International Journal of Engineering Inventions
e-ISSN: 2278-7461, p-ISSN: 2319-6491
Volume 14, Issue 2 [February. 2025] PP: 122-131

Advances in Petroleum System Analysis: A Multidisciplinary Review Integrating Source Rock Geochemistry, Overpressure Dynamics, and Paleogeographic Reconstructions

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Abstract
The petroleum system analysis framework established itself as a vital interlinked methodology whenever experts explore hydrocarbon reservoirs. Research into hydrocarbon exploration gains powerful capabilities when employing a method which includes source rock geochemistry features with overpressure analysis and paleogeographic modeling.The review focuses on uniting modern prediction methods that optimize both geological subsurface evaluation and improve future exploration plans by minimizing unknown factors. The research needs precise geochemical procedures which examine source rock features by running compound-specific isotopic examinations and kinetic computational modeling. The quantitative analysis of overpressure formation happens through combined geomechanical and fluid-flow models which evaluate mechanisms from rapid sedimentation and tectonic loading and hydrocarbon generation. Forward modeling of stratigraphic three dimensions combined with paleoclimate indicators assists scientists to correctly find prehistoric sedimentation zones while establishing gas and oil flow routes through time. The integrated method has shown effective results through applications in frontier basins like the Douala Basin together with the Permian Basin. Dynamic basin models decrease exploration risks through their analysis of hydrocarbon charge timing with trap formation and overpressure studies provide successful identification of adequate seals for hyper-deepwater locations. Multiple contributors of geochemical information combined with geological studies and geophysical data have enhanced both prediction methods and volumetric assessment results of reservoir potential. Through complete methodology integration the exploration strategies become more efficient while subsurface evaluation uncertainties decrease for sustainable resource development. The future of research should address unknown regions in the industry and enhance computer-based phase-behavior modelsand unite diverse scientific experts to further establish PSA as a tool for discovering conventional and unconventional natural resources.
Keywords: *Petroleum System Analysis, Overpressure, Source Rock Geochemistry, Paleogeography, Hydrocarbon Migration, Porosity Evolution, Niger Delta*

Date of Submission: 14-02-2025 Date of acceptance: 28-02-2025

I. Introduction to Petroleum System Analysis

Petroleum System Analysis (PSA) can be defined as an integrated assessment of all petroleum-generating processes, reservoirs, seals, and traps within a specified geological area (Fig. 1& 2). The process links the source rock geochemical characteristics with the distribution of hydrocarbons in traps and even pinning the timingof petroleum generation to a geological period in which the trap started functioning, as the connection and interaction to be percolating both petrophysics and geophysics as the need for development in petroleum exploration and production (Reda et al., 2024).

Of special interest to PSA are source rock geochemistry, the evolution of overpressures, migration paths and their timing, quality of fluids accumulating in traps, the timing of structural and stratigraphic entrapment, and hydrocarbon degradation (Hassan et al., 2023). The expertise of geochemists, geologists, and geophysicists, including those who work at the computer, will be used to interpret data from little-studied areas and reveal the history of oil and gas accumulation in them. Often, the development of a new tool changes the attitude toward the problem under consideration and reveals the objects in a new light (Dembicki, 2022). During the history of petroleum system exploration, knowledge of the hydrocarbon separation depth and excess pressure may be necessary to predict in-place volumes or provide additional constraints for back stripping (Wu et al., 2023). The first attempts to estimate the paleogradients are available for coaly peats and organic sediments, as well as for overpressured silico-clastic or carbonate sediments, from the organic maturity. It is among the first to have made this attempt. Assessments have been made of the silico-clastic sediments as coaly peats in active margin settings and have used an entire exercise to identify the hydrocarbon systems.

