Geophysics in 'gold' hydrogen exploration

Mengli Zhang and Yaoguo Li, Center for Gravity, Electrical, and Magnetic Studies (CGEM), Department of Geophysics, Colorado School of Mines, Golden CO 80401*

SUMMARY

There is a growing recognition of the potential for naturally occurring geologic hydrogen (gold H_2) as a low-carbon primary energy resource that can be readily introduced into the existing energy supply. Thus, gold H_2 is gaining attention as one of potential new forms of low-carbon energy and can contribute to the transition toward net-zero carbon energy. It is anticipated that subsurface exploration using geophysics will play a critical role in such endeavors. We will discuss a potential geophysical strategy for H_2 exploration based on our current understanding of geologic hydrogen systems and selected scenarios.

INTRODUCTION

Climate change is one of the most pressing challenges of our times and the transition to a net-zero carbon energy supply is a key component to tackling the challenge. The transition will require a multifaceted approach that includes carbon capture utilization and storage (CCUS) and a significant build-up in renewable energy such as solar and wind. However, the magnitude of CCUS and renewable energy development necessary to achieve this goal will require an unprecedented amount of new infrastructure and supply of critical minerals, which are significant obstacles to meeting this objective. Consequently, all new forms of low-carbon energy are important and gaining increased attention. Within this context, there is a growing awareness of the potential for naturally occurring geologic hydrogen (H_2) as a low-carbon primary energy resource that can be readily introduced into the existing energy supply.

Thus, geologic hydrogen exploration could be a game changer for net-zero emission energy transition (Prinzhofer et al., 2018; Gaucher, 2020; Milkov, 2022). Geophysics is anticipated to play a significant and critical role in the search for natural hydrogen, since the search necessarily requires subsurface exploration using geophysics. There are many questions on how to use geophysics in this endeavor, but our recent work has identified several key aspects. Our work suggests that recombining and reconfiguring exploration geophysical methods traditional used for mineral deposits and natural gas, integrating with the emerging understanding of hydrogen systems and the corresponding petrophysical data, could offer an effective path forward. In this abstract, we discuss a potential geophysical strategy for H_2 exploration based on our current understanding of geologic hydrogen systems and selected scenarios.

GEOPHYSICAL EXPLORATION FOR HYDROGEN

A simplified hydrogen system's perspective

Let us consider a hydrogen system that generates enough hydrogen (H_t) to support possible economic accumulations. A portion of the hydrogen would be consumed by abiotic and biotic reactions on its upward migration (H_c), and another portion could have dissipated to the atmosphere and be lost (H_d). The remaining portion could potentially accumulate in economic form in reservoirs. We refer to this portion as the retention of hydrogen (H_r) in the subsurface. There are certainly many other factors, but conceptually it is reasonable to assume that the sum of these three portions should be approximately equal to the total hydrogen generation in a system,

$$H_t \longleftrightarrow H_c + H_d + H_r \tag{1}$$

which essentially states a conservation of hydrogen in a system. We do not consider this being a quantitative equation, but it provides a conceptual relational context for discussions. The problem of exploring for hydrogen then becomes one of estimating these four parameters in the subsurface locations containing hydrogen source rocks and searching for subsurface regions where the hydrogen retention H_r is above an economic threshold.

The total hydrogen generation H_t would be related to the available source rocks, such as ultramafic rocks, which can be delineated by geophysical method and then characterize by using recovered geophysical properties. The consumption H_c and hydrogen dissipation H_d could be estimated from combined use of geochemistry and geophysics. It may be possible to develop direct means of estimating hydrogen retention H_r, but most likely we need to consider these major component to arrive at an estimation indirectly. This conceptual equation could be used to arrive at an indirect estimate of hydrogen retention by using geophysics to form proxies of these components.

