Geologic hydrogen exploration: An emerging role of mining geophysics

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BIOGRAPHY

Dr. Yaoguo Li is a Professor in the Department of Geophysics at the Colorado School of Mines, where he has been leading the Center for Gravity, Electrical, and Magnetic Studies (CGEM), co-leading the Geo-Multiphysics Research Consortium (GMRC), and co-leading a newly formed joint industry program on the Potential of Geologic Hydrogen Gas Resources. Dr. Li's research interests include inverse theory, and inversion of gravity, magnetic, electrical, and electromagnetic geophysical data, joint inversion, and geology differentiation for imaging geology and reservoir systems. His research covers a broad range of geoscientific problems in mineral exploration, geologic hydrogen exploration, and carbon storage monitoring. He is a co-recipient of the 1999 Gerald W. Hohmann Award, and an Honorary Member of the Society of Exploration Geophysicists (SEG).

SUMMARY

Geologic hydrogen has emerged as a potentially transformational energy resource in the quest to transition to net-zero emission energy supplies. If realized, this new form of energy resource could circumvent the insurmountable challenge of finding and producing enough metals and critical minerals to meet the demands of clean energy by year 2025. The technical challenge to finding geologic hydrogen requires the reconfiguration and recombination of two major branches of exploration geophysics, namely, the mineral exploration and oil and gas exploration and, therefore, could provide unprecedented opportunities for the exploration geophysicists from both energy section and mineral sectors and the Society of Exploration Geophysicist in general. In this presentation, we briefly review geologic hydrogen as an energy resource and the need for integrated exploration strategies to find it, and discuss the role of hard rock mineral exploration geophysics in a source rock-centered strategy for geologic hydrogen exploration. The latter could provide exploration geophysicists a new cycle of opportunities and new space of applying our expertise, albeit in reconfigured and recombined modes.

Key words: Geologic hydrogen, source rocks, mining geophysics, exploration

INTRODUCTION

The transition to net-zero emission energy supplies requires multiple components and no single resource will be sufficient to achieve the net-zero goal by year 2050. The current thinking has focused on carbon capture and storage (CCS) and a significant build-up in renewable energies such as solar, wind, and geothermal. However, the magnitude of CCS and renewable energy development necessary to achieve this goal will require an unprecedented investment in new infrastructure and supply of raw materials such as critical minerals, which are significant obstacles to meeting the objective. It is also now understood that it is nearly impossible to find and produce the metals necessary to fully tap into the renewable energies (Jones, 2023), unless disruptive technologies emerge in the near future. Thus, all new forms of low-carbon energy are important and must be considered as necessary components towards a successful energy transition.

Geologic hydrogen (H_2), which is found naturally in subsurface accumulation, requires no significant processing like blue H_2 from steam reforming of methane or green H_2 from electrolysis of water using renewable energy. Geologic H_2 transitions the role of H_2 from an energy carrier to an energy resource by and of itself. This change puts geologic H_2 in a category of its own as it is no longer in service as a means of using other energy resources.

Many types of geologic hydrogen generation mechanisms with associated sources have been identified. Among these are the serpentinization of ultramafic rocks, radiolysis, and deep-sourced H_2 possibly of mantle or primordial origin (Milkov, 2022).

Among these mechanisms, serpentinization of ultramafic rocks is investigated as an important means for the geologic hydrogen generated in the Earth's crust (McCollom and Seewald, 2013). The chemical reaction is described by,

$$3Fe2SiO4 + H2O \rightarrow 2Fe3O4 + 3SiO2 + 2H2 \quad (1)$$

in which water reacts with Fe(II)-rich minerals such as olivine in ultramafic units to produce H2 gas while also producing other minerals such as magnetite.

The process in equation 1 occurs naturally and produce natural geologic hydrogen. This process can also be artificially stimulated by introducing water and catalysts into ultramafic rocks to engineer the production of H_2 gas, which is referred to as the stimulated hydrogen. We focus on naturally occurring geologic hydrogen in this presentation.