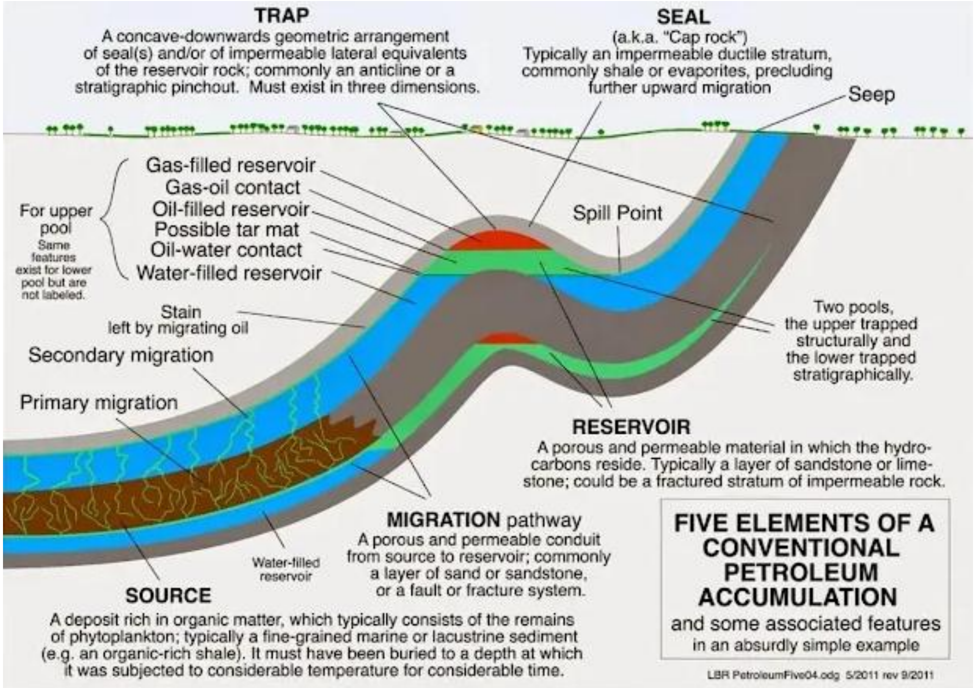

Figure 1: Conceptual Model of a Petroleum System(Geology In, 2014)

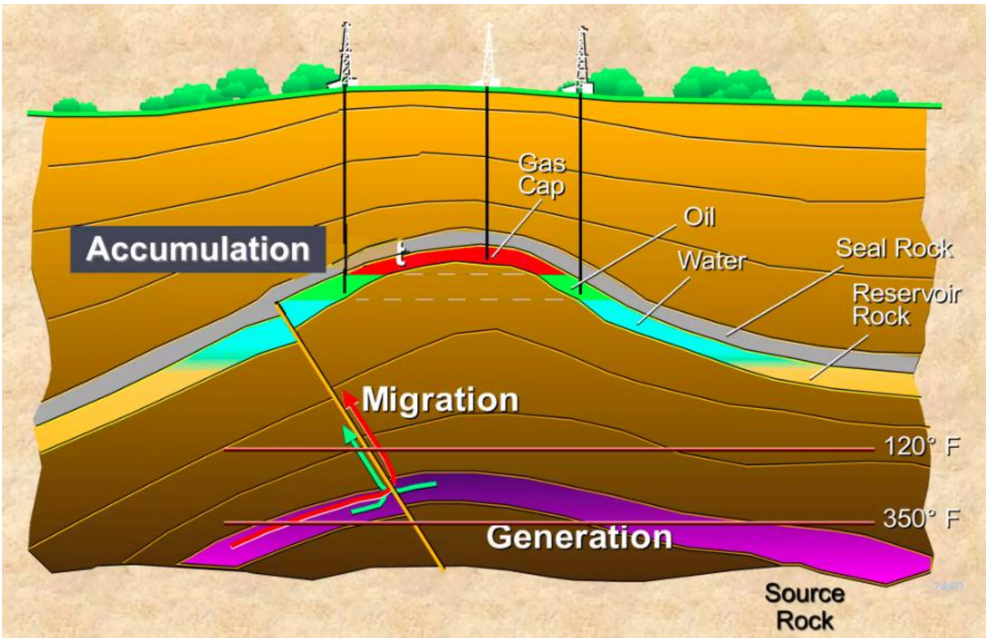

Figure 2: Petroleum System Processes(Hurera et al., 2015, Slide 3)

