ALBERTA INNOVATES CLEAN RESOURCES FINAL REPORT:

DEVELOPING COMMERCIAL-SCALE NATURAL HYDROGEN IN ALBERTA

Public Report

PREPARED BY:

NORTHERN HYDROGEN SOLUTIONS INC.

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2. APPLICANT INFORMATION (NON-CONFIDENTIAL):

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3. FUNDING AND PARTNERS

CONTRIBUTING PARTNERS:

Organization Name	Cash Funding	In-Kind Contribution	Committed?
Northern Hydrogen Solutions Inc.	$6,000	$175,000	yes

PARTNERS AND SUPPORTERS (OTHER THAN CONTRIBUTING PARTNERS):

Organization Name	Nature of Support
N/A	

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A. EXECUTIVE SUMMARY

Introduction and objectives

Northern Hydrogen, with the support of Alberta Innovates has completed an investigation of the new energy field of natural (geologic) hydrogen exploration and possible production, as applicable to Alberta. Northern Hydrogen Solutions' study team is comprised of professional geoscientists and engineers with extensive experience accumulated during many successful campaigns of oil and gas and mineral exploration, development and production in Alberta, Canada's North, offshore East Coast and Internationally.

Project Approach

Part 1 the study completed a survey of the current state of knowledge of geologic hydrogen, including hydrogen properties, history of its discovery and industrial use. A discussion follows of potential sources of natural hydrogen, an inventory of world's areas with documented hydrogen potential and a presentation of companies and government organizations actively involved in exploring for natural hydrogen.

Globally there has been direct evidence of the potential for geologically generated (natural) hydrogen underground accumulations and production (e.g., in Mali, USA, South Australia, Finland and France). Natural hydrogen however has not been fully demonstrated at commercial volumes. There is no commercial natural hydrogen production within Alberta or North America. Helium however, which is sometimes associated with Hydrogen, is being successfully produced in the Alberta basin.

Part 2 of the report continues with examination of the modern knowledge of natural hydrogen systems and presents Alberta's geologic hydrogen potential in relation to its Precambrian basement and Phanerozoic basin geology. The report concludes with a preliminary examination of commerciality of hydrogen accumulations should they be present.

Key Findings

Alberta has more than 540,000 wells and there are hundreds of wells with indications of hydrogen significantly above background readings. Our work in Phase 1 of this project was to determine if there are potential areas within the province containing higher concentrations of hydrogen, trapped either as distinct pools or associated within oil and gas pools that could be accessible through either conventional or unconventional drilling techniques, that could potentially be commercially exploited.

Our findings confirm that hydrogen is present within the basin, it does migrate through the sedimentary column and is trapped in all types of oil and gas reservoirs, sandstones, carbonates, and even shales. It was primarily detected in sandstone and carbonate reservoirs during our assessment. We have also realized that there are many places where the public data from well tests, including gas sample analysis, is misleading, inaccurate or simply missing from public government databases.

Northern Hydrogen Solutions' staff sifted through Alberta's large well data base and examined of hundreds of wells that have shown hydrogen in gas samples or tests. Most of the wells have low values, less than 10% hydrogen. There are also wells with high hydrogen values on tests (in excess of 50%) with the majority being errors in the recorded data, or hydrogen gas filling casing or tubing over long shut-in time periods that are not related to significant amounts of hydrogen within the reservoir.

The misleading data suggesting high percentage of hydrogen indicators are mostly found in wells that have been suspended for years or decades and then are tested and found to have extremely high values of hydrogen. These tests are showing hydrogen that has, over time, accumulated within the wellbore and displaced the other gases present in the reservoir, strictly by density contrast, where the lightest hydrogen gas fills the wellbore and reservoir top. The important question that remains to be answered is how much of the tested hydrogen is derived from natural sources versus derived from biogenic or chemical alteration of the ferrous wellbore tubulars causing reactions that generate hydrogen within the wellbore and near wellbore. This problem is relevant to the very high hydrogen wells and may also be present in the lower percentage hydrogen wells that we have encountered in our studies.

Northern Hydrogen also developed an initial commercial hypothesis for natural hydrogen exploitation in Alberta. This includes defining the sources for hydrogen, the migration pathways, and the principal trapping mechanisms. Furthermore, we examined various production techniques, and created a basic economic model, that estimates natural hydrogen on a $/kg basis.

Many of the subsystems (including drilling/completion, gathering, processing and delivery to market) necessary for exploring and developing a geologic hydrogen resource are all commercially available in ready to access oil and gas applications, but key exploration technologies/processes, including source distribution, reservoir characterization, resource identification and modeling, are at their earliest stage.

An additional complexity is hydrogen presence within oil zones, primarily heavy oil zones. We see modest to good indicators within the gases derived from the associated gases in oil fields, but looking deeper into the reservoirs near the basement we see no hydrogen within the tested wells. We again question either our understanding of hydrogen migration, or whether in associated gas tests are derived from biogenic processes within the heavy oil fields.

Our analysis of the hydrogen play in Alberta suggests that it is unlikely we will find stand-alone commercial hydrogen fields in the province. However, we believe that is possible to find a natural gas field with 20 to 25% hydrogen content within the reservoir zone and produce and separate the hydrogen from the natural gas. Our geologic and economic analysis would suggest that this type of compound play is feasible within the province and may become a viable form of natural hydrogen production for the province of Alberta

B. INTRODUCTION

Northern Hydrogen Solutions is a leading organization in the exploration, development and commercialization of geologic hydrogen in Alberta. This endeavor holds the potential to revolutionize the energy landscape, offering a path towards large-scale, zero-emission hydrogen production.

The purpose of this report is to present findings on the potential of natural hydrogen exploration and production in Alberta, focusing on the geological conditions, commercial feasibility, and future development of this clean energy source. This report summarizes the results of the first phase of this exercise, and advances the understanding of commercial geologic hydrogen by completing the following activities:

- A review of existing literature and data on hydrogen systems, prospects, and discoveries (on a global basis), as well as discussions with experts in the field.
- Identification and review of most promising areas in the Western Canada Sedimentary Basin and other basins in Alberta, along with the development of an initial commercial hypothesis in Alberta, including sources, migration, trapping mechanisms, and production techniques, and an economic model.
- Identifying key impacted groups, including regulators, local communities, and indigenous groups, and perform an initial assessment of key concerns and opportunities for these groups to participate in the development of this resource.

Sector Introduction

The current demand for Hydrogen in Alberta exceeds 2.5 MT/yr; representing an annual market of more than $3 Billion. The growth in demand in low carbon hydrogen could reach 8 MT/yr or higher by 2050, depending on growth in key industries and, exports.

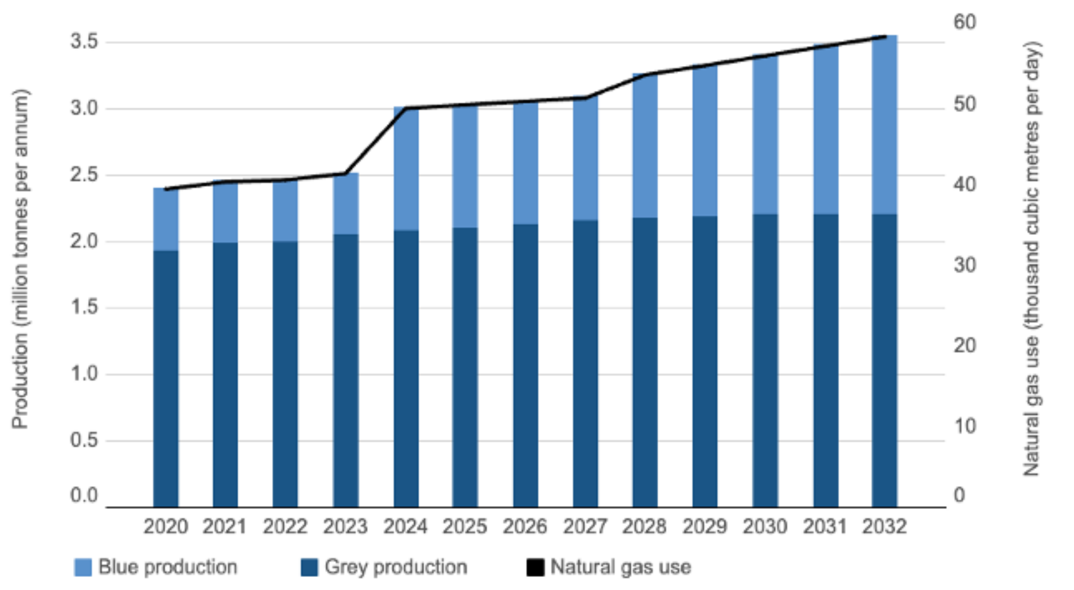

Figure 1: Hydrogen Production Growth in Alberta[1]

Lower-carbon sources of hydrogen are expensive relative to hydrogen from Steam Methane Reformers (SMRs), also known as grey hydrogen (grey hydrogen is produced from natural gas without capturing the CO_2 emissions). Alberta is advantaged vs. other regions with extensive blue hydrogen opportunities (again produced with SMRs while capturing the CO_2 emissions); however, in all cases blue hydrogen is expected to be double the cost of grey hydrogen. Widespread industrial adoption will require lower-carbon hydrogen to be at or below the cost of grey hydrogen.

Initial cost estimates of natural hydrogen appear very favourable as a source of hydrogen production. Hydroma's published cost of production in the west African country of Mali is estimated to be below $0.50/kg; initial estimates peg the full cycle cost at or below the cost of grey hydrogen, currently $1-$1.5/kg.

[1] Alberta Hydrogen Roadmap, 2021 (Government of Alberta)

The current technology readiness state of the overall process to find and produce natural hydrogen in Alberta is at a low level. Natural hydrogen production opportunity, if realized, has the potential to drastically reduce emissions, as well as open significant export markets for hydrogen and hydrogen-derived products.

The support from Alberta Innovates for Phase 1 has allowed us to complete a series of critical scientific and engineering tasks related to the exploration for and the development of natural hydrogen.

Knowledge

Phase 1 (the subject of this report) was focused on developing a complete understanding of the current knowledge base on natural hydrogen, including;

- A review of existing world-wide literature and data on hydrogen systems, prospects, and discoveries (on a global basis), as well as discussions with experts in the field.
- Identification and review of most promising exploration subbasins in Alberta.
- The development of an initial commercial hypothesis for hydrogen exploitation in Alberta, including identification of sources, migration mechanisms, reservoirs, trapping mechanisms, and production techniques, and an economic model (estimating hydrogen costs on a $/kg basis).
- Identify key impacted groups, including regulators, local communities, and indigenous groups and perform an initial assessment of key concerns and opportunities for these groups to participate in the development of this resource.

Alberta has multiple geologic formations that are known to be potential source rocks for the generation of natural hydrogen. This includes multiple basement terrains with serpentinites, metamorphic ultramafic rocks containing iron minerals, as well as basement igneous formations with large amounts of Uranium, and Thorium that are radioactive, and produce natural hydrogen both from radiologic decay and interaction with water. We will discuss the basement geology and areas of high potential within the province later in the report.

Once hydrogen is generated within basement terrains, Alberta has the right geology to allow the migration and trapping of hydrogen gas. Alberta's complex basement structure, with associated post emplacement faults and fractures created by interactions between

Archean-aged basement rocks are the source rocks for hydrogen. Later, reactivations of faults and fractures due to the British Columbia accretion collisions of the Laramide Orogeny from the Early Cretaceous to the Oligocene (~75 to 23 million years ago) created migration pathways for the generated hydrogen. This complex geology and tectonics have provided pathways for the hydrogen's upward migration from the basement, throughout geologic time, and this migration continues today.

Multiple formations have variable lithology with porosity and permeability near potential hydrogen source formations, making them a viable candidate for both hydrogen migration, trapping and accumulations of hydrogen gas.

C. PROJECT DESCRIPTION

Project Description and Objectives

The Northern Hydrogen team has now completed Phase 1 of a multi-phase phased project to advance the commercial development of geologic hydrogen in Alberta. This first phase focused on developing a complete understanding of the current knowledge base on natural hydrogen. This was accomplished by completing the following:

Literature review

To establish a comprehensive knowledge base for the project, we conducted an extensive literature review. This involved examining existing studies, data, and reports on natural hydrogen systems, prospects, and discoveries on a global scale. Additionally, we engaged in discussions with experts in the field to gather insights and perspectives on natural hydrogen exploration and production.

Review of geology and well databases

To identify the most promising areas for natural hydrogen exploration in Alberta, we started by reviewing the geological potential of the province. We focused on the Precambrian basement and Phanerozoic basin geology, which are known to host potential hydrogen source rocks and migration pathways.

We then examined Alberta's extensive well database, consisting of over 540,000 wells, using S&P's *well view* database. We specifically looked for wells with indications of hydrogen and categorized the data into three groups: erroneous data, chemically generated shows, and apparent hydrogen shows. This process helped us identify areas with potential hydrogen accumulations and understand the nature of hydrogen presence in different geological formations.

Using this approach, we were able to determine the most promising areas in the Western Canada Sedimentary Basin and other basins in Alberta, along with the development of an initial commercial hypothesis in Alberta, including sources, migration, reservoirs, trapping mechanisms, and production techniques, and an economic model.

Assessment of Key Impacted Groups

Phase 1 of the project was a province-wide review of exploration, production, and commercial parameters necessary for successful natural hydrogen production, and considered multiple basins. As such we were unable to focus on specifically affected groups, but as part of this report identified key stakeholder/regulatory groups, potential concerns, and proposed preliminary avenues to advance the understanding and public acceptance in advance of the commercial development of the resource in the province. As specific geographical areas are assessed to have natural hydrogen potential, it will remain important to engage communities, including local indigenous groups to assess concerns and opportunities.

The key impacted groups include the following:

Table 1 Overview of impacted groups

Stakeholder Group	Key Concerns	Opportunities
Regulators	Environmental protection, resource management, public interest	Development of a new energy resource, economic growth, job creation
Local Communities	Disruption to daily life, environmental impacts	Economic benefits, job opportunities, improved infrastructure
Indigenous Communities	Impacts on traditional land use, cultural heritage, environmental stewardship	Economic participation, partnership opportunities, capacity building

It will also be important to balance local development impacts with global environmental and commercial benefits.

The Government of Alberta and its regulators may need to develop strategies to encourage development of natural hydrogen, including royalty and land regimes as well as technology development. This is work that will proceed as geographic areas are identified as having natural hydrogen potential.

Updates to Project Objectives

Phases 2 and 3 will focus on identifying and evaluating key fairways and building leads and prospects through the acquisition and analysis of key datasets, including gas analysis with the ultimate objective of being ready to move to field exploration (drilling and seismic) or a joint venture with a company with currently producing gas or oil fields with economic hydrogen in the geologic column or gas stream. These next Phases will move this opportunity from a TRL 4 to 6 and enable Northern Hydrogen to begin acquiring land and developing a resource extraction plan to advance the commercial production of geologic hydrogen in Alberta to reality.

Performance Metrics

The project's performance metrics, as outlined in the Project Agreement, were focused on advancing the TRL of natural hydrogen (from TRL 4 to 6), as well as advancing the commercial understanding of the technology through the development of a commercial model. The progress towards these metrics is summarized in the table below:

Table 2 Performance Metrics

Performance Metric	Project Target	Commercialization Target	Comment on progress
TRL Advancement	Advance to TRL 6 (from 4)	At a TRL6 this would allow us begin field drilling/operational testing (to ultimately advance to TRL9)	**Partially Successful;** the team has fully explored publicly available well data and identified promising basins; more proprietary data and/or well sampling data is required before drilling
Commercial model development	Commercial model developed for natural hydrogen in Alberta, including target reservoirs, production rates and total recovery, production, processing and transport costs	Commercial model applied and validated	**Successful;** A commercial model (in excel format) has been developed and applied to initial well data
Prospective hydrogen plays mapped in Alberta	Development of a map identifying the most promising formations and fairways for hydrogen production	Exploration/development wells successfully drilled and tied in in one or more of the promising fairways	**Successful;** several promising formations and fairways were identified for further investigation.

METHODOLOGY

The goals for Phase 1 of the project were to identify the most promising areas in Alberta for natural hydrogen, the development of initial commercial model, and develop an exploration plan to enable Northern Hydrogen to progress to actively exploring, quantifying and ultimately producing commercial quantities of hydrogen in Alberta.

This was done in Phase 1 by:

- Completing a comprehensive literature and data review on hydrogen systems, leads, prospects and discoveries (on a global basis).
- Identifying promising areas in the WCSB and other basins in Alberta, along with the development of an initial commercial hypothesis, including sources, migration, trapping mechanisms, and modeling of production techniques for hydrogen.

Phase 1 involved a geological assessment of the hydrogen potential of the various basement terrains that underlie the WCSB in Alberta to determine the areas of the province where hydrogen generation is occurring.

This was followed by a review of the areas where post-basement tectonics generated fault systems that provide multiple paths for the movement of hydrogen from the basement rocks through the subsurface.

Finally, we followed the hydrogen system in these areas by examining the quantities of hydrogen found in gas well tests and catalogued the formations that exhibit elevated levels found in drill stem and production tests. The identification and development of our primary core areas for exploration takes us to the end of Phase 1 of the project.

D. PROJECT RESULTS

The project was designed to test the hypothesis that natural hydrogen is present in the Alberta Basin and has the potential to be produced, either as a standalone gas or as a portion of a stream of hydrocarbon or non-hydrocarbon gases.

We began the geological portion of the project with a two-phase approach. The first was to understand the basement geology of the province, as the gases are sourced from the underlining igneous and metamorphic rocks. The second portion of the project was to review and understand the public database, available through the Alberta Energy Regulator, AER, that houses all the data from over 540,000 wells drilled in the province.

We digitally reviewed every hydrogen indication that was seen in well and production tests and catalogued the various types of gas analysis into three categories: 1) Erroneous data, 2) Chemically generated shows, 3) Apparent hydrogen shows. Erroneous data consisted of simple mistakes on test data, for example, where methane and hydrogen numbers were interchanged on the test data.

Chemically generated shows are wells where no hydrogen was initially tested, and where we believe acid gases (CO_2 and/or H_2S) were present and reacted with iron, and over some period of time the gas analysis changed to show hydrogen. These later tests were reported to have material quantities of hydrogen, sometimes as high as 90%. Our conclusion is that these data points are not showing reservoir hydrogen gas, but merely a chemical weathering reaction of steel and acid gas.

Apparent hydrogen shows are wells where we cannot explain the test results other than to indicate geologically sourced hydrogen, generated from the basement rocks. The basic reaction for creation of hydrogen from Serpentinization of mafic and ultramafic rocks is as follows:

$$3FeO(silicate) + H_2O = Fe_3O_4 + H_2$$

See Appendix p. 41 for further discussion of geochemistry of hydrogen generation.

Most of these wells show some tests, either upon drilling the exploration well, or within the production stream as gas or associated gas, where there is a measurement of hydrogen well above the normal background readings of ~0.01% with 100 to 1,000 times the background of hydrogen in the sample. We believe these gas tests to be valid, and these gas analyses need to be confirmed as some initial steps of the next phase of this study by sampling these wells.

The following figure contains 2 maps of Alberta, on the left showing wells testing >/= 2% hydrogen (on DSTs or production data) and on the right showing wells testing >/= 5% hydrogen. While hydrogen appears to be ubiquitous in the Alberta basin, there appear to be areas of local concentration (or generation!) that may be explained by the distribution of basement faults and/or regional arches or noses (as a migration-driven process), by local traps (as a trap-driven process), or by more random, uncertain drivers. Using a higher threshold of hydrogen (@ 5%) the map on the right shows several areas of local concentration as seen in the 2% map, but with more clarity.

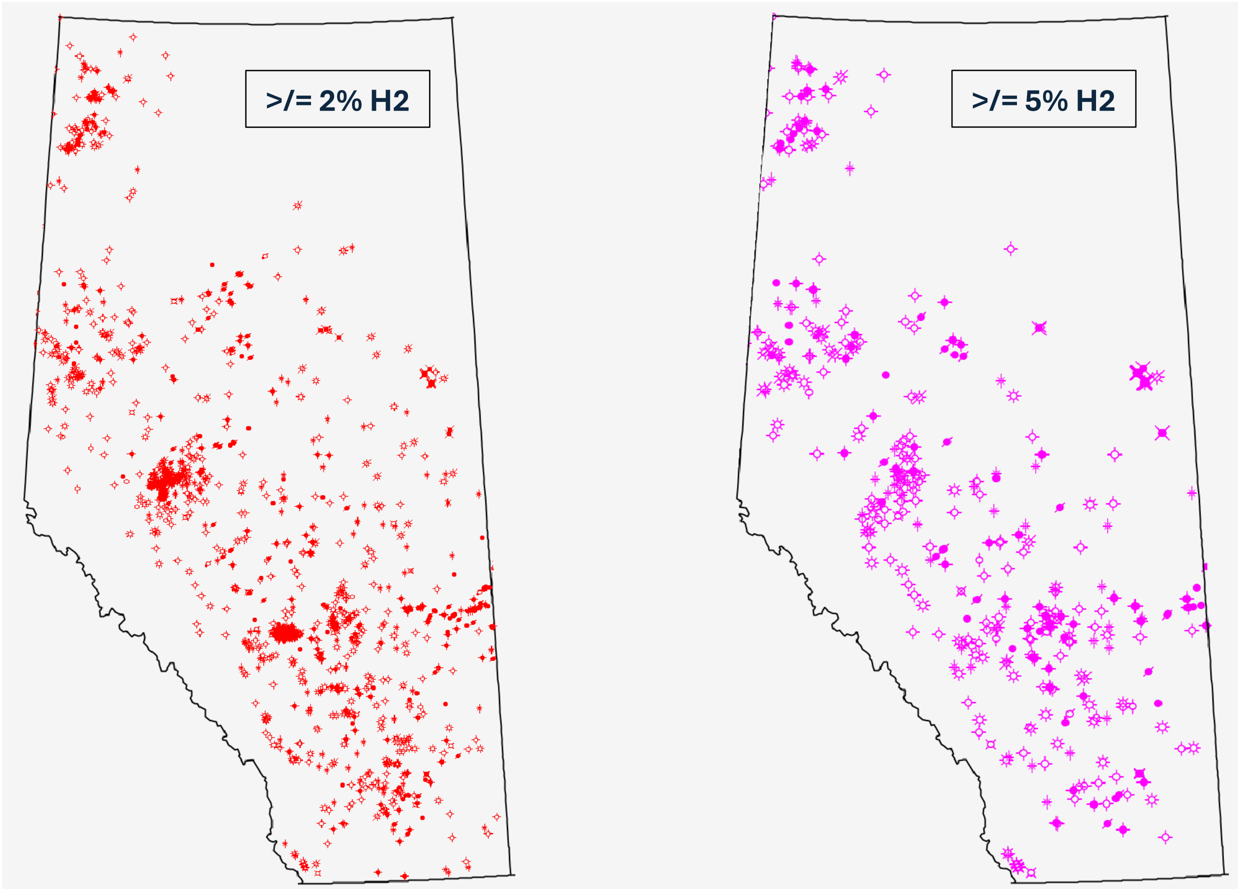

Figure 2: Concentrations of tested hydrogen gas in Alberta wells

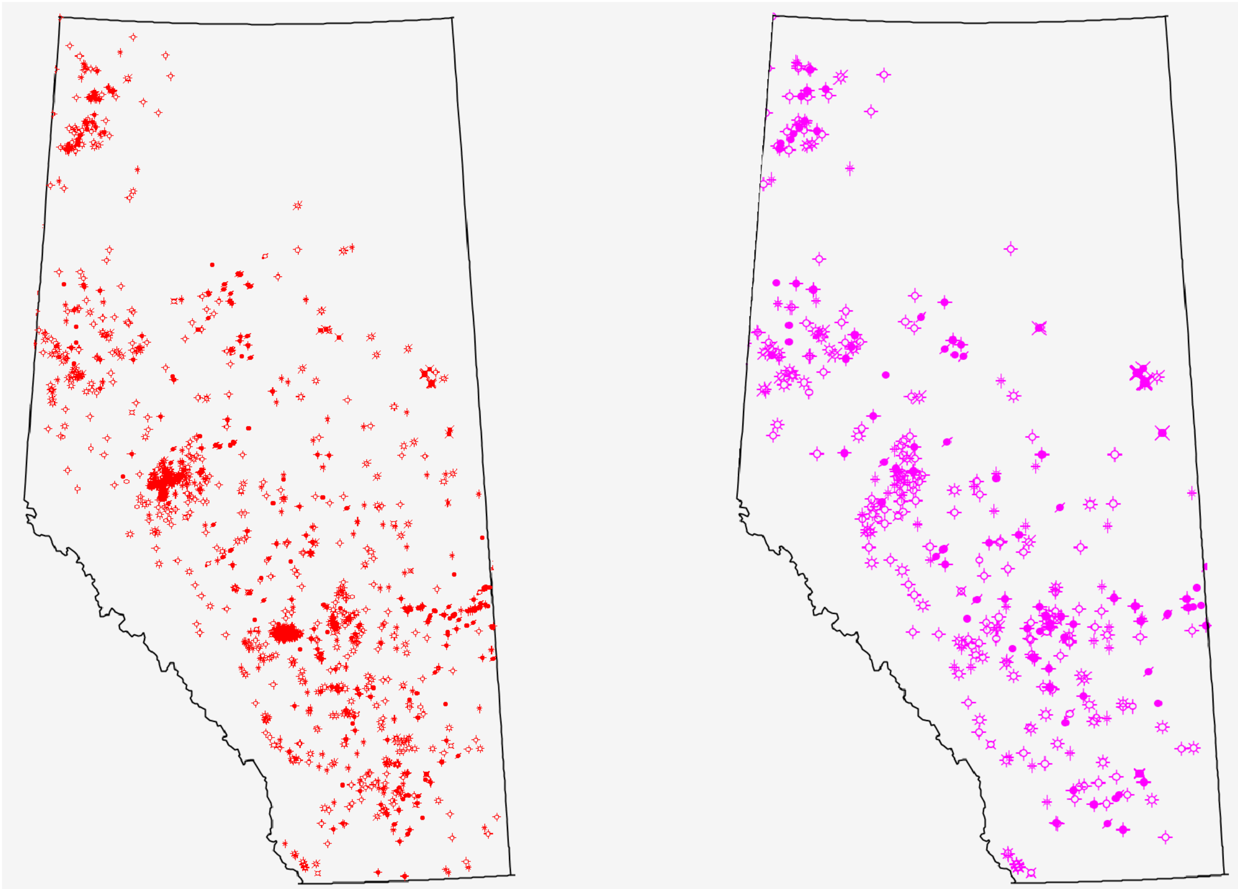

Figure 2 shows wells where the concentration of H2 exceeded 2% (in red on the left) and 5% (in fuchsia on the right).

