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Exploring natural hydrogen potential in Alberta's Western Canadian Sedimentary Basin

D.B. Wijayarathne [a], T.A. Morais [a,*], A. Jaggi [a], J.J. Gibson [b], P. Eby [b], M. Huard [c]

[a] InnoTech Alberta, 3608 - 33 St NW, Calgary, Alberta, T2L 2A6, Canada
[b] InnoTech Alberta, 3-4476 Markham Street, Victoria, BC, V8Z 7X8, Canada
[c] InnoTech Alberta, 250 Karl Clark Road, NW, Edmonton, Alberta, T6N 1E4, Canada

A R T I C L E I N F O

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A B S T R A C T

Natural hydrogen, or "white hydrogen", has recently garnered attention as a viable and cost-effective energy resource due to its low-carbon footprint and high energy density, positioning it as a key contributor to the transition towards a sustainable, low-carbon energy system. This study represents Alberta's first systematic effort to evaluate natural hydrogen potential in the province using publicly available geological, geospatial, and gas composition datasets. By mapping hydrogen occurrences against key geological features in the Western Canadian Sedimentary Basin (WCSB), we identify regions with strong geological potential for natural hydrogen generation, migration, and accumulation, while addressing data uncertainties. Within the WCSB, formations like the Montney, Cardium, Bearpaw, Manville, Belly River, McMurray, and Lea Park are identified as zones likely for hydrogen generation, by prominent mechanisms including hydrocarbon decomposition, water-rock reactions with iron-rich sediments, and organic pyrolysis. Formation proximity to the underlying Canadian Shield may also suggest potential for basement-derived hydrogen migration via deep-seated faults and shear zones. Salt deposits (Elk Point Group - Prairie evaporites, Cold Lake, and Lotsberg) and deep shales (e.g., Kaskapau, Lea Park, Wapiabi), provide effective cap rock potential, while reservoirs like porous sandstone (e.g. Dunvegan, Spirit River, Cardium) and fractured carbonate (e.g. Keg River) formations offer favorable accumulation conditions. Hydrogen occurrences in relation to geological features identify Southern, Eastern, and West-Central plains as prominent natural Hydrogen generation and accumulation areas. Alberta's established energy infrastructure, as well as subsurface expertise, positions it as a potential leader in natural hydrogen exploration. As Alberta's first systematic investigation, this study provides a preliminary assessment of natural hydrogen potential and outlines recommended next steps to guide future exploration and research. Targeted research on specific generation and accumulation mechanisms, and source identification through isotopic and geochemical fingerprinting, will be crucial for exploration, de-risking, and viability assessment in support of net-zero emission initiatives.

1. Introduction

Canada's commitment to achieving net-zero greenhouse gas (GHG) emissions by 2050 emphasizes the urgent need for innovative, sustainable energy solutions [1]. Transitioning from carbon-intensive fuels requires exploring alternative energy sources capable of supporting economic growth and environmental sustainability. Among these, natural hydrogen, often referred to as "white" or "gold" hydrogen, is gaining global attention as a cost-effective and environmentally sustainable resource [2]. Unlike manufactured hydrogen, which relies on energy-intensive processes, natural hydrogen is generated through geological mechanisms [3,4], offering a promising low-carbon alternative. Natural hydrogen supports Canada's net-zero goals by providing a low-carbon energy alternative [5–7].

Hydrogen gas has been observed in a variety of geological contexts worldwide, though its presence above trace levels (>0.1 %) [8,9] is relatively rare, having been reported in only a few dozen fields among millions of drilled oil and gas wells [10–13]. This can largely be attributed to hydrogen's diffusive and reactive nature, making its economic accumulation relatively rare [3]. Historically, petroleum exploration has not targeted hydrogen, and geologic settings conducive to hydrogen generation, such as ophiolites, mid-ocean ridges, and

* Corresponding author.
E-mail address: tiago.morais@innotechalberta.ca (T.A. Morais).

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Precambrian cratons, are not typically associated with oil sands or traditional oil and gas fields [2]. Hydrogen is often consumed during migration, particularly when it interacts with thermally mature organic-rich rocks, where it can participate in hydrocarbon-forming reactions [14]. Historically, mineral exploration activities have likewise focused on shallow mineral occurrences, seldom incorporating measurement of gas composition, and therefore overlooking potential for hydrogen accumulation.

Natural hydrogen is emerging as a significant focus of research and exploration globally, driven by its potential to contribute to rising energy demands projected to exceed 500 Mt annually by 2050 [15]. The discovery of a natural hydrogen accumulation in Mali in 2012 ignited interest in Africa, leading to exploration efforts in Morocco [16], Djibouti [17], Australia [18,19], Iceland [20], Russia [21], France [22], USA [23,24], Albania [25], and Namibia [26]. In 2021, approximately one-third of South Australia (570,000 km^2) was leased for hydrogen exploration, reflecting the region's commitment to advancing clean energy initiatives [27]. In the United States, the first exploratory well for hydrogen was drilled in Nebraska [28], with subsequent exploration activities expanding to Kansas [23] and nationwide [24]. Notably, the USGS launched North America's first funded research project dedicated to natural hydrogen exploration in 2022 [24]. While these initiatives highlight the growing recognition of hydrogen's potential, the natural subsurface flux of hydrogen (an estimated 23 million tonnes annually) [29] highlights the need for innovative exploration, efficient trapping mechanisms, de-risking, and scalable production strategies to meet global demand.

Natural hydrogen exploration is not yet a common focus in Canada, though interest is steadily growing as the energy sector seeks cleaner alternatives. Recent developments in Saskatchewan, where subsurface gases containing high-purity hydrogen (up to 96.4 %) has been discovered [30], suggest that the geological features of the Western Canada Sedimentary Basin (WCSB) may hold significant potential for natural hydrogen. In Quebec, Séjourné et al. (2024) [9] provided a comprehensive review of hydrogen generation through processes like serpentinization, emphasizing the region's prospects for hydrogen exploration. Alberta, despite incorporating vast areas of the WCSB and Canadian Shield, as well as favorable geological structures and existing infrastructure, has not yet been widely investigated for natural hydrogen occurrences, although limited work has been carried out on hydrogen storage potential [31,32]. This gap emphasizes the need for targeted studies to assess Alberta's capacity for natural hydrogen generation, transportation, storage, and utilization, paving the way for Alberta to potentially play a leading role in Canada's transition to cleaner energy resources.

The formation and accumulation of natural hydrogen depend on a combination of geological processes and structural conditions, referred to as natural hydrogen play elements, which facilitate its generation, migration, and retention. Understanding these play elements is crucial for identifying areas with high potential and financially viable natural hydrogen reservoirs. Key elements include the presence of *hydrogen generation sources*, such as Fe-rich and uranium-bearing minerals or rocks, which can drive hydrogen production through processes like serpentinization [3,33], radiolysis [9,34], or water-rock reactions [31,35,36]. Additional sources include thermogenic breakdown of hydrocarbons in deep sedimentary basins [37] and mantle-derived fluxes [38–41].

Once generated, hydrogen migrates through the subsurface along deep-seated fractures and faults, which act as primary *migration pathways*. Structural and stratigraphic *traps*, such as anticlines, salt domes, and mature rocks, provide potential reservoirs for accumulation [32]. Reservoir quality is enhanced where porous units are sealed by *impermeable layers* such as shale, evaporites, or salt, the latter being particularly effective in preventing hydrogen escape [31]. Evidence of hydrogen anomalies in drill holes, such as those reported in Mali and Saskatchewan, further highlights the importance of targeted exploration in areas with favorable geological conditions [30].

These processes have been documented worldwide, demonstrating the diversity of settings capable of generating and hosting natural hydrogen. Examples include Oman and Australia for serpentinization [3,33], the Canadian Shield and South Africa's Witwatersrand Basin for radiolysis [9,34], and the Cooper Basin for thermogenic hydrogen generation [37]. Recent work in China's Songliao and Bohai Bay Basins has further highlighted the role of abiogenic and mantle-derived hydrogen in sedimentary basins [40,41]. Collectively, these play elements define the exploration strategy for natural hydrogen, guiding researchers and industry toward promising hydrogen plays globally.

Alberta's geological landscape offers a unique and underexplored niche for natural hydrogen exploration due to its distinct geological features and vast subsurface knowledge derived from the oil and gas industry. The province's extensive and varied formations, particularly within the WCSB, present a significant opportunity for natural hydrogen accumulation. With fault systems that may act as conduits for hydrogen migration, porous reservoirs like sandstones and fractured carbonates ideal for storage, and impermeable cap rocks like evaporites and shale to trap hydrogen over geological timescales, Alberta possesses the geological conditions to potentially foster large-scale natural hydrogen accumulations. Additionally, Alberta's established infrastructure, along with its skilled workforce and expertise in subsurface resource management, places the province in a prime position to lead in this emerging field. The convergence of these geological advantages and industry expertise creates a rare opportunity to not only explore but also unlock the vast potential of natural hydrogen as a sustainable energy resource, positioning Alberta as a key player in the global transition to a low-carbon economy.

This manuscript is intended as a first step towards a comprehensive evaluation of the potential for natural hydrogen generation, migration, storage, and trapping by identifying key geological features associated with this process within the province of Alberta. Our objective was to assess whether lessons learned from similar scoping investigations in other jurisdictions, combined with the existing geological and gas composition data on hydrogen in natural gas tests in the province, could support an informative first evaluation. As a preliminary investigation, this work provides the foundation for mapping hydrogen potential in the province against key geological features in the WCSB, and for outlining next steps for targeted research, isotopic fingerprinting, and higher-resolution studies.

2. Methodology

The evaluation of Alberta's natural hydrogen potential was conducted using a multidisciplinary approach that included regional structural and stratigraphic analysis, examination of natural hydrogen gas concentrations from energy well data, and geospatial overlay analysis. Publicly available datasets were compiled, including data on lithostratigraphy, tectonic structures, geological formations, mineralogy, and hydrogen concentrations from natural gas samples collected from energy wells. Using these datasets, tables were created to rank the potential of formations for natural hydrogen generation and storage within the WCSB. Hydrogen concentration analysis was then performed on natural gas samples, focusing on wells with hydrogen concentrations exceeding 0.1 %. This analysis helped identify regions with higher potential for natural hydrogen generation and accumulation.

2.1. Regional Geologic and stratigraphic analysis

The analysis was based on the Alberta Table of Formations [42], which offered a detailed geological framework encompassing eight geological regions across the province, covering a majority of the WCSB. The eight geological regions include the Northern Mountains and Foothills, Central Mountains and Foothills, Southern Mountains and Foothills, Southern Plains, West-Central Plains, East-Central Plains, Northwest Plains, and Northeast Plains [42]. This resource offered a detailed overview of Alberta's geological formations within each geological region, highlighting their lithological characteristics, spatial distribution, and relationships. Additional literature was consulted to assess potential natural hydrogen generation processes, migration pathways, and storage and trapping sites, with a focus on critical geological features such as lithology, formations, tectonic features, structural settings, and mineralogy, and their potential occurrence within Alberta's unique geological settings. Additional parameters, such as depth, thickness, and Pressure-Temperature (P-T) conditions, were also examined to explore hydrogen generation processes, migration pathways, and the storage and trapping potential in each geological region.

While the primary focus was on WCSB, the Precambrian Canadian Shield, comprising bedrock, remains a significant source of hydrogen. The presence of deep faults and shear zones that could facilitate hydrogen migration creates pathways for the migration of natural hydrogen generated in the basement or mantle. Additional datasets, including Precambrian basement characteristics, isostatic gravity residuals, and aeromagnetic anomaly maps, were utilized to evaluate the impact of deep geological structures on hydrogen generation and migration.

