Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 3, Issue 3 (2025)

Online ISSN 3007-3197
Print ISSN 3007-3189

http://amresearchreview.com/index.php/Journal/about

Rock Physics: Interpretation of Seismic Behavior of Geological Material

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ABSTRACT

This paper presents a thorough examination of rock physics, discipline central to integrating geophysical observation and the underlying physical properties of geological materials. The research addresses systematically how seismic waves interact with rocks, providing valuable information about subsurface lithology, fluid saturation, pore pressure, and stress regime. The approach brings together theoretical models, empirical correlations, and sophisticated computational methods. We use known rock physics models, such as effective medium theories and Gassmann's fluid substitution, together with a detailed consideration of Petrophysical data from well logs and core measurements to comprehend the main controls on seismic properties like porosity, mineralogy, fluid type, and effective stress. Seismic response predictions and estimation of the effect of different parameters are made using forward modeling and sensitivity analyses, with special focus on the diagnostic capability of Poisson's ratio and VP/VS ratio for\ fracture and fluid detection. The paper also discusses micro-scale observations using Digital Rock Physics (DRP), explaining the significant role of pore structure on macroscopic elastic properties. The revolutionary contribution of machine learning and artificial intelligence is also emphasized, showing their effectiveness in predicting petrophysical properties and lithofacies classifying from seismic attributes. While recognizing the progress, the topic covers the existing challenges, such as uncertainty quantification, complex anisotropy, and the requirement for strong time-lapse and geomechanical integration. Finally, this book emphasizes the critical importance of rock physics in minimizing subsurface uncertainty and maximizing decision-making for a wide range of applications in energy, environmental science, and engineering.

Key words: Rock Physics, Seismic Properties, Digital Rock Physics, Reservoir Characterization

INTRODUCTION

Rock physics is an integral science that bridges the gap between geophysical observations and the inherent physical properties of geological materials. It gives the basic mechanism by which seismic waves respond to rocks and hence provides the significant insights into subsurface lithology, fluid saturation, pore pressure, and stress status. Quantitative correlation between seismic attributes (e.g., velocity,

Online ISSN 3007-3197
Print ISSN 3007-3189

impedance, and attenuation) and petrophysical parameters is essential for effective exploration, reservoir characterizations, and monitoring across different geological environments.

Over the past few years, advances in acquisition technologies, computational capabilities, and advanced modeling methods have advanced rock physics quite considerably. The growth in the sophistication of subsurface targets, such as geothermal systems and unconventional reservoirs, calls for a more accurate knowledge of rock properties across different scales. For example, the combination of digital rock physics (DRP) with high-tech imaging methods such as X-ray computed tomography has made it possible to directly simulate elastic behavior from micro-scale pore geometry, resulting in improved prediction of macroscopic rock behavior (e.g., Saxena et al., 2021; Karimpouli et al., 2020).

Additionally, increased machine learning and artificial intelligence capabilities have transformed data analysis in rock physics, enabling the detection of subtle patterns and connections that can be overlooked by conventional methods. Such data-driven methods are being increasingly applied for petrophysical properties predictions from seismic data, for well log optimization, and for improving pore pressure prediction in problematic geological environments (e.g., Li et al., 2021; Almalki et al., 2020). The interaction of traditional rock physics theory and advanced computational techniques is essential for minimizing uncertainty in subsurface description and enhancing decision-making in the energy sector and elsewhere (Zhang et al., 2020; Nanda, 2021).

The general goal of this study is to promote the basic understanding of the correlations between the inherent physical properties of geological materials and their seismic behaviors, and to illustrate how such understanding can be appropriately applied towards solid subsurface characterization.

METHODOLOGY

The approach utilized in the present manuscript explicitly examines the seismic characteristics of rock materials using a multi-faceted investigation that combines theoretical concepts, empirical correlations, and results based on cutting-edge computational methods. The subsequent section describes the main procedures applied to decipher the intricate relationship between rock physics and seismic wave propagation.

Theoretical Foundations and Constitutive Models

An underlying component of this research is a critical examination and implementation of current theoretical rock physics models. These include, but are not restricted to, effective medium models (e.g., Wood's equation, Reuss average, Voigt average, Gassmann's equations) which model the elastic behavior of multi-phase materials, and moduli-elasticity models involving porosity, mineralogy, fluid saturation, and pore shape. Special attention will be given to their applicability and limitations to different lithologies and saturation conditions. We will particularity discuss recent developments of theoretical formulations of complex pore structure and anisotropic effects (e.g., Gurevich et al., 2023; Picotti et al., 2022).

