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An In-Depth Review of Petroleum System Elements in Maui Field, Taranaki Basin: Analyzing Accumulation and Charging Histories

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Abstract

Extensive research has been undertaken to model the petroleum system of the Maui Field within the Taranaki Basin, New Zealand. Nevertheless, there are persistent uncertainties surrounding its intricate petroleum system, the processes of hydrocarbon generation, and migration. Despite its status as New Zealand's largest petroleum producer, the historical account of hydrocarbon formation, migration, and charging in this field remains largely enigmatic. This systematic literature review offers a comprehensive summary of recent advancements and various scenarios pertaining to the accumulation and migration of hydrocarbons in the Maui Field, situated within the Taranaki Basin. The insights derived from this review hold substantial significance for both scholars and industry professionals, providing guidance for future research and enhancing the oilfield sector's capacity to assess hydrocarbon potential and gain a deeper understanding of the petroleum system operating within this basin.

Subject Areas

Geology

Keywords

Hydrocarbon Migration Scenarios, Maui Field, Systematic Literature Review, Uncertainties, Basin Modeling

1. Introduction

The Maui Gas Field, New Zealand's largest hydrocarbon-producing field situated in the southern Taranaki Basin, spans an extensive 150 square kilometers

(Figure 1). Its discovery in 1969 marked a significant milestone in offshore energy exploration and exploitation. Hosting the immense Maui Deposit, with over 6 trillion cubic feet of gas as per [1], this field stands as the country's most substantial gas reservoir. However, a notable geographical separation exists between the Maui Field, divided by the significant Cape Egmont Fault Zone, and the likely source region for gas expulsion, as highlighted by [2]. This source area, known as the Maui sub-basin, originated as a rift graben during the Cretaceous era within the southern Taranaki Basin, as outlined by [3] (refer to Figure 1). Despite likely reaching the required maturity for gas release during the Neogene era, the Maui Field grapples with geological challenges owing to this separation [4].

Given the pivotal role that the Maui Field plays in New Zealand's energy landscape and the increasing interest in exploring similar Paleogene coastal margin plays in the offshore region, it's somewhat surprising that there has been relatively little published information regarding the overall Maui petroleum system. Specifically, there is a dearth of research on the topics of petroleum migration and the charge mechanisms that have fueled the Maui Field.