In parallel with the geoscience efforts conducted during Phase 1 of the project, literature reviews and analogs were developed regarding the reservoir types which may trap hydrogen accumulations and methods of production.

No matter how the hydrogen is generated or migrates, if trapped it will eventually find itself in one of three potential reservoirs: conventional clastic or carbonate formations, or an unconventional shale reservoir. For initial production scenarios, the three reservoir types were characterized as follows:

1. A conventional sandstone gas reservoir, 1000m in depth at reservoir top, naturally pressured (10 MPa) with 25m of net pay at 25% porosity, 60% gas saturation and a drainage radius of 1000m. The reservoir is developed with vertical or horizontal wells.
2. A conventional carbonate reservoir, 2,500m in depth at reservoir top, naturally pressured (25 MPa) with a net pay of 50m at a 15% porosity. With a 75% gas saturation this reservoir will be developed by horizontal wells with a throw of 1000m.

3. An Unconventional shale reservoir, 1000m in depth at reservoir top, naturally pressured (10 MPa). This reservoir would be developed using horizontal, fracked wells with a 2000m throw, and a drainage box or 2000m x 200m x 200m.

In the first two reservoirs, conventional vertical, deviated, or horizontal wells will be drilled and completed off a drilling pad of at least eight wells. These wells may or may not be stimulated, depending on reservoir quality and characteristics.

In the last, unconventional reservoir, gas is trapped both in pore spaces and adsorbed onto rock faces, and will require multi-stage fracturing as well as yet undeveloped completion and production stimulations to recover adsorbed hydrogen. Northern Hydrogen believes that a significant segment of globally announced hydrogen "discoveries" are in this later trap category, and will require novel technology development to enable commercial production.

For sales processing, raw gas from each well and pad will be treated either at the pad or at a central plant, depending on rates and field geometry. The first process step in the three-part process will be the removal of bulk water, intended for re-injection. The second step, only required in the lower concentration hydrogen scenarios, will be a concentration step, using a mol-sieve or membrane, where 75%+ of the co-produced nitrogen or methane will be "rejected" to a sales gas stream. Any required trim dehydration will be performed prior to compression and sales.

The third step will be a cryogenic purification of the hydrogen (and any co-produced helium). Residual methane will be fed into the trim dehydration process and sold. Hydrogen will be either compressed for transport or consumed on-site to produce ammonia or electricity, depending on location and volumes.

Identification of stakeholders, potential concerns and opportunities

Advancing the exploration and development of natural hydrogen in Alberta will impact various groups, and requires careful consideration of potential concerns, as well as opportunities for impacted groups.

Regulators

Alberta Energy Regulator (AER): The AER is responsible for regulating energy development in Alberta; currently it is unclear whether or not the AER will be responsible for hydrogen exploitation in the province; however we anticipate that they would be, given the similarities to oil and gas production. Their primary concerns will likely revolve around ensuring that natural hydrogen exploration and production are conducted in an environmentally responsible manner, with appropriate wellbore integrity, surface casing requirements, and emergency response plans in place. They will also focus on resource conservation and maximizing benefits for Albertans.

Alberta Geological Survey (AGS): The AGS will be interested in the geological data gathered during exploration, contributing to a better understanding of Alberta's subsurface geology and hydrogen potential. They might also have concerns about data accuracy and sharing protocols but may also be willing to share expertise and data.

Alberta Environment and Protected Areas (AEPA): This department will be concerned with potential environmental impacts, including effects on water resources, air quality, and biodiversity. They will require detailed environmental impact assessments and mitigation plans for the first commercial development plans for natural hydrogen. This will include wellpads, as well as gathering systems, gas processing facilities and long-distance transport.

Local Communities

Residents: People living near exploration sites may have concerns about noise, dust, increased traffic, and potential disruptions to their daily lives. They will also be interested in the economic benefits and job creation opportunities associated with the project.

Businesses: Local businesses may be impacted by changes in land use, infrastructure development, and increased demand for goods and services. They will be looking for opportunities to participate in the supply chain and benefit from the project economically.

First Nations and Métis Communities: Indigenous communities with traditional territories in the exploration areas have inherent rights and interests that must be respected. Their concerns may include impacts on:

- Traditional land use: Potential disruption to hunting, fishing, trapping, and gathering activities.
- Cultural heritage: Impacts on sacred sites, burial grounds, and other culturally significant areas.
- Economic benefits: Ensuring equitable participation in the economic opportunities created by hydrogen development.
- Environmental stewardship: Protecting the environment and ensuring the sustainable use of natural resources for future generations.

Preliminary engagement strategy

Described below is a high-level, preliminary engagement strategy, which will be more fully built out once the specific region for exploration and development is identified, and local impacted groups are engaged to understand their specific concerns.

Regulators: Collaboration in developing regulations and guidelines for natural hydrogen exploration and production. Participation in environmental impact assessments and monitoring programs.

Local Communities: Open houses, community meetings, and public forums to provide information and gather feedback. Opportunities to participate in the supply chain and benefit from local procurement.

Indigenous Communities: Meaningful consultation processes to ensure that their rights and interests are respected. Partnership opportunities in exploration and development. Capacity building and training programs to support Indigenous participation in the hydrogen industry.

Northern Hydrogen believes that early and ongoing engagement with all impacted groups is essential for the successful and sustainable development of natural hydrogen resources in Alberta. By understanding and addressing stakeholder concerns and providing opportunities for participation, we can build trust and ensure that the benefits of this new energy source are shared by all Albertans.

E. KEY LEARNINGS

This project has provided our team with a much greater understanding of the habitat of hydrogen in the Alberta Basin.

Our key learnings include the following:

1. Hydrogen is found within the Alberta Western Canadian Sedimentary Basin
2. The basement geology of Alberta contains the source rocks necessary to generate hydrogen
3. There are hydrogen indications in wells that require further investigation. These wells have gas tests on drill stem tests, in exploration wells that show quantities of hydrogen that if confirmed would allow for the separation of the hydrogen at commercial quantities
4. Some hydrogen shows are a result of chemical alteration of steel by acid gases, thus producing an anomalous readings of hydrogen
5. The public database, available through the Alberta Energy Regulator contains erroneous data, which is understandable with 540,000 wells
6. It appears unlikely that a high percentage (greater than 75%) stand-alone hydrogen gas field will be found in the Western Canadian Sedimentary Basin in Alberta.
7. The Athabasca Basin in northeastern Alberta may still hold potential for a hydrogen gas field.
8. With our currently limited understanding of hydrogen trapping mechanisms, it appears to be feasible to commercially produce hydrogen from several different reservoir types.
9. Co-producing 25% hydrogen with either 75% methane or Nitrogen appears to be economic at projected "blue" hydrogen pricing.
10. There is currently no royalty regime in place in the province for hydrogen, it would be helpful to have both an understanding of the royalty and a potential royalty holiday for such a nascent industry, to foster further exploration efforts.
11. The regulatory procedures within Alberta make exploration for hydrogen difficult. Hydrogen is treated as part of the hydrocarbon stream by the regulators, thus there is no potential to explore for and produce hydrogen from a specific formation without the acquisition of a petroleum and natural gas license. There is also no current Royality Regime for hydrogen in Albert: we believe that as a nascent industry, incentives are necessary and the government should consider a royalty holiday, or no royalty until payout of the capital cost for the exploration and development of new hydrogen production.
12. The regulatory procedures within Alberta make exploration for hydrogen difficult. Hydrogen is treated as part of the hydrocarbon stream, P&NG, by the regulators. With much of the province licensed by operators specifically for hydrocarbons, posting and purchasing a license for hydrogen is currently not feasible. In addition, it would be beneficial for there to

be a pause on royalty collection for hydrogen plays, until the point that a commercially viable industry has been established in the province.

F. OUTCOMES AND IMPACTS

Project Outcomes and Impacts

Our findings confirm that hydrogen is present within the basin, it does migrate through the sedimentary column and is trapped in reservoirs. In addition, we have documented natural hydrogen sources, migration paths, and potential areas of interest for future exploration activities.

While it is unlikely we will find stand-alone commercial hydrogen fields in the province, it is possible to find a natural gas (or nitrogen) field with 20 to 25% hydrogen content within the reservoir zone. It is possible to produce and separate the hydrogen from the other components for sale. Our geologic and economic analysis would suggest that this type of compound play could be economic within the province and may become a viable form of natural hydrogen production for the province of Alberta.

It is challenging to quantify the economic impacts of the natural hydrogen sector, both in Alberta and globally, as it is at a very early stage of growth. However, we can look to other emerging sectors like green hydrogen to understand the potential growth. According to Canada's Hydrogen Strategy, it is estimated that more than 350,000 Canadians could be working in the hydrogen sector by 2050.

In Alberta alone, it is anticipated that by 2030, the hydrogen economy will generate tens of thousands of jobs. This provides an opportunity for workers from traditional energy sector jobs as well as create new jobs. For another example, the UK's hydrogen strategy aims to support 9,000 direct hydrogen jobs across the country by 2030, with up to 100,000 supported directly by 2050.

Clean Energy Metrics

Hydrogen today is used in several industrial processes which underpin modern society (Smil, 2022). The process of refining fuels and of creating ammonia for use in fertilizers contributes between 5% and 10% of global CO_2 emissions. There is no avoidance mechanism for these emissions, a switch to biofuels from diesel will continue to require hydrogen for processing. The removal of ammonia generated in the Haber-Bosch process (the second most common use case for hydrogen, after refining) would result in approximately one-half of the world's calories being removed from the food supply chain. Natural hydrogen can also help decarbonize emissionsintensive industries like steel, cement, and chemical production. The replacement of "gray" or "blue" hydrogen with natural hydrogen would decarbonize these industrial inputs at competitive costs. These are the initial global natural hydrogen markets.

In 2022 Alberta consumed 2.5 MT (about 1Bcf) of hydrogen, almost entirely in industrial processes. This volume will undoubtably grow as population and demand for products grow world-wide. The development of low carbon hydrogen sources will enable Alberta's industry to thrive in a regulatory world where carbon dioxide emissions may be taxed or constrained. This thriving will maintain employment and economic capacity for decades to come.

Natural hydrogen is produced naturally underground, resulting in fewer emissions during production and use. The large wind and solar (renewable electric) farms and electrolysis water usage are not required for natural hydrogen production therefore reducing construction emissions and land use requirements.

Program Specific Metrics

TRL Advancement: The project as proposed would advance the TRL of Natural Hydrogen in Alberta from a TRL 3-4 to TRL 6, delivering drill-ready prospects and enabling natural hydrogen discoveries. The first phase of the project was intended to deliver prospective areas for natural hydrogen using existing data which could then be further refined through acquisition of new geophysics. This progress would represent a TRL 4-5.

Prospective Hydrogen Plays: By demonstrating natural hydrogen is present in Alberta, and by locating several prospective trends defined by hydrogen indication and basement geology, Phase 1 of the project has delivered to TRL 4-5. This is despite the flaws in data uncovered by the team, which in hindsight would lead us to say the state of the art at project start was a TRL 3, versus 4.

Commercial Model Development: The team has created a commercial model, the results of which are shared later in the report. The model includes assumptions regarding hydrogen pricing, reservoir characteristics, and capital and operating costs of production. The model also reveals two distinct types of hydrogen trapping mechanisms, which are not explicit in the literature.

The commercial model also reveals that natural hydrogen production would be competitive with blue hydrogen, implying a reduced cost intensity of CO_2 reduction for hydrogen supplies.

Project Outputs

Given the brief timeline of this initial work on Natural Hydrogen, no patents have been formally developed. Within the work products several geographic and geologic leads have been postulated and go forward work would focus on acquiring geophysics necessary to create exploration drill ready prospects.

There are several papers being considered, depending on appropriate forums and acceptance. These papers will be provided to Alberta Innovates as they are developed.

G. BENEFITS

Economic & Environmental

Hydrogen today is used in several industrial processes which underpin modern society (Smil, 2022). The process of refining fuels and off creating Ammonia for use in fertilizers contributes between 5% and 10% of global CO_2 emissions. There is no avoidance mechanism for these emissions, a switch to biofuels from diesel will require hydrogen for processing. The removal of ammonia generated in the Haber-Bosch process would result in approximately one-half of the world's calories being removed from the food supply chain.

The replacement of "gray" or "blue" hydrogen with natural hydrogen would decarbonize these industrial inputs, which make up between 20 and 20% of global CO2 emissions[2]. These are the initial global natural hydrogen markets.

Alberta already has an established and robust market for grey hydrogen, and an emerging market for low carbon hydrogen, including Dow's greenfield petrochemical facility, Imperial oil's renewable diesel project at their refinery in Ft Saskatchewan, and CNRL's upgrader in Sturgeon County.

The natural hydrogen price will initially be set by competing hydrogen supplies, including whether a CO_2 price is included in the competitions' pricing. Current pricing for (gray) hydrogen produced via a Steam Methane Reformer (SMR) is estimated between $1.50 and $2 /kg. SMR with carbon capture and sequestration (blue) hydrogen is estimated to cost approximately $3.50 /kg. (Clota Varde, 2023). Electrolysis (green) hydrogen is expected to cost more than $6 /kg. It is expected that as industrial carbon taxes grow, SMR hydrogen prices will increase to reflect those taxes. In our

[2] . (https://climatepodnotes.substack.com/p/h2-where-were-at-where-were-going?r=2buc3&utm_medium=ios&triedRedirect=true)

conceptual economics a price of $3 /kg has been used to reflect increasing hydrogen pricing while maintaining a price advantage over blue hydrogen.

Concentrating on industrial hydrogen, for existing (fuel, fertilizer) and future (chemical processing, smelting) uses removes the requirement for government support beyond carbon pricing, as natural hydrogen will be competitive with other hydrogen sources in markets that will be ongoing. Depending on other, government supported markets (transport) exposes capital developments to future regulatory and subsidy risk.

Reservoirs and Production

No matter how the hydrogen is generated or migrates, if trapped it will eventually find itself in one of three potential reservoirs: Conventional clastic or carbonate formations, or an unconventional shale reservoir. For initial commercial scenarios, the three reservoir types will be characterized as follows:

1. A conventional sandstone gas reservoir, 1000m in depth at reservoir top, naturally pressured (10 MPa) with 25m of net pay at 25% porosity. 60% gas saturation and a drainage radius of 1000m. The reservoir is developed with vertical or horizontal wells.

These factors yield a pore volume of $20\ 10^6\ m^3$, and a gas accessible volume of $12\ 10^6\ m^3$. B_g for hydrogen in this case is 100, yielding $1.2\ 10^9\ m^3$ of H_2 if the gas available space is 100% H_2, or 42 Bcf ($97\ 10^6$ kg), per well.

There are two cases for gas production, 1 and 2 mmcf/d, with a plateau for three years and declining after that at 10%/yr. The initial cases will have 100% H_2 in the gas phase, and 10% water production by mass, accelerating after year 3. A second set of production cases will have 25% H_2 (by mass) in both production streams, with either methane or nitrogen as the remaining volume fraction.

2. A conventional carbonate reservoir, 2,500m in depth at reservoir top, naturally pressured (25 MPa) with a net pay of 50m at a 15% porosity. With a 75% gas saturation this reservoir will be developed by horizontal wells with a throw of 1000m.

These factors yield a pore volume of $25\ 10^6\ m^3$, and a gas accessible volume of $3.7510^6\ m^3$. B_g for hydrogen in this case is 250, yielding $700\ 10^6\ m^3$ of H_2 if the gas available space is 100% H_2, or 25 Bcf ($57\ 10^6$ kg), per well.

There are two cases for gas production, 2 and 4 mmcf/d, with a plateau for three years and declining after that at 10%/yr. The initial cases will have 100% hydrogen in the gas phase, and 10%

water production by mass, accelerating after year 3. A second set of production cases will have 25% hydrogen (by mass) in both production streams, with either methane as the remaining volume fraction.

3. An Unconventional shale reservoir, 1000m in depth at reservoir top, naturally pressured (10 MPa). This reservoir would be developed using horizontal, fracked wells with a 2000m throw, and a drainage box or 2000m x 200m x 200m.

In an unconventional reservoir, hydrogen is stored in two ways. The first is within the 5% porosity in the pores within the shale. Arithmetically this yields a pore volume of 4 $10^6 m^3$. With a B_g of 100 this yields a H_2 volume of 320 $10^6 m^3$ (11 Bcf) at 80% gas saturation.

Hydrogen is also stored by adsorption onto charged areas of the shale matrix. Using a value of 10m3/m3 rock, this yields an adsorbed volume of 800 $10^6 m^3$ or 28 Bcf[3].

In aggregate the hydrogen contained in the unconventional reservoir, described above, could be up to 40 Bcf, or 90 10^6kg per well.

There are two cases for gas production, 2 and 4 mmcf/d, declining initially at 35%/yr. The initial cases will have 100% H_2 in the gas phase, and 10% water production by mass, accelerating after year 3. A second set of production cases will have 25% H_2 (by mass) in both production streams, with either methane or nitrogen as the remaining volume fraction.

Capital and Operating Costs

Hydrogen development will use current best drilling practices, including pad-based drilling. For our initial estimate we will use a generic pad design of 8 wells per pad, with associated pad-based production facilities. The costs used are modified from AER / PSAC data, a summary table is produced below.

- For Conventional Case 1, a vertical/directional well of ~, 1200m a drill and complete Capital Expense (CapEx) of $2 M was used, based upon data from the Manville and Shunda.
- For Conventional Case 2, a horizontal well of ~ 2500m depth and a throw of 1000m (~4000m TMD) a drill and complete CapEx of $6 M was used, based upon data from the Cardium.

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[3] Truche et al., 2018: Clay Minerals Trap Hydrogen in the Earth's Crust: Evidence from Cigar Lake

- For the unconventional Case 3, a horizontal fracked well of ~ 1000m depth and a 2000m throw, a drill and complete CapEx of $8 M was used, based upon data from the Montney and Duvernay.

Raw gas from each well and pad will be treated either at the pad or at a central plant, depending on rates and field geometry. The first process step in the three-part process will be the removal of bulk water, intended for re-injection. The second step, only required in the 25% hydrogen scenarios, will be a concentration step, probably using a mol-sieve or membrane, where 75%+ of the co-produced methane will be “rejected” to a sales gas stream. Any required trim dehydration will be performed prior to compression and sales.

The third step will be a cryogenic purification of the hydrogen (and any co-produced helium). Residual methane will be fed into the trim dehydration process and sold. Hydrogen will be either compressed for transport or consumed on-site to produce ammonia or electricity, depending on location and volumes.

For these conceptual cases plant CapEx is set at $4M per pad. Gas processing will be done at a third-party plant, with Fixed Operating Expense (OpEx) in all cases set at $40k/well/year. Variable OpEx will be set at $65/10^{3}m^3 of raw produced gas, these were taken from the AER, described in Table 3.

Table 3 Average well production, cost data (AER 2023)

Table S5.6 Alberta natural gas supply costs by PSAC area, 2023

Area	Formation	Type of well	Type of gas	Total measured depth (m)	Initial productivity (10^3 m^3/d)	Total capital cost (Cdn$000)	Fixed operating cost (Cdn$000/year)	Variable operating cost (Cdn$/$10^3$ m^3)	Natural gas supply cost - single well (Cdn$/GJ)	Natural gas supply cost - 4 well pad (Cdn$/GJ)
PSAC 2	Shunda	Directional	Sour	3 565	14.4	3 354	49.93	68.96	5.22	n/a
PSAC 2	Cardium	Horizontal	Sweet	5 000	30.8	5 964	41.12	64.58	3.00	2.51
PSAC 2	Montney	Horizontal	Sweet	5 000	58.2	12 954	41.12	64.58	5.30	4.20
PSAC 5	Manville	Vertical	Sweet	1 150	3.2	1 356	25.50	80.36	8.57	n/a
PSAC 5	Duvernay	Horizontal	Sweet	6 000	39.0	11 991	41.12	80.36	7.37	6.10
PSAC 6	Grand Rapids	Vertical	Sweet	600	2.6	1 278	32.02	59.29	13.35	n/a
PSAC 7	Montney	Horizontal	Sweet	4 500	61.8	8 528	57.77	58.54	1.87	1.19
Shale	Duvernay	Horizontal	Sweet	6 000	40.9	10 352	41.12	64.58	7.06	5.58
CBM - MNN[b]	Manville	Horizontal	Coal gas	2 400	1.5	2 795	25.50	25.20	20.42	n/a

Note: Cost data from petroCUBE, Sproule, and Enserva Well Cost Study Winter 2023 have been used to estimate the supply costs.

[a] Not applicable (n/a).

[b] Coalbed methane Manville Corbett.

Conceptual Business Scenarios

Several business cases were prepared for the varied scenarios listed above. These business case should be viewed with the following understandings:

- All cases are un-risked, meaning there are no dry holes – an unlikely case. Because of this, returns will probably be lower.
- The case presented has only 8 production wells, which carry the entire up-front costs of exploration and development. A successful exploration and development campaign would result in future developments, yielding a higher ultimate economic return.
- The field gate price, set here at $3 /kg, will depend on proximity to markets and uses. Returns may be higher or lower depending on size, rate and transportation options.

The tabulated results are summarized in Table 4.

Table 4 Summary of Economic Cases

		Alberta Hydrogen Cases					
Reservoir:		Conventional Clastic		Conventional Carbonate		Unconventional Shale	
CapEx (Wells)	M$	2.5		6		8	
CapEx (Pad)	M$	0.5		0.5		1	
Fixed OpEx	k$/w/yr	40		40		40	
Variable Opex	$/1000m3	65		65		65	
	$/mcf	1.84		1.84		1.84	
H2 Price	$/kg	3.00		3.00		3.00	
Initial Production	mmcf/d	1	2	2	4	2	4
	1000m3/d	28.3	56.6	56.6	113.3	56.6	113.3
Initial Decline	%	10		10		35	
100% H2 Case	IRR (%)	37	59	39	63	28	55
	PV9 (M$)	57	140	116	282	52	159
25% H2 Case	IRR (%)	22	41	23	44	9	33
	PV9 (M$)	23	71	48	145	12	71

In none of these un-risked cases is the cash flow negative. It is readily apparent that the discovery of a major hydrogen field in a conventional reservoir could have a compelling business case, particularly where close to market.

Social:

As noted above, industrial hydrogen is a key building block of modern society, with no substitutes in areas of food and fuel production. Reduction in consumption is not only unlikely but would lead to social unrest particularly as food is impacted. Decarbonizing hydrogen consumed is an immediate and material method of climate mitigation.

In 2022 Alberta consumed 2.5 MT (about 1Bcf) of hydrogen, almost entirely in industrial processes. This volume will undoubtably grow as population and demand for products grow world-wide. The development of low carbon hydrogen sources will enable Alberta's industry to thrive in a regulatory world where carbon dioxide emissions may be taxed or constrained. This thriving will maintain employment and economic capacity for decades to come.

Building Innovation Capacity

The creation of natural hydrogen exploration and production intellectual property (patents, exploration techniques and production know-how) will enable Alberta to create a local new hydrogen source in Canada. More than that, any leadership in the global race to find and develop natural hydrogen would become a competitive advantage for Alberta enterprises. As with other energy, medical and information technologies, a head start in hydrogen exploration and production techniques would yield economic advantage to Alberta.

H. RECOMMENDATIONS AND NEXT STEPS

The work of Phase 1 has demonstrated that Alberta has natural hydrogen within the sedimentary column throughout the Western Canada Sedimentary Basin. There are still significant challenges in confirming the quantity of hydrogen within our key areas and ground truthing the public domain data from the Alberta Energy Regulator.

The regulatory procedures within Alberta make exploration for hydrogen difficult. Hydrogen is treated as part of the hydrocarbon stream by the regulators, thus there is no potential to explore for and produce hydrogen from a specific formation without the acquisition of a petroleum and natural gas rights.

With much of the province licensed by operators specifically for hydrocarbons, posting and purchasing a license for hydrogen is not feasible. Also, there is no current Royality Regime for hydrogen in Alberta and we believe that as a nascent industry, incentives are going to be necessary and the government should consider a royalty holiday, or no royalty until payout of the capital cost for the exploration and development of new hydrogen production.

Recommendations:

1. Hydrogen is a critical element for future reduction of climate change and the transformation of the Alberta economy. While considerable efforts are being placed on infrastructure and transportation, resources are required to encourage development of natural hydrogen potential within the province. The activity seen in other jurisdictions (Australia, US Mid-West) are illustrative of the economic and environmental potential of the nascent resource.
2. Industry in early phases of exploration relies on geological surveys, who are directed by government to do fundamental science and engineering. The Alberta Government could direct the Alberta Geological Survey to provide some fundamental science in support of hydrogen exploration and allocate further Alberta Innovates (AI) resources to developing promising prospects.
3. Natural hydrogen will require new technologies or techniques for subsurface production and surface utilization of hydrogen to capture value. Subsurface technology would include well completion and enhanced reservoir recovery techniques, unique to hydrogen. Surface technology would include remote ammonia production and hydrogen separation. Alberta could use existing technology organizations (AI, C-FER, Universities) in concert with commercial partners to develop these technologies to enable economic growth as Alberta did with the Oil Sands.
4. This energy transition requires an "all hands-on deck" approach to develop commercial options for decarbonization. Natural hydrogen is a significant opportunity to decarbonize industrial process which require hydrogen, and is a complement to the "Blue" hydrogen (*SMR* + Carbon Capture) projects being supported by Alberta today. Private organizations such as the Gates Foundation have invested significantly in natural hydrogen globally, and seed capital from Alberta could highlight and attract that capital to Alberta's advantage.

I. KNOWLEDGE DISSEMINATION

The knowledge gained from Phase 1 of this study has brought the team a much better understanding of the potential for hydrogen in the province as we have discussed.

Dissemination of knowledge is supported by all of the team members. And this must be balanced with the commercial potential of this early exploration effort, both for Northern Hydrogen and for the Province of Alberta. There is much more work to do and we must be deliberate with how and how much of our understanding that we publicly disclose in order to maintain an competitive advantage in this nascent field of research.

We have also engaged with the Geological Survey of Canada, in Calgary, to discuss our findings and fundamental questions that still challenge our team members. The GSC is interested in many of the same problems/challenges and together we have decided to host a session at the Canadian

Energy Geoscientist Association, CEGA, formally the Canadian Society of Petroleum Geologists, CSPG conference in May of 2025 to bring some of the major scientists to Calgary to discuss the exploration efforts for hydrogen in North America.

