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Exploration of White Hydrogen: Drawing Global Analogy to Unveil the Potential of the Andaman Basin's Sea Floor Spreading Center

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ABSTRACT

Hydrogen is increasingly recognized as a critical element in the global energy transition, offering a path to decarbonize power generation, industry, and transportation. While green and blue hydrogen dominate current production strategies, natural hydrogen—commonly termed white hydrogen—remains largely underexplored despite its potential as a continuous, low-cost, and carbon-neutral energy resource. White hydrogen forms endogenously through geological processes, including serpentinization of ultramafic rocks, mantle-derived reactions, radiolysis, and organic matter decomposition. Global occurrences in cratonic shields, ophiolites, intracratonic basins, and mid-ocean ridges demonstrate the widespread yet underutilized nature of this resource. This study investigates the Andaman Basin, a tectonically active seafloor spreading center, as a prospective frontier for white hydrogen exploration. Integrating geological and seismic observations with the hydrogen system model, I evaluate the mechanisms controlling hydrogen generation, migration, and accumulation. Seismic data reveal structural and stratigraphic features conducive to serpentinization-driven hydrogen generation, fault-controlled migration pathways, and potential entrapment beneath marine shales. The study further identifies complementary targets in the western Andaman subduction zone. A strategic exploration framework combining play- and prospect-level investigations—including geophysical surveys, soil gas sampling, exploratory drilling, and laboratory analyses—is proposed to systematically delineate potential accumulations. The findings underline the scientific and economic promise of white hydrogen in the Andaman Basin, offering insights for sustainable energy development and informing global analogs in hydrogen exploration.

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1. Introduction

Hydrogen is emerging as a critical component of the global energy transition, with significant potential to decarbonize power generation, industry, and transportation [1]. As the lightest and most abundant element in the universe, hydrogen possesses high energy density and produces only water upon combustion, making it an attractive candidate for a low-carbon energy system [1]. Despite this abundance, hydrogen rarely occurs freely on Earth, and its availability depends largely on production through chemical or geological processes [2, 3].

Hydrogen is commonly classified according to its production pathway and environmental impact. Green hydrogen is produced via electrolysis using renewable energy, whereas blue hydrogen derives from fossil fuels coupled with carbon capture and storage (CCS) [1, 4]. Grey hydrogen is generated from fossil fuels without CCS, and additional types—brown, black, turquoise, and yellow hydrogen—are defined by specific feedstocks and production methods [2]. In contrast, white hydrogen, or natural hydrogen, forms endogenously within the Earth's crust through geological processes, most commonly through water–rock interactions such as serpentinization of olivine and pyroxene [5, 3]. Fig. (**1**) summarizes the main hydrogen types and their characteristics.

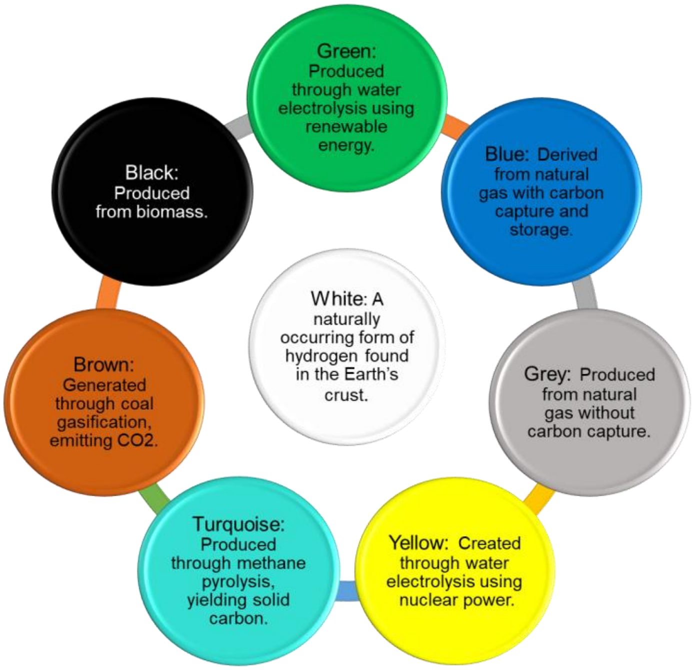

Figure 1: Comprehensive overview of hydrogen variants and their key characteristics, aimed at providing a thorough understanding of the diversity present in different types of hydrogen.

The global hydrogen market is expanding rapidly. Under current policy frameworks, hydrogen production is projected to reach approximately 180 million tonnes by 2030, with even higher levels anticipated under net-zero pathways. Hydrogen is recognized as a versatile energy carrier capable of decarbonizing hard-to-abate sectors such as steelmaking, refining, ammonia production, and mobility, while also serving as a medium for energy storage [1]. According to the Hydrogen Council, hydrogen could meet up to 18% of global final energy demand by 2050, potentially avoiding six gigatonnes of CO_2 emissions annually. While green and blue hydrogen currently dominate global strategies, natural hydrogen remains largely unexplored despite its potential as a continuous, low-cost, and carbon-neutral energy resource [2, 3].

Evidence of natural hydrogen has been documented in a variety of geological contexts, including cratonic shields (Russia, Mali, Brazil), ophiolitic belts (Oman, Philippines), intracratonic basins (United States, Australia), and mid-ocean ridges (Atlantic) [6-11]. For example, the Bourakébougou site in Mali hosts a natural hydrogen accumulation that has been used for local electricity generation, while circular depressions in Russia have been linked to deep crustal hydrogen seepages [6, 7]. In Australia, Proterozoic basins contain hydrogen-rich accumulations, and studies along the Mid-Atlantic Ridge indicate H_2 fluxes associated with serpentinization and hydrothermal activity [8, 9].

