Geologic hydrogen exploration and the influence of reservoir diffusive zone

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BIOGRAPHY

Dr. Mengli Zhang, Co-Director of the Center for Gravity, Electrical, and Magnetic Studies at the Colorado School of Mines. Dr. Zhang's research focuses on geologic hydrogen and critical minerals for clean energy after she spent 10 years in the oil and gas industry. She is one of the three co-founders of the world's first industry-supported geologic hydrogen consortium formed jointly by the Colorado School of Mines and the U.S. Geological Survey. She is currently the PI of a major grant by ARPA-E on geophysical monitoring of stimulated geologic hydrogen. Dr. Zhang was an invited speaker on geologic hydrogen at the AAAS 2024 Annual Meeting as geologic hydrogen was selected as one of the 10 science breakthroughs of 2023 by Science Magazine.

SUMMARY

The energy transition is happening, and more and more clean energy are in demand in the near future. Geologic hydrogen can be an important clean energy component among the hydrogen family including other members such as blue hydrogen from fossil fuel and green hydrogen from wind and solar. To explore this form of clean energy, we are faced the challenge that the properties of hydrogen reservoir could be significantly different from those of hydrocarbon reservoirs, so different geological models such as those include the diffusive zone. In this presentation, we examine the effect of a possible diffusive zone surrounding a hydrogen reservoir. We illustrate through simulations that the traditionally successful seismic method in hydrocarbon exploration may lead to false positives and false negatives in the exploration for geologic hydrogen in such cases. Therefore, we conclude that we need to adapt and improve geophysical exploration tools and methods for geologic hydrogen reservoir exploration because of the influence of the diffusive zone.

Key words: Geologic hydrogen, reservoir, seismic, diffusive zone, exploration

INTRODUCTION

Climate change is one of the most urgent issues of our time, and transitioning to a net-zero carbon energy supply is essential to addressing it. Achieving this transition requires a diverse strategy that includes blue hydrogen along with carbon capture utilization and storage (CCUS), and green hydrogen along with renewable energy sources like solar and wind. However, the scale of CCUS and renewable energy development needed to reach this goal demands an unprecedented amount of new infrastructure and a supply of critical minerals, presenting significant challenges.

Thus, exploring for all new forms of low-carbon energy is crucial and is receiving growing attention. In this context, there is an increasing recognition of the potential of naturally occurring geologic hydrogen (H_2) as a low-carbon primary energy resource (Gaucher, 2020, Milkov, 2022) that can be seamlessly integrated into the existing energy supply. Consequently, geologic hydrogen exploration could be a transformative component in the transition to net-zero emissions.

Although there are many similarities between traditional natural gas reservoirs and geologic hydrogen reservoirs as well as associated exploration geophysical tools (Zhang and Li, 2023), there are also significant differences. Consequently, challenges arise in exploring for geologic hydrogen reservoirs. In this presentation, we will first describe a new model of geologic hydrogen model with diffusive zone, and we then work on the seismic simulations and present two comparisons with different scenarios. The first is a comparison between reservoir models with and without a diffusive zone, and the second is the comparison between small reservoirs without a diffusive zone and large reservoirs with a diffusive zone. These comparisons based on simulations demonstrate that we may encounter false positive and false negative conclusions when interpreting seismic images for hydrogen reservoirs if we direct apply the exploration strategies from hydrocarbon reservoirs.

METHODS & SIMULATIONS

Diffusive zone in geologic H_2 reservoir

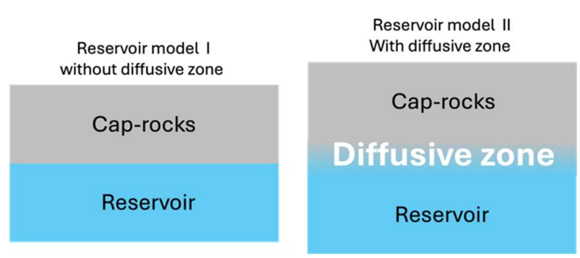

Figure 1. Geological models with and without a diffusive zone. A diffusive zone refers to the smooth transition zone between cap-rocks and reservoir. The physical properties within the diffusive zone will change smoothly.

In traditional hydrocarbon reservoir models, there are multiple layers with sharp contrast between layers such as the scenario on the left in Figure 1. This type of reservoir model is the one without diffusive zone. However, sometimes, there is diffusive zone between two layers such as illustrated on the right in Figure 1. For this type of reservoir model, instead of a sharp contrast at the boundary, the property changes smoothly between the two layers and form a transition zone exists, which we refer to as the diffusive zone here.

The reservoir model with sharp contrast has been successfully used in the traditional hydrocarbon exploration. However, this model may not be applicable in the geologic hydrogen exploration. We highlight two reasons here. The first is the difference between hydrocarbon systems and hydrogen systems (Zhang and Li, 2024), and the second is the well log data from hydrogen well in Mali (Prinzhofer, et. al, 2018).