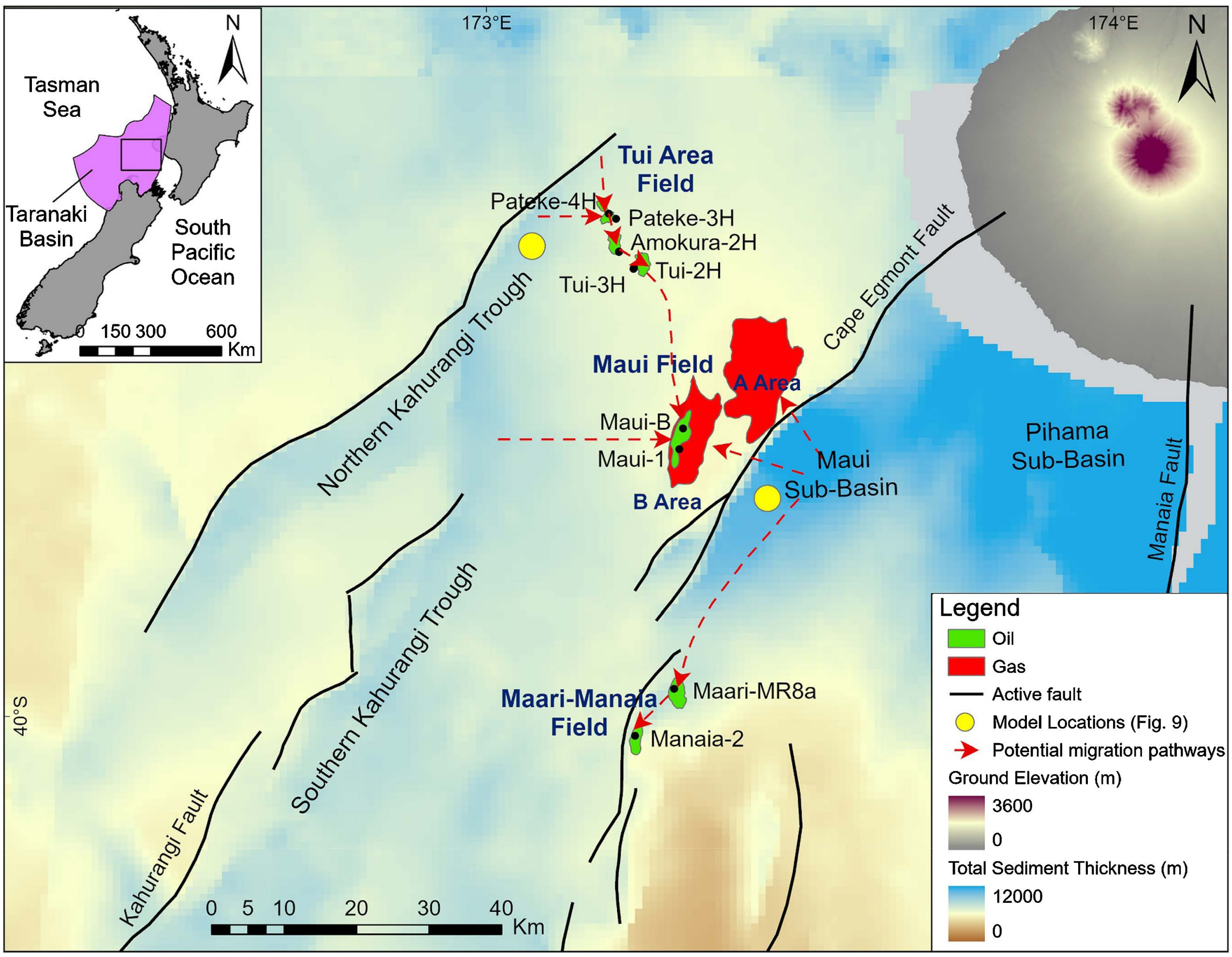

Figure 1. Map showing location of the study Maui field [5].

We shall embark on an exploration of a myriad of intriguing scenarios regarding the infusion of oil and gas into the illustrious Maui Field, exquisitely depicted in **Figure 2**. One of these captivating scenarios unfolds with the simultaneous infusion of both oil and gas originating from the enchanting Maui sub-basin, gracefully situated in the east. The ballet of hydrocarbon migration elegantly waltzes across the stage of the Cape Egmont Fault. In this entrancing narrative, we envision the grand overture commencing with the initial ballet of oil during the Middle and Late Miocene's dramatic pas de deux of contractional deformation. This is then followed by a splendid encore, where gas takes the spotlight during a reawakened performance of extension structures [2].

