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Review

A review of the progress for hydrocarbon migration technology: Mainstream methods, frontier trends, and future prospects

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Abstract: Oil and natural gas, as fluid minerals, flow within the Earth's crust under the influence of various driving forces such as pressure, buoyancy, and gravity. This phenomenon is known as hydrocarbon migration. Hydrocarbon migration is a crucial component of the reservoir formation process, and accurately analyzing its direction affects the precision of trap prediction, well positioning, reservoir size, and morphology evaluation, thereby influencing the difficulty and cost of hydrocarbon development. However, most of the currently discovered hydrocarbon reservoirs have undergone multiple transformations or destructions, increasing the challenges of hydrocarbon development. Through an extensive literature review, this paper summarizes and categorizes the main current methods of studying hydrocarbon migration, including sedimentological methods, geochemical tracers, numerical simulation, and geophysical methods. Furthermore, this paper discusses and explores the frontier trends in hydrocarbon migration, mainly reflected in artificial intelligence (AI) methods, digital oil fields, geological big data analysis, and high-resolution seismic imaging technology. Looking to the future, there are significant opportunities in hydrocarbon migration research in data integration and intelligent analysis, high-resolution detection technology, digitization and automation, and the application of green technologies. However, there are also severe challenges regarding data quality and integration, the complexity and uncertainty of models, environmental and safety concerns, technology costs, and interdisciplinary collaboration. In conclusion, this paper clarifies the hydrocarbon migration process by reviewing, summarizing, and analyzing existing literature to understand hydrocarbon reservoirs' formation and distribution patterns. It also delves into the mainstream methods, frontier trends, and prospects of hydrocarbon migration technology, providing valuable insights for future research.

Keywords: hydrocarbon migration; mainstream methods; frontier trends; future prospects; opportunities and challenges

1. Introduction

Petroleum and natural gas are minerals that have the ability to flow. They may migrate within the Earth's crust under the influence of various driving forces such as pressure, buoyancy, and gravity. Any movement of hydrocarbons within the crust is referred to as hydrocarbon migration. It is well known that hydrocarbons form in fine-grained sediments rich in organic matter, but they are mostly stored in coarse-grained rocks with higher porosity and permeability. The transition of hydrocarbons from a dispersed state in the source rock to an accumulated state in reservoir rocks involves a migration process. Hydrocarbon migration is a critical link between hydrocarbon generation and reservoir accumulation and is one of the crucial aspects of petroleum geology [1]. Hydrocarbon migration is an essential step in the reservoir formation process, and accurately analyzing the direction of migration impacts the accuracy of trap prediction, well placement, and the evaluation of reservoir size and morphology, thereby affecting the difficulty and cost of oilfield exploration and development [2].

Based on migration characteristics, hydrocarbon migration can be divided into primary and secondary migration [3]. Primary migration refers to the process of hydrocarbons moving from the source rock to the reservoir or carrier bed (often called expulsion) and the migration of hydrocarbons within the source rock itself [4]. Secondary migration refers to all subsequent movements of hydrocarbons after they enter the reservoir or carrier bed, including the migration of hydrocarbons through the carrier bed to a trap, as well as any secondary migration that occurs when an already-formed hydrocarbon accumulation is affected by changes in external geological conditions [5]. This classification enhances the clarity of hydrocarbon exploration. Research on primary migration can help identify potential source rock regions that are fundamental to hydrocarbon generation. By analyzing the maturity, type, and content of organic matter in the source rocks, it is possible to predict which areas might contain hydrocarbon resources. Research on secondary migration focuses on how hydrocarbons migrate from the source rock to the reservoir, ultimately forming hydrocarbon accumulations. This helps to identify key exploration areas, specifically those with favorable reservoir and trap conditions. Consequently, exploration strategies can be further optimized, development plans more targeted, and the risks associated with exploration and development can be assessed more accurately.

The main research content of hydrocarbon migration includes both dynamics and kinematics. The dynamics aspect primarily explores, within a specific geological unit and under the framework of the corresponding source rock and fluid conduction system, the multidisciplinary comprehensive research system that quantitatively analyzes the entire process of hydrocarbon generation, expulsion, migration, and accumulation leading to reservoir formation. This is achieved through an extensive quantitative study of various physical and chemical fields such as temperature, pressure (potential), and stress, historically reconstructing the entire process against the background of paleostructural development [6,7]. The kinematics aspect examines the phase state, pathways, direction, main periods, and quantities of hydrocarbon migration. Hydrocarbon migration research involves both fundamental theoretical research and applied research.

In the field of hydrocarbon migration research, a variety of mainstream methods have been widely used by predecessors and have achieved significant results. For instance, sedimentological methods reveal the pathways of hydrocarbon migration by analyzing structural ridges and geochemical indicators. In the integrated study of the thermodynamics and reservoir dynamics of the Nanpu Depression evolution in the Jidong Oilfield, a systematic analysis of the controlling effects on oil and gas reservoir formation was conducted through the study of sedimentary facies and depositional systems [8]. Geophysical methods, especially seismic exploration techniques, provide key information on the subsurface structure for hydrocarbon migration. Some scholars used this data to predict the favorable hydrocarbon migration pathways in the Binbei area of the Songliao Basin [9]. In the long-term exploration practices in the Tarim, Sichuan, and Ordos basins, a series of oil and gas reservoir models suitable for the specific geological conditions of the study areas have gradually been formed and established. These models not only guide exploration discoveries but also enrich and develop the geological theory and target evaluation technology of China's characteristic marine deep oil and gas exploration. Geochemical methods track the source and migration process of oil and gas by analyzing changes in their chemical composition. Some scholars used pyrrole-type nitrogen compounds for oil and gas migration analysis, helping to identify the migration pathways and sources of oil and gas [10]. Some scholars studied the migration and mixing of oil in the Junggar Basin of northwest China using reservoir fluid inclusion analysis [11]. Numerical simulation methods also play an increasingly important role in hydrocarbon migration research. For example, some scholars reconstructed the hydrocarbon migration pathways in the Nanpu Depression of the Bohai Bay Basin through simulation and tracing techniques. In addition, some scholars proposed a new method for quantifying the micro-migration of oil and gas in shale. By establishing a kerogen oil and gas generation evolution model through IBM-SPSS numerical simulation and correcting the residual oil and gas volume based on light hydrocarbon calibration, the true potential of oil and gas generation can be obtained [12]. Regarding secondary migration, some scholars used numerical simulation technology to describe the changes in hydrocarbon migration pathways during the scaling-up process [12]. The comprehensive application of these methods provides us with a more comprehensive perspective to understand the complex process of hydrocarbon migration, thereby providing more accurate guidance for oil and gas exploration and development. With the development of technology and the application of new methods, hydrocarbon migration research could continue to deepen, providing scientific support for the development of the energy industry.

Based on the background mentioned above, the migration and accumulation of hydrocarbons in the Earth's crust is an exceedingly complex dynamic process that involves the coupling of various geological, geochemical, and geophysical factors. Describing this process requires quantitative analysis and temporal accuracy, meaning determining when migration and accumulation occur and how these processes change over time [13]. Therefore, conventional dynamic analysis methods, such as spatiotemporal matching and relative sequencing, are no longer sufficient to meet current research needs. Accurate timing is crucial for precisely quantifying and coupling various geological factors, which poses a significant challenge in geoscience research [13]. Additionally, due to the destruction of hydrocarbon reservoirs caused by spillage, leakage, or structural movements that impair the trapping capability, leading to remigration [14]. Most of the hydrocarbon reservoirs discovered today have undergone multiple modifications and disruptions. Therefore, understanding the process of hydrocarbon migration is crucial for grasping the formation and distribution patterns of hydrocarbon reservoirs, which in turn is essential for selecting the correct exploration methods. The main objective of this research is to critically analyze existing mainstream methods of hydrocarbon migration, to review the frontier technologies in hydrocarbon migration, and to forecast future opportunities and challenges. The goal is to improve resource utilization efficiency, reduce environmental pollution, and promote the energy industry's sustainable development.

2. Literature review

The current mainstream methods for studying hydrocarbon migration are extensive and involve a wide range of approaches. However, these methods are typically not used in isolation; instead, they are combined, complementing and validating each other. After a comprehensive review of the relevant literature, this paper categorizes the existing research methods for hydrocarbon migration into four main types: Sedimentological methods, geochemical tracers, numerical simulation, and geophysical exploration. Each of these methods contributes to understanding and predicting hydrocarbon migration behavior, sources, and reservoir characteristics, and they provide support in the practical exploration and development of hydrocarbons.

2.1. Sedimentological methods

The principle of using sedimentological methods to study oil and gas migration primarily involves analyzing the porosity, permeability, depositional facies, and depositional environment of sedimentary rocks to reveal the sources, migration pathways, and accumulation conditions of oil and gas. By studying the physical characteristics of different sedimentary layers and the evolution of depositional systems, combined with structural features such as faults and folds, it is possible to infer the generation, migration, and reservoir areas of oil and gas. Sedimentological methods also help determine the distribution and migration processes of oil and gas by analyzing the relationship between source rocks, cap rocks, and the evolution of sedimentary layers. The application of sedimentological methods in hydrocarbon migration research is multifaceted. From macroscopic sedimentary facies analysis to microscopic analysis of porosity and permeability, each method provides critical information for understanding the migration and accumulation of hydrocarbons in complex subsurface environments.

2.1.1. Sedimentary facies analysis and migration pathways

Sedimentary facies analysis is the process of studying the formation environment and characteristics of sedimentary rocks. The distribution of sedimentary facies is often correlated with the distribution of hydrocarbon reservoirs. Hydrocarbons typically migrate and accumulate in sand bodies with better physical properties, such as porosity and permeability, while ancient sedimentary environments control the distribution characteristics of these sand bodies. By identifying and interpreting sedimentary facies sequences and distributions, possible migration pathways of hydrocarbons underground can be inferred. For example, some scholars identified that in the Zhongguai Area of the Junggar Basin, hydrocarbons in the Sangonghe Formation are mostly distributed near the river channels and the front of the braided river delta on the delta plain, where physical properties are better [15]. Some scholars used sequence stratigraphy to study ancient sedimentary environments in the Lunnan area of Tarim Basin, finding that the Triassic primarily developed braided river delta facies, meandering river delta facies, and lake facies [16]. Developing coarse-grained conglomerates and sandstones in the braided river and underwater distributary channels facilitates hydrocarbon migration, providing a geological foundation for exploring lithological hydrocarbon reservoirs. Some scholars established delta-lake sedimentary and lake carbonate sedimentary models for the Jurassic Ziliujing

Formation in northern Sichuan [17]. They found that high-quality lake mudstones and various reservoir sands at the delta front interbedded with carbonate platforms, forming complex sedimentary sequences that may contain multiple hydrocarbon migration pathways and seal layers.

