Int. J. Econ. Environ. Geol., Vol. 17, Issue 2, 2026, 123-129 doi: 10.46660/int.j.econ.environ.geol.v17i2.861.
Journal home page: www.econ-environ-geol.org

ADVANCES IN SEISMIC INTERPRETATION FOR RESERVOIR CHARACTERIZATION: A REVIEW ARTICLE

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Received: *26 May, 2026* ***Accepted:*** *30 June, 2026*

Abstract: From deep underground echoes, we map oil and gas zones - this method shapes how earth layers are seen below. Picture rock patterns stretched across miles, revealed through sound waves bouncing back to surface gear. Over years, tools that gather these signals grew sharper, capturing finer details than before. Instead of guesswork, clearer views now guide decisions about where drilling might work - or fail. Better software cleans up noise, pulls out hidden features, leaving fewer surprises once rigs start running. This study looks at new trends in reading earthquake wave data to learn about oil storage areas underground. Structural insights come alongside clues from layer patterns, both pulled from scans of Earth's layers. Scans rely on how sound waves bounce back through different materials below ground. Computers now help more by spotting patterns once missed by human eyes. Clearer images show where the edges of a reservoir sit beneath the surface. Rock kinds and their traits become easier to tell apart using updated tools. Watching changes while pulling resources out gains accuracy with better tracking. Each step ties closer to real world shifts seen over time. Progress has been noted, yet challenges remain - like complex geology, mismatched data types, one field's findings clashing with another's. Even so, new tools powered by smart algorithms and faster machines now help shape better underground pictures. The combination of old-school quake-wave analysis with today's digital techniques is changing the way rock zones are studied. This combination helps to improve the accuracy of results when tracking oil-rich areas. Insights pile up: older techniques gain strength when wired into current tech flows.

Keywords: Seismic interpretation, reservoir characterization, seismic attributes; seismic inversion, Artificial Intelligence, 3D seismic.

Introduction

Seismic surveys use elastic waves to generate a "computed tomography (ct) scan" of the Earth's subsurface. They are among the most effective and efficient non-destructive methods for remotely characterizing and predicting subsurface properties. The seismic value chain primarily involves transforming seismic data into geological features through a series of operations, including acquisition, data processing, imaging, migration, and qualitative and quantitative seismic interpretation (e.g., attribute extraction, seismic inversion, and rock physics inversion). As geological environments become more complex and challenges associated with exploiting hydrocarbon resources increase, the industry's need for advanced technologies that can provide accurate data for building more realistic reservoir models and supporting effective oilfield management becomes even more apparent. Seismic methods have over time evolved to be the most effective ways of imaging geological structures and evaluating reservoir properties.

Seismic interpretation involves a study of processed seismic data for structural and stratigraphic features, reservoir boundaries, faults, fractures, and lithological and fluid characteristics (Sheriff, 2002). Seismic interpretation is conceptualized as the link between seismic reflections and geological information. Seismic interpretation bridges the gap between reflection and geological information (Doyen, 2007). Seismic technology has greatly enhanced the resolution and quality of subsurface imaging. Previously, analysts relied on flat images generated from two-dimensional data that limited the accuracy of estimation and analysis because of limited viewing angles. 3D scanning operations have transformed the way in which data can be interpreted. They allow for hidden geological layers to be visualized in a clearer way, and for structural details previously unclear to be revealed (Brown, 2011). Monitoring changes over time through 4D seismic surveys has offered an effective way of tracking fluid movement within reservoirs, providing a better understanding of pressure variation and internal reservoir dynamics, and helping to improve production management and operational decision making.

Seismic data acquisition, processing, and interpretation techniques have improved significantly over the past few decades, greatly enhancing the accuracy of hydrocarbon reservoir characterization. Modern seismic interpretation relies on structural analysis, stratigraphic interpretation, seismic attribute analysis, tectonic inversion, and quantitative reservoir characterization. These orders can determine integrated news, that can help to better understand the within difference between the terrestrial structure of the reservoirs (Chopra & Marfurt, 2007). The unification of terrestrial, petro-physical and geophysical data has likewise increased the confidence on the repository models and reduced the doubt in predicting repository possessions and behaviour. Seismic profiles are ultimately correct, itemized and important new form to show subsurface structures. They provide information, not surely discernible from common basaltic profiles. The reasoning of the differing traits of the

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Table 1. Comparison of major seismic survey types used in reservoir characterization.