The feasibility of hydrogen containment in geological systems was evaluated, considering factors such as formation thickness, stratigraphic continuity, and geological stability. Particular emphasis was placed on formations with low-permeability, such as shales and evaporites, which are typically favorable for serving as potential cap rocks, and porous, high-permeability units, such as sandstone and fractured carbonates, which are often suitable for storage. Regional stratigraphic analysis was conducted to identify the distribution, depth, and structural complexity of formations across Alberta. This involved assessing the geological history and depositional environments of the formations to understand how their properties may have evolved over time. Depth and P-T conditions were critical considerations, as they directly influence hydrogen containment, solubility, and the likelihood of its escape through diffusion. Formations at appropriate depths were assessed for their ability to maintain the physical and chemical stability of accumulated hydrogen under subsurface conditions. The suitability of formations for *hydrogen accumulation* was further evaluated through a framework which included metrics such as cap rock integrity, aquifer porosity and permeability, and the compatibility of formation properties with hydrogen storage requirements. Additionally, formations were assessed for their ability to safely contain hydrogen over extended periods, accounting for the gas' high diffusivity and reactivity with surrounding materials.

To ensure the reliability of the analysis, findings were validated by comparing Alberta's geological formations to analogous formations globally recognized for their suitability in gas accumulation. This comparative approach provided insights into best practices for identifying and utilizing formations with similar lithological and structural characteristics. The integration of stratigraphic, and lithological data ensured a robust evaluation of Alberta's potential for natural hydrogen generation and accumulation.

2.2. Gas composition investigations

Hydrogen gas concentration data from publicly available natural gas analysis tests in Alberta [43] were utilized in this study, based on data collected from 22,636 energy wells across the province. Wells with hydrogen concentrations exceeding 0.1 %, a threshold commonly used in global studies [8,9] to assess natural hydrogen potential, were identified for further examination. This threshold was selected because concentrations above 0.1 % generally indicate a meaningful presence of hydrogen in natural gas, suggesting the potential for naturally occurring hydrogen in the subsurface.

For regional context, a recent discovery of 96.4 % high-purity hydrogen in Saskatchewan [30] demonstrates that significant natural hydrogen accumulations are possible in the Western Canadian Sedimentary Basin. The use of a 0.1 % threshold in this study is adapted to Alberta's geological context, where most data derive from routine natural gas analyses. This approach provides a conservative yet meaningful indicator of hydrogen potential while recognizing that higher concentrations may occur locally under favorable geological conditions.

The hydrogen concentration data from natural gas samples was crucial in identifying regions with higher hydrogen concentrations, which are indicative of areas with greater potential for natural hydrogen generation and accumulation. This data was incorporated into the stratigraphic and overlay analysis to highlight and prioritize regions with the highest likelihood of hydrogen occurrence. As a result, the analysis provided a more targeted approach for identifying areas with significant exploration potential, guiding future investigations that could potentially uncover natural hydrogen accumulations.

2.3. Natural hydrogen potential mapping

To create a map illustrating Alberta's natural hydrogen potential, data on hydrogen generation mechanisms, migration, and accumulation characteristics were integrated with spatial geological information for the eight geological regions. A GIS platform was utilized to overlay the spatial extents of the identified geological regions, with corresponding attributes assigned based on the likelihood of hydrogen generation and the formations' suitability for accumulation, as derived from the information gathered in the Alberta Table of Formations [42]. The final map provides a spatial visualization of Alberta's natural hydrogen potential, categorizing each region as having high, moderate, or low potential for the occurrence and preferential accumulation of hydrogen.

To further examine Alberta's natural hydrogen potential, a weighted GIS overlay approach was used to combine various geological, structural, geochemical, and hydrogeological datasets into a single hydrogen potential map. Each dataset was standardized to a uniform grid (100 × 100 m), rasterized, and normalized on a 0–1 scale, where 0 indicates the least favorable and 1 the most favorable conditions for natural hydrogen occurrence. Datasets were split into sub-layers (e.g., Geological & structural controls → geology, tectonic structures, reservoir units, and seal units) and assigned relative importance (critical, useful, and validation) based on geological reasoning and analogues from other studies (e.g., Quebec framework [9], USGS [24]). Critical datasets, including geological formations, lithology, faults, shear zones, lithium, iron, and evaporites, were assigned higher weights. Conversely, useful proxies such as igneous intrusions, bedrock valleys, and glacial landforms received moderate to low weights. Weights were subsequently applied to each normalized raster, and the weighted rasters were aggregated to create a composite hydrogen potential raster. The hydrogen gas concentration dataset was treated as a reference layer for validation, not as a weighted input. Validation was carried out by overlaying measured H_2 concentrations to assess spatial correlation.

3. Results & discussion

3.1. Assessment of natural hydrogen generation and migration potential

The evaluation of geological mechanisms for natural hydrogen generation in Alberta revealed several key processes influenced by specific geological conditions. Serpentinization, a process involving chemical reactions between water and ultramafic rocks, was found to have limited potential due to the sparse occurrence of ultramafic materials in Alberta, which are primarily restricted to isolated areas within the Precambrian Shield. Radiolysis of water, driven by radioactive decay, showed Low to moderate potential, particularly in shale formations with elevated concentrations of uranium, thorium, or potassium. Hydrocarbon decomposition emerged as a highly likely mechanism in deeper sedimentary formations rich in hydrocarbons, where elevated temperatures facilitate the breakdown of hydrocarbons into hydrogen. This classification is supported by the detection of hydrogen in thousands of natural gas samples across Alberta [43] (see Section 3.3), particularly from hydrocarbon-rich formations, and is consistent with published evidence linking organic matter degradation and pyrolysis to hydrogen generation [37]. Water-rock reactions involving iron-rich sediments were also assessed, with moderate potential identified in formations containing iron-bearing sandstones. Pyrolysis of organic material in deeply buried shales presented a high likelihood of hydrogen generation, supported by the abundance of organic-rich shales in the region. Table 1 provides a clear foundation for the evaluation of hydrogen generation mechanisms in Alberta.

Hydrocarbon decomposition and organic matter pyrolysis were identified as high-potential mechanisms, with deep formations containing hydrocarbons or organic-rich shales offering favorable conditions for hydrogen generation. Moderate potential exists for radiolysis and water-rock reactions, particularly in formations with radioactive elements or iron-rich minerals, which provide the necessary conditions for these processes. Conversely, mechanisms such as serpentinization and mantle degassing were deemed to have low potential due to the scarcity of ultramafic rocks and limited tectonic activity within the region. Although this stratigraphic analysis focuses on the sedimentary successions overlying the Canadian Shield, the proximity of the basement to the WCSB must also be considered. For instance, in the Peace River Arch, uplift and faulting bring the Precambrian basement close to WCSB, creating potential pathways for basement-derived hydrogen to migrate upward. Similarly, in northeastern Alberta near the Athabasca region, the sedimentary cover is thin and directly overlies Shield rocks, where radiogenic processes could sustain hydrogen generation. These relationships highlight the importance of examining Shield–basin interactions, which is addressed in more detail later in this manuscript.

Table 2 evaluates the potential for each hydrogen generation mechanism across the eight geological regions in Alberta, as shown on the map, based on geological characteristics and formation types.

The regional assessment of Alberta's potential for natural hydrogen generation identified varying degrees of suitability across different geological regions. High-potential regions, such as the Southern Plains, West-Central Plains, and East-Central Plains, are characterized by abundant organic-rich shales and hydrocarbon reserves (mostly sandstone), making them ideal for processes like hydrocarbon decomposition and pyrolysis. Similarly, the Northern, Central, and Southern Mountains and Foothills regions exhibit justifiable conditions for hydrogen generation, driven by multiple mechanisms, including hydrocarbon decomposition and radiolysis in deep formations. Moderate-potential regions, such as the Northwest Plains and Northeast Plains, were found to be favorable for water-rock reactions with iron-rich sediments and hydrocarbon decomposition. Overall, serpentinization and mantle degassing were identified as low-potential mechanisms across Alberta, with only localized occurrences possible in areas with deep faults and areas where the Canadian Shield is close to WCSB. Despite the relatively low potential, the potential for hydrogen generation and migration to the WCSB from the Precambrian basement and mantle degassing are further evaluated in Section 3.5. This spatial variability underscores the importance of region-specific geological characteristics in determining the feasibility of natural hydrogen generation.

Table 1
Possible Hydrogen generation mechanisms in Alberta.

Hydrogen generation mechanism	Geological indicator	Selected formations/ lithologies in Alberta	Likelihood of occurrence
Serpentinization of Ultramafic Rocks	Ultramafic rocks	Precambrian Shield	Low
Radiolysis of Water	High uranium/ thorium/ potassium content in shales	Precambrian Shield, Exshaw formation	Low to Moderate
Hydrocarbon Decomposition	Hydrocarbon-rich formations	Montney, Cardium, Manville group, Bearpaw, Belly River, McMurray	High
Water-Rock Reactions with Iron-Rich Sediments	Iron-rich sediments	Peace River, Spirit River, Belly River	Moderate
Pyrolysis of Organic Material in Shales	Organic-rich shales	Bearpaw, Lea Park, Smoky, Wapiabi, Fernie, Colorado group, and Clearwater	High

3.2. Assessment of natural hydrogen accumulation potential

For natural hydrogen accumulation, key considerations shift slightly compared to CO_2 accumulations. Hydrogen requires highly impermeable cap rocks to prevent escape, as its a small, highly diffusive molecule. Suitable cap rocks (seal) formations require dense, low-porosity materials, such as clay-rich shale, and evaporites. Porous formations, like sandstone, with limited fractures and highly fractured carbonate rocks, are suitable for storage aquifers.

Building upon the regional analysis of geological mechanisms for natural hydrogen generation, the next phase of this investigation evaluates the potential of specific geological formations to act as cap rocks (seals) or storage for hydrogen accumulation. Unlike the earlier region-based approach, this analysis focuses on formations that are geologically continuous across multiple *geological* regions. The assessment integrates insights from the Alberta Table of Formations [42] and previously developed data tables to systematically evaluate the suitability of each formation for hydrogen storage and seal based on four key considerations. These include (i) geological time and lithology, (ii) geological and thermodynamic parameters, (iii) leakage and diffusion risk, and (iv) comparative suitability against CO_2 storage. This structured approach transitions from identifying mechanisms of hydrogen generation to evaluating formation-specific properties critical for hydrogen accumulation (storage and seal).

3.2.1. Geological time and lithology

Adding geological time and lithology context will provide insights into the historical suitability and stability of formations across Alberta for hydrogen accumulation. The formations in Alberta vary significantly in age, lithology, and consolidation, which impact their hydrogen containment capabilities. Table 3 shows how different periods, and lithological characteristics contribute to the potential of each formation.

The analysis highlights key candidates for hydrogen accumulations, emphasizing both cap rock and storage potential. Upper Cretaceous formations such as the Bearpaw, Lea Park, Wapiabi, and Kaskapau shales emerge as excellent cap rocks due to their impermeability and extensive consolidation over millions of years. Sandstone formations from the same period, including the Dunvegan, Spirit River, and Cardium, show promise as reservoirs owing to their porosity, provided they are paired with overlying cap rocks. The Triassic Montney Formation, consisting of sandstone and siltstone interbedded with shale, demonstrates versatility with its moderate impermeability, offering potential as both a cap rock and a reservoir depending on the layer's specific characteristics. Additionally, Devonian limestone formations such as Slave Point and Leduc, with their low porosity and stability, present strong cap rock potential if fractures are minimal. Furthermore, Devonian salt deposits, the Elk Point Group - Prairie evaporites, Cold Lake, and Lotsberg, have an excellent potential to act as cap rocks due to low permeability, substantial thickness, and lateral continuity.

3.2.2. Geological and thermodynamic parameters

To further refine the assessment of Alberta's geological formations for hydrogen accumulations, additional geological and thermodynamic

Table 2
Hydrogen generation potential by geologic regions in WCSB.

