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(REVIEW ARTICLE)

EVALUATING ADVANCES IN INTEGRATED GEOPHYSICAL AND GEOLOGICAL METHODS FOR UNCONVENTIONAL RESERVOIR CHARACTERIZATION IN THE UNITED STATES: A NARRATIVE REVIEW

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ABSTRACT

Unconventional oil and gas reservoirs have revolutionized U.S. energy, but their complex geology and low permeability demand new characterization approaches. This narrative review critically examines recent advances in integrating geological and geophysical methods for unconventional reservoir evaluation. We synthesize how multidisciplinary approaches, ranging from pore-scale imaging to seismic and electromagnetic surveys, augmented by machine learning, reveal reservoir heterogeneity and sweet spots. Key trends include high-resolution petrophysical analyses (nuclear magnetic resonance (NMR, core imaging), geophysical innovations, and data-driven inversion and modeling frameworks. The major knowledge gaps identified in this review include linking nanoscale properties to field-scale flow, robustly quantifying induced seismic risks, and integrating the full petroleum system (source, rock, fracture networks) into models. It is concluded that continued integration of diverse data (seismic, well logs, core, and micro seismic) through advanced rock-physics and AI-driven workflows promises deeper insight into U.S. unconventional reservoirs. These trends have broad implications for exploration, production optimization, and low-carbon initiatives in unconventional plays.

Keywords: Hydrocarbon, Seismic, Petro Physics, Shale, Integrated Modeling, Machine Learning.

1 INTRODUCTION

Unconventional reservoirs such as organic-rich shales, tight oil sands, and coalbed methane have transformed the energy landscape, accounting for the majority of U.S. hydrocarbon production. The U.S. Energy Information Administration reports that in 2020, shale gas accounted for approximately 78% of U.S. dry natural gas production (Mukherjee & Vishal, 2023). Production from shale gas and tight oil formations such as the Marcellus, Eagle Ford, Permian Wolfcamp, Bakken, and Niobrara has altered global hydrocarbon supply dynamics and redefined subsurface exploration priorities (Katz et al., 2021). Unlike conventional reservoirs, unconventional systems are characterized by ultra-low permeability, nanoscale pore networks, strong lithological heterogeneity, and complex geomechanical behavior (Afagwu et al., 2020). These properties complicate reservoir characterization and reduce the effectiveness of single-method subsurface evaluation approaches (Muther et al., 2022).

Reservoir characterization involves describing reservoir architecture, mineralogical composition, pore systems, fluid distribution, natural fractures, and geomechanical properties using subsurface data (Pourpak et al., 2022). In unconventional systems, accurate characterization directly influences drilling placement, hydraulic fracturing design, production forecasting, and reserve estimation. Conventional characterization (single datasets or methods) relying on isolated petrophysical interpretation or seismic analysis often fails to capture the multi-scale heterogeneity (porosity, brittleness, and fracture networks) inherent in shale and tight formations (Muther et al., 2022).

Consequently, integrated geological-geophysical approaches have become essential. In effect, recent studies indicate that poor understanding of reservoir geology and limited engineering technology have hindered unconventional plays but emphasize that cross-scale integration is beginning to overcome these barriers (Xu et al., 2022). Integration may involve combining well logs with seismic inversion, linking mineralogical analyses to rock physics models, incorporating production data into machine learning frameworks, or coupling geostatistics with geomechanical simulations. Recent advances in computational geoscience, cloud computing, and machine learning have accelerated the development of integrated workflows capable of handling high-dimensional reservoir datasets (Tahmasebi et al., 2020; Wang et al., 2024).

The rise of machine learning has further reshaped reservoir characterization research. Algorithms such as Random Forest, support vector machines, gradient boosting, and artificial neural networks (ANN) are increasingly integrated with geological and geophysical data to automate facies classification, fracture prediction, total organic carbon estimation, and production forecasting (Rashid et al., 2026). Studies from the Marcellus and Eagle Ford basins have shown that machine learning models can integrate well logs, completion data, mineralogical datasets, and production records to identify sweet spots and estimate reservoir performance (Vikara et al., 2020; Karacan et al., 2025).