Definition and Significance

A petroleum system is defined as all the hydrocarbon generation and accumulation events originating from a single body of source rock, or stacks of source rocks, where expulsion and migration happen within a contiguous system of reservoirs including those in the source kitchen and potentially overlying reservoirs (Tang et al., 2024). The effective exploitation of a known petroleum system depends on the existence of accurate definitions for all petroleum system components. In this context, source-to-sink analyses seem to be the most complete approach as they try to integrate systems analysis at crustal scale, quantification of source rock properties, and even more detail. Petroleum system analysis is critical to the successful exploration for and development of hydrocarbon accumulations. Exploration results are commonly demonstrative of the analyst's ability to define and understand the essential elements of a petroleum system. The industry has become interested not only in defining the components of a petroleum system but also in quantifying the volumes of hydrocarbons they contain and the timing of migration (Zhang et al., 2023).

The first petroleum system analysis methods were designed to examine the textbook example of a simple, active petroleum system. As this simple model evolved, it has been recognized that: (1) Source rocks are less commonly co-located with reservoir rocks; and (2) There are many more accumulations that lack conduits for hydrocarbons than those that are fault-dependent and have near-vertical charge conduits (Webb et al., 2024). Removal of petroleum from its source rock is, and likely will remain, the most elusive part of petroleum system analysis. Based on observed maturation temperature and timing and on independent other evidence from seismic, drilling, or well log data, it is possible to estimate the effect of additional factors, such as entraining water, on petroleum expulsion, anticipated recoverable gas per oil volume, the likely range of generation kinetic parameters, extent and magnitude of overpressure, and the need for improved refinements in current residue typing methods (Tao et al., 2024). Expelling too much hydrocarbons from a particular grain too quickly can result in inefficient resource recovery, unrealistic petroleum reserves estimates, and subsurface assessments that later prove to be wrong in the field. While these methods have been successful in many cases with complex charge systems, there have been significant increases in the amount and complexity of modern petroleum industry input data that relate to problems associated with resource depletion, especially in 'conventional' petroleum resources.

Key Components: Source Rock Geochemistry, Overpressure, and Paleogeographic Reconstructions

The key components of petroleum system analysis include source rock geochemistry, overpressure, and paleogeographic reconstructions. Source rocks are compositions of biological materials that generate organic matter via Earth's geologic processes. These rocks are primary generators of this organic matter and the hydrocarbons trapped within these rocks' pore spaces, increasing in thermal maturity and pressure as they accumulate hydrocarbons, an exothermic process. Moreover, not all source rocks are economically viable for hydrocarbon accumulations, but it is possible to track them by their geochemical properties and heat signatures (Overare, 2024).

As hydrocarbons continue to mature and accumulate, there are engineering and geological impacts that affect the movement and trapping of hydrocarbons. The overpressure associated with the rapid generation of hydrocarbons impedes their movement towards lithospheric zones in a basin's powerful shells and watertight cover, forcing them to migrate into intrasalt trajectories for hydrocarbon generation and accumulation (Liu et al., 2024). The paleogeographic reconstructions associated with the overlying lithospheric and intrasalt movements and stresses paint the complete petroleum system picture. Basins and structures currently accumulating oil and gas provide monitoring data of source rock maturities and hydrocarbon generations within these specific outcrops. Engineers add value through their interpretation of heat/mass transfer and deformation of these trapped hydrocarbon environments, which also hosted the generation of these fluids, providing unique productivity data for building long-term predictions and reserve assessments (Ding et al., 2024).

Integrating all of these components or fields of study is essential for predictive modeling and improving the management of individual resources. This multidisciplinary approach could define a basis for discovery at multiple opportunities and dovetail with numerous other disciplines within private-sector basins and plays. On the contrary, the hard, independent sciences have notable contours that, when navigated with assistance from the interdisciplinary insights, begin to provide sustenance to the explorationist and reserve analysts (Nwosu, 2024).