We have discussed providing the public with some of our basic understanding of the source rocks, reservoirs and challenges with data in Alberta though geoscience conferences in Alberta and potentially talks at some of the universities in Alberta. Any of these talks will include the acknowledgement of the support provided by Alberta Innovates for Phase 1 of the project.

From the work that we have completed there are also engineering related questions that we believe can best be answered within Alberta's academic and research institutions. Thes questions include the development of completion and production technologies, as well as scalable technologies for the remote use of hydrogen, for example remote ammonia production. We have been in conversations with the University of Calgary, Facility of Engineering to see if we can gain more insight into these fundamental questions around the production and use of Hydrogen. We foresee expanding those conversations within the academy and research organizations within Alberta through 2025.

J. CONCLUSIONS

The following are the consolidated conclusions from this phase of the project:

- Hydrogen systems do exist and have many similar characteristics to hydrocarbon systems.
    - Hydrogen source rocks, migration paths, reservoir rocks and seals are well documented in Alberta.
    - There are clear indications that natural hydrogen is generated in the Precambrian basement and deeper crustal rocks, and moving within the sedimentary formations of the Alberta Basin, part of Western Canada Sedimentary Basin (WCSB).
    - There are hundreds of wells with gas tests that show hydrogen content above background average.
- Clusters of wells with significant hydrogen concentrations were seen in the Deep Basin and Northern Alberta
    - These indications show some relationship to basement geologic features.
    - These indications appear throughout the stratigraphic column.
    - There are significant uncertainties due the quality, and quantity of well data that is available in the public domain.
- To date, no hydrogen accumulations of significant volume have been discovered in Alberta.
    - Global examples, while publicized, have not been fully geologically described, nor demonstrated to be of sufficient volumes for commercial viability. (eg. Mali)

- Upon reviewing Alberta's well data, we observed that most wells having single zone gas tests with elevated hydrogen concentrations (e.g., >10% H_2) are surrounded by wells with very low or zero hydrogen concentration.
- We observe that most moderate or high concentrations of tested hydrogen do not persist with repeated testing, suggesting either an episodic man-made origin and/or depletion of a small pocket of hydrogen gas. Hydrogen is typically seen in the drill stem test, but not in the production testing.
- These observations/conclusions suggest that pockets of higher concentration of hydrogen gas can exist, even trapped inside gas or oil pools, such as can be observed in complex (compartmented) stratigraphic traps in hydrocarbon systems.

- There are untested exploration play types that may yield significant hydrogen volumes and concentrations both in Alberta and globally.
  - There is still unexplored hydrogen potential within the non-hydrocarbon, uranium-prone Athabasca Basin, in faulted basement blocks and fractured Precambrian sediments.
  - Hydrogen gas is generated at significantly lower rates than hydrocarbons but are generated over a significantly longer geologic timeframe.
    - This requires geologically long-lived traps to capture significant volumes of generating and migrating hydrogen.
    - The role of hydrocarbon flushing of hydrogen accumulations depends on basin history (burial rate, heat flow, etc.) and remains under-evaluated.
    - Hydrogen gas may accumulate in larger volumes where it is not diluted or flushed by hydrocarbons, thus the potential remains below the hydrocarbon source rocks within the WCSB.
  - There may be areas in the WCSB that are in hydrocarbon migration 'shadows' where any persistent traps could accumulate larger volumes and higher concentrations of hydrogen.
  - These hypothesized areas would likely be where well control and data could be quite limited.
  - Such exploration work would be supported by the strategic benefit of opening a new type of energy frontier.
- Hydrogen has been observed in existing hydrocarbon fields and may offer a lower risk/cost option for advancing commercial hydrogen production.
  - Discovering hydrogen gas within associated gas from a heavy oil field is also possible.
  - Novel production engineering technologies may be required hydrogen production in situ. For example, well stimulation (i.e. water or CO_2 flood, fracking of iron rich deposits) as a mechanism to create commercial-scale hydrogen production?
  - Enhanced in-situ production may also be an opportunity: Suncor patent application:
    - How to seed formations with H2, iron filings etc.[4]

[4] (Bunio et al author) https://www.ic.gc.ca/opic-cipo/cpd/eng/patent/3159645/summary.html?query=bunio&type=basic_search

Why should Alberta care about developing the natural hydrogen sector:

The development of the natural hydrogen industry in Alberta offers a significant opportunity to advance the province's decarbonization goals while leveraging its existing energy infrastructure and expertise. Here's how it can contribute:

1. Low-Carbon Energy Source

Natural hydrogen can be produced with minimal carbon emissions compared to conventional methods like steam methane reforming (SMR). Using this low-carbon hydrogen as a fuel source can help reduce greenhouse gas (GHG) emissions in various sectors, such as industry, energy production, and transportation.

2. Integration with Existing Energy Infrastructure

Alberta's energy industry is already equipped with infrastructure, such as pipelines, storage facilities, and expertise in subsurface resource extraction. These can be repurposed for hydrogen production, storage, and distribution, reducing costs and accelerating deployment. This reduces the carbon footprint of transitioning to a hydrogen economy.

3. Support for Decarbonizing Heavy Industries

Industries like steel, cement, and chemicals are challenging to decarbonize due to their reliance on high-temperature processes. Hydrogen can replace fossil fuels in these sectors, enabling significant emissions reductions while maintaining economic competitiveness.

5. Job Creation and Economic Diversification

Developing the hydrogen industry could create new jobs in engineering, manufacturing, and research while reducing the province's dependence on traditional fossil fuels. This diversification aligns with Alberta’s goals to transition to a sustainable economy.

6. Export Opportunities

Alberta could position itself as a global supplier of low-carbon hydrogen and derivatives, tapping into growing international demand for clean energy. Exporting hydrogen would reduce emissions in importing regions while diversifying Alberta’s economy.

K. ADDENDUM - ADDITIONAL PROJECT DOCUMENTATION

Natural Hydrogen Overview

Hydrogen Properties

Hydrogen is the lightest chemical element, has the symbol H and number 1 in the periodic table of elements. At standard conditions for temperature and pressure (STP), hydrogen is a gas of diatomic molecule with the notation H_2 or H2, commonly called molecular hydrogen or simply hydrogen. It is colorless, odorless, tasteless and non-toxic. It is highly flammable, with an ignition energy that is twenty times smaller than that of natural gas or gasoline.

Hydrogen is the lightest element and will escape quickly into the atmosphere from shallow geological formations as it is a very diffuse gas. As comparison, the mass of one US gallon of gasoline (3.785 litres) is approximately 2.75 kg where one gallon of hydrogen has a mass of only 0.000075 kg (at 1 atm pressure and 20°C). Hydrogen and helium (He), the second element in the periodic table, are often companion elements in the subsurface, when detected in fractures, reservoir water, aquifers and gas fields. Both are very light gases and to minimise leakage and maintain purity, they need specifically engineered infrastructure such as suitable insulated vessels for storage and pipes to transport.

Hydrogen is an important input to several industrial processes including fertilizer and fuel production. Hydrogen is also highly combustible, a property that makes it sought after as a replacement for hydrocarbons in the internal combustion, chemical and reaction engines. Hydrogen gas is an ultra-light energy carrier, and is very promising as a fuel substituting coal, diesel, biodiesel, petrol, gasoline, aviation gasoline, ethanol, methanol, LPG, methane, natural gas, etc., that release carbon dioxide along with other pollutants (NOx and SOx) during combustion. Hydrogen is also abundant, can be produced now on industrial scale, and is environmentally friendly as its oxidation (burning) produces only water (Grochala, 2015). There is a continuous demand to increase the production of hydrogen, which is one of the most important paths to decarbonization of economy.

Hydrogen Based Technologies

The following review of some of the main technological discoveries made during the past two centuries shows that present applications of hydrogen in the economy have deep roots in the efforts of generations of scientists, engineers and inventors from many countries. Particularly, the use of hydrogen in transportation, receives a renewed interest due to world's present commitment to economy decarbonization (Moriarty and Honnery, 2019).

In 1800 Nicholson and Carlisle, followed by Ritter, managed to decompose water into its elemental constituents using electrolysis. This is one of the processes used today, to produce the so-called Blue Hydrogen through a photochemical process (Grochala, 2015). During the 19th century, significant steps in the producing and usage of hydrogen happened such as: Davey discovery the concept of the fuel cell (1801), the de Rivaz engine, the first internal combustion engine powered by a mixture of hydrogen and oxygen (1806), Brown testing of an internal combustion engine using to propel a vehicle (1826), Faraday laws of electrolysis (1834), Grove developing the first fuel cell (1842), Renard and Krebs' first hydrogen filled airship (1884), the development of hydrolysis in 1885, Sabatier use of hydrogenation (1897), Dewar's hydrogen first liquification (1898) and solidification (1989), and finally the launch of the first hydrogen filled Zeppelin airship (1900).

An emerging hydrogen industry started in the 20th century, involving the lightness, combustion, easy bonding, and high thermal conductivity properties of the element. Hydrogen was produced in ever growing quantity mainly through water electrolysis or steam reforming and new applications emerged. Thus, in 1901, Norman introduced the hydrogenation of fats with following countless applications in the food industry. In 1903, the Russian scientist Tsiolkovsky theorized rocket propulsion using liquid hydrogen and oxygen. Same year, Lane introduced the “Lane hydrogen producer” based on steam-iron process and water gas ($CO+H_2$ from vapors), that was used to manufacture lifting gas for airships (Hurst, 1939). This process provided high quantities of hydrogen (24,000,000 m^3 in 1913) and dominated the market until mid-1940s when was displaced by a cheaper method of hydrogen production that used oil or natural gas as feedstock (Fan, 2011).

Haber patents the Haber process in 1910, that remains the main industrial technique to produce ammonia for fertilizer. It uses atmospheric N_2 reacting with H_2 in presence of a metallic catalyst and is known as the Haber-Bosch process. Two major technologies were developed in the German chemical town Leuna: hydrocracking for commercial hydrogenation of brown coal (1920) and steam reforming used to produce methanol (1923).

In 1874 the prophetic science-fiction author Jule Verne, wrote in his novel The Mysterious Island: “...*I believe that water will one day be employed as fuel, that hydrogen and oxygen which constitute it, used singly or together, will furnish an inexhaustible source of heat and light, of an intensity of which coal is not capable*."[5]

The first Earth's circumnavigation by a hydrogen-filled Zeppelin takes place in 1929, that covered 33,234 km during a 21 days and 31 minutes. In 1937, the Zeppelin Hindenburg filled with hydrogen is destroyed by fire with loss of life in New Jersey, and this marked the abrupt end of the airship era.

Same year, the German inventor Erren patented the first combustion engine using a mixture of hydrogen and oxygen as fuels and, at his aviation factory near Rostock, Heinkel,

[5] http://www.online-literature.com/verne/mysteriousisland/33/

and his engineers, von Ohain most noted, developed the first jet engine running on hydrogen.

In USA, gaseous hydrogen went into service in 1937 as the coolant in a hydrogen-cooled turbo generator at the Dayton Power & Light in Ohio. The following year Sikorsky, a Russian - American aircraft designer who promoted helicopter development and production, proposed liquid hydrogen as a fuel for aviation use. Also in 1938, the first Rhine-Ruhr compressed hydrogen pipeline was built that is 240 km long and is still in operation. Gaffron, a German biochemist discovered in 1939 that unicellular green algae can produce H_2 in presence of light. Using his pioneering work, many efforts ensued in several advanced countries to develop hydrogen as a renewable biofuel from water and solar energy (http://www.fotomol.uu.se/Forskning/Biomimetics/solarh/photobio.shtm)

During the 2nd World War there were numerous advances in using hydrogen in weaponry. In 1943 liquid hydrogen was tested as rocket fuel at Ohio State University. Zettersröm, a Swedish engineer, invented hydrox, a gas mixture of hydrogen and oxygen used for breathing during deep water diving.

Hydrodesulfurization is commercialized starting in 1949. This is a catalytic hydrogenation chemical process to remove sulfur from natural gas, gasoline, diesel, jet fuel, etc., and reduce sulfur dioxide emissions. In 1951, the first hydrogen underground storage was used, a technology meant to replace storing liquid hydrogen in tanks at high pressure and low temperature (Foh et al., 1979). Presently, hydrogen is stored in salt domes, caverns, purpose-built large cave in impermeable granites and in depleted oil and gas fields.

Hydrogen makes an excellent chemical fuel and in 1957 Pratt & Whitney launches a jet engine using liquid hydrogen as fuel and was evaluated for the first time as part of the Lockheed CL-400, a high-altitude reconnaissance aircraft. Fuel cell engines using hydrogen were developed for tractors (1958), welding machines (1959), forklifts (1960) underwater research vessel (1964), golf carts (1965), automobiles (GM in 1966), for NASA missions (during 1960s) and submarines (1980s). At the Philips Research Laboratories, it was discovered that hydrogen could be reversibly taken up by intermetallic compounds in the form of a hydride (Van Vucht et al.,1970). Now of widespread use, the term Hydrogen Economy was coined by two academics in US in 1970.

Starting in 1960 and continuing to today, various liquid hydrogen/liquid oxygen engines were built for US space programs administered by NASA, including the Space Shuttle. Similar propellants are used in European partnership space program since 1990s (Arianne rockets).

The beginning of the 21st century has seen significant development towards lighter and more capable hydrogen fuel cells. A fuel cell is a device that converts the chemical energy contained within hydrogen into electric energy, with water and heat as byproducts. The process within a fuel cell is essentially the inverse process used to first generate the hydrogen fuel. the first mass-produced nickel–metal-hydride battery-powered vehicles hit the roads of Japan in 1997.

Fuel cells started to be used in, submarine, unmanned submarine vehicles, trams, buses, boats, mining locomotive (first demonstrated in 2002 in Val d'Or, Quebec), hydrogen trains (Hydrail, first in 2006 in Japan) and many passenger trains in Japan, USA, Germany, China, Spain, Dubai, UK, Taiwan and France. some of the hydrails in these countries were small, limited time running, demonstrative projects. Fuel cell electric vehicles (FCEVs) for passenger and freight transport are an emerging market. Three car companies, Toyota (2014), Hyundai (2018) and Honda (2016 and 2021) have manufactured hydrogen fuel cell vehicles, and many other manufacturers have hydrogen cars in development. 2019 seen the first liquid hydrogen carrier vessel being launched in Japan. Several airplane manufacturers have built prototypes for passenger and cargo planes.

The first Canadian hydrogen train using Canadian made fuel cells, "steamed" in the summer of 2023 from Montmorency Falls in Quebec City to Baie-St-Paul, carrying 120 passengers in two railcars. Scaling up this Canadian hydrail experiment to the totality of urban setting, mining ventures, land and marine provincial, inter-provincial and across-country transportation systems, will replace vast quantities of fossil fuels and dramatically reduce the CO_2 and other pollutant emissions.

In Alberta, hydrogen powered trains are operating on a test basis for the Calgary -Edmonton track by CP Rail with ATCO as a contractor. [6] In addition Alberta's first commercial hydrogen fueling station for trucks, busses, and cars is now operating in Nisku, south of Edmonton. Hydrogen buses for public transportation were evaluated in Edmonton and Strathcona County. The city is Canada's first hydrogen hub, having operated since 2021. Canadian Pacific Kansas City (CPKC) and ATCO EnPower recently completed the construction of hydrogen production and refuelling facilities in Calgary and in Edmonton. As part of its innovative efforts, CPKC is retrofitting a number of diesel locomotives with hydrogen fuel cells, so they can operate without directly generating carbon dioxide emissions. In addition, hydrogen is being used as a fuel for a combined heat and power generating facility at the Fort Saskatchewan Millenium Place, and ATCO is also piloting the blending of hydrogen into the gas distribution network[7].

The hydrogen to be used in fuel cells is expensive to produce by either green, blue, or grey methods. Securing in Canada an economic subsurface accumulation of natural hydrogen will make a significant impact in the fight for industry decarbonization. Natural hydrogen is found underground and is geologically generated by several physicochemical processes rather than manufactured. Alberta, where hydrogen gas was occasionally tested in older hydrocarbon wells drilled in Western Canadian Sedimentary Basin (WCSB) or the western

[6] https://majorprojects.alberta.ca/details/CP-Hydrogen-Locomotive-Project/10590
[7]

end of the Canadian Shield, is well positioned to become an active exploration area for hydrogen and other valuable element gases (e.g. He, inert gases), trapped in province's underground.

Sources of Natural Hydrogen

Over the last two decades, the occurrence of natural hydrogen and its sources have been discussed extensively in the scientific literature and raised continuous interest in industrial circles (Zgonnik, 2020; Milkov, 2022; Rigollet and Prinzhofer, 2022; Lodhia et al., 2024; Blay-Roger et al., 2024). Current research within both academia and energy industry is focused on geoscience exploration of possible underground accumulations and feasibility of adding natural hydrogen as an energy resource.

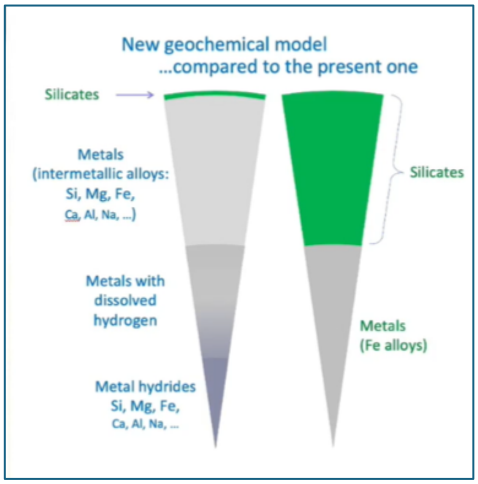

Figure 3: Evolving geochemical models of the earth

The emission of natural hydrogen and gas from surface seeps has been recognized for millennia. The permanently burning Olympic flame at Mount Olympus, Turkey, was first mentioned in antiquity (2500 BP) and now is estimated to comprise 7.5%–11.3% hydrogen (Hosgörmez, 2007). Another example is "Los Fuegos Eternos" (the eternal flames), discovered in the Philippines over two centuries ago with hydrogen concentrations of 41.4%–44.5% (Abrajano et al., 1990).

The first scientific mention of natural hydrogen dates to 1888, when Mendeleev, a Russian geochemist, and the father of the periodic table, reported hydrogen seeping from cracks in a coal mine in Ukraine (Zgonnik, 2020). Russian and Soviet petroleum geochemists were more inclined to measure for hydrogen in mines and boreholes as they were believers in a now discredited theory that oil and gas are synthesized from substantial amounts of primordial hydrogen reacting with the carbon present in rocks. In Canada, most petroleum geoscientists are followers of the competing organic theory of hydrocarbon generation. However, we cannot deny that deep crustal originating seeps of hydrogen and hydrocarbons were encountered on mines and superdeep boreholes located on crystalline shields, in volcanoes and at mid-ocean vents (e.g. Sherwood Lollar et al., 2002; Kutcherov and Krayushkin, 2010; Zgonnik, 2020; Figures 1 and 2).

During the 1970s and continuing in the 1980s, a race to drill deep into the Earth's crusts and eventually reach the Mantle, using advanced drilling technologies, occurred between the American and the Soviet scientists and engineers. Unlike the space race, this effort was won by the Soviets, benefiting from unlimited state funds and cheap workforce. Several boreholes were drilled in the Kola Peninsula within the Feno-Scandinavian Precambrian shield close to older mines. The deepest named Kola Superdeep Borehole SG-3 reached the record depth of 12,262 m in 1989 (Popov et al., 1999). This is still the deepest vertical borehole in the world. The technology used and results of drilling were a state secret until the collapse of the Soviet Union. SG-3 penetrated rocks over 2.5 billion years old and was stopped only when encountered elevated temperature (180 ^{0}C) and pressure made the Archean rocks behave more like plastic materials and the drilling equipment began to malfunction. Drilling the deep Kola holes, the most surprising discoveries were the presence of microscopic plankton fossils found 6 kilometres below the surface in Precambrian rocks, of liquid saline water at unexpected depths and of large amounts of hydrogen gas present at various depths (https://www.census.gov/history/pdf/kola-superdeep-usgs.pdf). The geologists assigned to the project wrote that the drilling mud returned from the borehole was "boiling" with hydrogen gas (Bodén and Eriksson,1988). The quantity of hydrogen gas was reported to increase with depth (Zgonnik, 2020). When this observation was communicated to the international geoscience publications and meetings, a vivid debate ensued on the origin of the natural hydrogen gas, encountered in the Kola wells and later at many other deep wells drilled in USA, Germany, Sweden, Finland, China.

With the advent of the anthropogenic climate change theory (end of 1980s) and especially after the signing of the Kyoto accord (1997), scientists and industry began to look for renewable, non-polluting, carbon free forms of energy. Geologically generated hydrogen started to be discussed and systematically researched, first where seepages occurred, on mid-oceanic ridges, surface circular features, major fracture zones and then in mines and wellbores (Apps and Van De Kamp 1993; Smith et al., 2005; Lollar et al., 2014: Larin et al., 2015; Prinzhofer et al., 2019; Moretti et al., 2021; Milkov, 2022; Lodhia et al., 2024).

Figure 4: **"Fairy Circles" in Western Australia.**

A major fault is just east of the string of circular depressions. Image of the Day for September 5, 2023, NASA, Landsat 9 — OLI-2.

Hundreds of hydrogen seeps have now been documented around the world. By measuring surficial gas emanations, scientists have concluded that many circular-like depressions found on land on all continents are due to seepage of hydrogen (Larin et al., 2015; Zgonnik, 2020; Moretti et al., 2021; Figure 4).

These widespread shallow, circular depressions, some devoid of vegetation and varying from meters to hundreds of meters across, have received the name of "fairy circles." They measure between tens and to hundreds of meters across and form when upward moving hydrogen reacts with minerals in underlying rocks, leading to slumping and supressed vegetation (e.g. Zgonnik et al., 2020).

Several of these features were systematically surveyed along the U.S. East Coast, Brazil, Western Australia, Namibia, Russia and elsewhere (Zgonnik et al., 2015; Prinzhofer et al., 2019; Moretti et al., 2021 a and b; Rezee, 2021; Frery et al., 2021; Figure 4). Researchers found that that hydrogen concentration grow with depth and varies periodically with season and time of the day. While not all observed fairy circles are related to hydrogen migration, the circular features can be considered as proxies of deeper accumulations of hydrogen and indicators of migration paths if anomalous amount of the gas is detected by sensors. While undoubtedly present, there is no systematic research study of these circular features in Canada to see if they associate with hydrogen emanations.

Extensive accounts of the geological controls on the sources of natural hydrogen have been made (Apps and Van De Kamp,1993; Smith et al., 2005; Zgonnik et al., 2015; Truche et al., 2020; Klein et al., 2020; Milkov, 2022; Arrouvel and Prinzhofer, 2021; Vidavskiy and Rezaee, 2022; Zhao et al., 2023; Knez and Zamani, 2023; Hutchinson et al., 2024; Lodhia and Peeters, 2024).

The present consensus is that sites for natural hydrogen presence include hydrocarbon-bearing basins, young organic-rich sediments, coal beds, fault zones, extrusive igneous rocks, alkaline igneous complexes, geothermal fields, intracontinental basins, crystalline basements, potash-bearing strata, salt-bearing strata, and belts and intrusions of ultramafic rocks.

According to Zgonnik et al. (2015) the geologically controlled sources of natural hydrogen can be grouped into four main families of processes:

a) Water hydrolysis processes (several processes that include the oxidation of ferrous minerals, radiolysis, cataclasis, and metamorphism)

b) Organic matter decay (including thermal maturation)

c) Methane and/or ammonia decomposition during metamorphism, and

d) Deep Earth degassing.

From our scientific literature research and own company's hydrocarbons and mineral exploration expertise, we conclude that there are three main subsurface viable sources of natural hydrogen, two hosted in the Earth crust and involving water, and one deeper in the Earth lower mantle and possible its core (Figure 5).

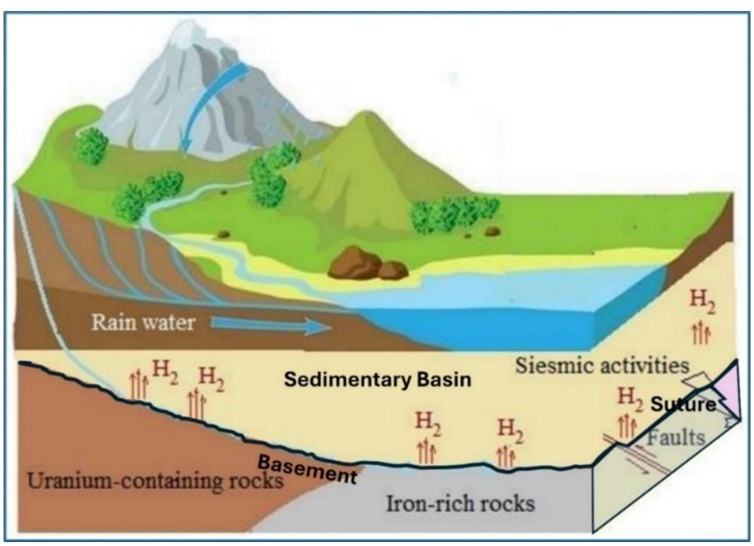

Figure 5: **Simplified diagram showing the three main sources of natural hydrogen**

Figure 5 illustrates the potential sources of hydrogen considered by our company to be present in Alberta's Precambrian Basement: 1. Ultramafic and other iron rich rocks 2. Basement geo-bodies enriched in Uranium and other radioactive elements, and 3. Deep fracture and suture zones reaching into the basin's sedimentary fill (modified after Knez and Zamani, 2023).

1. Serpentinization of mafic and ultramafic rocks. Mafic and ultramafic rocks are composed of mineral phases rich in iron–magnesium–calcium. These rocks comprise peridotites, encountered mostly in the Earth's mantle, and gabbros, found underground in the vicinity of volcanoes and in oceanic crust near mid-ocean spreading centers. Gabbros are also found on continental shields and within mountain chains, conserved in ophiolite and greenstone belts that mark locations of suture zones, sites where ancient oceans have closed during subduction and collision. Other known ultramafic rocks are dunites and kimberlites.