Also, the progress of integrated reservoir characterization has emphasized the value of historical subsurface datasets in the petroleum sector. The United States has a significant collection of 2D and 3D seismic and other of exploration data, which were previously classified as non-reservoir due to technological limitations. However, the advances in seismic reprocessing, geological, and machine learning techniques have enabled a more precise reevaluation of these datasets by improving signal-to-noise ratios, retrieving previously unknown stratigraphic features, and assisting in digitizing and analyzing previously inaccessible well records (Brancatelli et al., 2022; Lai et al., 2022). As such, these advances have converted old databases into significant exploration assets for unconventional reservoir characterization at a low cost.

It is known that in petroleum systems in shales, only the co-location of source rock, suitable maturity, reservoir presence (porosity/permeability), and trapping/fracture networks yields viable production (Katz et al., 2021) and failures in a single element often leads to disappointing results in some plays. Thus, reservoir characterization must link geology (stratigraphy, facies, organic content, natural fractures) with geophysical signatures (seismic attributes, log responses, stress fields) and engineering data (micro seismic, production). As Katz et al., (2021) emphasize, successful unconventional development demands a full assessment of the petroleum system and not just a simple resource count.

Despite all the progress in the field, significant gaps remain. Conventional petrophysical relations often break down: for example, porosity alone is a poor predictor of production because reservoir quality in shale appears to be more associated with the ability to fracture than inherent porosity. Similarly, seismic methods tuned for layered sands may miss thin, laterally varying shale sweet spots. Thus, this review aims to synthesize the current state of integrated methods in U.S. unconventional reservoirs. We critically evaluate approaches (lab vs field, data types, and algorithms) and identify which trends hold promise. The objective is to chart expert-driven themes (e.g., rock-physics integration, machine learning, new survey methods) rather than systematically list every study. This focuses on peer-reviewed advances that combine geophysical and geological insights to improve unconventional reservoir models in the U.S.

2 METHODS

This study follows a narrative review approach to critically examine recent advances in integrated geophysical and geological methods for unconventional reservoir characterization in the United States. Unlike a systematic review, the objective was not to exhaustively identify all available studies but to synthesize current knowledge, emerging trends, and expert perspectives within the field. Peer-reviewed articles published were identified through major scientific databases, including Scopus, Web of Science, ScienceDirect and Google Scholar, using combinations of keywords related to unconventional reservoirs, seismic interpretation, well-log analysis, rock physics, geomechanics, machine learning, and integrated reservoir characterization. Priority was given to studies reporting methodological innovations, field applications, and multidisciplinary workflows relevant to major U.S. shale and tight reservoirs. The selected literature was analyzed to identify research outcomes, technological developments, unresolved challenges, and opportunities for future investigation, thereby providing an interpretative synthesis consistent with contemporary narrative review standards.

3 RESULTS

The reviewed studies consistently report four major areas of development in integrated geological and geophysical characterization of unconventional reservoirs. The findings are presented thematically including multiscale petrophysics and rock physics integration, advanced geophysical imaging and monitoring, and data driven modeling and machine learning integrated characterization approaches. Across these themes, the studies describe the methods applied, the datasets integrated, and the principal findings obtained from laboratory experiments, well log analysis, seismic investigations, numerical modeling, and field applications.

3.1 Multiscale Petrophysics and Rock-Physics Integration

The reviewed studies show an increasing application of multiscale petrophysical methods that integrate laboratory measurements, well logs, and rock physics models to characterize unconventional reservoirs. Across the studies, nuclear magnetic resonance (NMR) logging and core analysis have emerged as powerful tools combined to quantify pore characteristics and fluid distribution within shale formations. NMR logging provided estimates of total and effective porosity, pore size distribution, clay bound water, wettability, and fluid occurrence across nanometer-to-meter scales (Elsayed et al., 2022; Yuan et al., 2023). Yuan et al., (2023) further demonstrates that integrating laboratory NMR measurements with logging data improves the characterization of shale nanopore structures and increased the accuracy of shale gas resource estimation by incorporating pore scale information into reservoir models.