Seismic Type	Main Characteristics	Advantages	Limitations
2D Seismic	Single seismic profile	Low cost and rapid acquisition	Limited spatial coverage
3D Seismic	Volumetric subsurface imaging	Improved structural and stratigraphic interpretation	Higher acquisition and processing costs
4D Seismic	Repeated 3D surveys over time	Reservoir monitoring and production optimization	Expensive and data intensive

seismic signal will immediately manage much easier to label signs in addition to fractures, sedimentary channels and lithological alterations.

This reasoning has established a large number of signs: signal size, progression of reflections, fundamental curve, temporal and ghostly traits of tectonic waves. Out here, judgments from aforementioned studies combine accompanying basaltic inversion plans to turn inexperienced basaltic signals into clear rock details. These contain by means of what much space lies between grains, what fills that breach, plus whether fluids inside are lubricated, smoke, or water. With a clearer picture, finding good fuel spots becomes less guesswork. This type of processing of the sound waves enhances the visibility of rock properties: advanced seismic inversion techniques turn the reflected seismic data into quantitative estimates of rock properties, and hence assist in the detection and accurate identification of hidden subsurface features (Veeken, 2007).

Interpretation of seismic data is an important part of calculations for signal analysis and for detection of geologic features such as faults and subsurface structures. It is one of the modern tools used in the interpretation of seismic data, and which decrease the need of direct human intervention in analysis stages. With better software and algorithms, we can automate the interpretation of data and produce more detailed maps of the rock strata. It may also use sophisticated classification and analysis techniques to aid in the separation of rock types, which are difficult to distinguish by conventional methods. Furthermore, machine learning algorithms may improve the accuracy of interpretation by learning the relationships and patterns within the seismic data.

These developments are not intended to replace human expertise, but to help it by reducing the time and effort needed for analysis and improving the quality of the results. Challenges include the limited generalization of models beyond their training data and the substantial computational resources required for certain applications (Pendrel, 2001).

Also, the understanding gap for some artificial intelligence models brings up the issues of result reliability, i.e., constant verification of data quality and assumptions used in analysis. Despite much progress in seismic interpretation over the years, hydrocarbon exploration is still very difficult in regions with deformed structures, thin beds, extensive fracture and fault networks and deep or thin reservoirs. To make a difference and meet the challenges stated above one has to develop a completely new approach that would involve the synthesis of various scientific disciplines rather than just making some small improvements on the existing conventional methods.

The future of reservoir characterization and mapping is based on advanced technology and multi-source data. More visible images of subterranean rock coatings are now accepted by improved forms for reading temblor dossiers (Abdel-Fattah *et al*., 2020). As a result, previously overlooked connections between structures become apparent. Plans for field management and well excavation may gradually change as these insights develop. The use of accurate details and data instead of rough estimates increases the effectiveness of exploration operations and decreases the uncertainty in data interpretation (Romero *et al.*, 2023). This performance is further improved by cumulative improvements in seismic processing and interpretation methods.

This section is dedicated to the morphological features and geologic interpretation of the seismic reflection expressions in the subsurface. It also describes the procedures of converting seismic data into clear images of the subsurface structure, and discusses the present technical limitations, challenges and prospects for future development. The section ends with a summary of the main results of the review (Taner, 2001). The general workflow for seismic interpretation and reservoir characterization discussed in this review is shown in Figure 1.

Review Methodology

The review first analyzed literature on the role of seismic data in rock strata characterization and subsurface geological formations mapping. The main goal was to include the most relevant studies to create a comprehensive knowledge base, and to ensure that no important results or discoveries, that could improve the understanding of the matter, were missed. Hence, a systematic research methodology was adopted to cover a broad spectrum of scientific literature with stringent selection and quality sources (Maurya *et al*., 2020). The main criterion for study selection was the scientific quality, not the diversity of the studies that were included in the literature review. Only studies that have a clear and real scientific contribution to the field were accepted. The tension between broad coverage and in-depth analysis was resolved.

In attempting this, we did not depend solely on quantitative or statistical measures of the significance of the studies.

Therefore, the references were selected based on their direct relevance to the study objectives and their capacity to provide information that contributes to the enrichment of the research findings (Xu *et al*., 2025).

Literature Search Strategy

The search was carried out through major scientific databases including Scopus, Web of Science, ScienceDirect, Springer and Google Scholar. We searched extensively for seismic measurements and subsurface geological analysis, but found relevant studies only when combining specific words in the search. The evolution of key phrases, including seismic interpretation, reservoir characterization, seismic attributes, and seismic inversion (Zhao *et al*., 2025) was before the development of reservoir characterization. Representative studies reviewed included Maurya *et al. (2020)*, Xu *et al. (2025)* and Zhao *et al*. (2025), covering seismic inversion, reservoir characterization, and AI-based seismic interpretation.

