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The role of geophysics in geologic hydrogen resources

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Abstract

Transition to cleaner energy sources is crucial for reducing carbon emissions to zero. Among these new clean energy types, there is a growing awareness of the potential for naturally occurring geologic hydrogen (H_2) as a primary energy resource that can be readily introduced into the existing energy supply. It is anticipated that geophysics will play a critical role in such endeavors. There are two major different types of geologic H_2. One is natural H_2 (referred to as gold H_2), which is primarily accumulating naturally in reservoirs in certain geological setting; and the other is stimulated H_2 (referred to as orange H_2), which is produced artificially from source rocks through chemical and physical stimulations. We will first introduce geophysics in geologic H_2 in comparison and contrast to the scenarios of blue and green H_2. We will then discuss the significance of geophysics in both natural H_2 and stimulated H_2 in term of both exploration and monitoring tools. Comparing and contrasting the current geophysical tools in hydrocarbon exploration and production, we envision the innovative geophysical technologies and strategies for geologic H_2 resources based on our current understanding of both natural and stimulated geologic hydrogen systems. The strategies for H_2 exploration will involve a shift from reservoir- to source rock-centered approaches. Last, we believe that the geophysical methods including integration of multi-geophysics, efficient data acquisition, and machine learning in geologic H_2 could be potentially provide sufficient new directions and significant opportunities to pursue research for the next one or two decades.

Keywords: hydrogen; geophysics; energy; ergodic; machine learning; exploration

1. Introduction

Hydrogen has been a significant component in energy transition, the International Energy Agency's (IEA) Net-Zero by 2050 roadmap states a demand of 500 Mt/year of hydrogen (IEA 2019, 2021, DOE 2021). Current supplies cannot satisfy this demand. Thus, disruptive resources are needed, and geologic hydrogen including natural H_2 and stimulated H_2 has the potential to meet this goal (Yedinak 2022). Based on the research by scientists from USGS and across the globe, geologic hydrogen reserve potential varies from 500 000 tones/year (Lollar 2014) to billions of tones/year (Klein *et al.* 2020, Zgonnik 2020, Ellis and Gelman 2022). The evidence for the presence of geologic H_2 has been found all over the world, such as Mali (Caby 2014), Oman (Neal and Stanger 1983), the USA (Guélard *et al.* 2017), Australia (Boreham 2021), France (Lefeuvre *et al.* 2022), and Brazil (Prinzhofer *et al.* 2019). For instance, Zgonnik (2020) presents a global H_2 seeping map.

Researchers in these publications use various colors to refer to different origins of hydrogen gas in energy supplies. Figure 1 shows four different origins of H_2 and their commonly used color designation. Blue H_2 is derived from fossil hydrocarbon via steam reforming, and the resultant CO_2

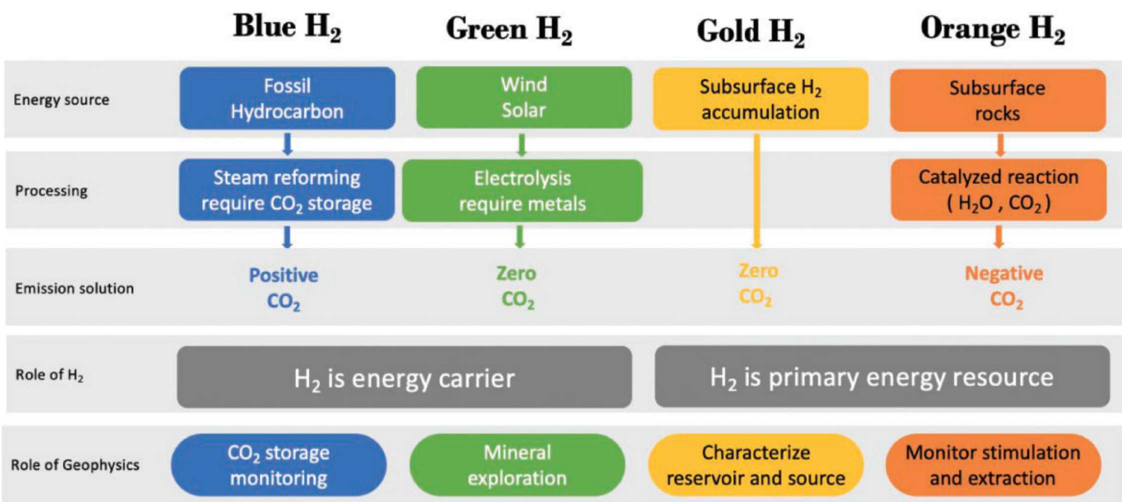

Figure 1. Color representation of different H_2 in energy transition. The biggest difference from blue H_2 and green H_2 is that geologic H_2 is primary energy resource instead of energy carrier. Meanwhile, the role of geophysics also changes with different H_2.

must be captured and stored. Blue H_2 could have a positive CO_2 emission, and is used as an energy carrier. Geophysicists contribute to CO_2 storage and monitoring. Green H_2, generated through the electrolysis of water, produces near net-zero CO_2 emissions and remains an energy carrier. One major challenge with green hydrogen is the metals required for solar panels and wind turbines, where geophysicists can aid in the mineral exploration.

