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Integration of Geochemical, Geological, and Geophysical Data to Understand Petroleum Systems

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ABSTRACT

Understanding petroleum systems requires more than just studying rock layers or searching for hydrocarbons. It involves piecing together multiple types of data that each tells a different part of the story. This paper explores how the integration of geochemical, geological, and geophysical data improves our understanding of petroleum systems, from the generation and migration of hydrocarbons to their eventual accumulation in reservoirs. By combining these datasets, geoscientists can build a more accurate and complete picture of subsurface conditions, which is essential for reducing exploration risk and making informed drilling decisions. The paper also highlights the role of each data type, the value of their integration, and the challenges and opportunities this approach presents for future exploration. The study shows that effective data integration is not just useful but necessary for successful petroleum exploration in today's geological environments. The study equally found out that, integration allows for the correlation of observations across disciplines, which helps reduce uncertainty in exploration (Tissot & Welte, 1984). For example the study avered that, seismic images might reveal a structural trap, but without geochemical data, it's difficult to know if hydrocarbons ever migrated into it. Similarly, the study noted that rock samples from field mapping might show a good reservoir, but without seismic and well logs, its extent and depth remain unclear. Based on the findings of the study it thus recommended that, there is need for investment in data integration technologies that allow seamless merging and analysis of multiple data types, including 3D modelling, machine learning, and AI-driven tools. Conversely, consistent data collection methods and quality control practices should be prioritized to improve the reliability and compatibility of datasets.

Keywords: Integration, geochemical, geological, geophysical data, petroleum systems, generation, migration, hydrocarbons, reservoirs.

INTRODUCTION

A petroleum system refers to the natural process through which oil and gas are generated, migrate, and accumulate within the Earth's subsurface (Magoon, 1989). It consists of several key elements that must work together over geologic time. These elements include the source rock, where hydrocarbons are formed from organic matter; migration pathways, through which these hydrocarbons move; a reservoir rock, where they are stored; a seal rock, which prevents them from escaping; and a trap, a geological structure that holds the hydrocarbons in place. All of these must align correctly within a proper timing framework, meaning the trap and seal must be present before or during hydrocarbon migration for accumulation to occur (Magoon & Dow, 1994).

Understanding each of these components in detail is crucial. Without a full grasp of the petroleum system, exploration can be risky, expensive, and ultimately unsuccessful. For instance, discovering a well-developed reservoir without a seal or finding hydrocarbons that have migrated beyond the trap would result in a dry well. Therefore, a detailed study of petroleum systems helps geologists reduce uncertainty and increase the chances of making economic discoveries (Tissot & Welte, 1984).

To analyse petroleum systems effectively, geoscientists rely on three major types of data: geochemical, geological, and geophysical. Each of these provides a unique set of insights. Geochemical data help identify the origin, type, and maturity of hydrocarbons. Geological data give information about rock types, structures, and depositional history. Geophysical data, particularly from seismic surveys, reveal what lies beneath the Earth's surface and help build a three-dimensional understanding of the subsurface. On their own, each data type provides useful but limited information. However, when they are integrated,

they provide a more comprehensive and accurate understanding of how petroleum systems work (Gluyas & Swarbrick, 2004).

This paper aims to explain how these three data types, geochemical, geological, and geophysical, can be combined to study petroleum systems more effectively. It reflects that their integration leads to better decision-making, improved exploration success, and a better understanding of subsurface processes.

Statement of the Problem

The complexity of petroleum systems in Nigeria's hydrocarbon basins necessitates a holistic understanding of subsurface processes, yet the prevalent practice of analyzing geochemical, geological, and geophysical data in isolation leads to fragmented and often inaccurate interpretations. This siloed approach hinders the identification of hydrocarbon prospects, obscures migration pathways, and compromises exploration strategies, ultimately affecting discovery rates and resource estimation. Methodological gaps, data inconsistencies, and inadequate integration frameworks exacerbate these challenges, underscoring the need for a more integrated approach that leverages multidisciplinary data to de-risk exploration, optimize resource targeting, and enhance Nigeria's hydrocarbon resource discovery and production. The consequences of inaction include prolonged exploration cycles, increased costs, and missed opportunities for resource growth.