Region	Serpentinization of ultramafic rocks	Radiolysis of water	Hydrocarbon decomposition	Water-rock reactions with Iron-rich sediments	Pyrolysis of organic material in Shales
Northern Mountains and Foothills	Low – Limited ultramafic material	Moderate – Potential in Exshaw	Moderate – Hydrocarbon-rich Cardium formation	Low – Lack of iron-rich sandstone	Moderate – Potential in Smoky
Central Mountains and Foothills	Low – Limited ultramafic material	Moderate – Potential in Exshaw	Moderate – Hydrocarbon-rich Cardium formation	Low – Lack of iron-rich sandstone	Moderate – potential in Alberta
Southern Mountains and Foothills	Low – Limited ultramafic material	Moderate – Potential in Exshaw	Moderate to High – Hydrocarbon-rich Cardium and Bearpaw formations	Low – Lack of iron-rich sandstone	Moderate – potential in Fernie and Wapiabi
Southern Plains	Low – Limited ultramafic material	Moderate – Potential in Exshaw	High – Rich hydrocarbon presence in Mannville group, Cardium, and Bearpaw	Moderate – Iron-bearing Belly River	High – Bearpaw, Lea Park and Wapiabi shales
West-Central Plains	Low – Limited ultramafic material	Moderate – Potential in Exshaw	High – Rich hydrocarbon presence in Mannville group, Montney, Cardium, and Bearpaw, Belly River	High – Sandstones in Peace River and Spirit River	High – Bearpaw, Lea Park and Wapiabi shales
East-Central Plains	Low – Limited ultramafic material	Low – lack of High uranium/thorium/potassium	High – Rich hydrocarbon presence in Mannville group, Cardium, Bearpaw, and Belly River	Moderate – Iron-rich sediments in Belly River	High – Organic material in Bearpaw, Colorado group, Lea Park
Northwest Plains	Low – Limited ultramafic material	Low – lack of High uranium/thorium/potassium	Moderate – Cardium, Montney, hydrocarbon presence	High – iron bearing sediments in Peace River and Spirit River	High – Shale potential in Bearpaw, Lea Park
Northeast Plains	Low – Limited ultramafic material	Low – lack of High uranium/thorium/potassium	High – McMurray, Clearwater hydrocarbon-rich	Moderate – Iron-rich sediments in McMurray and Grand Rapids	High – Abundant organic shales in Colorado and Clearwater

parameters such as depth, thickness, and regional P-T conditions were evaluated. Depth is a critical factor, as greater depths typically provide higher overburden pressure, enhancing the containment of hydrogen in its molecular state and reducing the risk of leakage. Thickness contributes to both containment and storage capacity, with thicker formations offering a larger volume of rock that can serve as a robust barrier or expansive reservoir. Regional P-T conditions also play a significant role, as pressure enhances hydrogen retention within reservoirs, while temperature influences hydrogen mobility and its potential interactions with surrounding minerals. Table 4 shows the cap rock (seal) efficiency and aquifer suitability based on depth, thickness, and P-T conditions.

The analysis highlights the varying suitability of formations for hydrogen containment and storage. Deep formations such as Montney, Slave Point, and Leduc exhibit high-pressure conditions at great depths, making them ideal for containment. Montney offers dual potential as a cap rock and reservoir, while the thick carbonate structure of the Leduc and Slave Point Formations and the salt deposits from the Elk Point Group support their stability as cap rocks. Moderately deep formations like the Kaskapau, Colorado Group, and Mannville Group balance pressure and temperature conditions. The Kaskapau and Colorado Group shales act as excellent cap rocks, while Mannville's porous sandstones offer storage potential. Relatively shallower formations, including Bearpaw and Lea Park, are characterized by thick, low-permeability shales that maintain containment potential despite reduced pressures at shallow depths.

3.2.3. Leakage and diffusion risk

Creating a risk matrix for hydrogen leakage and diffusion involves evaluating each formation's geological characteristics that impact containment security. Key factors influencing leakage and diffusion risk include permeability, fracturing, lithology, and formation consolidation. Table 5 shows a structured risk matrix, ranking formations by low, moderate, or high leakage and diffusion risk.

Low-risk formations such as Bearpaw, Lea Park, Colorado, Wapiabi, and Kaskapau exhibit thick, dense shale layers with excellent sealing properties, reducing the likelihood of hydrogen diffusion. These well-consolidated shales, combined with moderate depths, make them ideal candidates for safe containment. Devonian salt deposits, including the Elk Point Group - Prairie evaporites, Cold Lake, and Lotsberg, are also excellent candidates for hydrogen containment due to their low permeability, substantial thickness, and lateral continuity. However, localized salt dissolution can cause collapse features and secondary porosity that greatly increase leakage risk. Moderate-risk formations, including Leduc, Montney, Mannville, Spirit River, and Dunvegan, present a mix of lithologies or potential fractures. While their depth and partial sealing from interbedded layers offer some containment, careful monitoring would be necessary to mitigate leakage risks. High-risk formations like Cardium, McMurray, Clearwater, and Grand Rapids are characterized by shallow depths, sandy lithologies, and inconsistent cap rock layers, significantly increasing the risk of hydrogen diffusion and leakage. To address these risks, enhanced monitoring techniques, such as regular pressure and gas composition checks, are recommended for high-risk formations. Additionally, engineering solutions, including synthetic cap rocks or advanced sealing techniques, could improve containment in formations where natural cap rocks are inadequate. This risk-based evaluation provides a framework for selecting suitable formations for hydrogen storage, balancing geological suitability with mitigation strategies to address potential diffusion and leakage challenges.

3.2.4. Key differences and requirements for hydrogen vs. CO_2 storage

Table 6 outlines the specific requirements and differences between hydrogen and CO_2 storage. Since hydrogen is a smaller, more diffusive molecule than CO_2, it has unique storage needs, particularly regarding cap rock permeability, sealing integrity, and formation porosity and permeability. This table explains why certain formations may differ in suitability for hydrogen storage compared to CO_2.

The suitability of Alberta's geological formations for hydrogen and CO_2 storage varies based on lithology, depth, and permeability. Formations such as Bearpaw, Lea Park, Kaskapau, and Colorado Group, with their thick, low-permeability shales, provide excellent sealing properties for hydrogen storage. Their depth and thickness ensure that hydrogen, despite its high diffusivity, can be effectively contained. In addition to these formations, salt deposits within the Elk Point Group are also excellent candidates for long-term hydrogen storage. On the other hand, formations like Mannville, Cardium, and Spirit River, with high-porosity sandstones, are better suited for CO_2 storage. These formations offer adequate sealing for CO_2 at moderate depths but lack the extremely low permeability required for hydrogen containment. Some formations, such as Montney, show dual suitability for both hydrogen and CO_2 storage due to their mixed lithologies and moderate permeability.

Table 3
Geological time and lithology context for key geological formations.

Formation/Group	Geological period/epoch	Age (Million Years)	Lithology	Hydrogen storage relevance
Bearpaw	Upper Cretaceous	65.5–83.5	Shale	Highly impermeable shale provides excellent cap rock potential due to fine grain size and consolidation.
Lea Park	Upper Cretaceous	80.6–83.5	Shale	Dense shale with low permeability, ideal as a cap rock.
Colorado Group	Cretaceous	83.5–108.8	Primarily Shale	Thick shale units are well consolidated, ideal for hydrogen containment.
Wapiabi	Upper Cretaceous	70.6–90	Shale	Deep, extensive shale serves as a strong hydrogen seal; well-consolidated due to geological age.
Dunvegan	Upper Cretaceous	93.6–99.6	Sandstone	Sandy aquifer potential, but less effective as a cap rock. Mixed lithology reduces overall hydrogen sealing ability.
Spirit River	Lower Cretaceous	106.4–108.8	Sandstone	Contains sandy aquifers; limited hydrogen sealing capability due to mixed lithology.
Kaskapau	Upper Cretaceous	85.8–93.6	Shale	Dense, thick shale layers provide excellent hydrogen cap rock potential.
Montney	Triassic	247–252	Sandstone	Well consolidated; suitable for both aquifer and cap rock in specific layers.
Cardium	Upper Cretaceous	65.5–99.6	Sandstone	Primarily a high-porosity aquifer, suitable for hydrogen storage but not as a cap rock.
Mannville Group	Lower Cretaceous	99.6–145.5	Primarily Sandstone	Contains porous sandstones for storage, though shale layers are less continuous as cap rocks.
McMurray	Lower Cretaceous	113–126	Sandstone	Sandstone aquifer potential with interbedded shale layers and bitumen for partial sealing; requires additional cap rocks or thick bitumen accumulations.
Clearwater	Lower Cretaceous	100–125	Shale	Predominantly shale and mudstone with subordinate siltstone, with limited cap rock potential.
Grand Rapids	Lower Cretaceous	95–113	Sandstone	Sandy aquifers with partial sealing from shale interbeds; may require additional cap rock.
Slave Point	Middle Devonian	385.3–397.5	Limestone	Highly consolidated carbonate rock with low porosity; potential as cap rock if impermeable enough.
Leduc	Upper Devonian	374.5–385.3	Limestone	Well-cemented limestone and dolostone, offering low permeability suitable as cap rock if unfractured.
Keg River	Middle Devonian	385.3–391.8	Limestone	The Rainbow member reefs offer good hydrogen storage potential due to porous, fractured carbonates, while the overlying Prairie Evaporite (Limestone and dolostone ± sandstone interbedded with anhydrite) provides an excellent caprock
Prairie Evaporite (Elk Point)	Middle Devonian	382.7–387.7	Halite	Coarse to fine crystalline halite interbedded with variable amounts of shale, anhydrite, and dolomite; Potential cap rock.
Cold Lake (Elk Point)	Lower Devonian	391.8–397.5	Halite	Very coarse crystalline halite interbedded with basal red calcareous to dolomitic shale; Potential cap rock.
Lotsberg (Elk Point)	Lower Devonian	385.3–397.5	Halite	Very coarse crystalline halite interbedded with red and green calcareous shale; Potential cap rock.

3.2.5. Focus on strategic formations/groups

Alberta's Bearpaw, Lea Park, and Kaskapau formations, as well as the salt units of the Elk Point Group are prime candidates for hydrogen containment due to their robust cap rock potential, with characteristics that align closely with successful storage sites worldwide (Table 7). The Bearpaw Formation, which is Upper Cretaceous in age, consists of thick, dense shale interspersed with minor siltstone and sandstone. Its extremely low permeability, a result of the fine-grained and compacted shale, enhances its ability to prevent hydrogen diffusion. The low to moderate depth supports a stable pressure environment, minimizing the risks of destabilizing hydrogen. Global case studies support Bearpaw's potential; for example, the Tuscaloosa Marine Shale in the U.S. Gulf Coast [45], with a similar compact, organic-rich shale structure, has shown high containment effectiveness for gases in lab studies. Similarly, the Upper Jurassic shale in the Paris Basin, France [46], has demonstrated successful long-term natural gas storage, supporting Bearpaw's viability as a hydrogen cap rock.

The Lea Park Formation, also late Cretaceous, is primarily shale with minor siltstone, contributing to dense and continuous sealing properties. The very low permeability of the shale enhances its sealing ability. Case studies further validate Lea Park's potential; the Netherlands Rotliegend Shale [47], used for natural gas storage, shares similar depth and

Table 4
Analysis of cap rock efficiency and aquifer suitability based on geological and thermodynamic parameters.