The main mineral in mafic and ultramafic rocks is olivine, which is a magnesium iron silicate with the general chemical formula $(MG,Fe)_2SiO_4$. Olivine gives its appellation to a large group of minerals that take a variety of names depending on the proportion of magnesium versus iron, or the presence of other element such as manganese, calcium, or nickel in the crystal structure. Hydrothermal water in the Earth's crust reacts with these ultramafic rocks, transforming Fe-Mg (iron-magnesium) silicates such as olivine, pyroxene, or amphiboles into serpentine minerals. One of the byproducts of this process is the production of free hydrogen. The overall reaction can be simplified to (McCollom and Bach, 2009; Truche et al., 2020; Zhao et al., 2023; Hutchinson et al., 2024; Blay-Roger et al., 2024):

$$6[(Mg_{1.5}Fe_{0.5})SiO_4](\text{olivine}) + 7H_2O = 3[Mg_3Si_2O_5(OH)_4](\text{serpentine}) + Fe_3O_4(\text{magnetite}) + \mathbf{H_2}$$

Hydrogen is freed from the rock formation creating serpentine and magnetite in the process (figure 3). Serpentinites are water-rich rocks that contain mostly serpentine-group minerals (chrysotile, lizardite and antigorite) (Sleep et al., 2004). The serpentinization geochemical reaction can be further simplified to the oxidation of ferrous (Fe^{2+}) to ferric (Fe^{3+}) iron by the reduction of water to hydrogen:

$$3FeO(\text{silicate}) + H_2O = Fe_3O_4 + \mathbf{H_2}$$

This is usually a fast and renewable reaction that generate natural hydrogen in subsurface. The alteration of Fe^{2+} bearing minerals is the most reported source of natural hydrogen seepages encountered at mid-oceanic ridges and in ophiolitic massifs, where mafic and ultramafic are altered (Zgonnik et al., 2015 and 2019; Deville and Prinzhofer, 2016; Zgonnik, 2020; Milkov 2022; Lodhia et al., 2024).

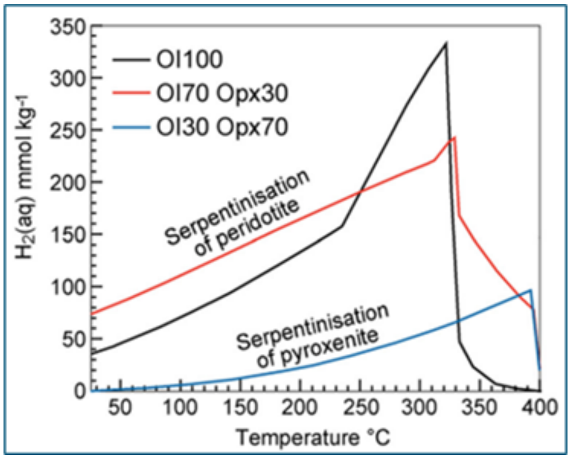

Figure 6: The serpentinization reaction

Modelled concentrations of hydrogen at equilibrium between ultramafic mineral assemblages and an aqueous fluid at a pressure of 50 MPa (corresponding to a depth of approximate 2 km) as a function of temperature. Water–rock ratio is unity. Ol100 = 100% olivine; Ol70 Opx30 = 70% olivine 30% pyroxene; Ol30 Opx70 = 30% olivine 70% pyroxene. Source: diagram adapted from Klein et al. (2013) and illustration reproduced from Hutchinson et al. (2024).

The primary controls on serpentinization, and therefore of the rates and volumes of hydrogen production, are petrological composition of the ultrabasic geobody, olivine composition (Fe versus Mg), effective grain size, temperature, and water–rock ratio to (Hutchinson et al., 2024). According to Klein et al. (2013), serpentinization can proceed over a wide range of temperatures, but the ideal temperatures for large hydrogen production rates and volumes lie between 200 - 300°C (Figure 6).

Beside direct measurements of hydrogen in natural seeps and subsurface hydrocarbon reservoirs located in vicinity to ultramafic rocks, serpentinization reactions with production of hydrogen has been demonstrated in laboratory experiments (Milkov, 2022). Moreover, patents have been obtained or applied for technologies meant to industrially stimulate in-situ production of hydrogen from underground ultramafic rock formations and use drilling and extraction technologies borrowed from the oil industry (Knez and Zamani, 2023). It is estimated that the serpentinization process produces approximately 80% of the world's natural hydrogen, freed when seawater interacts with ultramafic igneous rocks continuously created as new ocean floors or when subterraneous water reacts with uplifted and exposed fragments of oceanic crust and underlying upper mantle.

2. Radiolysis of water. Radiolysis is the splitting of chemical molecules under the influence of natural or induced ionizing radiation. The dissociation of chemical bonds happens when a strong energy flux is directed to a certain chemical substance. The radiolysis of water is a phenomenon known for more than one century and it is well understood (Draganić, 2005). Radiolysis can be produced in laboratories and specialised plants, and takes place naturally in the atmosphere, hydrosphere, and Earth's subsurface (Draganić, 2005; Le Caër, 2011).

The primary sources of natural radioactivity in rock and soil are radionuclides of the uranium, thorium, and potassium (referred to as radioelements), specifically the uranium-238, thorium-232, and potassium-40 decay chains. In certain geological settings, hydrothermal water and these long-lived radioactive elements are in contact, and a fission chain process may be triggered (Figure 3). In the presence of water, rocks containing minerals with relatively high concentrations of these radionuclide elements are subjected to radiolysis, with hydrogen and helium generated during the long geologic time the process is active. Soils and clastic sedimentary formations mirror the radioelement concentrations of their parent rock and may be subjected to radiolysis.

The natural radiation intensity of soil and rocks depends upon their mineralogical composition. Granitic rocks and their erosional derivatives composed of minerals with high concentrations of uranium, thorium, and potassium have high natural radioactivity. Minerals with high radioactivity include Autunite (hydrated calcium uranium phosphate), Brannerite (uranium titanate), Carnotite (potassium uranium vanadate), Monazite (a mixed rare earth and thorium phosphate), Thorianite (thorium dioxide) and Uraninite (uranium dioxide). Accessory minerals found in granitic rocks, including orthite, apatite, zircon, and sphene, generally have higher concentrations of thorium and uranium. In addition, the rock-forming minerals in granite, such as feldspar and mica, are abundant and rich in potassium.

These minerals are usually present in trace concentrations, disseminated in the rock matrix or as veins. More rarely, they are concentrated in mineable orebodies within granitic intrusive rocks or in granite wash rock type (sandstones and conglomerates). Radiolysis of water in subsurface happens when alpha, beta and gamma particles are released in the radioactive decay of U-, Th- and K-bearing minerals (Parnell and Blamey, 2017; Truche et al., 2018; Wang et al., 2019; Zgonnik, 2020; Sauvage et al., 2021; Milkov, 2022). Energy released from the decay of these radioactive elements dissociates water molecules (Figure 7).

Exposed to natural radiation, water breaks down into hydrogen radicals, hydrogen peroxide, free electrons, hydroxyl (OH) radicals and various other ions and minor compounds. The water radiolysis take place in three stages (Le Caër, 2011; Figure 7).

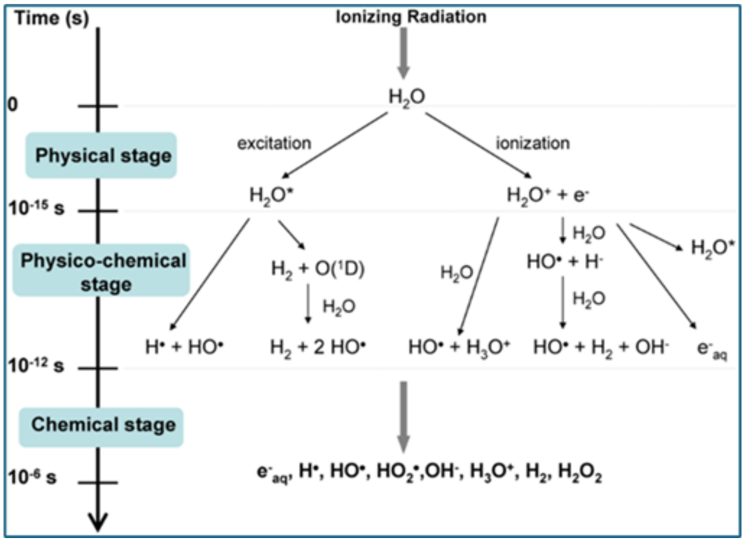

Figure 7: Main reactions pathways for hydrogen formation thru radiolysis

Figure 7 describes the main reactions occurring during the three stages of water radiolysis described by Le Caër (2011). Ionizing radiation stems from the decay of radioactive nuclei such as Uranium, Thorium, Potassium, etc.

When ionizing radiation passes through water, it leads to the formation of ionic and excited states, which further decompose or recombine to produce radical and molecular species according to the following equations (Pastina and LaVerne, 2001; Lin et al., 2005; Wang et al., 2019; Milkov, 2022):

H_2O (water) +ionizing radiation → $H\cdot + OH\cdot + H+ + OH^- + e^-$ + minor components

$e^- + \rightarrow e^-_{aq}$ (hydration)

$e^-_{aq} + H+ \rightarrow H\cdot$

$e^-_{aq} + e^-_{aq} + 2H_2O \rightarrow H_2 + 2OH^-$

$e^-_{aq} + H\cdot + H_2O \rightarrow H_2 + OH^-$

$H\cdot + H_2O \rightarrow H_2 + OH\cdot$

$H\cdot + H\cdot \rightarrow \mathbf{H_2}$

Measurements of groundwaters in Precambrian cratons show that they consistently contain hydrogen in variable percentage together with other gases including abiogenic methane (Etiope and Sherwood Lollar, 2013; Sherwood Lolar et al., 2014). This hydrogen content is attributed to the long-term radiolysis of water due to natural radioactivity (Lin et al., 2005: Sherwood Lollar et al., 2007 and 2014; Parnell and Blaney., 2017; Zgonnik, 2020; Milkov, 2022).

In summary, radiation generated within the granitoid family of rocks (granite, granodiorite, sienites, etc.), which contains radioactive elements such as U, Th, K, dissociates the underground extant water with liberation of hydrogen. Likewise, radioactive decay of granite and other rocks in Earth's interior provides sufficient energy to heat the water (Hand, 2023). Underground water was encountered in deep wells up to 8 km depth (Zgonnik, 2020). Radiolytic production is the second important physico-chemical process that generates natural hydrogen in subsurface.

3. Deep Earth degassing. Degassing of primordial hydrogen has been present in the Earth since its formation (Larin, 1993; Gilat and Vol, 2005, 2012; Larin et al., 2015; Yang et al., 2016). Larin (1993 and earlier in Soviet literature), hypothesized that the Earth's core consists of iron and silicon hydrides and thus contains a significant amount of hydrogen, which is gradually released and seeps into the atmosphere (Figures 3 and 5). But the theory of this vast, deep store of hydrogen is still controversial. However, there are clear records and indications that streams of hydrogen generated in the deep crustal-upper mantle, and even lower crust-core regions may rise in the melts and then along major faults, suture zones, volcanoes, plate boundaries, failed rift zones and present-day central axis of mid-ocean ridges (Larin et al., 2015; Zgonnik, 2020; Lefevre et al., 2022; Milkov, 2022 and Figure 5).

While hydrothermal water was found in the superdeep SG-3 Kola well up to 8 km depth, hydrogen was recorded in the borehole down to the well bottom at 12,262 m, implying a deeper source than a hydrolysis process (Popov et al., 1999; War et al., 2019; Zgonnik, 2020). Changes in the in the crust’s stress regime may lead to fault movements and earthquakes. It is well-known that hydrogen emanations were recorded along crustal faults before and during major earthquake activity. Also, the circular depressions identified in many world locations are often associated with major, deep penetrating faults (Zgonnik et al., 2015; Prinzhofer et al., 2019; Moretti et al., 2021 a and b; Frery et al., 2021: Rezee, 2021; Lodhia et al., 2024).

Hower, up to now, deep Earth degassing is considered only a minor source of natural hydrogen, as no accumulation was encountered that can be entirely attributed to primordial hydrogen. Discriminating between deep mantle and crustal /shallow originating hydrogen is done using isotope ratios as mantle hydrogen is characterised by specific isotopic signatures, such as high $^{3}He/^{4}He$ and low D/H ratios (Milkov, 2022; Lodhia et al., 2024).

Other sources of natural hydrogen. While the above three main sources are mentioned by most researchers and tracked by hydrogen prospectors, many other likely origins of geologic hydrogen were discussed, mostly by academia. Milkov (2022) lists twenty-four natural abiotic, four natural biotic and four anthropogenic hydrogen generating processes, all well documented by field or laboratory experiments.

Among these, pyrolysis is another suggested hydrogen generator source. This is a thermal chemical process responsible for transforming organic matter into simpler compounds at high temperature and in absence of oxygen. In sediments such as organic-rich shales, under elevated pressure and temperature (300 - 600 °C), which can happen during metamorphism, near magma chambers or active volcanoes, kerogen via pyrolysis will release hydrogen gas. Several authors have stated that "hydrogen is prolifically generated from overmature organic matter in shales and coals," and after hydrocarbon generation is over (Parnell and Blamey, 2017; Horsfield et al., 2022). Similarly, breakdown of methane (CH_4) will form graphite and hydrogen at high (>600◦C) temperatures during metamorphism (Parnell and Blamey, 2017; Truche et al., 2018; Milkov 2022).

Other processes of generating hydrogen in subsurface discuss in literature are hydration of biotite in felsic rocks such as granite, hydration of siderites, oxidation of Fe^{2+} from magnetite to Fe^{3+} to hematite in presence of water, weathering of iron banded formations, fault plane commination and release of hydrogen from fluid inclusions (Zgonnik, 2020; Milkov, 2022 and his references; Arrouvel and Prinzhofer, 2023; Lodhia et al., 2024).

Anthropogenic processes causing false tests may occur more often than suggested and need to be avoided during exploration as the non-geologic hydrogen produced is very local and quantitative uneconomic (Knez and Zamani, 2023; Hogg, personal communication, August 6, 2024).

Figure 8: University and institute study groups for natural hydrogen[8].

Natural Hydrogen Exploration

Natural hydrogen exploration projects are increasing around the world as a credible alternative to hydrocarbons (Rigollet and Prinzhofer, 2022). The resource is huge, as shown by the USGS stochastic models in which natural hydrogen production reaches 50% of the forecast green hydrogen production by the year 2100 (Ellis and Gelman, 2022). According to USGS "model predictions based on known behavior of hydrogen in the subsurface and geologic analogues indicate a global resource potential in the millions of megatonnes, which could meet projected demand for thousands of years" (Ellis, 2023),

The presence of naturally occurring hydrogen has been researched and documented in many of world's geologic environments since the beginning of 20st century. However, out of the millions of oil and gas wells that have been drilled to date in the world's sedimentary basins, only a few, including in Alberta, have tested hydrogen in substantial quantities, but none have been declared a stand-alone hydrogen discovery.

Mali Discovery. While drilling a shallow location for water in 1987, in a remote village in Mali, a surprising discovery was made when the well produced a flow of flammable gas. Two decades later, Petroma, a Canadian registered oil company, returned to the site looking for hydrocarbons and found that the well contained hydrogen at a proportion of almost 98%, with minor parts methane and helium (Brière and Jerzykiewicz, 2016; Brière et al., 2017). The discovery well had an approximate flow rate of 1,500 m^3 H_2/day. This is the first significant discovery of natural hydrogen in the world and the first one to be put to semi-industrial use. The company changed its name to Hydroma, built a natural hydrogen run pilot plant to electrify the village of Bourakébougou in 2012, and started geochemical and geophysical prospecting in the area around the discovery well. Hydrogen seeping out of circular depressions had been observed and measured in the vicinity of the discovery and subsequent drilling identified five geologic reservoirs containing nearly pure hydrogen gas (Prinzhofer et al., 2018).

[8] After Ball and Czado, 2024. https://geoscientist.online/sections/unearthed/natural-hydrogen-the-race-to-discovery-and-concept-demonstration/

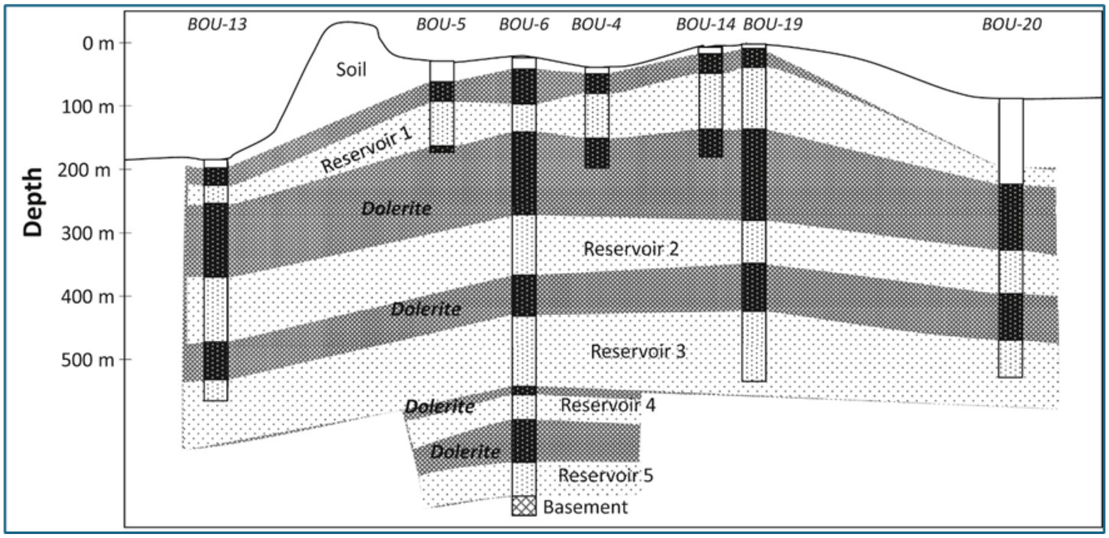

Figure 9: Cross-section of Bourakebougou hydgogen field

Figure 9 shows the cross-section of the Bourakebougou hydrogen field through several wells, including the representative, deeper Bougou#6 well (after Prinzhofer et al., 2018; Maiga et al., 2022).

Twenty-four other exploratory boreholes have demonstrated the presence of natural hydrogen in the Bourakebougou village's surrounding area but shown variable hydrogen content in individual wells ranging from 15% to 98% (Prinzhofer et al., 2018; Maiga et al., 2023 and 2024; Figure 8).

The discovery well Bougou #1 and subsequent 24 Hydroma wells are all in the Tamboura Subbasin, a shallow graben at the southwestern side of Taoudeni Basin filled with Neoproterozoic and lower Paleozoic sediments and Mesozoic volcanics (Figures 9a and b). The basement rocks are mostly granitic which are unconformable, and overlain by sedimentary formations of Neoproterozoic age, characterized by sandstone-pelitic formations and carbonates (Maiga et al., 2023). The Mesozoic dolerite intrusions crosscut both the basement and the Neoproterozoic sediments forming mega-sills in the drilled area. Dolerite or Diabase is a mafic, holocrystalline, subvolcanic rock equivalent to volcanic basalt or plutonic gabbro (Figure 9a and b).

The delineation wells drilled on a shallow, gentle anticline, have confirmed the presence of an extensive hydrogen field featuring at least five stacked reservoir intervals containing significant hydrogen that cover an estimated area well superior to 8 km in diameter, i.e.~50 km^2 (Prinzhofer et al., 2018). The Bougou #6 borehole is the most characteristic for the field and terminated in the basement at 1800m (Figures 8, 9a and b, and 10). The hydrogen recorded in the well may be sourced either through hydrolysis from the granitic basement or from oxidation of Fe^{2+}-rich rocks such as dolerites and/or Precambrian banded iron formations, associated with water reduction.

According to Maiga et al. (2023 and 2024), the shallowest main reservoir showing the highest content of hydrogen is a dolomitic carbonate, largely karstified and showing variable porosity (0.21–14.32%).

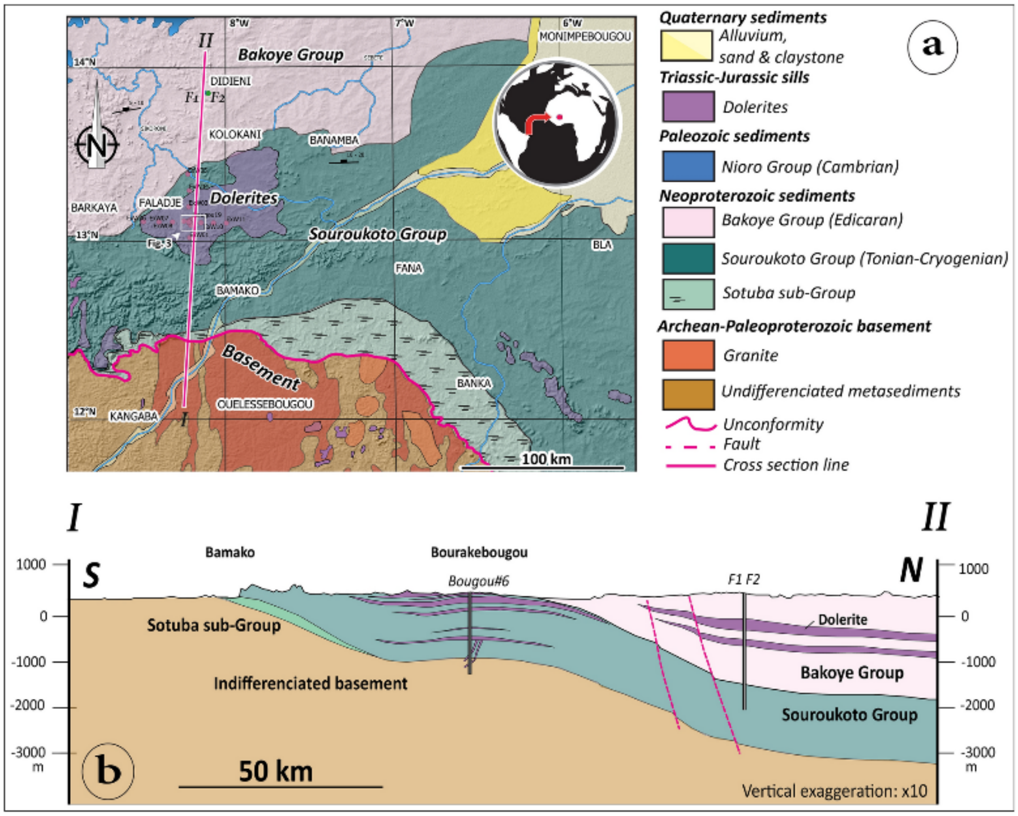

Figure 10: Location and surface geology of Bourakebougoo Area, Mali

Figure 10 shows the location and surface geology of the Bourakebougou area, Mali, where the first hydrogen deposit was discovered; b) Simplified geological cross-section through Bougou#6 borehole and environs (after Maiga, 2023).

The accumulation of hydrogen occurs in the karst voids representing secondary porosity in the carbonate rock. Other deeper reservoirs are porous sandstone rocks with homogeneous porosities (4.5–6.4%). High hydrogen content was also detected in the basement rocks. The neutron porosity tool used for logging is the main indicator of hydrogen presence in reservoirs (Figure 10). During exploitation for electricity generation, the initial pressure in the discovery well never decreased, suggesting that the hydrogen reservoir is a dynamic system, and reservoirs are progressively recharged in hydrogen-rich gas at the production timescale. In the field, water helps in the hydrogen migration and entrapment process, as it is located above the hydrogen phase. Thus, the shallowest aquifer might also trap the hydrogen, alongside the diabase sills (Prinzhofer et al., 2018).

Provisory resource calculations for the Malian Bougou hydrogen field were computed by Chapman Petroleum Engineering of Calgary (CPE), which also provided geoscience technical support to Hydroma (Brière et al., 2017; Hand, 2023).

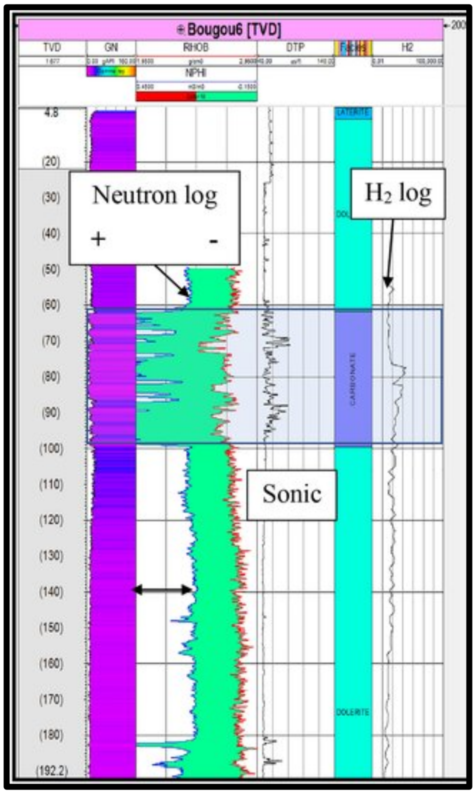

Figure 11: Neutron porosity log indicated hydrogen filled secondary porosity in karstified carbonate

(drilled and cored at Bougou#6 well (after Maiga et al., 2023))

According to Brière, the field is large containing at least 60 billion cubic meters of hydrogen, or about 5 million tons, trapped by sills of dolerite rock (Hand, 2023). Due to relatively low production at around 5 tonnes per year, as well as political instability in the country, and lack of committed capital, this natural hydrogen field remains undeveloped as of 2024 (Hand, 2023). More laboratory studies and geoscience work are ongoing.

Recent Hydrogen Exploration

The modern exploration for natural hydrogen accumulations for industrial use has truly started when the Mali discovery was made public, and several articles were presented, published, widely distributed, and cited (Brière and Jerzykiewicz, 2016; Prinzhofer et al., 2018). Since then, the number of papers on natural hydrogen has grown exponentially. For many decades before the Mali discovery, scientists were aware of the presence of hydrogen as emanations from mid-ocean ridges, land seepages, rift systems, ophiolite belts, fault planes, mines, abandoned hydrocarbon wells, mineral boreholes, hydrothermal springs, etc. A number of authors made inventories of word locations and presented global or regional maps of occurrences of geologic hydrogen (Lollar et al., 2014; Prinzhofer et al., 2018 and 2019; Zgonnik 2020; Milkov, 2022; Lefevre et al., 2022; Blay-Rogers et al., 2024; Lodhia et al., 2024 and Figure11).

