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Turbidite Dynamics and Hydrocarbon Reservoir Formation in the Tano Basin: A Coastal West African Perspective

Michael K. Appiah[1*], Sylvester K. Danuor[1], Striggner Bedu-Addo[1], Alfred K. Bienibuor[2]

[1]Department of Physics, Kwame Nkrumah University of Science and Technology (KNUST), Kumasi, Ghana
[2]Department of Chemical Sciences, University of Energy and Natural Resources, Sunyani, Ghana
Email: *mikeappiah2003@gmail.com

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Abstract

This study examines the turbidite dynamics and hydrocarbon reservoir formation in Ghana's Tano Basin, which is located in coastal West Africa. Through an exploration of geological processes spanning millions of years, we uncover key factors shaping hydrocarbon accumulation, including source rock richness, temperature, pressure, and geological structures. The research offers valuable insights applicable to exploration, management, and sustainable resource exploitation in coastal West Africa. It facilitates the identification of exploration targets with higher hydrocarbon potential, enables the anticipation of reservoir potential within the Tano Basin, and assists in tailoring exploration and management strategies to specific geological conditions of the Tano Basin. Analysis of fluvial channels sheds light on their impact on landscape formation and hydrocarbon exploration. The investigation into turbidite systems unveils intricate interactions involving tectonics, sea-level fluctuations, and sedimentation patterns, influencing the development of reservoirs. An understanding of sediment transport and depositional settings is essential for efficient reservoir management. Geomorphological features, such as channels, submarine canyons, and distinct channel types, are essential in this situation. A detailed examination of turbidite channel structures, encompassing canyons, channel complexes, convex channels, and U-shaped channels, provides valuable insights and aids in identifying exploration targets like basal lag, channel levees, and lobes. These findings underscore the enduring significance of turbidite systems as conduits for sediment transport, contributing to enhanced reservoir management and efficient hydrocarbon production. The study also highlights how important it is to examine the configuration of sedimentary layers, stacking patterns, and angular laminated facies to identify turbidites, understand reservoir distribution, and improve well design. The dynamic nature of turbidite systems, influenced by basin characteristics such as shape and slope, is highlighted. The research provides valuable insights essential for successful hydrocarbon exploration, reservoir management, and sustainable resource exploitation in coastal West Africa.

Keywords

Reservoir Characterization, Tano Basin, Seismic Data, Hydrocarbon Potential, Channels, Turbidites

1. Introduction

A region of significant geological interest and activity, the Coastal West African Basin is home to a wide range of geological characteristics that have for years captured the interest of scientists and enthusiasts of exploration. In this large basin, the Tano Basin becomes a focus of scientific research and could provide an important understanding of the complex mechanisms controlling hydrocarbon reservoir formation. The need for an in-depth understanding of the geological complexity present in these basins is becoming more and more essential in light of the world's growing energy demand, and this is important for the sustainable exploration and production of hydrocarbon resources [1] [2].

Extending along the western coastline of Africa from Côte d'Ivoire to Angola, numerous hydrocarbon basins, including the Tano Basin in Ghana-Côte d'Ivoire, the Niger Delta Basin in Nigeria, the Rio del Rey Basin in Equatorial Guinea and Cameroon, the Douala Basin in Cameroon, the Gabon Basin in Gabon, the Congo Basin in Congo (west-central Africa), and the Kwanza Basin in Angola, have been subject to extensive exploration for petroleum, yielding substantial success [3] [4].

Turbidite channel reservoirs are frequently found in deep marine environments, including the Coastal West African Basins. They are characterized by their high porosity and permeability, which make it easier to extract oil and gas from these reservoirs efficiently [5] [6] [7]. One of its benefits is that they have apparent well-sorted sandstones that are low in clay, which makes them suitable for exploration. Widely acknowledged as important hydrocarbon reserves in the search for deep-water facies, the exploitation of these reservoirs requires the use of specialised drilling techniques, such as horizontal drilling, to optimise production [8] [9] [10].

Several studies have explored sedimentation in deep-water environments, focusing on submarine fans and reservoir characterization. These studies have analyzed various factors influencing sedimentation, including the spatial and temporal distribution of depositional components and stratigraphic units. One such study focused on the "Y" Field in the Niger Delta, and used 3D seismic data and well log information to map reservoir properties such as thickness, net-to-gross ratio, pore fluid, porosity, permeability, and water saturation [11] [12]. Another study addressed sedimentology and reservoir modeling in the Rovuma Basin of East Africa, with a specific emphasis on deep-water gravity sediment systems, submarine channels, and lobes [13]. Further studies have examined facies, net-to-gross ratios, clay volume, porosity, and permeability based on core data, modeling stacked turbidite channels in Angola and identifying collapse margin deposits as primary barriers to permeability [14]. Gamma ray logs have also been used to identify and characterize sand bodies in the EMK field within the Niger Delta region, while seismic reflection data has been used to investigate subsurface fluid flow features and their correlation with hydrocarbon systems in Egypt's Alamein basin [15] [16] [17] [18]. Other studies have focused on characterizing reservoirs in different regions, including fluvial reservoirs in the Laohekou Oilfield, China, fluvial channel systems and gas sand reservoirs in Australia's Carnarvon Basin, and submarine channels and valleys in the eastern Mediterranean Sea [19] [20] [21]. These studies highlight the importance of understanding sedimentation mechanisms and geological structure in deep-water environments, as well as the significance of various tools and data for reservoir characterization and exploration.

Other researchers have conducted studies on turbidite systems in the United States and Canada, as well as in other regions of the world [22]. Researchers have explored factors that affect these systems, including tectonics, climate, and sedimentary processes [23]. They have also examined the Makran Basin off the coast of Pakistan and the Magallanes Basin in southern Chile to better understand how sedimentation patterns form [24] [25]. Studies have shown that meandering channels can exhibit various stacking patterns over time [14]. Meanwhile, researchers have also looked at deep-water sinuous channel depositional features in New Zealand and evaluated petrophysical parameters of the reservoir in the Tano Basin in Western Ghana [26] [27]. However, there is limited research on basins in Ghana or West Africa as a whole. Turbidity currents are complex and can range from cohesive debris flows to dilute turbulent flows. Turbidite systems consist of three main components, including a conduit for turbidity currents, a depositional area near the basin where flows slow down, and a basin-distal depositional area where upper turbulent flows deposit sediment [28]. Geological similarities between the Suriname Basin and the Ghana Basin have been highlighted, emphasizing shared features such as Late Cretaceous erosional canyons, a broad shelf with strong long-shore currents, organic-rich hydrocarbon source rock, and extensional fault networks [29]. These similarities are relevant in the context of petroleum exploration in Ghana. Process-based methodology is important in understanding the formation of deep-water sedimentary systems, with tectonic events and basin formation playing a crucial role in shaping these sedimentary basins [30].