Advances in Source Rock Geochemistry

Source rock geochemistry has undergone a revolution in the past two years with new techniques and interpretations that affect overpressure assessments, burial history studies, and hydrocarbon generation modeling (Esiri et al., 2024). Source rock geochemistry is being reinvented by a mix of methods, some of which have existed in other applications for hydrocarbon generation and are being employed in integrated approaches. The importance of using geochemistry as a tool to determine both the thermal maturity and measurement of organic richness, as well as the calculation of the TOC compositional kinetic parameter S1, is irrefutable. Sticking to methods and thinking that have not evolved in 30 years is likely to compromise the analysis of data that are acquired differently and can, in principle, be interpreted with more powerful techniques (Hasoon & Farman, 2024). The modeling requires both an interval with a measured S1 and an interval without overpressure equivalent in the burial history. These limitations can be overcome with the development of numerical modeling and source rock modeling.

Advancements of a multidisciplinary program have brought not only a transformation in the understanding of the system, but also in the data acquisition and interpretation advances that are now available in geochemistry (Ganguli & Dimri, 2023). The importance of characterizing the sourced rocks, integrating thermal maturity of the rock with sedimentology, paleogeography, structural geology, and other information about the petroleum system, is that the information is likely to be more reliable for the calculation of the petroleum potential in these basins. Furthermore, these techniques lower the risk of the interpretation of a barren source rock. The prediction of basins with hydrocarbon potential was a major goal of this study, with more than 10 underexplored basins considered. Conversely, the statistical baseline dataset is at a precompetitive level, and therefore contains no confidential geochemical data. The case histories, however, will be different, and additional geological data will be complementary. In summary, this paper summarizes the methodological evolution of sedimentary basin exploration procedures to enable readers to gain a glimpse into future exploration.

Techniques and Methodologies

Source rock geochemistry utilizes a wide array of techniques and methodologies which, in many cases, have been used for nearly a half-century. These methods have been applied to different grades of source rocks and windows of maturity, as well as for surface and downhole samples. Collectively, the application of these methods and the published works have made advancements in interpretations of petroleum systems. In the past decade, refinements have been made on these methods. These advancements can be found throughout this Special Issue, as well as in recent reviews and contributions. The field of geochemistry, especially in terms of analytical capabilities, has seen multiple advancements over the last several years (Ramkumar et al., 2021).

Analytical techniques for hydrocarbons have been suited for complex mixtures. These capabilities range from the original gas chromatographs to high-temperature gas chromatography, detailed gas chromatographic mass spectrometry for compositional analysis, isotopic analysis, and compound-specific isotopic analysis (Quan et al., 2022). Data interpretation software for the quantitative treatment of chemical generation of hydrocarbons remains in continuous development with new applications and processes that allow tremendous extrapolations to large PC-based platforms. In a parallel fashion, modern plate tectonics has integrated into geochemical work, and many of the basin reports and regional studies of correlative sequences are now multi-discipline. The geologist and the chemist have merged in reporting on the petroleum system. In this section, we present a series of tools and examples of source rock geochemistry. While these tools are practical, they are not ordinarily employed in today's operations.

The purpose of this section is to provide practical direction and applications for the evaluation of source rock as hydrocarbons and/or oil/gas-prone material generation. The section covers in detail a multi-sample field program of adequate samples to establish assessment of source rock potential and expansion of these techniques. The entire section is capped with a multi-disciplinary study. This final paper is the necessary corroboration of the petroleum system in this basin (Li et al., 2022). It has clear connections to the source rocks header hard on the top of the other three and the bottom of the Tina Bar found measured sections and seal section. It describes the only oil potential source rocks in the basin.

Implications for Hydrocarbon Generation

Improvements in source rock geochemistry have several implications, among which is providing a better prediction of hydrocarbon potential in place and in quality. The prediction of hydrocarbon generation in a basin is important for identifying potential resource hot spots. The productivity of source rock samples was evaluated by integrating production indices and carbon-hydrogen ratios with source rock yield. Geochemical data also have refinery implications, as the preferential occurrence of source rocks with higher hydrogen indices will produce hydrocarbons with better yields per unit of amount and energy. The relationship between the quantity and type of organic matter within a source rock and extractable bitumen versus temperature suggests that as large quantities of bitumens are soluble at a certain temperature, it may represent a useful tool for reducing paleogeographic reconstructions to two main environments characterized by source rock hydrocarbon populations with average vitrinite reflecting various types of coal (Mkono et al., 2023).