Similarly, several studies employed rock physics models to establish relationships between mineral composition and elastic properties. An examination of heterogeneous shale formations composed of quartz, clay, kerogen, and natural fractures and reported pronounced elastic anisotropy associated with variations in lithology and organic matter distribution (Sadeghnejad et al., 2021; Lee & Lumley, 2023). Lee and Lumley (2023) developed a deep feedforward neural network (DFNN) that predicted elastic stiffness tensors directly from well log data. The results showed that the model reproduced shale anisotropy by incorporating mineralogical variations, organic content, and fine layering, while also demonstrating that omission of anisotropic properties produced inaccurate hydraulic fracture predictions.

In addition, recent investigations expanded conventional rock physics models by incorporating the effects of organic matter, compaction, fracture development, and kerogen maturation. Qi et al., (2024) reviewed advances in rock physics for unconventional reservoirs and reported that newly developed models account for the distinct pore systems and mineral assemblages found in shale formations. The review also documented the application of discrete fracture network (DFN) models constrained by seismic attributes to represent fracture distributions more realistically during reservoir characterization. Furthermore, several studies combined laboratory measurements, computed tomography (CT) imaging, well logs, and seismic inversion to construct rock physics templates linking mineralogy, pore fluids, and elastic properties. These templates were subsequently applied during seismic and well log inversion to estimate reservoir properties. Gharavi et al., (2023) reported that multidisciplinary workflows integrating core analysis, well logs, and dynamic production data produced detailed petrophysical evaluations of unconventional reservoirs. Likewise, Muther et al., (2022) and Gharavi et al., (2023) documented that integrated petrophysical analyses using multiple datasets consistently reduced uncertainty while capturing heterogeneity from nanopore systems to field scale stratigraphic variations.

3.2 Advanced Geophysical Imaging and Monitoring

Studies demonstrate increasing integration of multiple geophysical techniques for shale reservoir characterization and monitoring. Conventional three-dimensional seismic surveys remained the primary method for structural mapping, although several studies reported modifications to improve imaging of thin and laterally heterogeneous reservoirs. Time lapse seismic surveys were applied in selected pilot projects to monitor pressure and fluid changes associated with carbon dioxide injection and hydraulic fracturing, although reported field applications remained limited. Hui et al., (2022) investigated microseismic monitoring during hydraulic fracturing and found that the spatial distribution of induced seismic events was strongly associated with fault systems, in situ stress conditions, and the distance to crystalline basement. The study integrated microseismic observations with geological information, including fault mapping and pressure data, to characterize fracture development.

Electromagnetic methods are also turning prominent in recent studies of unconventional reservoirs. Yan (2024) reviewed laboratory investigations and field applications of controlled source electromagnetic (CSEM) surveys and reported that electrical resistivity and polarization measurements responded sensitively to hydrocarbon saturation and fracture fluids. The review presented field examples in which electromagnetic attributes, including resistivity and anisotropy, identified hydrocarbon bearing intervals that exhibited limited seismic impedance contrast. In one reported case, CSEM surveys delineated two high total organic carbon sweet spots in the northwestern and eastern sections of the study area, and subsequent drilling confirmed significant shale gas production from these locations (Fig. 1) (Yan, 2024). The reviewed studies also reported that electromagnetic datasets were increasingly calibrated using rock

physics models that incorporated pore geometry and clay content to estimate total organic carbon (TOC) and fluid distribution.

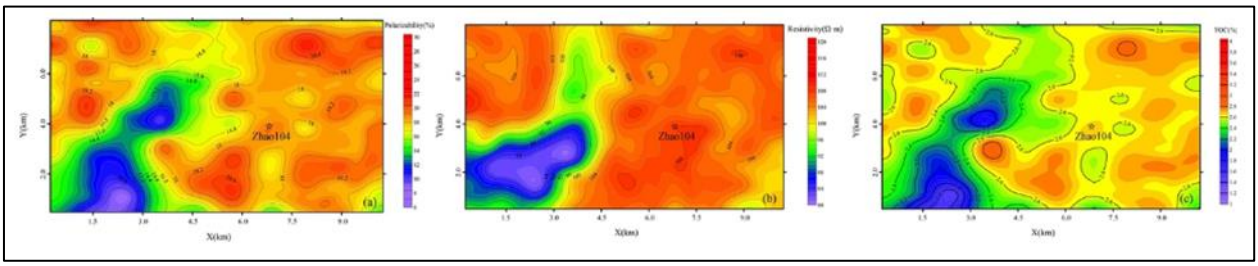


Figure 1: 3D maps showing (a) inverted polarization, (b) inverted resistivity, and (c) high TOC anomaly map used to delineate regions rich in TOC (from Yan, 2024)

