Advances in Integrated Geophysical Exploration Techniques for Hydrocarbon Prospecting: A Systematic Review

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ABSTRACT

The geophysical workflow required for hydrocarbon prospecting is increasingly complex, and must be able to resolve complex subsurface architecture as well as differentiate between geophysical features that cannot be described by any single observational technique. Seismic imaging, seismic inversion, electromagnetic methods, potential field interpretation, well logging, three dimensional modelling and computational analysis have opened the doors to additional information for decision making in exploration. The evidence for how these techniques can be made to function is, however, spread throughout various methodological or geological contexts. This systematic review aims to assess the progress in the field of integrated geophysical exploration techniques for hydrocarbon prospecting with a focus on the methodological integration, technological development, exploration applications, limitations and emerging directions. The review follows the Preferred Reporting Items for Systematic Reviews and Meta Analyses (PRISMA 2020) guidelines and includes systematic identification, screening, eligibility assessment and qualitative synthesis of relevant peer-reviewed studies. Due to the methodological diversity of the available evidence, the synthesis is based on thematical comparison instead of statistical meta-analysis. The literature review indicates that the seismic interpretation methods gradually evolved to include integrated workflows with seismic attributes, inversion, well data and electromagnetic data, geological modelling, and machine learning and physics constrained methods. Joint inversion and multimodal integration can be used to complement each other when the individual geophysical responses are ambiguous, and probabilistic methods can be used to account for uncertainty in subsurface predictions. New research has also revealed growth in the application of automated interpretation, high performance computing and digital modelling. However, the spatial resolution, physical sensitivity, data quality, and computational demands, combined with the lack of independent validation still limit integrated workflows. This makes it hard to imagine that the future exploration will be based on single technical innovations but rather on the reliability of physically informed, uncertainty aware, multimodal geophysical systems.

Keywords: Integrated geophysics, hydrocarbon exploration, geophysical imaging, seismic methods, electromagnetic methods, gravity and magnetic methods, geophysical inversion, PRISMA.

INTRODUCTION

The identification of a geological structure of interest is only a small component of a much larger subsurface characterisation problem, particularly in exploration environments where hydrocarbons are being sought in a geological environment. Exploration targets can be under thick sedimentary successions, in structurally deformed basins, around salt bodies, in carbonate systems or in reservoirs with properties which change significantly over short distances. This is a context where it is challenging to adduce fluid potential and reservoir distribution from a single observation type. It has been found by Ganguli and Dimri (2023) that

geological complexity is still a challenge in reservoir characterisation and Kaura et al. (2025) emphasized a multi-disciplinary approach to reservoir characterisation and the integration of geological, geophysical and formation evaluation data in unconventional reservoir assessment.

New expectations for geophysical investigation have been placed on the increasing complexity of the targets of investigation. Previous exploration programs tended to focus on the discovery of structural closed areas, and then testing those with wells. Today's exploration involves a lot more information before drilling than before because the existence of a structural closure does not imply reservoir quality, integrity of the seal, content of formation fluids, or commercial potential. In their review of the northern Gulf of Mexico offshore super basin, Sneden et al. (2020) also looked at reservoirs, source rocks, seals, and traps and successes found in the exploration or production of these resources as an interconnected geological system, rather than a series of components.

The settings are also deep and complicated structurally, further adding to the challenge. McArthur et al. (2022) studied sedimentation over structurally complex deep water slopes, and Bosworth and Tari (2020) studied hydrocarbon accumulation in basins with multiple stages of extension and inversion. These studies demonstrate the effects of structural history and depositional architecture on potential reservoirs and traps distribution. Exploratory methods therefore need to deliver information at a number of different geological scales, ranging from regional basin architecture to local reservoir properties, and will have to become increasingly more sensitive in the future.

This is even more apparent in carbonate and unconventional reservoirs. Li et al. (2025) summarised the technical progress and ongoing problems related to carbonate reservoir evaluation, while Chen et al. (2023) analysed the variations in carbonate reservoir attributes and their effect on exploitation in the Tarim Basin. The diversity of this heterogeneity can lead to many possible geologic solutions for a geophysical response. One of the major reasons for the increased importance of integrated interpretation is this non uniqueness.

This lesson explains the various geophysical methods used to locate hydrocarbons.This lesson discusses the different geophysical techniques used to find hydrocarbons.

The use of geophysical techniques for indirect measurement of physical properties of the subsurface and hence a significant part of the modern hydrocarbon exploration program. Seismic methods are particularly important for mapping geological interfaces, structural discontinuities and depositional architecture. In addition to using sequence stratigraphy for reservoir prediction, seismic sedimentology and facies analysis have been employed. For instance, Wu et al. 2020 made use of seismic sedimentology in combination with facies studies to predict reservoirs in fan delta deposits.