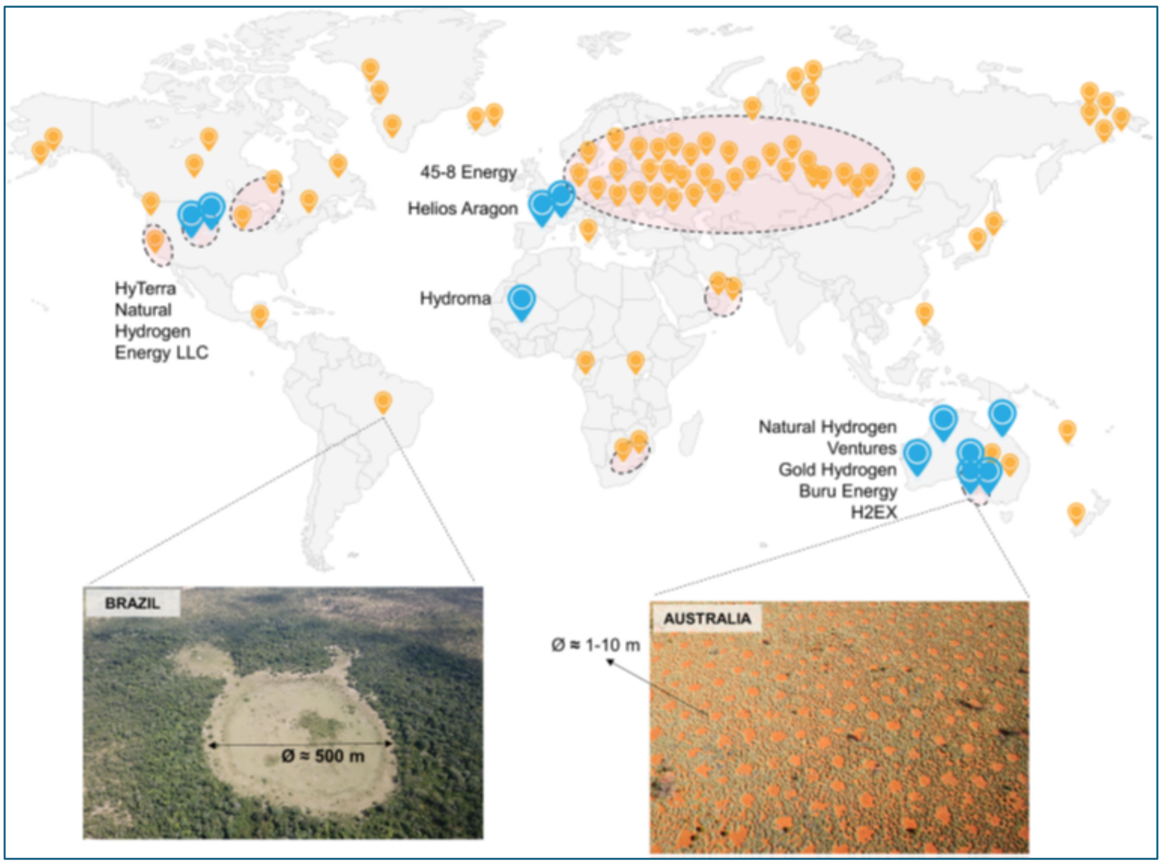

Figure 12: Locations of known natural hydrogen occurrences and "fairy circles" shown only for Brazil and southeastern Australia

(after Prinzhofer et al., 2019; and many other sources). Activity area of several commercial startup enterprises, some discussed in this section, are also indicated in blue dots. Reproduced from Blay-Rogers et al., (2024).

In recent years, exploration startups have been rushing to find drilling location for hydrogen in France, Australia, Spain, Morocco, Brazil, Canada and, in the USA, in Nebraska, Arizona, and Kansas states (Figure 9). Bill Gates has joined the hydrogen search, making a major investment in a Colorado based start-up Koloma, which is exploring for hydrogen along the 1,900 Km Mid-Continent Rift south of Lake Superior, through Wisconsin and into Kansas.

Research and geoscience exploration also take place in Africa, in Mali, greenstone belts in the West African craton, Morocco, Djibouti, Oman, Turkey, Tanzania and Namibia; in Europe in Pyrenees, Aquitaine Basin, Corsica, the Alps, Greenland, Albania, Serbia, Montenegro, Poland, Ukraine, Russia, and Iceland; in South America: Brazil and Colombia; in Australia: Amadeus, Adelaide Rift and Perth basins and Asia in Philippine, China, India, S. Korea, Kazakhstan and others (Ellis, 2023; Lodhia et al., 2024; Hnat 2024 - Program-2024 and Figure 11). Every month there are new articles published or conference presentations on newfound locations around the globe with indications of natural hydrogen occurrence associated with favourable rock formations. Rystad Energy research shows that at the end of 2023, 40 companies were searching for natural hydrogen deposits, up from just 10 in 2020 (https://www.rystadenergy.com/news/white-gold-rush-pursuit-natural-hydrogen).

Prospectors are searching for hydrogen deposits in cratons, the ancient cores of continents, where trapped within crystalline or sedimentary rocks are iron-rich greenstone belts, remnants of ocean crust squeezed between the cratons in ancient continental collisions. They also look for exposed or buried granitic terranes that have high content in radioactive minerals to enable radiolysis processes in contact with underground aquifers. The search is extended to mountain ranges that include ophiolite belts or sedimentary basins underlined by old crystalline shields. Following, are some recent example of hydrogen discoveries and follow up exploration in such geological settings.

Australia. The Commonwealth of Australia is one of the world’s most prospective locations for natural hydrogen due to its old geology, including a vast Precambrian shield, Paleozoic basins, and presence of cap rocks such as salt, shale, and dolerites.

The Australian government has intensely promoted the hydrogen exploration drive. Since 2019 the country has had a National Hydrogen Strategy and Geoscience Australia, the agency of the Australian Government that conducts geoscientific research, has a leading involvement. Australia had early R&D natural hydrogen targeted programs through organization such as Geoscience Australia, Geological Survey of New South Wales, CSIRO, Mineral Resource Tasmania, state universities etc., who carried out field and laboratory research and extensively published on the hydrogen subject (Rezaee, 2021; Boreham et al., 2021; Frery et al., 2021; Vidavskiy and Rezaee, 2022; Lodhia and Peeters, 2024). Geoscience Australia maps the resources necessary for the net zero transition and strive to create free satellite data products for the benefit of the country. Several Australian state authorities have recently amended their petroleum exploration licensing to include natural hydrogen. The country has a high drive for becoming the leader in the natural and manufactured hydrogen global market. In every tectono-structural unit of the continent, numerous "fairy circles" together with high concentrations of hydrogen in seepages were identified. Hydrogen content indications are also present in oil and gas and mineral wells, and in active or abandoned mines (Frery et al., 2021; Rezaee, 2021; Vidavskiy and Rezaee, 2022, Lodhia et al., 2024).

The Australian Continent geology is dominated in the western-central portion by a large Neoproterozoic shield comprising several exposed craton areas, large sedimentary basins, and a few fold belts. In the eastern part there are Paleozoic accreted arc systems docked to the continent during several orogeny (Figure 12).

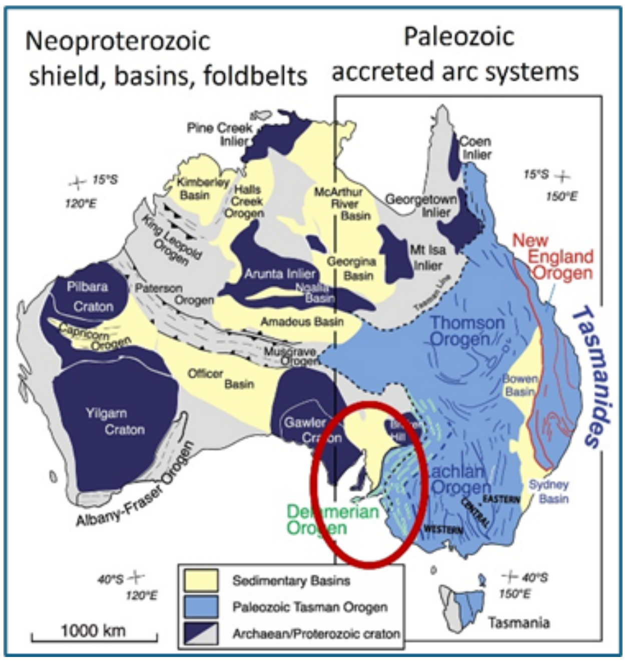

Figure 13: Major structural units of the Australian continent showing cratons, basins, fold belts and accreted terranes

(modified after (https://earthscience.stackexchange.com/). The brown ellipse shows the area where Gold Hydrogen Ltd is actively exploring for natural hydrogen in the Gawler Craton and Stansbury Basin, part of the Adelaide Rift Basin of Southern Australia.

The Gawler Craton (dark blue in Figure 12) contains old and very old basement complexes that comprise ca. 3150 Ma granites and granite gneisses, along with ca. 2555–2480 Ma supracrustal sequences that include mafic and felsic volcanics and mafic and ultramafic volcanics. These basement complexes are overlain by Paleoproterozoic volcano-sedimentary successions deposited between ca. 2000 and 1740 Ma. The Adelaide Rift

Complex (yellow in Figure 12) comprises a series of rift and sag basins initiated during the Neoproterozoic at ca. 820 Ma and continued into the early Cambrian. This rifting was related to break up of the supercontinent of Rodinia, formed about 1.2 B years ago and disassembled from 825 Ma to 740 Ma.

Since 2021, Southern Australia (SA) has witnessed intense hydrogen exploration in the Gowler Craton and especially in the Adelaide Rift Basin (Figure 12). Natural hydrogen exploration became possible in Southern Australia starting in February 2021 when changes to the Petroleum and Geothermal Energy Regulations 2013 added hydrogen as a "regulated substance" and this enabled grant of exploration licenses targeting natural hydrogen.

Earlier, prerequisites of hydrogen presence in the subsurface of Southern Australia were investigated and discussed in scientific publications. Thus, Zgonnik (2020) found and discussed records revealing significant hydrogen contents from analyses of gas samples taken from historic South Australian drillholes: American Beach Oil 1 drilled in 1921 (64.4-80% H_2) and Ramsay Oil Bore 1 drilled in 1931(51.3-84% H_2), both abandoned and located in Stansbury Basin. Stansbury Basin is a branch of the Adelaide Rift Complex filled with Early - Middle Cambrian sedimentary formations. Moretti et al. (2021) suggested that salt lakes on Yorke Peninsula and Kangaroo Island were natural hydrogen seeps appearing as circular depressions known as "fairy circles".

Gold Hydrogen Ltd., a company registered in Brisbane, has a large exploration license (PEL) for the Yorke Peninsula and Kangaroo Island in South Australia, where hydrogen was discovered by chance during hydrocarbon exploration in the 1930's. Iron and uranium mines in the area point to the existence of source rocks needed for both serpentinization and radiolysis. In 2024, after reviewing older geoscience data and collecting new ones, Gold Hydrogen drilled two wells in the southern Yorke Peninsula/Stansbury Basin in the vicinity of the hydrogen rich Ramsay Oil Bore 1. The 2024 drilled Ramsay 1 is the first dedicated natural hydrogen exploration well in Australia, penetrating to 1.8 km depth into the Precambrian basement (Figure 13).

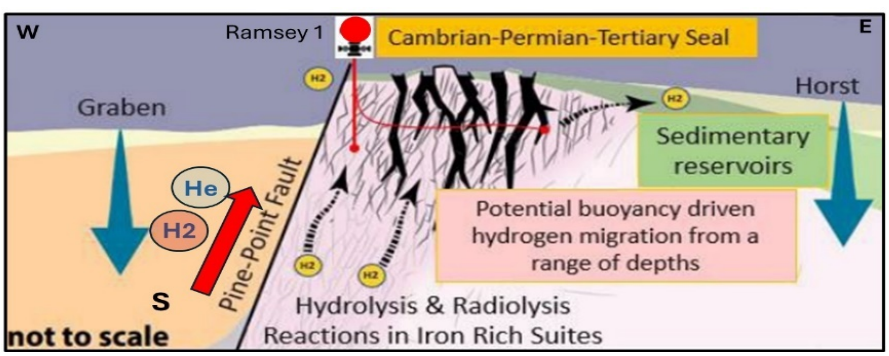

Figure 14: Schematic geologic cross-section showing location of Ramsay 1 well on the Yorke horst.

Also shown are the Precambrian fractured basement and Cambrian section. Arrows indicate possible provenance of hydrogen and helium, now encountered in carbonate formations and fractured basement (modified after Gold Hydrogen - Non-Deal Roadshow).

Their new Ramsay wells targeted the Cambrian Parara and Kulpara limestone formations and terminated in the fractured granite basement. The granite basement is both iron and uranium rich. This means the hydrogen can be the result of either radiolysis – splitting of water due to radiation from Uranium decay – and/or hydrolysis – oxidation of iron-rich mineral upon contact with water. The fractures in the basement and micro fractures in the limestone provide good porosity and permeability. The Kulparara dolomite formation tested in the Ramsay 1 and Ramsay 2 wells have resulted in natural hydrogen and helium being detected at surface with high purity levels of 17.5% helium and 95.8% natural hydrogen (air corrected). The origin of both gases can be explained by hydrolysis and radiolysis processes in the iron-rich basement or from deep mantle sources using the fault system (Figure 13). Isotope studies are ongoing at CSIRO and other world laboratories to obtain convincing data on the provenance of the gases (crustal versus mantle origin).

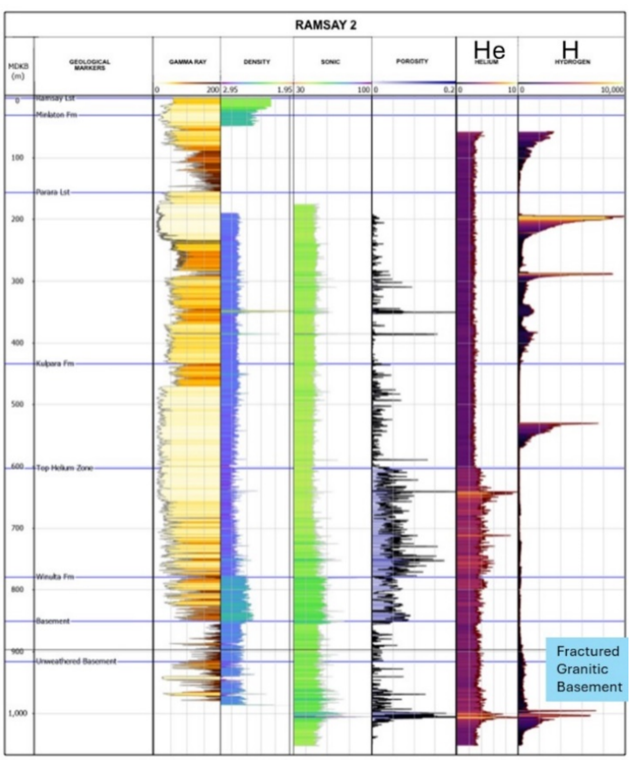

Figure 14 : Geologic formations, well logs, and helium and hydrogen content in the Ramsay 2

Well drilled in 2024 by Gold Hydrogen on Yorke Horst, Southern Australia (modified after Gold Hydrogen web presentation).

The existence of a helium system in the Yorke horst represents an important added value to the Ramsay Project. Unlike hydrogen, helium cannot be easily manufactured and presently is a commercially valuable commodity. According to company news releases the results of testing the two well confirm that the “Ramsay Project has significant potential to be a commercially attractive Natural Hydrogen and Helium producer.” New seismic data collected in the 2024 (570 Km of 2D survey), has confirmed several structural highs that will be evaluated in the future. A collaboration with the Japanese investment company Mizuho is ongoing. Gold Hydrogen intends to build a pilot plant for the separation of hydrogen and helium and commercialization of these products.

Further potential exists in Western Australia that has all the required elements to support natural hydrogen generation and accumulations. The Archean Yilgarn Craton (Figure 12) has abundant iron-rich rocks and ample mafic to ultramafic dykes. A complex set of fault systems that can become migration pathway for the generated gas was mapped in the region. Banded iron formation and good reservoirs are in the Eocene cover of the craton and numerous circular features like the ones present in Southern Australia have been mapped (Rezaee, 2021).

France. In Folschviller, Lorraine Basin, geologists studying coal bed methane in a former mining area, measured a large volume of hydrogen in the FOLS1A stratigraphic borehole drilled in 2006 (Pironon and de Donato, 2023). Lorraine Basin is a sedimentary basin of Carboniferous (Westphalian to Stephanian) age located on the border between France and Germany. The Paleozoic basin is covered by the younger formations of the country-wide Mesozoic Paris Basin. The Lorraine Carboniferous basin extends in the Saar region of Germany and is known for its past active coal and iron mining and steel fabrication.

Figure 15: The downhole SysMoG™ probe

The downhole SysMoG™ probe is made by Solexperts which was used to analyse in- situ the gas dissolved in formation water. The probe sampled gas contained in rock formations at different depths in the FOLS1A well.

At 1,250 m depth in the FOLS1A well, hydrogen represents 18% mol of the gas mixture and dissolved concentration in waters is around 3.7 mg/L. The hydrogen concentration increases with depth giving authors hope for reaching concentration of about 60% mol (30.8 mg/L) at 3 km depth (Pironon et al., 2024). The tests were done in collaboration with the company Solexperts, using their SysMoG™ probe, an innovative tool which allowed in situ measurements of the gas dissolved in formation water (Figure 15).

The Lorraine-Saar Basin has iron-rich clastic formations. Fe^{2+} in siderite ($FeCO_3$, iron carbonate) and ankerite ($Ca(Fe,Mg,Mn)(CO_3)_2$, minerals found in these clastic formations, may reduce water in hydrogen at deeper levels of the Carboniferous, as shown by the chemical equation:

$3FeCO_3+H_2O=Fe_3O_4 + 3CO_2+\mathbf{H_2}$

While this was the author's initial preferred hydrogen generation process, hydrogen genesis from subbituminous hard coal (houille) cannot be excluded, as the Carboniferous sequence in the area include 50-71 coal beds, 310 Ma old (Pironon and de Donato., 2023; Pironon et al., 2024). The detection of gas dissolved in the formation waters revealed at depth >800 m the presence of a mixture dominated by methane and hydrogen (Michels, 2014). It is known that chemical processes of organic matter that form coal can release methane and can produce hydrogen (e.g. Zgonnik, 2020; Milkow, 2022). The most recent presentations on the Folschviller gas build up indicates that the natural hydrogen originates from coal beds located at more than 3000 m depth (Pironon et al., 2024; Michels, 2024).

Based on the assumption that concentration of hydrogen in the deposit will increase linearly with depth and hydrogen concentration extends to the entire coal basin, Pironon and de Donato (2023) estimated that the Folschviller deposit may contain contingent resources between 46 million to 260 million metric tons (several years' worth of world's 2020s hydrogen production). Deeper drilling, delineation drilling and more tests will be needed to confirm the contingent size of the find.

In 2023, President Emmanuel Macron of France said his government would provide incentive funds to research and explore for natural hydrogen.

Spain. Helios Aragon, a startup pursuing hydrogen in the foothills of the Spanish Pyrenees, was founded by geoscientists on old data showing 25% hydrogen in the gas tested by Monzon-1 well, drilled in 1963 to a depth of 3.7 km by the National Petroleum Company of Aragon. The hydrogen show was in a good quality sandstone reservoir overlain by a thick salt section. Helios Aragon now owns exploration permits in Spain's Aragon region and will drill Monzon-2 appraisal well in 2024 at a cost of € 12 million to a depth of approximately 4,000 m (Figure 16). Resource estimates for the well are 1.1 million tons of hydrogen, and the company claims the Monzon field holds 5 to 10 million tons within its permits. Additional locations were identified on seismic and gravity data.

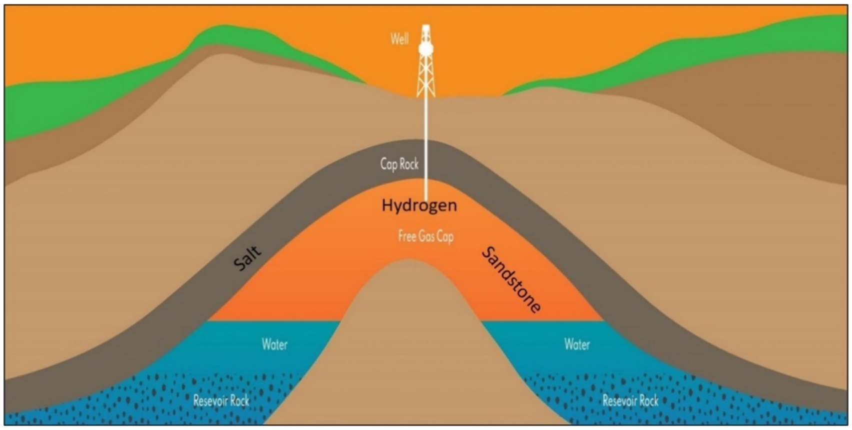

Figure 16: Monzon-2 well

Drilling location for Monzon-2 well and conceptual trapping mechanism for hydrogen in a sandstone reservoir located in the Pyrenees foothills (modified after https://helios-aragon.com/)

The company owners, their scientific advisers (U of Durham, U of Oxford, and Squire Patton Boggs) and investment partners (US based Ascent Funds Management LLC) believe that they found an ideal site for hydrogen exploration. In the core of the Pyrenees there are iron-rich mafic rocks, squeezed and lifted when the Iberian Plate rotated eastward, closed an ocean arm, and rammed into France block about 65 million years ago. The prospect is based on the concept that hydrogen produced at depth from ultramafic rocks migrates upward along deep faults and feeds into a porous sandstone layer, which is capped by salt (Figure 16). The company is drilling on an oil and gas lease, as for now, Spain does not have regulation for the exploration and production of hydrogen. Several other legal aspects are not resolved. Recently Helios has expanded their hydrogen search into the UK, Poland, and Oman.

USA. The first pure hydrogen exploration well in the USA, Hearty NE3, was drilled by **Natural Hydrogen Energy LLC (NH2E)**, near Geneva, Nebraska. Viacheslav Zgonnik, a geochemist who worked on hydrogen research both in Ukraine and US and publish on natural hydrogen (Zgonnik et al., 2015 and 2019; Zgonnik, 2022) is the Co-founder and CEO of the small private NHE company funded in 2012 and headquartered in Denver, Colorado. After analysing geoscience data both old and new to assess the regional and local geology, the Hoarty NE3 well was spudded in 2018 in the middle of a” fairy circle” and in February

2019 successfully drilled to 3.4 km depth (Figure 17 and 18). The now shut-in Hoarty NE3 well that targeted Precambrian basement rocks is located close to deep faults that might connect at depth to basement and intersected sedimentary formations within the Mid-Continent Rift zone (MCR). The publicly available well results shows that hydrogen and helium were encountered, and that company completed swab testing in 2022. Published accounts report that hydrogen was present in the flare and drilling mud in significant quantities.

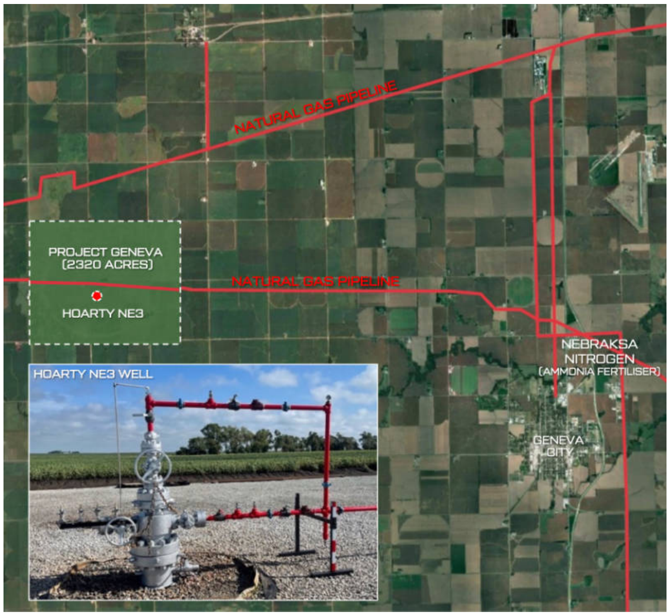

Figure 17: Location and wellhead of Hoarty NE3 well in Nebraska

Mid-Continent Rift System. https://stockhead.com.au/energy/hyterra-in-pole-position-as-natural-hydrogen-emerges-in-2023/

NHE did not published details on the hydrogen flow test and size of resource, but in April 2022, the Australian company HyTerra bought a 15% stake in the operation to earn 51% of the find. A HyTerra presentation says gas from the well “burned with a clear flame” a further indication that hydrogen is predominant in the gas mix. Extended testing was performed by the two companies including measuring gas composition, pressure, and flow rate, but up to now results are confidential.

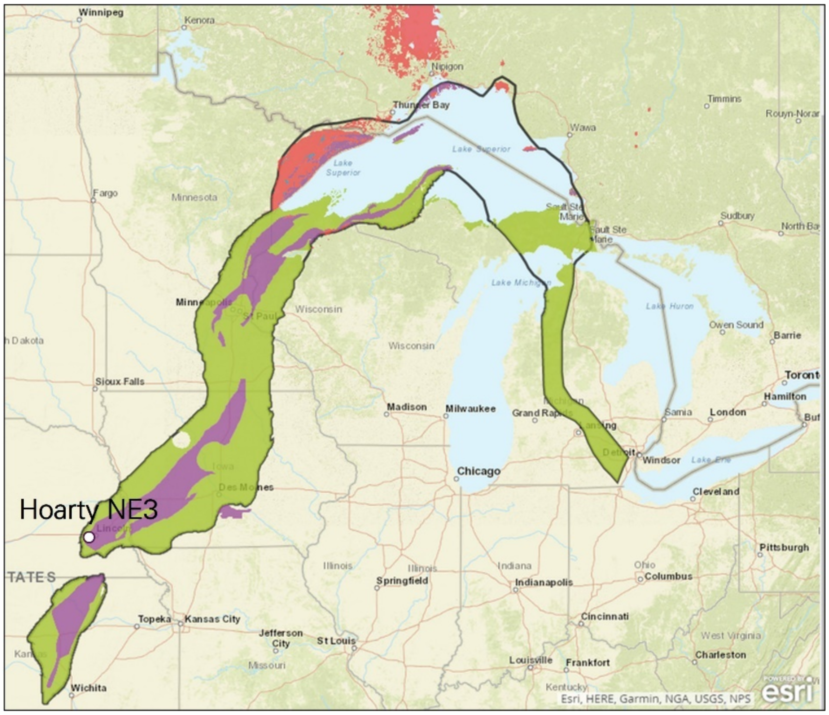

Figure 18 : **Mid-continent rift system**

The 1.1-billion-year-old Mid-Continent Rift System straddling the central Canada and USA is outlined in black line. Mostly gabbroic intrusive rocks are in red, mostly basalt and lesser rhyolite lava flows volcanic rocks in purple and sedimentary rocks in green (Mineral Deposits of the Midcontinent Rift System (usgs.gov).

