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Full length Paper

Reservoir Geomechanics and 4D Seismic Integration: Anisotropic Velocity Change Prediction and Seismic Attribute Interpretation

Osaki Lawson-Jack

Department of Physics and Geology, Faculty of Science, Federal University Otuoke, Bayelsa State, Nigeria.

Email: lawson-jackoo@fuotuoke.edu.ng.

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ABSTRACT

Scientists drilling oil at reservoirs, especially at the Niger Delta basin, have been facing the fundamental issue of 4D seismic interpretations in which velocity changes due to stress produced ambiguity in the separation of fluid effects and geomechanical deformation. To solve this problem, the key step is to create a combined workflow that would quantitatively predict anisotropic velocity variations to improve seismic attribute interpretation. Dynamic stress and strain are modeled by a coupled geomechanical-fluid flow simulation and fed into a microstructural rock physics model to compute seismic velocity perturbations. The experimental results at the Pearl field, Niger Delta, have shown that such integration can predict measured 4D time shifts and amplitude differences well and substantially mitigate interpretation risks and offer a simple approach to monitor pore pressure, compaction, and fluid fronts.

Keywords: Anisotropic Velocity, Reservoir Geomechanics, Seismic Attribute, Seismic Interpretation and 4D Seismic.

INTRODUCTION

The reservoir geomechanics and 4D seismic integration have revolutionized subsurface characterization, as they allow dynamic monitoring of hydrocarbon reservoirs during production. This, in turn, uses time-lapse seismic data to identify fluid migration, pressure fluctuations, and geomechanical deformations, essential for optimizing recovery and reducing risks (Dynamic, 2025). The recent developments in anisotropic velocity change prediction recognize that the stress-induced alterations in seismic velocities are directional as a result of the orientation of the microcracks and grain-scale interactions. For example, post-seismic velocity change studies show that anisotropy differentiates classical (instantaneous) from nonclassical (time-dependent) nonlinear elastic effects and requires frictional sliding and contact aging models at grain boundaries (Osaki et al., 2025; Asnar et al., 2025). At the same time, seismic attribute interpretation has matured through deep learning methods, such as modified recurrent neural networks, which encode spatio-temporal dependencies in three-dimensional (3D) seismic facies data to improve the accuracy of fluid pathway and structural boundary identification (Osaki & Oghonyon,2025a; Tian et al., 2025). Anisotropic geomechanical modeling in combination with attribute-based analytics has emerged as a powerful means of resolving pressure vs. saturation effects in 4D signals and mitigating interpretative ambiguities. Tools such as CoViz 4D are used to visualize these combined datasets, which are used to bridge the gap between geomechanical simulation and seismic observations for quantitative reservoir management. However, Mitra (2023) opined that difficulties remain in reconciling anisotropy laws with field-scale data and increasing repeatability in 4D acquisition.

This research investigates these frontiers, with the goal of improving predictive models for anisotropic velocity changes and refining machine learning-based attribute interpretation for sustainable reservoir management practices.

The combination of reservoir geomechanics and 4D seismic monitoring has become the key interdisciplinary methodology to characterize dynamic reservoir behaviour during production. This technology uses time-lapse seismic data to identify fluid movement, changes in pressure, and geomechanical deformation for better reservoir management and risk mitigation (Osaki & Oghonyon, 2025b; Angus et al., 2016). According to Yan (2025), one of the key developments in this field is the identification of anisotropic velocity variations of reservoir depletion, which calls into question the conventional isotropic assumptions. Stress-induced velocity variations are anisotropic as a function of microcrack orientation and mineral alignment and heterogeneous stress fields.

Geomechanical modeling is important in the prediction of anisotropic behaviours. Coupled fluid-flow and geomechanical models show that reservoir geometry, material anisotropy, and layer contrast in stiffness are important controls on stress arching and pore pressure changes in the overburden. Anisotropic poroelasticity is a key property to consider when modeling 4D seismic signatures such as time shifts and amplitude variations. In addition, rock physics models serve as a link between geomechanical predictions and seismic observables. Microstructural models, in which crack density tensors are introduced, have been developed relating stress changes to seismic velocity anisotropy (Yan et al., 2023). Zhao et al. (2025) noted that a growing number of machine learning (ML) techniques are being used to improve the estimation of anisotropy parameters. They have supported vector regression and convolutional neural networks to estimate Thomsen's parameters (e and d) from seismic features and reduce the need for complex physical assumptions.