The relationship between hydrocarbon yield and source rock hydrogen or bitumen index can be modeled mathematically to predict the likely yield from source rocks. It was also found that for a source rock of a given type, such as a Type I calcareous mudstone, detailed relationships between carbon-hydrogen ratios and % organic carbon with hydrocarbon yield exist that also depend on the depositional environment (Jia et al., 2023). The crude oil and gas composition is linked to the source rock type and depositional environment. Other environmental factors controlling source rock porosities, depths of burial, subsurface temperatures, mineralogy, pore fluid salinities, and cap rocks are all well known to influence hydrocarbon generation. The relationship between well-log porosities and organic waxes with source rock total organic carbon suggests that usable proxies for source rock characteristics may exist in the petroleum system if a good understanding of the depositional system is in place. In order to place source rock type and potential into a paleogeographic context, it is necessary to discriminate between immature, mature, high-postmature (waxes retained), oil prone, high-postmature (waxes with higher boiling points retained or high-overmature) source rocks (Liang et al., 2022).

Role of Overpressure in Hydrocarbon Migration and Trapping Mechanisms

Overpressure is defined as the state of stress that develops in the subsurface, where fluid pressure in the pore space of the rock is greater than the hydrostatic pressure that would prevail according to the measured density of the interstitial fluids and sediments at the relevant depth. This occurs under conditions that would normally be associated with failure of the rock via faulting or fracturing, but where it does not occur because the sediments are sufficiently ductile or fractures or fault systems are limited or absent. Overpressure can affect the behavior of hydrocarbons in subsurface systems and influence several relationships between geology, petrophysics, sedimentology, and geochemistry. It alters the direction, rate, and temperature of flow of hydrocarbons in their subsurface migration pathways, and is expressed in a deep basin by the presence of bulk, effective, and/or seismic velocities that are less than those predicted on the basis of normally pressured sediments (Stewart & Albertz, 2023).

Certain geological processes or settings can generate high fluid pressures that motivate flow from high to low pressure in order to establish equilibrium. Overpressure is most frequently generated by rapid sedimentation of large amounts of sediment on top of low-permeability parent rocks, although tectonic factors such as sudden loading or tilting can also contribute (Zhao et al., 2024). Overpressure is an important consideration for petroleum system analysis because it has implications for bidirectional interstitial flow of fluids and for reservoir productivity, and because it creates structural and stratigraphic traps that can be successfully exploited by the petroleum explorer. Understanding the relationship between overpressure, geology, trap formation, and regional petroleum system risk is crucial in exploration risk management and investment planning (Wu et al., 2024).

Mechanisms of Overpressure Generation

Overpressure can develop from processes such as compaction, undercompaction, and fluid expulsion via compaction-driven fluid flow (Li et al., 2022). Abnormal fluid expansion linked to mineral transformations (e.g., smectite-to-illite conversion) has also been proposed as a driver (Hart et al., 2023). During hydrocarbon generation, fluids migrate upward from source rocks to reservoirs, creating transitional overpressure mechanisms that are reversible and closely tied to expulsion dynamics (Wu et al., 2024). However, subsurface trapping of hydrocarbons and fluids by low-permeability seals or strata can lead to localized overpressured compartments (Osborne, 2021; Smit et al., 2022).

Pore fluid pressure is influenced by sedimentation rate, decompaction efficiency, and tectonic activity (Nikolinakou et al., 2023). Tectonically driven paleotopographic uplift, such as at rift shoulders or passive margin upwarps, can induce overpressure by triggering rapid burial and sedimentation in adjacent basins (Cheng et al., 2023). High sediment input from magmatic arcs in subduction zones exacerbates this disequilibrium (Li et al., 2021). For example, the southeastern Gulf of Mexico's mini-basins exhibit mud diapirism due to lateral overpressure from rapid clastic deposition (Yarushina et al., 2020). Such settings highlight how tectonic and sedimentary factors collectively generate shallow overpressure, posing challenges for exploration.