Aim and Objectives of the Study

The study explored the integration of geochemical, geological, and geophysical data to understand petroleum systems. Specifically, the study:

1. Examined the basic idea behind petroleum systems and the roles of the major types of data used in understanding petroleum systems.
2. Explored the value of integration in petroleum system.
3. Assessed the challenges and limitations of integration, and the future of integrated petroleum exploration.

Research Questions

The study is guided by the following research questions:

1. What is the basic idea behind petroleum systems, and the roles of the major types of data used in understanding petroleum systems?
2. How does the value of integration enhance petroleum systems?
3. What are the challenges and limitations of integration, and the future of integrated petroleum exploration?

Significance of the study

This study on integrating geochemical, geological, and geophysical data to understand petroleum systems in Nigeria's hydrocarbon basin will:

1. Enhanced exploration success rates by identifying potential hydrocarbon prospects and reducing subsurface uncertainty.
2. Inform optimized exploration strategies, reducing costs and timelines.
3. Contribute to Nigeria's energy security and economic growth through improved resource discovery and production.
4. Advanced methodological frameworks for multidisciplinary data integration in petroleum exploration.
5. Support informed decision-making for policymakers, operators, and investors in the oil and gas sector.

Scope and Limitations of the Study

Scope

The focuses on the:

1. Basic idea behind petroleum systems and major types of data used in understanding petroleum systems.
2. Value of integration, case studies/ real world application of petroleum system.
3. Challenges and limitations of integration, and the future of integrated petroleum exploration.

Limitations

1. Data availability and quality may vary across basins
2. Integration methods may require adoption to specific basin characteristics.
3. Study focuses on Nigeria's hydrocarbon basins, with potential applicability to similar settings.
4. Results may not be directly transferable to other regions or resource types.

Literature Review

The Basic Idea behind Petroleum Systems

The concept of a petroleum system is built on the understanding of how oil and gas are naturally formed, move through the Earth, and become trapped in places where they can be discovered and extracted. The process begins deep underground, where organic-rich source rocks, usually made up of ancient plant and animal remains, are buried under layers of sediment. Over millions of years, and under the right temperature and pressure conditions, this organic material breaks down chemically and turns into hydrocarbons (Tissot & Welte, 1984).

Once these hydrocarbons form, they do not stay in the source rock. Because they are less dense than the surrounding materials, they begin to migrate upwards through porous rocks and natural fractures. This movement continues until they either reach the surface and escape or get trapped beneath a non-permeable layer called a seal rock. If the hydrocarbons are lucky enough to be caught in a geological trap (such as an anticline or fault trap) and held in place by a good seal, they can accumulate in a reservoir rock, ready to be discovered by geologists (Magoon & Dow, 1994). Understanding these systems is more than just scientific curiosity. It is essential for reducing the risks and costs that come with oil and gas exploration.

When geoscientists understand how a petroleum system works in a particular area, they can better predict where hydrocarbons are likely to be found. This knowledge helps avoid drilling dry wells and improves the efficiency of exploration investments (Gluyas & Swarbrick, 2004). However, petroleum systems are complex. Their success depends on many elements working together: a good source rock, a proper migration route, a well-formed reservoir, an effective seal, a reliable trap, and the right timing. To make sense of all these interacting factors, geoscientists must gather and combine various kinds of data.

Major Types of Data Used in Understanding Petroleum Systems

In petroleum exploration, data is everything. But not all data is the same. To fully understand how oil and gas behave in the subsurface, geoscientists rely on three major types of data: geological, geochemical, and geophysical. Each of these data types plays a unique role in interpreting different aspects of the petroleum system.

Role of Geological Data

Geological data is the foundation of petroleum system analysis. It involves studying the physical features and composition of the Earth's crust to understand where oil and gas might be found. This type of data provides key information about rock layers, faults, folds, sedimentary structures, and basin geometry (Selley, 1998). Understanding these elements helps geoscientists determine if an area has the right conditions for hydrocarbon accumulation.