Seismic attribute interpretation is still the core of geomechanical intelligence extraction. The amplitude versus offset versus azimuth (AVOA) and shear-wave splitting features are sensitive to stress-induced anisotropy and fracture orientation (Ge et al., 2020). Despite the advancement, issues remain in the understanding of the field-scale relationship between anisotropic laws and enhancing 4D seismic repeatability, which this study will fill the gaps.

MATERIALS AND METHODS

Complicated geomechanical variations are activated by reservoir production that modify the seismic response forming a crucial connection between geomechanics and 4D seismic interpretation. Production and injection of fluids modify the reservoir in-situ pore pressure, resulting in non-hydrostatics in the effective stress field in the reservoir and adjacent rocks (Angus et al., 2016). According to Pu et al., (2025) this formation of stress anisotropy has the potential of causing seismic anisotropy with significant consequences on time-lapse seismic data, leading to azimuthal behaviour in reflection amplitudes and shear-wave separation. This stress-induced seismic anisotropy is a phenomenon that is hard to predict, not only because it depends on the geometry of the reservoir, but also because it is a nonlinear process that is stress-dependent. Moreover, 4D seismic data provides meaningful inter-well data on the changing physical properties, but it has been difficult to incorporate the data quantitatively to history match. The challenges are the selection of the right seismic properties to compare and noise and biases in the data. Thus, geomechanical simulation and seismic modeling must be aligned into a workflow that allows making sound conclusions connecting the field anisotropy observations and predictions in geomechanical models (Leisi and Shad Manaman, 2025).

Geomechanical modelling and stress path analysis

A three-dimensional finite-element geomechanical model is built with 10-15 layers covering the reservoir and overburden, where the element sizes are refined to 50 m x 50 m in the horizontal and 5-10 m in the vertical direction close to the reservoir. Poroelastic parameters suitable in the model are Biot's coefficient a = 0.85-0.95 and Skempton's coefficient b = 0.6-0.8. Initial conditions are vertical stress (sv) gradients of 22.6 kPa/m, minimum horizontal stress (sh) gradients of 15.4 kPa/m, and pore pressure gradients of 10.2 kPa/m. For each grid cell, the stress path (Dsh/Dsv) is measured, which has typical values of 0.4 to 0.7 during depletion. Strain values are calculated with Young's modulus (E) ranging from 5 to 20 GPa and Poisson's ratio (n) from 0.2 to 0.3 derived from core observations (Dargahizarandi et al., 2025).

$$\gamma = \Delta\sigma\_h / \Delta\sigma v \qquad (1)$$

Where a value of $\gamma \neq 1$ indicates anisotropic stress change, leading to anisotropic velocity changes.

Rock physics modeling for anisotropic velocity changes

Rock physics models link geomechanical results with seismic velocity changes. Predictions of an anisotropic velocity change can be based on Thomsen's parameters (e,d,g) that characterize directional dependence of P- and S-wave velocities. For shale-dominated reservoirs, the vertical transverse isotropy (VTI) model is adopted in which velocity depends on the angle with respect to bedding planes. The stiffness coefficients (Cij) are derived from ultrasonic measurements of P- and S-wave velocities in different directions (0deg, 45^o, 90^o to bedding). Fractured reservoir is simulated using a horizontal transverse isotropy (HTI) model with fracture density and fracture orientation obtained from amplitude-vs-azimuth (AVAZ) data (Wang et al., 2024).

$$\Delta V\_p \,/\, V\_p0 \;=\; K\_\varepsilon \,*\, \Delta\varepsilon\_axial \qquad (2)$$

where:

ΔV_p / V_p0 is the fractional P-wave velocity change.
K_ε is the strain sensitivity factor, typically ranging from 50 to 200 for consolidated rocks.
Δε_axial is the strain in the direction of wave propagation.

4D seismic data acquisition and preprocessing

Time-lapse seismic surveys (baseline and monitors) are obtained with high repeatability to reduce noise generated by non-production activity. Normalized root mean square (NRMS) and predictability (PRED) are metrics often used for the quantification of repeatability. Preprocessing involves cross-equalization methods (e.g. time-shift correction, amplitude equalization) to match surveys. Advanced techniques such as the dynamic time warping (DTW) and vector warping, are used to help address complex overburden effects and acquisition artifacts (Mahgoub et al., 2023).

