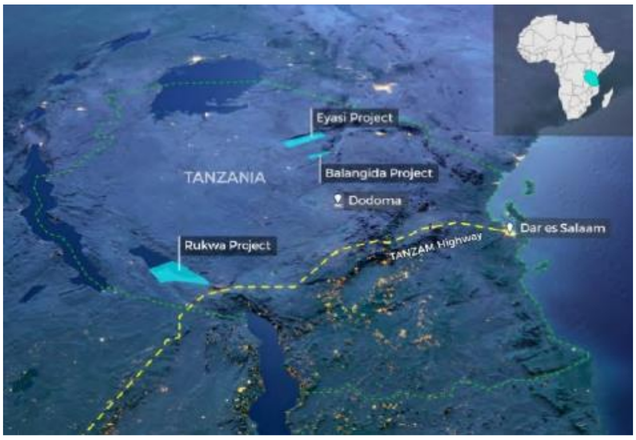

Fig 1. Helium One licensed basins in Tanzania

Introduction Helium One was founded in September 2015. The Company's focus is to explore, develop, and ultimately, become a producer of high-grade helium for the international market, a critical material essential in modern technologies.

Helium One holds 2,964km2 of exploration licences in highly prospective helium provinces in Tanzania (fig 1). The Company holds 100% of these licences and has exclusive rights to develop the assets. There are three distinct licensed areas within the Company's portfolio encompassing the Rukwa, Eyasi and Balangida Permian-Tertiary Rift Basins.

All three of these basins are known to contain helium occurrences with reports of hot springs containing nitrogen-helium mix dating back to the 1950s (Tanganyika Geological Survey). These seeps have been sampled in the field and sent to labs at The University of Oxford and Woods Hole Oceanographic Institute (WHOI) confirming up to 10% He concentrations.

Helium (4He) is actively being generated today by the radiogenic decay of uranium, thorium and their daughter products, hosted within Archaean/Proterozoic granites of the Basement rocks. Most likely source of the helium is through recent thermal perturbation of the stable ancient craton surround the rift basins (Ballantine and Barry, 2016). The Helium System model predicts that the helium migrates along faults and fractures in these active rift systems, and into structural trapping styles setup over basement highs, synrift geometries and hangingwall and footwall plays. Good to excellent reservoir quality is predicted in continental fluvial-deltaic reservoirs of both the Permo-Triassic Karoo, Cretaceous Red Sandstone Group and more recent Tertiary Lake Bed Formation. Reservoir-seal potential has been identified at multiple levels, with a 130m Karoo top seal and intraformational lacustrine seals within the Lake Bed Formation (fig 2).

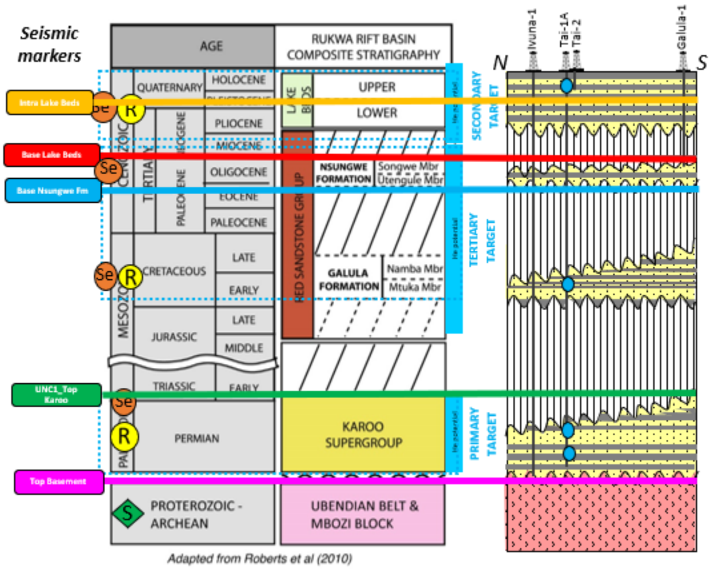

Fig 2. Stratigraphy of the Rukwa Rift Basin, Tanzania

In Q2 2021, Helium One acquired ~200 lkm of 2D onshore seismic over their licenses in the Rukwa Rift Basin (fig 3) and identified a robust structure closure in the Tai prospect. Tai-1/-1A was drilled in Q3 2021 to a depth of 1121m MD and encountered multiple helium shows in all targeted formations. Wireline logging of the uppermost Karoo indicated good reservoir potential with 15-20% porosities. Due to deteriorating hole conditions, no complete logging was carried out and no gas samples recovered to surface.