This research brings a region-specific, comprehensive, and detailed analysis of the Tano Basin, offering valuable insights for hydrocarbon exploration, reservoir management, and sustainable resource exploitation in coastal West Africa. The specific geological focus detailed examination of turbidite systems and emphasis on dynamic processes and basin characteristics.

2. Geological Setting

Located in Ghana, the Tano Basin is a sedimentary basin that dates back to the Cretaceous period and is situated along the edge of the West African Transform. Comprising the Saltpond Basin to the east and the St. Paul Fracture Zone to the west, it is considered to have been fed by the Tano, Ankobra, and Pra rivers [31] [32]. Demonstrating considerable hydrocarbon potential, particularly in its deepwater segment approximately 60 km offshore, with water depths ranging from 1200 m to 1500 m, the basin exhibits both stratigraphic and structural trapping mechanisms, with the former being predominant [33]. Exploration of the Tano Basin commenced in 1972 with the drilling of the first offshore well, revealing oil primarily located in stacked turbidite channels, levees, and splays [34] [35] [36] [37].

Based on Late Cretaceous and Tertiary reservoirs, the hydrocarbon potential of the basin has been noted since the 1890s [38]. Its stratigraphy has undergone modification due to tectonic evolution from the Late Jurassic to the Pleistocene, encompassing a diverse range of rock types, including Birimian Volcanics, Birimian Sediments, Tarkwaian, Upper Voltaian, Granite, Eocene, and Cretaceous formations [33] [39].

The submarine channels within the basin represent sediment-rich turbidites that flowed southwards until reaching the Côte d'Ivoire-Ghana Ridge, subsequently diverting towards the southwest [37]. The geological characteristics of the basin, which include high porosity (17% - 23%), permeability, anoxic conditions, and the deposition of marine shale, greatly contribute to its petroleum potential. The presence of type II and type III kerogen suggests the potential for the production of oil and gas [40] [41].

As a highly productive petroleum province, the Tano Basin has attracted considerable exploration endeavours in the ultra-deepwater areas. Promising hydrocarbon potential continues to be unveiled by ongoing exploration efforts, which has prompted the investigation into the dynamics of the basin to understand the complex interactions between geological events that have created its subsurface architecture over millions of years.

Due to its distinctive geometry, which is a result of both subsidence and tectonic forces, the Tano Basin's overall shape, size, and structural features must be understood to evaluate its hydrocarbon potential. Prominent structural features, notably faults resulting from tectonic activity, play a pivotal role in hydrocarbon formation and migration. The orientation, distribution, and activity of faults contribute to reservoir compartmentalization and overall structural integrity. Understanding the structural folds and flexures within the basin serves to explain its tectonic history and deformational events. Furthermore, the presence of structures like salt domes and diapirs could impact how the basin's structure evolves, possibly forming structural traps and affecting how sedimentary facies are distributed, which in turn influences the hydrocarbon accumulation (**Figure 1**).

The sedimentary record of the Tano Basin reflects its complex geological history, requiring a careful interpretation of its stratigraphic architecture imperative. This process entails the identification and interpretation of sedimentary rock layers formed over successive eras. One important aspect is identifying the source rocks, which is essential to determining the hydrocarbon potential of the basin. Within the Tano Basin, the type, distribution, and organic content of these source rocks exert a profound influence on hydrocarbon generation and migration. The stratigraphic distribution, porosity, and permeability of reservoir rocks—which are primarily made up of sandstones and other porous formations—play an important role in the successful recovery of hydrocarbons. Impermeable shales serve as stratigraphic seals, which are essential for trapping hydrocarbons within reservoirs. Assessing the distribution of these seals is essential in determining the basin's overall confinement capacity. When examining stratigraphic layers, fossil assemblages and microfossils may offer important historical and environmental insight [34] [41] [42] [43].

Fault-block traps, salt domes, anticlines, and faults are the structural features that characterize the basin, and there are a number of stratigraphic traps as well,