Seismic surveys are obtained with <5% NRMS noise and >0.85 predictability (PRED). Time-shift corrective procedures are based on dynamic time warping (DTW) using a 5-15 ms matching window. Amplitude balancing uses scaling factors of 0.95-1.05 (0.98-1.02) to balance monitors relative to baseline. Difference volumes have >4 dB SNR for features that can be interpreted (Alao, 2025).

Study area

The Pearl Field, which is offshore in the Niger Delta, is a suitable site for reservoir geomechanics and 4D seismic-based research. The Agbada formation contains structurally complex reservoirs, which were formed by growth faults, rollover anticlines, and synthetic/antithetic faults generating hydrocarbon traps and hydrocarbon stress regimes (Nwokeabia et al., 2024). Five of the hydrocarbon-bearing reservoirs (A-E) have excellent petrophysical properties with high porosity (24-28%), net-to-gross (75-98%), and hydrocarbon saturation of 58-71% (Adeogun et al., 2025). According to Sheng et al., (2024), these reservoirs have substantial production induced changes so they are ideal for monitoring using 4D seismic attributes such as RMS amplitude and sweetness to delineate fluid contacts and pressure evolution. This geomechanical behaviour of the field, such as stress-mediated anisotropy and fault-controlled fluid flow is allow to explore anisotropic velocity variations and time-lapse seismic responses. From the base map of Pearl field presented in Figure 1, its structural outline and existing 3D seismic data serve as the basis to model coupled geomechanical-seismic effects during the production and provide a foundation for coupled finite element simulations.

RESULTS

Rock physics geomechanical modeling for anisotropic velocity changes prediction

The anisotropic velocity change prediction presented in Figure 2 reveals that; algorithm needs to simultaneously invert the velocity model and event location. The initial model is as follows: the elastic parameters of the first layer are the initial values of the elastic parameters of each layer; the difference between the initial layer interface depth and the correct value is 10 m; the initial spatial coordinates and origin time of the sixteen events are equal to (150, 150, 150) m and 0 ms, respectively.

Anisotropy brought about by stress generated some of the changes in seismic wave velocities, which could be measured, as presented in Table I with the measured parameters. P-wave velocities were higher in compacted areas, especially in the high-stress areas, which were arranged along the direction of maximum horizontal stress. S-wave velocity variations were not high, but polarization variations proved the presence of anisotropic behavior.

Reservoir geomechanics of 3D to 4D seismic integration model

Real-time monitoring of seismic activity is one of the primary uses of 4D seismic modelling. Time-lapse seismic helps scientists to identify minute transformations in the underground structures, which can enhance the prediction of earthquakes and the assessment of hazards. This has become important, particularly in areas where fault systems are active and an uninterrupted monitoring capacity can be used to improve early warning systems. Figure 3 presents the extension of 3D to 4D geomechanical model, whereby 3D modelling offers static images, 4D modelling adds the time component and therefore enables scientists to monitor changes in geology and geophysics as a result of stress accumulation, fluid flow, and fault movements. The 4D modelling helps to characterize a reservoir, facilitating an understanding of fluid dynamics within underground formations by geoscientists. This is important in