Geologic H_2 includes natural H_2, which is referred to as gold H_2, and stimulated H_2, which is referred to as orange H_2. Natural H_2, found naturally in subsurface accumulation, requires no significant processing such as blue H_2 and green H_2 do, potentially emitting zero CO_2. Stimulated H_2, generated from artificially stimulating the chemical reaction in source rocks, also emits zero CO_2, and a potentially added benefit is that the production process could also serve as mineralized carbon storage if the catalyzed reactions involve the type that consumes CO_2. Geologic H_2 transitions the role of H_2 from an energy carrier (i.e. equivalent to the role batteries) to an energy resource. The importance of this change cannot be overstated in geologic hydrogen's role in helping achieve net-zero energy transition.

We seek to highlight the potential role of geophysics in geologic H_2 since nearly all these publications focus on geochemistry and geology, and there have been few discussions about geophysics. Geophysicists can explore for natural H_2 by identifying the source rocks and reservoirs, and can facilitate stimulated H_2 generation process by monitoring the stimulation and extraction. We anticipate an increase in research in these directions and by explicitly identifying the key challenges and methodological gaps we aim to prompt more innovative research from the applied geophysics community. Thus, geologic hydrogen is a clearly defined emerging field in which geophysics can directly contribute to maintaining stable energy supply and achieving net-zero CO_2 emissions.

In this paper, we will focus on the role of geophysics in geologic H_2. We first compare and contrast the key aspects of the hydrocarbon system and hydrogen system based on our current understandings. We then discuss natural H_2 system and stimulated H_2 system as two major components of geologic H_2. We discuss in distinct section the challenges and potential contributions by geophysics. One section will explore the challenges within natural H_2 system and the solutions that geophysics can offer. The other section examines the obstacles faced in stimulated H_2 system and how geophysics can provide the solutions. Last, we summarize these geophysical methods and the potential new directions for geophysicists to pursue in this field in the future.

2. Mechanism of geologic H_2 generation

From the perspective of a naturally occurring hydrogen system, geologists have identified many types of hydrogen generation mechanism and associated sources such as serpentinization (e.g. Coveney *et al.* 1987, Etiope *et al.* 2011, McCollom and Seewald 2013, Holm *et al.* 2015, McCollom *et al.* 2022), pyritization (e.g. Arrouvel and Prinzhofer 2021), and radiolysis (e.g. Bouquet *et al.* 2017). Metamorphism of ultramafic rocks (e.g. serpentinization) is an important means for the hydrogen generated in the Earth's crust (Milkov 2022). The chemical reaction is described by

$$3\,Fe_2SiO_4 + 2\,H_2O \rightarrow 2\,Fe_3O_4 + 3\,SiO_2 + 2H_2, \quad (1)$$

which produces H_2 as well as magnetite. This process in general could lead to increased magnetic susceptibility and reduced electrical resistivity in the resultant altered zones. The physical property changes associated with serpentinization

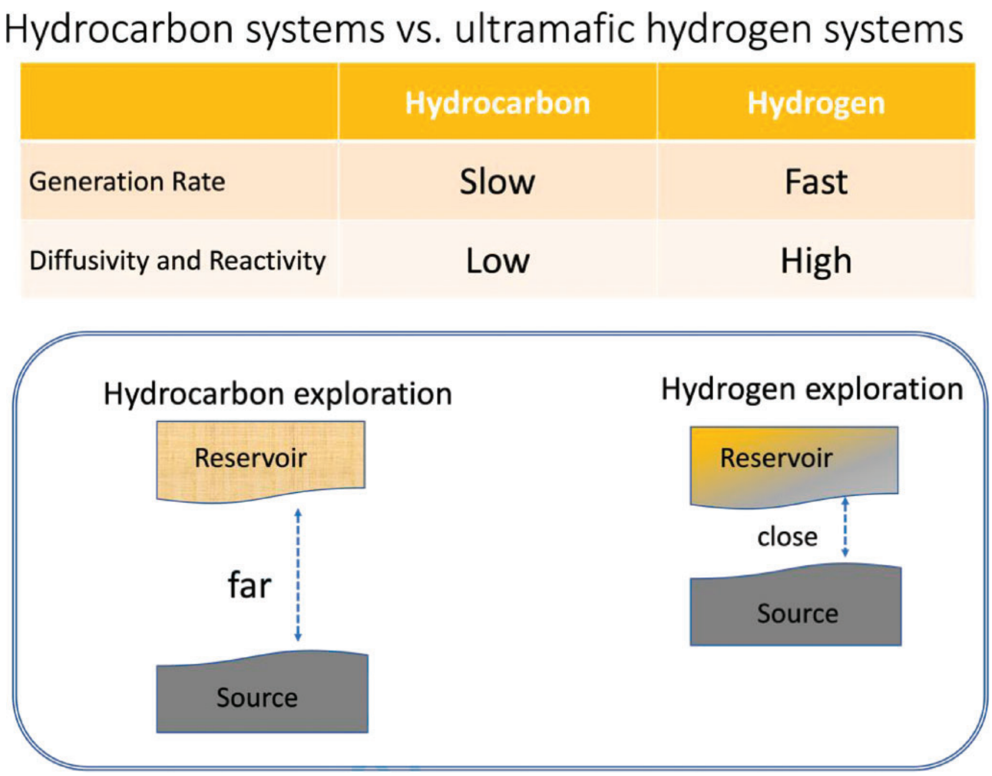

Figure 2. A summary of the contrast between a hydrocarbon system and one scenario of hydrogen system sourced from ultramafic rocks. The major differing factors to consider for hydrogen systems are the fast generation rate in the source rocks, the significantly higher diffusivity and reactivity, and the need for proximity between source rocks and the potential reservoir.

has been the subject of investigation in the context of traditional mineral exploration (e.g. He *et al.* 2018), and more recently in the context of carbon storage through mineralization in ultramafic (e.g. Cutts *et al.* 2021).