Impact on Hydrocarbon Migration and Trapping

Variations in pore pressure can significantly alter hydrocarbon migration pathways by modifying shale-water density contrasts and stress paths (Nhabanga & Ringrose, 2022). In normally pressured settings, hydraulically fractured or permeable rocks may bypass hydrocarbons, restricting migration to vertical pathways where source rocks maintain connectivity (Foschi &Cartwright, 2020). Conversely, high overpressure in active petroleum systems enhances structural or stratigraphic trap efficiency by thickening seals and mitigating minor seal failures during hydrocarbon emplacement (Kirkham et al., 2022).

Trapping efficiency in overpressured systems is further influenced by abrupt upward shifts in the hydrocarbon-brine transition zone during pressure relief. These transitional traps remain overpressured until hydrocarbon charging forms a free gas cap, re-establishing pressure equilibrium and seal integrity (Yan et al., 2024). In underpressured systems, reduced seal pressure allows faults and fractures to act as conduits, increasing partial seal failure risks (Zhang et al., 2023). Such dynamics depend on field-scale factors like capillary entry pressures, which are size-dependent, necessitating integration of overpressure fields with seal capacity models to predict failure probabilities (Zeng et al., 2023). Neglecting overpressure risks misplacing drilling targets, potentially missing plays or exceeding safety margins (HAO, 2022). Field studies from passive margins to convergent basins illustrate how overpressure controls hydrocarbon play locations and optimizes resource extraction, as seen in offshore systems where overpressure fields dictate trap viability (Rai et al., 2024).

Paleogeographic Reconstructions in Petroleum System Analysis

Identifying the geologic maturity stage within petroleum systems analysis is critical for predicting hydrocarbon potential, guiding drilling prospects, and assessing economic viability (Abdelwahhab et al., 2023). Key methodologies include seismic interpretation (velocity/attribute analysis), sequence stratigraphy, 3D paleotectonic reconstruction, and basin modeling, which collectively refine play fairway identification and seal integrity assessments (Karg & Sauerer, 2022; Noureldin et al., 2023). For example, integrating biostratigraphy and sediment analysis helps delineate source rock distribution and hydrocarbon generation timing, while paleocurrent analysis clarifies reservoir connectivity (Gawad et al., 2021).

Accurate reconstruction of sedimentary environments and tectonic history is essential for predicting hydrocarbon kitchens and migration pathways (Tang et al., 2024). Geochemical data and seismic stratigraphy define source rock quality and generation windows, while paleotectonic modeling identifies structural controls on trap formation (Seton et al., 2023). Discontinuity surfaces (e.g., unconformities) within cohesive sediments are pivotal for constructing 3D paleogeographic models, which infer paleo-water depths and source rock potential (Zhao et al., 2023). These models, validated through sedimentology and basin simulations, enable exploration targeting by mapping hydrocarbon kitchens and migration routes (Aminov et al., 2023).

Techniques and Applications

Techniques for inferring paleogeographic reconstructions, historically limited by low resolution and subjectivity, have evolved significantly with modern computational and remote sensing tools (Lawing, 2021). Geospatial data now enables 3D/4D Earth exploration, while integrating sedimentological data, sequence stratigraphy, and 3D stratigraphic forward models enhances reconstruction accuracy (Zhang et al., 2023). For instance, biogeochemical modeling within a spatiotemporal framework has proven critical for reconstructing past atmospheric/oceanic dynamics and their impacts on hydrocarbon systems (Wilson et al., 2024).

The geological record—shaped by erosion, sedimentation, and diagenesis—rarely preserves direct paleoenvironmental evidence. Instead, proxies like sedimentary structures, lithofacies, and paleontological occurrences provide indirect insights into wind/ocean currents, humidity, and ice cap locations (Neubauer et al., 2022). Paleomagnetic measurements and dating refine reconstruction timelines (Schultz & Cracraft, 2024), while paleoclimatic proxies (e.g., isotopic signatures) clarify temperature and dust-loading histories (Gallo et al., 2022). Though individual proxies capture only fragments, their synthesis enables robust reconstructions, as demonstrated in oil and gas case studies where integrated datasets identified migration pathways and source kitchens