In a typical petroleum system, three critical geological components are examined: traps, seals, and reservoirs. Traps are the structural or stratigraphic features that prevent hydrocarbons from migrating further upwards. Seals are impermeable layers, such as shale or salt, that stop hydrocarbons from leaking out of the trap. Reservoirs are porous and permeable rocks that store hydrocarbons, like sandstone or limestone (Gluyas & Swarbrick, 2004).

Identifying and analysing these components requires various geological techniques. Two of the most common methods are **field mapping** and **core sampling**. Field mapping involves observing surface rock outcrops to understand the structure and distribution of subsurface formations. It provides clues about fault lines, folds, and other features that influence hydrocarbon movement. Core sampling, on the other hand, involves drilling into the subsurface and retrieving rock samples. These cores are studied in detail to

understand porosity, permeability, grain size, and mineral composition — all of which are important in evaluating a potential reservoir (Ainsworth et al., 2013).

However, while geological data gives insights into the structure and physical properties of the subsurface, it does not provide information about the chemical nature of the fluids in the rocks. Knowing what types of hydrocarbons are present, where they came from, and how mature they are requires another kind of data.

Role of Geochemical Data

While geological data focuses on the structure and composition of rocks, geochemical data offers insights into the chemical characteristics of petroleum systems. It helps scientists understand the origin, type, maturity, and migration pathways of hydrocarbons. This kind of information is crucial in determining whether a potential source rock has generated oil or gas and whether the hydrocarbons have moved into reservoirs (Walters & Moldowan, 2005).

At the heart of geochemical analysis is the source rock — the rock formation where hydrocarbons are originally generated. Geochemists study the organic content of these rocks to assess whether they have the potential to produce oil or gas. One of the most common techniques used is Rock-Eval pyrolysis, which measures parameters such as Total Organic Carbon (TOC) and Hydrogen Index (HI). These values help determine the quality and thermal maturity of the source rock (Tissot & Welte, 1984). Another important application of geochemistry is the use of biomarkers — complex organic molecules preserved in oil and source rocks. These molecules act like chemical fingerprints, allowing scientists to match hydrocarbons found in reservoirs to their source rocks. This makes it possible to trace migration pathways and understand how oil and gas have moved through the subsurface over time (Peters et al., 2005).

Geochemical data also play a key role in assessing the timing of hydrocarbon generation and migration. This information helps determine whether the hydrocarbons were generated before or after traps and seals were formed. If the timing is not favourable, for example, if hydrocarbons were generated after the trap was already breached, the accumulation would be lost. By combining geochemical analyses with geological observations, scientists can begin to piece together a more complete picture of a petroleum system (Walters & Moldowan, 2005). But to locate potential reservoirs and identify their boundaries with greater accuracy, one more critical data set is needed: geophysics.

Role of Geophysical Data

Geophysical data brings another essential layer of understanding to petroleum exploration. While geology provides the structure and geochemistry deciphers the content, geophysics offers a way to "see" beneath the Earth's surface without drilling. This type of data focuses on the physical properties of subsurface materials and is especially useful in mapping the geometry and extent of rock formations, identifying traps, and estimating reservoir characteristics (Sheriff & Geldart, 1995).

One of the most widely used geophysical tools in petroleum exploration is seismic reflection surveying. In this method, sound waves are sent into the ground, and the time it takes for the waves to bounce back from subsurface layers is measured. These reflections are then used to create detailed images of underground rock structures. This allows geoscientists to identify features like faults, folds, and stratigraphic traps, which are essential in predicting where oil and gas may have accumulated (Telford, Geldart, & Sheriff, 1990). Another geophysical technique is gravity and magnetic surveying, which helps detect variations in the Earth's gravitational and magnetic fields caused by differences in rock density or composition. Though less detailed than seismic data, these methods are useful in regional exploration and in understanding the broader geological setting of a basin. By integrating seismic data with geological models and geochemical results, petroleum geoscientists can significantly reduce the uncertainties involved in exploration. Seismic data not only reveals the structure of potential reservoirs but can also suggest the presence of hydrocarbons through techniques like amplitude versus offset (AVO) analysis or seismic attribute interpretation. This integration makes it possible to go beyond speculation and base decisions on multiple, reinforcing lines of evidence. To understand how these datasets come together in practice, it is important to look at the value of integration itself — how these different disciplines connect to produce a clearer view of the petroleum system.