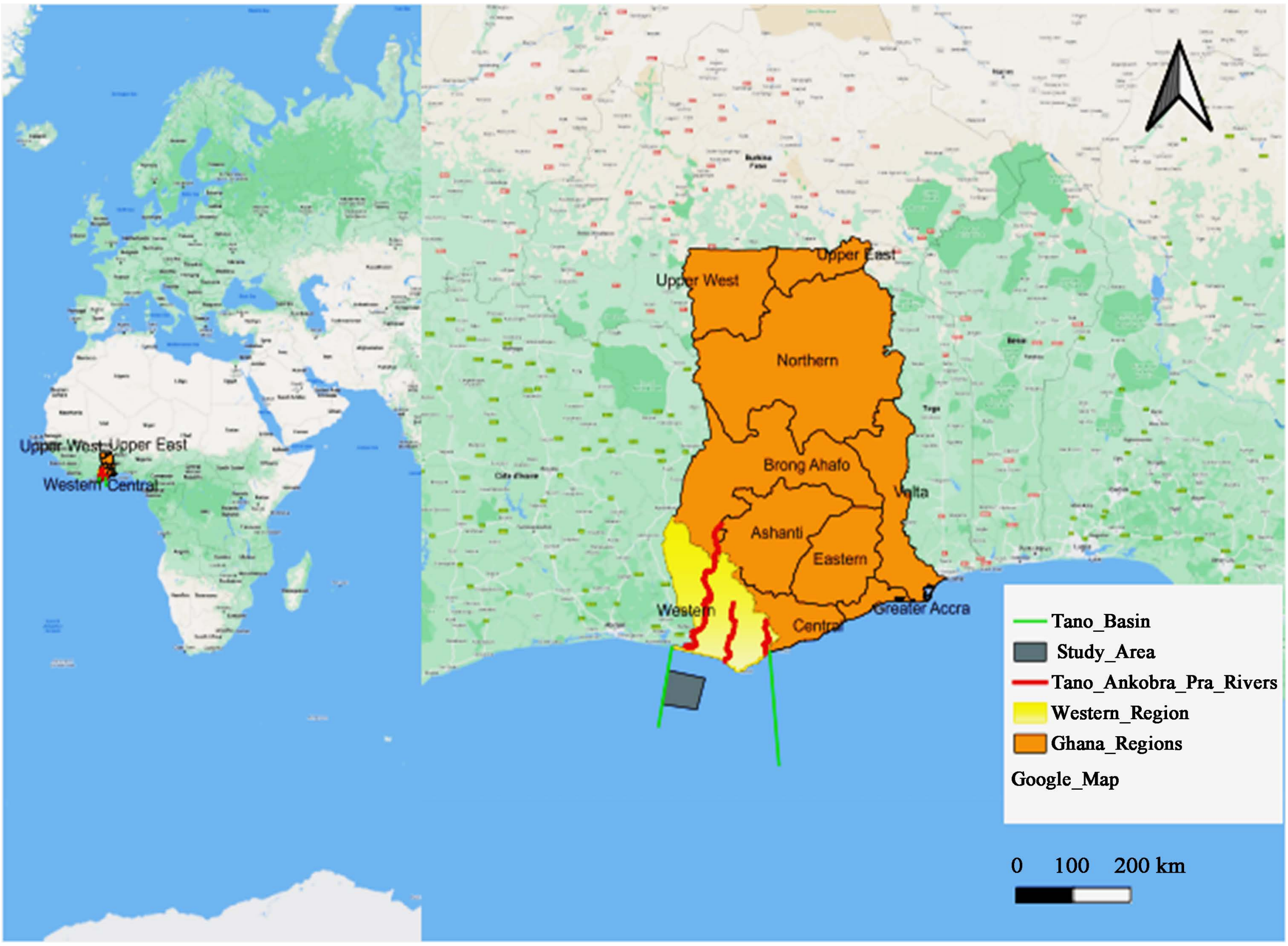

Figure 1. Tano Basin in West Africa.

including pinch-out traps, clastic deposit layers, and local facies variations [33]. The stratigraphy spans from Precambrian Basement rocks to recent sedimentation, featuring undifferentiated stratigraphic gaps. Marine sedimentary rocks from the Cretaceous to the Eocene include notable stratigraphic units, which indicate a tectonic progression from the Late Jurassic to the Pleistocene [44]. The Tano Basin's increased hydrocarbon potential can be attributed to the convergence of multiple structural and stratigraphic traps [45].

Notable hydrocarbon discoveries have been made in the Tano Basin, especially in its deep-water region. The Jubilee field, which was discovered in 2007 and is marked by stacked turbidite channels, fault blocks, and compactional drapes, is a significant discovery made in water depth exceeding 100 metres. The 2009 discovery of the Tweneboa field, which is ranked among the top 10 in the deep-water Tano Basin, is another notable finding. Fault blocks, compactional drapes, and layered turbidite channels serve as typical sources of oil. Among the top five discoveries in Africa, the 2010 finding of the Enyenra field is notable for having similar characteristics to oil found in compactional drapes, fault blocks, and stacked turbidite channels. Drilling in the Ntomme oil field in 2012 (which was initially thought to be a gas-condensate discovery) uncovered both oil and gas condensate in stacked turbidite channels, fault blocks, and compactional drapes. Furthermore, one of the major discoveries in the Tano Basin is the Sankofa field, which was found in the Cenomanian play in 2009. The Tano Basin has established itself as a petroleum-rich area with significant hydrocarbon potential owing to these discoveries, especially in the wake of its successful deep-water exploration efforts [46] [47] [48].

3. Data and Method

The study utilized high-quality processed post-stack 3D seismic data sourced from the Tano Basin.

To initiate a new research project using the Hampson Russel software, commence by launching the application and accessing the Project Manager tab. Within this tab, proceed to the Project Data section, and subsequently, navigate to the Seismic tab to reach the Seismic Import interface. Here, import the 3D seismic SEG-Y data by selecting and loading it into the software.

In the General Information tab, opt for a post-stack volume and affirm the inclusion of Inline and Xline numbers in the trace headers by selecting "yes." In the Trace Header Specification section, adjust the start column values for Inline and Xline numbers accordingly. Upon completing these configurations, proceed to the next step to scan the seismic data, revealing the geometry of the seismic. Confirm and proceed by selecting "OK" to visualize the seismic profile view within the dedicated seismic window.

Enhance the visual appeal of the seismic profile view by employing the View and Color Trace Show option to display the seismic data in colour. Subsequently, select "Next" to initiate the scanning process, culminating in the presentation of the seismic geometry. The refined seismic profile view is now prepared for interpretation.

With the groundwork laid, delve into the analysis and interpretation phase, leveraging the tools and functionalities provided by the software to scrutinize the seismic data comprehensively. This methodical approach ensures a systematic and visually enhanced exploration of the data, facilitating the research methodology.

4. Hydrocarbon Reservoir Formation Processes

The formation of hydrocarbon reservoirs is a complex and protracted geological process that takes millions of years to occur and involves multiple vital phases. These reservoirs are storage of natural gas as well as oil, and they are usually found within subsurface permeable and porous rock formations. The fundamental processes that lead to the development of hydrocarbon reservoirs are examined.

The process begins with organic matter accumulating in sediments that have been deposited in marine or lacustrine environments. This substance comes from decomposing plants and microorganisms including algae and plankton [49] [50]. It progresses as a result of the thermal maturation of these organic materials. Enhanced by the heat and pressure brought on by burial and compaction, this maturation produces source rocks that are rich in organic matter and convert into hydrocarbons, which include gas and oil [51]. One important aspect of this transition is called catagenesis, or thermal cracking, which is the process by which organic kerogens are thermally broken down to produce hydrocarbons. This process, which usually occurs at temperatures between 50˚C and 150˚C, is boosted by minerals present in the geological environment. The transformation of organic matter into liquid or gaseous hydrocarbons, resulting in the synthesis of petroleum, is the ultimate result of catagenesis. The two most common types of source rocks are mudstones and shale deposits [52].