3. H_2 system versus natural gas system

H_2 evidence has been found all over the world, such as Mali (Caby 2014), Oman (Neal and Stanger 1983), United States (Guélard *et al.* 2017), Australia (Boreham 2021), France (Lefeuvre *et al.* 2022), and Brazil (Prinzhofer *et al.* 2019), where Mali and Oman have better studies. Based on these examples and research studies, there are many differences between an H_2 system from serpentinization and a hydrocarbon system. In this paper, we only talked about the differences, which leads to different selections of geophysical scenarios.

We understand that the hydrocarbon in fossil fuel such as natural gas took over millions of years to form. Geologic hydrogen can be generated relatively fast, and the time scale may be on the order of years or decades (Neal and Stanger 1983; McCollom and Bach 2009, Klein *et al.* 2013, Leong *et al.* 2023). Meanwhile, natural gas is stable and has lower diffusion and lower reactivity than hydrogen, so natural gas can be more easily accumulated in the reservoirs. By contrast, geologic H_2 has high diffusion and high reactivity (Bardelli *et al.* 2014, Gaucher 2020, Ménez 2020). The high diffusivity and reactivity would imply that H_2 may not easily accumulate far away from the source because most H_2 could have been consumed on the way of long-distance migration. It is understood that some H_2 may have migrated over a long distance from mantle sources to near surface in the crust. However, given that the mantle source is deep, there is a low likelihood of large quantities of H_2 accumulation unless favorable geological settings, such as temperature and pressure, prevent the H_2 from being consumed by reactions and other factors during the long-distance migration. These factors associated with the long distance are likely to decrease the likelihood of H_2 accumulation compared with the situation of relatively short distances between source rocks and reservoirs. On the other hand, the properties of faster accumulation rates within shorter migration distance of geologic H_2 can also help recharge the reservoirs near the source rocks, so that large reservoirs are possible in the proximity of the source rocks. The key points of the comparison and contrast between natural gas and hydrogen systems are shown in Fig. 2.

Based on this reasoning, we propose a hydrogen exploration scenario for which the focus of early research and development is to develop tools to discover the H_2 accumulation occurring near the source rocks. The key understanding that sizable hydrogen accumulations are likely to happen

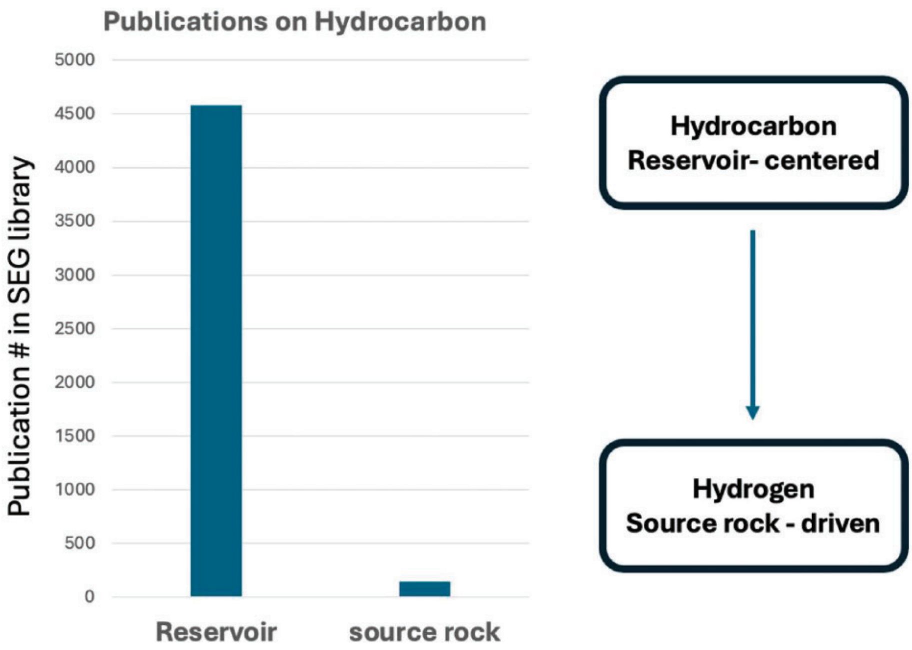

Figure 3. Number of publications on hydrocarbon exploration in the last two decades obtained from the Society of Exploration Geophysicists Library. There are 30 times more papers on reservoirs than on source rocks. This disparity in publications demonstrate the focus on reservoirs in the oil and gas exploration. Because of the importance of source rocks in geologic H_2, however, we envision a necessary shift in the exploration strategy. There needs to be much more source-rock-focused research and development in the hydrogen exploration.

closer to source rocks motivates us to introduce the source rock-driven strategies for the scenarios with hydrogen generation through serpentinization in ultramafic rocks. We emphasize that this strategy is in sharp contrast to the conventional hydrocarbon exploration approach that is reservoir-centered, as illustrated in Fig. 3, because the existence of large accumulations mean the hydrocarbon reservoir can be far away from the source rocks. Once hydrogen source rocks are located, however, we can explore for other components of H_2 migration and accumulation around source rocks. This feature of the hydrogen system will require the development of new integrated geophysical techniques for the effective characterization of essential hydrogen-system components and delineation of potential resource targets. We will discuss the relevant integrated geophysics in geologic hydrogen (Zhang *et al.* 2022, Zhang and Li 2023a) and the reason that reservoir-focused strategies may not be suitable for geologic H_2 in Section 5 on Geophysics.

