Geologic hydrogen: An emerging role of mining geophysics in new energy exploration

Yaoguo Li and Mengli Zhang*
Center for Gravity, Electrical, and Magnetic Studies, Department of Geophysics, Colorado School of Mines

ABSTRACT

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-center 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.

GEOLOGIC H_2: FUTURE CLEAN ENERGY

The transition to net-zero emission energy supplies require a 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.

This challenge is highlighted by the projects shown in Figure 1, which is the US Department of Energy's reference scenario of electrical power generation. Renewable is projected to supply less than 50% of the electrical power, while fossil energy will make up about 44%. Several questions arise from this project, but chief among them are: (1) Will we be able to capture and sequester the CO_2 from the 44% of energy supply by fossil fuels? (2) What other energy resources could be discovered and develop to change the scenario for the better? Within this context, geologic hydrogen has emerged as a promising contender.

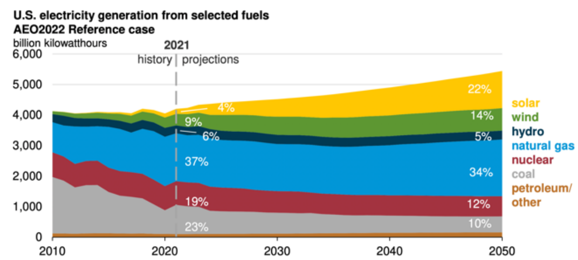

Figure 1. Projected reference scenario of US energy supplies. (U.S. Energy Information Administration, AEO 2023)

Geologic hydrogen (H_2), 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 them are the serpentinization of ultramafic rocks, radiolysis, and deep-sourced H_2 possibly of mantle or primordial origin (Milkov, 2022).

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

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

in which water reacts with Fe(II)-rich minerals such as olivine in ultramafic units to produce H_2 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 H2 gas, which is referred to as the stimulated hydrogen. The Advanced Research Projects Agency–Energy (ARPA-E) in the U.S.

has launched the world's first funded research program supporting this research (ARPA-E, 2024).

We will focus on naturally occurring geologic hydrogen in this abstract. 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). Although much of it may be out of reach economically, such as those too far offshore or in too small pockets to be produced profitably by the energy industry. However, 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.

GEOPHYSICS FOR GEOLOGIC H_2

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 would excel. We discuss two aspects below. 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 2 illustrates the connections between components of a geologic H_2 system with various geophysical methods.

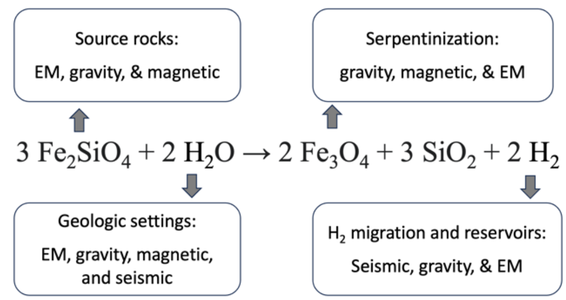

Figure 2. A simplified illustration of different geophysical methods, such as electromagnetic (EM), gravity, magnetic, and seismic, that are important to different components of geologic H_2 exploration.

SOURCE ROCK-DRIVEN EXPLORATION FOR H_2

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, the question of where to explore is largely a billion-dollar question. 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, hydrogen gas is highly reactive and diffusive. Hydrogen is also known to serve as a primary energy source for microbes. 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 H2 exploration. We discuss two components below.

Source rock delineation

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).

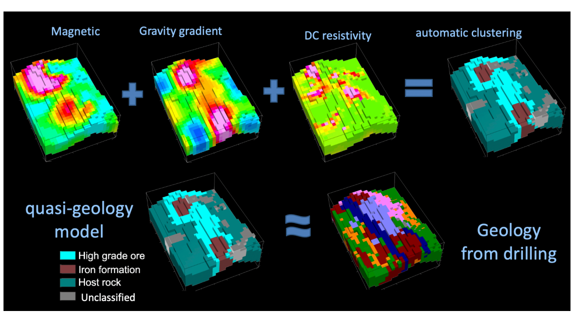

Figure 3. An illustration of using multiple geophysical data sets to image geology through quasi-geology models. The top row shows the susceptibility, density, and conductivity models obtained through the individual inversions and a quasi-geology model obtained through unsupervised ML. The bottom row 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 resources. The vast amount of development in instrumentation, data acquisition (e.g., Zhang and Li, 2023a, 2023b), 3D inversions, and integrated geophysics can all be applied to H_2 exploration. As an example, we illustrate in Figure 3 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.