It is estimated that the total potential reserve of geologic hydrogen in the earth crust can be as high as 10s of millions of Mt (Ellis and Gelman, 2022). Even if a small portion can be found and produced, it will supply the equivalent of current H_2 demand for hundreds of years. Therefore, geologic H_2 could potentially form a significant part of energy supply, helping with hard-to-abate use-cases such as aviation, steel making, and heavy machinery, where electrification is unfeasible by the current technologies.

As a type of resources hosted in the Earth's crust, geologic H_2 must be found through exploration, and that is where exploration geophysics could excel. Therein also lie the significant novel opportunities for exploration geophysicists.

GEOPHYSICS IN GEOLOGIC H_2

There are two aspects of geophysics associated with the exploration of naturally occurring geologic hydrogen. The first is a general understanding of geophysical exploration for geologic H_2. The second is a source rock-driven approach to H_2 exploration, which can significantly leverage, benefit from, the knowledge, expertise, and technologies developed and accumulated over more than seven decades.

Equation 1 describes the chemical reaction that underlies the generation of geologic hydrogen in the subsurface, but it also serves as an excellent guide to different components of exploration. The Fe(II)-rich source rock on the left-hand side of equation 1 links to the source rocks such as ultramafic and geologic environments such as hydrothermal systems, which are the conditions enabling the reaction in the past and at present. The alteration results in new minerals and H_2 generation on the right-hand side of equation 1, and leads to changes in magnetite content in the source volumes and accumulation of H_2 gas in the vicinity. The H_2 accumulation is likely near the source rock to be rechargeable. Therefore, the physical properties variations in source volumes and nearby H_2 accumulation will support the geophysical exploration to identify the source zone and its vicinity for potential H_2 resource.

Thus, equation 1 allows geophysicists to form a geophysical hydrogen system model for use in developing exploration strategies while geologists and geochemists are working on the understanding and developing hydrogen system models from those perspectives. Examining these components also leads to the understanding that geologic H_2 exploration would be the prime opportunity to reconfigure and recombine two major branches of exploration geophysics, namely, mineral exploration geophysics using electrical, electromagnetic, gravity, and magnetic methods, and the oil & gas exploration geophysics using primarily seismic methods. Figure 1 illustrates the connections between components of a geologic H_2 system with various geophysical methods.

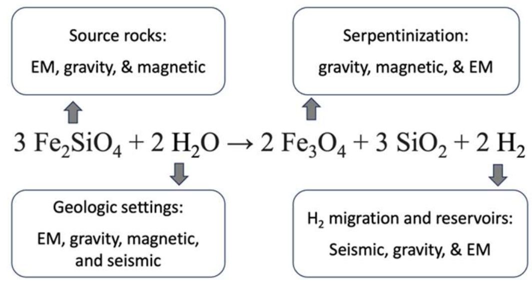

Figure 1. A simplified illustration of different geophysical methods, such as electromagnetic (EM), gravity, magnetic, and seismic, that are important to different components of geologic H_2 exploration.

SOURCE ROCK-DRIVEN EXPLORATION FOR GEOLOGIC H_2

The question of where to explore is undoubtedly a billion-dollar one, except for a few areas in the world that have attracted attention of hydrogen exploration efforts because of previous hydrogen showing or other observational evidence. There is a great deal of "white spaces" of potential plays for geologic hydrogen. We need to reduce the search space by excluding sterile areas and high-grading high prospectivity areas. One strategy is to focus on source rocks (Zhang et al., 2022).

We hypothesize that the presence of partial serpentinization is a key component as such conditions mean that the reservoir would have been recharged in recent geological time. A completely or mostly 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 nearby. Therefore, the separation in time between serpentinization process in the source rock and H_2 accumulation could be a key factor, and we anticipate shorter time separation in H_2 system than in hydrocarbon systems.

