Introduction to this special section: Reservoir characterization

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Reservoir characterization is at the forefront of the energy transition, having evolved from its traditional role in hydrocarbon exploration to playing a vital role in developing subsurface energy solutions. As our industry navigates the complexities of meeting global energy demands while pursuing climate goals, the accurate characterization of subsurface formations has never been more important. The integration of multiple disciplines — from geophysics and geology to petrophysics and reservoir engineering — aids in the characterization framework for understanding the complex subsurface systems that will help power our future.

Recent advances in computing, machine learning, and seismic imaging technologies have transformed our approach to understanding reservoir properties and behavior. These developments enable precision in mapping subsurface features, from natural fracture networks to subtle stratigraphic variations, supporting conventional energy production and emerging applications. The integration of full-waveform inversion (FWI), high-resolution 3D seismic analysis, and artificial intelligence is pushing the boundaries in reservoir modeling and interpretation, while modern processing techniques continue to enhance our ability to image and characterize reservoirs beyond traditional resolution limits, even in more challenging acquisition environments.

The capabilities of using geophysics in reservoir characterization are also continually advancing due to innovations in data acquisition and processing. Advanced seismic monitoring techniques allow us to track fluid and reservoir changes over time with improved precision. And by combining geoscience expertise with machine learning approaches, we have revolutionized our ability to identify and map complex structural and stratigraphic features that control reservoir behavior, leading to more accurate and efficient characterization workflows.

This special section of *The Leading Edge* showcases workflows and real-world applications that demonstrate how reservoir characterization is adapting to meet modern challenges. The featured research spans multiple scales and applications, from basin-wide studies to detailed reservoir-level analyses. This convergence of traditional characterization methods with cutting-edge technologies reflects the field's evolution toward more integrated and sophisticated approaches to subsurface characterization.

In the special section's first paper, Weston sets the stage by clarifying the meaning of reservoir characterization. Reservoir characterization requires answers to many questions that may vary with the reservoir project at hand. The right tools, a concerted data discovery effort, and open-minded and engaged creative teams that allow the latitude to explore data from multiple quantitative and qualitative perspectives are some requirements that will provide valuable contributions to all decision-making related to subsurface operations.

By leveraging geophysical data sets including 3D seismic imaging, image logs, microseismic monitoring, and crosswell distributed strain sensing from three areas within the DJ Basin, Jin et al. explore how natural fractures affect hydraulic fracture propagation, particularly from the Niobrara and Codell formations. Key observations from their paper include (1) high natural fracture densities and orientations notably influence the propagation of hydraulic fractures in the Niobrara Formation deviating from the max stress direction, (2) hydraulic fractures in the Codell consistently align with it, but lower natural fracture densities are observed, and (3) the natural fractures add fracture network complexity. The findings are suggestive of the need for a comprehensive natural fracture characterization and tailored fracturing strategies to optimize well placement and completions.

Tawadros et al. introduce a novel approach called full-wavefield regularization (FWR) and present its application on a sparse 3D low-fold offshore seismic data set. To avoid aliasing issues that sparse data can typically create, the FWR approach regularizes both the seismic signals and coherent noise wave trains to a narrower spacing such that the reflection and surface-wave components can be easily distinguished and the noise readily eliminated.

Wang and Al-Dossary showcase the application of a 3D integration orientation operator to enhance subsurface images. This method improves the delineation of subsurface edges by addressing the limitations of traditional 2D gradient operator-based edge detection, among other things. The example data set demonstrates more coherent edge identification, and computational efficiency shows a significant improvement, highlighting the effectiveness of this 3D approach.

Oliveira et al. demonstrate the application of machine learning to seismic data for fault interpretation by using a 2D convolutional neural network methodology on a seismic data set from the Atlanta Field, a postsalt asset in Brazil's northern Santos Basin. Even with the high structural complexity of the field due to the salt tectonics, requiring additional labeling interpretation to capture different fault patterns and train the algorithm to predict faults within the seismic volume, the machine learning approach reduced the interpretation effort by 60%.

Kumar and Ali examine ways in which FWI products can be used in the seismic interpretation process. They highlight the importance of looking at the FWI-derived reflectivity product and present a workflow that improves reservoir characterization

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in their case study area, offshore Trinidad, particularly by illuminating the reservoir below the more complex overburden.

Li et al. introduce an inversion-based method for enhancing seismic resolution. The method utilizes seismic data coupled with regularizations to drive the inversion, thereby avoiding bias from well data. The applications cited for both conventional and unconventional assets demonstrate how enhanced resolution of seismic data resulted in improved well planning, reduced drilling uncertainties, and enhanced reservoir delineation.

Masaya describes numerical experiments aimed at characterization and monitoring underground hydrogen storage. Similar to the workflow using elastic FWI for time-lapse surface seismic data, data are generated from several synthetic subsurface models, including a hydrogen plume under different conditions, and numerical experiments are conducted to discuss the validity and challenges of hydrogen characterization using elastic FWI. The results depict not only a marked improvement in the signal-to-noise ratio but also improved computation of high-quality seismic attributes like coherence and curvature, which support better interpretation of the seismic data.

In this special section's final paper, Roche discusses how time-lapse multicomponent seismic data collected during a CO_2 injection program in the San Andres carbonate reservoir in Vacuum Field in New Mexico can detect changes in bulk rock properties related to reservoir processes. Additionally, changes in shear-wave traveltime and polarization can be linked to alterations in reservoir pore pressure and fluid composition. By differencing seismic measurements over time — specifically observations related to S-wave birefringence — insights can be gained into the relative permeability characteristics.

As we look to the future, reservoir characterization will continue to play a crucial role in addressing global energy challenges. The techniques and workflows presented in this special section represent not just incremental improvements but transformative approaches that will help guide our industry toward a more sustainable and energy-secure future. Whether supporting conventional energy production, enabling carbon storage, or facilitating the transition to renewable energy sources, the art and science of reservoir characterization will continue to be fundamental to our success. TLE