Formation/Group	Depth (m)	Thickness (m)	Pressure-Temperature (P-T) Conditions	Cap rock efficacy	Aquifer suitability
Bearpaw	Near surface to a few 100 m	183–230	Low P -T conditions	High – Thick shale, stable at moderate depths	Low – Low porosity, unsuitable for storage
Lea Park	hundreds to ~1200 m	152–270	Moderate P-T conditions	High–density shale with good sealing ability	Low – Primarily a cap rock
Colorado Group	100 s m to ~1000 m+	150–1000	Low to Moderate P-T conditions	High – Thick shale layers with low permeability	Low – Shale dominated, unsuitable for storage
Wapiabi	Near surface to several 100 m	319–640	Low P -T conditions	High – Deep, dense shale, good containment	Low–density shale, not suitable as an aquifer
Dunvegan	Outcrop to ~800 m	160–180	Low P -T conditions	Low – Mixed lithology, limited sealing	Moderate – Suitable as an aquifer
Spirit River	1000 m+ (Deep)	~348	Moderate to High P-T conditions	Low – Limited by sandier layers	High – Sandstone aquifer potential
Kaskapau	hundreds to >1500 m	160–900	Low–Moderate P -T conditions	High – Thick shale with strong containment	Low – Primarily suitable as a cap rock
Montney	1000 – >2500 m	200–280	Moderate to High P-T conditions	Moderate – Mixed lithology, some permeability	High–depth and P-T favorable for storage
Cardium	500–1500 m	22.6–108.8	Moderate P-T conditions	Low – Sandstone dominated, not suitable for cap rock	High – High porosity, good aquifer potential
Mannville Group	Near surface to several 100 m	~144.8	Low to Moderate P–T conditions (depends on location)	Moderate – Some shale layers, limited seal	High – High porosity, good aquifer potential
McMurray	Near surface to ~600 m	Up to 130	Low P -T conditions	Low – Limited sealing, shallow depth	Moderate – Aquifer potential with shale beds
Clearwater	Shallow to ~1000 m	Up to 85	Low to moderate P-T conditions	Low – Inconsistent shale layers	Low – interbedded sandy layers for limited aquifer use
Grand Rapids	Near surface to a few 100 m	Up to 90	Low P -T conditions	Low – Limited sealing with mixed lithology	Moderate – Aquifer potential
Slave Point	1000–2500 m (Deep basin)	30–120	Moderate to High P-T conditions	Moderate – Carbonate rock, unfractured areas only	Low – Less porosity, suitable as cap rock
Leduc	>1200 m (commonly deeper)	180–300	Moderate–High P -T conditions	High – Consolidated carbonate, good sealing	Low – Low porosity, suitable for cap only
Keg River	Deep Basin	10–300	Moderate–High P -T conditions	High – Consolidated carbonate, good sealing	Highly fractured carbonate rocks
Prairie Evaporite (Elk Point)	Several 100s to >1500 m	Up to 218	Moderate P-T conditions	High – Continuous layers of halite.	Low – Low porosity, suitable for cap only
Cold Lake Formation (Elk Point)	Several 100s–1000 m	56–117	Low to Moderate P-T conditions	High – Continuous layers of halite	Low – Low porosity, suitable for cap only
Lotsberg (Elk Point)	Several 100s to >1000 m	Up to 229	Moderate P-T conditions	High – Continuous layers of halite	Low – Low porosity, suitable for cap only

lithological properties, including low permeability and high shale content. The Mancos Shale in the San Juan Basin, USA [48], assessed for natural gas storage, also shows similar structural integrity to Lea Park, reinforcing the suitability of Lea Park for hydrogen containment.

The Kaskapau Formation, primarily composed of dense shale with interbedded siltstone providing sufficient overburden pressure for hydrogen containment. The low permeability of the Kaskapau Formation's shale structure is essential for trapping hydrogen. Research on similar formations, such as Bowland Shale in the UK [49], which has shown promising containment potential for hydrogen, supports Kaskapau's viability as a hydrogen storage formation.

The Elk Point Group, characterized by thick sequences of halite and other evaporite minerals, presents excellent potential for hydrogen storage. Its low permeability and ductile behavior allow it to act as a cap rock, preventing the upward migration of hydrogen. The substantial thickness and lateral continuity of the Elk Point Group enhance its sealing capacity, providing a reliable barrier. Similar evaporite formations worldwide [50,51] have proven effective in trapping gases, further supporting the suitability of the Elk Point Group as one of the target areas for hydrogen storage in Alberta.

3.3. Hydrogen concentration in natural gas samples

3.3.1. Hydrogen distribution in the WCSB

Oil and gas exploration data from the WCSB across Alberta provide critical insights into the occurrence and distribution of migrating gases in the subsurface. A review of publicly available databases [43] identified 40,424 gas analyses from 22,636 wells, of which approximately 89.6 % (20,285 wells) included at least one hydrogen analysis, totalling 34,373 hydrogen analyses. In addition to hydrogen, the dataset included information on other key gases such as helium (He), nitrogen (N_2), carbon dioxide (CO_2), and hydrocarbons (C_1–C_7), which are important for assessing fluid origins and potential hydrogen generation or migration pathways.

The vast majority (92.3 %) of measured hydrogen concentrations were below 0.001 mol fraction (0.1 %), indicating that background levels of hydrogen are generally low. However, a subset of the data revealed notable hydrogen concentrations: 2643 analyses from 2292 energy wells reported hydrogen concentrations exceeding 0.1 %, 430 analyses from 374 wells recorded concentrations above 1.0 %, and 50 analyses from 46 wells showed hydrogen concentrations exceeding 10 % (Fig. 1). These elevated concentrations are of particular interest, as they may indicate localized conditions conducive to hydrogen generation and/or accumulation. For reference, a spatial map showing the locations of all sampling points is included in Supplementary Material (Fig. S1).

The distribution of wells with significant hydrogen concentrations is illustrated in a spatial maps, providing insights into regional variations (Figs. 2 and 3). As observed, a significant number of samples with hydrogen concentrations above 10 % are concentrated in the west-central plains, suggesting localized geological conditions favorable for hydrogen accumulations. In contrast, samples with concentrations exceeding 1 % and 0.1 % are more widespread across the province, occurring frequently across the northwest plains, west-central plains, east-central plains, and southern plains. These preliminary findings highlight the variability in hydrogen presence across different geological regions, emphasizing the need for further assessment of the underlying controls, such as reservoir lithology, structural features, and potential hydrogen migration pathways.

Table 5
Hydrogen leakage and diffusion risk matrix for Alberta formations.

Formation/Group	Risk & mitigating characteristics	Leakage and diffusion risk
Bearpaw	Fine-grained dense shale with low permeability; well-consolidated	Low
Lea Park	Thick, continuous shale; good sealing properties with low permeability; limited fracturing	Low
Colorado Group	Well-consolidated thick shale layers with low permeability	Low
Wapiabi	Thick, extensive shale with low permeability	Low
Kaskapau	Thick continuous shale with low permeability; well-consolidated	Low
Cold Lake (Elk Point)	Continuous salt deposit with variable non-salt materials	Low
Lotsberg (Elk Point)	Thick, continuous salt deposits with variable non-salt materials	Low
Prairie Evaporite (Elk Point)	Thick, continuous salt deposit with variable non-salt materials; Salt dissolution	Low to Moderate
Leduc	High consolidation; thick, deep carbonate; may have fractures	Low to Moderate
Montney	Mixed lithology with some sandstone	Moderate
Mannville Group	Mixed sandstone and shale, with some discontinuities	Moderate to High
Spirit River	Limited cap rock properties due to sandy composition	Moderate to High
Dunvegan	Limited hydrogen sealing capability due to mixed lithology	Moderate to High
Cardium	High porosity allows for easier hydrogen escape; limited shale an effective cap rock	High
McMurray	Porous sandstone with limited sealing potential	High
Clearwater	Predominantly shale and mudstone with subordinate siltstone, with limited cap rock potential.	High
Grand Rapids	Sandy aquifers with partial sealing from shale interbeds	High

A more detailed investigation was conducted for all wells with hydrogen concentrations greater than 5 %. For these wells, the total depth was compared with geological maps and publicly available datasets to identify the producing formation. Although information was missing for approximately 30 % of the wells, we were able to compile a list of the producing formations for most wells with hydrogen concentrations above 5 %. Among the producing formations with the highest occurrence of natural gas samples with more than 5 % hydrogen, the most prominent were Leduc (14), Mannville (7), Slave Point (5), and Keg River (4). Other formations with at least three occurrences included Beaverhill Lake, Gething, Mount Head, and Cummings.

To better understand the spatial patterns and significance of hydrogen occurrences, stratigraphy analysis and spatial overlay were performed, integrating geological and geospatial parameters with hydrogen concentration data (Figs. 2 and 3). This approach has enabled the identification of regions with anomalously high hydrogen concentrations and highlighted areas where further investigation may be warranted. By incorporating multiple layers, this analysis provides a more comprehensive understanding of the factors influencing hydrogen distribution, aiding in the identification of potential exploration targets.

3.3.2. Hydrogen association with other gases

The correlation analysis between H_2 and other gases provides valuable insights into potential formation mechanisms and subsurface associations. The results show weak positive correlations between H_2 and H_2S (+0.13), He (+0.09), N_2 (+0.07), and CO_2 (+0.07) (Table 8). These low positive correlations are more likely to reflect post-generation alteration processes, such as microbial consumption or water–rock interactions, rather than indicating shared genetic origins.

In contrast, hydrogen exhibits a weak negative correlation with CH_4 (−0.15), while methane also shows strong negative correlations with

Table 6
Comparative analysis: Hydrogen vs. CO_2 Storage requirements in Alberta formations.

Requirement	H_2 Storage	CO_2 Storage	Implications for Formation Suitability
Molecular size and diffusivity	Small, highly diffusive; prone to leakage	Larger, less diffusive; better containment	Hydrogen requires higher impermeability and thicker cap rocks to prevent diffusion
Cap rock permeability	Extremely low permeability needed	Moderate to low permeability sufficient	Formations like Bearpaw and Kaskapau are ideal for hydrogen due to dense shale; Salt deposits from the Elk Point Group are also excellent candidates; CO_2 can use formations with slightly higher permeability, like Colorado Group
Porosity in aquifer layers	Moderate porosity preferred for hydrogen retention	High porosity is preferred for CO_2 to enhance storage volume	Low to moderate porosity formations, such as Montney, are more suited to hydrogen storage; high-porosity formations (e.g., Cardium) suit CO_2
Cap rock thickness	Requires thicker cap rock due to hydrogen's higher mobility	Moderate thickness usually sufficient	Thick shales like in Bearpaw, Lea Park, and Colorado provide better containment for hydrogen
Depth	Deep (1500+ m) ideal to maintain hydrogen in a molecular state under pressure	Moderate to deep (800+ m)	Deeper formations (e.g., Montney and Leduc) are more suitable for hydrogen, while CO_2 can be stored at moderate depths (1000 m)
Temperature sensitivity	Low to moderate temperatures; high temperatures increase reactivity and mobility	Moderate to high temperatures generally acceptable	Low-temperature formations like Bearpaw and Lea Park are better for hydrogen, while CO_2 can tolerate a wider temperature range
Sealing integrity	Must withstand hydrogen's ability to escape through minor fissures	Moderate to high integrity, but minor cracks can be tolerable	Hydrogen requires higher sealing integrity; formations with continuous, unfractured layers and salt deposits are more suitable
Chemical reactivity with formation	Reactive, can be affected by certain minerals, especially iron	Relatively inert in most sedimentary formations	Sandstone formations with reactive minerals are less ideal for hydrogen storage, whereas they're suitable for CO_2
Safety and leakage concerns	High sensitivity to leakage due to flammability and diffusivity	Moderate, with heavier gas allowing for easier monitoring	Hydrogen storage requires intensive leakage monitoring and risk management; CO_2 storage is easier to monitor and less prone to accidental release

Table 7
Summary of strategic formations for gas storage.

Formation	Lithology (Primary)	Depth (m)	Thickness (m)	Comparative case studies	Containment potential
Bearpaw	Shale	Near surface to a few 100 m	183–230	Tuscaloosa Shale (USA), Paris Basin Shale (France)	High – Thick shale, ideal depth for stability
Lea Park	Shale	Hundreds to ~1200 m	152–270	Rotliegend Shale (Netherlands), Mancos Shale (USA)	High – Continuous, low-permeability shale
Kaskapau	Shale	hundreds to >1500 m	160–900	Bowland Shale (UK)	High – Deep, thick shale structure
Elk Point Group	Halite	Several 100s to >1500 m	56–229	Thick salt deposits in various geological settings (Spain, China, and the USA)	High – Continuous, very low-permeability salt units

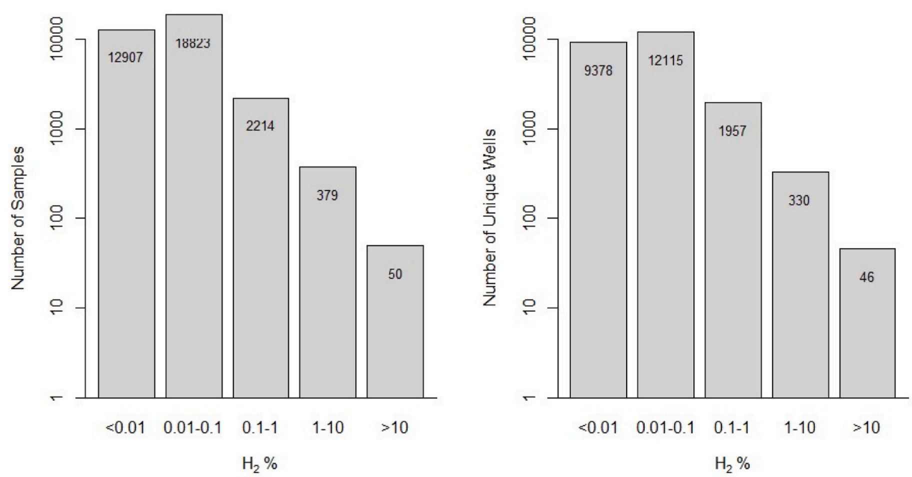

Fig. 1. Distribution of the total number of samples and unique wells from gas composition analysis in natural gas samples across different hydrogen concentration ranges.

both N_2 (−0.64) and CO_2 (−0.44). Rather than indicating distinct genetic pathways, these negative relationships are more plausibly explained by dilution effects, where the relative abundance of CH_4 (dominant gas) reduces the apparent concentrations of H_2. This interpretation highlights the importance of considering compositional mixing when evaluating hydrogen associations in subsurface gas datasets.