After hydrocarbons are produced, migration takes place as these substances move from the parent rock to other, more porous and permeable substrates [53]. Since hydrocarbons are less dense than the surrounding rocks and fluids, they float, and the migration occurs along channels like faults, fractures, and porous rock layers [54].

Hydrocarbons accumulate in reservoir rocks, which are generally characterized by permeability and porosity, such as sandstones, limestone, or fractured rocks [55] [56]. Hydrocarbons can be stored more easily when there is porosity present, and they can migrate more easily within the rock matrix when there is permeability [52].

Geological structures must be present to trap migratory hydrocarbons for a viable reservoir to form [57] [58] [59]. Common processes of trapping include structural traps, which are created by faults, folds, and fractures; stratigraphic traps, which result from differences in the types of rocks and their geometries;

and combination traps, which combine stratigraphic and structural features [60] [61].

One of the most important components in keeping hydrocarbons from escaping upward is a cap rock, also known as an impermeable or seal rock. The cap rock, which covers the reservoir and forms a barrier that essentially confines the hydrocarbons, is usually made up of thick rocks like mudstones or shales [56] [52].

The potential of the reservoir, including its size, configuration, characteristics, and hydrocarbon quality, is evaluated through the application of geophysical and geological techniques.

5. Factors Influencing the Accumulation of Hydrocarbons in a Basin Environment

The accumulation of hydrocarbons in a basin environment is a complex and protracted geological process influenced by several key factors, including organic-rich source rocks, temperature and pressure conditions, reservoir rocks' properties, and geological structures such as anticlines, fault traps, and salt domes. The quality of source rocks, temperature, pressure, porosity, permeability, and the physical composition and textural attributes of rocks are pivotal in hydrocarbon generation, migration, and accumulation. Geological structures play a crucial role in the entrapment of hydrocarbons within a basin, serving as critical reservoirs for the accumulation and storage of oil and gas [62]. Hydrocarbon migration and accumulation in a basin depend on factors such as the tectonic history, sedimentary rock distribution, magma circulation, and chemical reactions like diagenesis and catagenesis. Understanding these processes is necessary for assessing a basin's potential for hydrocarbon generation and retention [63]. The accumulation of unconventional hydrocarbons is influenced by saline lacustrine fine-grained sedimentary rocks and salinity. All things considered, the combined effect of these elements determines a basin's hydrocarbon potential and is necessary for successful exploration and extraction [64].

6. Channel Features Relevant to Hydrocarbon Reservoirs

The characteristics of channel features are highly relevant to hydrocarbon reservoirs, especially when it comes to reservoir geometry that is shaped by the depositional environment, especially the sandstones present within the channels. These sandstones are important reservoir rocks because they provide the required porosity and permeability for the storage and flow of hydrocarbons.

Sedimentary structures like planar bedding, laminations, and other stratification features create stratified planar flow, which is one way that channel features influence flow [65]. This effect is more noticeable when permeability obstacles like graded beds, clay partings, or finer-grained laminae are present. These barriers affect the distribution and concentration of hydrocarbons in the reservoir as well as the preferential flow pattern within it.

A reservoir's quality depends on its storage capacity and deliverability, which are influenced by porosity and permeability. Channel features shape these properties and have a significant impact on overall reservoir quality. Reservoir characterization requires accounting for uncertainties in channelized reservoir connectivity. Amalgamation curves are useful tools for quantifying uncertainty in hydrocarbon distribution within the reservoir [66].

The formation of hydrocarbon reservoirs is highly dependent on the depositional environment, which includes features like channel sands and submarine fan sequences. Key reservoir characteristics including porosity, permeability, and hydrocarbon saturation are significantly influenced by these characteristics. Evaluation of the reservoir's capacity for hydrocarbon accumulation and preservation, in turn, depends on these factors.

7. Channel Characteristics

Natural channels like rivers and streams are characterized by different features and attributes that play an important role in shaping landscapes, facilitating sediment transport, and influencing ecological and geological processes. These features include the channel's geometry such as its width, depth, and sediment transport and deposition patterns. Understanding specific channel characteristics like sinuosity, sediment load, and hydraulic properties is important when exploring for hydrocarbons, as they impact the accumulation and retention of these resources in underground geological formations.

Fluvial channels come in a variety of geometries with differing dimensions, forms, and flow characteristics. These configurations include rectangular, straight, meandering, and braided channels [67]. The sinuosity ratio serves as a metric for distinguishing between straight and meandering channels. Braided channels arise from the division of a stream channel into multiple smaller channels due to the accumulation of sand or gravel bars [68]. The geometry of fluvial channel bodies is influenced by factors such as channel-body thickness and cross-stream width.

Sinuosity is a measure which influences sediment deposition patterns and fluid dynamics in channels. It plays a role in channel design. Dimensions, especially depth and width variations, directly affect fluid volume and sediment transport capacity; deeper and wider channels can usually hold more sediment [69].

Cross-sectional shape, whether V-shaped in high-energy rivers or U-shaped in lower energy environments, shapes sediment deposition patterns [70]. The process of sediment transport involves two types of particles: larger particles that rest on the channel bed, called bedload, and smaller particles suspended within the water column, called suspended load. The size of the sediment grains is important because it affects how effectively the channel can transport and deposit sediment [38].

Hydraulic characteristics, notably water velocity, are essential to sediment transport, with higher velocities facilitating the movement of larger sediment particles. Flow regime, whether laminar or turbulent, is dictated by variables like channel slope and roughness. Erosion and sediment transport are greatly facilitated by turbulent flow, which is characterized by increased kinetic energy.

When a river suddenly changes course, it creates new places for sediment to gather and new formations in the landscape. This is called an avulsion event. It can cause unique environmental conditions and geological features to form [71]. Channel configuration has a big impact on sedimentation processes, which in turn affects reservoir rock development. These patterns may include meandering curves or braided splits into smaller channels.

Channels in deltaic environments play a significant role in depositing sediment, which shapes reservoir rock. The type of delta, whether it is dominated by rivers or waves, also affects how sediment is distributed. The interplay between fluvial processes and tectonic activity in river channels is essential in forming reservoirs [72].

Straight channels have little curvature and are common in steep terrain like mountains. On the other hand, plains and valley bottoms with mild slopes are more likely to have meandering channels with clear bends. When the mass of sediment is greater than the velocity of the stream, sand or gravel bars accumulate and separate the water flow, forming braided channels [73].