Other geophysical techniques provide data which is physically distinct from seismic response. Gravity measurements mainly react to the changes in the subsurface density and can contribute to the basin and structural interpretation. Magnetic measurements are used to complement information on magnetic susceptibility, and are especially useful for regional geological and basement interpretation. Electrical and electromagnetic methods are useful for additional information on the electrical properties of the subsurface that can be provided in addition to seismic data. The utility of this complementarity is demonstrated by Saleh et al. (2023) who coupled seismic quantitative interpretation with 3D controlled source electromagnetic and magnetotelluric inversion to rank the hydrocarbon prospects and to identify the sweet spots.

Well logging is in a different category as it does give detailed measurements at specific borehole locations. Local constraints on lithology and formation properties can be set by gamma ray, resistivity, density, neutron, sonic and image logs. They have small spatial extent though and cannot be used to represent the subsurface in a region on their own, to be able to delineate a prospect. This scale difference was solved by El-Qalamoshy et al. (2023) using a mix of seismic data and well logs and fault seal analysis to identify hydrocarbon traps.

Another means of combining these datasets is by using 3D geological modelling. Cao et al. (2024) discussed 3 dimensional geological modelling as a way to represent geological structures and subsurface information and

Imam et al. (2022) mapped the geological structures in a hydrocarbon field by seismic interpretation and 3 dimensional modelling. This framework enables observations made at various scales to be represented in a common geological model.

1.3 Limitations of Individual Geophysical Methods

The principal justification for integrating geophysical techniques arises from the fact that each method observes only particular physical properties of the subsurface. Seismic data provide detailed information on elastic contrasts and geological geometry, but interpretation may remain ambiguous where different lithologies produce similar seismic responses. AVO analysis addresses part of this problem by examining amplitude behaviour with offset or angle. Allo et al. (2022) demonstrated the value of constraining AVO interpretation with a localised rock physics template for reservoir characterisation and hydrocarbon detection.

Gravity and magnetic methods face a different limitation. Their responses can be valuable for regional structural and basement interpretation, but the measured anomaly may arise from several subsurface configurations. Their principal strength is therefore complementary rather than equivalent to the high resolution structural information obtained from seismic surveys. This distinction explains why integrated potential field interpretation is useful for establishing a regional framework within which more spatially detailed seismic observations can be interpreted.

Electromagnetic methods provide information on electrical resistivity and can therefore respond differently from seismic measurements. Saleh et al. (2023) demonstrated the application of seismic and electromagnetic integration to prospect ranking, while Namazi et al. (2026) extended multimodal integration to geophysical and geochemical information for subsurface characterisation. Their work illustrates the broader principle that complementary physical sensitivities can provide additional constraints on an otherwise ambiguous subsurface interpretation.

Well logs provide the opposite situation: high local detail but limited lateral extent. This makes them valuable for calibrating regional geophysical predictions but unsuitable as a standalone means of mapping an entire reservoir. Onita et al. (2023) addressed this relationship through the integration of seismic petrophysics and quantitative interpretation. The resulting logic is straightforward: regional geophysical measurements provide spatial coverage, whereas borehole measurements provide local physical constraints.

1.4 Emergence of Integrated Geophysical Exploration

The shortcoming of individual techniques has paved the way toward multimethod and multiphysics interpretation. One of the most obvious indicators of this change is known as joint inversion. In Zhdanov et al. (2021), advanced joint inversion techniques for multiphysics data were reviewed and in Zhang et al. (2023), mixed structural and rock physics coupling constraints are introduced for joint inversion. These methods attempt to make use of the common geologic data, but maintain the separate physical sensitivities of the contributing data sets.

There are multiple levels of integration. The most basic level of independence is when the datasets are separately analyzed and then combined. A more limited approach is that of relying on one set of data to help interpret another set of data. Different datasets can be solved simultaneously at the inversion level with structural, petrophysical or other coupling constraints. Astic et al. (2021) applied a dynamic Gaussian mixture model to assist with multiphysics inversion with geological and petrophysical information.

Integration is thus more than just a matter of more data. The goal is to minimize ambiguous interpretation because the differences between physical responses. If two methods react differently to the same geologic body, then the interpretation of the two in concert can remove some of the possibilities that would be left if either one or the other dataset were considered alone.

1.5 Recent Technological Advances

The capability of acquiring, processing and assimilating geophysical data has increased with technological progress. The advances in seismic imaging has brought quantitative interpretation closer to the goal of full waveform inversion, and high-performance computing has made increasingly challenging numerical workflows possible. Agudo et al. (2022) discussed full waveform inversion of seismic data and Guo et al. (2024) presented an extended source formulation in time domain for FWI of seismic data.

The computational aspect is gaining more and more significance because the need for substantial processing resources has grown with the increase in the scale of the imaging and inversion. A framework for processing large-scale integral operators and 3D Marchenko imaging by least squares inversion has been developed by Ravasi and Vasconcelos (2021) that takes advantage of high performance computing. Arrowsmith et al. (2022) discussed big data in seismology and Ni et al. (2025) cloud computing applications in seismology.