Additionally, sedimentary structures are key indicators in analyzing sedimentary rocks' depositional environment and facies [18]. Features such as bedding, ripple marks, and erosional surfaces not only record the physical conditions during sedimentation but may also directly influence hydrocarbon migration mechanisms. For example, erosional surfaces may form preferential pathways for hydrocarbon migration. Furthermore, analyzing sedimentary structures can reveal the continuity of strata and the presence of unconformities, which significantly impact hydrocarbon migration and accumulation. In the research, lamination, a common sedimentary structure in fine-grained sedimentary rocks, is strongly correlated with reservoir capacity and hydrocarbon accumulation [19]. Laminated fine-grained sedimentary rocks in lacustrine basins exhibited better reservoir properties and a greater ability to enrich hydrocarbons compared to non-laminated or weakly laminated fine-grained sedimentary rocks.

Fluvial facies sediments often create complex bedding structures, which may contain multiple pathways for hydrocarbon migration and barriers that impede its flow. In contrast, marine facies sediments may form more continuous reservoirs conducive to lateral hydrocarbon migration. Sedimentary facies analysis also includes the paleogeographic reconstruction of the depositional environment, which helps determine the migration direction of hydrocarbons from source rock to reservoir. This is crucial for improving the success rate of hydrocarbon exploration, optimizing development strategies, reducing exploration and development risks, protecting the environment, and achieving the sustainable utilization of hydrocarbon resources.

2.1.2. Porosity and permeability analysis

Porosity and permeability are vital parameters determining a rock's ability to store and transmit hydrocarbons. They significantly impact the dynamic factors of hydrocarbon migration and accumulation. The porosity of sedimentary rock determines its capacity to store hydrocarbons, while permeability dictates the ability of hydrocarbons to flow through the rock [1].

From a microscopic perspective, studying a rock's porosity and permeability reveals that the pore size, type, and uneven connectivity distribution can impact hydrocarbon migration. Some scholars suggest that factors influencing primary migration include compaction, thermal effects, and clay dehydration, while the sedimentary factors affecting secondary migration mainly involve the deposition and diagenesis of sandstone [20]. The uneven compaction of overlying sediments causes the rearrangement of clastic particles, with fluids flowing out along the direction of the pressure gradient. As depth increases, the temperature of the rock rises, causing organic matter to expand due to heat, expelling gaseous and liquid products that drive hydrocarbon migration. Additionally, with increased burial depth, clay minerals release bound water and residual pore water, which can serve as effective carriers for hydrocarbon migration.

The uneven distribution of porosity and permeability is macroscopically reflected in oil reservoirs' interlayer and planar heterogeneity [21]. Interlayer heterogeneity in reservoirs is mainly characterized by changes in the heterogeneity of multiple oil layers in the vertical direction, including differences in rock properties, pore structure, permeability, and oil saturation between different layers [22]. Since hydrocarbons tend to migrate through high-permeability strata while encountering resistance in low-permeability strata, this selective migration may lead to the accumulation of hydrocarbons in certain layers. In contrast, others have little or no hydrocarbons. Interlayer heterogeneity reduces the overall efficiency of hydrocarbon migration. In heterogeneous strata, hydrocarbons may struggle to migrate effectively from source rocks to reservoirs or may not distribute evenly within the reservoir, affecting the efficiency of hydrocarbon accumulation and trapping. This heterogeneity impacts hydrocarbon storage and development, necessitating more precise identification and assessment of different layers' hydrocarbon potential and reservoir properties [21]. This often requires more detailed geological and geophysical data and more complex interpretative techniques, increasing the difficulty of exploration and development [21]. Planar heterogeneity within an oil reservoir can lead to uneven hydrocarbon distribution. Even within the same oil field, different regions may exhibit varying hydrocarbon contents, resulting in differences in development difficulty and effectiveness [21].

Therefore, sedimentological methods are one of the key approaches for studying hydrocarbon migration. By analyzing the characteristics of sedimentary rocks and depositional environments, these methods infer the processes of hydrocarbon generation, migration, and accumulation. Sedimentology can provide direct evidence for hydrocarbon migration research by interpreting depositional environments, conducting facies analysis, and clarifying porosity and permeability based on existing core data. Through sedimentological studies, it is possible to reconstruct ancient depositional environments and understand the evolutionary history of sedimentary basins, which is crucial for comprehending the background and conditions of hydrocarbon migration. However, sedimentological interpretations often involve multiple possible explanations and complexities. The same sedimentary feature might correspond to various depositional environments and processes, potentially leading to uncertainties in interpreting hydrocarbon migration pathways. Moreover, sedimentological research typically requires extensive fieldwork and laboratory analysis, which can be time-consuming and costly. The effectiveness of sedimentological methods largely depends on the quality and quantity of samples obtained, as well as the accuracy and reliability of the analytical techniques. Insufficient data or analytical errors may lead to incorrect conclusions. Additionally, since hydrocarbon migration is a dynamic process and sedimentological methods focus more on static sedimentary features, there are certain limitations in using these methods to interpret dynamic hydrocarbon migration.

2.2. Testing methods

2.2.1. Electron microprobe analysis

Electron Probe Micro-Analysis is an instrument used for compositional analysis of micro-regions, combining features of Scanning Electron Microscope and X-ray Fluorescence Spectroscopy. The electron probe uses a focused, high-energy electron beam as an X-ray excitation source to perform qualitative and quantitative chemical analysis on fine particles or micro-regions on the surface of solid materials. This technique enables micro-area and on-site analysis, allowing for elemental composition analysis within regions as small as a few cubic micrometers (μm^3) without the need to extract the object from the sample; thus, it can directly analyze tiny areas within large specimens. The electron probe technique also has a broad analytical range, capable of analyzing elements from atomic number 3 (lithium) to 92 (uranium).

The electron probe technique analyzes petroleum inclusions and original samples encapsulated in mineral lattice defects or fractures during hydrocarbon migration and accumulation [22]. Through electron probe analysis, approximate characteristics of hydrocarbons, migration stages, and contributions to reservoir formation can be obtained, providing valuable insights into the processes of hydrocarbon migration and accumulation.

The electron probe technique also applies to microthermometry of inclusions, which is one of the essential methods for studying hydrocarbon inclusions [22]. By measuring the homogenization temperature and freezing point of inclusions, it is possible to reconstruct the conditions during hydrocarbon reservoir formation, establish diagenetic and mineralization models, and use inclusion studies to locate blind ore bodies.

The electron probe technique is widely applied in hydrocarbon reservoir studies, particularly in data testing, information organization, and practical applications [23]. For example, by measuring the homogenization temperature of petroleum inclusions, this technique can be broadly utilized in hydrocarbon reservoir research to help identify oil-bearing layers, non-oil-bearing layers, migration pathways, and relationships between replacement oil and gas layers. This technology provides crucial scientific support for oil and gas exploration and enhances understanding of reservoir formation mechanisms.

Through electron probe compositional analysis, some scholars identified various components within micro-dissolved pores in limestone, such as organic matter, calcite, and pyrite [24]. This information allows for inferences about hydrocarbon source and maturity, aiding in determining the type of source rock and its hydrocarbon-generating potential. The distribution of different components within these micro-dissolved pores reveals the flow paths of hydrocarbons and water within the reservoir, contributing to an improved understanding of hydrocarbon migration and accumulation mechanisms.

The advantage of electron probe technology lies in its ability to provide high-resolution micro-area compositional analysis, allowing researchers to precisely identify and quantify the elemental composition of samples on a microscopic scale, including organic matter, minerals, and fluid components. This technique reveals intricate details of the rock's microstructure, such as various components within limestone micro-dissolution pores, aiding in understanding hydrocarbon migration pathways, reservoir properties, and transformation potential. The high sensitivity and accuracy of electron probe technology make it an indispensable tool in hydrocarbon exploration and development, particularly for assessing the pore structure of reservoir rocks, the history of fluid infill, and the mineral composition of rocks.

2.2.2. Scanning electron microscope

A Scanning Electron Microscope is an instrument that utilizes a focused electron beam to scan the surface of a sample, observing and analyzing the sample's composition, morphology, and structure by detecting signals generated from electron-sample interactions. Its fundamental principle involves directing an electron beam from an electron gun, which, after being focused, performs a raster scan on the sample surface. Signals such as secondary electrons, backscattered electrons, absorbed electrons, Auger electrons, cathodoluminescence, and characteristic X-rays are detected to provide detailed information.

Scanning Electron Microscope/Environmental Scanning Electron Microscope is widely used to analyze clay minerals. These play a significant role in petroleum generation, migration, accumulation, and oil and gas exploration and development research. Scanning Electron Microscope provides direct visual information on the morphology and distribution of clay minerals, which is crucial for understanding their distribution within the reservoir and their impact on hydrocarbon migration.

Through the analysis of Scanning Electron Microscope, it is possible to identify hydrocarbon migration pathways, which are essential for comprehending the processes of hydrocarbon migration and accumulation within reservoirs. For instance, in a study of the Binnan Sag within the Zhanhua Depression, researchers determined various migration representation parameters. They calculated the "migration parameter change rate" to quantitatively establish the ranges of migration parameters associated with overpressure, buoyancy-driven, and mixed-driving forces. This approach effectively characterizes the driving forces, migration mechanisms, and boundaries involved in hydrocarbon migration processes [3].

Some scholars used the Scanning Electron Microscope to distinguish pore sizes between dolomite and limestone, providing insights into rock brittleness and fracture susceptibility [24]. This enables a more accurate assessment of reservoir pore structure, which is crucial for understanding hydrocarbon flow and distribution within the reservoir. Variations in pore size between different rock types (such as dolomite and limestone) can indicate reservoir storage characteristics and help determine which rocks are more favorable for hydrocarbon storage.