Geophysics for key hydrogen system components

In our study we have focused on hydrogen systems that generate hydrogen by geochemical processes such as serpentiniza-

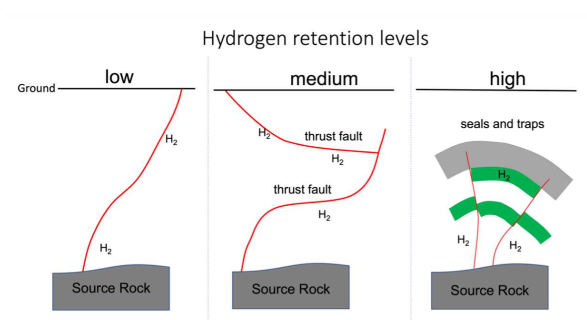

Figure 1: Conceptual illustration of three potential levels of H_2 retention in hydrogen systems as influenced by the structural complexity above the source rocks.

10.1190/image2024-4100404.1

tion in ultramafic rocks. We have proposed a source-rock-driven exploration strategy. Given the accumulated petrophysical property data such as electrical conductivity and magnetic susceptibility of ultramafic rocks, electromagnetic method such as magnetotellurics (MT) and magnetic method can be used jointly to delineate hydrogen sources rocks where H_2 was, or is being, generated through serpentinization. A source rock-driven exploration to identify H_2 would be a shift from the reservoir-centered approach that has been prevalent in the natural gas exploration.

The next key factor is the hydrogen consumption. We examine three conceptual scenarios that could have different retention rates as illustrated in Figure 1. The first one would have low retention rate due to the presence of steep faults acting as hydrogen escape conduits. The second has more gently sloping faults leading to slower hydrogen leakage or dissipation. There may be exciting fairy circles on the surface of these two types. The third type has overburden seals and traps so that a large amount of hydrogen accumulation could occur, and the corresponding retention rate could be the highest. Locations consistent with the third scenario will likely be the most prospective regions for natural H_2 and may form the focus of the early efforts in the hydrogen exploration. MT and active-source electromagnetic, magnetic, and seismic methods could be used in combination to differentiate these scenarios. The effort to investigate retention rate through geophysical proxies would be qualitative or semi-quantitive, and may be used to constrain geochemical data to fully estimating hydrogen consumption. Such an approach would combine the strengths of geophysics in imaging volumes of subsurface at large depth with the strengths of geochemical data in their direct characterization of the hydrogen generation processes and reactive loss.

The last step is to calculate the hydrogen retention rate from the subtraction of the above two factors. In general, geophysics needs to be combined with geology and geochemistry to achieve the assessment of H_2 in place. This would be a late stage science and technology development, and associated research will likely be pursued if, and only if, successful wildcat wells are drilled.

Based on the available understanding of hydrogen systems and the associated exploration challenges, it is clear that geophysics is a requisite part of the toolkit for geologic hydrogen exploration. Recombining existing geophysical methods can help produce more accurate delineation and imaging of the source rock and serpentinization degrees therein, which determine the upper limit for H_2 generation. In the early stages of hydrogen exploration, either as an emergent industry or on a project time scale, a reliable estimate of the upper limit is significant, or even critical, for the industry to make major exploration decisions, such as where to invest for exploration and where to drill wildcat holes. More important geophysical contribution is, perhaps, to the question of where not to drill based on source rock delineation.

Unlike the early days of wildcat drilling in the oil exploration, we now have decades of accumulated knowledge and technological advances that can be reconfigured to support the hydrogen exploration from the very beginning. The venture capital projects will still drive the wildcat drilling, but geophysics is well-positioned to guide the effort. That is, the mindset for the early stage of hydrogen exploration may very well be geophysics-guided wildcat drilling.