Channels are formed by water and sediment dynamics, stream equilibrium, and environmental features. Sediment discharge, particle size, streamflow, and stream slope impact channel formation and can disrupt equilibrium, leading to changes in channel size and configuration [74].

Various factors like bed sediment, bank material, vegetation, valley slope and width contribute to channel formation and affect its stability and erosion rates [75]. Additional factors such as slope movements, hillslope contribution, constriction ratios, and valley-floor morphology further shape river and stream channels, particularly in mountainous regions [76].

8. Factors Influencing Turbidite System Formation

Turbidity currents, which are fast, gravity-driven underwater currents that carry a mixture of water and sediment from continental slopes into deep-sea basins, deposit sediment-laden turbidites, which are sedimentary layers. These distinct layers show graded bedding, in which differences in flow velocity cause the silt in each stratum to get increasingly finer from the bottom to the top. Turbidites are typically embedded within more extensive sedimentary sequences, where they appear as distinct, relatively thin strata within the sedimentary rock record [77] [78].

A turbidite system has different parts, including a Canyon, which is a steep valley that goes into the deep sea, carrying sediment-laden water. The Canyon has a Channel, which is a narrow path that moves the sediment-laden water downslope. Channel levees, which are raised banks on either side of the channel, form when sediment settles from the turbidity current. Overbank deposits consist of fine sediment that is deposited when the turbidity current slows down and spreads out, extending beyond the levees. At the end of the channel system, lobes, which are fan-shaped accumulations, form. Beyond these lobes lies the Basin plain, which is a flat area that receives fine sediment from the turbidity current [79] [80] [81]. Together, these components form a turbidite system that is distinguished by sedimentation caused by turbidity currents. Seismic data, well logs, and outcrop studies are all useful tools to identify these components, which can reveal important information about the depositional environment and sedimentary processes at work.

Turbidite systems are influenced by various factors, such as the location of mountains, distance from the shoreline, and the characteristics of the shelf and continental slope. Tectonic activities like faulting, subsidence, and folding create distinct shapes in the reservoir geometry and sediment supply. Changes in sea level, caused by tectonic activity, affect the timing and frequency of turbidity events, which shapes the stratigraphy of the reservoir [7] [82].

Sea level variations are a major factor in the formation of turbidite systems. Variations in sea level affect the amount and characteristics of turbidity currents by affecting sediment supply, hydrodynamic conditions, and sedimentation rates. For example, because of the increasing water depth brought on by rising sea levels, there may be reduced sediment supply, which could decrease turbidity current activity. On the other hand, falling sea levels may increase the amount of sediment supply in shallower waters, which would increase turbidity current activity. As such, variations in sea level, in addition to tectonics, climate, and sedimentary processes, are a major predictor of the features of turbidite systems.

Sedimentation patterns and turbidity currents are determined by sediment concentration, slope gradient, water depth, grain size, and flow velocity. These factors are all part of the sedimentary processes, which also include basin topography, flow dynamics, and sediment supply. All of this together influences the way turbidite systems are formed and the properties of reservoirs [83].

The shape of the ocean floor, including canyons, channels, and gullies, affects how sediment is deposited in turbidite systems. The steepness of the slope determines the speed and direction of turbidity currents, which in turn affects the type and amount of sediment deposited [7] [84].

The kind of sediment being transported affects how it behaves during transport and settles, which in turn affects where it ends up in the turbidite system. The fluid that carries the sediment, determined by its density and viscosity, also plays a crucial role in shaping turbidity currents. It can change the speed and direction of the currents, which then affects how sediment is deposited [85] [86].

Changes in the amount of sediment that gets deposited in the ocean affect the thickness and composition of the deposits, which in turn affects the way that sedimentary features and turbidite deposits look. To accurately predict how a turbidite system will behave, we need to understand how tectonic activity works, because plate movements have a big impact on the structure of the ocean floor and the direction of turbidity currents [87] [88] [89].

Turbidite successions, which are rock formations created by underwater landslides, have certain characteristics that affect how easy it is for fluids to move through them. These characteristics, known as hydraulic features, determine if the formations act as barriers to fluid flow or allow fluids to move through them. This affects how easily sediment is deposited and how fluids move through the formation [90]. The interaction between turbidity currents and contour currents in distant depositional areas adds complexity, requiring a thorough understanding of their relationship and impact on the development of turbidite systems [91] [92].

The quality and dispersion of turbidite systems are affected by basin morphology, which includes factors such as slope, shape, and subsidence rates. These factors also control turbidity current courses and volumes. The creation of turbidite reservoirs is greatly facilitated by the existence of sediment bypasses and submarine canyons [93] [94] [95]. Climatic changes and sea-level fluctuations play vital roles in the regulation of turbidite systems [96]. Variations in rainfall, sediment delivery, and glacial melting influence the frequency and size of turbidity currents, thereby impacting the architecture of reservoirs. Sea-level fluctuations, influence connectivity and compartmentalization within turbidite reservoirs [97].

The way sediment moves depends on the difference in density between water from rivers and water from oceans. When river water has lower density than ocean water, it creates a hypopycnal flow. But when it has higher density, it results in a hyperpycnal flow, which directly transfers sediment from the source to the receiving basin. The distance that the sediment travels also affect how mature it is when it reaches the ocean [98] [99] [100].

9. Discussion

Turbidite systems commonly exhibit distinctive geomorphological features, notably channels and submarine canyons. Submarine canyons, in particular, serve as significant conduits for the transportation of sediment from continental shelves to abyssal plains, thereby influencing the distribution of reservoirs and sedimentation processes.

The identification of four distinct channel types, denoted as canyons, channel complexes, convex channels, and U-shaped channels, contributes significantly to the understanding of turbidite reservoirs. Canyons, characterized by their profound, steep-walled valleys exhibiting a V-shaped profile, are outcomes of erosion processes, frequently carved by turbidity currents. Submarine canyons, located underwater on the continental slope, manifest this distinctive V-shaped profile. The observed V-shaped canyons within the designated study area (**Figure 2**) are likely attributed to the erosive impact of rivers such as the Ankobra, Tano, and Pra, owing to the prolonged down-cutting action of their flowing waters.

Channel complexes represent interconnected channels within a sedimentary basin, showcasing variations in size, shape, orientation, and channel types. Constituting a network of channels, these complexes are associated with depositional environments influenced by processes like river or tidal currents. The sedimentary deposits within channel complexes exhibit heterogeneity, reflecting variations in energy conditions, sediment supply, and depositional processes.