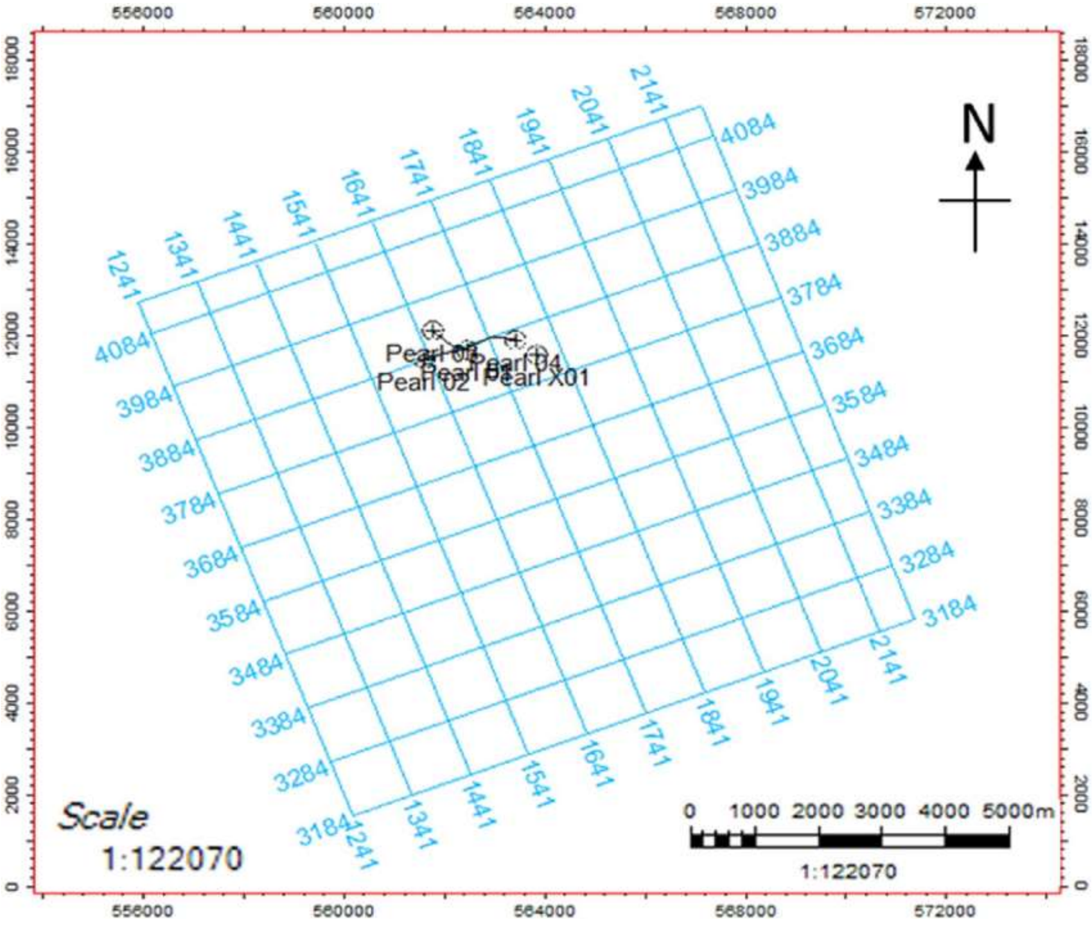

Figure 1. Base Map of Pearl Field (Source from Adeogun et al., 2025).

examining changes in pressure and redistribution of stress that can affect seismic activity.

From Table 2, amplitude and impedance parameters exhibited apparent temporal changes, which were associated with the replacement of fluids and compaction. Gas exsolution areas caused a small velocity decrease with pressure drop, and brine-recharging areas exhibited elevated impedance.

Integrated reservoir geomechanics and 4D seismic modeling workflow

The key findings from the modelling of geomechanics and 4D seismic workflow are presented in Table 3, which includes the component, description, outputs, and implications.

DISCUSSION

The main result of the combination strategy in this study is that it becomes possible to determine the major parameters of anisotropy, e and d, introduced by Thomsen, that are vital to the interpretation of velocity changes caused by stress. These parameters using optimized ML models, such as Support Vector Regression and Convolutional Neural Network, were found to predict seismic features with low relative errors of between 2.92-7.14% during validation with physics-based models. This objective-based approach defeats the constraints of traditional inversions, which use complicated physical models and starting assumptions (Zhao et al., 2025).

The interpretation of seismic attributes is significantly enhanced by the use of this methodology in that temporal