HyTerra. HyTerra registered in Subiaco, a suburb of Perth, Western Australia, and was the first company to list on the ASX with a focus on natural hydrogen. The company is also searching for hydrogen in the USA, where according to a spokesperson, operating conditions are better than in Australia and a vast archive of exploration data is available. The company's main projects are Project Geneva in Nebraska (farm-in into NHE lands) and Project Nemaha in Kansas, situated respectively on the western and eastern margins of the Mid-Continent Rift System. Under the southernmost part of the MCR, the Salina Basin is underlain by an iron-rich basement widely considered to be the source of the historic hydrogen occurrences in the hydrocarbon or mineral wells (Figures 18 and 19).

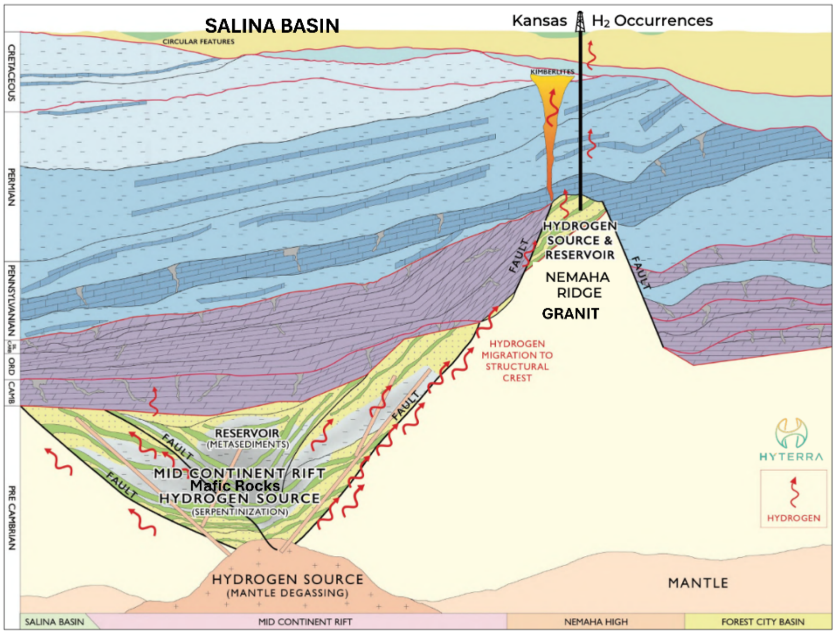

Figure 19: HyTerra potential structural play for hydrogen on top of Nemaha Ridge showing migration of hydrogen from the MCR mafic rocks

(modified after HyTerra presentation).

In addition to its joint venture with NH2E (Project Geneva), HyTerra assembled a portfolio of 100% owned and operated lease holdings on the Nemaha Ridge (Figure 19), totalling 21,044 hectares. Within this acreage at least ten historical recorded occurrences of natural hydrogen exist, one testing up to 92% hydrogen. Nemaha Ridge is the most prominent structural high in the region and could be a focal point for hydrogen migration. (Figure 19). An independent prospective resource assessment of the Nemaha Ridge leases was conducted by Sproule Incorporated of Calgary, using extensive geophysical, geological and wells data in the area. At P50 Net Hydrogen Prospective resources are 100.2 BCF (237,543 tonnes) with a minimum (P90) of 47.1 BCF (111,738 tonnes) and a maximum (P10) of 238.4 BCF (565,390 tonnes) This are complemented by P50 Helium Prospective Resources of 0.47 BCF. In October 2024, HyTerra announced that the giant Australian mining and investment company Fortesque, intends to acquire 39,8% of HyTerra shares subject to shareholders approval. Fortesque will finance Hyterra's 2025 6-wells drilling program in the Project Nemaha in Kansas and additional geoscience surveys. They will also establish a Strategic Alliance to find exploration opportunities globally (https://hyterra.com/).

Desert Mountain Energy. Desert Mountain Energy Corp (DME) is a Canadian company formed in 2008 and based in Vancouver. The company is engaged in the exploration, development and production of helium and natural gas properties in the U.S. Southwest. DME exploration focus is the Arizona's helium prone Holbrook Basin and central New Mexico. DME has drilled eight wells and discovered four high-grade helium fields in nitrogen environments. During the drilling campaign, DME by chance discovered hydrogen in some of the McCauley Helium Field boreholes. The hydrogen is slated for operating the Helium Processing Facility that opened in January 2023. The pilot plant uses pressure swing absorption membrane technology to separate gases. No evaluation of the hydrogen resource in the field is available. One of the McCauley well drilled by DME has tested a section containing nitrogen 92%, helium 4% and hydrogen 4%. In the basin wells, helium occurs up to 9%, proportionally dominated by nitrogen or carbon dioxide gases. The origin of the gases is probable the U and Th decay within the granitic basement underlying the Holbrook Basin and possible deeper in the mantle.

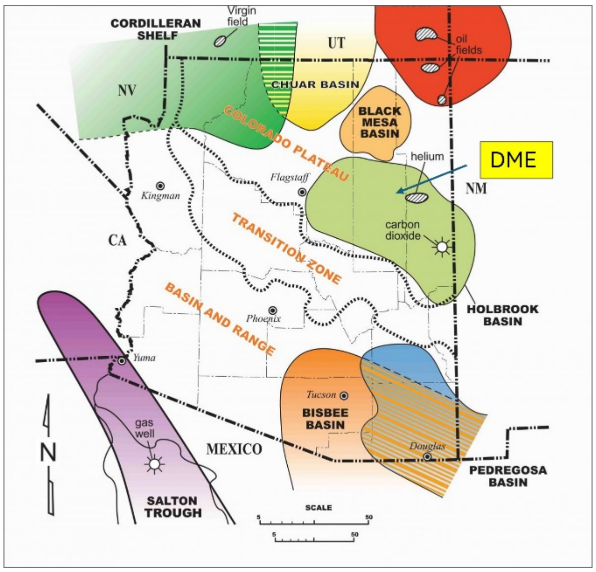

Figure 20: Location of Holbrook Basin in Arizona where DME is actively searching for helium and more recently for hydrogen

(modified after Arizona oil & gas poster | AZGS).

Holbrook Basin, located on the Colorado Plateau in northeastern Arizona, contains a 1200-1500 m Paleozoic to Mesozoic sedimentary fill above a deformed Paleozoic basement. The eolian, Coconino sandstone Permian-aged is the main helium reservoir, but Lower Devonian sandstones and Mississippian limestones also have good reservoir qualities. Potential hydrocarbon source rocks are immature, and methane is very rarely present in the wells. Basement compressional faults extend in the basin fill allowing gases from the basement to move into traps. Traps are structural, some are fault bounded, relatively shallow (about 1200 m) and reachable with air drilling. DME is the first explorer that discovered hydrogen in the basin's gas mix and is intending to commercialize it. The company has an agreement with Beam Earth Ltd., a Texas based company, to commence systematic hydrogen exploration in Arizona and New Mexico.

Koloma. Colorado-based start-up Koloma was funded in 2021 as a data-driven, natural hydrogen exploration company. Unlike some of the companies discussed here, Koloma is a well-capitalized company with solid scientific and financial backing. The company asserts that they developed the technology to identify, access, and produce natural hydrogen (https://koloma.com/).

In 2023, Koloma entered an exclusive partnership with Xcalibur Smart Mapping, a worldwide leader geophysical company, to accelerate the discovery and development of geologic hydrogen resources in the US and around the word. Xcalibur is a potential field mapping and interpretation company that uses aero surveying and a world-recognized software (LCT) to process and interpret collected data. Besides providing high resolution regional and detailed airborne geophysical services, Xcalibur uses AI-assisted laser imaging and satellites to assess sites with hydrogen shows and potential deposits of natural hydrogen.

Starting in 2022, Bill Gates, through Breakthrough Energy Ventures, and Jeff Bezos, via Amazon's Climate Pledge Fund, have made significant investments in Koloma, highlighting its potential in the clean energy sector. Their backing adds substantial credibility to the company, attracting further interest from other green committed investors and stakeholders and enhances the visibility of natural hydrogen as a viable energy solution. In October 2024, Koloma closed a Series B round of $245 million- Mitsubishi Heavy Industries, Ltd. (MHI) has invested in Koloma through Mitsubishi Heavy Industries America, Inc. (MHIA), which joins a syndicate of investors, including Breakthrough Energy Ventures, Amazon's Climate Pledge Fund, United Airlines' Sustainable Flight Fund and Energy Impact Partners. Since its 2021 launch, the company's total investments amount to more than $350 million.

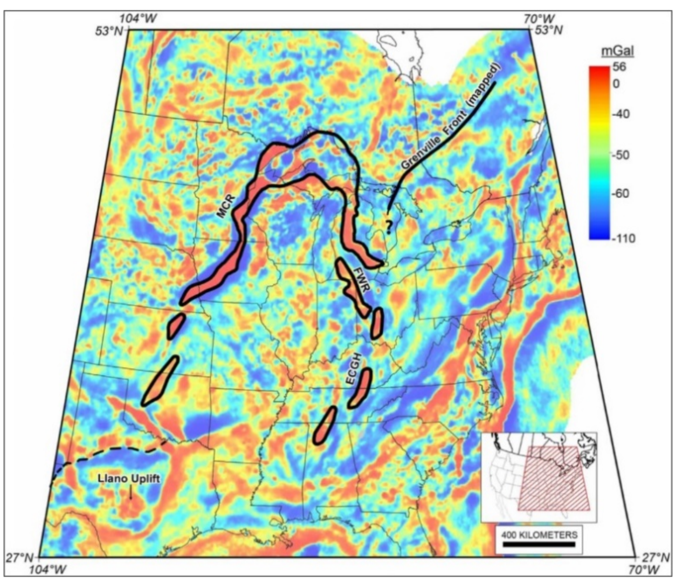

Figure 21: Processed Gravity Bouguer map showing the Mid-Continent Rift (MCR)

Figure 21 shows where Koloma is searching for Hydrogen. Fort Wayne Rift (FWR) and East Continent Gravity High (ECGH) are segments of the eastern rift arm (after Stein et al., 2018).

Koloma, is hunting for hydrogen along the 1930 km Mid-Continent Rift (Figures 18,19 and 21). The formation of the Mid-Continent Rift System started about 1 billion years ago when the supercontinent of Rodinia started to break up. A mantle upwelling extended the crust of the Laurentia plate and basaltic dykes were emplaced in several locations along the nascent rift zone. The main extensional event occurred between about 825 million and 740 million years ago with formation of a chain of Precambrian basins and emplacement of basalt extrusions all along the region now known as the Mid-Continent Rift. During its evolution the rift system experienced extension, volcanism, sedimentation, subsidence, and inversion (Stein et al., 2018). This deep, failed rift zone extents now from Canada to Michigan, Lake Superior, Nebraska, and Kansas. There is also an eastern arm of the failed rift represented by Fort Wayne Rift (FWR) and East Continent Gravity High (ECGH) (Figures 18,19 and 21).

Figure 22: Koloma natural hydrogen drilling site

Image credit Mitsubishi Heavy Industries.

Koloma has drilled several wells in the MCR area, but did not disclose the exact locations and results are kept confidential. The company has about 35 employees in Denver and several in the research lab at OSU, Columbus, OH. There are unconfirmed accounts that the company intends to produce stimulated hydrogen by injecting brine in mafic rocks (serpentinization process) or granitic basement (radiolysis process) and continuously produce hydrogen in an economic way.

Other Commercial Outfits. **H2Au**, a U.K.-based hydrogen company and **45-8 Energy**, a French company have joint forces to explore two projects in USA (Figure 11). The Humboldt project focuses on key prospects along the Nemaha Ridge, Kansas, an area which has historically shown high hydrogen and helium shows of over 90% and 3% respectively (Figures 18,19 and 21). The Fayette project is a new promising natural hydrogen play, developed around the Northeast Iowa Intrusive Complex (NEIIC), an ultramafic igneous intrusion. Since acquiring its first round of funding, the H2Au has established a portfolio of over 12 million acres hydrogen potential across the USA and South Africa. Alongside the acreage in the USA, 45-8 Energy has interest in four prospective areas in France, two in Germany and one in Kosovo.

GEO4U, is Brazilian oil and gas services company that has a 25-year-old expertise in services and research for the oil, gas, and environment sector. The company performs organic and inorganic analyses, including isotope work. Allan Prinzhofer, a world leading researcher and author in natural gases and natural hydrogen is a founder and scientific director at GEO4U. The company offers training courses in" Hydrogen and noble gases in the exploration of natural gases." Lately, the company is increasingly doing more hydrogen work in Brazil and elsewhere.

A natural deposit of helium and hydrogen was discovered in Rukwa, Tanzania by **Helium One**, a company registered in British Virgin Islands with head office in London, UK. The project is located within the Rukwa Rift basin which occupies the western branch of the East Africa Rift System.

Canada. Due to its large size and complex geological constitution, Canada is offers numerous opportunities for natural hydrogen exploration. Canada can be divided into six regions, each characterized by distinctive rock types: the Canadian Shield, Interior Platform, Appalachian Orogen, Innuitian Orogen, Cordillera and Western Canada Sedimentary Basin, and the Eastern Continental Margin (Miall, 2006). Half of the country is dominated by the Precambrian Canadian Shield. Moreover, the shield extends into the Interior Platform, Arctic islands, under the Rocky Mountains and Hudson Bay area where it is covered by sedimentary rocks ranging from the Cambrian to Cenozoic eras. Canadian Shield is made up of igneous and metamorphic rocks that are some of the oldest on Earth.

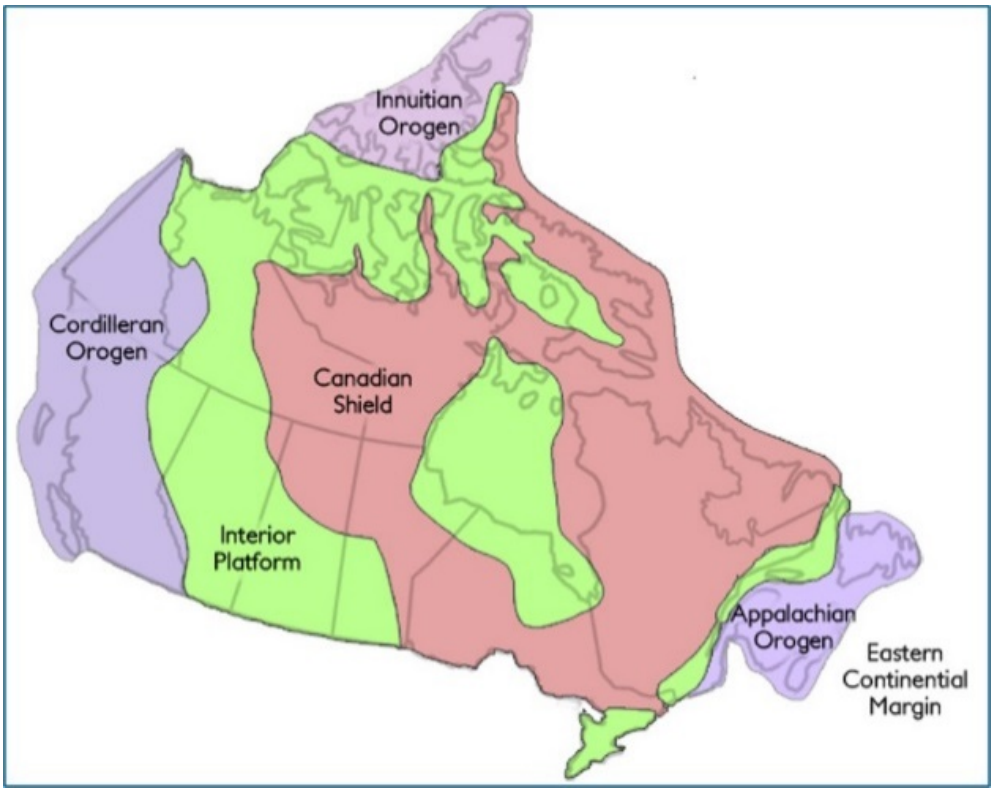

Figure 23: Principal geological regions of Canada (after Miall, 2006).

These rock formations include mafic and ultramafic belts, granite intrusion enriched in radioactive minerals, major sutures and fault zones, dyke swarms, kimberlite pipes, impact structures, uranium ore bodies, etc. Areas containing the above rock-types are all favourable for hydrogen exploration.

Max Power Mining (MPM), a Vancouver based mining company announced in the summer of 2024 that has secured exploration permits to search 1,244 sq km in southeastern Saskatchewan for natural hydrogen. This land package referred to as the "Rider Natural Hydrogen Project," is situated within a 200 km long NE-SW trending corridor. In this sector of the WCSB, the presence of hydrogen in proportion varying between 1 to 96%, has been detected in dozens of historical hydrogen showings in hydrocarbon exploration and production wells. About 15% of the wells drilled in the Rider Project perimeter showed hydrogen grades >10% at varying depths; the rest of the wells showed hydrogen grades between 1% and 10%. Denis Brière, VP Engineering for Chapman Hydrogen and Petroleum Engineering Ltd (CHPE), who examined and published on Mali hydrogen discovery (Brière et al., 2017), is a special adviser to MPM. The company believes that the source of hydrogen is in the basement of WCSB, where mafic rocks are serpentinized and hydrogen released. All of the wells that Max Power are discussing are showing the hydrogen within heavy oil fields found throughout south and southwest Saskatchewan, where little attention is paid to the associated gas from the production of the heavy oil.

Institut National de la Recherche Scientifique (INRS), based in Quebec City, has initiated a program to research hydrogen potential of the Quebec's side of the Canadian Shield. Their findings document the presence of rocks capable of naturally producing hydrogen in both southern Quebec sedimentary basins and the northern Canadian Shield. INRS partnered with a Vancouver-headquartered mining company, Quebec Innovative Materials Corp. (QIMC) and conducted a soil gas survey near the town of St-Bruno-de-Guigues (Ville Marie project), where QIMC's acquired claims. The survey indicated high hydrogen percentages along several transect of the shield covered by Quaternary deposits.

Alberta. The Precambrian crystalline basement rocks that form the basement of WCSB in Alberta comprises several Archean- to Paleoproterozoic-aged tectonic provinces of the Canadian Shield (Ross et al., 1994; Pana, 2003; Branscombe et al., 2018). The basement contains complex rock assemblages of metamorphic and igneous rocks that extend under the WCSB and Athabasca Basin and are exposed only in the northeastern corner of Alberta. WCSB basement constitution and distribution of various accreted terrains can be estimated from the interpretation of land or aero gravity and magnetic data, reflection, and refraction seismic surveys. Direct knowledge and ground truthing of the basement nature and age beneath the WCSB can be established on the results of hundreds of boreholes that penetrated basement, core data and U-Pb geochronology (Burwash et al.,1994; Burwash and Cumming, 2011; Burwash, 2011; and https://ags.aer.ca/atlas-the-western-canada-sedimentary-basin/). Certain basement domains contain ultramafic rocks and others contain granitic rocks with proven concentration of radioactive minerals (Burwash et al., 1994; Ross et al.,1994; Pana,2003; Burwash, 2011; Burwash and Cumming, 2011). Our team has distinguished three potential area for hydrogen exploration in Alberta, all underlain by or within the Proterozoic and Archean rocks of the Canadian Shield (Figure 25):

1) the western and central part of the WCSB (basement 2-4 Km deep),

2) the eastern, shallower part of the WCSB (basement under 2 km deep), and

3) the Canadian Shield exposed or covered by Quaternary deposits, including the western part of the Proterozoic-aged, Uranium prone Athabasca Basin.

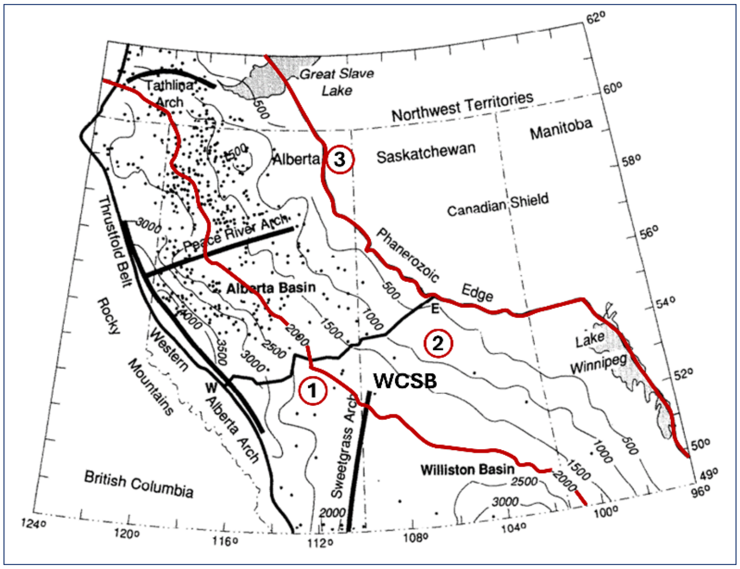

Figure 24: **Map of Western Canadian sedimentary Basin Hydrogen Potential.**

The three potential area for natural hydrogen in Alberta recognized by our team based on geological setting and depth to Precambrian basement: 1) basement depth 2 to 4 km, 2) basement depth 0 to 2 Km, and 3) Canadian shield exposed or covered by Quaternary deposits. Major tectonic lineaments and wells drilled to the basement are also shown.

According to Sherwood Lollar et al. (2014), hydrogen production from the Precambrian continental lithosphere has been greatly underestimated. Hydrocarbon, coal and mineral wells, and mining works in Alberta have occasionally indicated presence of natural hydrogen in the provinces subsurface.

Calgary-based Chapman Hydrogen and Petroleum Engineering, of Mali exploration fame, plans to drill in northern Ontario summer/fall of 2024 in the hopes of finding enough hydrogen underground to produce and market the gas. For now, no public natural hydrogen startup is conducting systematic research and exploration work in Alberta.

Phase one of the study is to locate on Alberta geological map specific regions of higher hydrogen potential. These will be where the crystalline basement contains: a) ultramafic, iron enriched rocks, b) granites and granodiorites with high content of radioactive U, Th and K and, c) major suture zone and deep fracture zones that may bring hydrogen into the shallow basement and the overlying Phanerozoic sedimentary rocks. For regional correlation purposes the study was extended to northeastern British Columbia and southwestern Saskatchewan.

Summary

Hydrogen is continuously generated in the Earth's subsurface by various chemical and physicochemical processes and the current estimate of the flux suggest that more than 23 million ton of hydrogen per year is generated from all geological processes. Finding natural hydrogen accumulations in subsurface may be the most economical solution to produce a carbon-neutral source of energy and is competitive with fossil fuels. As shown by the examples discussed in this section, the procedure is similar to natural gas production. It includes prospection using robust geological knowledge of the area, application of modern geophysical and geochemical methods, subsurface mapping, selection of most favourable sites, drilling, extraction and separation of gases and distribution of high purity hydrogen to potential users (Ellis, 2023: Rigollet et al., 2023; Gelman, 2024).

For brevity, only the countries with high hydrogen prospectivity and only a selection of companies, academic or government organizations were reviewed in this section. Start-ups are now active on North and South America, Europe, Asia, Africa, and Australia continents. Multinational large and medium size oil companies “are hanging back, waiting and watching while startups and wildcatters are trying to understand the geogenic hydrogen systems and taking on the risky exploratory work” (Hund, 2023). Historically, when well loggers recorded their borehole gas emanations, they rarely measured for hydrogen. “The bottom line—they weren’t really looking for hydrogen,” (Ellis, personal communication, GeoConvention 2024). Lack of more sampling of hydrogen in hydrocarbon wells drilled around the world might also be explained by standard analytical techniques in gas chromatography, which traditionally used hydrogen as an inert gas to carry samples (Zgonnik, 2022). Hence, even if the hydrogen gas was present in a sample, it would not be detected. This statement is valid for Alberta, especially when analysing drilling reports older than 20-30 years.

There is no doubt that natural hydrogen is a viable energy source of the future. Natural hydrogen may be renewable, it is non-polluting and may be obtained at lower costs than manufactured hydrogen, if large deposits are found. Hydrogen dedicated groups such as those discussed in here are mainly exploring for it in cratons (shields) - the ancient cores of continents, where trapped within them are bands of iron-rich, mafic, and ultramafic greenstone belts or granite intrusions enriched in radioactive minerals. This potential hydrogen generated rocks extend under intra-continental and fail rifts sedimentary basins. These geological settings are present in Alberta where WCSB is underlain by Precambrian basement and where several rifted areas are documented.

Figure 25: **Large companies and stat-ups exploring for natural hydrogen[9].**

[9] After Ball and Czado, 2024. https://geoscientist.online/sections/unearthed/natural-hydrogen-the-race-to-discovery-and-concept-demonstration/

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Hydrogen Systems

Source:

There are two, possibly three mechanisms thought to generate significant hydrogen in the Earths' subsurface: radiolysis, serpentinization, and deep earth degassing (Zgonnik, 2020; Lefevre et al., 2022; Milkov, 2022). Additional mechanisms include the high temperature alteration of hydrocarbons or source rocks.

Radiolysis:

Natural radioactive decay provides the energetic radioactive feedstock to split off oxygen atoms from water, generating hydrogen. This process would occur at mineral-water interfaces of fractures in radioactive basement rocks in the Alberta Basin, typically granites (Figure 998). This system can be geologically predicted where granitic rocks of high uranium, thorium, and/or potassium content are found, as well as in areas of radioactive mineralization.

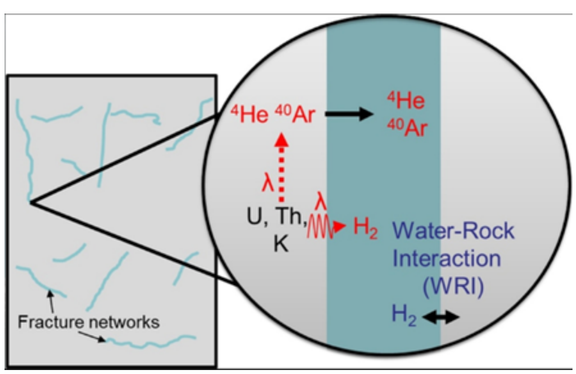

Figure 26: Radiolysis process (Warr, et al., 2019)

Radioactive decay can provide the needed energetic particles to create Hydrogen over geologic time, even billions of years. The concentration of radioactive species probably correlates with the volume and rate of hydrogen generation, assuming available ground water over time. Estimates of the radioactive content and 3D geometry of granitic rock types would be needed for an attempt to numerically estimate hydrogen ‘productivity’ rates and volume over time for a given area. Warr, et al., 2019; Truche, et al., 2018; Lollar, et al., 2014; and Warr, et al., 2023 provide examples of calculations used to assess Hydrogen charge volumes created by radioactive decay. Estimated order of magnitude rates for radiolysis related hydrogen production are around $3X10^{-9}$ moles H2 per m^3 granitic basement rock per year (Warr, et al., 2023).