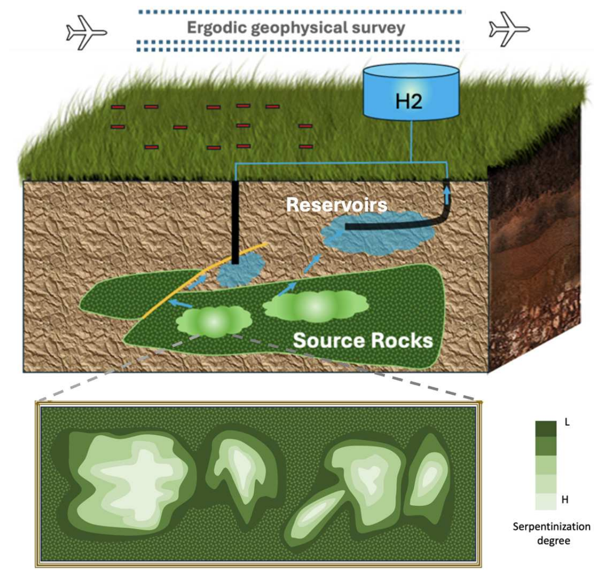

Figure 2: Illustration of geologic H_2 model including source rocks and reservoirs. The top portion indicates airborne and ground geophysical efficient data acquisition using ergodic sampling. With geophysical data, we can image both reservoir and source rocks in the subsurface, and petroleum engineers can adapt existing technologies to extract hydrogen with vertical or horizontal wells guided by geophysics. Two types of reservoirs are illustrated. One is H_2 accumulation under gentle faults, and the other is H_2 concentration in reservoir rocks. In term of H_2 source rocks, the different serpentinization degree, volume, and location are illustrated in the bottom panel.

Based on our current understanding, we illustrate geologic hydrogen system in Figure 2. On the top is an illustration of natural H_2 exploration using geophysics including airborne, ground and borehole surveys coupled with efficient ergodic survey designs (Zhang and Li, 2022, 2023). Besides collecting data and identifying source rock locations, the other component that needs to be understood is the hydrogen accumulation. In Figure 2 we illustrate two different type of hydrogen accumulation. The first type is under gentle faults, such as thrust faults, which is the structural reservoir. Some hydrogen could

Hydrogen system components	Geophysical methods
Source	
Ultramafic rocks	EM, Magnetic, Gravity
faults	Seismic, Magnetic
Migration pathway	
Faults	Seismic, Magnetic
High permeability strata	Seismic, EM
Reservoir	
Siliciclastic	Seismic, EM
Carbonate, dolomite	Seismic, gravity, magnetic
Fractured crystalline	EM
Trap/seal	
Structure	Seismic, EM
Stratigraphic	Seismic
Preservation	
Faults	Seismic, EM

Figure 3: A preliminary summary of multiple geophysical methods for exploring different components of geologic hydrogen system.

10.1190/image2024-4100404.1

accumulate in such structure related traps. The second type is hydrogen accumulation in the reservoirs because of the overburden seals, namely, lithologic reservoirs.

GEOPHYSICAL TOOLS AND EXPLORATION STRATEGIES

To image the subsurface, geophysical methods are necessary tools. Figure 3 lists multiple geophysical methods for exploring different components of the geologic hydrogen system. This is a preliminary summary, and the tools will likely be changed and updated after more testing and verification as the field of hydrogen exploration develops and matures. These geophysical methods can provide subsurface physical properties and structures through inversion and imaging to delineate and characterize hydrogen source rocks and reservoirs. For example, integrating different geophysical data sets by combining the resistivity from electromagnetic data, velocity from seismic data, and density from gravity data so that potential hydrogen reservoir can be imaged and de-risked.

There is a scarcity of field data for studying geophysics. Currently, petrophysical data from Oman and well log data from Mali provide the basis for us to generate geophysical models of source rocks and hydrogen reservoirs, which enable us to investigate different geophysical methods.

For source rocks such as dunite at Oman site (Hong et al., 2022; Aiken et al., 2022), our numerical studies indicate that magnetic data can have sufficient response to partial serpentinization. If a dunite unit is serpentinized, both susceptibility and remanent magnetization decrease at Oman site. Assuming a tilted dunite stratum as that present at the Oman drilling project site, we have carried out numerical simulations to understand the magnetic signature. Partial serpentinization of a dunite unit will lead to substantial changes in the total-field anomaly. Thus, magnetic method can be sensitive to the serpentinization at different depths.