The advantage of the Scanning Electron Microscope lies in its ability to provide high-resolution images of surface morphology and microstructure, allowing researchers to visually observe and accurately measure the pore size, shape, and distribution in rock samples, thereby evaluating reservoir characteristics and rock brittleness. This technology is precious in the oil and gas industry, as it reveals rock fracture susceptibility, optimizes reservoir stimulation strategies, predicts hydrocarbon migration pathways, and enhances hydrocarbon recovery rates while reducing environmental impact. Scanning Electron Microscope thus serves as a powerful analytical tool for oil and gas exploration and development.

2.3. Geochemical tracing

The geochemical method for studying oil and gas migration is primarily based on analyzing the chemical composition of oil and gas, isotopic characteristics, and the evolution of organic materials to trace the source, migration process, and accumulation areas of oil and gas. By chemically analyzing source rocks, oil reservoirs, and fluid samples, geochemical methods can reveal the maturity, source type, and migration path of oil and gas. Specific chemical indicators, such as hydrocarbon distribution and stable carbon isotopes, help identify the evolutionary history of oil and gas. By comparing the chemical characteristics of different regions, the migration paths and accumulation areas can be inferred. In addition, gas composition analysis and isotopic comparison can effectively identify the mixing processes of oil and gas and their interactions with different rock layers. Organic geochemistry is a leading method in international geological research. Geochemical techniques allow researchers to track petroleum movement, which is crucial for reconstructing the history of hydrocarbon reservoir formation.

2.3.1. Saturated hydrocarbons and aromatic compounds

Saturated hydrocarbons and aromatic hydrocarbons can provide information on crude oil's thermal evolution and maturity parameters and could serve as biomarker tracers for hydrocarbon migration.

Saturated hydrocarbons

In saturated hydrocarbons, n-alkanes and terpene series compounds are often used as biomarkers for tracing hydrocarbon migration. The n-alkane series constitutes a major component of crude oil, accounting for approximately 15%–20% of the total oil volume, provided it has not been biologically degraded [19]. During migration, hydrocarbons experience a "geological color layer" effect; shorter-chain and lower molecular weight n-alkanes are more easily transported than longer-chain, higher molecular weight compounds such as nC28 and nC29, and tend to become relatively enriched in the migration direction. Some scholars suggested using the light hydrocarbon isomer ratios iC4/nC4 and iC5/nC5 to analyze the migration direction of oil and gas [20]. Some scholars found that the ratio (nC21 + nC22)/(nC28 + nC29) increases in the direction of oil migration [21]. In practical petroleum tracing applications, when the ratio of nC21/nC22 increases with decreasing depth, it indicates vertical migration from deeper to shallower layers. Among the numerous parameters of the terpene series, C29Ts/(C29Ts + 17α-C29-hopane), Ts/(Ts + Tm), and the ratio of tricyclic terpenes to [tricyclic terpenes + 17α(H)-hopane] are commonly used to trace petroleum migration and accumulation processes. In practical applications, these parameter ratios generally decrease with increasing migration distance [25]. Therefore, by extracting crude oil from reservoirs at different depths and analyzing its maturity parameters, the trends in these parameters across different layers can indicate the migration direction of petroleum within the conduits [25].

Aromatic compounds

Because the composition and structure of aromatic hydrocarbons change with maturity, different ratios of aromatic hydrocarbons can reflect variations in maturity. Some scholars have suggested that alkylated dibenzothiophene compounds, such as 4-

methyl dibenzothiophene (4-MDBT), 1-methyl dibenzothiophene (1-MDBT), 1,4-dimethyl dibenzothiophene (1,4-DMDBT), 2,4-dimethyl dibenzothiophene (2,4-DMDBT), and 4,6-dimethyl dibenzothiophene (4,6-DMDBT), can serve as molecular markers for tracing the direction and pathways of petroleum accumulation [26]. These parameters generally decrease with increasing migration distance [25].

Therefore, saturated hydrocarbons and aromatic hydrocarbons can serve as biomarkers for tracing hydrocarbon migration. Saturated hydrocarbons are characterized by their high stability and ease of preservation, with minimal environmental impact. In contrast, aromatic hydrocarbons are more susceptible to degradation by light, oxidation, and other factors, which can reduce their traceability. However, aromatic hydrocarbons can also be effective biomarkers under certain conditions.

2.3.2. Nitrogen-containing compounds

Nitrogen-containing compounds exhibit significant oil and gas migration fractionation effects. During migration, polar nitrogen-containing compounds interact with the surrounding rock surfaces, gradually decreasing their concentration. Consequently, the abundance ratios between different isomers may vary, making them useful indicators for hydrocarbon tracing. For example, some scholars observed that with increasing hydrocarbon migration distance, the isomer ratio of benzocarbazole [a]/([a] + [c]) gradually decreases [21]. Some scholars studied the fractionation effects in crude oil from the Puwei area of the Dongpu depression and found that the carbazole series becomes relatively enriched with increasing migration distance compared to the benzocarbazole series [27]. Additionally, shielded isomers become relatively enriched for carbazole molecules with increasing migration distance. However, in practical cases, extraction methods can affect carbazole compounds and may be unstable, sometimes failing to accurately indicate migration directions. In contrast, benzocarbazole is less affected by extraction methods and is more stable, providing a more accurate indication of hydrocarbon migration direction [28]. Therefore, depending on the characteristics of different types of hydrocarbons and geological conditions, appropriate nitrogen-containing compound indicators need to be selected for monitoring and analysis to enhance their application value and accuracy in the oil and gas industry.

2.3.3. Oxygen-containing heterocyclic aromatic compounds

The total amount of dibenzofurans can be used as a migration parameter for tracing reservoir charging pathways. Because the concentration of dibenzofurans is significantly higher in marine and terrestrial crude oils compared to nitrogen-containing compounds like carbazoles, dibenzofurans are generally considered to have better tracing effectiveness. This is especially true in light oils and condensate reservoirs with low non-hydrocarbon content, where the tracing effectiveness of dibenzofurans is superior to that of nitrogen-containing compounds [21].

2.3.4. In-situ minerals of the reservoir

Due to the effects of multi-source and multi-phase mixing and secondary alterations in some structurally complex basins, conventional organic geochemical indicators often struggle to pinpoint the organic geochemical records of each phase of crude oil migration. Since fluid types undergo organic-inorganic interactions with rocks and water in the formation during migration, accompanied by material exchange, analyzing the elemental and isotopic composition of diagenetic minerals in the reservoir can help reverse-engineer the hydrocarbon migration process. This offers a novel approach and methodology for hydrocarbon migration tracing research. For example, the carbon isotopic ratio of in-situ calcite formed by the participation of carbon dioxide in natural gas can indicate the maturity of the natural gas [29]. In practical applications, some scholars used the relationship between the carbon isotopic ratio of in-situ calcite and natural gas maturity, along with the corresponding carbon isotopic values of carbon dioxide in the Ordos Basin, combining the characteristics of gas generation and migration in this basin, to use the carbon isotopic values of in-situ calcite as a tracer for hydrocarbon migration [30,31]. The carbon isotopic ratio of calcite lightens with hydrocarbon migration [31].

2.3.5. Noble gas isotopes

With its simple composition, natural gas presents challenges in studying its migration process. The common approach is to investigate its migration by examining its compositional characteristics and carbon isotope features. Although noble gases are present in deficient concentrations in natural gas, they contain valuable geochemical information. The concentration of noble gases in natural gas depends on two processes: Mineral release and fractionation during the gas migration process. During migration, lighter noble gases move faster than heavier ones, increasing the light/heavy noble gas ratio (such as $^{4}He/^{40}Ar$, $^{20}Ne/^{36}Ar$) with increasing migration distance, making these ratios useful for tracing natural gas migration [32]. For example, some scholars used the light/heavy noble gas ratio in natural gas to trace the migration process of natural gas in the western Sichuan Basin depression [33]. They found that the $^{4}He/^{40}Ar$ ratio is only effective for analyzing natural gas migration when the migration distance is significant, as the difference between ^{4}He and ^{40}Ar is not noticeable over shorter distances [34]. Additionally, they noted that for gas sourced from the crust, the $^{3}He/^{4}He$ ratio depends on the amount of ^{4}He. When minerals release ^{4}He, which migrates with the natural gas, the $^{3}He/^{4}He$ ratio decreases with increasing migration distance, while $\delta^{13}C_1$ generally decreases with migration distance [35].

2.3.6. Unconventional isotopes

In recent years, the fields of petroleum geochemistry and petroleum systems have rapidly developed under the guidance of new technologies, methods, and approaches, playing a significant role in the exploration and development of deep, unconventional, and complex oil and gas reservoirs [36]. Among these, unconventional isotope systems such as metal isotopes (non-traditional stable isotopes), halogen isotopes, and high-dimensional stable isotopes (cluster isotopes, triatomic isotopes, polysulfur isotopes, and intramolecular isotopes) have garnered significant attention in academia and have become one of the fastest-growing areas in geochemistry. Traditional isotope techniques are continuously updated, with C, H, O, S, and N isotope series analysis remaining central. Meanwhile, halogen and Si isotope analysis technologies are advancing rapidly. The dating techniques for reservoir formation have entered a new phase of precise age determination, and new organic chemical analysis techniques have made the identification of new compounds possible, providing new clues for the study of petroleum genesis.

Metal isotopes, such as Mo, Fe, Cu, and Zn, are primarily used in petroleum geochemistry to trace sedimentary environments and the physicochemical conditions during petroleum generation. For example, Mo isotopes can indicate the redox conditions of ancient oceans, which is crucial for understanding organic matter preservation and petroleum formation.

Halogen isotopes, particularly those of Br and I, can be used to trace the migration pathways and sources of oil and gas. These elements may undergo isotopic fractionation during the migration process, so analyzing the halogen isotopic composition in reservoirs can provide insights into the migration history and sources of the oil and gas.

High-dimensional stable isotopes, such as clumped and triple oxygen, can provide direct information on environmental parameters like temperature, pH, and redox conditions. These isotope systems hold potential value for studying the physicochemical conditions involved in generating and migrating oil and gas.