The comprehension of channel complexes facilitates the discernment of reservoir-quality rock distribution and the connectivity of different reservoir components, offering invaluable insights for effective reservoir management and hydrocarbon extraction strategies. Visual representations of these channel types in **Figure 2** and **Figure 3** provide an overview of their geological characteristics. For example, **Figure 3** illustrates convex channels and U-shaped channels, with the former appearing wider compared to the latter, which appears deeper and narrower.

The thalweg, an imaginary line tracing the lowest points along a riverbed or valley floor, signifies the path of maximum water flow, following the deepest parts of the river channel, where sediment transport is high, as depicted in **Figure 2**.

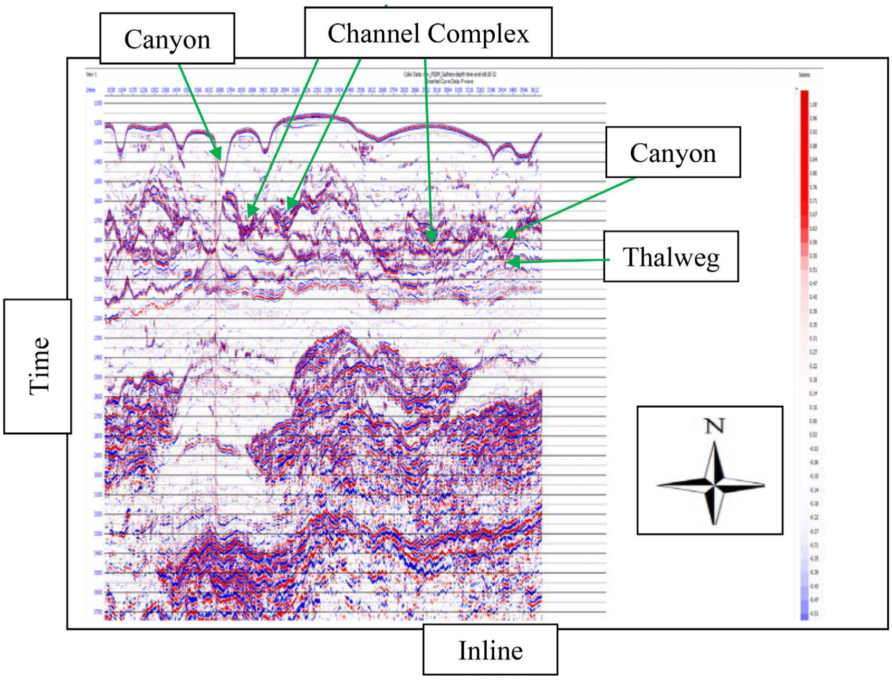

Figure 2. Canyon and channel complex on seismic.

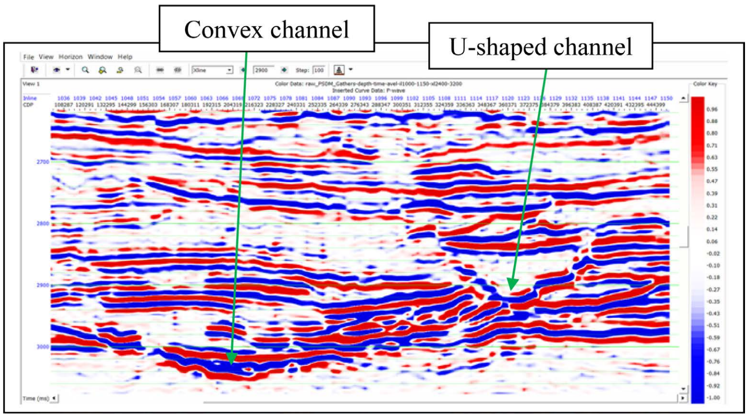

Figure 3. Convex channel and U-shaped channel on seismic.

In a convex channel, the banks slope away from each other, with the channel bed rising toward the center. This configuration concentrates water flow in the center and often leads to sediment deposition and the development of bars or islands.

A U-shaped channel, resembling a "U-shaped valley" or "U-shaped canyon," is a distinctive feature reminiscent of glacial valleys. Its broad U-shaped cross-section is characterized by steep, straight sides and a relatively flat or gently sloping floor, primarily formed by the erosive action of glaciers. **Figure 3** provides a visual representation of these channels.

The basal lag, a distinctive sedimentary facies predominantly composed of coarse-grained materials such as gravel or sand, serves as a key marker bed in turbidite sequences. It lacks discernible structure and signifies initial sediment deposition resulting from turbulent flows. Often located at the lowest part of river channels, basal lags can also be observed in bars within the river channel, such as point bars or mid-channel bars, formed by sediment deposition in areas with reduced flow velocity. **Figure 4** offers a visual representation of the basal lag.

Channel levees are elevated embankments or ridges found alongside a river channel, typically formed through sediment deposition during flooding events when the river spills over its banks. Functioning as natural barriers, these levees confine the river within a specified channel, preventing overflow onto the adjacent floodplain during regular flow. Their structure commonly exhibits distinct layers, with coarser sediments at the base and finer particles at the top, a consequence of sequential deposition during flooding. In natural river management, channel levees play essential roles as barriers, curbing excessive meandering of the river channel and providing protection against flooding. Additionally, these levee structures significantly influence the overall architecture of reservoirs. **Figure 5** illustrates a channel levee in action.

Channel lobes form within river channels when sediment-laden flows enter deeper basins, decelerate, and deposit materials in cone or fan-shaped structures. These lobes gradually extend into the basin, accumulating diverse sediments like sand, shale, and mud. Channel lobes possess reservoir qualities, hosting valuable hydrocarbon deposits and serving as significant targets for exploration. Turbidity currents, with their high erosive potential, contribute to the removal and deposition of materials in these lobes. Channel lobes may exhibit reservoir characteristics distinct from other sedimentary deposits like levees or point bars, showing heterogeneity in sediment types and structures. **Figure 4** provide visual representations of massive lobe structures that can be promising targets for exploration.