A geophysical hydrogen systems approach

The concepts of mineral system-based exploration and the reduction of the search space are widely applied in mineral exploration, especially as we look for large deposits under cover and at large depths. As discussed in the preceding section, a system-based approach will also be important in geologic H_2 exploration.

However, the understanding and description of geologic hydrogen systems are still an active area of research. In the absence of a sufficient understanding to direct exploration strategies, we can rely on phenomenological observations and draw partial parallels with mineral systems.

The genesis of geologic hydrogen is closely connected to, or even coincides with, that of many mineral deposits. A prime example is the podiform chromite deposits, whose formation is associated with serpentinization of ophiolite in the environment with sufficient permeability and conduits for the hydrothermal fluid. Cases of the coinciding presence of chromite deposits and hydrogen gas abound, including the chromite deposits associated with ophiolite complex in Southeastern Desert, Egypt (Saleh, 2006), chromite deposit of an Archean-Paleoproterozoic Greenstone Belt in Brazil (Portella et al., 2019), and chromite mine in Bulqizë ophiolite in Albania (Truche et al., 2024). The Bulqizë chromite mine also contains a sizable H_2 gas reservoir below the mine.

The significance of this connection is manifold. There has been a great deal of research and field data accumulated on chromite deposits and their prospective regions. Figure 4 is a worldwide distribution of ophiolite belts and podiform chromite deposits published by Prichard et al. (2015). The tectonic settings of these deposits are clear, and provide the first-order indicators to the prospective regions of geologic hydrogen resources.

Emerging role of mining geophysics in geologic hydrogen exploration

Equally important is the understanding of geophysical signatures of the altered ophiolite that hosts chromite deposits, and the established geophysical strategies for finding chromite deposits. For instance, He et al. (2018) use audio-frequency magnetotelluric (AMT) data to image serpentinization zone in an ophiolite complex to locate chromite deposits. Li et al. (2023) present a case study on integrating 3D inversions of gravity, magnetic, and controlled-source AMT data to target chromite deposits. These studies showcase the unique capabilities and advantages of mineral exploration geophysics that can be readily adapted for finding the suitable source rock regions with geologic hydrogen potentials in the proximity.

Thus, we have developed a phenomenological observation-based geophysical model for geological hydrogen system, which we refer to as the *geophysical hydrogen system*. It centers on finding zones in the ophiolite complex with suitable volume of partial serpentinization, extends to mapping potential hydrogen migration pathways, and focuses on locating in-situ or nearby reservoirs. Methods developed in mineral exploration such as ergodic data acquisition (e.g., Zhang and Li, 2021, 2022, and 2023b) and multiphysics integration (e.g., Astic and Oldenburg, 2019; Melo and Li, 2021) can respectively accelerate the exploration cycles and enable effective imaging of the geology of geophysics hydrogen systems. In general, this model calls for the extensive use of expertise and technologies from hard rock mineral exploration as well as unprecedented integration of all branches of exploration geophysics.

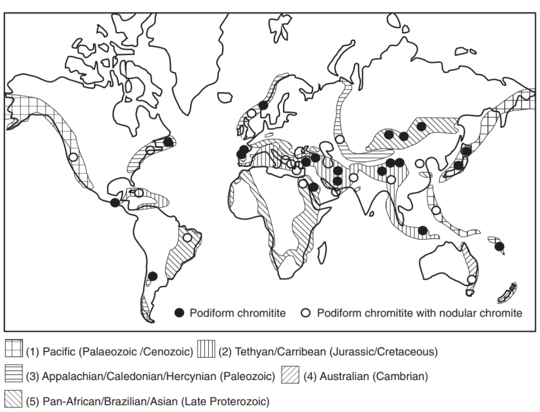

Figure 4. Distribution of ophiolite belts and podiform chromite deposits (Prichard et al., 2015).

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.

ACKNOWLEDGEMENTS

We thank Skye Hart for the assistance with the research. This work is supported in part by an industry consortium on *Potential for Geologic Hydrogen Gas Resources* jointly, led by Colorado School of Mines and U.S. Geological Survey. We also thank the sponsoring members of *Geo-Multiphysics Research Consortium* that supports the development of multiphysics technologies.