There is a new dimension to interpretation, thanks to machine learning. Ali et al. (2024) used convolutional neural networks and transfer learning to predict reservoir properties from synthetic and real seismic data, and Ren et al. (2026) combined the technique of spectral decomposition with automatic machine learning to optimize seismic attributes for reservoir prediction. While these advances point towards automated and computer-assisted interpretation, they cannot supplant geological and physical constraints.

1.6 Problem Statement and Knowledge Gap

Significant development of individual geophysical techniques, and of combinations of selected datasets is found in the literature. But there is still a scattered distribution of evidence from various methodological traditions. The study of seismic inversion, AVO, electromagnetic methods, spectral decomposition, machine learning, multiphysics inversion and geological modelling and quantification of uncertainty have been treated separately. Purnomo et al. (2023), Sun et al. (2024) and Ren et al. (2026) discuss various aspects of the quantitative seismic reservoir prediction; Saleh et al. (2023) discusses about seismic and electromagnetic integration.

The fragmentation makes it hard to know if a given integration strategy is always beneficial in geologic environments. The differences in data quality, acquisition geometry, spatial resolution, geological environment, and inversion formulation and validation procedure add to the sense of comparability. Xu et al. (2025) identified uncertainty quantification and multi-source data fusion, physical and geological consistency as ongoing challenges within machine learning seismic characterisation.

This is not just a dearth of new geophysical techniques, but a lack of knowledge. Instead, it is necessary to join together the available and new techniques and explain why specific sets solve certain problems in exploration; what value new combinations add; where and why the transfer of techniques between geologic environments is possible and where it is not; and what problems remain that cannot be solved by the techniques available..

1.7 Aim of the Review

This review aims to systematically evaluate advances in integrated geophysical exploration techniques for hydrocarbon prospecting, with particular emphasis on methodological integration, technological developments, exploration applications, advantages, limitations and emerging research directions.

1.8 Review Objectives

The review seeks to:

1. Examine the major geophysical techniques currently used in hydrocarbon prospecting.

2. Identify advances in the integration of seismic, electromagnetic, gravity, magnetic, well logging and related geophysical datasets.
3. Evaluate applications of integrated geophysical workflows in hydrocarbon exploration.
4. Examine the role of inversion, imaging, computational methods and machine learning in integrated interpretation.
5. Identify limitations, uncertainties and challenges associated with integrated geophysical exploration.
6. Determine emerging trends and future research directions.

1.9 Review Questions

The review addresses five questions:

1. What geophysical techniques are most frequently integrated for hydrocarbon prospecting?
2. What technological advances have enhanced integrated geophysical exploration?
3. How does geophysical integration improve subsurface imaging and hydrocarbon prospect evaluation?
4. What are the principal limitations of current integrated approaches?
5. What emerging technologies are likely to influence future hydrocarbon exploration?

METHODOLOGY

2.1 Review Design

The review will be conducted as a systematic literature review, based on the framework of the Preferred Reporting Items for Systematic Reviews and Meta Analyses (PRISMA 2020). The systematic design is suitable, since the literature of integrated geophysical exploration involves a multitude of technical fields and studies with quite diverse objectives, datasets, and validation methodology. A structured review therefore offers the possibility to select studies not based on the relevance of the narrative, but rather in accordance to explicit criteria.

The review has four major stages: identification, screening, eligibility and inclusion. The different stages offer a clear pathway for moving from the original body of literature to the studies that directly address the research questions.

One important difference between literature identification and interpretative synthesis is that it is preserved. The first is subject to a standardized search and eligibility process, while the second classifies the incorporated evidence based on geophysical method, integration method, exploration purpose and technological advancement.

2.2 PRISMA Framework

The PRISMA structure starts with the identification of potentially relevant records in the chosen bibliographic databases and additional sources. Once a duplicate record is found it is then eliminated prior to title and abstract search. During this stage, records are eliminated if their content is explicitly not related to hydrocarbon exploration, geophysical methods or integration.

All records that could be relevant are assessed in full text. The full text stage will decide if the study meets the substantive eligibility criteria, which includes the availability of adequate methodological information, and

whether it addresses either the integration of geophysical data sets or an advanced technology that is directly relevant to integrated exploration.

The last step is the studies that meet the eligibility criteria and provide evidence for the qualitative synthesis. Completed manuscript should contain the actual numbers retrieved, screened, excluded and included for each stage. These numbers should be taken from the documented search, and not estimated.

2.3 Identifying sources of information and choosing a database.

The information sources that are planned include Scopus, Web of Science, ScienceDirect, SpringerLink, Wiley Online Library and IEEE Xplore for computational and sensing studies. Google Scholar can be used as a secondary search tool to find possibly relevant literature that cannot be accessed easily via the main bibliographic databases.

Multiple databases are offered to decrease reliance upon a single discipline indexing system. This is especially significant for the present review because the evidence pertaining to this topic is found throughout the petroleum geoscience, geophysics, computational science, remote sensing and engineering disciplines.

To ensure reproducibility the final search record should specify the database name, date of search, search fields and the number of retrieved records. Although the syntax for each database is different, the concept is the same and the Boolean expression is modified to suit the needs of each.