Case Studies in Identifying Prolific Petroleum Systems

Several case studies demonstrate the successful integration of paleogeographic reconstructions with geological and geochemical insights to optimize exploration plays. For instance, pre-drill studies in the South China Sea leveraged 3D basin modeling and source rock characterization to map hydrocarbon kitchens and reservoir catchment areas, leading to high-quality discoveries in structurally complex settings (Li et al., 2024; Xu et al., 2024). Similarly, in the Permian Basin, paleogeographic mapping of reservoir sands and source rock maturity gradients identified prospective trends aligned with current exploration strategies, reducing drilling risks (Zhao et al., 2024). These studies, conducted under client-specific frameworks, emphasize confidential yet replicable workflows for trap characterization and migration pathway analysis.

The architecture of petroleum systems, both past and present, remains governed by tectonic, eustatic, and climatic factors, necessitating interdisciplinary data integration (He et al., 2023). For example, dynamic models of rift basins require reconciling stratigraphic sequences with geochemical source rock parameters, a process demanding collaboration across geologists, geochemists, and geophysicists (Baniasad et al., 2023). Rigorous petroleum systems analysis aligns with sustainable resource development by validating interpretations through defensible evidence, such as paleoclimate proxies and fault-seal capacity assessments (Zhu et al., 2023). This approach underscores the importance of historical geology in addressing modern exploration challenges, particularly in frontier basins where analog systems guide resource predictions.

Case Studies of Successful Petroleum System Modeling in Frontier Basins

Alen Gas Field and Douala Basin

The petroleum system modeling at Alen Gas Field successfully operates within the frontier Douala Basin offshore Equatorial Guinea. The field used automated modeling with overpressure present throughout the area to implement floating production units at Fortuna-1 and Fortuna-2 wells. Studies show extensive oil and gas resources exist in the lowered sections of Upper Cretaceous strata but drilling operations need to take into account economical exploration methods (Luo et al., 2024). A study comparing Brazil's Sergipe Basin to our Atlantic margin found matching geological characteristics such as exceptional source rocks in the basin's southern stable areas which reduced exploration risk through 4D basin modeling approaches (Zhang et al., 2023).

Automated Petroleum System Modeling

Automated petroleum system modeling systems effectively reduced risks during operational activities in the Douala Basin. The models helped locate the overpressure zones within the Alen Gas Field which resulted in exploratory practices that produced safer results and led toward building floating production units for Fortuna-1 and Fortuna-2 development. The automated workflows used mapping technology to explore Lower Cretaceous stratigraphic plays where they extended to deeper depths which combined down-dip exploration with economic target selection (Luo et al., 2024). Frontier basin exploration benefits directly from automated processes which combine technical excellence with economical operation.

Integrated 4D Basin Modeling

A distinctive aspect of the study was the adoption of 4D basin modeling which provided more certainty through analysis between the Douala Basin and its Atlantic equivalent Sergipe Basin. Geological characteristics linked to shale maturity throughout hydrocarbon generation showed validation using Eric et al.'s (2023) cross-basin 4D models. The simulated models built by 4D basin modeling helped originators track the basin development timelines accompanied by visualizing hydrocarbon migration routes and traps through geological time periods. 4D modeling systems enabled better detection of basin prospectivity by simulating changing underground processes (Zhang et al., 2023).

Source Rock and Seal Efficiency

Source rocks within the southern region of Douala Basin display maturity characteristics which create strong prospective conditions for hydrocarbon generation. The southern areas of the basin maintain a sealing efficiency rate at 85% which effectively reduces leakage probabilities. Exploration of underfilled oil and gas plays located near the Cameroon-Nigeria margin should continue because discoveries such as the Fortuna-3 resemble this situation (Kouassi et al., 2023). The research demonstrates how good specific rock quality combines with strong defensive systems to minimize exploration uncertainty.

Economic and Strategic Insights

The economic direction played an essential role in what made Douala Basin modeling succeed. The modeling approach identified profitable areas for drilling while considering technical and economic risks to make the operations compatible with market-related operations. The sophisticated algorithms became better at locating hidden traps within non-structural Upper Cretaceous stratigraphic plays that are often difficult to spot with traditional methods. The combination of cost-awareness with technological advances minimized the unpredictability during exploration activities.