There is a significant distribution of different granitic basement lithotypes in Alberta, which exhibit a rough correlation to the known occurrences of subsurface hydrogen observations (or ‘shows’). This is probably the primary hydrogen play type in Alberta.

Serpentinization:

Ultramafic rocks (containing Fe-rich olivine), when in contact with water, will react in paired reactions (involving Mg and Fe) with aqueous silica and water to form hydrogen (Figure 997). These systems can be geologically expected where ultramafic rocks are found, such as with oceanic crust and hyperextended failed rift margins. The best examples of serpentinization-related hydrogen creation are the mid-ocean ridges and in active oceanic volcanic centers, such as Iceland. Worman, et al., 2016, suggests that rates of hydrogen production are probably an order of magnitude higher at the mid-ocean ridges than at any other oceanic or continental setting. This suggests a relationship between hydrogen generation rates and proximity to the freshest oceanic crust at the ridges, implying some process change (or supply exhaustion) away from the ridges themselves. Skelton et al., (2005) estimated the serpentinization process to at mid ocean ridges to last roughly 100K – 1MM years, based of chemical balance estimates.

Estimates for global serpentinization (and hydrogen generation) rates of mafic rocks in continental basement settings (roughly 25% mafic & 50% ultramafic in Proterozoic and Archean respectively) is on the order of 735 – 1700 moles of H2 / km3 / year (using the data of Sherwood Lollar, et al., 2014): 18-42 m^3 H2/km/year.

Serpentinization related hydrogen generation is also believed to be active in continental settings where former oceanic crust, rift basins, and/or basic volcanic rocks are present. Such examples include the midcontinent of the United States where hydrogen traces (or ‘shows’) evidence hydrogen potential and active hydrogen exploration is now underway in Kansas, Nebraska, and Iowa. Similar potential is under examination in Alberta, where various basement rock types conducive to the serpentinization process are observed.

$$Mg_2SiO_4(olivine) + SiO_2(aq) + 4H_2O \leftrightarrow 2Mg_3Si_2O_5(OH)_4(serpentine)$$

$$3Fe_2SiO_4(olivine) + 2H_2O \leftrightarrow 2Fe_3O_4(magnetite) + 3SiO_2(aq) + 2H_2(aq/gas)$$

Figure 27: Serpentinization reactions (Jackson, et al., 2024)

Both Serpentinization and Radiolysis processes require the presence of water. A factor that increases the effectiveness of water through increased mobility is the presence of faults and fractures as both water delivery and hydrogen expulsion mechanisms. Roughly estimated global rates of hydrogen generation (Figure 996) suggest that Serpentinization is the most dominant global hydrogen producing mechanism. For global rates, these are small numbers (relative to oil charge rates) and concentrating hydrogen charge may become a key parameter in an exploration model.

Hydrogen generation is globally widespread, diffuse, geologically slow compared to the expulsion rates and volumes of hydrocarbons generated from very localized hydrocarbon source rocks. For example, some giant (>500 MMBO) oil fields in California have been charged in only 1MM years within very efficient petroleum systems. Hydrogen systems do not appear to have the potential to ever be that volumetrically efficient (mid-ocean ridges excluded). Due to this uncertainty, it appears critical to recognize areas where hydrogen migration can be focused or concentrated (see ‘Migration’).

Scaling these generation rates to geologic time (6 – Orders of Magnitude) is highly uncertain, but a careful analysis is warranted to evaluate basin and prospect scale Hydrogen flux rates & timing and to comparatively evaluate these to hydrocarbon systems to assess hydrogen dilution & flushing risk.

Sources	x10⁹m³ H_2 /year	Tg/year (=10⁶ t/year)	Reference
Geological			
Mid-oceanic rift system	1.3	0.12	(Welhan and Craig, 1979)
	2	0.18	(Charlou et al., 2012)
	3.7	0.33	(Cannat et al., 2010)
	4.3	0.38	(Keir, 2010)
Oceanic crust, by various oxidations	10 ± 7	0.9 ± 0.6	(Bach and Edwards, 2003)
Oceanic crust serpentinization	**1.8–2.9**	**0.16–0.26**	**(Canfield et al., 2006)**
	8.5	**0.76**	**(Sleep and Bird, 2007)**
	22.4	**2**	**(Worman et al., 2016)**
Ophiolite massifs	2–4	0.18–0.36	based on (Zgonnik et al., 2019)
Basaltic layer of the oceanic crust	**84**	**7.5**	**(Sleep and Bird, 2007)**
	139	**12.6**	**(Holloway and O'Day, 2000)**
Precambrian basement	0.45–4.3	0.04–0.38	(Sherwood Lollar et al., 2014)
	0.9–1.2	0.08–0.11	(Warr et el., 2019)
Volcanoes and hydrothermal systems	**108 ± 81**	**9.6 ± 7.2**	**(Holland, 2002)**
Subaerial volcanoes	2–7.7	0.18–0.69	(Canfield et al., 2006)
	2.7	0.24	(Stoiber, 1995)
Mid-ocean ridge volcanoes	0.2–0.6	0.02–0.05	(Canfield et al., 2006)
Coal metamorphism	0.02	0.0014	(Koyama, 1963)
Deep-seated hydrogen	**?**	**?**	
Sub-total for geologic	254 ± 91	**23 ± 8**	

Table 5: Estimates of annual global H2 generated volumes: 250 Bm3 / year (Ellis, 2023 & 2024)

System	H_2 production (10^{11} mol yr^{-1})	Reference
Ocean crust	0.8 to 1.3	Ref. 7
Ocean crust	1.9	Ref. 6
Ocean crust	2.0	Ref. 9
Slow-spreading ridges	1.67	Ref. 8
Basaltic ocean crust	4.5 ± 3.0	Ref. 5
Continental Precambrian radiolysis	0.16 to 0.47	This study
Continental Precambrian hydration reactions	0.2 to 1.8	This study

The table shows global estimates of H_2 production from water–rock alteration reactions (in units of 10^{11} mol yr^{-1}) from marine lithosphere and H_2 production estimates from radiolysis and hydration of mafic/ultramafic rocks from Precambrian continental lithosphere derived in this study. Estimates made using conservative assumptions. For details of all calculations see Methods. Volcanic, mantle-derived or microbial sources of H_2 are not incorporated.

Table 6: Estimates of H2 production from water-rock reactions Lollar, 2014

The details of hydrogen migration are relatively undocumented but is believed to follow similar physical processes that control hydrocarbon migration. Experimental studies and modeling of hydrogen solubility in aqueous solutions indicates exhibits very poor solubility in water (Figure 995), so that once hydrogen crosses the bubble point in the subsurface we have a 2-phase system of hydrogen gas, small amounts of dissolved hydrogen in subsurface water, and the presence of a buoyance-driven migration system. Chabab, et al., 2020 acknowledge the absence of Hydrogen solubility studies under significantly higher-pressure conditions than Zhu et al., 2022 (3600 psi), so there are uncertainties in predicting Hydrogen behavior in the deep subsurface, where migration is suggested to originate from.

These data suggest that Hydrogen will be highly insoluble to water under most subsurface conditions. Hydrogen gas will be evolved very early in the generation/expulsion phase and is expected to migrate as a gas phase in a water wet buoyancy driven system. To better understand buoyancy driven migration, please refer to Schowalter (1979) for basic principles on wettability, contact angles, and 2-phase migration processes (in the context of hydrocarbons). These principles, with adjustments for the physical properties of hydrogen, specifically wettability and density, should provide reasonable first order descriptions of hydrogen migration systems.

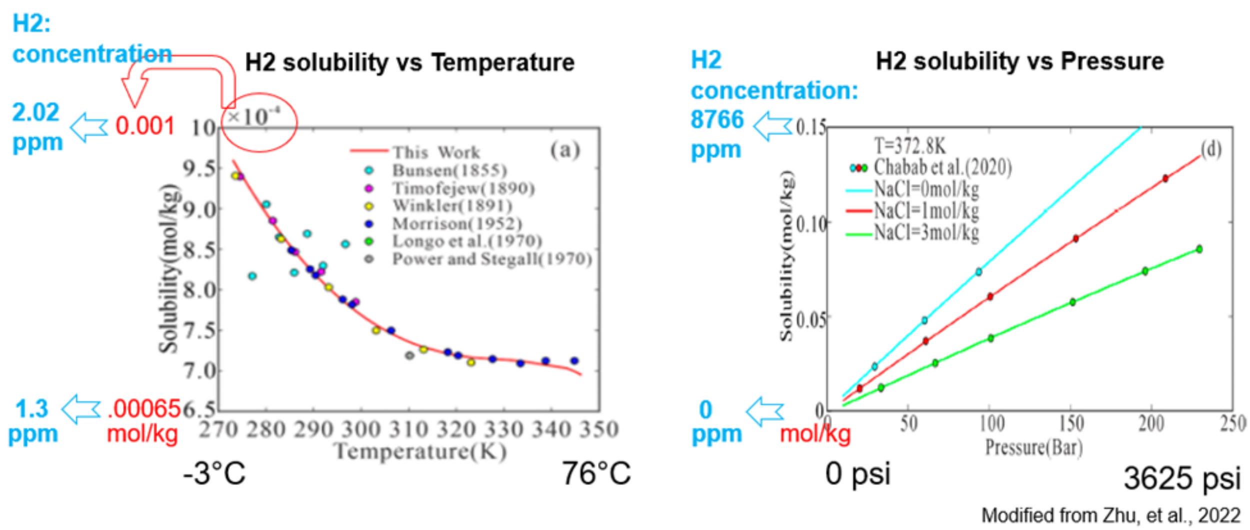

Figure 28: Hydrogen solubility in NaCl solutions. (modified from Zhu, et al., 2022)

Structural focusing of Hydrogen migration is believed likely and helps establish exploration and prospect models that can fetch more significant hydrogen volumes.

Deep basement rooted faults are probably important conduits for hydrogen charge and migration. The association of surface seep locations with faults, especially deep basement involved faults was observed by Donze, et al, 2020; Donze, et al., 2022; and Guelard, 2016. Exploration models should consider structural focusing of Hydrogen charge both before and after any vertical migration along faults.

Reservoir

There are no known constraints to the variety of conventional reservoirs that could serve as reservoirs for hydrogen. There is abundant research on hydrogen storage that suggests reservoir is not a constraint to the system. Unconventional reservoirs are not considered at this point in order to threshold test the best producing (i.e., concentration, volume, and rate) reservoirs in economic models.

Trap & Seal

Structural and stratigraphic traps are the targets of hydrogen exploration. While faults should provide an efficient migration path for an accumulation, faulted traps are uniquely risky in hydrogen exploration. Fault seal has proven to be easy to model and predict and very challenging to predict effectively! A faulted trap needs to remain unperturbed over geologic time to maintain an effective seal to hydrogen.

Laboratory measurements of the physical properties of hydrogen suggest that capillary seals should be as effective for hydrogen accumulations as they are for hydrocarbons (HC). Measurements of hydrocarbon gas – water fluid interfacial tension (30-70 dynes/cm) are very similar to hydrogen gas – water systems (43-73 dynes/cm) (Chow, et al., 2018) and hydrogen fluid-water contact angles (25-45) are similar to hydrocarbon contact angles of 30-75 degrees (Hashemi et al., 2021 & Iglauer, et al., 2020). This indicates that conventional seals to hydrocarbons should provide sufficient displacement pressure for hydrogen gas accumulations and that similar accumulation column heights (100s of meters) can be expected. This discussion may only be limited to water wet reservoirs. Reliance only on salt seals is not warranted, with a possible exception of adsorption and diffusion processes in seal lithologies.

Therefore, the array of sealing lithologies effective for hydrocarbons should also be viable for hydrogen. Stratigraphic traps in clastics and carbonates are expected to be prospective in this context.

Preservation

Hydrogen gas appears to be very unreactive (insoluble) in water. The reactivity of hydrogen gas with non-wet environments is expected, but its geologic significance is highly uncertain. Examples include oil-wet reservoirs, and adsorption onto clay minerals. It is suspected that hydrogen is reactive with hydrocarbons. Hydrogen – oil and hydrogen - hydrocarbon gases reactivity has not been examined. Adsorption and/or diffusion into the mineral surface of seal lithologies is not well studied nor scaled to geologic time. Therefore, the issue of hydrogen reactivity in a subsurface trap over geologic time remains an exploration uncertainty.

The presence of hydrocarbon systems in a basin may provide additional risk to hydrogen systems due to displacement, dilution, or reaction with hydrocarbons. Careful examination of the interplay of hydrocarbons and Hydrogen systems is warranted, especially if envisioned hydrogen traps could also be subject to hydrocarbon entrapment. Certain exploration play types address these risks.

Hydrogen Play Types & Exploration Methods

General Observations About Hydrogen Exploration (non-specific to a play type):

- Long lived traps are needed in order to accumulate slowly generating hydrogen over significant geologic time.
- Faults play a unique role in hydrogen generation and migration. They provide conduits for water to reach either radioactive or iron-rich rocks to form hydrogen, as well as to create ‘vertical’ fetch volumes of generated hydrogen, and provide an efficient path for vertical hydrogen migration.
- Structural re-activation is probably a more severe compromise for hydrogen accumulations than for hydrocarbons.
- Hydrogen solubility indicates gas as the dominant migrating species.
- Sealing lithologies common to hydrocarbons ‘should’ work for hydrogen, based on hydrogen wettability. Potential reactivity to hydrogen is highly uncertain and may represent sealing risk, especially in non-water-wet situations. Evaporites are expected to be the best seals for minimizing that risk.
- hydrogen is found in low (>>0.1%) and variable concentrations in many gas fields of the WCSB. This may represent hydrocarbons diluting hydrogen or vice versa!
- When evaluating the impact of hydrocarbons and hydrogen mixing or migrating in the same setting, examining the time frames of hydrogen & hydrocarbon generation/migration will inform the evaluation of preservation risk.
- There is probably much hydrogen passing through the basin via faults and stratal carrier beds, creating opportunities for many other trap types. Paying attention to trace ‘shows’ of hydrogen in well tests will provide context to hydrogen systems and should help the explorer to recognize natural hydrogen prospect opportunities.

Native Hydrogen Play Types

Play Types naturally separate into radiolysis and serpentinization generated Hydrogen, owing to their unique lithologies and geologic settings associated with these processes. Radiolysis hydrogen requires a strongly radioactive energy source, which is found in granites. Granites can vary significantly in their U-Th-K content. Serpentinization of hydrogen requires iron rich rocks, the best example of which are mafic (acidic) lithologies found in oceanic crust. These play types can be somewhat geographically close to each other If their geologic domains happen to coincide.

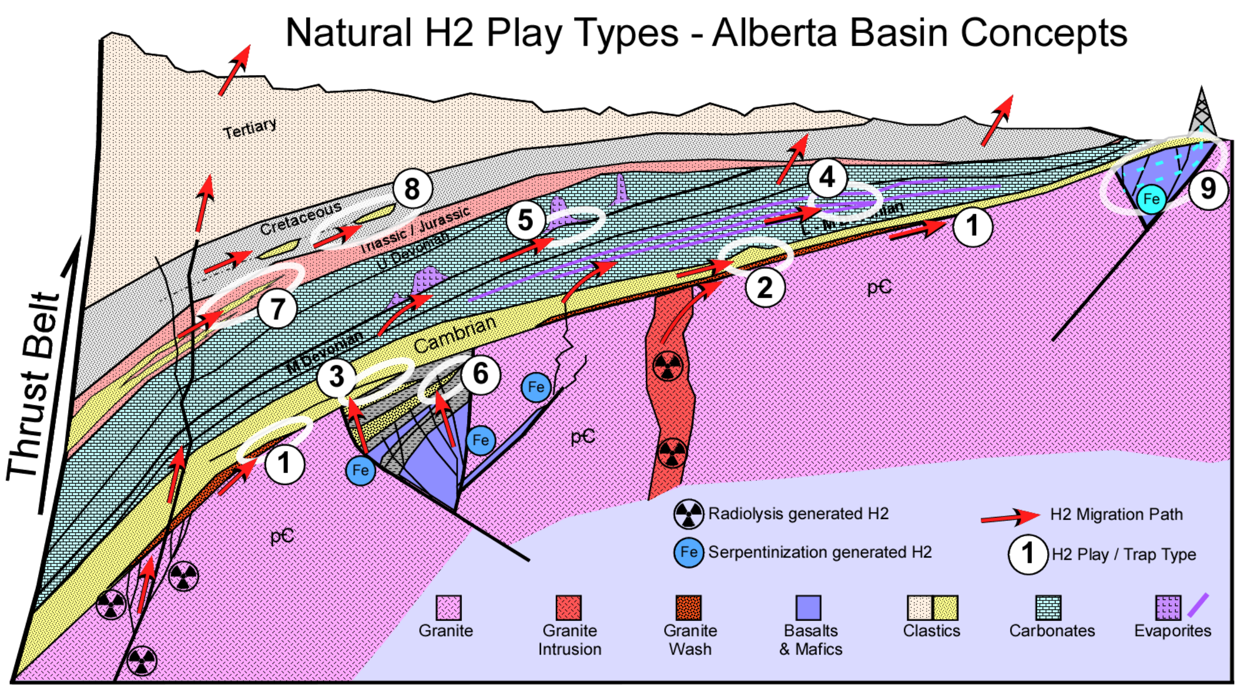

Figure 29: Native hydrogen play types possible in Alberta

Radiolysis Related hydrogen Plays

Alberta is host to many granitic basement domains as well as younger (and possibly more radioactive) granitic intrusions that may serve as a more geographically limited hydrogen source (Figure 994). The extent of faulting may play into the net rate of hydrogen generation at any location. These faulted settings may underlie an unconformity, setting up a basal (Granite wash) sandstone target wherever a structural closure or a stratigraphic pinch-out may occur. ("1" in Figure __)

If any basement faults are reactivated then seals in the granite wash setting could be compromised, allowing migration to climb upsection into younger Cambrian sediments. In the foreland basin setting a strong migration bias is set up, allowing any small structural or stratigraphic closures to trap hydrogen. ("2" & "3" in Figure __)

Hydrogen, migrating further upsection into the Devonian carbonates, may be focused by interlayered evaporites, possibly being trapped stratigraphically in the bedded evaporites (#4 in Figure __) or trapped below diapiric salt (#5 in Figure __).

Serpentinization Related Hydrogen Plays

Rift margins and volcanic provinces may have the right geologic elements for this play type. Old rifts (failed rifts or fully separated rift margins) may provide uniquely favorable settings for hydrogen exploration. Dense networks of faults and fractures would provide higher Hydrogen volumes and if the rift basin is unconformably sealed (i.e., not reactivated) successful sealing of the major rift faults might occur ("6" in Figure __). Syn-rift reservoirs could host structural and stratigraphically trapped Hydrogen.

Additional stratigraphic plays are possible in shoreface sandstone pinchouts and channel sandstones in the Jurassic and Cretaceous ("7" & "8" in Figure___).

An additional hydrogen 'Engineering Play' might exist in shallow rift basins or flood basalts. Paired horizontal wells could be placed in a frac stimulated location to feed water into the system and to produce Hydrogen ("9" in Figure __). Again, generation rates would be critical here.

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Alberta Basement Regional Geology

Western Canadian Sedimentary Basin

As previously discussed in the hydrogen systems section of this report, both granitic-rich and Iron-rich mafic and ultramafic rocks are the primary source rocks for the hydrogen discoveries to date. These source rocks are well documented from both well control and seismic data in the basement terrains beneath the Western Canadian Sedimentary Basin (WCSB). Previous accepted Uranium-lead (U-Pb) geochronology work dates the western most extension of Canadian Shield as being comprised of Precambrian rocks ranging in age from 2.32-1.79 Ga (WCSB Atlas ch4). These rocks comprise the various basement terrains beneath the WCSB (Figure 10- arc map).

A series of accretionary and collisional events in the Paleoproterozoic resulted in the formation of western most part of the Canadian Shield. Several Early Proterozoic orogenic belts in Western Canada include Wopmay Orogen (1.97-1.84 Ga), Thelon-Taltson Orogen (2.0-1.9 Ga) and Trans-Hudson Orogen (1.88-1.79 Ga) (ref atlas). These orogenic belts are characterized by deformed and metamorphosed passive

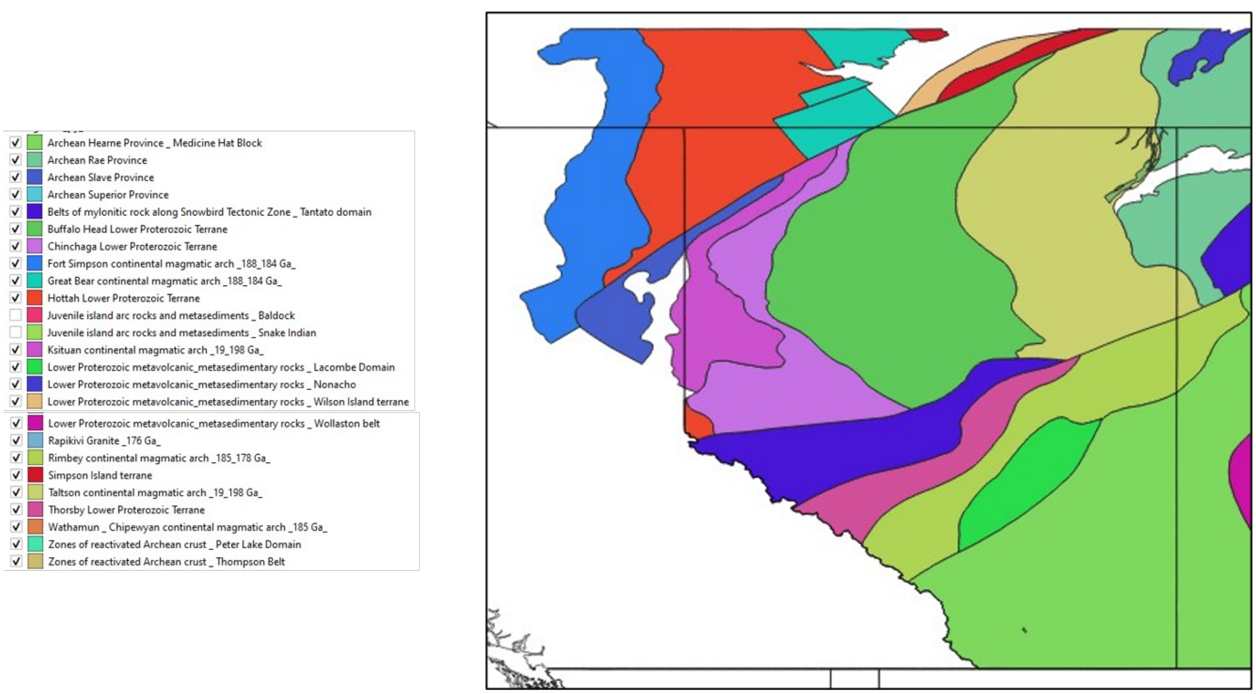

Figure 30: Map of the various Basement Terrains of the Western Canadian Sedimentary Basin (ref Atlas). Revise with main structural domains and Peace River Arch axis.

Margin and foreland basin sedimentary sequences, meta volcanics and, continental margin magmatic arcs which are calc-alkaline in nature. In northern Alberta, the Proterozoic orogens welds older Archean Rocks of the slave province, to the northwest Churchill province. Similarly, the Wopmay Orogen forms the weld between the Proterozoic crust (1.97 GA) of the Hottah Terrane and Slave Province (WCSB Atlas, Ch 4). Granitic rocks throughout these orogenic belts, in conjunction with Archean rocks which host granitic plutons, and deeper mafic sills are key for source rocks for the hydrogen play in Alberta.

The collisional events responsible for the formation of the western most Canadian Shield, resulted in several major SW-NE trending structural discontinuities. The two most prominent discontinuities include The Great Slave Lake Shear Zone (GSLSZ) and The Snowbird Tectonic Zone (STZ). Both structural elements are characterized by distinct belts of mylonitic rocks. The GSLSZ has several broad bands of mylonite and formed between 2.0-1.9 Ga (WCSB Atlas, Ch 4). In places, 1.93 Ga granite veins cut the greenschist-facies ultramylonite belts (ref Pana, 2003). These granitic veins also display foliation, indicating that they were also crosscut and underwent deformation. This implies that the GSLSZ remained a zone a crustal weakness for some time (Pani, 2003). The Snowbird Tectonic Zone is a prominent aeromagnetic and gravity feature which separates the Rae from the Hearne provinces and is extensive across the Canadian Shield. While timing, movement and significance are uncertain, the Snowbird Tectonic Zone may be of particular interest in the story of hydrogen in Alberta

The Snowbird Tectonic zone separates the more tectonically active northern half of the basin from the more relatively simple structural story in the south. The Peace River Arch (PRA) is a southwest to northeast striking cratonic element of the WCSB. The PRA is underlain by, and oriented perpendicular to crystalline basement rocks which have been subdivided into four distinct tectonic domains (Kiskatinaw, Ksituan, Chinchaga and Buffalo Head) based on aeromagnetic signatures (Figure 10).

Several other prominent structural elements in the basin north of the Snowbird Tectonic Zone include The Peace River Arch, The Kistuan High Continental Magmatic Arch, The Athabasca Basin, and numerous fault zones inferred in the Athabasca Polymetamorphic Terrain, as well as other prominent faults in the basin (Fig 11 see arc map – structural elements).