Taken together, these relationships imply that hydrogen is more likely to occur in specific geological settings where nitrogen, helium, and carbon dioxide are also present. The inverse relationship with methane further suggests that hydrogen may be more prevalent in non-hydrocarbon-associated environments. Understanding these correlations not only offers insights into the formation mechanisms of hydrogen but also aids in identifying favorable geological conditions for its accumulation, providing valuable targets for future exploration.

3.3.3. *Considerations and potential biases*

While the existing data provides valuable insights, hydrogen concentration data must be interpreted carefully due to various biases. The dataset used is primarily based on analyses targeting helium concentrations greater than 0.1 %, rather than a comprehensive evaluation of hydrogen alongside hydrocarbons. This discrepancy in sampling methods could lead to underreporting or inconsistent hydrogen measurements, particularly in regions where accurate hydrogen data is crucial for exploration. Additionally, the geographical distribution of the dataset is not ideally suited for natural hydrogen exploration, as certain areas may be underrepresented, potentially limiting the broader applicability of the results.

Moreover, as indicated by previous investigations [9,44] hydrogen detected in gas samples may also result from non-geological sources such as drilling operations, microbial-induced corrosion, metal corrosion, which can potentially lead to 'false positives'. These factors introduce the risk of misattributing detected hydrogen to geological sources when it may not be of natural origin. Other potential sources of bias include energy well completion and sampling factors, as hydrogen may preferentially accumulate at the top of the well casing headspace, leading to elevated concentrations that may not reflect true subsurface anomalies.

Despite these limitations, the gas composition data holds significant value in advancing our understanding of natural hydrogen potential in the province. It provides a useful starting point for exploration, but future investigations must address these challenges. Key priorities for future studies include verifying whether the detected hydrogen concentrations in wells represent true anomalies and distinguishing between natural and anthropogenic (non-natural) sources. This will require not only extensive field sampling but also a systematic review of historical gas composition records and well reports to eliminate false positives. In addition, stable isotope, complete gas composition, and noble gas analyses should be incorporated to strengthen source attribution and provide additional lines of evidence for hydrogen's natural provenance. By refining sampling techniques, expanding geographical coverage, and carefully evaluating the potential sources of hydrogen, future research can more accurately assess the potential for natural hydrogen as a resource.

3.4. *Natural hydrogen potential mapping in the WCSB*

The assessment of Alberta's geological regions highlights significant variability in the potential for natural hydrogen generation and accumulation. Key hydrogen generation mechanisms, including hydrocarbon decomposition, water-rock reactions with iron-rich sediments, and organic pyrolysis, are closely linked to the lithological and structural characteristics of each region. Regions such as the Southern Plains, West-Central Plains, and East-Central Plains show high potential due to their abundant organic-rich shales, extensive hydrocarbon reservoirs,

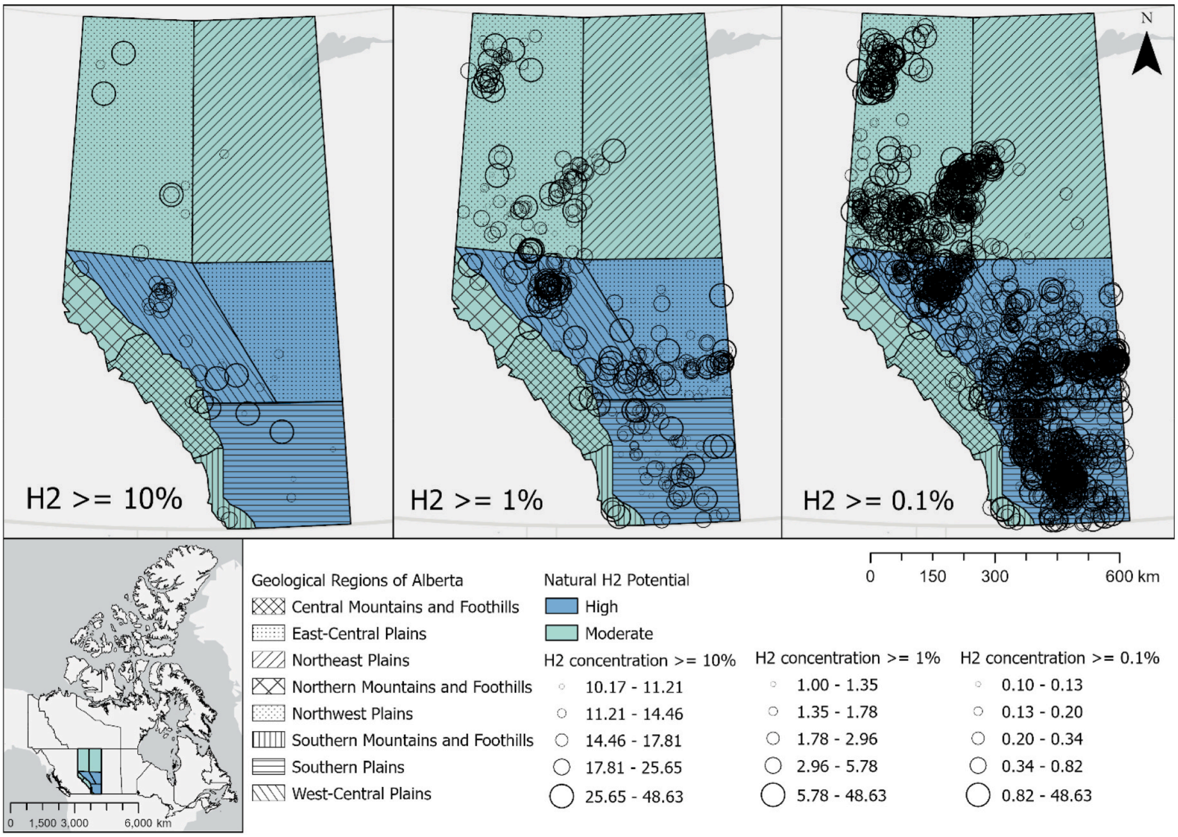

Fig. 2. Spatial map illustrating the potential for natural hydrogen occurrence across the eight geological regions of the province and the distribution of hydrogen concentrations greater than 10 %, 1 %, and 0.1 % in natural gas samples.

and the presence of thick, impermeable cap rocks paired with suitable aquifers. Moderate potential was identified in the Northern, Central, and Southern Mountains and Foothills, as well as the Northwest and Northeast Plains, where favorable mechanisms exist but are limited by less continuous cap rocks or shallower aquifers. Table 9 summarizes the hydrogen generation and accumulation potential across Alberta's geological regions, categorizing them into high, and moderate potential based on their geological characteristics and suitability for hydrogen-related processes derived from the Alberta Table of Formations [42]. Hydrogen generation mechanisms, such as hydrocarbon decomposition, radiolysis, and water-rock interactions, were evaluated in conjunction with key geological indicators, including organic-rich shales, hydrocarbon reservoirs, iron-rich sediments, and ultramafic rocks. Storage suitability was assessed by examining the presence of thick, impermeable cap rocks, high-porosity aquifers, and stratigraphic continuity. Regions were assigned an overall potential—high, moderate, or low—by integrating these factors. High-potential regions exhibit optimal conditions for both hydrogen generation and accumulations, while moderate-potential regions have some favorable characteristics but face limitations, such as less extensive cap rocks or shallower aquifers. This table serves as a comprehensive framework for visualizing the spatial distribution of Alberta's hydrogen potential.

The final spatial map of natural hydrogen potential in the WCSB, derived from stratigraphic analysis, provides a comprehensive view of the varying potential for hydrogen occurrence across Alberta (Fig. 2). The analysis highlights three primary regions with the highest natural hydrogen potential: the West-Central Plains, East-Central Plains, and Southern Plains. These geological regions stand out due to their favorable geological and geophysical conditions, which include the presence of potential source rocks, reservoirs, and other structural features that could facilitate hydrogen migration and accumulation. These geological settings make these regions particularly promising for further exploration and potential development of natural hydrogen resources.

The West and East Central Plains region has been identified as a high-priority area, with a combination of geological features that support the potential for significant hydrogen generation and accumulation. In contrast, the Northern Plains exhibit moderate potential for hydrogen, with regional conditions less conducive to widespread hydrogen generation. However, it is important to note that within this area, there are localized occurrences of elevated hydrogen concentrations, suggesting that certain geological settings could enhance hydrogen accumulation in some areas. These localized anomalies may be linked to the proximity of faults, deep sources, or other structural features that provide preferential pathways for hydrogen migration. This highlights the complex interplay between regional geological factors and localized structural settings, which could potentially lead to hydrogen occurrences even in areas with generally lower potential.

Further investigation into the areas exhibiting elevated hydrogen concentrations is essential. By focusing on these regions, particularly those near fault systems or other anomalies, future studies could provide more detailed insights into the factors that control hydrogen generation, migration, and accumulation in the WCSB. Such targeted exploration efforts will be critical for refining the overall assessment of natural hydrogen potential and identifying high-priority areas for future development in the region.

The integration of geological, structural, magmatic, mineralogical, and hydrogeological datasets into a weighted overlay framework provides the foundation for high-resolution mapping of Alberta's natural hydrogen potential. Table 10 provides a summary of the datasets employed, including their rationale, significance, and the weights allocated to each group of layers. The weighting scheme guarantees that the model accurately reflects both the primary geological factors influencing hydrogen generation and storage, as well as auxiliary proxies that offer indirect evidence of optimal conditions.

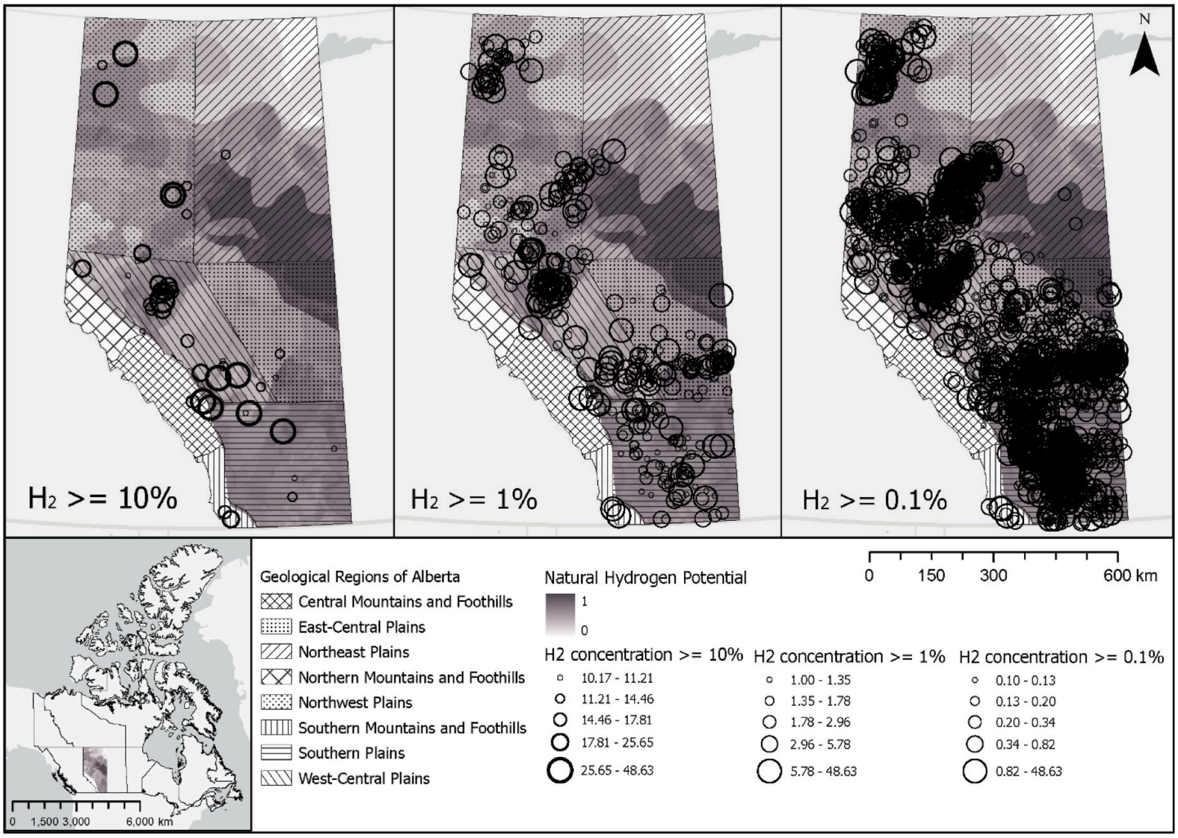

Fig. 3. Relative hydrogen potential surface of Alberta from weighted overlay analysis (0 indicates the least favorable and 1 the most favorable conditions for natural hydrogen occurrence).