2.3.7. Fluid inclusions

Fluid inclusions are fluids trapped within mineral crystals during mineral formation, preserved in lattice defects or cavities, with no exchange of substances with the external environment, and the original physical properties of the medium remain unchanged. This independent, closed system is known as a fluid inclusion [37]. During the migration, accumulation, and formation of oil and gas, trace amounts of fluid may be captured to form fluid inclusions. These trapped fluid inclusions contain information about the temperature, pressure, and composition during oil and gas migration and filling. Utilizing this information can provide strong evidence for reconstructing reservoir paleotemperatures and paleopressures, determining the timing of oil and gas migration and accumulation, and delineating the stages of reservoir formation [38].

Oil and gas inclusions are primary records of oil and gas migration. In regions where fluid inclusions develop, studying the distribution direction and periods of inclusions filled in structural mineral veins or fractures can infer the dynamics and relative timing during oil and gas accumulation. This helps in the simulation of oil and gas migration directions and pathway systems. Using fluid inclusions to calculate paleofluid potentials can address the limitations of traditional methods, potentially providing insights into the migration, evolution, and accumulation of oil and gas over long geological periods [39]. Some scholars used fluorescence spectroscopy and geochronology analyses of primary and secondary oil-bearing inclusions from the Fuman Oilfield in the Tarim Basin to determine that there were three phases of crude oil injection and one phase of natural gas injection [40]. This understanding of how oil and gas migrate from source rocks through various geological structures (such as faults and fractures) to reservoirs helps reveal the migration pathways and methods of oil and gas.

2.3.8. Surface geochemistry

Surface geochemistry is the study of the chemical characteristics of the Earth's surface and their relationship with subsurface geological activities. In oil and gas exploration, it identifies potential hydrocarbon reservoirs by detecting chemical traces, such as hydrocarbons and trace elements, that migrate from underground reservoirs to the surface. Common techniques include soil gas analysis, trace element analysis, and microbiological surveys. Surface geochemistry complements other geophysical and geological methods, enhancing the accuracy of subsurface resource exploration [41].

Surface geochemical exploration techniques can be used to detect active hydrocarbon micro-leaks from deep oil and gas reservoirs. The results of such detections help identify prospective areas in new and mature basins. By analyzing surface geochemical anomalies, the scope of research areas can be significantly narrowed, allowing more expensive exploration technologies, such as 3D seismic surveys, to be focused on the most likely locations for hydrocarbon accumulation and potential reservoirs within the basin. For example, some scholars applied microbiological geochemical exploration techniques in the exploration of oil and gas in the Bayanhushuo fault depression and found a good correspondence between microbial anomalies and hydrocarbon-bearing structural units [42].

In oil and gas migration studies, surface geochemistry offers significant advantages. It can provide early detection clues, reduce exploration costs, and supplement information from other geological methods, thereby enhancing overall exploration accuracy. Additionally, surface geochemistry has minimal environmental impact, is suitable for various geological environments, and offers high flexibility. It can also dynamically monitor chemical changes during the oil and gas migration process. These advantages make it a powerful supplementary tool in oil and gas exploration.

As the complexity of oil and gas exploration targets increases, the demand for oil and gas geochemistry research has become even more pressing. Developing and applying new technologies is a critical mission for future oil and gas geochemistry and petroleum system sciences researchers. These advancements drive progress in the field and provide scientific support for sustainable development and utilization of global energy resources. Geochemical tracing can offer high-resolution information, enabling the identification and tracking of oil and gas migration paths at the microscopic scale, which is highly beneficial for understanding the sources and migration mechanisms of oil and gas. It provides direct evidence for oil and gas migration, which can be used to validate and supplement geological and geophysical data, thereby enhancing our understanding of the migration processes. However, interpreting geochemical data can be highly complex, as various geochemical changes, such as biodegradation, water washing, and thermal maturation, may occur during migration, potentially masking or altering the original chemical markers. In actual petroleum systems, oil and gas may originate from multiple source rocks and may undergo mixing during migration. This multi-source mixing can make it challenging for geochemical tracers to distinguish the contributions of individual source rocks.

2.4. Numerical simulation method

The principle of numerical simulation methods in studying oil and gas migration mainly involves creating mathematical models to simulate the generation, migration, and accumulation processes of oil and gas in the subsurface. These models are based on principles of rock physics, fluid dynamics, and thermodynamics, and numerical methods are used to solve the flow behavior of oil and gas under various geological conditions. Factors such as porosity, permeability, pressure gradients, and temperature changes are considered as they determine the migration paths and rates of oil and gas. Numerical simulations track the dynamic migration of oil and gas over time and space, helping to predict future distribution and migration trends. Moreover, numerical simulation can integrate geological, geophysical, and geochemical data for a more comprehensive analysis, providing more accurate predictions of oil and gas migration, which in turn supports decision-making in exploration and development. Since the migration of oil and gas within a basin cannot be directly observed, it can only be indirectly confirmed through various methods or simulated using modeling techniques [43]. The numerical simulation method utilizes computer science and technology to incorporate geological structures, the physical properties of underground reservoirs, fluid dynamics, and chemical reactions into mathematical models [43]. This method simulates the movement of subsurface fluids, analyzes the impact of various factors on the migration and accumulation of oil and gas, and provides predictions and optimizations.

2.4.1. Basic steps of the numerical simulation method

The numerical simulation method employs computer-based mathematical modeling to simulate reservoirs, wellbores, formations, and other geological features, enabling predictions of their behavior, changes, and productivity under various conditions to facilitate efficient resource development and management. Typically, this process begins with constructing an accurate geometric model of the geological structure, encompassing the reservoir, wellbore, and strata. This model is designed to capture the detailed physical properties of the subsurface reservoir, such as porosity and permeability, translating the complexity of the geological structure into mathematical language to establish a foundation for subsequent numerical calculations. However, in practical applications, it is often necessary to conduct comprehensive research on hydrogeology, hydrodynamic environment, fluid characteristics, and the chemistry of oil and gas migration [43]. Some scholar’s studies on the dynamics model and numerical simulation of oil and gas migration in compacted basins used numerical simulation technology to establish a migration dynamics model for the third member of the Shahejie Formation, providing numerical methods for simulating paleo hydrodynamics, paleo-fluid potential, migration speed, and history [44]. This model describes the hydrodynamic sources within unit control volumes in the carrier layer, which are primarily composed of dewatering from the compaction of overlying and underlying mudstone layers, with the underlying mudstone compaction being the main contributor [44]. The stagnant flow zones formed by the overlying and underlying mudstone layers create ineffective hydrocarbon expulsion zones, with their thickness influenced by various factors. The mudstone layers provide hydrodynamic forces and serve as seepage boundaries, ensuring the unidirectionality and irreversibility of vertical fluid flow.

Next, it is necessary to establish the boundary conditions for the model, including the inflow and outflow of fluids, as well as variations in pressure and temperature. The specification of boundary conditions is crucial for the accuracy of the simulation, as they define the external constraints of the model. Additionally, selecting appropriate material constitutive models is essential for accurately describing the flow behavior of oil and gas within the reservoir. These models include Darcy's law and non-Darcy flow models, which characterize the movement of fluids in porous media. Physical parameters, such as oil and gas density, viscosity, and water content, along with fluid parameters like compressibility and thermal conductivity, are vital for simulating oil and gas migration. These parameters must be obtained from experimental data and set accurately within the model.

Subsequently, model validation and simulation predictions are carried out. Known subsurface information is input into the mathematical model for calculation, and the results are compared with actual conditions to confirm the model's accuracy and reliability. Model validation is performed either in the laboratory or in the field. The validated mathematical model is then used to simulate different scenarios, such as optimizing recovery methods, analyzing source-sink relationships, and characterizing spatial effects within the reservoir. This process helps to identify the spatial distribution patterns of sedimentary rock reservoirs and includes data related to seismic rays. As a result, predictions can be made regarding oil and gas abundance, production rates, and extraction effectiveness under various conditions, providing guidance and scientific basis for oil and gas exploration and development.

To ensure the accuracy of the simulation results and computational efficiency, a grid sensitivity analysis is performed. This analysis determines the most suitable grid size to balance computational resources and simulation precision. By varying the grid size and observing its impact on the results, the optimal grid configuration can be identified.

Finally, model optimization is performed. Based on the simulation results, the deviations and errors in the study are analyzed and compared, and the mathematical model is refined accordingly, with continuous optimization. This process encompasses parameter optimization, mathematical formula optimization, and more. Parameter optimization is a crucial step in enhancing simulation accuracy. Physical and mechanical parameters are adjusted through parameter sensitivity analysis and optimization algorithms to minimize discrepancies between model predictions and actual data. This may involve an iterative process to identify the best combination of parameters. Additionally, optimizing mathematical formulas may be necessary to improve simulation accuracy, which could involve refining existing mathematical models or developing new ones to better capture the complexities of hydrocarbon migration. The optimized formulas could provide more accurate predictive results.

The integration of experimental data and numerical simulations is key to enhancing the accuracy of model predictions. By incorporating experimental results into the numerical model, calibration and optimization can be achieved, ensuring that the model accurately reflects actual geological conditions and hydrocarbon migration behavior. This approach provides more reliable guidance and scientific support for oil and gas exploration and development.

2.4.2. Application of software tools

COMSOL Multiphysics

COMSOL means COMputational Modeling and Simulation Language. COMSOL Multiphysics is a powerful multiphysics simulation software capable of simulating various physical processes such as fluid dynamics, heat transfer, and electromagnetism. In hydrocarbon migration simulations, COMSOL can model the flow of oil and gas within reservoirs, including multiphase flow and reactive transport processes. Its strengths lie in handling complex geometrical structures and boundary conditions, providing flexible model setup and post-processing capabilities.

FLAC3D

FLAC3D (Fast Lagrangian Analysis of Continua in 3 Dimensions) is a three-dimensional geological engineering simulation software widely used in geomechanics and mining engineering. In the oil and gas sector, FLAC3D can simulate the stress-strain behavior of oil and gas reservoirs, predicting rock deformation and failure during extraction processes. Its advantages include the ability to handle complex geological conditions and nonlinear material behavior, providing dynamic boundary condition simulations.