The conceptual understanding of natural hydrogen has advanced through frameworks such as the hydrogen system model, which defines four critical stages: generation, migration, accumulation, and preservation [12]. This model provides a structured approach for assessing hydrogen potential in sedimentary and tectonic environments [12]. Complementary advances in geochemical modeling, isotopic tracing, and subsurface monitoring have improved the ability to quantify fluxes, distinguish sources, and evaluate the sustainability of hydrogen resources [13].

In this study, the potential for natural hydrogen in the Andaman Basin, a tectonically active seafloor spreading center, is investigated. By integrating geological observations, geochemical data, and the hydrogen system model, the study aims to evaluate the conditions controlling hydrogen generation, migration, and accumulation in this region [12,14,15].

2. Natural Hydrogen Generation

Natural hydrogen originates through a series of complex geological and geochemical processes that collectively control its formation and release in the Earth's crust [3, 5, 16]. Multiple mechanisms have been proposed to explain the occurrence of hydrogen in subsurface environments [2, 7, 17]:

2.1. Direct Degassing from the Earth's Core

Hydrogen can ascend from the deep mantle and be released at the surface, often associated with volcanic or tectonic activity. Mantle-derived fluids transport hydrogen-rich gases through fractures and faults, contributing to natural seeps [7].

2.2. Water–rock Interactions (Serpentinization)

Serpentinization occurs when water reacts with ultrabasic rocks, such as peridotite, in the mantle. This process generates hydrogen (H_2) along with serpentine and other secondary minerals. Serpentinization is particularly important in hydrothermal systems at mid-ocean ridges, where geothermal heat facilitates hydrogen release [5, 8, 9].

2.3. Reactions with Reducing Agents in the Mantle

Reducing agents, notably iron-bearing minerals, can react with water under high-temperature and high-pressure conditions to produce hydrogen. These mantle reactions serve as a continuous source of H_2 in specific tectonic settings [18].

2.4. Natural Radiolysis

Radioactive decay of elements such as uranium and thorium can split water molecules, generating hydrogen through radiolysis. This process is localized to rocks rich in radioactive isotopes and contributes to hydrogen generation in continental crustal settings [16].

2.5. Decomposition of Organic Matter

Organic-rich sediments, peat, and plant material can produce hydrogen during decomposition, particularly under anaerobic conditions. Such environments, including marshes and sedimentary basins, serve as additional sources of natural hydrogen [19].

Fig. (**2**) highlights the diverse processes involved in the generation of white hydrogen, revealing its inherent nature. Jointly, these processes explain the occurrence and availability of hydrogen in diverse geological environments. A comprehensive understanding of these mechanisms provides insight into how hydrogen is generated, accumulated, and potentially extracted from the Earth's crust. Table **1** summarizes the number of studies or sites reporting various natural hydrogen generation processes.

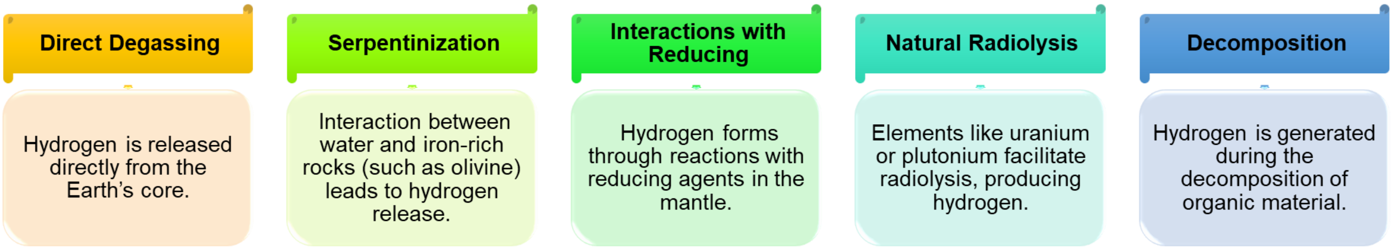

Figure 2: Detailed illustration of the various processes inherent in the generation of white hydrogen, offering valuable insights into its natural formation mechanisms.

Table 1: Natural H_2 generation—world sites.

Process	No of Studies/Sites
Serpentinization	9
Mantle degassing	12
Radiolysis	3
Organic decay	8

3. States of Occurrence

Natural (white) hydrogen exists inherently within the Earth's crust and is not artificially generated. It occurs in multiple forms; each associated with specific geological settings [3] (Fig. **3**):