The organization of sedimentary layers within turbidite systems plays a pivotal role in the formation of hydrocarbon reservoirs. Numerous factors, such as sediment supply, sediment concentration, flow velocity, and sediment composition, contribute to the arrangement of these layers, ultimately influencing the configuration and distribution of reservoirs. **Figure 4** depicts a turbidite system

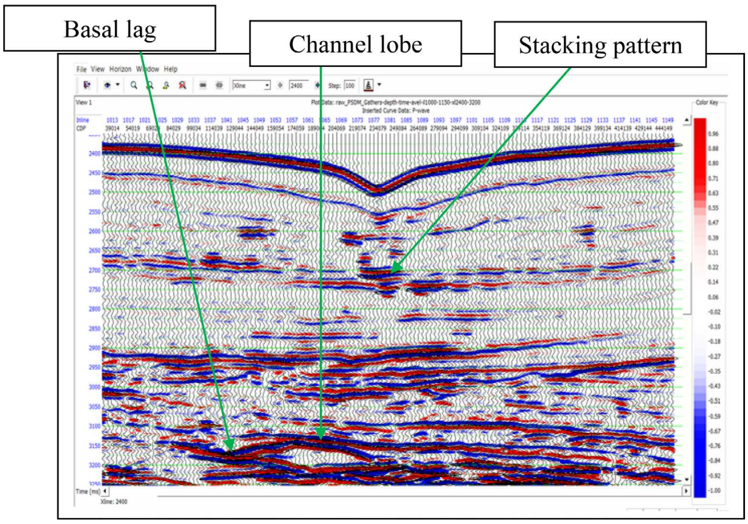

Figure 4. Basal lag, channel lobe and stacking pattern on seismic.

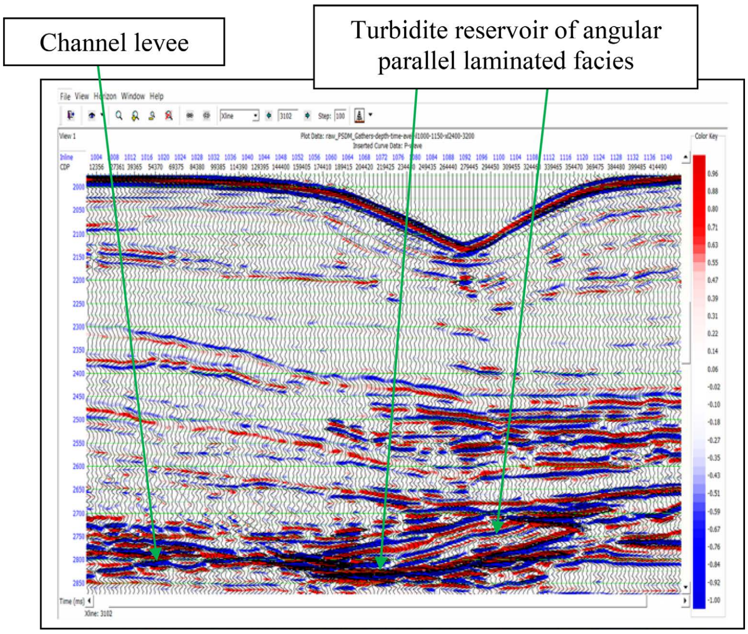

Figure 5. Channel levee and turbidite reservoir of angular parallel laminated facies on seismic.

with stacked layers, while **Figure 5** provides a seismic illustration of a turbidite reservoir characterized by angular parallel laminated facies.

Channelized sandstones are deposits of sediment that form in channels eroded into underlying deposits. They have coarser sandstones than the surrounding areas and display a pattern of getting coarser towards the top. These deposits are important because they often contain the highest-quality reservoir rock. **Figure 6** is a visual representation of channelized sandstones inside the channels.

Turbidite systems have specific patterns and sequences. These are influenced by changes in sediment supply, flow dynamics, and basin subsidence. They are favourable for reservoir development because of the distinctive stacking patterns of sand bodies. The sediment layers' arrangement in turbidite systems plays a

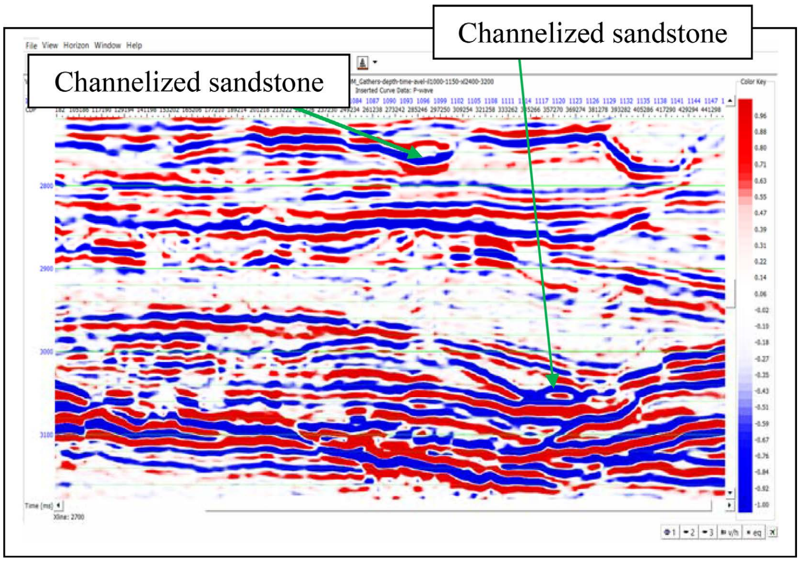

Figure 6. Channelized sandstones.

significant role in hydrocarbon reservoir formation. Channel stacking is a common feature in turbidite systems and reveals two distinct migration architectures within the same channel complex: lateral migration and vertical stacking patterns. Lateral migration patterns show earlier water breakthrough and higher gas-to-oil ratios. The continuity of these heterogeneities has a significant impact on recovery factors, with effects magnifying over time. Meandering channels in turbidite systems exhibit diverse stacking patterns that range from lateral migration to vertical stacking in cutoff regions. Analyzing sedimentary formations and stacking patterns provides insights into past climatic and tectonic events. Vertical stacking may indicate minimal channel migration, while lateral stacking suggests migration in a specific direction. Understanding stacking is crucial for identifying turbidites and comprehending reservoir distribution, influencing well-design strategies for optimal production. Most turbidite systems also manifest repeated channel cutting and filling, evident in seismic profiles. Channels undergo cycles of filling, followed by erosion and further filling. The complex internal stratigraphy resulting from repeated cutting and filling poses challenges in reservoir characterization. This cyclic process, common in turbidite systems, underscores their role as long-term conduits for transporting sediments along slopes over millions of years. Figure 7 is a visual representation of stacking patterns and repeated cutting and filling.