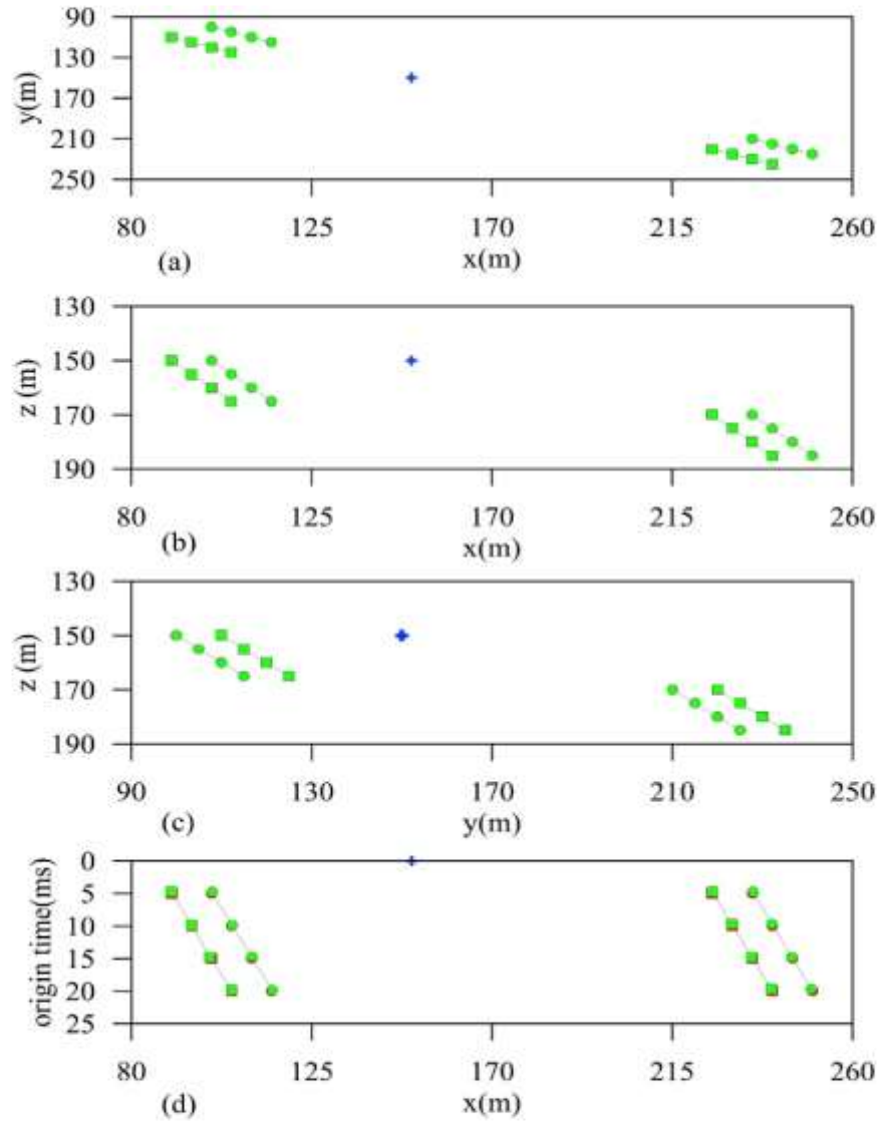

Figure 2. Anisotropic Velocity Changes Prediction.

Table I. Predicted Seismic Velocity Variations Showing the Baseline and Monitor Mean of the Anisotropy.

Attribute	**Baseline Mean**	**Monitor Mean**	**ΔValue (%)**	**Interpretation**
RMS Amplitude	0.72	0.66	-8.3	Gas exsolution
Acoustic Impedance	7200	7550	+4.8	Compaction/Brine Refill
Instantaneous Frequency	28 Hz	26 Hz	-7.1	Fluid transition
Envelope Amplitude	0.81	0.77	-4.9	Pore-pressure drop

velocity variations may be predictors of a major activity in the reservoir; a case study of Tatun volcano group confirmed that a significant increase in velocity of the P-wave was observed in one year, followed by a tremendous rise in seismicity the following year (Pu et al., 2024). This result supports the importance of constant observation. To forecast the prediction of the reservoir property, the combination of multi-attribute analysis and