4. Natural H_2 system versus stimulated H_2 system

We discussed the difference between hydrocarbon (natural gas) systems and naturally occurring geologic hydrogen systems in the preceding section. However, there are two H_2 systems from which we can produce geologic hydrogen. The first is from the naturally occurring H_2 accumulations and the second is through stimulated H_2 systems. It is important to draw the distinction between natural H_2 and stimulated H_2 systems.

The occurrence of natural H_2 in large quantities requires multiple suitable conditions such as the reaction in Equation (1) (Milkov 2022), which may not easily occur spontaneously in nature. Since the subsurface can continuously generate hydrogen through natural geochemical and biological processes (Dopffel *et al.* 2023), we can accelerate these processes artificially. Osselin *et al.* (2022) propose stimulated H_2 generation in which one artificially stimulates H_2 source rocks under controlled conditions such as temperature, pressure, pH level of water, selected source-rock composition, and rock-water ratio (Neal and Stanger 1983; McCollom and Bach 2009, Klein *et al.* 2013, Leong *et al.* 2023). This artificial action stimulates hydrogen generation directly from the source rocks without the need of a reservoir.

In the naturally occurring H_2 systems, the reservoir accumulation stage and the hydrogen generation from source rocks are commonly separate in both geological time and space, even though the time separation is shorter than that in the hydrocarbon systems and the spatial distance is closer than the hydrocarbon system. Therefore, it is possible to look for the reservoir and source rocks separately in the exploration for natural occurrence of H_2.

By contrast, the reservoir and source rocks in the stimulated hydrogen are mixed in time and space. Therefore, we have to pay attention to both reservoir and the source rocks simultaneously. The dynamics from the overlap of the hydrogen generation and accumulation in the source rocks stems from stimulated H_2 generation first and then from the action of extracting H_2 within a short time span or simultaneous to the stimulation activities. To ensure sustained and efficient production of stimulated H_2, we must monitor the H_2 generation process such as serpentinization and ensure its continuation and efficiency and also monitor the change of fluids and rocks with time associated with the H_2 extraction. Therefore, a major task is to monitor the serpentinization in the hard rock settings during the stimulation process, which is a significant departure from the monitoring reservoir in the hydrocarbon production.

5. The role of geophysics in geologic H_2

Whether to look for reservoirs and source rocks in natural H_2 exploration or to monitor the dynamics of the stimulated H_2 generation, we need to image the variation in the subsurface as a function of location and time. This is the realm of geophysics. Thus, geophysics plays an important role in the geologic hydrogen exploration and production in general. However, the use of geophysical tools and emphases are significantly different in natural and stimulated geologic hydrogen.

For natural H_2 exploration, many geophysical tools used in the traditionally hydrocarbon exploration can be applied to the aspect of locating and delineating reservoir, but new techniques are required for source-rock delineation. For stimulated hydrogen, the monitoring need to focus on both stimulated chemical reaction and the fluid-dynamics of H_2 extraction, a distinct set of geophysical imaging tools is needed. It follows that the research and development and the use of geophysics on geologic H_2 will likely follow two rather distinct trajectories. We briefly discuss the two trajectories next.

6. Exploring natural H_2 (gold H_2) using geophysics

6.1. Integration of gravity, magnetic, EM, and seismic

Because H_2 has strong diffusivity and reactivity, the farther the H_2 migrates after having been generated, the less likely it will be preserved. H_2 can be consumed along the migration pathway due to high reactivity and biological consumption, or be dissipated due to the high diffusivity. Thus, there is the potential for some H_2 to migrate long distances along the conduits such as suitable faults with the right condition, but it is more likely that smaller-sized H_2 accumulations would occur in higher probabilities than those of hydrocarbon after migrating along the pathways of similar distances in similar geological environments. Therefore, to achieve the same economic volume of deposits as those for hydrocarbon, it is logical to infer that there should be shorter distances between hydrogen reservoirs and source rocks. This contrast is highlighted in the illustration in Fig. 2.

The source rock would also be partially serpentinized with uneven distribution (e.g. He *et al.* 2018). We hypothesize that the presence of partial serpentinization could also be a key component as that means the reservoir would have been recharged in recent geologic time. A completely or largely altered source-rock volume would likely indicate a longer lapsed time since the active generation of geologic hydrogen and lower likelihood of preserved hydrogen accumulation. Therefore, the separation in time between serpentinization process and current state of source rock could also be a key factor.

It follows that the regions of higher H_2 prospectivity for natural H_2 exploration would be near the source rocks that have sufficiently large volume and have undergone partial serpentinization. It remains to be understood as to how large a volume is "sufficient" through future research and analyses of exploration data, but these two aspects are necessary conditions. Therefore, looking for source rocks in H_2 system is an indirect way to help discover the H_2 reservoir nearby. Our proposed source rock-driven strategy would then be able to utilize the multiphysics approaches that have been developed in mineral exploration, which employ electromagnetic, gravity, and magnetic data (e.g. Nabighian and Asten 2002, Dentith and Mudge 2014) as well as the integrated imaging of subsurface geology using quantitative interpretation tools such as inversion, joint inversion, and geology differentiation (e.g. Li and Oldenburg 1996, 1998, Oldenburg *et al.* 2005, Holtham and Oldenburg 2010, Sun and Li 2016, Devriese *et al.* 2017, Melo and Li 2021). These tools will enable the mapping and delineation of the presence of source rocks such as Fe(II)-rich ultramafic rocks (Equation (1)) and also estimate the volume and degree of serpentinization within the source rocks.