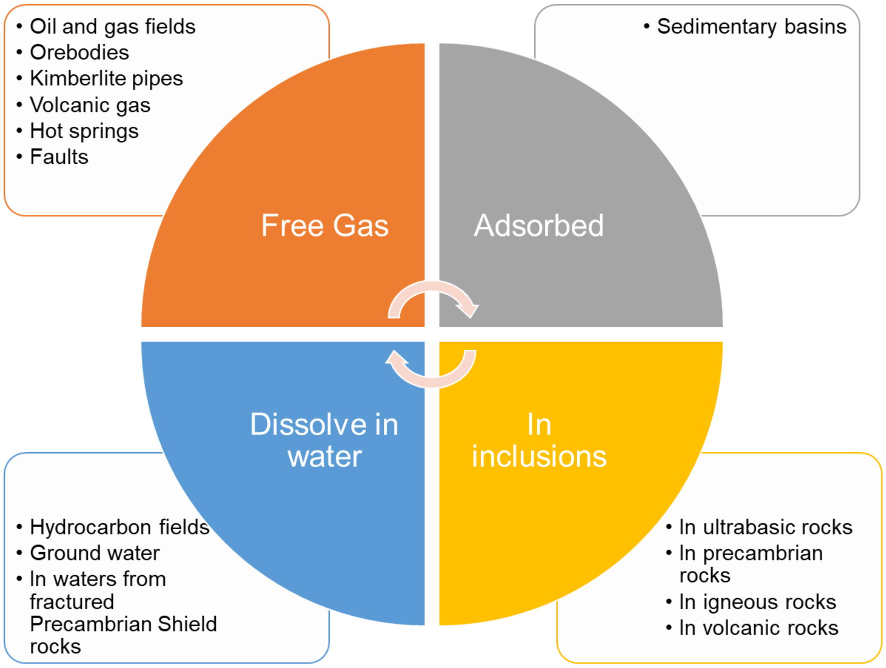

Figure 3: Visual depiction showcasing manifestations of white hydrogen and its diverse natural occurrences, emphasizing the varied states of existence across geological contexts.

3.1. Free Gas

White hydrogen is commonly encountered as a free gas in isolated subsurface pockets. It is particularly abundant in regions uplifted by tectonic processes, such as ophiolites. Additional occurrences have been documented in rift zones, mid-ocean ridges, Precambrian formations, hydrothermal systems, geysers, kimberlite pipes, coal basins, and igneous rocks [7, 8, 16].

3.2. Adsorbed Form

In some cases, hydrogen molecules adhere to the surfaces of minerals, forming an adsorbed phase. This occurs in materials such as clays, zeolites, or activated carbon, which provide high surface area and act as natural traps for hydrogen [20].

3.3. Inclusion in Rocks

A less common occurrence involves hydrogen being physically enclosed within rock matrices due to its high diffusivity. This form is observed in rocks spanning different geological ages, including Precambrian formations, igneous and volcanic rocks, kimberlites, and mineralized ore bodies [19].

3.4. Dissolved in Water

Hydrogen is also present in aqueous environments, dissolved in groundwater or formation waters under certain geological conditions. Exploration in regions such as Western Siberia and Crimea (Ukraine) has revealed hydrogen dissolved in water associated with deep faults, rift zones, and active tectonic settings [19].

Collectively, these diverse states—free gas, adsorbed, included in rocks, and dissolved in water—illustrate the multiple pathways through which hydrogen occurs naturally in the crust. A thorough understanding of these occurrences is essential for guiding effective exploration and sustainable utilization strategies. The Table **2** presents notable global occurrences of natural hydrogen, highlighting maximum reported concentrations, discovery periods, and the form of hydrogen.

Table 2: Global natural hydrogen.

Country	Max H_2 (%)	Discovery Year	Type
Mali	98	2011–2018	Free gas
Russia	16	2008–2013	Seep/gas
Australia	12	2006–2021	Seep
USA	5	2020–2023	Dissolved
Brazil	14	2012–2015	Gas/Seep

4. Conceptual Model and Challenges

The modern understanding of natural hydrogen began with its accidental discovery in 1987 at Bourakébougou, Mali. Globally, only a few regions actively explore this unique resource, and Mali remains the only site currently producing hydrogen at scale [7]. Foundational work by Prinzhofer *et al*., Rigollet and Prinzhofer, and Zhao *et al*. introduced the Hydrogen System Logic, a conceptual framework that challenges conventional ideas of hydrogen confinement and reservoir formation [12, 15, 21].

The hydrogen system model provides a dynamic perspective on hydrogen behavior in geological settings. Unlike traditional views, which consider hydrogen as trapped beneath impermeable barriers, this model proposes that hydrogen exists as a mobile, continuously replenished system within fractures, pores, and reactive mineral matrices [12]. Groundwater interacting with iron-rich minerals, such as olivine, facilitates hydrogen generation and renewal, while microbial consumption and hydrocarbon formation can locally deplete it [22].

According to this model, residual hydrogen may accumulate in porous rocks, provided that effective sealing structures exist [12]. This approach offers a comprehensive view of hydrogen dynamics, encompassing mineral–water interactions, microbial processes, and structural controls, and provides a framework to understand hydrogen occurrence, distribution, and potential reservoir formation.

Challenges include hydrogen generation rates, which remain poorly constrained across rock types, pressures, and temperatures [2]; lack of detailed quantification for individual production mechanisms [19]; poorly understood accumulation depths [23]; uncertainties in seal integrity in shales, mudstones, or other lithologies [12, 17]; and the scarcity of field discoveries [24].

5. Exploration History

Scientific interest in natural hydrogen gained momentum following the discovery of a well in Bourakébougou, Mali, in 2018, which produced gas with 98% hydrogen content [7]. Since then, extensive exploration activities and research efforts have focused on understanding the occurrence, generation mechanisms, and accumulation processes of white hydrogen [8, 11, 25]. Investigations have been carried out across multiple continents, including Africa, Australia, Europe, Brazil, and the United States.