2.4 Search Strategy

The hydrocarbon exploration group contains the following terms: hydrocarbon exploration, petroleum exploration, oil and gas exploration and reservoir characterisation. Geophysical is a subgroup of engineering, which contains the terms geophysical exploration, seismic, electromagnetic, gravity, magnetic, well logging and related terms. The integrated geophysics, joint inversion, cooperative inversion, multiphysics, seismic electromagnetic and data fusion are all the elements of the integration. The technology group contains the terms of geophysical inversion, full waveform inversion, machine learning, AI, advanced imaging, and other terms related to this technology.

The strategy should be tailored for each database, but must maintain the conceptual structure. This way, it is less likely that the nature of the search syntax in the databases will significantly affect the nature of the review.

2.5 Eligibility Criteria

Studies are eligible if they are related to hydrocarbon/petroleum exploration and involve or test geophysical methods that relate to exploration or prospect evaluation or reservoir characterisation. Research using two or more geophysical data sets or integrating geophysical information with well, geological, geochemical or petrophysical data sets is given particular emphasis.

Eligible studies should give adequate methodological detail to ensure that the data gathered, the way in which data were integrated and the exploration aim were determined. Peer reviewed publications in the defined period of publication are preferred.

Studies are not included if they have been published more than once, presented as a conference abstract with insufficient methodological detail, editorials, opinion papers, or are nonacademic web materials. Research that is specifically outside of the scope of hydrocarbon exploration is not included. If a study fails to include any meaningful discussion of integration, it does not qualify for being considered as a study based on a single geophysical method. Publications that do not provide adequate methodological information are also excluded since there is insufficient information to assess them reliably.

2.6 Study Selection Procedure

Study selection is done based on title and abstract screening and then to full text assessment. The first screening is made based on the relevance to hydrocarbon exploration, geophysical methods and methodological integration. The full text assessment then reviews the research objective, geological context, dataset(s), integration approach, exploration application, and the sufficiency of the results reported.

Ideally, screening should be done by two reviewers separately. Disagreements should be settled by discussion and a third reviewer should be involved when an agreement cannot be reached. This procedure reduces the influence of individual judgement on study inclusion.

The reasons for excluding the full text should be recorded in a systematic manner. Common reasons are no hydrocarbon relevance, insufficient methodological description, absence of geophysical integration, inappropriate publication type or not meeting the specified publication interval.

2.7 Data Extraction

The information provided from the included studies is organised in a standardised way. The extracted fields include author and year, geological setting, basin or field, hydrocarbon type (when reported), geophysical method, integration approach, data type, imaging/inversion technique, computational method, objective of the exploration, main result or finding, advantages of the exploration and uncertainty considerations.

Important for the present review, the same term (e.g., integration) can refer to very different approaches. For instance, independent interpretation of seismic and electromagnetic data is different from joint inversion, where both types of data are directly contributing to a common solution.

2.8 Quality Assessment

Methodological quality evaluation should be carried out by means of preestablished evaluation criteria that should include: clarity of the research objective, description of the geological context, in adequacy of information acquired and processed, explanation of the integration procedure, validation, reporting of the results, uncertainty assessment, and methodological reproducibility.

Studies can then be ranked as high, medium or low quality based on the number of criteria that they meet. Quality assessment is not to be used exclusively to decide whether to include or exclude a piece of work for interpretation. A technically innovative study may have substantial relevance but limited external validation, while a more established workflow may provide stronger evidence because it has been tested against independent observations.

2.9 Data Synthesis

Given the considerable differences in the geological setting, acquisition design, physical measurements, integration approach and performance indicators that are observed across the studies reviewed, a qualitative thematic synthesis would be more appropriate than a statistical meta analysis.

The evidence has thus been structured under six broad categories: geophysical method, integration type, exploration objective, geological environment, imaging or inversion approach and computational technology. Performance data of studies (quantitative) can be presented within the thematic category, for example in terms of prediction accuracy, imaging resolution, capability for anomaly detection and uncertainty reduction.

This way numerical comparisons of fundamentally different experiments are avoided, and the aim is to find consistent methodological patterns in the literature.

2.10 Bias and reporting issues

There are multiple types of bias that might affect what's in the literature. The choice of database might influence the results obtained and language filters might limit your access to relevant non-English publications. Publication bias is also likely to occur in that successful applications will be published, whereas unsuccessful exploration attempts will not be. There are many differences in reporting methods across studies, which makes direct comparisons difficult.

Clear reporting of the search process, exclusion criteria and included studies characteristics offers a way to reduce such effects. The review is therefore not concerned with the novelty of the approach but with the strength of the evidence and does not assume that the fact that a particular method has been published as a successful case study necessarily means that it is effective overall.

3.0 Fundamental Geophysical Techniques for Hydrocarbon Prospecting:

3.1 Seismic Methods

Seismic methods are at the heart of hydrocarbon exploration as they give detailed information on the sub-surface geo-architecture. The common interpretation of reflection seismic data involves defining structural boundaries, faults, stratigraphic relationships and reservoir geometry. The relationship between seismic character and depositional facies continues with seismic sedimentology. Wu et al. (2020) showed how seismic sedimentology and facies analysis can be applied to make predictions of reservoirs in fan delta systems.