Table 8
Correlation matrix of gas concentrations in natural gas samples.

	H_2	He	N_2	CO_2	H_2S	CH_4	C2–C7
H_2	+1.00						
He	**+ 0.09**	+1.00					
N_2	+0.07	+0.18	+1.00				
CO_2	+0.07	+0.02	+0.04	+1.00			
H_2S	**+ 0.13**	+0.03	−0.03	+0.15	+1.00		
CH_4	**−0.15**	−0.19	−0.64	−0.44	−0.27	+1.00	
C2–C7	+0.01	+0.08	+0.18	+0.14	+0.08	−0.77	+1.00

Geological and structural controls make up 55 % of the total weight, highlighting their essential role in controlling hydrogen generation, migration, and accumulation. Within this category, geologic formation and lithology were highlighted as one of the important factors, since felsic basement rocks can produce hydrogen through radiolysis, while mafic and ultramafic units are susceptible to serpentinization reactions. Reservoir formation units, including porous sandstones and fractured carbonates, were assigned considerable importance due to their role in storage. Additionally, seals such as thick shale and evaporite formations were regarded as essential for retention. Tectonic features—including faults, shear zones, and basement arches—were highlighted as major conduits, influencing the migration of hydrogen.

Magmatic and mineral indicators collectively contribute 25 % of the

Table 9
Summary of spatial distribution for Alberta's hydrogen potential.

Geological Region	Hydrogen generation mechanisms	Key geological indicators	Storage suitability	Overall potential
Southern Plains	Hydrocarbon decomposition, radiolysis, water-rock reactions, pyrolysis	Organic-rich shales, Radioactive minerals, iron-rich formations, hydrocarbon-rich formations	Thick, impermeable cap rocks paired with high-porosity sandstone aquifers	High
West-Central Plains	Hydrocarbon decomposition, radiolysis, water-rock reactions, pyrolysis	Organic-rich shales, Radioactive minerals, iron-rich formations, hydrocarbon-rich formations	Cap rocks with low permeability and extensive sandstone aquifers	High
East-Central Plains	Hydrocarbon decomposition, water-rock reactions, pyrolysis	Organic-rich shales, iron-rich formations, hydrocarbon-rich formations	Strong sealing formations with thick cap rocks and interconnected aquifers	High
Northern Mountains and Foothills	Hydrocarbon decomposition, radiolysis, pyrolysis	Organic-rich shales, Radioactive minerals, hydrocarbon-rich formations	Moderate sealing and storage capacity	Moderate
Central Mountains and Foothills	Hydrocarbon decomposition, radiolysis, pyrolysis	Organic-rich shales, Radioactive minerals, hydrocarbon-rich formations	Moderate sealing and storage capacity	Moderate
Northwest Plains	Hydrocarbon decomposition, water-rock reactions, pyrolysis	Organic-rich shales, iron-rich formations, hydrocarbon-rich formations	Limited cap rock continuity; aquifer suitability varies by location	Moderate
Northeast Plains	Hydrocarbon decomposition, water-rock reactions, pyrolysis	Organic-rich shales, iron-rich formations, hydrocarbon-rich formations	Limited cap rock continuity; aquifer suitability varies by location	Moderate
Southern Mountains and Foothills	Radiolysis, hydrocarbon decomposition, pyrolysis	Organic-rich shales, Radioactive minerals, hydrocarbon-rich formations	Impermeable cap rocks paired with porous sandstone aquifers	Moderate

Table 10
Weighted dataset framework for natural hydrogen potential mapping in Alberta.

Main Division	Dataset	H_2 Rationale	Importance	Sublayer/Metrics	Weight (%)
Geological & Structural Controls (55 %)	Geology	Governs H_2 generation (e.g., felsic radiolysis, mafic/ultramafic serpentinization)	Critical	1. Formations (Montney, Cardium, Bearpaw, Lea Park, Colorado, Mannville, Spirit River, McMurray, Clearwater) 2. Lithology classes (organic-rich shale, shale with elevated concentrations of uranium, thorium, or potassium, deeper sedimentary basins rich in hydrocarbons, iron-bearing sandstones) 3. Volcanic rocks	15
	Tectonic structures	Act as migration pathways and traps	Critical	1. Lineaments (Surface and sub-surface) 2. Shear zones 3. Faults 4. Peace River Arch	10
	Reservoir units	Allow accumulation (e.g., sandstones/carbonates)	Critical	1. Formations (Dunvegan, Spirit River, Cardium, Montney, Mannville, Leduc, McMurray, Clearwater, Grand Rapids, Swan Hills, Granite Wash, Keg River) 2. Lithology classes (high-porosity sandstones, fractured carbonates)	15
	Seal units	Prevent H_2 leakage (e.g., evaporites/shales)	Critical	1. Formations (Bearpaw, Lea Park, Colorado, Kaskapau, Montney, Slave Point, Leduc, Elk Point, Cold Lake, Lotsberg, Prairie Evaporite, Wapiabi, Mannville, Keg Rive) 2. Lithologies (thick dense shale, salt, unfractured consolidated carbonates, continuous layers of halite) 3. Storage cavern 4. Evaporites (Salt, Potash)	15
Magmatic & Mineral Indicators (25 %)	Metallic mineral occurrences	Geochemical evidence for environments capable of generating natural hydrogen (e.g., Redox-active minerals drive serpentinization reactions, Radioactive elements contribute to radiolytic H_2 generation, reactive brines facilitate ion transport and hydrothermal circulation)	Critical	1. Uranium 2. Lithium 3. Magnetite 4. Iron 5. Thorium 6. Prospective mineral exploration zones 7 Lithium content in formation waters	10
	Igneous intrusions	Ultramafic/alkaline intrusions drive serpentinization Kimberlites linked to mantle H_2/He.	Useful	1. Kimberlite intrusions 2. Rocky Mountain intrusions	10
	Non-metallic minerals (KIMs)	Kimberlite indicator minerals (KIMs) provide evidence of mantle-sourced magmatic systems	Useful (local)	1. Diamond 2. Clinopyroxene 3. Spinel 4. Ilmenite 5. Garnet 6. Prospective mineral exploration zones	5
Hydrogeology & other Proxies (20 %)	Hydrogeology	Aquifers and hydraulic properties control migration, dilution, and trapping	Useful	1. Hydrogeological regions (mean sediment thickness)	1
	Glacial landforms	May act as near-surface migration pathways	Useful	1. Eskers 2. Meltwater channels	2
	Geothermal	High geothermal favorability indicates regions with elevated temperatures, porous aquifers, and suitable structures, which enhance natural hydrogen generation, migration, and accumulation.	Critical	1. Geothermal favourability 2. Formations (Leduc, Swan Hills, Slave Point, and Granite Wash)	15
	Bedrock valleys	May provide migration conduits for fluids	Useful	Thalwegs of bedrock valleys	1
	Geophysical survey	Lines indicate where deep-crustal surveys were conducted, providing a framework for structural interpretation and potential H_2 pathways	Useful	Lithoprobe transects	1
Reference Datasets (Not Weighted)	Gas concentrations	Direct evidence, used only for validation (not predictive)	Validation	Hydrogen	–

weighting. Metallic mineral occurrences (notably uranium, lithium, magnetite, and iron) were considered critical geochemical proxies for environments where radiolysis, redox reactions, or hydrothermal circulation may generate hydrogen. Igneous intrusions such as kimberlites and ultramafic bodies were weighted as useful indicators of serpentinization and mantle-derived gases. Kimberlite indicator minerals (KIMs) were also included as local proxies for deep magmatic processes.

Hydrogeological and other proxy datasets account for 20 % of the weight. Hydrogeological regions were included to represent aquifer flow regimes that control hydrogen migration and dilution, while glacial landforms (eskers and meltwater channels) were considered potential shallow migration pathways. Geothermal favourability was emphasized as a critical proxy, given its influence on temperature-driven hydrogen generation and circulation in key carbonate formations. Bedrock valleys and deep geophysical survey transects (Lithoprobe lines) were also included as additional indicators of subsurface fluid pathways. The reference Hydrogen dataset was excluded from the weighting and instead used for validation.

This weighting framework shows that the overlay map is mainly influenced by the core geological and structural context, supported by mineralogical and hydrogeological evidence. The final weighted overlay map therefore offers a balanced view of Alberta's hydrogen potential for natural hydrogen generation, migration, and accumulation.

The weighted overlay analysis produced a continuous hydrogen potential surface for Alberta (Fig. 3). Unlike previous categorical maps that divided the province into discrete classes (high, moderate, low), this approach generates a relative index that highlights spatial gradients in potential rather than fixed thresholds. Areas with higher composite scores reflect the cumulative influence of favorable geology, formations, structures, magmatic and mineral indicators, and hydrogeological settings, whereas lower values indicate less favorable combinations. Importantly, this map should not be interpreted as an absolute prediction of hydrogen presence or absence. Instead, it provides a relative favourability index, identifying areas where conditions are comparatively more conducive to hydrogen generation, migration, or retention. This continuous approach avoids artificial cut-offs and directly addresses earlier concerns that “high” versus “low” classes could not be justified against background variability. Overlaying measured hydrogen concentrations shows that known anomalies preferentially coincide with zones of elevated relative potential, although hydrogen is also observed in some lower-ranked areas. This outcome underscores that the weighted overlay provides a first-order screening tool, not a deterministic predictor. It highlights spatial trends that can be further refined using more advanced approaches, including machine learning and probabilistic modeling, as recommended for future work.

Finally, it is also important to recognize that some hydrogen anomalies may reflect false positives from anthropogenic sources or uncertainties related to sampling quality. Variability in conditions, including producing formations, intervention history, and well depth, can all influence reported concentrations. Moreover, because the gas composition dataset is based on wells where helium concentrations were measured, it is possible that many other natural gas tests could also reveal hydrogen anomalies, even if helium is absent. As a result, hydrogen may occasionally be detected in areas ranked as low potential, while some high-potential zones may not exhibit measurable anomalies. These limitations emphasize the need for cautious interpretation of the maps and point to the value of additional data collection and validation before drawing firm conclusions.

3.5. *Assessment of potential basement and mantle sources*

3.5.1. *Precambrian Canadian Shield*

Natural hydrogen present in the WCSB may be migrating from the Canadian Shield and mantle. In the Precambrian Canadian Shield, higher hydrogen concentrations (>10 %) were generally observed near major shear zones, igneous complexes of the lower Proterozoic, and lithological units with brittle deformation from the Proterozoic/Archean (Fig. 4). These features suggest that hydrogen migration from deep basement and mantle sources could play a significant role in the observed accumulations in the WCSB.

Migration pathways for hydrogen in the Canadian Shield appear to be primarily restricted to areas near significant faults and shear zones, where structural features provide preferential pathways for fluid migration. These faults and shear zones act as conduits that can facilitate the upward movement of gases, including hydrogen, from deeper regions of the crust, such as the Precambrian Canadian Shield and mantle.