In contrast, gravity and passive seismic methods appeared less frequently in shale reservoir investigations. Gravity surveys were primarily used to identify regional structural features such as basement faults because hydraulic fractures generated relatively small gravity anomalies. Mukherjee and Vishal (2023) reviewed passive seismic applications and reported that naturally occurring microseismic activity was used to evaluate subsurface stress conditions and reservoir integrity. The review also documented the potential application of passive seismic methods for imaging deeply buried hydrocarbon accumulations within source rocks where conventional seismic methods provide limited resolution.

Downhole logging technologies also showed continued development across the reviewed studies. Lai et al., (2024) showed that modern logging-while-drilling (LWD) systems and advanced logging suites, including NMR, microresistivity imaging, dipole sonic, were applied simultaneously to characterize structural features, stratigraphy, pore systems, and fluid saturation. Image logs were consistently used to identify natural fractures and fracture networks, while NMR measurements quantified pore geometry and bound water distribution. Gharavi et al., (2023) further produced workflows that integrated well logs with core measurements and seismic data to construct three-dimensional reservoir models representing lithology, fracture systems, and fluid distribution.

3.3 Data-Driven Modeling and Machine Learning

Based on the literature reviewed, there is an increasing application of machine learning and data driven approaches for integrating geological and geophysical datasets during unconventional reservoir characterization. Most investigations focused on predicting petrophysical properties directly from well log measurements using regression techniques and neural network models. Wang et al., (2024) and Osei, D. A, & Yakin, Z. (2025) reviewed machine learning based log inversion methods and presented workflows that predicted porosity, permeability, and elastic anisotropy from well log data while incorporating geological constraints during model development. The reviewed studies also reported that geological information was routinely combined with machine learning models to improve prediction accuracy and reduce inconsistencies during log inversion (Wang et al., 2024).

Li et al., (2024) also compared linear regression, nonlinear regression, and piecewise models approaches for porosity prediction and hydrocarbon loss correction (Fig. 2). The analysis showed that kernel ridge regression (KRR) produced more accurate porosity log predictions than traditional petrophysical equations under the evaluated conditions. The study also demonstrated that advanced regression techniques improved agreement between predicted and measured porosity values after calibration with available reservoir data.

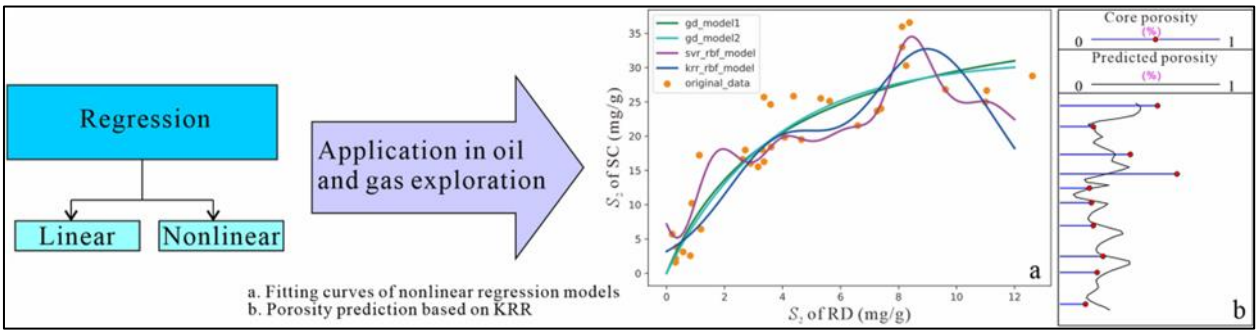


Figure 2: Diagram demonstrating the significance of Kernel Ridge Regression for porosity-logging curve prediction (Li et al., 2024)

Machine learning applications also extended to seismic interpretation and fracture characterization. Qi et al., (2024) reported that artificial intelligence methods were applied to identify fractures from core images and well logs, while another showed deep learning models being trained to estimate reservoir properties, including pore pressure and brittleness, directly from seismic volumes using well calibrated datasets (Wang et al., 2024). Across these studies, supervised and unsupervised learning techniques were applied for seismic attribute extraction, feature recognition, and reservoir property prediction.