In the context of today's quickly evolving digital environment, artificial intelligence has become an essential tool for companies of any size. It is important to note that businesses utilizing these kinds of technologies observe a significant increase in their operational efficiency. Furthermore, when they choose to integrate automated processes into their operations, corporations witness a dramatic decrease in superfluous expenses. However, it is important to understand that technology by itself will not ensure success. After all, it is the responsibility of every business to promote innovation and make sure that the employees are encouraged and sufficiently trained to use such powerful tools as digital technologies (Oyedele *et al*., 2020).

Practical Applications of Seismic Survey Types

The seismic survey methods depend upon the stage of development of the reservoir and the geological complexity. For example, 2D seismic surveys provide a cost-effective means of locating local geological structures and selection of potential drill sites, and have been widely used in early stages of exploration. 3D seismic surveys, in contrast, generate high resolution volumetric images and accurately define faults, stratigraphic features and reservoir boundaries, making them the standard tool for detailed reservoir characterization. 4D seismic surveys are also frequently used to monitor fluid movement, pressure changes and reservoir depletion over time in the production of oil fields to support reservoir management and production optimization.

Seismic interpretation has greatly enhanced reservoir characterization, well placement, and hydrocarbon recovery in major hydrocarbon fields, including the Ghawar field in Saudi Arabia, the Rumaila and West Qurna oil fields in Iraq, and several North Sea reservoirs. According to earlier studies, 2D, 3D, and 4D seismic surveys improve structural mapping, fluid and pressure change monitoring during production, and reservoir identification (Brown, 2011; Lumley, 2001; Elgendy *et al*., 2025).

Data Extraction and Analysis

In the era of modern technologies, artificial intelligence plays a vital role in the development of any business. The main advantage of such programs is that almost any company can optimize its work and increase its efficiency by using them. In addition, the use of technology reduces the time and money spent on work. Nevertheless, it should be emphasized that the described effect is only achieved, if people are ready for innovative changes and are knowledgeable about the features of the new technologies.

This would make it easier to compare them systematically, as well as to observe the dominant trends in research and the technology that have developed in the area under study, and to spot gaps and issues that still need further inquiry. Maurya *et al*. (2020), Xu *et al*. (2025) and Zhao *et al*. (2025) were among the representative studies that were assessed, they addressed reservoir characterisation, seismic inversion, and AI-based seismic interpretation. Sections 4-6 examine the collected findings, which were categorized into subject groups and covered seismic interpretation techniques, reservoir applications, difficulties, and future prospects.

Scope of the Review

It covers the methods used for interpreting seismic data for studies about reservoirs with their structural interpretation, stratigraphic analysis, and both traditional and modern techniques of seismic property analysis.

The seismic inversion technique is the methodology applied for the conversion of seismic signals into interpretable rock properties. The interpretation of three-dimensional as well as time-based seismic surveys is carried out for understanding the spatial and temporal variations in reservoirs. Integrated models and intelligent algorithms enhance the accuracy of interpretations. The strengths and weaknesses of different techniques highlight new opportunities for the industry. Previous studies have addressed these criteria: Abdel-Fattah *et al*. (2020) for seismic attributes and inversion; Lumley (2001) for time-lapse seismic monitoring; Elgendy *et al*. (2025) for 3D reservoir modeling; and Xu *et al*. (2025) and Zhao *et al*. (2025) for AI-based seismic interpretation and reservoir characterization.

Limitations of the Review

This study analyzed total 53 sources. Despite efforts to include the most relevant research, limitations may arise from database coverage, publication availability, language barriers, and the rapidly evolving nature of seismic interpretation technologies. As a result, at the time of this review, certain recently published research might not have been included. Although, extensive efforts were made to include relevant literature, limitations may still exist due to database coverage, publication availability, language restrictions, and rapid technological evolution. Consequently, some recently published studies may not have been included at the time of this review.

Figure 1 shows how reservoir characterization and hydrocarbon resource evaluation are aided by seismic data collecting, processing, interpretation, seismic characteristics, inversion, and AI-based techniques. In addition to supporting reservoir modeling, development planning, and decision-making, these integrated methodologies assist in identifying reservoir geometry and characteristics, and assessing possibly hydrocarbon-bearing zones.