The preserved H_2 would have migrated to reservoirs with overburden caps or accumulate to locations such as those with gentle faults. We could extract H_2 by horizontal wells in the reservoir sealed by the overburden layers or by vertical wells in the situation the H_2 is trapped by faults or structural traps. The seismic method would provide the tools for imaging the reservoirs, seals, faults, and structural traps. Many of the methodologies developed in conventional natural gas exploration could be adapted and modified for finding and delineating H_2 reservoirs. These methods include imaging approaches (e.g. Baysal *et al.* 1983, Chang and McMechan 1994, Zhang *et al.* 2016), attributes analyses (e.g. Marfurt *et al.* 1998, Dou *et al.* 2017, Yang *et al.* 2017), and full waveform inversion for the fluid content in the reservoirs (e.g.Virieux and Operto 2009, Wu and McMechan 2019).

If we were to follow the strategies in natural gas exploration and sought to apply the same approach to natural hydrogen exploration, we may consider that only seismic method might be needed to identify H_2 reservoirs. However, the previously mentioned factors unique to natural H_2 may lead to the sole application of a seismic method of exploration to produce false positives or even discovery of natural

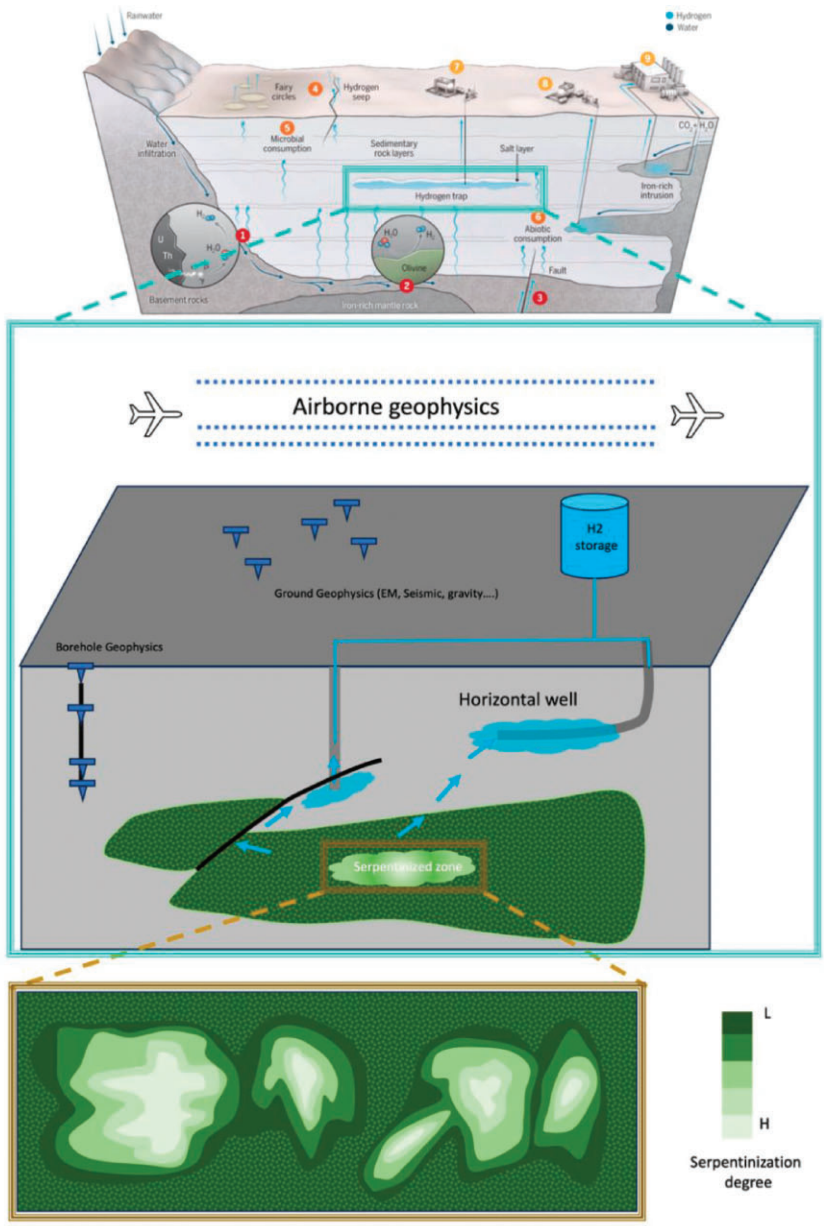

Figure 4. Illustration of geophysics in natural H_2. Integration of geological tools can help identify both source rocks and reservoirs to avoid positive false and negative true of H_2 accumulation. The imaging using geophysical data can guide the well drilling. Efficient geophysical acquisition design can help reduce the data collection cost. (Top image from Hand 2023; Figure credit for middle and lower panels: Mengli Zhang.)

gas reservoirs unintendedly. Meanwhile, depending on the thickness of transition zone between H_2 reservoir and the capping seal, there may be a smooth velocity change in this transition zone such that little reflections can be observed in the seismic data. Consequently, direct application of seismic method may cause false negative results in H_2 exploration.