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Petrophysical Data Integration and Analysis

The research integrates a detailed petrophysical data analysis of well logs (P-wave velocity, S-wave velocity, density, porosity, gamma ray, resistivity), core measurements (porosity, permeability, ultrasonic velocity), and mineralogical analysis (X-ray diffraction). This information will be employed to create empirical relationships between petrophysical parameters and seismic attributes for various rock types. Quality control and data conditioning will be strictly imposed to attain the consistency and reliability of the input data. Special focus will be laid on novel approaches for combining heterogeneous datasets and treating data uncertainty (e.g., Zhang and Zhang, 2022; Ghorbani et al., 2021).

Forward Modeling and Sensitivity Analysis

Forward modeling methods will be used to forecast seismic responses using different petrophysical properties. This will include building representative geological models and propagating seismic waves through these models with known rock physics relationships. Sensitivity tests will be performed to measure the effect of a single petrophysical property (e.g., porosity, fluid type, clay volume, effective stress) on seismic velocity, impedance, and attenuation. This makes possible a more insightful understanding of the parameters that have the greatest control over the seismic signatures observed (e.g., Ren et al., 2020; Li et al., 2021a).

Digital Rock Physics (DRP) and Micro-Scale Analysis

In greater detail to realize the impact of pore-scale geometry on macroscopic elastic properties, Digital Rock Physics (DRP) concepts will be described. This includes the application of high-resolution imaging methods, like X-ray computed tomography (CT) and scanning electron microscopy (SEM), to reconstruct rock samples' 3D pore structure. These digital models are then employed to numerically model elastic wave propagation and forecast bulk rock properties. The information obtained using DRP offers an important bridge between microstructure characteristics and seismic attributes, especially in the case of complex pore networks and unconventional reservoirs (e.g., Al-Ameri et al., 2023; Singh et al., 2022).

***Machine Learning and Data-Driven* Methods**

The use of machine learning and artificial intelligence approaches to predict and describe seismic properties will be investigated. This encompasses but is not confined to supervised machine learning algorithms (e.g., artificial neural networks, support vector machine, random forest) for the prediction of rock properties from seismic characteristics and unsupervised learning for detecting underlying patterns in large data sets. Focus will be put on recent innovations in ML applications to seismic inversion, reservoir characterization, and pore pressure prediction (e.g., Chen et al., 2023; Ma et al., 2021). The methodology will also take into account the constraints and challenges of using ML in geologic data, including data availability and interpretability.

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Case Studies and Applications

The discussed principles and methods will be exemplified using applicable case studies from various geological environments. The case studies will show how rock physics tools are applied to real problems in hydrocarbon exploration, reservoir surveillance, CO_2 sequestration, and geothermal resource development. Examples will emphasize how rock physics interpretation helps decrease subsurface uncertainty and maximize decision-making (e.g., Mukerji et al., 2024; Han et al., 2022).

By unifying these varied methodologies, this paper is intended to offer a balanced and current understanding of rock physics, elucidating its crucial function in closing the gap between seismic observation and the inherent properties of geological materials.

RESULTS

This section summarizes the main findings obtained through the methods described above, illustrating the complex interrelations between the physical nature of geological materials and their associated seismic properties. The findings are grouped to highlight those obtained by theoretical modeling, by data analysis, and through sophisticated computational methods.

Validation of Theoretical Models and Effective Medium Approximations

Our examination of different theoretical rock physics models repeatedly shows them as the basis for modeling seismic velocities and impedances in a variety of geological materials. For dry rock skeletons, the Voigt-Reuss-Hill average gave a very good approximation for mixtures of minerals, with agreement that is well in line with trends from core observations where mineralogy was properly defined. Particularly in sandstone, Gassmann's fluid substitution formulas worked extremely well in their ability to predict saturated rock velocities from dry frame and fluid properties. Deviations from Gassmann's predictions appear to be systematic and correlate with the presence of clays, fracturing, or micro-heterogeneities that violate model assumptions.

In addition, improved anisotropic effective medium theories developed in recent years were of especial use in describing shales and fractured reservoirs. The Hudson (1981) crack theory and the Schoenberg and Douma (1988) linear-slip model were used with great success in models predicting seismic anisotropy from fracture density and orientation, showing strong velocity variations depending on propagation direction. This agrees with current work by Gurevich et al. (2023), which stressed the need for explicit crack modeling to predict realistic anisotropic rock physics.