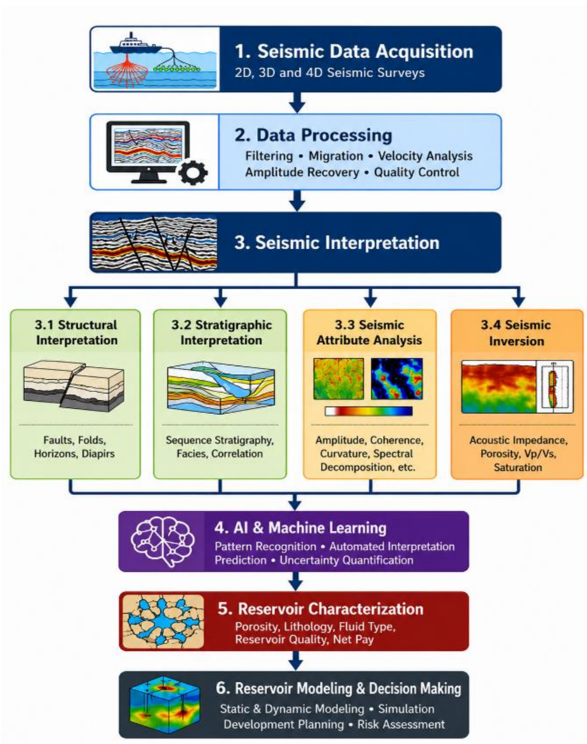

Fig. 1 Workflow of seismic interpretation for reservoir characterization and hydrocarbon resource evaluation.

Advances in Seismic Interpretation and Reservoir Characterization

From seismic signals, geologists extract information about subsurface rock formations. Hidden layers, ancient depositional features, and pore-space variations can be inferred through careful analysis of seismic reflections. When rock knowledge teams up with well logs and sound-wave maps, interpretations become more reliable when multiple datasets align across fields and formations (Elgendy *et al.*, 2025). Most seismic surveys fall into one of three kinds: 2D, 3D, or 4D. Though built on similar principles, each reveals distinct details about space and time in a reservoir. Information comparing them appears in Table 1. Still, 3D seismic holds steady as the go-to method for studying reservoirs - its clear visuals make it tough to beat. On the flip side, 4D steps in when teams need to track shifts underground while keeping output efficient. Looking at a reservoir means checking its shape, rock types, how much space exists between grains, how easily fluids move, plus where those fluids accumulate. Lately, analysts blend clues pulled from quake waves, data conversion tricks, and smart algorithms so estimates reach closer to reality - all feeding stronger forecasts without extra guesswork (Naseer *et al.*, 2025).

Major Seismic Interpretation Methods Used in Reservoir Characterization

Seismic characteristics, inversion, time-lapse seismic monitoring, and seismic stratigraphy were developed and applied thanks to early research by Taner (2001), Pendrel (2001), Lumley (2001), Chopra and Marfurt (2007), and Veeken (2007). The integration of the major seismic interpretation techniques and their contribution to reservoir characterization are summarized in Figure 1. From shaky ground signals, experts piece together underground shapes.

Because details matter, they track rock types along with where oil or water settle. One way reveals faults, another spots layer patterns. With each method, clarity grows about how things sit below. Fluid pathways can be identified when time-lapse seismic responses are properly aligned and interpreted. Structures twist and dip - clues appear through careful reading of waves (Corrales *et al.*, 2024).

Structural interpretation: Movements of the earth's crust have changed the rocks into which they have been folded, faulted, or fractured. These are some of the most significant structures geologists work with. Most of the time, these structures have created natural traps for oil and gas; therefore, a proper understanding of them helps in locating the reservoirs and defining their boundaries. Many exploration and drilling errors stem from insufficient understanding of these structures, resulting in less accurate and higher-risk decisions (Liu *et al.*, 2024).

Stratigraphic interpretation: Stratigraphic features include old river channels, structures associated with coral reefs, and surfaces developed during periods of discontinuity of sedimentation. These features help geologists interpret the relationships between sedimentary layers, understand their formation and modification through time, and build a more realistic picture of the geological history of the study area (Negm *et al.*, 2025).

Seismic attribute analysis: Seismic attributes such as amplitude, coherence, and curvature reveal structural and stratigraphic features that may not be visible in conventional seismic images. Faults appear where attribute values change sharply, fractures are indicated by abrupt signal variations, and channels and lithological differences become identifiable through these attribute responses (Lumley, 2001). Channels turn through layers, showing in one way what others do not notice at all. Even types of rock stand out once you follow such information. Most likely, these are features that would be missed by standard imaging (Lumley, 2001).