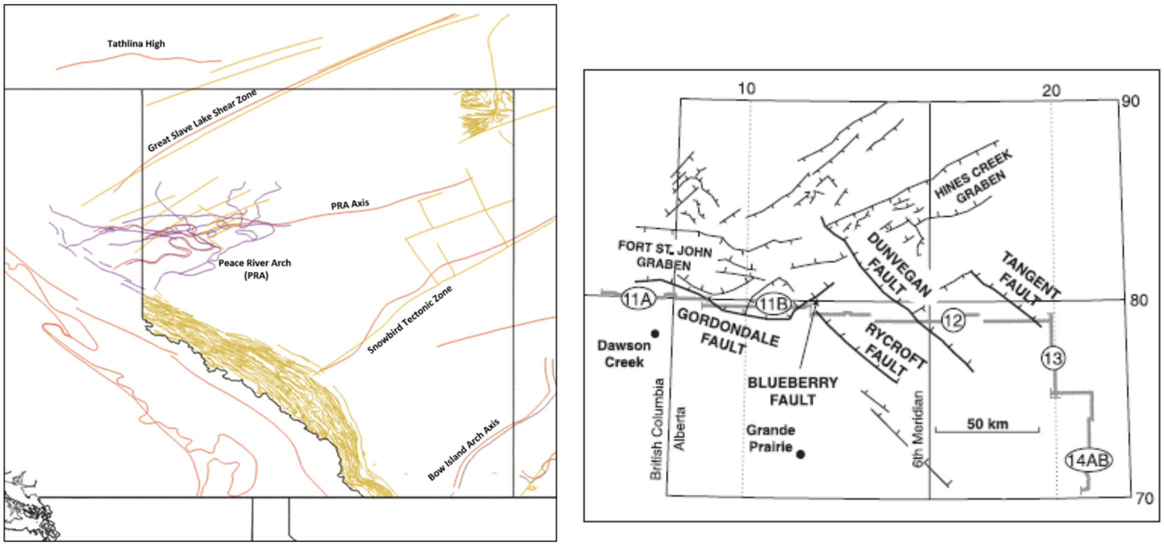

Figure 31: **Key structural elements of the Western Canadian Sedimentary basin (our compilation). Peace River Arch region map after Richards et al.,1994).**

In addition, the length of the PRA axis is greater than the width of any of the individual basement domains that it crosses, suggesting that the formation of the arch was not influenced or controlled by the Precambrian structure of the basement (Pana, 2003). The predominance of magmatic rocks suggest evolution in an arc-subduction system, with multiple collisional events from the west into the existing shield. These collisional events are also coincident with timing of magmatic events. Highly continuous Winagami Reflections observed on the 1994 Lithoprobe seismic reflection dataset in the Peace River Arch (PRA) show evidence of tabular, intrusive mafic sills which were coeval with the collision of Slave Province and the western Canadian Shield (Figures 12 and Eaton, 1999).

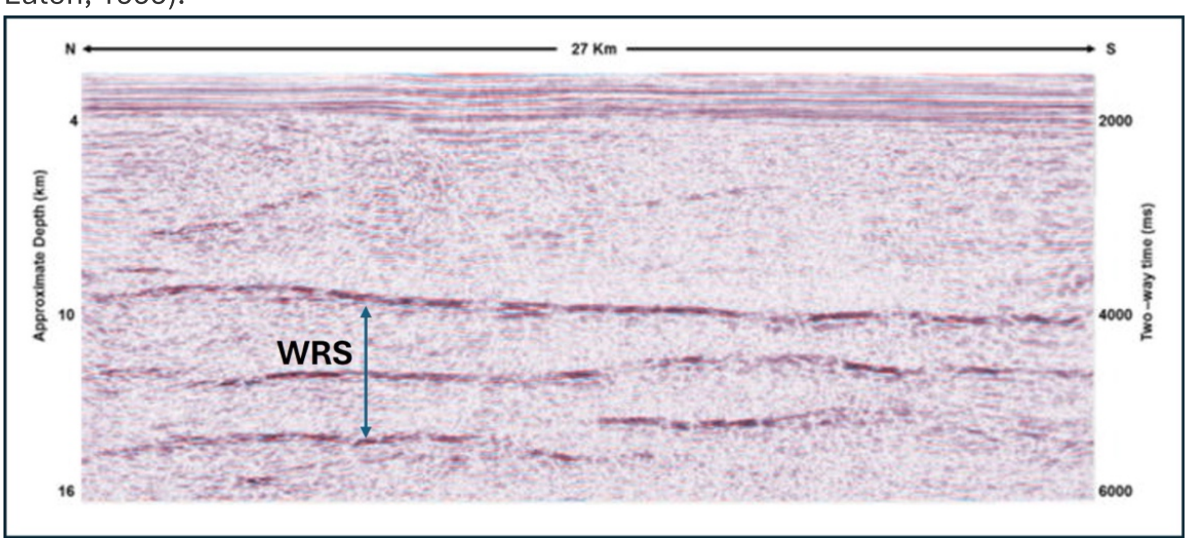

Figure 32: **Depth seismic reflection line (Lithoprobe) in PRA region showing the Winagami Reflection Sequence (WRS) interpreted as quasi-horizontal sheetlike mafic intrusions, located in mid crust (modified after Ekpo et al., 2017).**

While the composition of these mafic sills is unknown, their presence in the basement is a critical observation in support of serpentinization as a possible mechanism for the generation of hydrogen in the basin.

There have been three distinct phases of evolution identified for the PRA. Phase one coincided with the establishment and development of a passive margin along the western margin of the Canadian Cordillera (ref Eaton, 1999). It lasted until mid-Devonian time, during which time, the PRA was topographically high and was also one of several arches in the basin. The second phase which lasted from the Carboniferous to Triassic time, saw collapse of the PRA and formation of the Peace River Embayment (PRE). This embayment experienced greater e subsidence than the rest of the basin. The third and final phase of evolution within the PRA was characterized by enhanced Mesozoic subsidence within the PRE and was coeval with the initiation and evolution of thrust loading from the west, and development of the Alberta basin foredeep.

From a hydrogen exploration perspective, the PRA is of particular interest due to magnitude of faulting in both the basement and overlying sedimentary succession. As discussed in previous sections of this report, basement involved faulting is one of the critical play elements for a hydrogen play. The collapse of the arch is related to the high degree of normal basement faults and graben structures.

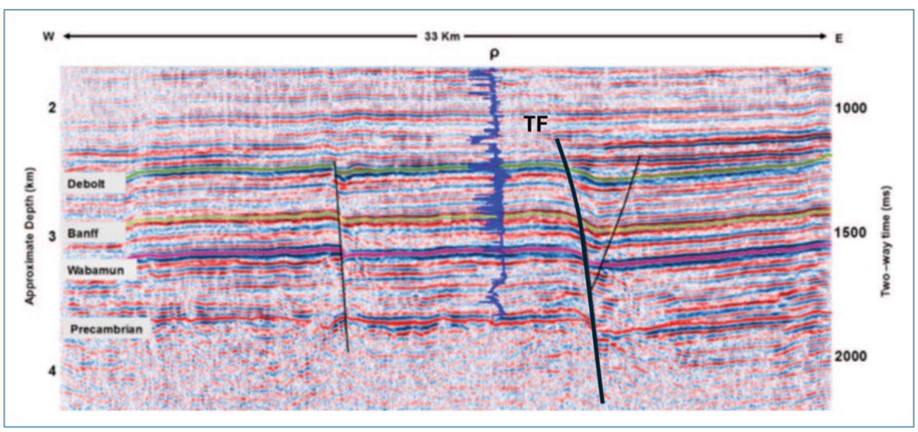

Figure 33: **Interpreted Lithoprobe data from Peace River Arch in NW Alberta.**

Aeromagnetic map used to define the different domains is shown in the insert. Aeromagnetic profile corresponding to the seismic line is shown at the top. Highly

reflective, sub horizontal Winagami Reflections in the Buffalo Head and Chinchaga Domains are interpreted as mafic sills (Ross and Eaton 2002).).
Figure . Seismic line across the Tangent Fault (TF) in PRA region showing faults affecting the basement. A density well log is used to obtain stratigraphic ties to main horizons (modified after Ekpo et al., 2027

As well, several basement faults documented in published geological reports in the PRA region have vertical offsets of several hundred metres (Pană et al., 2001). It is also important to mention that while it is difficult to discern the degree to which these older Paleoproterozoic faults were reactivated, if at all during the second phase of the PRA evolution, there are Phanerozoic faults which display significant offset at the top of basement. An alternative model for the origin of these faults is that they originated in the basement. There are five large scale normal faults which show offset at the base of the sedimentary succession. These include The Dunvegan, Gordondale, Rycroft, Tangent and Blueberry faults (Figure 11). All of these faults show offset at the top of the Precambrian basement and are possible migration pathways for natural hydrogen from the basement into the overlying sedimentary succession (Figure 13).

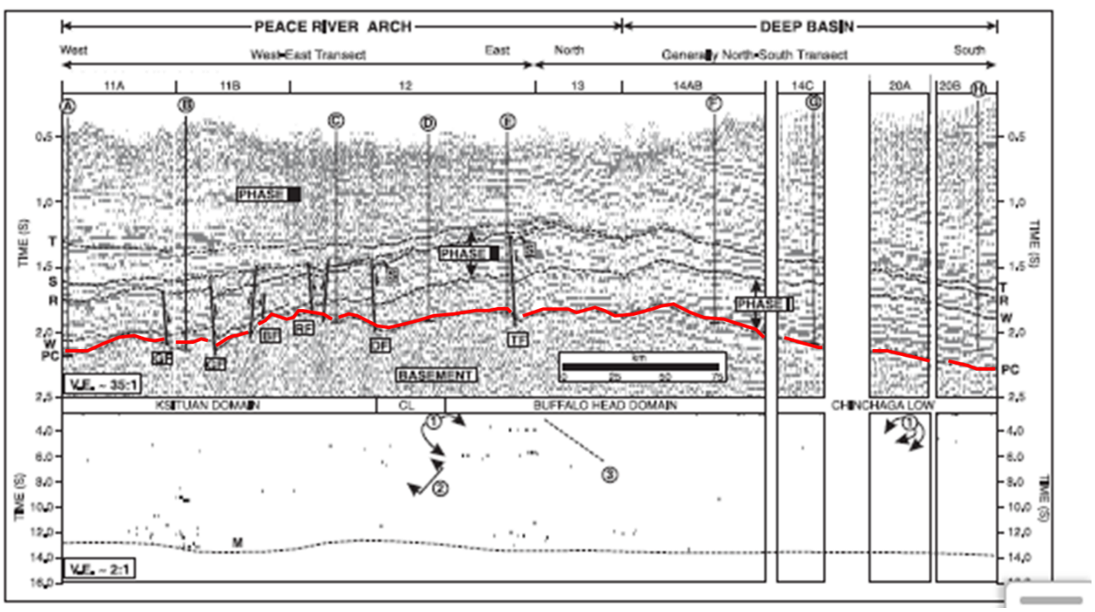

Figure 34: Regional seismic profile across the Peace River Arch.

The top of Precambrian Basement (PC) is shown in red. Significant offset is observed on the basement surface at the Dunvegan Fault (DF), Gordondale Fault (GF), Rycroft Fault (RF), Tangent Fault (TF) and Blueberry Fault (BF). These faults may provide a conduit for hydrogen from the basement to the overlying sedimentary succession (modified after Eaton et al.,1999)

Beneath the PRA, there are two very prominent aeromagnetic signatures which define the Ksituan High and the adjacent Chinchaga Low (Figure 10). The Ksituan high is a prominent north to northeast trending, aeromagnetic high and sits immediately beneath the Peace River Arch. The feature is 130 km wide at its southern boundary against the Chinchaga Low and narrows to 10 km wide at its northern boundary, where it truncates against the GSLSZ (Figure 10) (ref Pana, 2003). The high is comprised of magmatic arcs of the Canadian Shield, which in turn have a very high aeromagnetic signature. Internally, the aeromagnetic fabric of the Ksituan high is characterized by moderately elongate, positive domains separated by narrow lows; this suggests that the basement rocks have undergone penetrative deformation (ref Pana 2003). This fabric may be evidence of both hydrogen source rocks in the form of mafic sills as observed on the PRA from the lithoprobe lines, and granitic intrusions. The Chinchaga low is a curvilinear feature which wraps around the Ksituan High. It is truncated in the north against the GSLSZ but is abruptly juxtaposed against the Wabamum High across the Snowbird Tectonic Zone in the south. The strongly negative aeromagnetic signature of the low suggests a very different crustal origin from the Kistuan High to the west, and the Buffalo Head terrane to the east.

Athabasca Basin

The Final structural element of interest for hydrogen in Alberta is the Athabasca Basin. The Athabasca Basin covers an area of approximately 100,000 km^2 and extends across northern Saskatchewan and Northeastern Alberta. The basin reaches up to 1500 m thickness and is filled by relatively undeformed sedimentary rocks known as the Athabasca Group. Fluid inclusion studies suggest the Athabasca Basin reached a maximum burial depth of 5–7 km but has been uplifted and eroded to its current thickness of 1–2 km (Pagel, 1975; Pagel et al., 1980; Ramaekers et al., 2007). Unconformity-related uranium deposits are thought to form due to the circulation of basin-derived, oxidizing, uranium-bearing fluids along faults that crosscut the unconformity. Mixing these fluids with basement-derived reducing fluids induces the precipitation of uraninite. Uranium deposits are typically located at the intersection of reactivated basement faults and the basin-basement unconformity. Unconformity-related uranium deposits are thought to form due to the circulation of basin-derived, oxidizing, uranium-bearing fluids along faults that crosscut the unconformity. Mixing these fluids with basement-derived reducing fluids induces the precipitation of uraninite.

One of the largest Uranium ore deposits, Cigar Lake is in the eastern portion of the Athabasca Basin (Figure 14). Located at a depth of 450 m below surface, Cigar Lake deposit was identified by electromagnetic survey. The ore body is flat lying and lensed-shaped. It is 2 km long by 50 m wide and is hosted by sandstone. Mineralization is structurally controlled by an east-west trending shear zone. The Cigar Lake U deposit

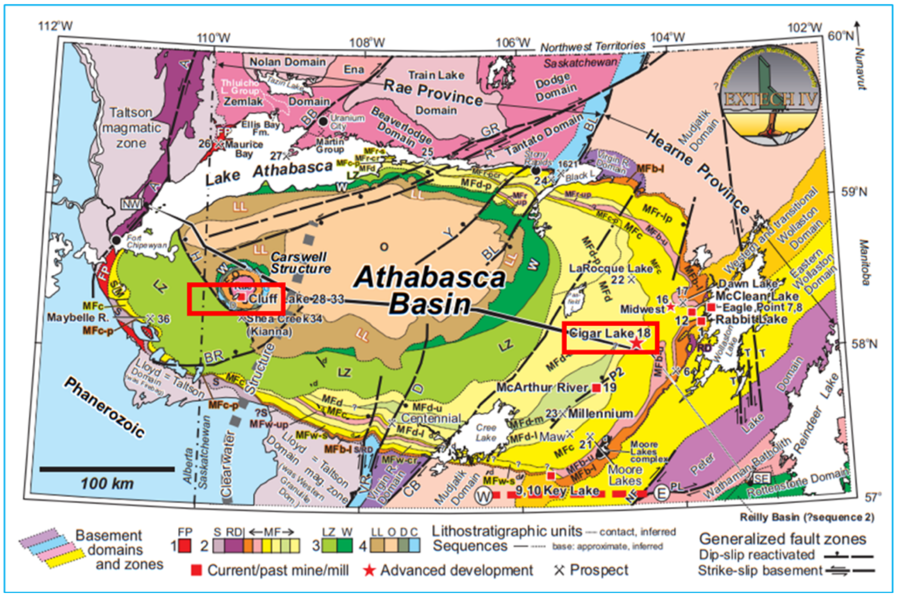

Figure 35: Map of the Athabasca basin in NW Saskatchewan and NE Alberta showing past, present and prospective mines.

Of particular interest is the Maybelle R prospect mine in NE Alberta (Jefferson et al., 2007).

geological architecture includes heterogeneous basement lithologies, a local basement high and sub-vertical faults. The sub-vertical faults are classified further into faults that are restricted to the basement, termed basement faults and faults that are distinctly related to post-Athabasca fault reactivation, in that they extend upward into the sandstone, termed extended basement faults (Figure 15) Along and near these structures, uranium bearing oxidizing fluids (e.g., Athabasca Basin brine) met and reacted with reducing agents, such as graphite, hydro-carbonaceous material, mobile hydrocarbons, aqueous ferrous iron or ferrous iron-rich lithologies and precipitated uraninite. The sandstone-hosted type of unconformity related uranium deposits such as Cigar Lake, were mainly associated with discharge (egress flow) of the basement fluids (Kotzer and Kyser, 1995; Fayek and Kyser, 1997; Jefferson et al. 2007). The extended basement faults enhance the permeability of an E-W corridor within the sandstone and significantly strengthen the overall upwelling flow above the basement faults, promoting

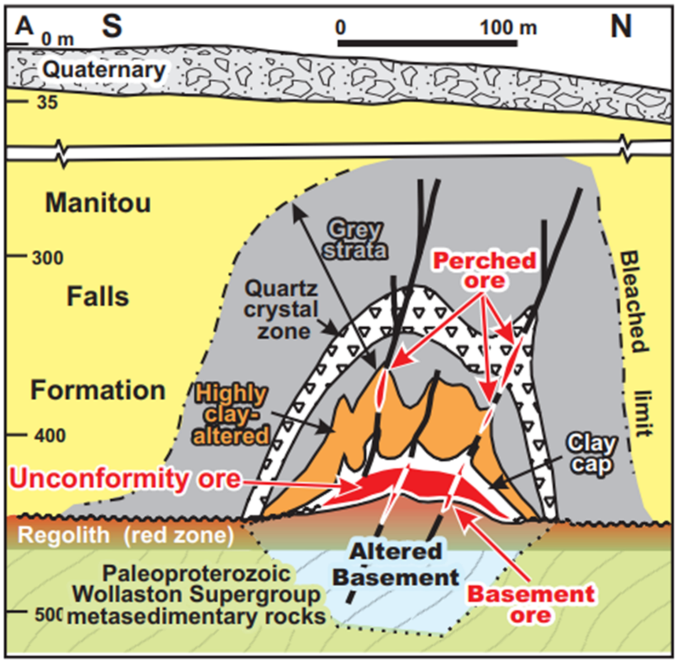

Figure 36: Schematic of the Cigar Lake Uranium deposit.

Key play elements include basement involved and reactivated faults, the Sudoite clay cap in white, and the highly altered zone above and below the ore deposit (Jeferson et al, 2007).

The numerical results suggest that the main deposit likely formed via fluid convection of basin brines and basement brines during tectonically quiet periods. Extended Basement faulting played a critical role in increasing permeability, in turn, enhancing thermal convection (Eldursi et al., 2020).

Cigar Lake is also of particular interest for hydrogen exploration. To better understand the ore deposit, a substantial hydro chemical and mineralogical characterization was carried out for many years as part of the Natural Analogue project. The groundwaters sampled in the ore (boreholes 220a and 220b of Table 3.30 in Cramer and Smellie, 1994) were reducing: Eh = -242 mV, with a circumneutral pH = 7.32 and one of the most remarkable observations was the presence of high hydrogen levels (Cramer and Smellie, 1994). The large amounts of high-grade uranium ore presented the possibility of testing the potential influence of water radiolysis by alpha, beta and gamma radiation effects on the dissolution of the uraninite ore and the potential effects in other redox sensitive components. This work was initially triggered by the initial observation of a red halo at the clay surrounding the ore that was initially attributed to a potential radiolytic oxidation of ferrous to ferric iron and the generation of hydrogen at the ore core. According to the radiolyitic models for Cigar Lake, alpha radiation was the major contributor to the generation of hydrogen.

The ore deposit is surrounded by a large hydrothermal alteration zone extending upwards about 400 m into the Athabasca Group sandstones and some 100 m into the basement. (Figure 16). Adsorbed hydrogen concentration (red circles) and whole rock uranium content (blue diamonds) as a function of depth along borehole SF-910-07. The red circles correspond to the amount of adsorbed hydrogen released in the 80–300 ◦C T range during the thermal desorption runs. Hydrogen concentration decreases gradually when moving away of the deposit, but there is no direct correlation with the uranium content of the ore. The highest concentrations of adsorbed H2 are found in the ore zone and below in the sudoite-rich argilitized basement (Truche et al, 2018).

As shown in Figure 15, the deposit is overlain by altered clay called Sudoite $Mg_{1.9}Fe^{2+}_{0.1}Al_{2.9}Fe^{3+}_{0.2}Si_3AlO_{10}(OH)_{7.9.}$ Sudoite is a magnesium-rich aluminum dioctahedral chlorite and is platy to fibrous from SEM images. It is the main absorbent for hydrogen. Other papers mention the halo may also consist of dickite, illite, chlorite or simple altered clay. Given the size of the Cigar Lake deposit, a possible range for a hydrogen-rich ($[H_2] \geq 50$ ppm) rock tonnage of 1.84×10^6 tons at a mean hydrogen content of 190 ppm (n = 13), and an hydrogen-poor ($5 \leq [H_2] < 50$ ppm) rock tonnage of 8.46×10^6 ton at a mean hydrogen content of 15 ppm (n = 15). The current estimate of hydrogen trapped in the deposit is 476 tons (Truche et al., 2018). The observation of hydrogen at Cigar Lake is an important analogue for hydrogen exploration in the vicinity of other deposits in the Athabasca basin in Alberta. Of particular interest is the Maybelle R prospect mine in NE Alberta (Jefferson et al., 2007).

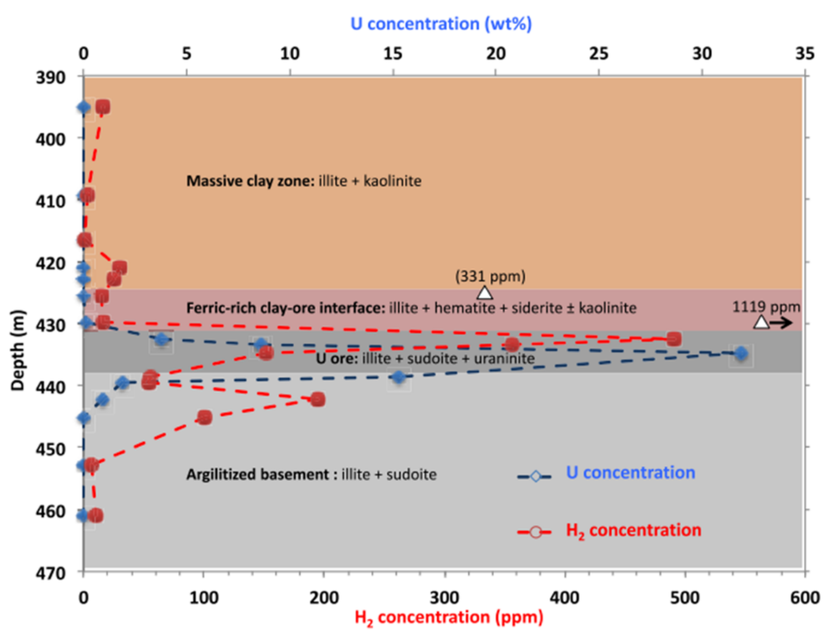

Figure 37: Absorbed hydrogen concentration with depth from the SF-910-07 borehole.

Uranium concentration is shown in heavy dashed blue, and H2 concentration in Heavy dashed red. There is a zone of increased H2 concentration above and below the main ore deposit (Truche et al., 2018).

Basement Composition

As discussed in the hydrogen exploration methodology section of this report, the two main mechanisms for generating hydrogen are serpentinization of mafic and ultramafic rocks, and radiolysis of granitic-rich rocks. The presence of mafic sills emplaced into granitic rich crust, as observed from the Lithoprobe seismic reflection dataset, suggests that serpentinization may be a viable mechanism for the generation of hydrogen in the WCSB. While the Lithoprobe data set is limited in extent, the consistent observation of the highly continuous Winagami reflections over various North to South segments of the survey suggests more widespread emplacement of these mafic sills, near basement involved faulting within the crust beneath the WCSB, too deep to be explored by well data.

The distinction between granite and gneiss in core samples, without supporting observations at the outcrop, becomes partly subjective (Burwash et al., 2000). The term ‘granite’ was used in a very broad sense to include rocks with hypidiomorphic granular texture that are weakly foliated or nonfoliated and range in composition from granite to quartz diorite, as defined by Streckeisen (1976). The ‘gneiss’ records deformation of granitoid rocks under medium- to high-grade metamorphic conditions. Thus, both are important for understanding hydrogen occurrences throughout the basin.

Conventional well data has confirmed the presence of granites in the basement immediately beneath the sedimentary cover. Outcrop data from the Hottah Terrane and well penetrations along the axis of the Peace River Arch in The Archean Slave Province, The Ksituan Magmatic Arch, The Chinchaga Lower Proterozoic Terrane, The Buffalo Head Lower Proterozoic Terrane, The Taltson Magmatic Arch and The Archean Rae Province have all confirmed the presence of granites. Outcrop data from the Hottah terrane is the westernmost exposed bedrock of the Canadian Shield. The Hottah terrane is comprised of deformed metasedimentary and meta volcanics intruded by diorites and granite plutons. The Hottah Plutonic complex is comprised of coarse-grained K-feldspar porphyritic biotite granite. This granite is similar to other ‘syenogranites’ throughout this area and previous investigators assigned it to the Hottah terrane (Hildebrand and Roots 1985). The Archean slave province is dominated by potassium rich granites. In northern Alberta, between the Taltson and Ksituan magmatic arcs, the Athabasca Polymetamorphic Terrane, which includes the Peace River Arch, consists of more than 80% gneiss and granulite, whereas inferred supracrustal rocks form less than 5% (Burwash et al., 2000). Core and cuttings data from wells along the axis of the Arch show the granitic-rich nature of the basement north of the Snowbird Tectonic Zone (Figure 17). The granitic-rich cores also correspond to the radioactive heat map from U-Th data as well, however those data suggest other possible areas with granitic-rich basement south of the Snowbird Tectonic zone. All these data support and corroborate the locations of high-graded wells, whose hydrogenconcentrations are greater than 5%.

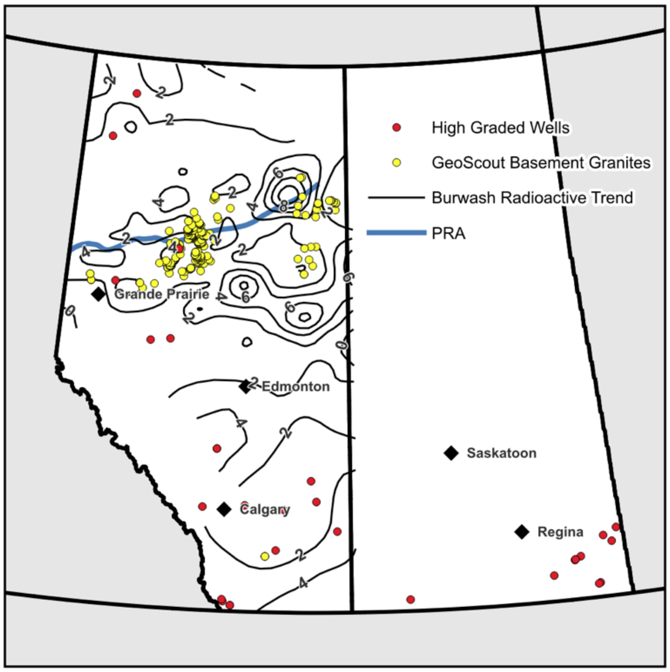

Figure 38: Locations of granitic control points throughout the WCSB.

The black contours show the Radioactive heat map from U-Th concentrations, as published by Burwash et al. Superimposed on these contours are the wells (yellow) with granites in the basement description from *Geoscout* and high-graded wells (red) with hydrogen concentrations greater than 5%. The axis of the Peace River Arch is show in heavy blue.

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