Three dimensional seismic interpretation has provided better spatial representation of these geological features and spectral decomposition has enabled the acquisition of frequency dependent data to help identifying subtle reservoir bodies. Egbokhare et al. (2026) used spectral decomposition and seismic sequence stratigraphy to delineate subtle reservoirs in the offshore Niger Delta.

3.2 Gravity Methods

The primary contribution of the gravity methods to the regional and structural interpretation is related to the sensitivity of the method to the variations of subsurface density. Their value is especially notable when the exploration problem demands an understanding of the architecture of the basin, the configuration of the basement or large scale geological structures. Gravity data are therefore best used in conjunction with techniques which have higher local spatial resolution.

3.3 Magnetic Methods

Magnetic surveys give information on the variation of magnetic susceptibility and are particularly useful in regional geological mapping and basement interpretation. These can be integrated with seismic observations to give a more general framework as to how to interpret detailed seismic features. This complementary role is significant in basins where it is hard to determine the depth structure from the seismic data only.

3.4 Electrical and Electromagnetic Methods.

Electrical/electromagnetic techniques give information of subsurface resistivity. They are physically sensitive, but not like seismic methods, which allows for complementary interpretation. Saleh et al. (2023) combined the techniques of seismic quantitative interpretation, controlled source electromagnetic and magnetotelluric inversion, and used the results to rank and identify sweet spots for hydrocarbons.

3.5 Well Logging

High resolution measurements are obtained at the borehole scale from well logs. They are important because they help to limit lithology, fluid related properties and petrophysical properties where the geological

interpretation can be directly tied to the location. El-Qalamoshy et al. (2023) combined well logs and seismic data and fault seal analysis, and Onita et al. (2023) used seismic petrophysics with quantitative interpretation.

3.6 Remote Sensing and Other Emerging Methods

The use of remote sensing and airborne geophysics allows for geophysical observation on areas where ground-based acquisition is challenging. Dadrass Javan et al. (2024) made a systematic review of Unmanned Aerial Geophysical Remote Sensing and Fenta et al. (2021) discussed about Fibre Optic Technologies as a developing tool in geophysical prospecting. They expand the range of platforms for exploration, but the value of the exploration depends on the ability to connect the measurements to subsurface geological models.

4.0 Advances In Integrated Geophysical Exploration

4.1 Seismic and Electromagnetic Integration

Seismic and electromagnetic methods provide complementary information, since they are sensitive to different physical properties. Seismic observations are used to give information on the elastic behaviour and geological architecture, while the electromagnetic methods is related to the electrical properties. This distinction is especially important when geological evidence is not enough to differentiate between the two scenarios.

To this end Saleh et al. (2023) showed that seismic quantitative interpretation could be integrated with 3D controlled source electromagnetic and magnetotelluric inversion to rank the prospect and identify the sweet spots. Namazi et al. (2026) also studied the use of a multimodal approach to subsurface characterisation involving AI fusion of geophysical and geochemical data. These studies suggest that multimodal integration is going beyond the traditional interpretation side by side to computational systems that can integrate information from different modalities.

The primary benefit of seismic electromagnetic integration is thus not just the extra data set. It is valuable due to the potential of having two different physical responses satisfied by the geological model. The main limitations relate to the resolution, acquisition configuration, complexity of the inversion and the requirement for the measurement of adequate coupling between the datasets.

4.2 Seismic and Gravity Integration

There is potential for complementary information at different geological scales provided by seismic and gravity data. Seismic techniques can provide information on fine structure, while gravity observations provide information on larger scale density variations. Their two-way match can, therefore, help to interpret the basin structure and deep structure.

Three dimensional modelling of the geology is an appropriate environment for such integration. Cao et al. (2024) reviewed three dimensional modelling as a tool to represent subsurface geological structures, and Imam et al. (2022) showed how seismic interpretation and 3D modelling can be used to map structures.

4.3 Seismic and Magnetic Integration

Magnetic data can be used to aid in the interpretation of basement configuration, regional structures, and tectonic lineaments. In addition to seismic observations, this information can help to give a larger geological picture to aid in the understanding of structures identified in the seismic volume.

This difference in scale and physical sensitivity is the strength of this combination. Seismic data can provide a relatively detailed sedimentary architecture while magnetic data can be used to extend the structural interpretation to deeper geological levels. This interpretation can be of special value in regions with a highly basement-controlled sedimentary basin geometry.

4.4 The combined effect of gravity and magnetic forces

Gravity and magnetic data are sometimes used in combination because they both carry regional information about subsurface structure, but they both are sensitive to different physical properties. They can be used together to enhance the delineation of the basin, basement interpretation, and regional tectonic analysis.