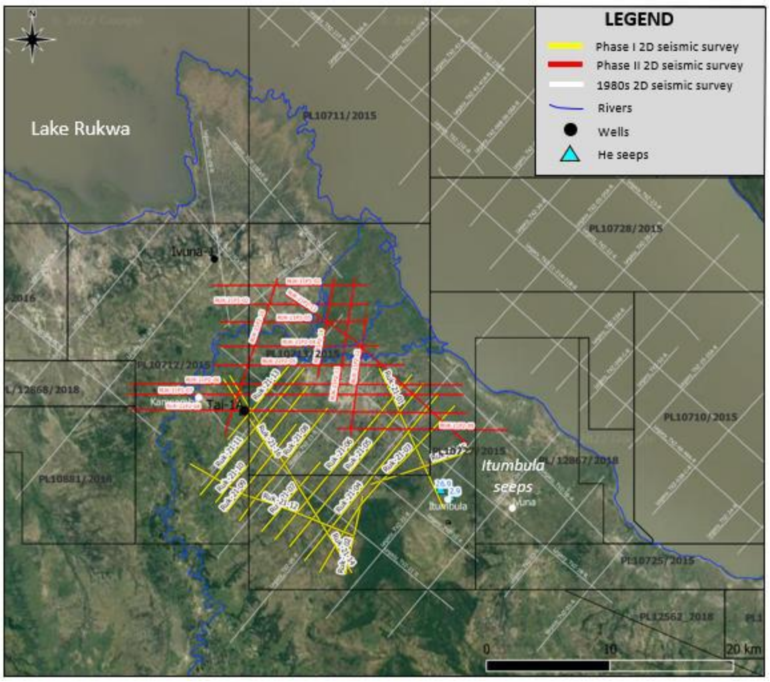

Fig 3. 2D seismic acquisition in the Rukwa Rift

Helium One since acquired an additional 200 lkm of 2D seismic in the Rukwa Basin, have undertaken a multi-spectral satellite spectroscopy study (MSS) across the Rukwa, Eyasi and Balangida basins as well as conducted additional fieldwork in Balangida Basin. The company are currently gearing up for a 2023 Phase II Drilling campaign in the hope to refine their understanding of the helium potential in the region and accelerate exploration activity in a helium-focused province.

Advanced Gas Mudlogging in Natural Hydrogen settings

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Objectives/Scope:

Mudlogging gas services use modular analyzers that can be adapted to quantify any kind of gaseous molecules extracted from a circulating fluid (mud) while drilling. The methodology has evolved to be applied to oil and gas exploration but now more specifically to new energies in geological contexts like geothermal fluids or natural hydrogen subsurface accumulations.

Different configurations can be proposed for the need of a project. For example, mudlogging degassing units can be temperature regulated (especially when oil based muds are used) and different degassers methodology can be setup with constant volume or constant flow extractors. Both techniques enable a regulated gas extraction.

The degasser is linked to an analyzer, here a gas chromatography system (□-GC), equipped with multi GC channels where gas components are analysed by thermal conductance detectors (TCD). The GC unit is preferably located at the mudpit /shale shaker, close to the degassing unit, and makes a short distance gas transfer from the mud extractor box to the GC analyzer. However, a gas line configuration can be also installed where gas is transfered for a short distance to a remote GC located in a mudlogging cabin. The real time gas chromatography have short cycles, which depend on the carbon range selected. At best □-GC analyses are complete in 20 sec and up to 70 seconds at most.