Digital rock physics represented another recurring data driven approach within the reviewed literature. Sadeghnejad et al., (2021) and Yuan et al., (2023) combined micro computed tomography imaging, scanning electron microscopy, and physics based numerical simulations to construct digital representations of shale cores. These studies simulated fluid flow and elastic behavior using observed pore structures and mineral distributions across pore and core scales. Sadeghnejad et al., (2021) further reviewed developments in multiscale pore network modeling and direct numerical simulation, indicating that these methods linked pore scale observations with larger scale reservoir property predictions through computational upscaling.

Another study presents a workflow that combined three-dimensional geological modeling, production history matching, and scenario-based reservoir simulation within a tight gas reservoir (Iqbal et al., 2025). The workflow integrated static geological information with dynamic production data to generate reservoir forecasts and monitor reservoir performance throughout field development. Collectively, the findings from these studies demonstrate a common goal of building integrated reservoir models.

4 DISCUSSION

The reviewed studies consistently demonstrate that integrating multiscale petrophysical measurements with rock physics models provides a more comprehensive approach to unconventional reservoir characterization than using individual datasets. Studies agree that combining core analysis, NMR measurements, laboratory experiments, well logs, and seismic data improves the representation of shale heterogeneity by linking pore scale properties with reservoir scale behaviour (Elsayed et al., 2022; Yuan et al., 2023; Gharavi et al., 2023). This development strengthens rock physics theory by establishing clearer relationships between mineral composition, pore structure, fluids, and elastic properties. Similarly, Lee and Lumley (2023) and Qi et al. (2024) show that incorporating anisotropy, organic matter, and fracture complexity produces models that better represent unconventional reservoirs than conventional isotropic assumptions.

An important methodological limitation is that most models are calibrated using limited core and well datasets, which restricts their transferability across different geological settings. Furthermore, differences in the spatial resolution of laboratory measurements, well logs, and seismic data continue to create scaling challenges during data integration (Muther et al., 2022; Gharavi et al., 2023). Nevertheless, these integrated workflows improve estimates of reservoir quality, fracture behaviour, and fluid distribution, thereby supporting well placement, hydraulic fracturing design, reserve estimation, and long-term reservoir management.

In the context of advanced geophysical imaging and monitoring, an observation across the literature is that no single geophysical method adequately characterizes the complexity of unconventional reservoirs. Instead, studies increasingly advocate combining complementary datasets because each technique responds to different subsurface properties. This reflects established geophysical theory, where variations in elastic, electrical, and density properties provide independent evidence of lithology, fluid saturation, fractures, and stress conditions. There is also strong agreement that microseismic monitoring has become an important component of hydraulic fracture evaluation because it provides direct observations of fracture growth during stimulation. As shown by Hui et al. (2022), induced seismicity is closely associated with geological structures and in situ stress conditions, indicating that fracture propagation is controlled by preexisting geological features rather than injection parameters alone. Likewise, studies involving controlled source electromagnetic surveys successfully identify hydrocarbon bearing intervals where conventional seismic techniques exhibit limited sensitivity Yan (2024). These findings collectively suggest that combining seismic and electromagnetic observations with geological information improves reservoir characterization by reducing ambiguity associated with individual datasets.

However, differences among the reviewed studies highlight certain constraints. Time-lapse seismic monitoring remains limited to relatively few field applications because of operational cost and data acquisition requirements, while gravity and passive seismic methods are less widely applied because their responses remain difficult to interpret within highly heterogeneous shale reservoirs (Mukherjee & Vishal, 2023). In addition, advanced logging technologies provide detailed information only near the borehole, yet their limited spatial coverage requires extrapolation when constructing reservoir scale models (Gharavi et al., 2023). Even so, integrated geophysical imaging improves drilling decisions, reservoir monitoring, and hydraulic fracturing evaluation. These advances also strengthen environmental management

by supporting fault characterization, induced seismicity assessment, and regulatory monitoring during field development (Hui et al., 2022).