Studies indicate that white hydrogen occurs predominantly as a free gas across diverse geological environments, including rift zones, back-arc basins, intracratonic and cratonic regions (often Precambrian), banded iron formations, mineralized zones, ore deposits, mid-ocean ridges, and orogenic belts [8, 6].

To assess the feasibility of natural hydrogen resources, the US Geological Survey (USGS) has applied the hydrogen system model to identify prospective areas for exploration in the United States [13]. Two regions have emerged as particularly promising: the Atlantic Coastal Plain—where iron-rich rocks formed during the basin's development and geophysical surveys suggest interactions between water and iron in these rocks produce hydrogen that may migrate toward the continental shelf through sedimentary sequences [13]; and the Central United States (Midcontinent Rift), where rocks associated with the ancient Midcontinent Rift formed approximately 1.1 billion years ago host iron-rich minerals capable of generating hydrogen [13].

Despite these promising indicators, the presence of hydrogen-generating rocks does not guarantee commercially viable hydrogen resources, and evaluating the potential requires careful investigation of additional geological components, including reservoir rocks and sealing formations [26].

6. Potential in India

6.1. Geological Setting

Global exploration studies and feasibility assessments, such as those conducted by the US Geological Survey (USGS), indicate that seafloor spreading centers can serve as highly prospective zones for natural hydrogen generation [13, 27]. Among these, the East Andaman Basin exhibits geological characteristics that suggest significant potential as a frontier for white hydrogen exploration [14, 27].

The basin contains source rocks enriched in key elements, including iron and uranium, which are critical for hydrogen generation through water–rock interactions [27]. Coupled with active tectonic and hydrothermal processes, these lithologies provide favorable conditions for natural hydrogen formation [14]. Serpentinization of mantle-derived peridotites, a well-documented hydrogen-generating process in global analogues such as the Midcontinent Rift, is likely a major mechanism in this region [5].

Seafloor spreading in the East Andaman Basin is accompanied by rift zones, fault networks, and volcanic activity. These structures serve as migration pathways, allowing hydrogen generated at depth to ascend toward the seafloor. At the same time, sedimentary overburden, aquifers, and evaporitic sequences function as natural seals, creating the potential for hydrogen accumulation and storage [14].

Fig. (**4**) provides a schematic representation of seafloor spreading in the Andaman Basin, illustrating the divergent tectonic boundary and the formation of new oceanic crust. The figure emphasizes volcanic activity and the potential release of hydrogen from deep-seated sources. Complementarily, Fig. (**5**) depicts the areal extent of seafloor spreading in the basin, highlighting the widespread geological features that control hydrogen generation and migration. Collectively, these observations reinforce the East Andaman Basin as a promising target for natural hydrogen exploration. The Table **3** compares key geological and geophysical criteria across the Andaman Basin, Mid-Atlantic Ridge, Oman ophiolites, and Mali with respect to their hydrogen generation potential.