Hydrocarbon systems vs. ultramafic hydrogen systems

	Hydrocarbon	Hydrogen
Generation Rate	Slow	Fast
Diffusivity and Reactivity	Low	High

Figure 2. properties comparison between hydrocarbon system and hydrogen system. The property of high diffusivity and reactivity may cause the diffusive zone between H2 reservoir and overburden rocks.

Figure 2 is a conceptual comparison and contrast between a hydrocarbon system and one scenario of hydrogen system sourced from ultramafic rocks. We understand that the hydrocarbon in the fossil fuel system such as natural gas has slow generation rates and 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. Meanwhile, natural gas is stable and has lower diffusivity and lower reactivity than hydrogen, so natural gas can more easily accumulate in the reservoirs. In contrast, geologic H_2 has high diffusivity and high reactivity. The high diffusivity and reactivity would imply that H_2 may not easily accumulate far away from the source rocks because most H_2 could have been consumed during the long-distance migration.

The difference in diffusivities between methane and H_2 is supported by the well log data from Mali. Figure 3 is modified from paper by Prinzhofer (2018). A mixture of H_2 and CH_4 is produced at this site. The concentration curves are superimposed on the lithologic log in Figure 3. We have highlighted the gentle slope in H_2 curve in red and the steep change in blue without a diffusive zone in CH_4 curve. The H_2 curve has a pronounced gentle slope compared to that of the hydrocarbon carve. This difference can be explained by the relative stability of hydrocarbon into reservoir, while the high diffusivity of hydrogen leads to the presence of a diffusive zone. Therefore, it is reasonable to build a hydrocarbon model with a sharp contrast between the reservoir and cap rocks. In contrast, a model with a diffusive zone in between is a more reasonable model to describe H_2 reservoirs.

Based on the well log evidence in Mali and the physical properties of H_2, we need to consider models with a diffusive zone between H_2 reservoir and overburden rocks in addition to the standard model without diffusive zone representing the case that the thickness of transition zone is thin.

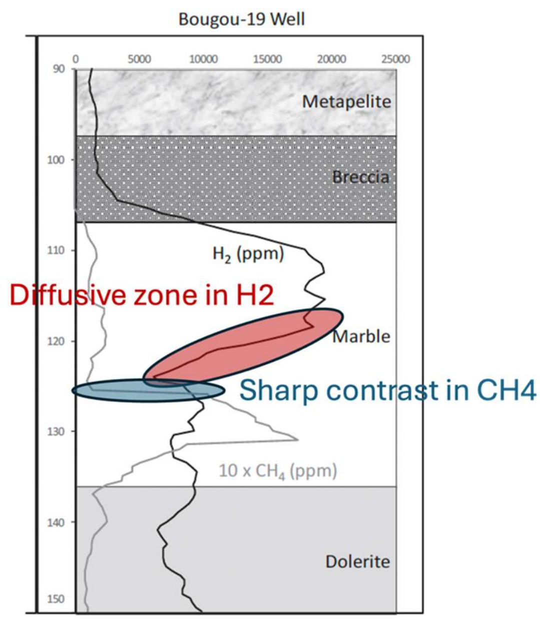

Figure 3. H2 reservoir well logs in Mali overlaid with the stratigraphic column (Prinzhofer, et. al, 2018). The two ovals highlight the difference in CH_4 and H_2 curves. H_2 curves has a gentle slope corresponding to a diffusive zone while CH_4 does not.

Seismic simulations of geologic H_2 reservoirs

We work on both reservoir models with & without a diffusive zone in this section, and simulate the seismic response of the two scenarios, respectively.

<u>Comparison of reservoirs with and without diffusive zone</u>

There are two reservoir models in Figure 4 with the same background seismic velocities. The velocity in the center of two reservoirs is the same and the volumes are also the same. However, one reservoir has no diffusive zone, and the other has a thick diffusive zone. In the middle row of Figure 4 is our numerical simulation and seismic imaging results. We compare the two post-stack images. The left panel shows a bright spot. In sharp contrast, in the right middle panel of Figure 4, the seismic event associated with the reservoir is not distinguishable from events above and below it.

We also compare the seismic impedance inversion results displayed at the bottom panels in Figure 4. The background structures are visible in both cases, but the reservoir on the left shows a clear anomaly. In contrast, for the same volume of reservoir with diffusive zone on the right, there is no obvious anomaly for us to identify the reservoir.

The reason for above difference is that seismic method is sensitive to velocity change but not directly to velocity itself. The more abrupt the change is, the stronger the reflection is. Although the reservoir volumes are the same in both models, the reservoir with diffusive zone will produce weaker seismic signature because of the smaller velocity contrast around the reservoir. As a result, this type of reservoirs is not easily detected using seismic imaging and could be missed completely.