Table 2. Major seismic interpretation methods and their applications in reservoir characterization.

Method	Primary Objective	Reservoir Applications	Main Advantages
Structural Interpretation	Mapping faults and folds	Trap identification and reservoir geometry analysis	Improves structural understanding
Stratigraphic Interpretation	Identifying depositional features	Reservoir continuity assessment	Supports facies prediction
Seismic Attributes	Enhancing seismic features	Fracture and channel detection	Rapid identification of geological anomalies
Seismic Inversion	Estimating rock properties	Porosity and lithology prediction	Quantitative reservoir evaluation
AI-Based Interpretation	Automated data analysis	Fault detection and property prediction	High efficiency and scalability

Seismic inversion: Out of seismic signals comes a clearer picture - turning echoes into numbers that hint at rock traits like how sound moves through them. From there, clues emerge about what kind of stone lies below, how much space it holds, also which zones might carry oil, water, or gas (Zhang *et al.*, 2025).

Artificial intelligence-based interpretation: Nowadays machines that learn help handle parts of reading earthquake signals. Faults get spotted through smart software instead of only human eyes. One task involves following layers underground across wide areas. Classifying rock types becomes faster when automated systems step in. Predicting what fills underground spaces relies on pattern spotting by computers. Efficiency goes up because these tools manage huge amounts of data quickly. Different ways to study quake waves appear together in a chart labelled Table 2. Integrated interpretation workflows that combine several of these thods generally provide more reliable reservoir models and reduce uncertainty in subsurface evaluation.

Seismic Interpretation Uses in Reservoir Analysis

Figure 2 presents an integrated workflow for reservoir characterization, highlighting the role of seismic interpretation in geological modeling, flow simulation, and production forecasting. Prior research has shown that reservoir characterisation, property prediction, and production-related decision-making can be enhanced by seismic interpretation and its integration with well and geological data (Elgendy *et al.*, 2025; Naseer *et al.*, 2025; Li *et al.*, 2025). Seismic wave data provide essential clues for constructing a clearer understanding of subsurface structures.

When these signals mix with rock details and well measurements, guesses about oil spots becomes less uncertain. Combining techniques improves the view rather than depending solely on one source. Making better decisions during the planning, digging, or extraction stages is a result of seeing deeper. When many types communicate with one another, information flows more smoothly. Only when ground samples and sound data go side in hand can clearer images appear. Because it verifies results and clarifies decisions when they are ambiguous (Li *et al.*, 2025).

Mapping Rock Layers

Deep below, shaking waves reveal hidden spots that can hold oil. Rock shifts or folds become visible when scientists send vibrations into the ground. Rather than assuming, experts chart each shape to understand its links. What looks broken might actually flow together under pressure. Clearer views uncover whether pockets connect or stay sealed off. Knowing structure means fewer surprises once drilling starts. Looking at earthquake signals, combined with processed scans and drill-hole measurements, helps guess rock types, space between grains, flow ability, and trapped liquids. With these guesses, building better underground storage pictures becomes possible, leading to smarter handling of resources (Tao *et al.*, 2025).

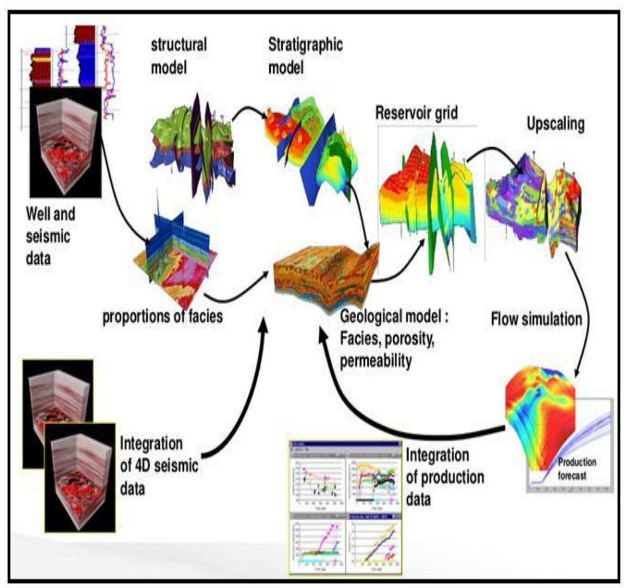

Fig. 2 Integrated reservoir characterization workflow.