PFC

PFC (Particle Flow Code) is a software based on the Discrete Element Method used to simulate the physical behavior of particulate materials. In hydrocarbon migration research, PFC can investigate particle flow and changes in pore structure within reservoirs, which is crucial for understanding the transport mechanisms of oil and gas in porous media. PFC's strengths include simulating interactions and dynamic behavior among particles, offering deep insights into changes in the microstructure of reservoirs.

CMG IMEX

CMG IMEX (Computer Modelling Group) is a reservoir simulation software specifically designed to model the development processes of oil and gas reservoirs. It can handle complex fluid flow within reservoirs, including black oil, compositional, and thermal recovery models. The advantage of IMEX (Implicit-Explicit) is its ability to simulate multiphase flow and phase change processes in reservoirs, providing optimization analysis for development strategies.

These software tools each have their strengths in hydrocarbon migration simulations, and their combined use can provide a comprehensive understanding of reservoir behavior, thereby offering strong technical support for oil and gas exploration and development. Through these tools, researchers can predict the responses of oil and gas reservoirs, optimize extraction strategies, and assess development risks.

2.4.3. Advantages and limitations of numerical simulation methods

Numerical simulation methods can model oil and gas reserves, flow patterns, and other metrics under various conditions in a relatively short time, helping professionals make quicker decisions and adjustments. The simulation process can efficiently and rapidly analyze and improve design plans, increasing resource utilization and reducing development costs. The ongoing advancements in computer technology have enhanced numerical simulations' reliability, accuracy, and practical value. Additionally, numerical simulation methods allow for parameter variation and sensitivity analysis of different influencing factors, providing more real-time model results to support subjective judgment.

At the same time, numerical simulation methods also have some limitations. These methods are based on mathematical modeling and involve complex theoretical calculations, requiring extensive physical formulas and computational models [45]. As a result, the quality and accuracy of the data and its sources directly impact the effectiveness of the simulation results. For more complex sedimentary rock formations and oil and gas migration processes, simplifications in the model can lead to omitting many real-world factors. Therefore, other measurements or experimental methods must be used to ensure the simulation results' reliability and applicability. Moreover, the models and computer equipment used in numerical simulations are constantly evolving, and their precision, simplicity, and applicability have their own limitations. They often need to be adapted to exploration objectives and conditions, and with improved data quality, more complex formulas may be required. Thus, it is necessary to carefully consider which methods are most suitable for specific situations. Addressing these issues is crucial for further improving and developing numerical simulation technology.

2.5. Geophysical methods

The principle of geophysical methods in studying oil and gas migration mainly involves analyzing the porosity, permeability, structural features, and spatiotemporal characteristics of migration in subsurface layers. Seismic, magnetic, and other techniques are used to infer the porosity and permeability of the strata, which affect the storage and migration capabilities of oil and gas. At the same time, geophysical methods can identify structural features, such as faults and folds, which have a significant impact on the migration and accumulation of oil and gas. Additionally, by monitoring the spatiotemporal variations in subsurface physical fields, geophysical methods can reveal the migration pathways and dynamics of oil and gas, providing crucial information about the migration process.

Geophysical methods utilize sound waves (such as logging techniques), electromagnetic waves (such as electromagnetic exploration), gravity, and magnetic fields (such as gravity and magnetic exploration techniques) to detect changes in the physical properties within hydrocarbon reservoirs. These methods can obtain key parameters about underground reservoirs, including density, acoustic velocity, dielectric constant, and resistivity, which can be used to infer information about oil and gas reserves, production, and permeability. These integrated detection technologies provide crucial support for the effective assessment of hydrocarbon resources.

Logging techniques provide detailed information about formation properties by directly measuring physical parameters in boreholes, such as resistivity, acoustic velocity, and radioactivity levels. This data is crucial for understanding the distribution and flow characteristics of oil and gas within reservoirs, particularly in assessing reservoir porosity, permeability, and fluid types [46]. Acoustic time delay is a typical geophysical method that refers to the time required for acoustic waves to travel a unit distance, usually expressed in microseconds per foot (μs/ft) or microseconds per meter (μs/m). During the compaction process of sediments, as depth increases and overlying pressure grows, the sediments' porosity gradually decreases, and the contact between particles becomes more compact, increasing the speed of acoustic wave propagation [47]. This change can be measured by acoustic logging, which records the propagation time of acoustic waves in the formations around the wellbore. According to the theory of oil phase migration, when the oil saturation in an overpressured layer within under-compacted mudrock reaches the critical value for two-phase migration, the oil phase tends to migrate from the mudrock to the reservoir. Compaction curves can effectively reveal the characteristics of these under-compacted mudrock zones. Under-compacted mudrock typically exhibits abnormally low velocities, and according to a large amount of well data collected, the greater the degree of undercompaction, the higher the formation pressure and the more favorable it is for oil and gas migration [47]. Therefore, acoustic time delay data can be used to determine the vertical and areal distribution characteristics of under-compacted mudrock, combined with dynamic analysis methods, which can be used to study oil and gas migration.

Seismic exploration technology provides high-resolution images of underground geological structures by analyzing the reflection and refraction responses of seismic waves. This is particularly useful for identifying the location, size, and shape of oil and gas reservoirs, especially in areas with complex geological formations. For example, seismic data and related attributes can be used to study the close relationship between features such as "gas chimneys", hydrocarbon leakage paths, shallow gas, and seabed anomalies [48]. A "gas chimney" refers to a phenomenon where, after the pressure balance in a source rock or early trap is disrupted, fluid leakage through the overlying strata creates uneven gas accumulation and carries materials, appearing as a chimney-like structure in seismic data. Permeable conduits show strong seismic amplitudes on seismic data. Through comprehensive interpretation of seismic data, "gas chimneys" serve as migration pathways in the vertical direction, transporting fluids to overlying reservoir units and creating good gas reservoirs around and at the top of the gas chimney zone.

Magnetic exploration technology detects subsurface rock magnetic differences by measuring local variations in the Earth's magnetic field. This method is particularly effective for identifying geological structures that may contain oil and gas, especially in complex terrains such as the Loess Plateau [49]. In the Wu Ba-Dan Ba area of northern Shaanxi, high magnetic residual anomalies show a certain correlation with oil well distribution, particularly with high-frequency, low-amplitude anomalies and high-value annular anomalies surrounding low-value zones, which correlate well with oil and gas reservoirs. This finding demonstrates the potential of magnetic surveying methods in identifying and predicting oil and gas reservoirs, providing an economical, rapid, and effective exploration tool beyond seismic methods. Both aeromagnetic survey and rock magnetic survey are forms of magnetic exploration that play significant roles in oil and gas migration research. Aeromagnetic surveys can reveal information about subsurface magnetic geological bodies. For example, in oil and gas resource exploration in the southwestern Tarim Basin, high-precision UAV (Unmanned Aerial Vehicle) aeromagnetic survey data have been used to examine the basin's basement structure, the distribution and characteristics of depressions, major fault structures, and how these features control oil and gas migration and accumulation. Such data help identify hydrocarbon migration pathways and potential reservoirs [50]. Rock magnetic survey, on the other hand, focuses on the magnetic properties of rocks, which can reveal information about rock composition, structure, and geological history. For instance, magnetic survey methods are used to identify reservoirs in oil and gas exploration in northern Shaanxi. Studies have shown that hydrocarbon seepage can alter the redox conditions above reservoirs, leading to changes in the magnetic properties of minerals in the overlying strata, thereby producing magnetic anomalies near the surface. These magnetic anomalies, once processed, can provide micro-magnetic anomalies highly correlated with hydrocarbon reservoirs [51]. Therefore, combining data from airborne magnetic exploration and rock magnetometry allows for more effective oil and gas exploration and resource assessment, providing a scientific basis for simulating and tracking hydrocarbon migration pathways.

Gravity exploration technology detects subsurface mass distribution irregularities by measuring slight variations in the gravitational field. This is significant for discovering geological structures with substantial density changes, such as salt domes and oil and gas reservoirs [52]. For instance, in the Ordos Basin’s Sulige gas field, researchers have used microgravity monitoring technology to describe the distribution of residual gas during the gas reservoir development process and assess the recoverable potential of the remaining gas [53].

Geophysical methods have significant advantages in studying oil and gas migration. Geophysical exploration can cover large underground areas, providing macroscopic information about underground structures and oil and gas distribution. It offers detailed images of subsurface structures, aiding in identifying migration paths and potential oil and gas reservoirs. Additionally, various types of data, such as seismic, gravity, magnetic, and electrical data, can be provided, and their comprehensive analysis helps in a more thorough understanding of oil and gas migration mechanisms. However, interpreting geophysical data often requires specialized knowledge and experience, as the data may be affected by various factors such as geological noise and instrument errors and may not perform well under certain geological conditions like complex fault zones or deep exploration. Furthermore, geophysical methods require expensive equipment and skilled personnel, making them relatively costly, especially for large-scale or deep exploration. Additionally, some geophysical exploration methods, such as seismic exploration, can generate noise pollution, which is detrimental to sustainable development.

This paper reviews various methods for studying oil and gas migration, including sedimentological methods, geochemical tracing, numerical simulation, and geophysical methods, and summarizes their characteristics, advantages, and disadvantages. These methods are detailed in **Figure 1**.