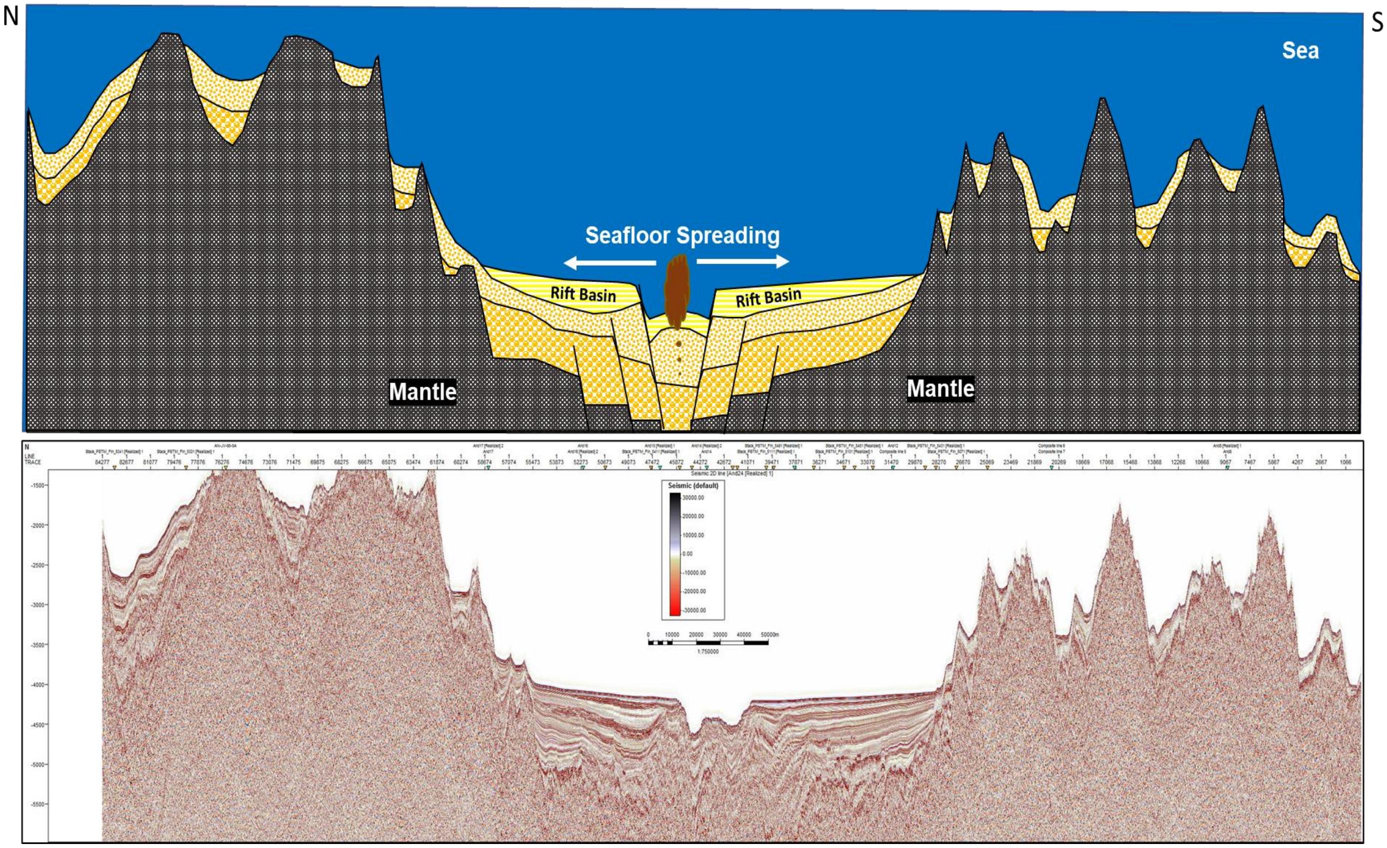

Figure 4: Elaborate visual representation highlighting the seafloor spreading phenomenon in the Andaman Basin, providing in-depth insights into the geological processes and distinct features of the region.

Table 3: Andaman vs. global analogues.

Criterion	Andaman Basin	Mid-Atlantic Ridge	Oman (ophiolite)	Mali
Spreading rate (mm/yr)	24–35	25–30	-	-
Seismic bright anomalies	Yes	Yes	Uncertain	No
Substantial sediment	Yes	No	No	No
Fault segments	4+	>=2	-	-
Magma-driven sills	Yes	Yes	No	No
Known H_2 seeps to date	Not confirmed	Multiple	Several	Yes

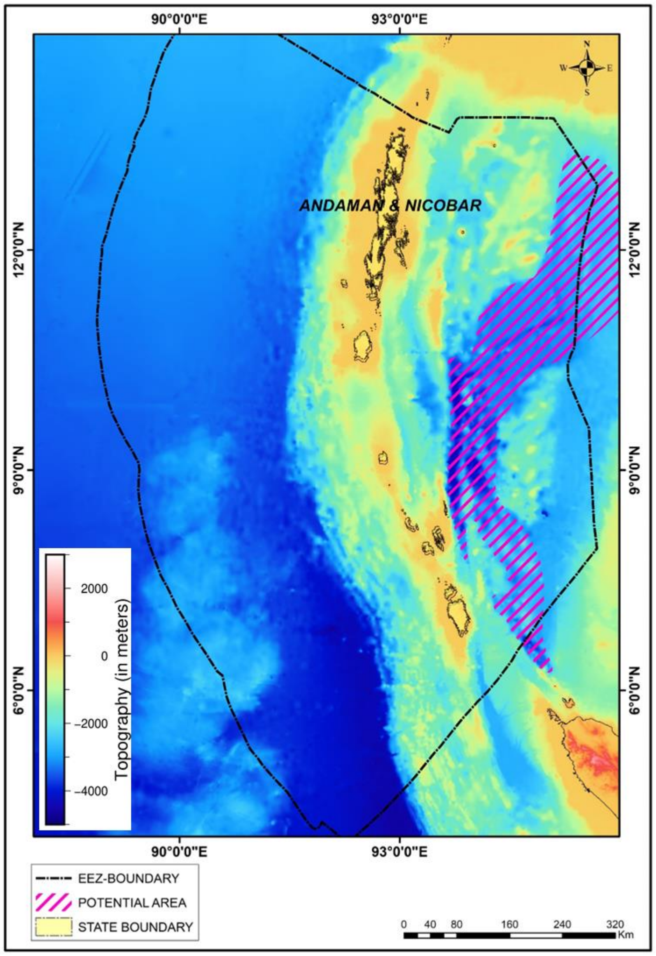

Figure 5: Visual depiction illustrating the spatial extension of seafloor spreading in the Andaman Basin, enhancing understanding of geological features critical to the potential exploration of white hydrogen.

6.2. Seismic Evidence

Seismic analysis of the East Andaman Basin, using two representative profiles (Fig. **6**, **7**)—north–south (N–S) and west–east (W–E)—reveals structural and stratigraphic features indicative of serpentinization and potential hydrogen migration [8, 14]. Schematics illustrate water–rock interactions within mantle-derived peridotites, highlighting how serpentinization may generate H_2 [8]. These diagrams also show potential upward migration pathways along fault systems and accumulation beneath marine shales, which could act as natural seals [8, 14].

RMS amplitude anomalies along the seismic profiles (Fig. **6b**, **7b**) suggest localized low-density gas pockets. Such bright amplitudes, however, can result not only from H_2 but also from methane, CO_2, or lithological variations. Magnified views (Fig. **6c**, **7c**) demonstrate the geometry of these anomalies and their structural control by faults, while mapping of the seafloor (Fig. **6d**, **7d**) highlights bathymetric variability that may influence gas migration and entrapment.

The paleoenvironmental setting, the presence of iron-rich, thermally altered rocks, and extensive fault networks provide favorable conditions for serpentinization-driven H_2 generation [14]. Coupled with potential trapping structures, these factors create promising targets for hydrogen accumulation. Despite these indicators, no exploratory drilling has yet been conducted to confirm the presence of H_2 in the basin.