We have also carried out simulation of hydrogen reservoir responses. We built a subsurface velocity structure model with an embedded oval-shaped reservoir. We use the physical properties at the Mali site (Maiga et al., 2023) for the surrounding rock units. Mali reservoir is located within carbonate and dolomite, which is lithologic reservoir since there is no structures such as faults involved. Based on well log data at the Mali site (Maiga et al., 2023), we estimate the velocity in hydrogen reservoir to be at 4,400 m/s. In contrast, the velocity in surrounding rocks is around 6,000 m/s. We built the velocity model in Figure 4 (a) using these data.

We carried out the seismic simulations and obtained seismic imaging result in Figure 4 (b). We note that the seismic bright spot shows up at the reservoir locations. We also produced the impedance inversion result Figure 4 (c). The structure of the model is clearly visible, while the reservoir boundary is also imaged. This numerical simulation shows that seismic imaging can work well. Although seismic imaging works on the model shown in Figure 4 (a), we anticipate that Figure 4 (a) may not be a totally realistic representation of lithologic

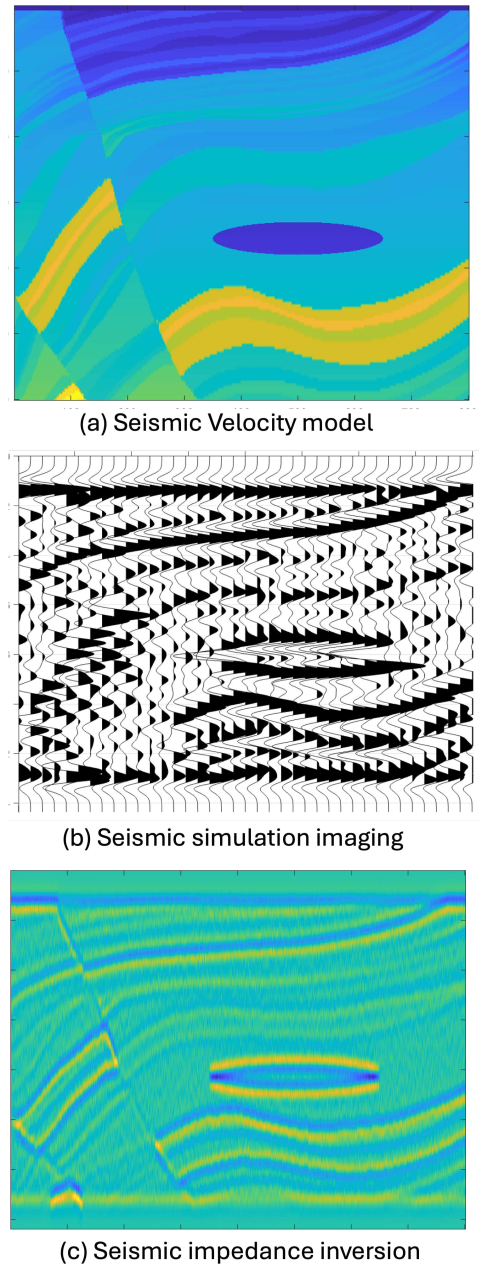

Figure 4: Seismic simulation to illustrate the delineation of a lithologic hydrogen reservoir. (a) Subsurface velocity model with an embedded hydrogen reservoir of an oval shape. (b) Seismic imaging result, and (c) impedance inversion result. Seismic data can image the reservoir model in (a) in this particular scenario.