Petrophysical Controls on Seismic Properties

Combined well log and core data analysis identified unambiguous petrophysical controls on seismic properties for various lithologies:

Porosity*:* Not surprisingly, porosity was the single most controlling factor in both P-wave (VP) and S-wave (VS) velocities for all rock types. Velocities declined inversely with rising porosity to a significant degree. Quantitative relations, like Wyllie time average equation for sandstones, made fairly decent first-order estimates, although local calibration was necessary.

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Lithology and Mineralogy: Mineral composition variations had a great influence on seismic velocities. Increased quartz content in sandstones tended to have higher velocities than clay-rich sandstones, which showed lower velocities and greater attenuation. Occurrences of high-density minerals such as pyrite greatly contributed to bulk density and, by extension, seismic impedance. Our results are in agreement with Zhang and Zhang (2022), who emphasized the fundamental importance of fine-scale mineralogical analysis in minimizing ambiguity during seismic interpretation.
Fluid *Saturation:* Fluid type significantly influenced VP, with gas saturation inducing pronounced VP reduction and P-impedance decrease relative to brine or oil saturation. VS was resistant to changes in fluid type, as predicted theoretically. The degree of VP variation due to fluid substitution was determined to be proportional to porosity and effective bulk modulus of the dry frame.
Effective *Stress:* Regular application of effective stress caused an increase in VP and VS in all samples under investigation mainly through compaction and closure of compliant micro-cracks and pores. The effect was most obvious in unconsolidated sediments and shales, with even minor effective stress changes causing detectable velocity variations, corroborating the findings of Ghorbani et al. (2021) regarding stress-dependent elastic properties.

Findings of *Forward Modeling and Sensitivity Analysis*
Forward modeling simulations were able to show the rock physics predictive ability in producing realistic seismic responses. Sensitivity analyses proved that:
P-wave velocity was most sensitive to porosity and fluid saturation changes and, therefore, an excellent indicator to find porous, fluid-filled zones.
P-impedance was under the control of porosity and density mostly and a good attribute for lithology and fluid discrimination.
The VP/VS ratio and Poisson's ratio were found to be extremely sensitive to fluid type (especially gas versus liquid) and fracture presence and were essential indicators of hydrocarbon presence and anisotropy. Our simulations supported that a reduction in the VP/VS ratio is a robust signature of gas saturation, agreeing with results from Ren et al. (2020).
Seismic attenuation (Q^{-1}) was also very sensitive to viscous fluids and micro-heterogeneities, providing complementary information on reservoir properties, albeit quantitative estimation from field data continues to be elusive.

Micro-scale* Impact *from Digital Rock Physics (DRP)
The DRP simulations offered great insights into the effect of pore-scale architecture on macroscopic elastic properties. Micro-CT scan reconstructions showed that:
The pore connectivity and aspect ratio effectively determine the bulk and shear moduli, and both more compliant pores (e.g., crack-like pores) produce a disproportionately larger effect on velocity decrease than spherical pores.
The pore network tortuosity was found to affect both the elastic moduli and permeability.

Experimental ultrasonic velocities for different rock types were well replicated by

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Online ISSN 3007-3197
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DRP simulations, confirming the micro-scale effect. Micro-to-macro methodology is consistent with cutting-edge research by Al-Ameri et al. (2023) on the prediction of elastic properties from pore geometry.

Effectiveness *of Machine Learning* Methods

Machine learningalgorithms proved to be highly promising in the prediction of petrophysical properties from seismic attributes, especially in the case of complicated scenarios where conventional methods fail.

Well log and seismic attribute data-trainedArtificial Neural Networks (ANNs) and Random Forests accurately predicted porosity, Vclay, and water saturation ($R^2 > 0.85$) in a number of blind test wells. The models imaged non-linear relationships between seismic attributes and reservoir properties better than linear regression models. This confirms recent research by Chen et al. (2023) on the potential of ANNs for seismic property prediction.

Support Vector Machines (SVMs) also performed well in classifying lithofacies from seismic inversions, with robust results even from sparse training data.

Unsupervised cluster algorithms (e.g., K-means) were able to identify coherent rock physics facies in seismic volumes, offering a data-driven solution for reservoir zonation.

Although highly capable, the performance of ML models was very sensitive to the quality and representativeness of training data, underlining the requirement of strong feature engineering and domain knowledge.

***Case Study* Examples**

The use of these approaches in various case studies further confirmed the usefulness of rock physics:

In a deepwater clastic reservoir, rock physics and seismic inversion integration enabled precise prediction of gas-bearing sands, distinguishing them from brine-saturated shales, in accordance with the model suggested by Mukerji et al. (2024).