Beyond the seafloor spreading center, research indicates another prospective white hydrogen play near the subduction zone in the western Andaman Basin. This hypothesis is supported by conceptual models of white hydrogen accumulation in subduction zones, where tectonic compression, hydration of subducted mantle rocks, and fluid migration may create favorable conditions for hydrogen generation and entrapment (Fig. **8**). These findings suggest that, in addition to the spreading center, the western Andaman subduction zone represents a complementary frontier for white hydrogen exploration in India.

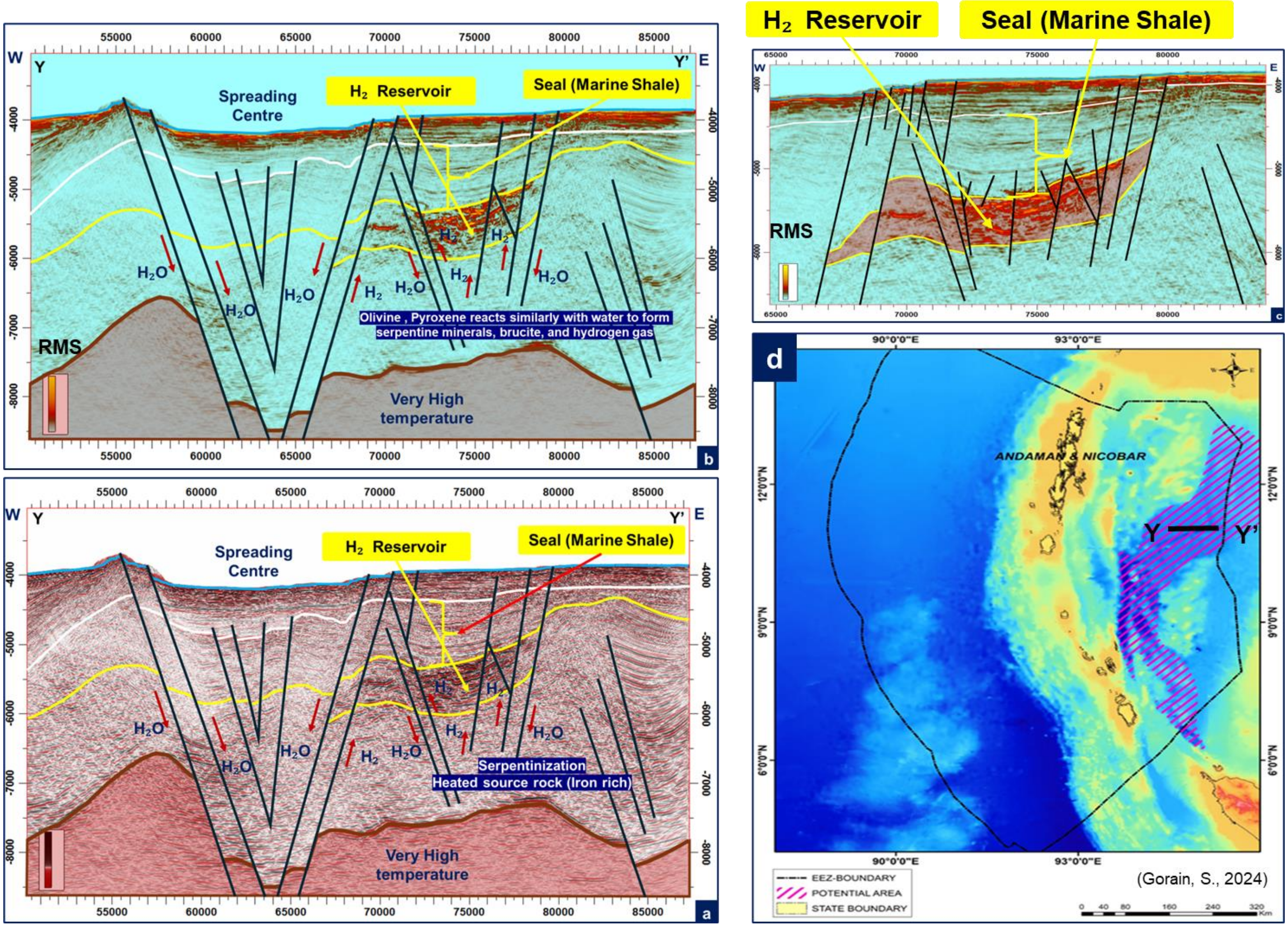

Figure 6: a) Illustrates hydrogen gas generation via serpentinization, highlighting migration pathways and potential entrapment by marine shale. **b)** Highlights RMS distribution along the same seismic profile as Fig. (**1a**). **c)** Zoomed-in view of Fig (**1b**), emphasizing hydrogen gas reservoir and fault network. **d)** The potential area for white hydrogen accumulation along the seafloor spreading centre of the East Andaman Basin. The background color indicates the topographical variability of the seabed.

6.3. Exploration Strategy

Effective exploration of natural (white) hydrogen requires a strategic framework built on multiple key considerations. Deep-seated faults, particularly basement structures, serve as primary migration pathways for hydrogen, and their detailed mapping and analysis are essential for identifying prospective zones [15]. Equally important is the evaluation of shallow sedimentary processes, which allows for the identification of potential hydrogen accumulations near the surface while accounting for local geological dynamics [8, 15].