Reservoir Property Prediction

When seismic features join with reversed outputs plus well records, spotting rock kinds gets easier. Pore spaces stand out more clearly if everything lines up right. Accuracy climbs in flow zones once separate data strands link into one picture. Fluid levels underground those too adjust in clarity as inputs combine. Models built afterward tend to hold up longer under scrutiny. Decisions around handling reserves shift only slightly at first - then steadily gain confidence (Naseer *et al.*, 2025).

Tracking & Adjusting Water Storage over Time

Later on, time-lapse seismic data reveals shift in underground zones as oil or gas is removed. As fluids shift position, changes become visible across repeated scans taken over months or years. Where pressure drops occur, imaging highlights those spots clearly. These updates guide adjustments in how wells are operated. Instead of guessing, teams respond to actual observed trends downhole. With each survey round, the picture improves slightly. Field decisions gain clarity because measurements reflect real conditions changing over time. From the start, reading quake signals helps map underground spaces more clearly. Instead of guessing, experts get sharper pictures beneath Earth's surface (Zhang *et al.,* 2025). Because details improve, estimates about rock traits become far more reliable. Alongside that, better data guides how oil or gas flows are managed over time. In the end, clearer images mean smarter choices during extraction.

Challenges and Future Perspectives

Reservoir characterisation still faces a number of difficulties despite improved instruments for deciphering seismic waves produced during seismic surveys. Noisy seismic signals, low-resolution features, and complex subsurface geometries reduce interpretation accuracy and slow analysis. Mixing information from ground scans, rock samples, well logs, output number is harder than it sounds - one piece never matches the next (Ba *et al.,* 2025).

Compared to seismic data processing or structural interpretation, there are distinct differences in applying AI to subsurface characterization in three aspects: relatively ambiguous and difficult-to-perceive seismic responses, sparsely labeled data of subsurface properties, and the inherent non-uniqueness of the subsurface inversion problem. First, whether in seismic data processing or the interpretation of structural features and geological bodies, the prediction target has a relatively straightforward pattern, similar to natural image processing. For instance, fault segmentation aims to identify discontinuities in seismic events, which resemble typical image features.

One day, computers might think more like people, spotting patterns in underground data without constant guidance. Instead of waiting for hours, results could appear faster because machines handle heavy number work quickly. Reading rocks the old way now dances with clever number games, mixing years of know-how with quick results. Programs learn from history to predict what lies under instead of rigid steps. People sleep and machines sort through waves of seismic data, gathering insight. Imagine a quiet partner seeing faint hints eyes would not see. Human skill paired with machine pace redraws the picture of where oil sleeps underground (Ravasi & Birnie, 2022).AI and machine-learning techniques have been shown to improve seismic inversion and subsurface characterisation in earlier research (Li *et al.*, 2020; Liu *et al.*, 2024; Xu *et al.*, 2025), demonstrating their efficiency and interpretive advantages over traditional methods.

Practical Implications

When geologists work closely with engineers, finding oil gets better. Instead of guessing, teams place wells where they perform best. Risks drop because decisions rely on clearer underground pictures. From start to finish, managing the reservoir becomes smarter. Using modern tools leads to stronger models of what lies below. Planning how much can be produced turns out more accurate (Li *et al.,* 2020).

Conflict of Interest

Regarding the publishing of this paper, the authors affirm that they have no conflicts of interest.

Funding: No funding was provided to the authors for the study's research, writing, or publishing.

Conclusion

Seismic vibrations provide essential information for identifying and understanding subsurface geological layers. Spotting shapes underfoot now leans on smart software instead of just guesswork. Tools that pull details from waves give clearer hints about what lies beneath. Where old maps once blurred, fresh methods sharpen the picture with fewer blanks. Even when rock patterns twist unpredictably, new number-crunching muscle helps make sense faster. Hidden flaws in raw signals get untangled by sharper algorithms over time. Speedy computers chew through messy inputs until useful forms appear. When clever code meets decades-old survey habits, results grow steadier. Predictions stand firmer where doubt used to rule every call. Clarity builds slowly, one refined echo at a time.

Overall, this analysis shows that reservoir characterisation is improved and subsurface uncertainty is decreased by combining seismic interpretation, inversion, seismic characteristics, and AI-based techniques. Future studies should concentrate on enhanced AI models, integrated multi-source datasets, and validation with production and well data.

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