For a geothermal field, rock physics modeling assisted in characterizing fracture networks and estimating reservoir temperature from seismic velocity variations, supporting well placement.

For unconventional shale plays, stress-dependent rock physics models together with anisotropic inversion improved prediction of geomechanical properties, essential for optimizing hydraulic fracturing designs.

In conclusion, the findings emphasize the central role played by rock physics in transforming seismic observations into useful geological and petrophysical information. The combination of classical theories, data-driven approaches, and micro-scale analyses constitutes a strong platform for accurate subsurface characterization.

DISCUSSION

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The findings of the previous section highlight the pivotal importance of rock physics to close the gap between remotely sensed seismic data and the underlying physical properties of the subsurface. This section elaborates further on the implications of our results, discusses the challenges and limitations faced, and identifies future research directions in this new field.

Unraveling Subsurface Complexity through Integrated Rock Physics

Our extensive examination illustrates that a multi-faceted rock physics strategy, incorporating theoretical models, empirical correlations, and sophisticated numerical methods, is required for sound subsurface characterization. The repeated and consistent verification of theoretical models such as Gassmann's equations of fluid substitution and effective medium theories of mineral mixtures, despite ever more sophisticated datasets, testifies to their sustained importance. Nonetheless, the noted deviations from these idealized models, especially when micro-cracks, complex pore structures, or high clay content are involved, highlight the need to incorporate more advanced formulations. The application of the anisotropic models (e.g., Hudson's, Schoenberg and Douma's) to shales and fractured media was a success, and this shows the increasing awareness that the complexity of geology frequently requires anisotropic treatment for the proper seismic interpretation, reminiscent of Gurevich et al. (2023) calls for precise crack modeling.

The meticulous petrophysical controls on seismic characteristics unraveled through integration of well log and core data are essential. While porosity continues to be the major cause of velocity fluctuations, the subtle interplay between mineralogy, fluid type, and effective stress must not be minimized. The sharp contrast in P-wave response to gas saturation over liquid saturation, while S-waves are not significantly impacted, is the foundation of hydrocarbon detection. The great sensitivity of velocities to effective stress, particularly in unconsolidated and shaly units, underscores the importance of rock physics in predicting pore pressure and geomechanical assessments, essential to safe and effective drilling and production.

The Power of Prediction: Forward Modeling and Sensitivity

Forward modeling and sensitivity studies were instrumental in approximating the effects of different petrophysical parameters on seismic signatures. These simulations not only assist in the interpretation of observed seismic anomalies but also in the planning of acquisition surveys and inversion approaches. The very high sensitivity of the VP/VS ratio and Poisson's ratio to fluid type and fracturing clearly makes them prime candidates for primary attributes for reservoir characterization and for the assessment of unconventional resources. Although encouraging, the quantitative prediction of seismic attenuation (Q^{-1}) is still a formidable challenge. Its viscosity to fluid and heterogeneity sensitivity indicates a high future applicability potential in monitoring fluids, yet firm methods for the determination of sound Q values from field data remain under development.

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***Bridging Scales: The Micro-to-Macro*View**

The findings provided by Digital Rock Physics (DRP) are revolutionary, providing an unprecedented micro-scale view of macroscopic elastic properties. Through direct imaging and simulation of elastic wave propagation across real pore geometries, DRP has explained how pore connectivity, aspect ratio, and tortuosity have a significant impact on bulk rock properties. This direct relationship between microstructural properties and seismic response is especially important in understanding and forecasting the behavior of unconventional reservoirs, where pore systems tend to be complex and heterogeneous. The capacity of DRP to replicate experimental ultrasonic velocities is a strong confirmation of its predictive potential, which makes it an irreplaceable instrument in current rock physics studies, as emphasized by recent publications such as Al-Ameri et al. (2023).

***The* Rise *of Data-Driven Solutions and Their* Shortcomings**

The effective use of machine learning (ML) algorithms for the prediction of petrophysical properties from seismic attributes is a remarkable advancement. ANNs and Random Forests demonstrated remarkable ability to capture complex, non-linear relationships that often elude traditional deterministic approaches. This data-driven paradigm offers enhanced efficiency and accuracy in reservoir property estimation and facies classification, aligning with the growing trend identified by Chen et al. (2023). Yet, it is important to recognize the intrinsic limitations of ML: their accuracy is largely reliant on the quality, amount, and representativeness of the training data. Overfitting, noninterpretability (the "black box" issue), and the necessity of adequate validation on unseen data are still major issues. Blending domain experience from traditional rock physics with ML pipelines is essential to produce physically consistent and geologically realistic predictions.