The potential field framework generated is particularly useful when combined with seismic data. Rather than relying on gravity and magnetic anomalies to be interpreted individually, the combination of both with the seismic structures and the geological model can be used to develop a more coherent interpretation of the architecture of the basin.

4.5 Integration of Geophysical and Well Log Data

The correlation of geophysical and well log data is critical for bridging the regional interpretation to the properties of the formations. Seismic velocity and density, acoustic impedance, and other parameters can be calibrated using well data. El-Qalamoshy et al., 2023, showed this approach using seismic data and well logs and fault seal analysis for the identification of traps.

Similarly, Onita et al. (2023) combined seismic petrophysics and quantitative interpretation. The role of well information is thus not restricted to after validation, but can also impact the building and fitting the geophysical model.

4.6 Multiphysics and Joint Inversion

Joint inversion is one of the most important advances in geophysical integration as it transfers the process of integration from an inspectional to mathematical approach. Zhdanov et al. (2021) summarized the advanced multiphysics joint inversion methods, and Zhang et al. (2023) added structural and rock physics coupling constraints to the joint inversion.

Incorporation of geological and petrophysical information in multiphysics inversion was achieved by Astic et al. (2021) using dynamic Gaussian mixture model. These techniques acknowledge that geophysical solutions can be constrained by the use of geological information, which is often ambiguous.

There is another dimension in the case of probabilistic formulations. Grana et al. (2022) tackled probabilistic seismic inversion to characterise reservoir petrophysics and gave an approach where uncertainty can be considered instead of being masked. This is especially important for exploration decisions as various subsurface models can be accommodated by the observations.

4.7 3D and 4D Integrated Geophysical Workflows

The use of 3D modelling has become a significant tool to incorporate geological and geophysical data. It was reviewed by Cao et al. (2024) for its application in various aspects of earth science research, and Imam et al. (2022) showed its application to structural mapping.

This idea is extended to the integration of time dependent observations into the concept of dynamic reservoir characterisation. The concept of a digital twin (DT) driven by artificial intelligence (AI) for real-time monitoring and predictive optimisation of hydrocarbon production from reservoirs has been proposed by Elbarouni (2024). Yan et al. (2025) also created a dynamic reservoir prediction model based on digital twins and simulation.

5.0 Advanced Imaging, Inversion And Computational Technologies

5.1 Full Waveform Inversion

Full waveform inversion is an important advancement to quantitative seismic imaging as it is a method that

relies on the shape of the waves to determine the subsurface models. Agudo et al. (2022) dealt with full waveform inversion of seismic data, and Guo et al. (2024) introduced a time domain extended source formulation.

The technique has also become more related to Machine Learning. Recently, Zhang et al. (2020) explored the adjoint driven deep learning for seismic full waveform inversion and Wang and Hu (2026) summarized recent advances on the intelligent approaches of FWI for oil and gas exploration. The developments are an example of how computational learning is being integrated into the more advanced seismic inversion phase of the interpretation process, rather than a standalone interpretation phase.

5.2 Reverse Time Migration

Reverse time migration is especially important for complicated wave propagation and challenging structures since it allows for full wavefield propagation. As surveys get larger and 3 dimensional more complex, so does the amount of computation required. High performance computing has thus been closely tied to the development of advanced imaging. Ravasi and Vasconcelos (2021) proposed a high performance framework for 3 dimensional Marchenko imaging and large scale least squares operations.

5.3 Seismic Inversion

Means of translating seismic observations into quantitative subsurface properties exist: Acoustic impedance, elastic impedance and simultaneous inversion. Purnomo et al. (2023) used enhanced extended elastic impedance inversion for prediction of reservoir petrophysical geobodies. Sun et al. (2024) proposed a fusion neural network for simultaneous estimation of A and P.

These studies illustrate a key advance in the use of seismic data: the use of seismic data for the estimation of properties relevant to reservoir evaluation.

5.4 Machine Learning and Artificial Intelligence

Seismic interpretation has seen advancements with machine learning in the range of computational tools available. Yu and Ma (2021) summarized the progress of deep learning in geophysics and Xu et al. (2025) summarized machine learning to seismic subsurface characterisation.

The applications include reservoir property prediction, automated interpretation and multimodal data fusion, seismic facies classification. Ali et al. (2024) applied convolutional neural network and transfer learning techniques to seismic data (synthetic and real) to predict reservoir properties. Ren et al. (2026) combined spectral decomposition and machine learning to optimise seismic attributes and prediction reservoir.

But, predicting with machine learning does not equal geologic certainty. Xu et al. (2025) noted that physical and geological consistency, uncertainty quantification and multimodal data fusion, are important issues in machine learning based seismic characterisation. Data requirements, transferability across geologic environments and interpretability and overfitting of models continue to be critical issues.

5.5 Cloud Computing and High Performance Computing

The amounts of seismic and multiphysics data are growing to the point where the traditional processing environment might not be adequate to solve the computational need. The development of big data in seismology was reviewed by Arrowsmith et al. (2022) and cloud computing applications were discussed by Ni et al. (2025).