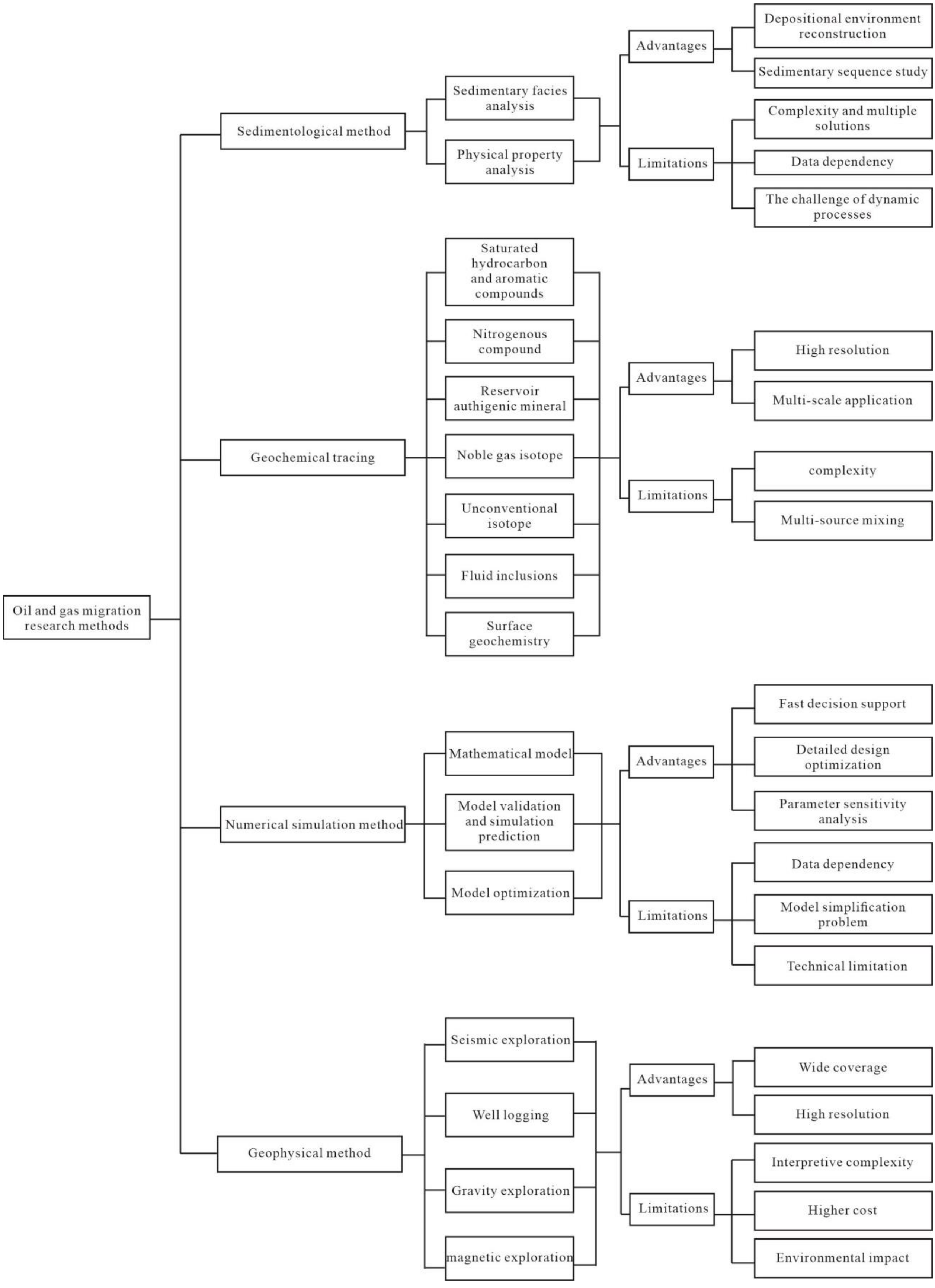

Figure 1. Study methods for exploring oil and gas migration.

3. Frontier trends and future prospects of oil and gas migration technologies

This paper reviews the cutting-edge technologies for oil and gas migration, explores future opportunities and challenges, and aims to improve the accuracy of oil and gas migration analysis in future exploration efforts. By enhancing resource utilization efficiency and reducing the environmental impact of oil and gas exploration, this work seeks to contribute to the sustainable development of the energy industry.

3.1. Frontier trends

3.1.1. Artificial intelligence methods

Artificial intelligence (AI) methods have powerful knowledge-learning, association, self-organization, and adaptation capabilities. Their applications in oil and gas migration research can mainly include the following three aspects:

- Data processing and analysis: AI methods can handle large volumes of seismic data, well measurements, and production data, extracting useful information to understand the patterns of oil and gas migration.
- Model building and optimization: AI algorithms can be used to develop predictive models for oil and gas migration, allowing for accurate predictions of migration states and thereby reducing exploration costs and improving efficiency.
- Anomaly detection: AI methods can be used to identify unusual patterns in oil and gas migration, enhancing the efficiency of detecting potential oil and gas reservoirs.

Artificial neural network (ANN) is a commonly used AI model in oil and gas migration research. They typically consist of an input, hidden, and output layer [54]. The network performs two main processes: Learning and evaluation/prediction [54]. The learning process includes forward propagation and backward propagation. During forward propagation, inputs are processed through the network to produce outputs. Backward propagation, on the other hand, is a correction process where errors are compared, and weights (connection strengths) are adjusted based on these errors. The evaluation/prediction process uses the trained network to solve and output values for given input nodes. For example, ANN models can be applied to simulate oil and gas migration and accumulation [54]. A three-dimensional gridding method can be employed to convert heterogeneous oil and gas migration and accumulation media into a finite number of homogeneous units. The criteria for this gridding are to reflect lithological and facies changes, as well as local traps in the horizontal direction, and to represent the structural development process and other geological features in the vertical direction. Data required for each unit includes initial hydrocarbon quantities, medium properties and characteristics, and driving forces. Initial hydrocarbon quantities can be obtained through traditional hydrocarbon depletion dynamics simulations while driving forces can be determined using classic dynamic methods. Medium properties and characteristics can be quantitatively obtained through three-dimensional structural and stratigraphic non-dynamic simulations. The process flow of oil and gas migration and accumulation simulation based on ANN models is illustrated in **Figure 2**.

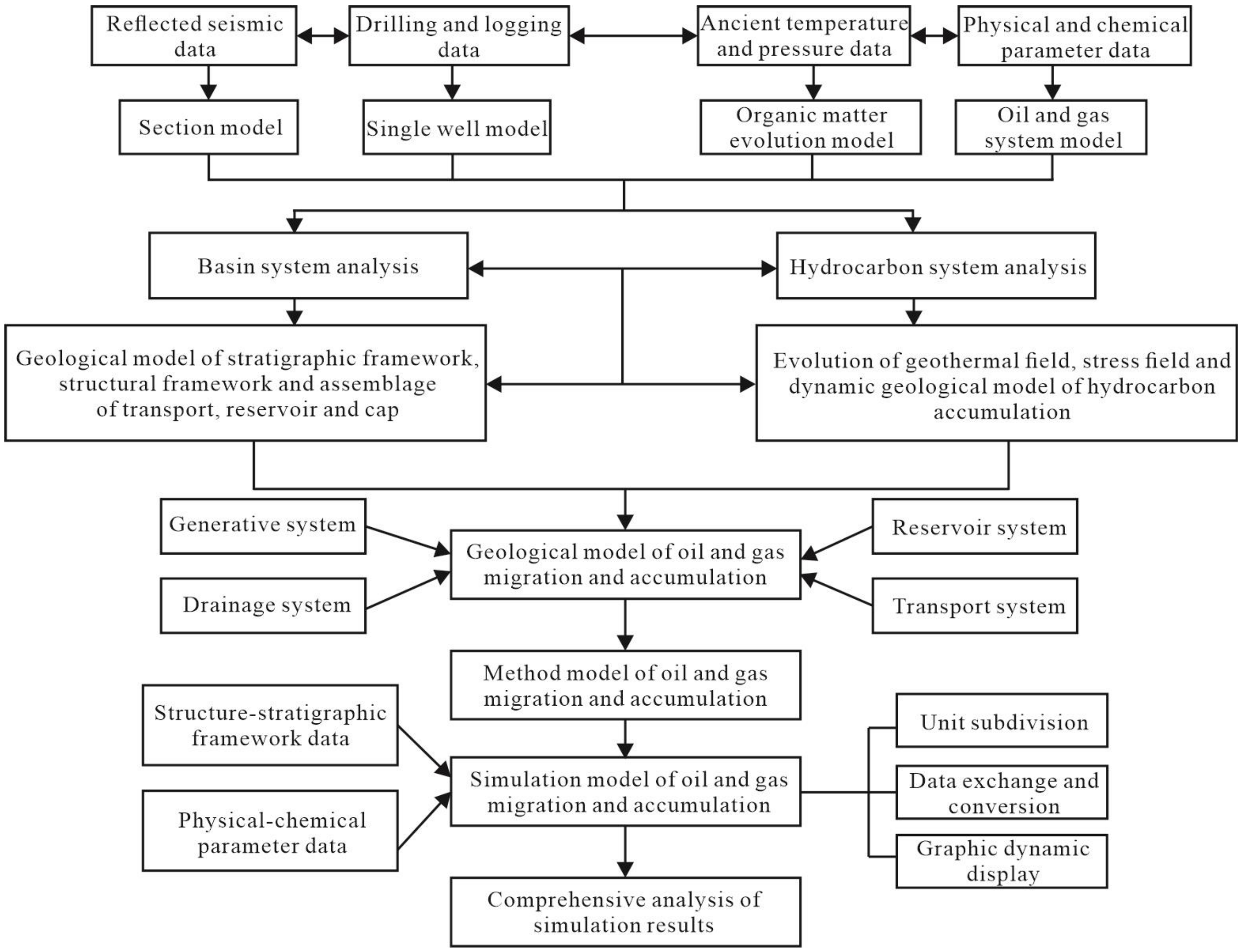

Figure 2. The process flow of oil and gas migration and accumulation simulation based on ANN models [54].

3.1.2. Digital oilfield

With the advancement of modern information technology, the oilfield industry is at a critical juncture for transformation and development. The rise of digital oilfields represents a cutting-edge application in oil and gas migration research. It plays a crucial role in the precise management and efficient utilization of oil and gas resources by integrating advanced technologies such as the Internet of Things (IoT), big data analytics, cloud computing, and AI.

Digital oilfields can use IoT technology to achieve real-time monitoring of reservoir pressure, temperature, and other parameters, providing real-time data on oil and gas migration. Under IoT technology, the various functional modules of an oilfield can develop intelligently based on the internet, enabling real-time interaction and communication between objects and between people and objects. All objects and corresponding functional modules within the IoT can act as independent information terminals, which can be freely combined to form a relatively complete information network system that meets specific requirements [55]. This improves the efficiency and accuracy of oil and gas migration research and lays a solid foundation for the intelligent and automated management of oilfields. The digital oilfield system makes remote monitoring and control of the oilfield possible, reducing the need for on-site operations and lowering labor costs and safety risks. Remote data acquisition systems are the collection layer in the digital oilfield architecture and represent a core application scenario of IoT technology in the digital construction of oilfields [55]. Remote monitoring systems can respond in real time to oil and gas migration anomalies, taking timely measures to prevent accidents. Digital oilfields also achieve data integration by consolidating various data sources (such as seismic data, production data, and environmental data), providing a comprehensive understanding of oil and gas migration conditions.