The Value of Integration

Understanding a petroleum system often requires more than just looking at one type of data in isolation. While geological data helps describe the physical structure of the basin, geochemical data gives insights into the origin and maturity of hydrocarbons, and geophysical data provides imaging of the subsurface. On their own, each type of data is useful, but when combined, they create a much clearer and more accurate picture of where oil and gas might be found and whether it's worth exploring further (Magoon & Dow, 1994).

Integration allows for the correlation of observations across disciplines, which helps reduce uncertainty in exploration (Tissot & Welte, 1984). For example, seismic images might reveal a structural trap, but without geochemical data, it's difficult to know if hydrocarbons ever migrated into it. Similarly, rock samples from field mapping might show a good reservoir, but without seismic and well logs, its extent and depth remain unclear. By combining datasets, geoscientists can better validate the presence of a complete petroleum system — source, migration pathway, reservoir, seal, and trap — all within the right timing window.

This integrated approach also supports risk assessment and decision-making in exploration projects. For instance, integrating basin modelling (which uses geological and geochemical inputs) with seismic interpretation helps in identifying "sweet spots," areas with the highest chance of commercial discovery. It also helps companies avoid dry wells and focus their resources on the most promising leads (Tissot & Welte, 1984).

Moreover, integration plays a vital role in digital modelling and simulation. Advanced software now allows geoscientists to create 3D models that incorporate multiple data layers. These models help visualise how fluids have moved over geological time, test various exploration scenarios, and even guide drilling decisions in real time (Dow, 1994). A number of successful oil and gas discoveries have come from the smart integration of geological, geochemical, and geophysical data. For instance, in the **Niger Delta Basin**, integration helped delineate hydrocarbon-bearing structures that weren't obvious on seismic data alone. By combining geochemical source rock evaluation with geological mapping and seismic interpretation, exploration teams were able to identify viable traps and predict fluid types more accurately (Onyewuchi et al., 2017).

Similarly, in the **North Sea**, integrated data allowed companies to revisit previously drilled dry wells. When new geochemical analyses were combined with updated seismic data, previously overlooked migration pathways were identified, leading to fresh discoveries (Magoon & Dow, 1994). These examples show that integration not only improves exploration accuracy but also reduces risk and guides better decision-making in complex petroleum systems.

In short, the integration of geochemical, geological, and geophysical data is not just a technical preference but a necessity for effective exploration. It strengthens interpretation, minimises guesswork, and leads to better exploration success rates.

Challenges and Limitations of Integration

While integrating geochemical, geological, and geophysical data improves understanding of petroleum systems, it also presents certain challenges. These issues can limit the effectiveness of exploration if not properly managed:

- I. **Data Quality and Availability:** Integration depends heavily on the quality and completeness of data. Poor resolution in seismic imaging, missing geochemical markers, or incomplete well logs can lead to inaccurate interpretations (Glassley, 2014).
- II. **Differences in Data Scale:** Each dataset operates on a different scale. Geological data might focus on formations across kilometres, while geochemical data often reflect microscopic rock properties. Aligning these scales can be difficult and may introduce errors (Ghassemi, 2012).
- III. **Interdisciplinary Gaps:** Integrating data requires collaboration between geologists, geochemists, and geophysicists. Miscommunication or lack of shared understanding among these fields can hinder progress (Axelsson, 2008).

- IV. Cost and Time Constraints: Collecting and processing large volumes of diverse data can be expensive and time-consuming. Companies must balance the benefits of integration with budget and project timelines.
- V. Software and Technical Limitations: Advanced integration often requires specialised software tools that may not be accessible to all organisations. Even when tools are available, they require expertise to interpret the results accurately (DiPippo, 2012).

Despite these limitations, careful planning, training, and investment can minimise their impact and make data integration more effective.

Future of Integrated Petroleum Exploration

The integration of geochemical, geological, and geophysical data is rapidly evolving with the help of emerging technologies. These advancements are reshaping how petroleum systems are understood and explored.