Large scale inversion and imaging requires numerical capacity, which is provided by the use of High performance computing. This has been shown by Ravasi and Vasconcelos (2021) in a high performance framework for three dimensional Marchenko imaging. The computational infrastructure thus becomes part of the exploration methodology to an increasing extent.

5.6 Uncertainty Quantification

Uncertainty quantification is needed, given the non-uniqueness of geophysical inversion. Grana et al. (2022) created a probabilistic approach to seismic inversion for reservoir petrophysical characterization. Another method for restricting solutions is via physics guided machine learning. Willard et al. (2020) discussed integration of physics based modelling and machine learning, and Schuster et al. (2024) reviewed physics informed machine learning for geophysical inversion.

It is assumed that the way to explore these things today is to differentiate between the detailed subsurface model and confidence in the model. An ambiguous but visually powerful interpretation might not offer as much decision value as a constrained interpretation with explicit uncertainty.

6.0 Applications Of Integrated Geophysical Techniques.

6.1 Structural Trap Identification

Integrated methods have broad applicability and are suitable for structural trap identification since each of the datasets can be used to constrain a different aspect of the structural framework. El-Qalamoshy et al. (2023) integrated seismic data, well logs and fault seal analysis for locating traps and Imam et al. (2022) employed seismic interpretation and three dimensional modelling for mapping the geological structure.

6.2 Stratigraphic and Lithological Interpretation

The geological constraints that guide reservoir delineation are from seismic sedimentology and from sequence stratigraphy. For predicting fans deltas, Wu et al. (2020) integrated seismic sedimentology and facies analysis, and Egbokhare et al. (2026) used seismic sequence stratigraphy and spectral decomposition to delineate subtle reservoirs in the offshore Niger Delta.

6.3 Reservoir Characterisation

Seismic, petrophysical and computational information are increasingly being used together in quantitative reservoir characterisation. Purnomo et al. (2023) predicted petrophysical reservoir geobodies by enhanced extended elastic impedance inversion, and Sun et al. (2024) predicted petrophysical properties by fusing acoustic impedance and porosity using a neural network.

6.4 Direct Hydrocarbon Detection

AVO and electromagnetic responses can offer information relevant to hydrocarbon prospectivity, but their interpretation needs to be held back by geological and rock physics evidence. Allo et al. (2022) employed the AVO constrained by a localised rock physics template for hydrocarbon detection, and Abd-Elfattah et al. (2025) applied machine learning to an AVO Class II workflow for hydrocarbon prospectivity in the offshore Nile Delta.

The presence of an anomaly should therefore not automatically be assumed to be indicative of hydrocarbons. Different geophysical conditions are possible, depending on the lithology, structure and fluid conditions. The value of integration lies in its ability to be tested with other evidence.

6.5 Complex Geological Environments

In deepwater, carbonate, salt affected and structurally complex environments integrated methods become even more critical. McArthur et al. (2022) explored sedimentation on structurally complex deepwater slopes and Yasin et al. (2023) used structure oriented filtering and seismic attributes to characterise complex reservoir.

The carbonate systems are more challenging to interpret because of the heterogeneities in reservoir properties. Li et al. (2025) have discussed the problems that arise in the evaluation of carbonate reservoirs; Chen et al.

(2023) have discussed the differential characteristics of carbonate reservoirs and problems of exploitation.

7.0 Critical Synthesis Of The Evidence

7.1 Comparative Performance of Integrated Approaches

Evidence examined indicates that the main contribution of integration is the joining of complementary physical information. Seismic methods provide detail structural and stratigraphic information, EM provides resistivity information, well logs provide local petrophysical constraints and potential field methods provide regional structural context. The use of seismic and electromagnetic information for prospect ranking has been shown to be useful by Saleh et al. (2023), and seismic and well log and fault seal information for trap identification by El-Qalamoshy et al. (2023).

The evidence also shows that interpretation is evolving to inversion. Joint inversion is a method in which multiple data sets are explicitly integrated into a unified estimation problem, while standard integration could be a comparison of independently derived interpretations. Multiphysics and structurally constrained joint inversion is an example of this transition (Zhdanov et al., 2021; Zhang et al., 2023).

7.2 Exploration Benefits

Some possible advantages are suggested by the reported usages. Seismic sedimentology and spectral decomposition have been employed to fine delineate reservoirs, and seismic inversion and machine learning have been applied to predicting reservoir properties.

The prime examples are those where the secondary data is used to correct for a known limitation of the primary data. The integration of seismic and electromagnetic, which has significance, is attributable to the difference in their physical sensitivities. Well calibration is useful because the information from the borehole applies to the local area and gives constraint to regional predictions. The physics guided learning is meaningful because the information that physics provides can limit the flexibility of the data-driven models.

7.3 Persistent Limitations

There is no certainty when integrating. Rather, it alters the manner in which uncertainty is bounded. Each dataset comes from a different acquisition geometry and physical sensitivity with varying spatial resolutions. Joint inversion can therefore be a complex calculation, and requires accuracy in the assumptions that are made to couple the datasets.