10.1190/image2024-4100404.1

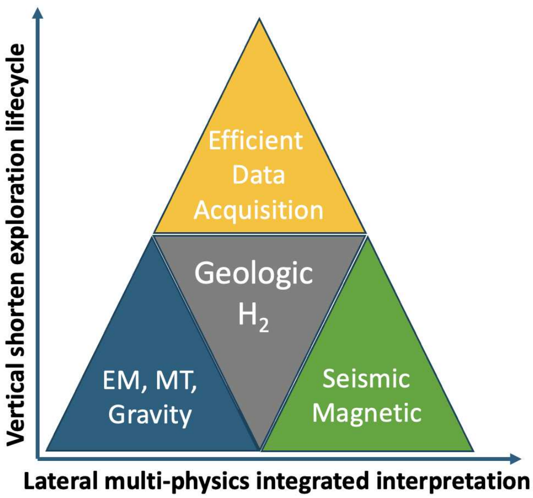

Figure 5: Integration in geologic hydrogen exploration. Multi geophysical methods (lateral integration) are needed to identify geologic hydrogen system, meanwhile, the life cycle from acquisition design to decision-making (vertical integration) is also necessary to accelerate geologic hydrogen exploration.

hydrogen reservoirs. Since hydrogen has high reactivity and diffusivity, we must take into consideration of their influence on the reservoirs. Our preliminary investigation indicates that seismic method can still be effective in certain models but not all, but multi-physical is needed to de-risk.

In summary, we investigated geophysical methods and their roles in imaging hydrogen systems. Different geophysical methods are effective for different components of H2 systems, and integrated multiphysics approach is likely essential in geologic hydrogen exploration.

INTEGRATION WITH EFFICIENT ACQUISITION AND AI/ML

We have illustrated the importance of multi geophysical methods using numerical simulations based on petrophysical data from field sites. As exploration geophysicists, we are fully aware that theoretical effectiveness is different from practical realizability. A key factor affecting the realizability is the time and efficiency of implementation in practice. Meanwhile, energy transition will not wait, and time is of the essence. Thus, we cannot be content with the traditional long-time scale of exploration-production cycle. To tackle the challenge, we must shorten the cycle by addressing the efficiency of all stages of the exploration. As we seek to develop geophysical strategies for natural hydrogen exploration by combining and reconfiguring existing methods from the past, we must also look to the future and adopt emerging technologies. Within geophysics, the key components are data acquisition, data integration, and decision making based on all information available. Two such emerging tools in geophysics that can significantly accelerate H_2 exploration are machine learning-assisted integration and efficient geophysical data collection. We summarize the integration concepts in Figure 5.

Imaging geology requires integrating geophysical information with known geological information such as that about hydrogen systems. The latter is often conceptual and descriptive. Machine learning provides an effective and efficient means to accomplish such integration. The works by Liu et al. (2020), Abubakar et al. (2022), and Di and Abubakar (2022) exemplify the on-going development. Another approach based on conditional variational autoencoder (CVAE) by McAliley and Li (2021) may also be positioned to contribute significantly to this direction. It is now feasible to produce subsurface images that are highly consistent with the true statistics including the petrophysical distribution and structural elements using machine learning approaches.

For the data acquisition, an emerging tool that can impact H_2 exploration cycles is the rapid and low-cost data acquisition. The newly developed ergodic sampling strategy (Zhang and Li, 2023, 2021; zhang and Li, 2023) can serve this purpose. The ergodic sampling can use as few as 25% of data stations but acquires the similar information. This approach has the potential to dramatically speed up the exploration. It is still to be understood how the efficient data acquisition will translate to exploration, but 2 to 10 times speed up will have a significant impact.

CONCLUSIONS

We present a source rock-driven approach to the exploration of the geologic hydrogen from ultramafic-source hydrogen systems. The essence of our proposed approach is to focus on source rocks and then estimate the retention rate indirectly using geophysical tools by imaging the structured traps and lithologic reservoirs that influence the hydrogen retention in the system. Our numerical simulation indicates that electromagnetic and potential-field methods are important in delineating and characterizing ultramafic source rocks and serpentinization degree, while seismic imaging will continue to play an important role in reservoir delineation.