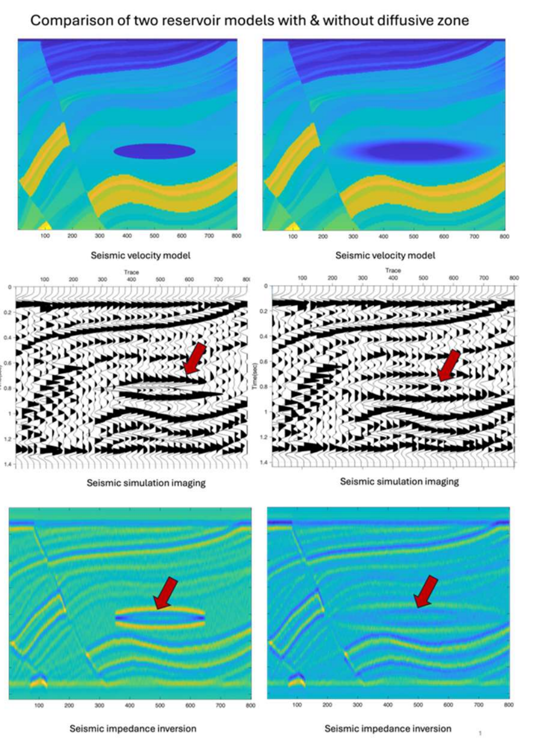

Figure 4. Comparison of reservoirs with and without a diffusive zone when reservoir is imaged using seismic method. Seismic works well when there is no diffusive zone but may miss the reservoir and lead to false negatives in the presence of a diffusive zone.

Comparison of reservoirs with different volumes

Figure 5 illustrates two reservoir models with the same background velocity but different reservoir sizes. The velocity value in the center of two reservoirs is the same but one has a smaller volume without the diffusive zone, whereas the other has a larger volume and a diffusive zone. In the middle row of Figure 5 are our numerical simulations and we can compare the two post-stack seismic images. The seismic imaging in the middle-left panel shows a bright spot. However, the reservoir event associated with the reservoir in the middle-right panel is indistinguishable from events above and below it.

We again compare the seismic impedance inversion results in the bottom row of Figure 5. The background structure is visible in both cases. However, the small reservoir on the bottom left shows a clear anomaly, but for the large reservoir with diffusive zone on the bottom right, there is no clear anomaly for us to identify it with.

The reason is that the small volume with sharp contrast can generate strong seismic signature and is visible in the imaging result. In contrast, the large-volume reservoir is influenced by its diffusive zone and does not produce significant seismic events. Therefore, this simulation reveals that the impact of diffusive zone can be greater than the impact of reservoir volume.

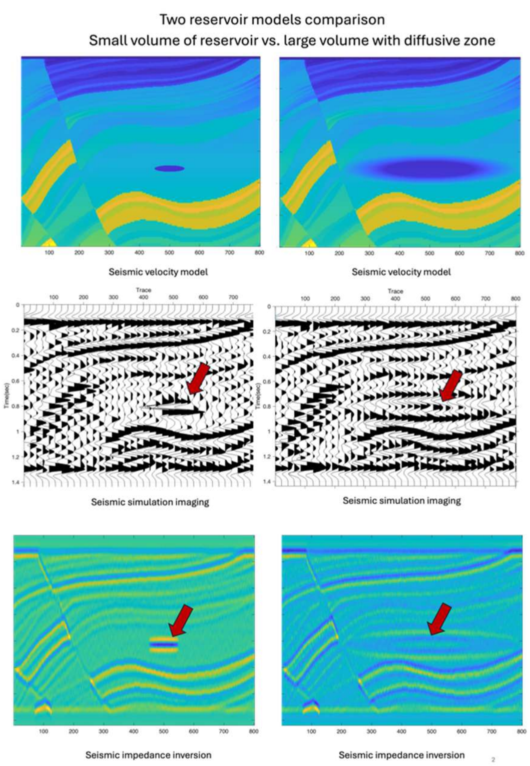

Figure 5. Comparison of reservoirs of small volume without diffusive zone and large volume with diffusive zone using seismic method. Seismic works well when there is no diffusive zone but may miss the reservoir and cause false negative when existing diffusive zone. Therefore, the boundary sharpness matters than the volume size in seismic method.

The above simulations demonstrate that we could be faced with false negative result for a large volume of H_2 reservoir using seismic method when applying it to the H2 reservoir in the presence of a significant diffusive zone. We also may run into false positive results with much reduced economic values if we drill a small-volume H2 reservoir hosted by a structure trap without a diffusive zone.

CONCLUSIONS

Geologic hydrogen is a promising clean energy, which has the potential to replace the hydrocarbon energy to accelerate the energy transition with zero-emission. Geologic hydrogen reservoir has some similarities to the hydrocarbon reservoirs, but the difference is also significant. Traditional geophysical tools such as seismic imaging may not be as effective for geologic hydrogen reservoirs as it is for hydrocarbon reservoirs. This paper demonstrates the possible occurrence of false positives and false negatives resulting from the traditional hydrocarbon reservoir-focused seismic tools. The understanding indicates that new geophysical exploration tools are necessary for exploring for geologic hydrogen reservoirs.

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