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Characterization and Monitoring of Unconventional Reservoirs using Muon Tomography

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Summary (Heading in Arial 12pt bold)

The global Enhanced Oil Recovery (EOR) market for unconventional reservoirs is projected to exceed 16 billion barrels in 2020, and will earn an estimated 80 billion USD in revenue (Mokheimer et al., 2019). Mass change occurs in unconventional reservoirs through the enhancing process (thermal or chemical) and extraction process. Small changes to operations can result in energy cost savings of up to 19.5% (Mokheimer et al., 2019). There is therefore a need to closely monitor the evolution of the reservoir during production, to optimize efficiency and mitigate hazards such as out-of-zone flow. This study investigates using cosmic ray muon tomography to monitor density depletion in a SAGD (steam-assisted gravity drainage) reservoir over 5 years of production. Simulated muon intensity and density data derived from a real SAGD reservoir is used over two time steps to model the density changes in the reservoir, and is compared with the true model. The advantages and limitations of this method are discussed, as well as the benefit of utilizing complimentary data types in joint inversion.

Theory / Method / Workflow

Cosmic ray muons are charged elementary particles which arise naturally from cosmic radiation interacting with the Earth's upper atmosphere. Particle showers of muons bombard Earth steadily, and are attenuated by their interaction with matter along their trajectory. Due to their relatively long half-life and high mass, muons can penetrate deep into the Earth's crust, up to hundreds of meters. This property is exploited in muon tomography to measure the integrated density along the particle's trajectory between the underground sensor and the surface. By measuring muon intensities from all directions above the sensors, geophysical inversion provides a means to model the density changes of a volume in high-resolution and in real time.

Density data derived from a real SAGD reservoir in the McMurray Formation in Alberta, are used as inputs for a forward model of synthetic muon intensities. The simulated detectors are placed below the reservoir, and they image conical volumes through the reservoir to the surface. The resulting 2D muon intensity images are inverted for density change, and are modeled in 3D at two time steps: 1.25 and 5 years after initial production. In both cases the exposure time of the sensors is 90 days. The inversion models from the muon data are compared with the true density change models to demonstrate the effectiveness of the technique.

Finally, a joint inversion between gravity and muon intensity data is conducted to demonstrate the benefit of joint inversion in improving model accuracy and resolution.

Results, Observations, Conclusions

The final models from the muon tomography inversion provide 3D high-resolution models of density depletion over two time steps after initiation of production: 1.25 years (rising phase), and 5 years (spreading phase). Figure 1 shows the resulting inversion model of density changes after

1.25 years compared with the true model. The inversion accurately localizes the steam chamber in both phases, and compares well to the true density models. The mean density difference between the true and inversion models are 16% and 9% for the rising and spreading phases, respectively. The lateral changes along the well-pairs are excellently constrained, while the vertical direction is less constrained. This is an expected result of the non-uniqueness of the inversion, where density-change distributions along particle trajectories are underdetermined. The joint inversion between gravity and muon intensity data mitigates these discrepancies by utilizing the respective strengths of each geophysical method, which both measure density, while differing in their sensitivity.

Novel/Additive Information

Enhanced oil recovery in unconventional reservoirs is becoming the dominant strategy for extraction in oil sands, but still requires improvements for efficiency and cost reduction. There is much to learn in terms of operational tuning and optimization, that will allow EOR to be an efficient method for oil recovery while minimizing economic and environmental impact. There exists a void in the proper monitoring of EOR practices, which requires high-resolution real-time surveillance. Muon tomography has never been used before for this purpose, and has large potential to fill this role.

Knowing the spatio-temporal density changes in real-time has many benefits. Firstly, operators can limit steam injection to locations which are not producing efficiently, and conversely increase injection to areas which are producing, to reduce energy costs. Also, environmental hazards such as out-of-zone flow can be detected and mitigated early. Muon tomography is demonstrated here to successfully model density changes in a SAGD reservoir, but has intrinsic limitations in the vertical resolution in the scenario presented. Joint inversion and/or strategic detector arrays (such as in vertical holes) can help to overcome these limitations, and increase the overall resolution.

Muon tomography has been implemented successfully in underground mining and other sectors, but has yet to be deployed in unconventional reservoirs. It presents an innovative, cost efficient, and feasible technology towards more efficient monitoring.

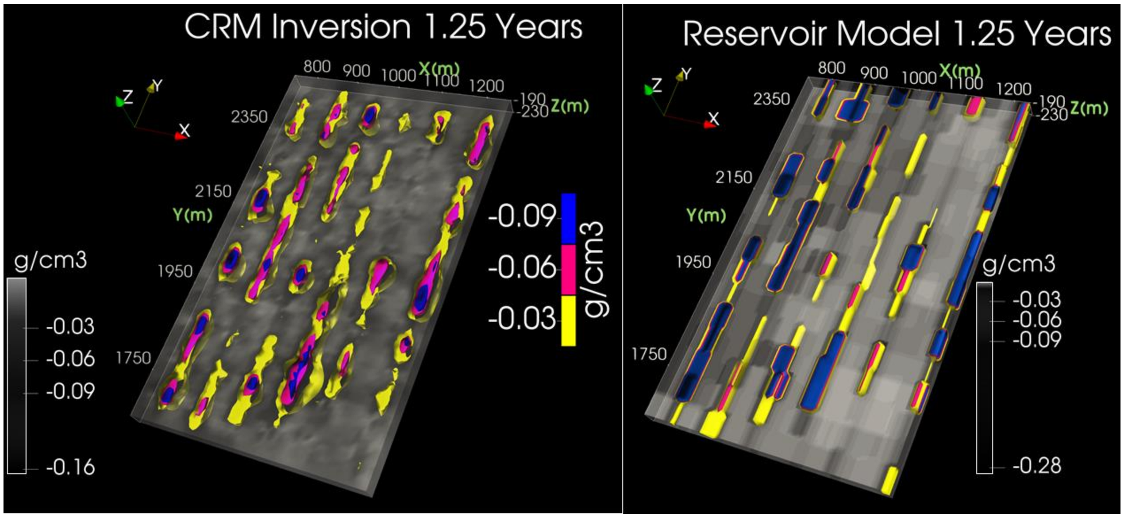

Figure 1: Inversion model of density changes after 1.25 years after initial production (left), compared with the true model (right). Iso-surfaces are shown in colours, and are placed within the entire volume showing all density changes in greyscale.

References

Mokheimer, E. M. A., Hamdy, M., Abubakar, Z., Shakeel, M. R., Habib, M. A., & Mahmoud, M. (2019). A Comprehensive Review of Thermal Enhanced Oil Recovery: Techniques Evaluation. *Journal of Energy Resources Technology*, *141*(3). https://doi.org/10.1115/1.4041096.