Geophysical exploration for geologic hydrogen can leverage the advances in two on-going research directions, namely, integrated subsurface imaging using machine learning (ML) to improve and speed up data interpretation and accelerating geophysical exploration using efficient data acquisition through ergodic sampling. The benefits derive from the two complementary components enabled by the new advances. Efficient data acquisition enables us to gather more information with the same budget, while the ML-assisted integration helps us extract more information through the integration of traditional geophysical methods used in natural gas and mineral exploration.

ACKNOWLEDGEMENT

We thank Dr. Geoffrey Ellis for many discussions. This research is supported in part by a JIP on Potential for Geologic Hydrogen Gas Resources and by Geo-Multiphysics Research Consortium.

REFERENCES

Abubakar, A., H. Di, A. Kaul, C. Li, Z. Li, V. Simoes, L. Truelove, T. Zhao, 2022, Deep learning for end-to-end subsurface modeling and interpretation: An example from the groningen gas field: The Leading Edge, **41**, 259–267, doi: doi: https://doi.org/10.1190/tle41040259.1.

Di, H., and A. Abubakar, 2022, Estimating subsurface properties using a semisupervised neural network approach: Geophysics, **87**, no. 1, IM1–IM10, doi: doi: https://doi.org/10.1190/geo2021-0192.1.

Gaucher, E., 2020, New perspectives in the industrial exploration for native hydrogen: Elements, **16**, 8–9, doi: https://doi.org/10.2138/gselements.16.1.8.

Liu, M., M. Jervis, W. Li, and P. Nivlet, 2020, Seismic facies classification using supervised convolutional neural networks and semisupervised generative adversarial networks: Geophysics, **85**, no. 4, O47–O58, doi: doi: https://doi.org/10.1190/geo2019-0627.1.

McAliley, W. A., and Y. Li, 2021, Machine learning inversion of geophysical data by a conditional variational autoencoder: First International Meeting for Applied Geoscience & Energy, SEG, Expanded Abstracts, 1460–1464, doi: https://doi.org/10.1190/segam2021-3594761.1.

Milkov, A., 2022, Molecular hydrogen in surface and subsurface natural gases: Review of abundance, origins and ideas for deliberate exploration: Earth-Science Reviews, **230**, 104063, doi: https://doi.org/10.1016/j.earscirev.2022.104063.

Prinzhofer, A., C. S. Tahara Cisse, and A. B. Diallo, 2018, Discovery of a large accumulation of natural hydrogen in bourakebougou (Mali): International Journal of Hydrogen Energy, **43**, 19315–19326, doi: https://doi.org/10.1016/j.ijhydene.2018.08.193.

Zhang, M., and Y. Li, 2021, Efficient ground EM acquisition using irregular sparse stations: A compressive sensing approach: First International Meeting for Applied Geoscience & Energy, SEG, Expanded Abstracts, 1241–1245, doi: https://doi.org/10.1190/segam2021-3581079.1.

Zhang, M., and Y. Li, 2022, Irregular acquisition design to maximize information: From cross-lines to ergodic sampling: Second International Meeting for Applied Geoscience & Energy, SEG, Expanded Abstracts, 1150–1154, doi: https://doi.org/10.1190/image2022-3729385.1.

Zhang, M., and Y. Li, 2023, Computational geophysical acquisition (CGA) as an enabler of geophysical solutions: Third International Meeting for Applied Geoscience & Energy, SEG, Expanded Abstracts, 1643–1647, doi: https://doi.org/10.1190/image2023-3908538.1.

Zhang, M., and Y. Li, 2023, Efficient magnetotelluric data acquisition using irregular stations and compressive sensing reconstruction: Journal of Applied Geophysics, **217**, 105169, doi: https://doi.org/10.1016/j.jappgeo.2023.105169.

Zhang, M., and Y. Li, 2023, Ergodic sampling: Acquisition design to maximize information from limited samples: Geophysical Prospecting, **72**, 435–467, doi: https://doi.org/10.1111/1365-2478.13419.