Challenges and Future Directions

There are still some challenges in rock physics, including:

Quantification of Uncertainty: Estimating the uncertainty of rock physics models and predictions is still a key area. Probabilistic rock physics workflows, commonly paired with Bayesian inference, are being increasingly used to deal with it, going beyond deterministic point estimates.

Anisotropy in Complex Media: Much has been achieved, but still proving difficult is the characterization and modeling of anisotropy within very heterogeneous and fractured media (for example, fractured carbonates, fault zones). Highly advanced seismic acquisition methods (for example, wide-azimuth, multi-component) and very complex anisotropic inversion algorithms are needed.

According to Time-Lapse Rock Physics: It is essential to understand how rock properties vary in time (e.g., in response to fluid injection, production, or CO_2 sequestration) in order to monitor reservoirs. Creating strong time-lapse rock physics models that consider changing pore pressures, saturations, and geomechanical conditions can be an ongoing area of research.

Coupling with Geomechanics: The interaction between rock physics and geomechanics is becoming increasingly crucial for drilling safety, hydraulic

Online ISSN 3007-3197
Print ISSN 3007-3189

fracturing optimization, and reservoir compaction. Future work will include the development of truly coupled poromechanical and rock physics models.

High-Resolution Rock Physics: The need for higher resolution reservoir models requires rock physics strategies to close the gap between core plug scale and seismic wavelength, perhaps through application of advanced DRP and multi-scale modeling.

In summary, rock physics continues to be a vital key to understanding the Earth's subsurface. Future developments will be driven by continued incorporation of theoretical bases into advanced computational tools, such as digital rock physics and machine learning, which will allow more precise and trustworthy characterization of multi-physics complex geologic systems for energy, environmental, and engineering purposes

CONCLUSION

Rock physics stands as a cornerstone in our quest to understand the Earth's subsurface, providing the essential link between seismic observations and the intrinsic physical properties of geological materials. This manuscript has systematically explored the multifaceted nature of rock physics, demonstrating its indispensable role in deciphering subsurface complexities for a wide array of applications, from hydrocarbon exploration to geothermal energy development and environmental monitoring.

Our study has confirmed the basis for theoretical rock physics models, including effective medium models and Gassmann's fluid substitution, in terms of predicting seismic responses. Although these models are strong structures, the necessity for sophisticated formulations that address complex pore structures, anisotropy, and micro-heterogeneities continues to be critical for precise characterization in difficult geological environments. Petroleum petrophysics has continued to confirm the overarching dominance of porosity, mineralogy, fluid type, and effective stress on seismic velocities and impedances through integration of petrophysical data from well logs and cores. This information is paramount in the accurate discrimination of lithology and fluids.

In addition, forward modeling and sensitivity analyses have been crucial prediction tools for anticipating seismic signatures and defining the effect of other petrophysical parameters. Parameters such as the VP/VS ratio and Poisson's ratio stand out as most sensitive for fluid type and fracturing, providing essential information on reservoir potential. The introduction of Digital Rock Physics (DRP) has transformed our comprehension of micro-scale controls on macroscopic elastic properties, with unprecedented insights into how pore architecture directly affects bulk rock behavior. This bridge between microscopic and macroscopic scales is particularly significant for unconventional reservoirs.

Importantly, the advent of machine learning (ML) and artificial intelligence (AI) has marked a new phase in data-driven rock physics solutions. These state-of-the-art algorithms have proved to have outstanding predictive capability for petrophysical properties and lithofacies classification, and subsequently address frequently difficult-to-quantify complex and non-linear relationships, which often prove problematic for conventional approaches. Nevertheless, effective implementation of

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Online ISSN 3007-3197
Print ISSN 3007-3189

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ML requires well-calibrated, representative data and careful awareness of model limitations, highlighting ongoing value in integrating domain knowledge.
Notwithstanding the great progress that has been made, rock physics remains an advancing field. Future studies will most certainly address solid uncertainty quantification, the improvement of models for anisotropy in very complex and fractured media, the development of sophisticated time-lapse rock physics techniques for dynamic reservoir surveillance, and further integration with geomechanics. Through ongoing advancements in theoretical insight, computational capacity, and data-centric methodologies, rock physics will continue to be at the vanguard of unlocking the Earth's secrets, fueling innovation, and guiding prudent resource stewardship in an ever-more intricate world.

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