The digital construction of oilfields is a long-term, systematic project. Relevant technical personnel should continue optimizing the platform during its usage phase, constantly improving data processing, enterprise management, and production service integration capabilities [56]. Digital oilfields, by integrating advanced information technologies and automation systems, not only help predict the distribution and flow paths of oil and gas and optimize exploration and development strategies but also enhance the depth and efficiency of research through intelligent analysis and decision support. With ongoing technological advancements, the potential of digital oilfields can be further explored.

The construction of digital oilfields is a complex process involving integrating multiple technologies, with the core goal of achieving digital and intelligent management of oilfields. By leveraging big data and AI, new methods and algorithms for reservoir modeling are developed, leading to intelligent geological modeling techniques that enhance modeling efficiency and accuracy. Research on intelligent numerical simulation technology for reservoirs aims to overcome the bottleneck of automated historical fitting and to develop a new generation of numerical simulators for wellbore and surface processes, improving the level of automation and intelligence in reservoir numerical simulations and supporting automated optimization of development plans. Based on the achievements in oil and gas production information technology, research is conducted on the construction of integrated "digital twins" for reservoirs, wellbores, and surface operations to enhance visual monitoring capabilities. Additionally, technologies for risk early warning in the oilfield development and production process are explored, enabling the prediction of risks associated with indicator changes, production fluctuations, safety and environmental protection, and reservoir management.

3.1.3. Geological big data analysis

Big data technology has been applied in many fields and has received widespread attention. It was also initially implemented in the geological and mineral sectors, providing technical support for geological exploration, mineral resource planning, and mineral reserve assessment [57]. Geological big data integrates and analyzes vast and multidimensional geological data, offering strong support for revealing oil and gas migration patterns in complex underground environments.

On the one hand, big data analysis can identify patterns and trends in oil and gas migration and predict future migration paths [58]. For example, using resistivity logging technology in conjunction with big data analysis of formation characteristics can help understand changes in formation conductivity and analyze mineral content, thereby determining oil and gas migration paths [59]. Additionally, geoscience big data visualization enables a more intuitive, clear, and comprehensive understanding of the data, facilitating direct analysis and interpretation [60]. This helps reveal spatial distribution characteristics [61,62], temporal evolution patterns [63,64], and interrelationships within the data, providing strong evidence for understanding oil and gas migration phenomena and processes [60].

On the other hand, big data analysis can accurately assess potential risks encountered during oil and gas exploration and help develop timely response strategies [58,65]. Information on formation permeability, porosity, and leakage can be obtained by analyzing the formation's physical properties combined with big data. This allows for a detailed and accurate description of leakage conditions in the project report to avoid accidents [59]. For example, oilfield personnel can use big data technology for intelligent operation and facility management, performing real-time analysis and monitoring to prevent facility damage or failures during operations [66]. Additionally, the results of big data analysis can be used to optimize exploration and development decisions, improving resource utilization efficiency [66].

In exploring oil and gas migration, the integration and fusion of geoscience big data face several challenges, including unclear data sharing mechanisms, dispersed data management, obstacles in data exchange between systems, insufficient updates and maintenance, and a lack of unified data sharing plans and regulations. These factors result in difficulties in integrating and merging heterogeneous data sources, creating "data silos" that severely hinder comprehensive analysis and in-depth exploration of big data and restrict its application in geoscience research [60]. To overcome these barriers, it is necessary to establish more open and collaborative data-sharing mechanisms, strengthen data management and maintenance, and develop unified data-sharing plans and regulations to promote the effective use of big geoscience data and advance research on oil and gas migration.

Applying geological big data technology in future oil and gas migration studies should focus on several aspects. First, big data technology can be utilized to analyze the geological conditions of exploration areas, such as the development of major and minor faults in different structural belts and stratigraphic levels. Second, big data technology can be applied in processing seismic exploration data, where attribute extraction from seismic data helps improve interpretation capabilities, providing more accurate geological information for oil and gas migration. Finally, optimal parameters for characterizing oil and gas migration can be identified through geological big data analysis, offering theoretical support for understanding the mechanisms of oil and gas migration [67].

3.1.4. High-precision seismic imaging technology

Supported by high-precision seismic imaging technology, oil and gas migration research is steadily deepening. High-resolution seismic imaging technology plays a critical role in enhancing the understanding of oil and gas reservoir structures, porosity, and permeability. Applying 3D seismic imaging, 4D seismic imaging, and multi-wave seismic imaging provides more detailed images of subsurface oil and gas reservoirs' structures and dynamics [68]. These advancements facilitate the identification of migration pathways and reservoir characteristics, monitoring dynamic changes in oil and gas migration, and optimizing development strategies. For example, some scholars used high-precision seismic imaging technology to study the Avatite area in the Kuqa Depression [69]. This region is characterized by significant surface elevation changes and highly complex underground structures, making accurate imaging difficult with traditional methods [69]. Using techniques such as near-surface pre-stack depth migration significantly improved the imaging quality of seismic data, laying a solid foundation for subsequent geological interpretation and oil and gas exploration. Some scholars focused on key technologies for processing deep-water seismic data in the South China Sea, including ghost wave suppression, pre-stack high-fidelity denoising, and full waveform inversion for high-precision velocity modeling, achieving good results in practical applications [70].

High-precision seismic imaging technology significantly enhances our understanding of the structure, porosity, and permeability of oil and gas reservoirs, which is crucial for studying the migration of oil and gas. For instance, the research team at the Institute of Precision Measurement Science and Technology Innovation of the Chinese Academy of Sciences has made new progress in high-resolution oil and gas exploration seismic amplitude preservation imaging. They have utilized multidisciplinary theories and methods such as artificial intelligence, scattered wave fields, and point spread functions to propose high-precision artificial intelligence velocity modeling, inverse scattering amplitude preservation imaging conditions, and point spread function depth domain inversion technology. These technologies provide new ideas for solving the challenges of reservoir feature inversion and prediction under deep and complex geological conditions. Accurate velocity models play a key role in high-precision seismic imaging, and deep learning methods are used to approximate nonlinear mapping functions between different data domains, thereby solving the problem of efficient velocity modeling for raw seismic data [71–75].

In addition, research progress in the characterization technology of unconventional reservoir pore structures has shown that various methods, such as nitrogen physical adsorption and mercury intrusion, are used to characterize the pore size distribution of Fluid Catalytic Cracking catalysts, and these technologies are also applicable to the characterization of oil and gas reservoir pore structures [76]. The application of fractal theory in the study of the characteristics of unconventional oil and gas reservoir pore structures further provides new methods for characterizing pore structures [77]. The advancement of these technologies enables us to more accurately identify the microstructure of oil and gas reservoirs, predict permeability, and better understand the mechanisms and pathways of oil and gas migration.

Through these technologies, researchers can construct more precise geological models, predict the direction and efficiency of oil and gas migration, optimize exploration and development strategies, and thereby improve the efficiency and yield of oil and gas resource development.

3.2. Future prospects

3.2.1. Opportunities

Data fusion and intelligent analysis

With advancements in high-resolution seismic imaging, digital oilfields, and IoT-enabled monitoring, the integration of data from geological, geochemical, geophysical, and numerical simulations has become increasingly feasible. This trend addresses inherent limitations in current methodologies, such as the reliance on single-dataset interpretations, which may fail to capture the full complexity of hydrocarbon migration processes. Traditional methods often depend on isolated data sources that limit the spatial and temporal resolution of predictions, resulting in uncertainties and less adaptable models.

Data fusion, combined with AI-driven analysis, represents a future-oriented solution by enabling sophisticated pattern recognition across diverse datasets, revealing interrelationships previously undetectable by conventional approaches. AI algorithms can manage and interpret complex, high-dimensional data, quantify uncertainties, and filter out noise, which significantly improves the precision and reliability of predictions. By developing integrated data processing platforms, the industry can consolidate multiple data types into a cohesive model, improving its comprehensive analytical capabilities. This approach not only enhances the accuracy of hydrocarbon migration predictions but also allows researchers to adapt models in near real-time, fostering a more dynamic understanding of subsurface conditions.

Overall, data fusion and AI-powered analysis are emerging as frontier trends because they address the need for high-resolution, adaptive, and multi-scale insights into hydrocarbon migration, which are critical for efficient exploration and production in increasingly challenging geological environments.

High-resolution detection technology

High-resolution detection technology is shaping up to be a critical trend in hydrocarbon migration research, addressing fundamental limitations of existing methods. Traditional exploration approaches, while useful, often suffer from limited spatial and temporal resolution, restricting our ability to capture the nuanced variations in subsurface properties essential for accurate hydrocarbon migration modeling. Conventional seismic methods may lack the precision to discern smaller-scale geological structures, and they often provide limited information on dynamic changes in reservoirs over time, which are crucial for predicting migration pathways and reservoir behavior.

Emerging high-resolution detection technologies—such as advanced seismic imaging, full-waveform inversion, and 4D seismic monitoring—allow researchers to achieve far greater detail in subsurface imaging. These methods enhance spatial resolution, revealing fine-scale heterogeneities within reservoirs and migration paths that were previously undetectable. They also improve temporal resolution, enabling dynamic tracking of fluid movement. These advances are essential as they offer a more precise understanding of reservoir structure, pore connectivity, and permeability variations, which are key to modeling complex migration mechanisms.

High-resolution imaging combined with real-time monitoring capabilities allows for adaptive exploration and production strategies, reducing uncertainties and optimizing recovery rates in increasingly challenging environments. By pushing the boundaries of spatial and temporal resolution, these technologies provide a much deeper and more reliable foundation for hydrocarbon migration research, ultimately contributing to more sustainable and efficient resource management [78].

Digitization and automation

Digitization and automation represent transformative trends in hydrocarbon migration research, poised to address critical limitations in traditional approaches. Conventional methods often rely on manual data collection and interpretation, which can be time-consuming, resource-intensive, and susceptible to human error, especially when handling the massive datasets produced by modern exploration and production activities. Additionally, static or infrequent data collection limits our ability to understand the dynamic nature of hydrocarbon migration, resulting in delayed decision-making and potential inaccuracies in predictions.