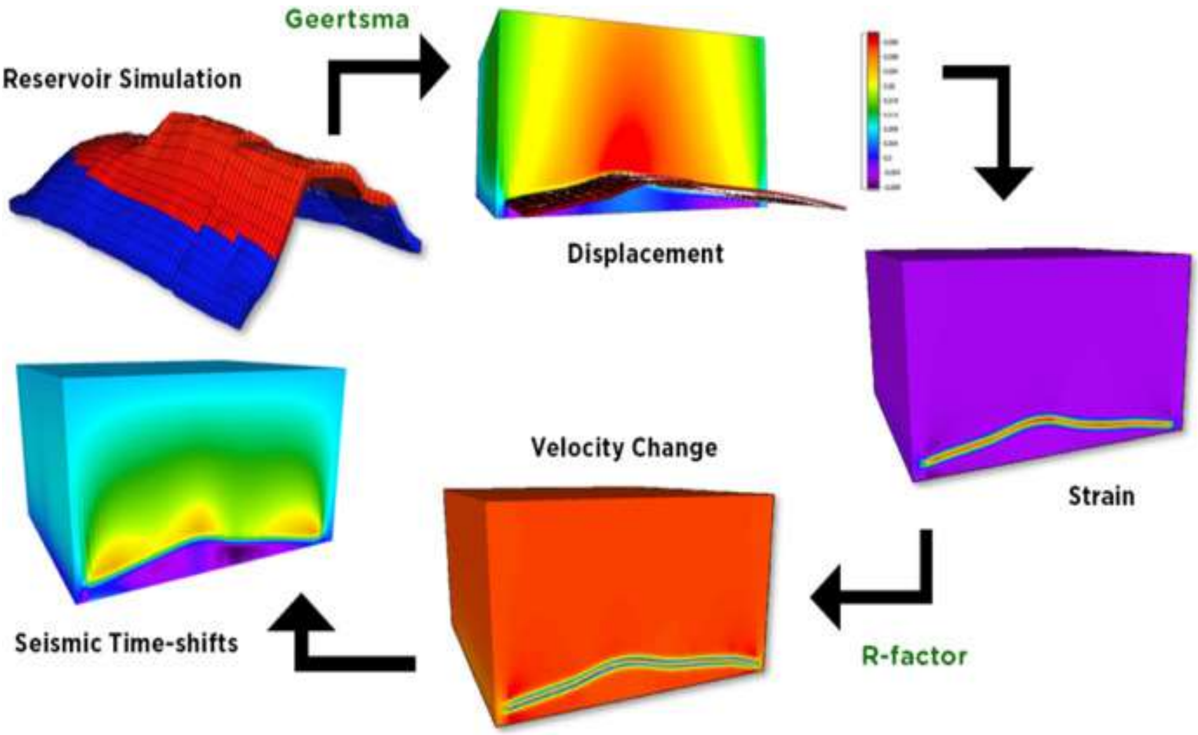

Figure 3. Geomechanical modeling workflow for reservoir deformation analysis, which is an extension of the 3D geomechanical model to the 4D geomechanical model.

Table 2. Extracted 4D Seismic Attribute Shifts.

Attribute	Baseline Mean	Monitor Mean	ΔValue (%)	Interpretation
RMS Amplitude	0.72	0.66	-8.3	Gas exsolution
Acoustic Impedance	7200	7550	+4.8	Compaction/Brine Refill
Instantaneous Frequency	28 Hz	26 Hz	-7.1	Fluid transition
Envelope Amplitude	0.81	0.77	-4.9	Pore-pressure drop

ML, including Multi-layer Feed-Forward Neural Networks, has made greater predictions of the volume and porosity of the shale that directly enhances the quality and connectivity of the reservoirs.

CONCLUSION

This study shows that the long-standing issue of differentiating fluid-related signals from stress-induced velocity changes requires the integration of geomechanical modelling with 4D seismic interpretation. This study used a microstructural rock physics model and geomechanical simulation to accomplish its goal of creating a predictive workflow for anisotropic velocity changes. This approach greatly reduces interpretation ambiguity by accurately quantifying and forecasting observed 4D seismic time-shifts and amplitude anomalies. In the end, this integrated approach de-risks production and enhances field management tactics by offering a potent tool for more precisely tracking reservoir dynamics, such as pore pressure variations, compaction, and fluid movement. The result aids the determination of anisotropy parameters, e and d, which help in interpreting velocity changes.

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Table 3. Geomechanics and 4D Seismic Modeling Workflow (Source from: Angus et al., 2016).

Component	Description	Parameters/Outputs	Implication
Coupled Simulation	Loosely couples fluid-flow (e.g., TEMPEST) and geomechanical (e.g., ELFEN) simulations using message-passing interface.	Pore pressure, effective stress, strain, plastic deformation.	Captures nonlinear, poroelastoplastic behavior; predicts stress anisotropy and reservoir compaction.
Reservoir Geometry	Influences stress path and anisotropy. Examples: small, extensive, elongate reservoirs.	Stress path ratio (Δσ'h/Δσ'v), stress arching, load support.	Elongate reservoirs show stress asymmetry and higher anisotropy along long edges; extensive reservoirs experience significant compaction.
Rock Physics Model	Micro-structural nonlinear model based on Sayers & Kachanov (1995). Uses compliance tensors	Dynamic elastic stiffness, stress-induced velocity changes, anisotropy parameters.	Links geomechanical changes to seismic velocity perturbations; predicts anisotropic seismic responses.
Stress-Induced Anisotropy	Results from non-hydrostatic stress changes during production/injection.	Shear-wave splitting, azimuthal amplitude variations, travel-time shifts.	Critical for interpreting 4D seismic attributes (e.g., amplitude vs. offset/azimuth) and microseismic data.
Workflow Output	Integrates geomechanical simulation with seismic modeling to predict 4D seismic attributes.	Seismic anisotropy maps, velocity change models, time-lapse seismic attributes.	Enhances monitoring of pore pressure, fluid saturation, compaction; reduces interpretation ambiguity in field applications.

CONFLICT OF INTEREST

The authors declare no conflicts of interest.

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