The combined strategy of source-rock delineation using EM, gravity, and magnetics and then exploring for H_2 reservoirs in the vicinity of the source rocks can not only mitigate these risks significantly, but also forms a necessary component. Figure 4 illustrates the concept of integrated exploration for the H_2 source rocks using multiple geophysical tools such as airborne magnetic, airborne gravity gradiometry, ground gravity, airborne and ground EM, and deep sensing electrical methods to map and delineate ion-rich source rocks such as ultramafics. Figure 4 illustrates the scenario of identifying H_2 reservoirs using high-resolution geophysical data, followed by the extraction from vertical wells or horizontal wells depending on the characteristics of the reservoirs.

6.2. *Efficient and high-resolution geophysical data collection*

An interesting observation is that there have been no discoveries of major H_2 reservoirs associated with oil and gas drilling over the decades in the major basins despite the fact that there are a substantial number of early wells with hydrogen gas. One possibility is that we have not been looking in the right places. However, cautionary reasoning must take into consideration the fact that most of the major basins have been explored for oil and gas, so there is a low likelihood of finding world-class H_2 reservoirs comparable to large natural gas reservoirs in these basins. It follows that high-prospectivity areas are likely on the margins of the basins or away from them. This consideration is also consistent with what we understand as being the requisite condition, namely, proximity to partially serpentinized ultramafic rock units. Meanwhile, the lack of major discoveries in basins also points to the likelihood that H_2 deposits or reservoirs could be occurring in smaller sizes compared to natural gas reservoirs. Thus, at least in the early stages of H_2 exploration and beyond wildcatter drilling, we must contend with the need to scan vast areas and image the subsurface volume to identify sterile regions and to high-grade more prospective areas.

Consequently, the spatial extent to be covered by geophysics increases dramatically and the cost of geophysical data acquisition, and accompanying geochemical and gas sampling, in large areas could become a significant obstacle to H_2 discoveries. Similarly, the time required for data acquisition could also have a major negative impact. Two factors become important: the ability to collect data efficiently and cost-effectively over large areas, and the ability to collect high-resolution data with available budget and within the time frame that is acceptable to venture investments.

Efficient and cost-effective geophysical data collection can be achieved by two approaches among others. One is through the adaptation of the low-cost and distributed sensors and equipment that are on the horizon or yet to be is invented and developed. The other is by applying new geophysical survey designs and field implementations. Compressive sensing-based acquisition in seismic exploration has seen great successes in low-cost seismic survey design and acquisition (e.g. Herrmann 2010, Li *et al.* 2013, Mosher *et al.* 2014, Brown *et al.* 2017; Zhang, 2020). The newly developed ergodic sampling (Zhang and Li 2022, 2023b) can also provide broadly applicable alternative survey designs for the low-cost ground and airborne acquisition of geophysical data including EM, gravity, gravity gradiometry, and magnetic data. This approach can be used to cover areas for reconnaissance surveys on the order of 2 to 10 times larger than what is feasible through conventional approaches. Equally importantly, ergodic sampling can be used to acquired data with much higher resolution in high-graded target areas without incurring increased cost or time. Thus, ergodic sampling can be used to gather much more information for detailed imaging of target areas.

6.3. *Interdisciplinary and machine learning integration*

The H_2 generation, migration, and preservation is a complex system that will have correspondingly complex geophysical signatures. The systems involve hard rock settings, water and hydrological components, chemical reactions, and soft rock setting for H_2 accumulation and preservation. Therefore, elements of at least three traditional systems, i.e. mineral system, hydrogeologic system, and petroleum system, are involved in H_2 exploration. Consequently, geophysical techniques from different subject areas including hard rock mineral exploration, soft rocks oil and gas exploration, and hydrothermal fluid in geothermal exploration will be required. The complexity associated with these systems and their interactions can only be understood through an interdisciplinary approach by using multidisciplinary knowledge. Thus, to recombine and re-configure these techniques is a key to discovering and producing geologic H_2. Furthermore, the complexity involved in integrating different types of geophysical data as well as geologic and site-specific information is expected to be a significant challenge. Machine learning and even artificial intelligence approaches will likely be a fruitful avenue and pave the way for effective integration and for information extraction in discovering H_2 resources.

7. Monitor stimulated H_2 (orange H_2) using geophysics

The subsurface can continuously generate hydrogen through natural geochemical and biological processes (Dopffel *et al.* 2023). However, the generation rates may not be enough in some cases (Aiken *et al.* 2022) to satisfy the demand for H_2. We can artificially produce much more H_2 if we can enhance or induce more H_2 generation process such as serpentinization and suppress the consumption of resultant H_2. This procedure is the stimulated H_2 discussed earlier. Meanwhile, source rocks such as olivine-rich ultramafics are widely distributed around the world. Stimulated H_2 production by taking advantage of the widely available source rocks can significantly lower the exploration requirements compared to natural H_2. At first, it may appear that the geophysics may not have much to do in the stimulated H_2 beyond mapping source rocks. That could be true if the stimulation is easily implemented on site as in the laboratory settings and the H_2 can be extracted without any environmental risk. However, there are many challenges in the stimulated H_2 processes that are not present in natural H_2 exploration. Therefore, we need innovative methods to address these challenges and geophysics has a critical role to play.