Finally, it is observed that machine learning enhances unconventional reservoir characterization when integrated with geological and rock physics information rather than applied independently. Across the literature, machine learning models consistently improved the prediction of petrophysical properties, seismic attributes, and reservoir characteristics when trained using representative geological datasets and calibrated with laboratory or well observations (Wang et al., 2024; Li et al., 2024; Osei, D. A, & Yakin, Z., 2025). These findings support the growing adoption of hybrid modelling frameworks that combine statistical learning with established geological and rock physics principles (Sadeghnejad et al., 2021; Yuan et al., 2023). These developments support theoretical frameworks that emphasize multidisciplinary integration for reducing uncertainty in subsurface characterization.

Although studies consistently report improvements in prediction accuracy, machine learning models depend on large, representative datasets and often show limited transferability across different geological settings. As a result, models trained within one geological setting may perform poorly when applied to formations with different lithological characteristics. Consequently, the reviewed studies consistently emphasize integrating data driven models with geological interpretation and production history rather than relying on purely statistical predictions (Wang et al., 2024; Iqbal et al., 2025).

From a practical perspective, these integrated workflows improve reservoir forecasting, production planning, and resource management by combining geological, geophysical, and production data. They also support technically defensible reserve estimation and field development planning, which are important for regulatory reporting and long-term resource management. Therefore, the reviewed studies indicate that advances in unconventional reservoir characterization increasingly depend on multidisciplinary integration, while challenges related to data quality, model transferability, and scale integration remain priorities for future methodological development.

5 FUTURE DIRECTIONS AND RESEARCH GAPS

Although integrated geological and geophysical methods have advanced unconventional reservoir characterization considerably, several research gaps remain. A major challenge lies in bridging observations across scales, particularly linking nanopore-scale processes identified through NMR, SEM, and digital rock analysis with field-scale fracture connectivity and production behaviour. Also, progress in seismic inversion and rock physics is constrained by the limited availability of standardized shale databases that integrate mineralogy, porosity, total organic carbon, and anisotropic geophysical properties under varying stress conditions.

Equally important is the need for robust data fusion frameworks capable of seamlessly integrating seismic, well logs, core analyses, and production data while explicitly accounting for uncertainty in reservoir predictions. As artificial intelligence becomes increasingly embedded within characterization workflows, future studies should also prioritize interpretable, physics-informed machine learning models that produce geologically meaningful results rather than purely statistical predictions. Furthermore, induced seismicity should be incorporated into reservoir characterization through integrated geomechanical and geological modelling to support safer field development and regulatory compliance.

Moving forward, the expanding role of unconventional reservoirs in carbon storage, geothermal energy, and hydrogen storage will require characterization workflows that integrate geochemical and microbial processes alongside conventional geological and geophysical datasets. Finally, greater attention should be given to the societal dimension of reservoir characterization by improving the communication of complex models to regulators, policymakers, and local communities, thereby supporting technically sound and socially responsible resource development.

6 CONCLUSION

This review evaluated recent advances in integrated geological and geophysical methods for unconventional reservoir characterization in the United States, with emphasis on emerging technologies, multidisciplinary workflows, and current research trends. The synthesis demonstrates that integrating geological observations with seismic imaging, petrophysical analysis, rock physics, geomechanics, and artificial intelligence has significantly improved reservoir characterization, sweet-spot identification, and production forecasting across major U.S. unconventional plays. The review further highlights that successful characterization depends on preserving geological context while leveraging data-driven techniques, particularly in addressing reservoir heterogeneity, uncertainty, and evolving energy-transition applications. It is therefore recommended that future research should prioritize physics-informed artificial intelligence, integrated digital platforms, and the revitalization of legacy subsurface datasets to support more reliable and cost-

effective reservoir evaluation. These advances will strengthen sustainable resource development and reinforce the role of integrated geoscience in meeting current energy demands and future subsurface energy applications.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

Disclosure of conflict of interest

The authors declare no conflicts of interest regarding this manuscript.

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