The validation of existing reports and surface observations is another critical component of the exploration strategy. Surface seeps, where hydrogen emerges naturally at the seabed or onshore, provide direct indicators of subsurface migration and reservoir potential, offering valuable geological insights that refine exploration targeting [13].

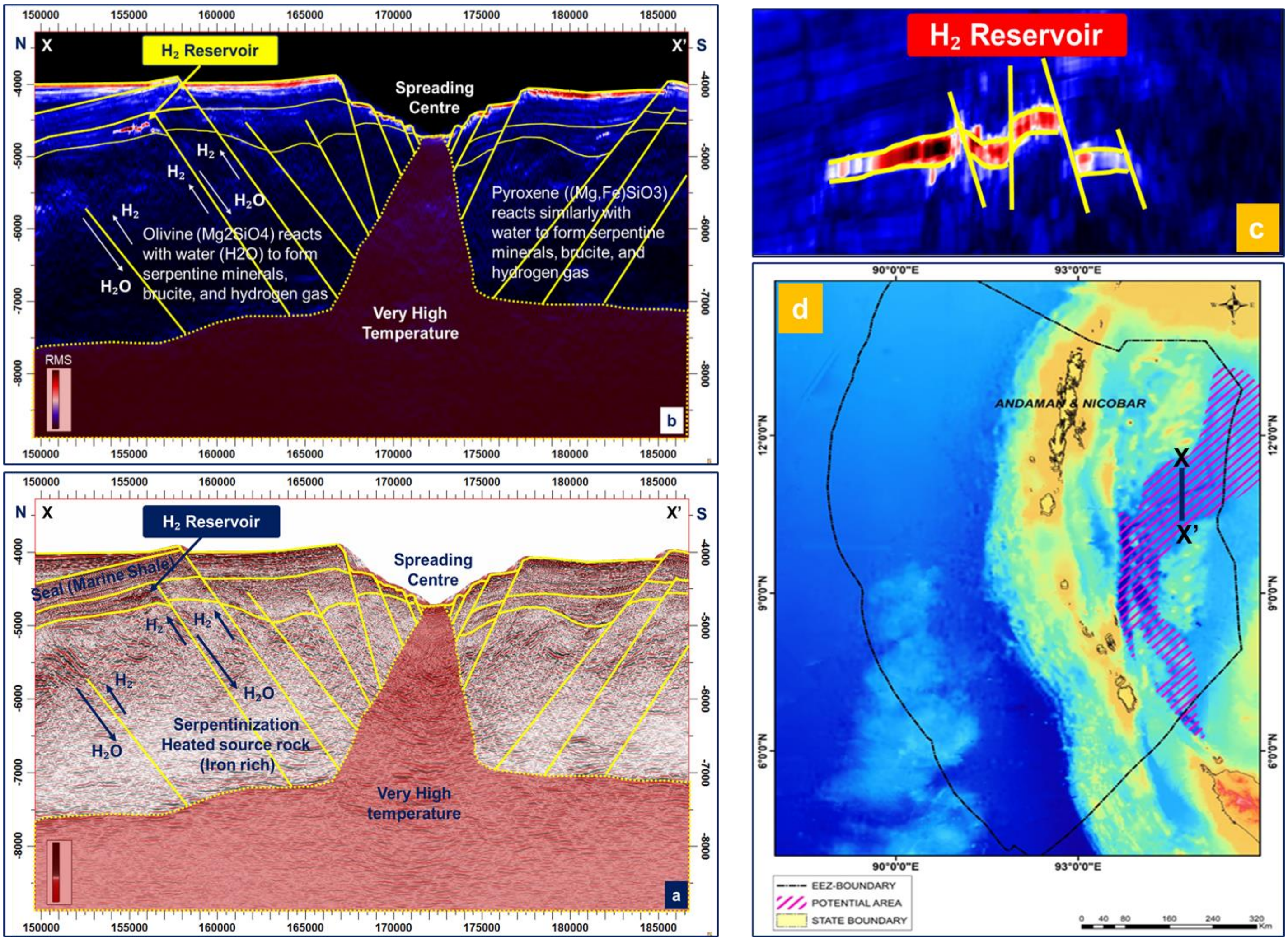

Figure 7: a) Illustrates hydrogen gas generation via serpentinization, highlighting migration pathways and potential entrapment by marine shale. **b)** Highlights RMS distribution along the same seismic profile as Fig. (**1a**). **c)** Zoomed-in view of Fig. (**1b**), emphasizing hydrogen gas reservoir and fault network. **d)** The potential area for white hydrogen accumulation along the seafloor spreading centre of the East Andaman Basin. The background color indicates the topographical variability of the seabed.

To implement this strategy, a combination of geophysical surveys, mapping, satellite imagery, soil gas sampling, exploratory drilling, and laboratory analyses is employed [15]. These methods validate conceptual models and investigate the characteristics of source rocks, fluid pathways, and seals within the East Andaman Basin.

Exploration operates on two hierarchical levels: Play and Prospect. At the Play level, geophysical surveys, satellite imagery, and regional mapping provide a broad framework for detecting subsurface signals [15]. Long-term monitoring captures evolving hydrogen dynamics, while radionuclide mapping identifies potential source zones [8]. Gravity–magnetic (gravi-mag) surveys assess structural variations within the crust [8]. At the Prospect level, focused investigations employ soil gas sampling, exploratory drilling, and 2D seismic acquisition to refine target areas [15]. This multi-scale approach integrates advanced techniques to systematically uncover natural hydrogen accumulations.