Machine learning adds other issues. Xu et al. (2025) have highlighted some general methodological challenges related to physical and geological consistency, multimodal data fusion and uncertainty quantification. Such issues can make it so that a model that works well on one set of geological data isn't necessarily as effective on another.

Limited independent validation is another important issue. Geophysical predictions are often tied to a fairly limited number of wells and, therefore, the success of an integrated model can be at least in part due to local calibration. Independent verification and uncertainty reporting is important.

7.4 Evidence Gaps

The reviewed literature reveals a few gaps. Firstly, there is no perfect method of integration. Which is the right one? This depends on the geological environment, the aim of the exploration, and the data base and physical characteristics of the target.

Second, it is still hard to make quantitative comparison of the different integration approaches due to the various performance measures used in studies. Thirdly, open, reproducible datasets are still crucial for

assessing the generalizability of machine learning and automated interpretation strategies beyond individual case studies.

Last, it is now more and more recognized that physical constraints should be used together with data driven techniques. The works of Liu et al. (2023), Lin et al. (2023) and Schuster et al. (2024) are all about physics informed or physics guided learning and inversion. The challenge of the research is now to figure out how these approaches can be implemented without loss of interpretability or undue computational complexity.

8.0 Future Directions

8.1 Full Integration Multiphysics Exploration

In the future, workflows will evolve in the direction of simultaneous analysis of seismic, electromagnetic, gravity, magnetic, well, petrophysical and geological data. Namazi et al. (2026) showed how to fuse the information from multiple modes using an AI-based framework, combining geophysical and geochemical data.

8.2 Physics Guided Machine Learning

As labelled exploration data is scarce, the use of Physics guided learning is likely to be increasingly significant. Willard et al. (2020) laid out the general idea of using physical modelling and machine learning; Liu et al. (2023) applied physics driven self supervised learning to seismic velocity inversion. These methods will be invaluable in the future if physical constraints can be used to enhance generalisation without undue complexity.

8.3 Independent Interpreted and/or Semi Independent Interpreted Services

The application of machine learning to the prediction of reservoir properties and seismic attribute analysis is already underway. Ali et al. (2024) applied CNN and transfer learning for seismic reservoir property prediction and Ren et al. (2026) applied spectral decomposition with automated machine learning. These advances drive the horizon tracking, anomaly detection and prospect screening toward greater automation.

8.4 Real Time Exploration Workflows

Increasing amounts of data are being processed due to the high performance and cloud computing. A comprehensive overview of the big data developments in seismology was presented by Arrowsmith et al. (2022), and cloud based applications were explored by Ni et al. (2025). These capabilities enable the possibility of minimizing the time lag between acquisition and processing and interpretation.

8.5 Digital Twins and Dynamic Reservoir Models

Digital twins are a fledgling concept connecting geophysical characterisation and reservoir management. Elbarouni (2024) presented an AI assisted real-time seismic monitoring and production optimization framework, which utilized digital twin and simulation methods, and Yan et al. (2025) presented a dynamic framework for digital twin and simulation reservoir prediction methods.

8.6 Sustainable and Cost Efficient Exploration.

Better integration can also help to make the exploration more efficient by minimizing duplicate surveys and increasing the information available prior to drilling. This potential, however, should be proven, and not assumed, in quantitative terms. The best evidence will be provided through studies that compare integrated workflows to traditional workflows with independent measures of drilling success, prospect ranking, uncertainty and exploration cost.

CONCLUSION

This systematic review shows that the use of hydrocarbon geophysical exploration is increasingly shifting from single data sets being interpreted in isolation to an integrated approach where complementary observations are interpreted in a shared geological model. While seismic methods continue to be important for structural and stratigraphic interpretation, the influence of seismic data is now complemented by electromagnetic, gravity, magnetic, well logging, petrophysical and geological data. We will follow the integration of seismic sedimentology, spectral decomposition, inversion and well data to illustrate how integration can extend the scope of the reservoir interpretation beyond the structural interpretation.

Another key advancement is from qualitative integration to quantitative inversion and computational interpretation. Joint inversion, probabilistic approaches, physics guided learning and multimodal machine learning offer means of synthesizing various physical responses, and tackle some aspects of subsurface non-uniqueness.

The evidence, however, contradicts the notion that integration always leads to a more accurate exploration model. Limiting factors are still spatial resolution, physical sensitivity, data quality and computational requirements. Machine learning raises additional issues of training data, generalisation, interpretability and uncertainty. In particular, Xu et al. (2025) emphasized physical and geological consistency, multimodal data fusion and uncertainty quantification as key factors for machine learning based seismic characterisation.

Integrated, physically constrained and uncertainty aware geophysical workflows will probably become the mainstay of hydrocarbon prospecting in the future. The best systems will not just be able to merge more data sets together, but will be able to provide meaningful relationships between seismic, electromagnetic, potential field, well, geological and computational data. Such integration provides a more defensible basis for prospect evaluation as it enables competing subsurface interpretations to be tested against various types of evidence, not just geophysical response.

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