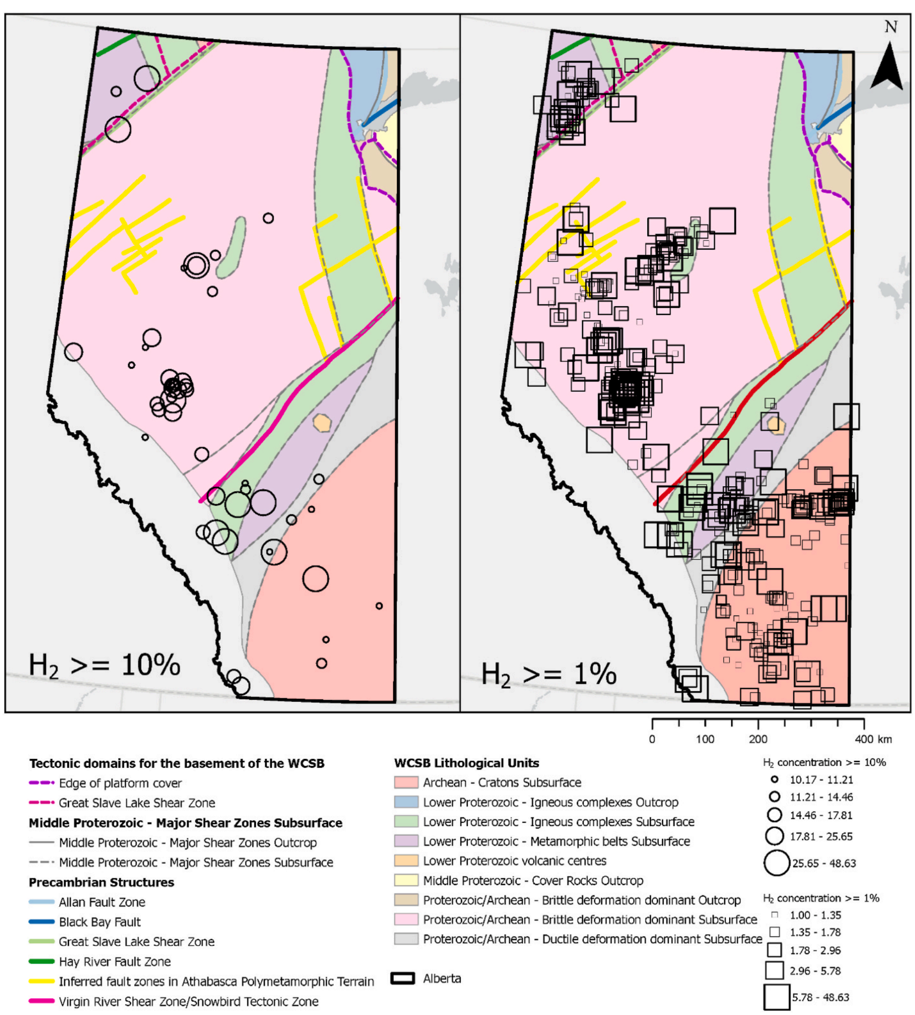

Fig. 4. Precambrian basement lithology map, including major tectonic features and the spatial distribution of natural gas samples with significant hydrogen concentrations. This map highlights the relationship between basement lithology, major structural features, and areas with elevated hydrogen concentrations.

Additionally, regions where the top of the basement beneath the WCSB is shallower also represent key areas for hydrogen migration. In these areas, the migration of gases may be more efficient due to the reduced distance for migration and the potential presence of fractures or other geological features that facilitate gas movement.

While these pathways limit the overall extent of hydrogen migration, they are likely critical in determining the areas where hydrogen accumulations are most pronounced within the WCSB. The migration of gases from deep intervals, particularly from the basement and mantle, might be a contributing factor to the hydrogen concentrations observed in certain regions of the province. However, the extent to which this migration influences hydrogen distribution remains unclear, requiring further investigation.

3.5.2. Isostatic gravity residuals

In this study, a preferential occurrence of samples with hydrogen concentrations greater than 1 and 10 % was observed in areas with higher gravity residuals (Fig. 5). These elevated gravity residuals typically indicate regions where subsurface materials are denser, such as igneous rocks, deep basement features, or other high-density geological formations. Such materials are often linked to significant geological structures like fault zones, fractures, or igneous intrusions, which can provide pathways for the migration of hydrogen from deeper sources. The presence of higher gravity residuals suggests that these areas may contain subsurface features that facilitate the generation and upward movement of hydrogen. Areas with greater density contrasts are likely more conducive to hydrogen generation, especially when structural features like faults or fractures create natural conduits for gas to move into the WCSB. This correlation indicates that areas with higher gravity residuals may represent more favorable for hydrogen occurrences, highlighting the potential for deeper, basement-related hydrogen sources influencing the hydrogen concentrations observed in natural gas samples from energy wells.

To assess whether natural hydrogen occurrences are preferentially associated with isostatic gravity residuals, statistical comparisons were performed between gravity residual values at H_2 sampling points ($n = 11,073$) and a randomly generated set of background points ($n = 11073$). A Welch two-sample *t*-test showed that mean residual values were significantly higher at H_2 points compared to random points ($p < 0.001$). A Wilcoxon rank-sum test confirmed this trend without distributional assumptions ($p < 0.001$). Distributional differences were further supported by a Kolmogorov–Smirnov test ($p < 0.001$). A chi-square test of binned residual values indicated that H_2 points are significantly overrepresented in the medium-to-high residual classes ($p < 0.001$). Collectively, these results demonstrate that hydrogen occurrences in natural gas samples are preferentially associated with elevated isostatic gravity residuals.

3.5.3. Aeromagnetic anomalies

Aeromagnetic anomalies further reinforce the correlation between

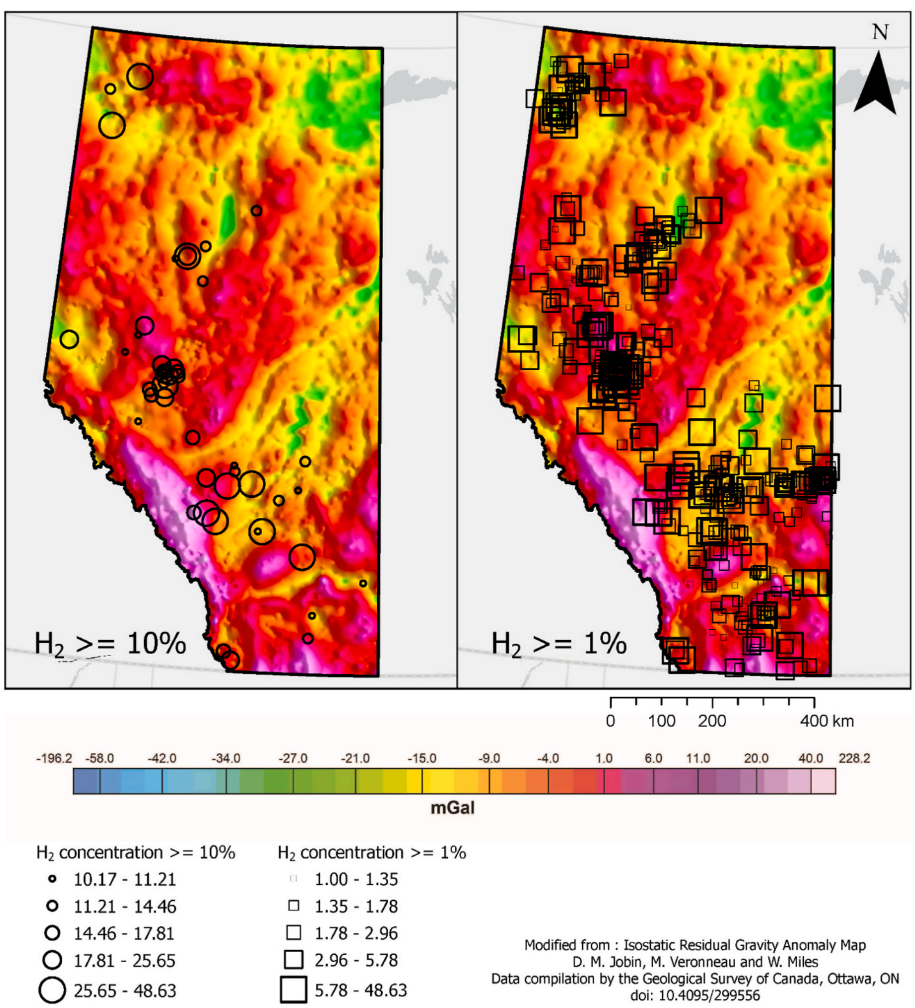

Fig. 5. Isostatic gravity residual map across Alberta, showing variations in subsurface density along with the spatial distribution of natural gas samples with hydrogen concentrations greater than 1 and 10 %. These gravity anomalies indicate dense basement structures, such as igneous intrusions or fault zones, which could influence hydrogen generation and migration.

specific lithological features in the basement and elevated hydrogen concentrations observed in the WCSB. Locations with hydrogen concentrations greater than 1 and 10 % are closely associated with regions exhibiting higher magnetic anomalies (Fig. 6). These anomalies often indicate the presence of magnetic minerals, particularly those found in igneous or metamorphic rocks, such as mafic or ultramafic intrusions. These rock types are known to undergo processes like serpentinization, which is a well-known source of hydrogen. The correlation between strong magnetic anomalies and elevated hydrogen concentrations suggests that these areas could be potential sites for hydrogen generation, either directly through chemical processes or indirectly via structural pathways, such as fault zones, that facilitate hydrogen migration. This suggests that regions with significant magnetic anomalies might provide important insights into locations where hydrogen is generated or accumulated, highlighting the potential role of these geological features in hydrogen distribution.

To assess whether hydrogen occurrences are preferentially associated with aeromagnetic anomalies, statistical comparisons were performed between the magnetic anomaly values at H_2 sampling points ($n = 11{,}073$) and a randomly generated set of background points ($n = 11{,}073$). A Welch two-sample *t*-test showed that mean anomaly values were significantly higher at H_2 points compared to random points ($p < 0.001$). A Wilcoxon rank-sum test confirmed this trend without distributional assumptions ($p < 0.001$). Distributional differences were further supported by a Kolmogorov–Smirnov test ($p < 0.001$). Finally, a chi-square test of binned anomaly values indicated that H_2 points are significantly overrepresented in the medium-to-high anomaly classes ($p < 0.001$). Together, these results demonstrate that hydrogen occurrences in natural gas samples are also preferentially associated with elevated aeromagnetic anomalies.

3.5.4. Role of Precambrian basement and mantle sources

The findings suggest that natural hydrogen in the WCSB may be migrating from deep sources, particularly in areas associated with significant geological features such as shear zones, igneous complexes, and brittle deformation zones in the Canadian Shield. These structural features likely provide pathways for hydrogen migration from deeper intervals to the WCSB. The analysis of isostatic gravity residuals and aeromagnetic anomalies further supports the idea that regions with higher gravity residuals and magnetic anomalies correlate with high hydrogen concentrations, emphasizing the potential role of deep basement-related sources in hydrogen accumulation.