The interdisciplinary nature of this strategy—merging structural geology, geochemistry, geophysics, and hydrogen system dynamics—underscores the scientific potential of white hydrogen within the marine setting of the seafloor spreading center [8].

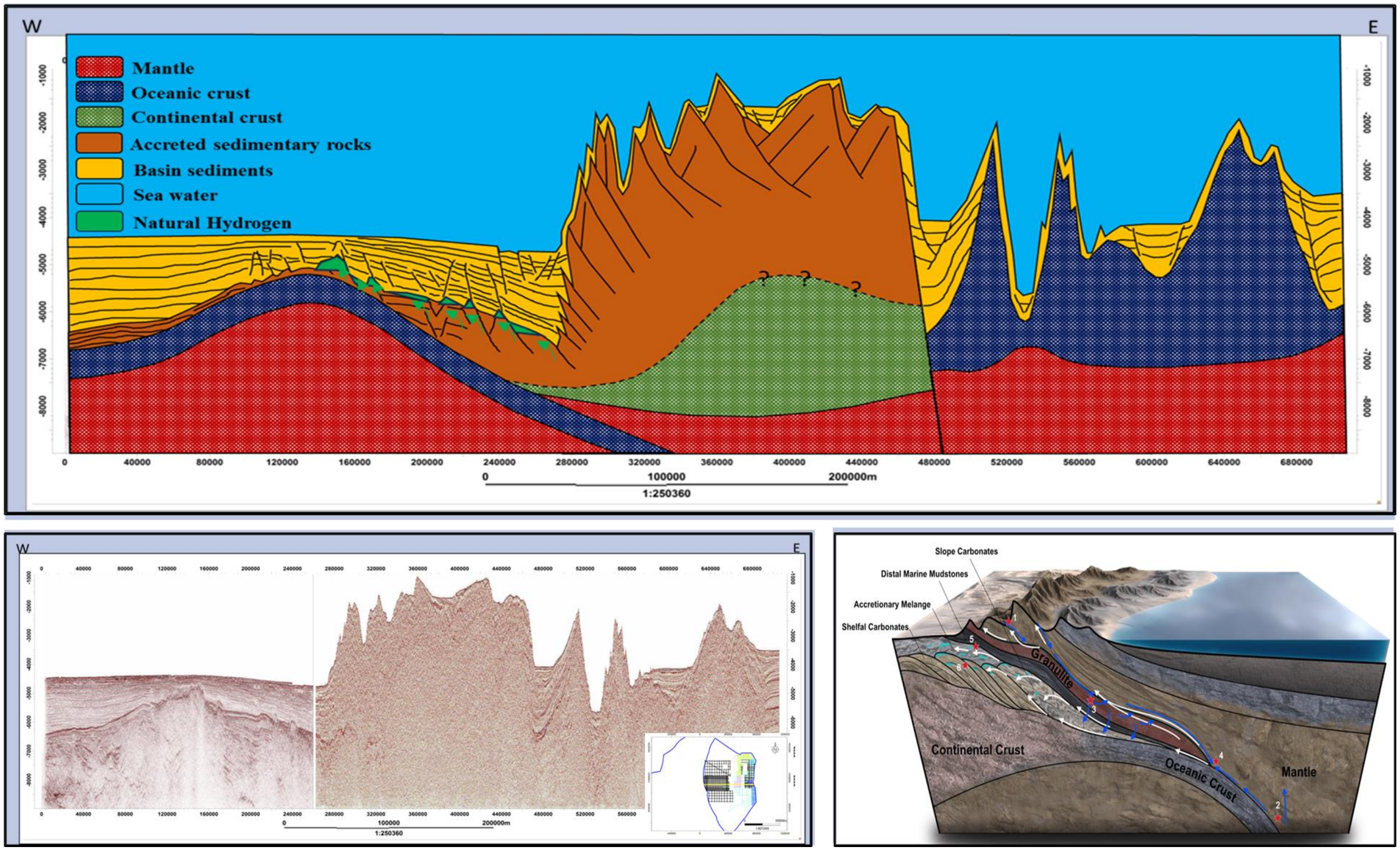

Figure 8: Conceptual model showing potential white hydrogen accumulation near the western Andaman Basin subduction zone, highlighting generation and trapping mechanisms.

7. Conclusion

The Andaman Basin presents a compelling case for white hydrogen exploration due to its unique tectonic setting, active seafloor spreading, and presence of iron- and uranium-rich lithologies. Seismic evidence indicates that serpentinization and fault-controlled migration pathways could enable localized hydrogen accumulations, while overlying marine shales may act as effective seals. By applying the hydrogen system model, this study highlights the dynamic processes of generation, migration, and entrapment, providing a framework to assess hydrogen potential systematically. The proposed multi-scale exploration strategy—integrating geological, geochemical, and geophysical data—enhances the likelihood of identifying economically viable hydrogen reservoirs. Beyond the spreading center, complementary exploration targets in the western Andaman subduction zone further expand the potential resource base. Overall, the findings demonstrate that natural hydrogen could serve as a sustainable, low-carbon energy source for India, complementing global energy transition goals. Continued interdisciplinary research and targeted exploration are essential to unlock the full potential of this underexplored energy frontier.

Conflict of Interest

The author declares no conflict of interest.

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