Meanwhile, the unique properties of hydrogen molecules pose significant challenges. Hydrogen gas is highly reactive and diffusive. It is also known to serve as a primary energy source for microbes in the earth's crust. It is expected that a significant amount of hydrogen gas would be consumed or lost once it leaves the generating source rocks. It is logical to expect higher likelihood of economical hydrogen gas accumulation in-situ or near the source rocks. Thus, the separation in space, i.e., distance, between partially altered source rock and potential H_2 reservoirs could also be a key factor, and we expect that H_2 reservoirs are closer to their source rocks than hydrocarbon reservoirs are to hydrocarbon sources.

The above understandings form the basis for source rock-centered strategies for H_2 exploration. This is where the geophysical tools and methodologies developed in mineral exploration will play an important role. In particular, electrical, electromagnetic, gravity, and magnetic methods will all be important for delineating source rocks and for characterizing the serpentinization zones in these rocks.

SOURCE ROCK DELINEATION AND CHARACTERIZATION

Serpentinization of ultramafic rocks in general leads to reduced density and increased electrical conductivity in the resultant altered zones (e.g., He at al., 2018; Cutts et al., 2021). The process can also lead to noticeable increase in the magnetic susceptibility in general, but overall decreased in total magnetization has also been observed. The physical properties of ultramafic rocks, and the changes in these properties caused by serpentinization, provide the basis for using a variety of mineral exploration geophysical methods and approaches to explore for, and delineate, the source rocks in hydrogen exploration.

It is noteworthy that both electromagnetic (EM) and magnetic data have been used extensively in exploration for ultramafic hosted nickel deposits (e.g., Watts, 1997). The combination of audio-frequency magnetotelluric (AMT) data with gravity and magnetic data has also been shown to be effective in exploring for chromite deposits (Li et al., 2023). The understanding of the physical property changes associated with serpentinization has been the subject of investigation in the context of traditional mineral exploration (e.g., He et al., 2018).

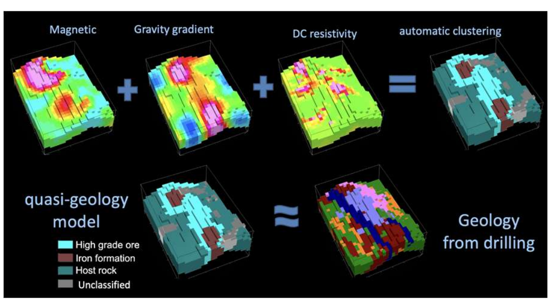

Figure 2. An illustration of using multiple geophysical data sets to image geology through quasi-geology models. The top row shows the susceptibility, density, and conductivity models obtained through the individual inversions and a quasi-geology model obtained through unsupervised ML. The bottom row compares the quasi-geology model with the geology block model from drilling.

In general, many of the methodologies and practices in hard rock mineral exploration can be readily applied to H_2 source rock exploration. This connection opens the avenue for the rapid deployment of mining geophysics in the emerging field of geologic hydrogen as a new energy resource. The vast amount of development in instrumentation, data acquisition (e.g., Zhang and Li, 2023a, 2023b, 2023c), 3D inversions, and integrated geophysics can all be applied to H_2 exploration. As an example, we illustrate in Figure 2 the integration of multiple geophysical data through the approach of geology differentiation (e.g., Melo and Li, 2021). This and many other approaches from hard rock mineral exploration can be readily adapted to explore for, and characterize, the suitable source rocks of geologic H_2 and determine the volume and degree of serpentinization.

This direction provides a completely new role for existing mineral exploration geophysics and the role will be a crucial one in the effort to find this new energy resource.

DISCUSSIONS

A simplified traditional categorization of exploration geophysics associates exploration seismology with energy exploration, and electromagnetic and potential-field geophysics with mineral exploration or mining geophysics. While it was feasible and practicable in the past when there was a clear separation of minerals resources and energy resources based on oil and gas, such a division should no longer be contemplated as we move to the era of new clean energy, especially when exploring for geologic hydrogen as a new energy resource. While exploration seismology will continue to be indispensable, mineral exploration geophysics will take on a much more important role. This change also presents hard rock exploration geophysicists with unprecedented opportunities, not only in finding the critical minerals for energy transition but also in finding energy resources directly.

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