The detection of Helium, Hydrogen, carbon dioxide and hydrocarbons up to pentane (including saturated isomers and unsaturated ethylene and propylene) are routine. The LOD is 1 ppm percent but analysers are able to validate concentrations reaching tens of percents. Oxygen is monitored to minimize air contamination and ensure a quality check of the gas probe's full insertion in mud. Advanced gas systems can be upgraded to the OUT and IN mud circulating in order to evaluate the impact of circulating muds and correct for contamination and background levels.

Advanced gas mudlogging is a key choice to detect and report hydrocarbons and non-hydrocarbons in real-time during a well drilling. Furthermore, it is well adapted to very mobile gases like hydrogen and helium from unconventional geological contexts that are being studied for new energies.

New Approaches to Helium Exploration Field Gas Sampling for Helium and Hydrogen- a trial study.

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Soil testing for Helium can provide evidence of an active helium system and focus the exploration effort. Helium plays are commonly associated with basin edges, migration fronts of supercharged petroleum systems and where source rocks are marginally mature for HC gas generation (include reference paper). Furthermore as Helium is the smallest molecule and highly mobile, a highly competent seal is a prerequisite for any accumulation. Seals such as evaporites (salt or anhydrite) or unfractured shale are a key play element. However, these sorts of seals are seldom regionally extensive. Helium can be used as a proxy gas in hydrogen exploration and has the advantage of being inert.

Basement faults and fractures could localise the vertical migration of helium-containing fluids. Thus, understanding the structural elements of the subsurface critical in the exploration for helium plays. Helium, being so small, is prone to migrate to the near surface where small volumes may be trapped in the shallow weathering zone and subsequently detected.

Pipeline and plant gas-leak detection equipment has been re-purposed to detect subsurface Helium. Helium concentrations are taken within the field using the Agilent Portable Helium Detector PHD-4, from holes drilled one metre into the soil, just below the shallow weathering profile. These shallow holes are cost efficient and environmentally friendly as they utilise a hand held, lithium battery powered drill. No expensive and large drilling methods are needed. Helium samples are recorded in field, therefore lab measurements , transport, storage and testing issues are eliminated.

The field results are interpreted, in combination with structural interpretations made on previously acquired geophysical data (gravity, magnetic & seismic) and satellite helium mapping. The outcome is a determination if an active helium subsurface system is present. The helium concentration and structural maps form the basis for recommendations for future work.

H2He has completed a project in the Southern Georgina Basin, Northern Territory for Global Oil & Gas (ASX:GLV) which showed an active helium system and has formed the basis for the upcoming exploration program. We believe H2He is the only exploration service company to have undertaken a helium specific in field study in Australia and have developed world leading proprietary equipment for future fieldwork. A follow up program is being developed together with long period hydrogen gas sampling.

This poster reflects on H2He methodologies and results of the helium field sampling program.

Geological Society
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Alarm Bells are situated throughout the building and will ring continuously for an evacuation.

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Exit via main reception onto Piccadilly, or via staff entrance onto the courtyard.

Lecture Theatre
Exit at front of theatre (by screen) onto Courtyard or via side door out to Piccadilly entrance or via the doors that link to the Lower Library and to the staff entrance.

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Straight out door and walk around to the Courtyard.

Close the doors when leaving a room. **DO NOT SWITCH OFF THE LIGHTS**.

Assemble in the Courtyard in front of the Royal Academy, outside the Royal Astronomical Society.

Please do not re-enter the building except when you are advised that it is safe to do so by the Fire Brigade.

First Aid
All accidents should be reported to Reception and First Aid assistance will be provided if necessary.

Facilities
The ladies toilets are situated in the basement at the bottom of the staircase outside the Lecture Theatre.

The Gents toilets are situated on the ground floor in the corridor leading to the Arthur Holmes Room.

The cloakroom is located along the corridor to the Arthur Holmes Room.

Ground Floor Plan of The Geological Society