1. Adoption of Machine Learning and AI: Machine learning is increasingly being used to process and analyse large volumes of subsurface data. These tools can detect patterns, predict reservoir quality, and assist in identifying potential hydrocarbon zones more efficiently than traditional methods (Al-Sharif et al., 2020). They are especially valuable in automating seismic interpretation, fault detection, and geochemical anomaly analysis.
2. Advances in 3D and 4D Modelling: Improved 3D and time-lapse (4D) modelling tools now allow geoscientists to visualise the subsurface more accurately. These models combine different datasets to create dynamic views of reservoirs over time, aiding in better decision-making and risk assessment (Ghassemi, 2012).
3. Improved Software Integration: Modern exploration software now supports seamless integration of diverse datasets. Platforms can now synchronise geological maps, seismic data, and geochemical logs, allowing a holistic interpretation of petroleum systems. This fosters more accurate exploration and better field development planning (Gehring & Loksha, 2012).
4. Application in Frontier and Unconventional Basins: Integrated methods are especially useful in underexplored and unconventional basins, where data is often sparse or complex. Combining available data sources helps reduce uncertainty and improve confidence in exploration efforts (MIT, 2006; Bertani, 2016).
5. Support for Energy Transition: As the energy sector shifts toward cleaner alternatives, integrated subsurface studies are aiding in identifying reservoirs suitable for carbon capture and storage (CCS). The same techniques used in petroleum exploration are being applied to manage geothermal resources and monitor CO₂ storage sites, contributing to broader energy transition goals (IRENA, 2020).

Summary of the Findings

The study with regards to the various research questions answered found out that:

1. The basic idea behind petroleum system is built on the understanding of how oil and gas are naturally formed, move through the Earth, and become trapped in places where they can be discovered and extracted. The study highlighted that, the process begins deep underground, where organic-rich source rocks, usually made up of ancient plant and animal remains, are buried under layers of sediment. In addition the study observed that, both the geological, geophysical and geochemical data types plays a unique role in interpreting different aspects of the petroleum system.
2. Integration allows for the correlation of observations across disciplines, which helps reduce uncertainty in exploration (Tissot & Welte, 1984). For example the study avered that, seismic images might reveal a structural trap, but without geochemical data, it's difficult to know if hydrocarbons ever migrated into it. Similarly, the study noted that rock samples from field mapping might show a good reservoir, but without seismic and well logs, its extent and depth remain unclear. The study further observed that, in the **Niger Delta Basin**, integration helped delineate hydrocarbon-bearing structures that weren't obvious on seismic data alone.

3. The challenges of integration include the following: data quality and availability, differences in data scale, interdisciplinary gaps, cost and time constraints, and software and technical limitations. However, notwithstanding these challenges the adoption of machine learning and AI, advances in 3D and 4D modelling, improved software integration, application in frontier and unconventional basins, and support for energy transition significantly enhances the exploration of petroleum systems.

CONCLUSION

Understanding petroleum systems requires more than just one type of data. By integrating geochemical, geological, and geophysical information, geoscientists can form a more complete and accurate picture of how hydrocarbons form, migrate, and accumulate. This combined approach reduces uncertainty, improves exploration success, and supports better resource management.

RECOMMENDATIONS

As petroleum systems become more complex and exploration moves into deeper or unconventional settings, there is a growing need for more effective data integration. This study highlights several challenges in working with isolated datasets, and the clear advantage of combining geochemical, geological, and geophysical information. Therefore, the following recommendations are proposed to improve exploration efficiency and reduce uncertainty:

- I. Promote Cross-Disciplinary Collaboration: Oil and gas exploration teams should encourage close collaboration between geologists, geochemists, and geophysicists to ensure data from each field is well-integrated and interpreted collectively.
- II. Invest in Data Integration Technologies: Exploration companies should adopt modern software platforms that allow seamless merging and analysis of multiple data types, including 3D modelling, machine learning, and AI-driven tools.
- III. Enhance Training and Capacity Building: Universities and industry programs should include more interdisciplinary training to equip geoscientists with the skills to interpret and use diverse datasets.
- IV. Focus on Data Quality and Standardization: Consistent data collection methods and quality control practices should be prioritized to improve the reliability and compatibility of datasets.
- V. Support Research and Development: Continued investment in R&D can drive innovation in data integration methods, improve predictive models, and support sustainable exploration practices.

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