The shape, size, and slope of a basin have a significant influence on turbidite systems. They affect where turbidity currents flow and how they deposit sediment, which in turn affects the quality, distribution, and formation of reservoirs in these systems. The steepness of the basin's seafloor plays a critical role in triggering turbidity currents. Steeper slopes can cause gravitational instability that initiates turbidity currents. The gradient of the seafloor also affects the speed and energy of the current, which impacts its ability to transport and deposit sediment. The shape of the basin can also influence the direction and characteristics of turbidity currents. Smaller, more confined basins may channel turbidity currents, directing them along specific pathways. Furthermore, the size of the basin affects how much sediment it can hold over time. Larger basins have more space to accommodate sediments and can host extensive turbidite systems. Figure 8 provides an example of a gently sloping basin with a slope oriented from east to west.

The angular parallel laminated facies, which are distinct horizontal layers observed in sediment deposits, indicate an even deposition process. This occurs when particles settle in a calm environment from turbidity currents. The angular parallel laminated facies characterize a sedimentary rock type that is formed through organized, layered sediment precipitation from turbulent water flows in a tranquil settling environment. Figure 5 shows the parallel layering that is typical of this type of sedimentary rock.

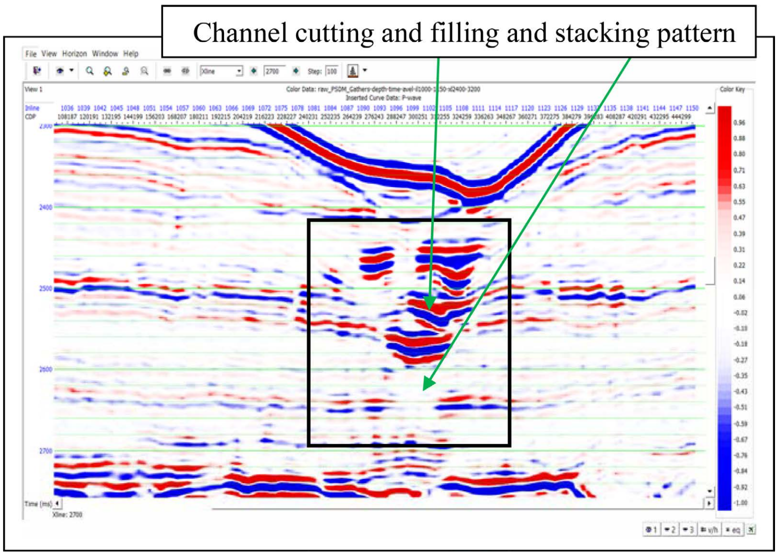
Channel cutting and filling and stacking pattern

Figure 7. Channel cutting and filling and stacking pattern.

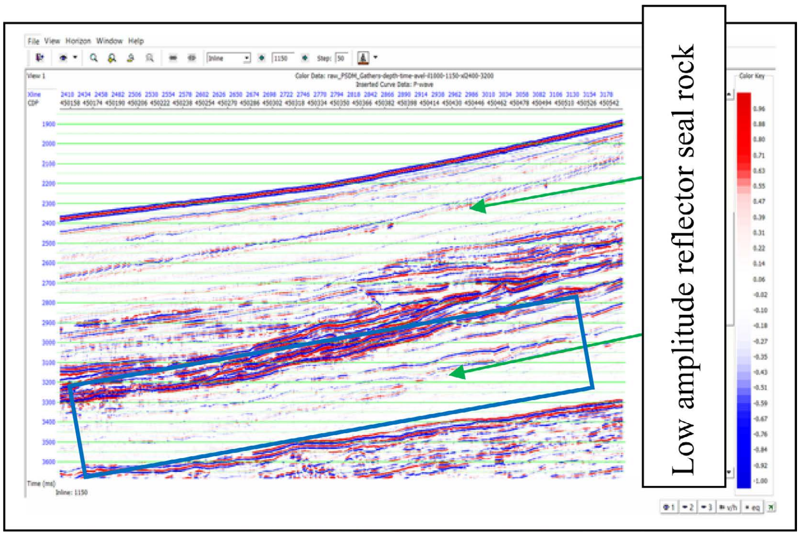
Low amplitude reflector seal rock

Figure 8. The regional seal shale rock and the topography of the basin are critical elements. The seal rock plays a crucial role in trapping hydrocarbons within reservoirs.

10. Conclusion

This study aims to investigate the intricate processes governing the formation of hydrocarbon reservoirs within the Tano Basin, with a particular focus on turbidite systems. The research highlights the significance of comprehending geological phases spanning millions of years, encompassing organic matter accumulation, hydrocarbon migration, and trapping within structural and stratigraphic traps. The research emphasizes the crucial role of various factors in hydrocarbon accumulation, such as source rock richness, temperature, pressure conditions, and geological structures. Furthermore, the study extends to fluvial channel features, examining sinuosity and hydraulic properties, which play a significant role in shaping landscapes and influencing hydrocarbon exploration. The exploration of turbidite systems reveals a complex interplay of factors, including tectonics, sea-level variations, and sedimentation patterns, which impact reservoir formation. Identifying geomorphological features like channels, submarine canyons, and distinct channel types becomes crucial for understanding sediment transport, reservoir development, and depositional environments. A detailed examination of turbidite channel structures, including canyons, channel complexes, convex channels, and U-shaped channels, offers valuable insights for effective reservoir management and hydrocarbon extraction. The presence of basal lag, channel levees, and channel lobes within turbidite systems adds further complexity, serving as potential exploration targets. Sedimentary layer organization, stacking patterns, and angular parallel laminated facies within turbidite systems become important considerations for identifying turbidites, understanding reservoir distribution, and optimizing well-design strategies. The study underscores the dynamic nature of turbidite systems due to various contributing factors, emphasizing the significance of basin characteristics such as shape, size, and slope. Overall, the research contributes to understanding the geological dynamics shaping hydrocarbon reservoirs, offering valuable insights for successful exploration, reservoir management, and the sustainable exploitation of petroleum resources.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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