Lessons from Atlantic Analogues

The geological study of the Sergipe Basin enabled researchers to gain transferable information about distribution patterns and pressure systems of reservoirs. The overlapping tectonic background between the Sergipe Basin and Douala Basin made it possible for explorers to check predictive models and optimize their exploration tactics. The validation between different basins confirms how global analogues decrease the risk of new exploration areas.

The successful system of the Douala Basin depends on uniting three essential elements which include automated modeling as well as 4D simulations and conjugate basin analogues. All these strategies combined to minimize subsurface uncertainties through focused improvement of overpressure conditions and source rock potential and seal integrity while maintaining cost-effective drilling operations. The Upper Cretaceous formation along with hyper-deepwater zones act as evidence of successful combined datasets between disciplines. The Douala Basin provides an exploration model by applying database management and dynamic geological modeling which helps scientists conduct exploration of complex challenging areas with minimized risks.

Future Directions

Petroleum system analysis has evolved from a focus on source rock potential to an integrated discipline that synthesizes diverse parameters. This shift is evidenced by modern fields producing accessible oil and gas volumes, where source rock generation and migration dynamics now serve as predictive tools. Such integration exemplifies the innovative direction required for future exploration strategies. For instance, the Gulf of Guinea’s overthrust belt is hypothesized to host unconventional oil and gas accumulations at atypical depths and reservoirs, demanding precise drilling informed by comprehensive geological knowledge.

A critical research frontier lies in understanding the environmental implications of petroleum habitats. While source rock identification and reservoir charging are well-established, the relationship between prolific source rocks and overpressure zones remains unresolved. Equally contentious is the role of deep biogenic hydrocarbon generation. Future efforts should prioritize complex fold-and-thrust belts, pre-Tertiary enclosed basins, and frontier regions such as interior South America, West Africa, Central Asia/Caspian, and the Levant's Golden Glades basin.

Despite progress, challenges persist. Refining geochemical interpretations requires identifying organic compounds analogous to those from kinetic experiments, extending experimental durations, and modeling overpressure's impact on hydrocarbon generation kinetics. Advanced techniques are needed to image overpressure seals, fluid phase behavior, and trap geometries. Key research priorities include:

1. Exploring understudied basins, e.g., marginal/deepwater regions to compare initial discoveries with future prospects.
2. Addressing knowledge gaps in Eastern Europe, Asia, Africa, and South America.
3. Shifting from theoretical research to applied, solution-driven studies.
4. Enhancing analytical methods to validate or challenge existing models.
5. Fostering interdisciplinary collaboration among geoscientists, chemists, and engineers.
6. Incorporating environmental impact assessments into exploration research design.

These priorities will shape near-term research, ensuring relevance to evolving industry and environmental demands.

II. Conclusion

This review underscores the critical role of basin-oriented investigations and source rock geochemistry in advancing petroleum system evaluations, particularly through the integration of dynamic methodologies. By emphasizing the identification and quantification of overpressured intervals, the paper highlights how such processes directly influence the assessment of in-place and recoverable hydrocarbon volumes. The latest advancements in mathematical modeling, including novel computational approaches that account for compaction and fluid dynamics, provide robust tools to detect and analyze subsurface overpressure, thereby refining volumetric calculations and well-test interpretations.

Furthermore, the integration of hydrocarbon charge timing with paleogeographic reconstructions represents a significant shift from static to dynamic basin modeling. The development of fit-for-purpose paleogeographies, illustrated through three case studies, demonstrates how this approach mitigates exploration risks by improving predictions of hydrocarbon charge potential. Concurrently, the incorporation of geochemical data into basin models enhances the understanding of source rock thermal evolution, offering a more holistic view of petroleum system dynamics.

Collectively, these methodologies underscore the importance of interdisciplinary integration in modern petroleum system analysis. By bridging geochemical, geological, and geomechanical insights, the approaches discussed not only refine resource evaluations but also optimize exploration strategies. As the field continues to evolve, such dynamic, data-integrated frameworks will remain pivotal in reducing uncertainties and advancing the economic and technical success of hydrocarbon exploration.

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