The higher frequency of hydrogen occurrences in relatively deep formations such as Leduc, Slave Point, and Keg River, which are in proximity to the Canadian Shield, further supports the hypothesis that the basement could be a source of hydrogen in the WCSB. Given that these formations are deep and likely influenced by basement structures, it is reasonable to assume that a fraction of the natural hydrogen present in these formations may be migrating from the basement through fault zones, fractures, or other deep geological pathways. This connection

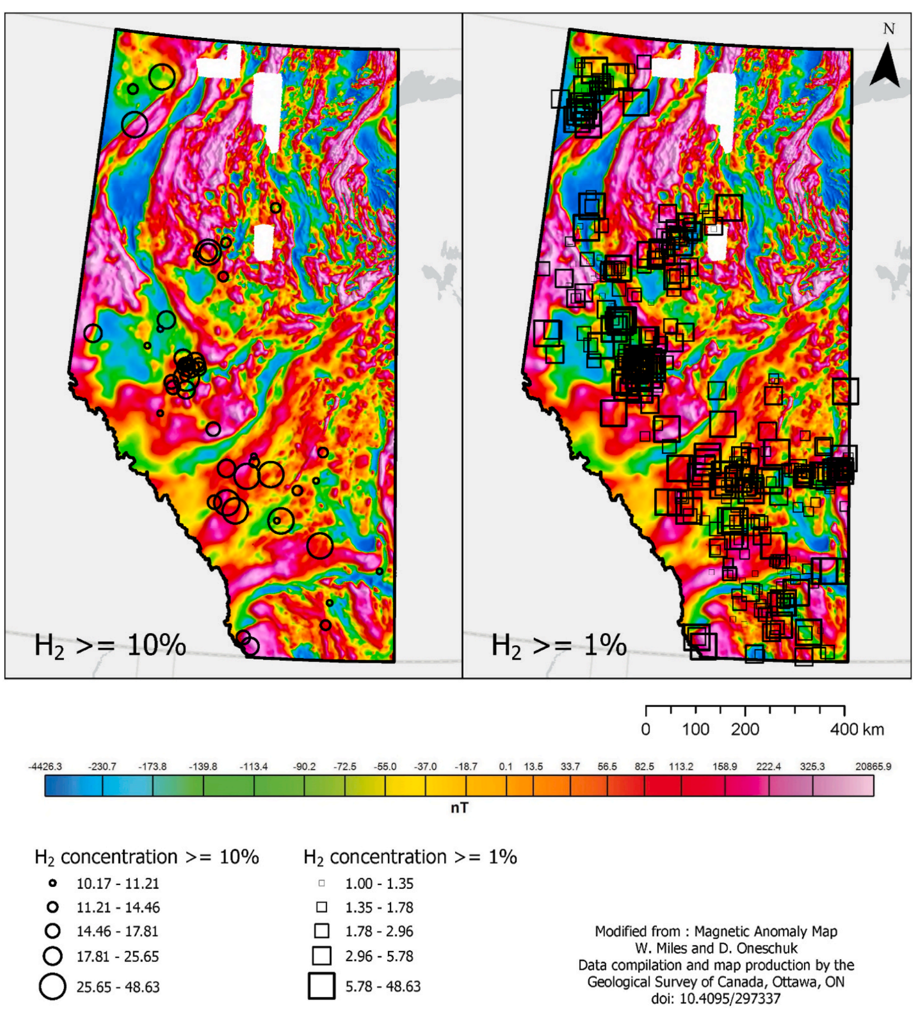

Fig. 6. Aeromagnetic anomaly map across the province, showing variations in magnetic intensity along with the spatial distribution of natural gas samples with significant hydrogen concentrations. The presence of hydrogen in regions with strong magnetic anomalies indicates a potential correlation between basement lithology and hydrogen occurrence.

between the deep geological settings and the observed hydrogen occurrences suggests that basement and mantle-related sources may play a role in the region's natural hydrogen potential.

Although these observations suggest a potential connection between basement and mantle sources and the observed hydrogen concentrations, the full extent of hydrogen migration and its role in the WCSB accumulations remains uncertain. While the data highlight specific areas with high hydrogen concentrations, further research is needed to better understand the underlying processes. Detailed investigations focusing on the geological features that facilitate or inhibit migration, such as fault zones, shear zones, and basement structures, will be essential in assessing the extent of hydrogen migration. In particular, investigating the hydrogen generation potential of the Precambrian basement is crucial, as it could be an important source of the observed hydrogen concentrations. Furthermore, quantifying the contribution of these deep sources to the overall hydrogen distribution in the WCSB will require more comprehensive studies. Therefore, exploration efforts targeting regions with potential correlations to deep basement and mantle sources will be critical to refining our understanding of how these sources contribute to hydrogen accumulation in the WCSB.

3.6. Hydrogen production and viability assessment

The spatial distribution of natural hydrogen potential in the WCSB highlights key geological factors influencing hydrogen generation, migration, and storage. The stratigraphic analysis identifies the West-Central Plains, East-Central Plains, and Southern Plains as regions with the highest potential, primarily due to the combination of source rocks, structural features, reservoirs, and seals that may facilitate hydrogen generation, migration and accumulation. The GIS weighted overlay map generated a continuous surface indicating hydrogen potential for Alberta (Fig. 3). While these regions exhibit the most promising conditions, the overall commercial viability of natural hydrogen as a resource depends on several interrelated geological and geophysical factors.

One important consideration is the potential for deep hydrogen migration from deep sources. The correlation between elevated hydrogen concentrations and structural features such as shear zones, brittle deformation zones, and igneous complexes suggests that deep-seated processes may contribute to hydrogen accumulations in the WCSB. Aeromagnetic anomalies and isostatic gravity residuals further support this hypothesis, indicating that basement-related features could play a role in hydrogen generation. However, the extent to which hydrogen migrates from deep sources and accumulates in the sedimentary basin remains unknown. Understanding these processes requires further geochemical fingerprinting, isotopic analyses, and structural mapping to differentiate between locally generated and hydrogen sourced from deeper reservoirs.

Localized geological settings also play an important role in determining where hydrogen may accumulate. The West-Central Plains stand out as a high-priority area due to the presence of extensive fault systems and organic-rich formations that could support both hydrogen generation and storage. Conversely, the Northern Plains, despite being classified as a moderate-potential region, exhibit localized occurrences of elevated hydrogen concentrations. This suggests that certain geological settings—such as proximity to faults, fractures, or deep-seated structures—may enhance hydrogen accumulation in specific areas even where the overall potential is lower. These findings highlight the importance of not only assessing large-scale geological trends but also identifying localized anomalies that may indicate viable hydrogen reservoirs.

To fully evaluate the commercial viability of natural hydrogen in the WCSB, further research is needed to quantify the rates of hydrogen generation, migration efficiency, and the longevity of potential accumulations. Additionally, the role of cap rocks high potential areas, such as evaporite and shale formations, must be considered to evaluated whether hydrogen can be effectively trapped over geologic timescales. Targeted exploration efforts should prioritize areas where multiple factors—such as deep-seated structures, favorable migration pathways, and effective trapping mechanisms—converge to create the most promising conditions for hydrogen accumulation.

Overall, while the WCSB shows promising potential for natural hydrogen, the long-term commercial viability of these resources depends on a deeper understanding of the interplay between basement-related sources, sedimentary basin sources, and structural controls on migration and trapping. A focused exploration strategy that integrates geological, geophysical, and geochemical data will be essential in refining assessments and determining whether natural hydrogen can become a viable energy resource in the province.

4. Future work

To further advance the exploration and utilization of natural hydrogen resources in Alberta, several key research areas and recommended next steps have been discussed below.

1. Review of Historical Reports

Validation of hydrogen anomalies observed in the gas composition dataset is a critical step to minimize potential false positives associated with sampling artifacts, analytical uncertainties, or operational factors such as acid treatments, well interventions, and casing integrity issues. Future work should include a systematic review of historical well reports, drilling/completion records, and gas composition analyses to ensure anomalies reflect true geological signals and to strengthen confidence in the dataset for exploration purposes.

2. Hydrogen Source Identification

The hydrogen gas concentration dataset includes contributions from both natural and anthropogenic sources, such as microbial activity or corrosion of steel casings. Future work should integrate isotopic tools together with complete gas composition and noble gas analyses to differentiate these origins, providing a robust method to validate hydrogen's natural provenance [52]. This combined approach will improve source attribution and further reduce the frequency of false positives and negatives.

3. Indirect Hydrogeochemical Indicators

Future studies should explore indirect proxies, such as groundwater salinity, CH_4, ^{222}Rn, CO_2, He to identify regions where deep fluids containing hydrogen ascend through fault zones. This approach could potentially include inventorying geochemical datasets and correlating these with mapped geological faults to enhance regional exploration strategies.

4. Evaluation of In-Situ Hydrogen Production

The potential for stimulating hydrogen generation from source rocks through water injection, particularly in conjunction with carbon sequestration, must be evaluated. This innovative method could expand Alberta's hydrogen resource base by leveraging hydrogen already present but not currently in economically viable accumulations.

5. Mapping Diffusive Circles

The presence of diffusive circles or "fairy circles" indicative of hydrogen emanations could be systematically mapped using remote sensing techniques. Future geospatial assessments might benefit by distinguishing these features from similar structures caused by permafrost or glacial activity, especially in regions such as the Canadian

Shield.

6. Hydrogen Storage and Geomechanical Modeling

Field testing and advanced geomechanical modeling will likely be helpful to evaluate the sealing properties of key formations for hydrogen accumulation. These studies would refine Alberta's strategic plans for long-term hydrogen production and storage, improving safety and efficiency.

7. Machine Learning Applications

To enable large-scale analysis, machine learning techniques, such as ML Mapper, could be beneficially employed. These tools can incorporate several datasets, including geomagnetic and remote sensing data, to identify high-potential zones for hydrogen exploration with improved accuracy and efficiency.

8. Economic Viability and Accessibility

We recommend that future work incorporate aspects of economic and social feasibility of hydrogen resource development. This includes prioritizing high-potential areas based on geological potential, accessibility, and the potential challenges associated with the transportation of natural hydrogen. Strategies should focus on local utilization until economies of scale make large-scale transportation viable.

9. Renewability and Production Rates

The slow natural production rates of hydrogen in some geological settings require assessment to evaluate long-term economic viability. This consideration is essential for designing a sustainable resource management strategy.

By addressing these gaps, Alberta can potentially advance its understanding of natural hydrogen resources, establish reliable exploration methodologies, and develop strategies to ensure economic and environmental sustainability.

5. Conclusion

Alberta's geological framework reveals exceptional potential for natural hydrogen generation, migration, and accumulation, underpinned by its unique stratigraphy and well-documented subsurface formations. Key mechanisms such as hydrocarbon decomposition, water-rock reactions with iron-rich sediments, organic pyrolysis, and radiolysis highlight formations like Montney, Cardium, Bearpaw, Manville, Belly River, McMurray, and Lea Park as critical formations for hydrogen generation, driven by their lithological and geochemical properties. Deep shale formations, including Bearpaw and Kaskapau, demonstrate exceptional cap rock potential due to their dense, impermeable nature, ensuring long-term containment of hydrogen. Additionally, porous reservoirs like the Dunvegan, Spirit River, Cardium, Mannville and Montney formations offer promising storage capabilities, combining suitable depth, pressure, and porosity for effective containment. Regionally, the Southern, East, and West-Central Plains stand out for their abundant organic-rich shales and hydrocarbon reserves, providing ideal conditions for both hydrogen generation and accumulation. While the potential for hydrogen migration from deep sources is generally low in Alberta, the proximity of certain deep formations to the Canadian Shield presents an additional consideration. The lithological and structural characteristics of the Canadian Shield, including the presence of deep-seated faults and major shear zones, may create pathways for hydrogen migration from the basement and be accumulated in the WCSB, especially in areas where thick, continuous salt units are present. This warrants further investigation into its role as a potential hydrogen source.

Alberta's existing oil and gas infrastructure, paired with its skilled workforce and expertise in subsurface resource management, offers a strategic advantage for rapidly advancing natural hydrogen initiatives. Although drilling new wells dedicated to hydrogen exploration could be cost-prohibitive, the repurposing of existing wells and leveraging of current infrastructure offers a practical way to significantly reduce development costs. In practice, opportunities may include the co-production of hydrogen and natural gas, in-situ hydrogen generation in suitable formations, or co-production of hydrogen and geothermal energy in areas with high geothermal potential. The province's geological parallels with successful hydrogen exploration regions globally further validate its potential as a key player in the transition to clean energy. To unlock this potential, focused research on hydrogen-specific trapping mechanisms, advanced geochemical fingerprinting, and tailored storage solutions is essential. This will not only reduce exploratory risks but also position Alberta at the forefront of the natural hydrogen industry, aligning with Canada's net-zero emissions goals and driving economic diversification.

CRediT authorship contribution statement

D.B. Wijayarathne: Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **T.A. Morais:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation. **A. Jaggi:** Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **J.J. Gibson:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Funding acquisition, Conceptualization. **P. Eby:** Writing – review & editing, Resources, Funding acquisition, Data curation, Conceptualization. **M. Huard:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijhydene.2025.151905.

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