Table 1. Contrasts between natural and stimulated H_2 systems.

	Natural H_2	Stimulated H_2
Generation and accumulation	different geologic time and different locations	same time and similar locations
Chemical reaction	little	rapid change (minute to hour)
Physical properties	stable	varying
Temperature and deformation	little change	rapid change and significant influence on H_2 generation

There are several challenges in a stimulated H_2 system that are not faced by natural H_2. Table 1 summarizes the contrasts. A key difference is that there are much more rapid changes in stimulated H_2 systems observable on the time scale of days or weeks.

Because of the overlap between the generation zone and accumulation zone in stimulated H_2, multiphysics integration of geophysical methods is a must. Meanwhile, there are rapid changes in stimulated H_2 process associated with the chemical reaction, resultant physical properties, and temperature and deformation fields so that real-time monitoring using geophysics is also necessary; in the following are our suggestions to apply geophysics.

7.1. *Real-time monitoring of H_2 generation process using integration of electromagnetic and magnetic*

Electromagnetic (EM) and magnetic data are efficient to collect and have for sufficient sensitivity to the electrical conductivity and magnetic susceptibility of ultramafic rocks and serpentinization zones therein. Integration of EM and magnetic data can be used to characterize ultramafic source rocks and to image serpentinization zones during H_2 stimulation. Ultramafic rocks have distinct ranges of physical property values (e.g. magnetic susceptibility, conductivity, and density) (e.g. He *et al.* 2018, Cutts *et al.* 2021), which will enable geophysics to image these source rocks. The serpentinization process changes the conductivity and susceptibility further, and these changes enable geophysics to image the occurrence, degree, and spatial extent of serpentinization. Using the imaged conductivity change from EM data and susceptibility change from magnetic data can delineate serpentinization zone where the H_2 is generated. Figure 5 illustrates the real-time monitoring using high-resolution geophysical data such as integration of electromagnetic and magnetic data with ground and borehole deployments.

7.2. *Characterize and monitor temperature field*

Imaging and monitor temperature field can also be significant in stimulated H_2. The importance of this component is 2-fold. First, both the injected water and serpentinization processes would alter the temperature field in the H_2 source rocks (e.g. Allen and Seyfried 2004), while temperature and heat flow have a profound influence on the serpentinization process and H_2 generation (e.g. McCollom *et al.* 2016). For example, some studies indicate the viability for low temperature H_2 generation below 100°C (e.g. Neal and Stanger 1983; Leong *et al.* 2023), while other studies suggest a higher temperature range above 200°C (e.g. McCollom and Bach 2009). Even though the optimal temperature for stimulated H_2 has not been established, we can be sure that the temperature monitoring is critical. Unlike in the sample-scale laboratory experiment, the temperature field cannot be directly measured throughout the volume of stimulated serpentinization. Geophysics can help monitor temperature through limited measurements and inverse reconstruction of the 3D temperature distribution. A fully imaged temperature distribution in the stimulation volume can potentially serve the dual role as an effective indicator of serpentinization degree and environmental and stimulation factors for maintaining and optimizing the H_2 generation.

7.3. *Characterize and monitoring deformation field*

The serpentinization reaction will lead to volume expansion (e.g. Cutts *et al.* 2021). Meanwhile, the thermal effect associated with the process as well as fracturing of the source rocks are also expected to result in deformation of the source-rock units during the stimulated hydrogen generation. Thus, using the deformation data such as strain measurements and imaging the source zones of deformation can provide additional information about spatial location and degree of serpentinization. The imaged deformation field can provide complementary information to characterize and image in real time the stimulated hydrogen generation process. Both surface deformation data and borehole strain data could be used for this purpose.

7.4. *Real-time feedback to engineering operation and control*

Imaging and monitoring the source-rock zones under stimulation is only a means to an engineering end. The monitoring will ultimately provide the actionable information for engineering operational decisions to adjust and control the stimulation process so as to sustain and optimize the H_2 generation and extraction. The research by McCollom and Bach (2009)