By contrast, digital and automated systems enable continuous, real-time data acquisition, advanced analytics, and adaptive response mechanisms. Real-time monitoring through IoT sensors, for example, provides instant access to critical subsurface and operational data, allowing for more responsive and accurate tracking of hydrocarbon movement. Automation, including machine-driven interpretation and remote operation capabilities, enhances precision, reduces manual workload, and minimizes operational risks, especially in challenging or hazardous environments.

Furthermore, the integration of digital twins—virtual models of physical systems—into oilfield operations facilitates more predictive modeling and scenario analysis, offering a proactive approach to resource management. Combining these digital models with AI-driven analytics enhances the ability to simulate complex migration processes, optimize exploration strategies, and anticipate potential issues before they escalate.

Ultimately, digitization and automation not only streamline processes but also bring a new level of intelligence to oil and gas research and operations. As the industry increasingly faces complex geological environments and stringent environmental and economic pressures, adopting these technologies is essential for improving accuracy, sustainability, and cost-efficiency in hydrocarbon migration research and resource development.

Application of green technology

Applying green technologies in oil and gas extraction and processing helps reduce environmental impact and carbon emissions [79]. Technological innovation can make the oil and gas industry more environmentally friendly and sustainable [79,80]. It is recommended that low-carbon technologies and ecologically friendly materials be developed to enhance energy efficiency and environmental performance during oil and gas production [81].

Incorporating green technology in oil and gas exploration, extraction, and processing is rapidly becoming essential, driven by stricter environmental regulations, global carbon reduction targets, and growing societal expectations for sustainable practices. Conventional methods often produce significant greenhouse gas emissions, hazardous waste, and ecosystem disruption, making green innovation critical not only to lessen environmental harm but also to ensure the sector’s long-term viability in a low-carbon economy.

Green technologies introduce transformative practices by emphasizing energy efficiency, emission reduction, and ecological protection. For instance, carbon capture, utilization, and storage (CCUS) directly addressed carbon emissions by capturing CO_2 at the source and either repurposing or storing it underground. These methods allow oil and gas operations to meet regulatory standards and reduce their climate impact. Similarly, the development and use of biodegradable drilling fluids and non-toxic fracking additives minimize groundwater contamination and soil degradation, creating safer extraction processes that align with ecological priorities.

Green technology enables the oil and gas industry to meet modern environmental standards, improve community relations, and contribute positively to climate goals. By rethinking extraction processes and prioritizing eco-friendly solutions, the industry can make meaningful strides toward sustainability, combining immediate environmental improvements with long-term resilience in a rapidly evolving energy landscape.

3.2.2. Challenges

Data quality and integration

The accuracy of oil and gas migration models fundamentally depends on the quality and consistency of multi-source data, as these models use geological and fluid dynamics principles to simulate subsurface conditions and predict migration pathways. When data from various sources are integrated, inconsistencies, noise, and uncertainties often arise, stemming from differences in data acquisition methods, temporal resolution, or scale. To address these challenges, it is essential to apply high-precision data collection techniques that align with the model's assumptions and physical parameters—such as pore pressure, permeability, and rock porosity—ensuring data reliability and compatibility. Furthermore, standardized data collection methods help minimize disparities across datasets, providing a more unified data foundation. By incorporating statistical analysis and machine learning techniques, researchers can further refine data integration, leveraging these methods to quantify uncertainties, filter out noise, and enhance model reliability and predictive accuracy.

Complexity and uncertainty of models

The inherent complexity of oil and gas migration models stems from the diverse geological, geochemical, and fluid dynamics principles that govern subsurface processes. These models often involve nonlinear interactions between parameters such as rock permeability, fluid viscosity, and pressure gradients, each contributing to potential uncertainties in prediction outcomes. For instance, even minor variations in assumptions about reservoir characteristics or input parameters, such as temperature or pressure conditions, can lead to significant deviations in model outputs. Addressing these uncertainties requires integrating multi-source data—such as seismic, magnetic, and well-log data—each offering unique insights into subsurface conditions. By adopting advanced modeling techniques, like stochastic simulations and machine learning algorithms, researchers can account for the probabilistic nature of these variables, refine predictions, and achieve a more robust understanding of subsurface migration pathways [82].

Environment and safety

Environmental pollution and safety risks in oil and gas exploration stem from fundamental extraction and processing mechanisms, such as drilling, hydraulic fracturing, and chemical treatments. Each of these processes can introduce pollutants—like volatile organic compounds, hydrocarbons, and heavy metals—into surrounding ecosystems, affecting soil, water, and air quality. Safety risks, such as blowouts or pipeline ruptures, arise due to pressure control issues and equipment failure, underscoring the importance of robust risk management frameworks. Mitigating these issues requires employing green technologies that operate on principles of waste minimization, carbon capture, and closed-loop systems. For example, vapor recovery units can capture emissions at processing sites, while using biodegradable drilling fluids reduces soil contamination. Implementing predictive maintenance using IoT and AI to monitor equipment health helps prevent accidents and manage safety risks effectively. Integrating such environmentally sustainable practices into operational protocols will enhance ecological preservation while minimizing safety hazards [83,84].

Technology costs

Applying advanced technologies like high-resolution seismic imaging and digital oilfields introduces significant costs, largely driven by the need for specialized equipment, data processing, and skilled personnel. High-resolution seismic imaging, for example, requires precise sensor arrays and powerful computing resources to analyze subsurface structures, which increases both initial capital expenditure and ongoing operational costs. Additionally, maintaining a digital oilfield entails substantial investments in IoT infrastructure, real-time data analytics systems, and cybersecurity measures to protect sensitive operational data. In economically constrained environments, these costs are particularly impactful, often necessitating a careful cost-benefit analysis. Reducing expenses in these areas relies on innovations such as modular technology, which allows for scalable expansion, and machine learning algorithms that optimize data processing. Automation in routine monitoring and predictive maintenance systems can also mitigate long-term operational costs by minimizing equipment downtime and extending asset life. By strategically implementing such innovations, companies can lower the overall cost of technology deployment, ultimately enhancing the economic sustainability and resilience of oil and gas development.

4. Conclusion

Oil and gas migration studies encompass multiple disciplines, such as geology, geophysics, and geochemistry. With the aid of numerical simulation methods, significant progress and achievements have been made in understanding the migration patterns of oil and gas under various geological conditions, leading to the development of a comprehensive theoretical framework. However, certain regions still require further in-depth research due to the complexity and diversity of geological conditions in oil and gas reservoirs. Through an extensive literature review, this paper introduces and categorizes the main methods currently used in oil and gas migration research, including sedimentological methods, geochemical tracing, numerical simulation, and geophysical techniques, providing detailed discussions of each approach.

Furthermore, with the support of modern science and technology, research on oil and gas migration is rapidly advancing. This paper further discusses and explores the cutting-edge trends in this field, focusing on areas such as AI methods, digital oil fields, geological big data analysis, and high-precision seismic imaging technology.

The opportunities in oil and gas migration research lie in advancing our understanding of the essential physical and chemical processes involved in hydrocarbon migration, enhancing their spatiotemporal resolution. This can be achieved through the integration of reliable fundamental data with intelligent analysis, high-resolution detection technologies, the application of green technologies, digitalization, and automation, as well as multidisciplinary approaches. These opportunities have emerged thanks to the rapid development of information technology and new detection methods. Data integration and intelligent analysis can combine multi-source data to provide more accurate oil and gas migration models. High-resolution detection technologies, such as 3D seismic exploration and microseismic monitoring, allow for clearer imaging of underground structures. Applying green technologies enables more sustainable and environmentally friendly oil and gas development, while digitalization and automation technologies enhance the efficiency of oilfield management and operations. However, oil and gas migration research also faces numerous challenges. Data quality and integration are primary concerns. With the increasing diversity and volume of data sources, effectively managing and utilizing this data has become a significant challenge. The complexity and uncertainty of models also pose substantial difficulties in predicting oil and gas migration, as migration patterns may vary significantly under different geological conditions, complicating model construction and validation. Additionally, environmental and safety issues cannot be overlooked. Minimizing environmental impact and ensuring production safety during oil and gas development are critical challenges that need to be addressed. The high cost of technology further limits the widespread adoption of new methods, especially in early-stage research and small oilfields. Moreover, the complexity of interdisciplinary collaboration increases the overall difficulty of research efforts.

In the future, it could be essential to improve the precision and reliability of numerical simulation methods through more refined data testing and experimentation, leveraging advances in computer technology [85]. Integrating AI into these processes and applying it to practical engineering development can drive technological progress and sustainable development in oil and gas exploration and production. For example, the introduction of AI and big data analytics holds the potential to significantly enhance the efficiency and accuracy of oil and gas migration research. Meanwhile, high-resolution seismic imaging technologies can provide more precise geological structure information, offering a more reliable foundation for studying oil and gas migration. Implementing digital oilfields and automated management systems can significantly improve oilfield development's efficiency and safety, reducing human factors' impact on production to enhance project workflow reliability [86,87]. Looking ahead at both opportunities and challenges, future oil and gas migration research should focus on several key areas: First, data integration and intelligent analysis—incorporating advanced data processing technologies and AI algorithms can improve data utilization efficiency and model prediction accuracy. Second, developing high-resolution detection technologies, such as high-precision seismic imaging and microseismic monitoring, provide clearer underground structural images for research. Third, applying green technologies promotes the environmental friendliness and sustainability of oil and gas development. Fourth, the widespread adoption of digitalization and automation technologies enhances oilfield management and operations modernization. Lastly, interdisciplinary collaboration across fields like geology, physics, and chemistry is crucial for advancing oil and gas migration research.

In summary, this paper has elucidated the importance and complexity of the oil and gas migration process, delving into the mainstream methods, cutting-edge trends, and future prospects of oil and gas migration technologies. Future research should emphasize interdisciplinary integration, enhance the accuracy of data processing and model prediction, and foster further development in oil and gas migration studies. This provides a solid theoretical foundation and technical support for oil and gas exploration and development. Through these efforts, oil and gas migration research is increasingly significant in improving resource utilization efficiency, reducing environmental impact, and promoting sustainable development across multiple dimensions, including the environment, region, society, and energy [88–90].

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