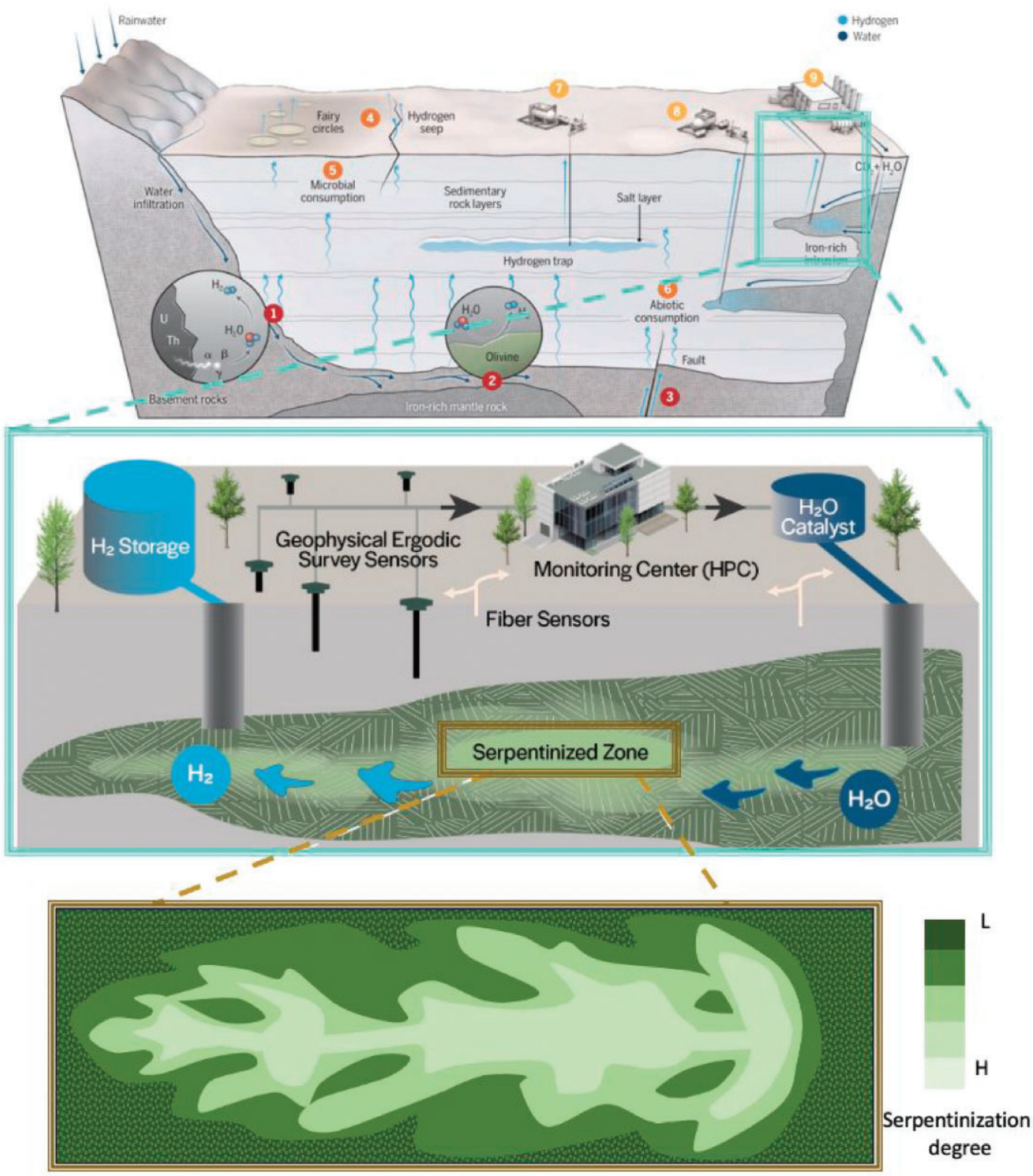

Figure 5. Illustration of geophysics needed in stimulated H_2. Real-time monitoring of H_2 generation process using integration of electromagnetic and magnetic data: characterizing and monitoring the temperature field, and real-time feedback to engineering operation using ML processing. (Top image from Hand 2023; Figure credit for middle and lower panels: Mengli Zhang and Jenny Crawford.)

indicates that lithologies, temperature, pressure, pH level of water, and water-rock ratio all influence H_2 generation rate and H_2 concentration. There is a body of work based on laboratory research, but the transfer of these research results to field-scale stimulated H_2 requires a crucial link that can remotely provide the parameters for use in dynamic control, and geophysical monitoring provides that link. To enable the processing and inversion of the geophysical monitoring data, we envision the use of high-performance computing. To extract the information from multiple geophysics data set in real time, machine learning (ML) approach would be a necessary and could prove to be an effective avenue of development. Figure 5 illustrates the concept.

8. Summary

The effort in producing geologic hydrogen consists of exploring for naturally occurring H_2 accumulation and stimulated H_2 production. Geophysics will play an important role in both scenarios. We have outlined possible geophysical strategies for natural hydrogen exploration and for stimulated hydrogen monitoring based on the current understanding of H_2 systems. As new discoveries and evidence emerge and the understanding of geologic H_2 systems improves, the geophysical strategies will certainly also evolve too.

It is clear that different geophysical tools are needed for natural H_2 resources exploration and production and

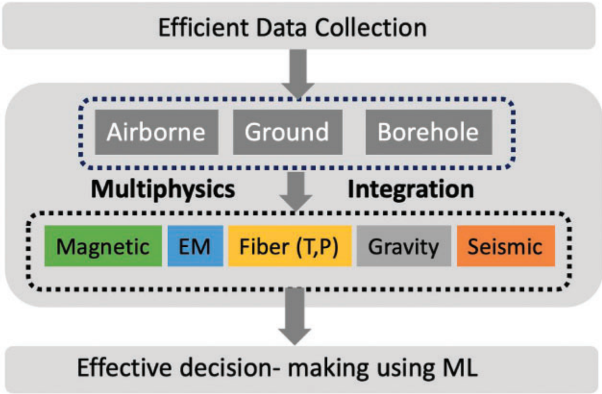

Figure 6. Summary of geophysical tools in geology H_2 and potential research directions.

for stimulated H_2 production. We summarize these tools in Fig. 6. Geophysical data collection is the first step, so efficient geophysical data collection including low-cost sensors and efficient survey design are needed. Airborne, ground, and borehole geophysical acquisitions can all be applicable depending on the geological setting and target sizes. In natural geological H_2, integration of EM, gravity, magnetic, and seismic data can characterize source rocks and reservoirs. These data types in conjunction with temperature and deformation data can monitor H_2 generation and extraction in the stimulated H_2. Ultimately, the objective is to make decisions efficiently by using with ML tools in processing and interpretation of these data in geologic hydrogen exploration and production.

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