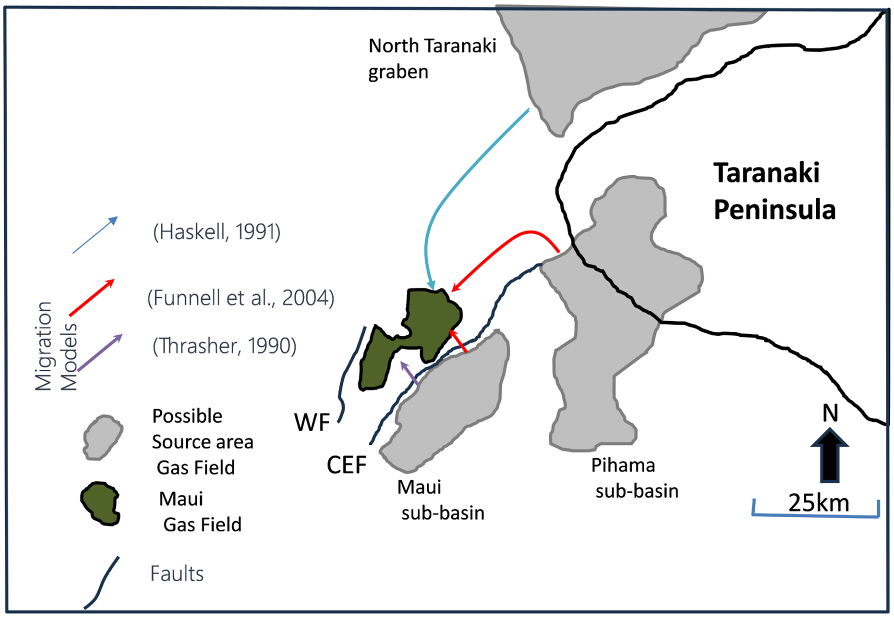

Figure 2. Visualization illustrates potential migration pathways for the charge of the Maui gas-condensate Field, from the source rocks of the Rakopi Formation in the Taranaki Basin, modified after [2].

On the other hand, Thrasher put forth an unconventional concept, indicating that the Maui aggregations are in a state of perpetual transformation. As per this viewpoint, hydrocarbons embark on a southward journey from the Northern Trench, resulting in the graceful transition of oil from the A-region to the B-region. This paradigm of movement draws its inspiration from the current architectural tendencies discerned within the field [5] [6].

The varying hypotheses regarding petroleum charge and migration mechanisms underscore the complexity of the Maui Field's geology and highlight the need for further research and exploration to gain a more comprehensive understanding of this critical hydrocarbon reservoir. The Taranaki Basin, located in northwestern New Zealand, preserves a rich geological past that traces the evolution of the Zealandia continent. This evolution encompasses a series of geological events, from the initial rifting of the Gondwana margin to the eventual development of a convergent plate boundary [7] [8].

1.1. Geological Setting

The geological story of the Taranaki Basin begins in the mid-Cretaceous with a two-phase rifting process [8]. This intricate unfolding eventually resulted in the disentanglement of Zealandia from the supercontinent Gondwana, birthing the Tasman Sea during the waning epochs of the Late Cretaceous [9]. The Late Cretaceous separation gave rise to a series of geological theaters, ushering in the creation of subsurface troughs, among them the Maui sub-basin nestled in the southern reaches of the Taranaki Basin [7] [10]. These subterranean theaters later became the receptacles for substantial accumulations of sedimentary layers, with the Pakawau Group embracing deposits amassing up to a staggering 4200 meters in depth. Within this ensemble, one encounters the Rakopi and North Cape formations [7].

Rifting persisted in parts of the basin until the late Paleocene, approximately 55 million years ago [3]. During the Paleocene and Eocene epochs, sedimentation in the southern Taranaki Basin continued with the deposition of terrestrial, coastal, and shallow marine sediments in extensional and passive margin settings. These sediments progressively covered the remaining basement highs. Periods of transgression and regression resulted in the formation of interbedded heterolithic successions and lithofacies ranging from sandy to muddy estuarine, shoreface, and shallow marine deposits. These deposits are associated with the Paleocene Farewell Formation and the Eocene Kaimiro and Mangahewa formations, collectively known as the Kapuni Group [11].

The Late Eocene marked a significant shift in tectonic activity, as movement along the Taranaki Fault to the east of the basin initiated convergent tectonic deformation [12]. This event preceded the eventual formation of a convergent plate boundary to the east of New Zealand, a process that unfolded from the Oligocene to the Late Miocene. As tectonic deformation occurred, the Taranaki Basin began to submerge, initiating the deposition of the transgressive Late Eocene Turi Formation. This submergence continued into the Oligocene and Early Miocene periods, resulting in the accumulation of mud- and carbonate-rich deep-water sedimentary formations such as the Tikorangi and Manganui formations [7] [11].

The geological landscape continued to evolve as structural changes occurred during the development of the plate boundary to the east of the Taranaki Basin. Simultaneously, climatic and oceanographic changes influenced sedimentation patterns. In the Middle Miocene, the Moki Formation marked the presence of sandy basin floor sedimentary systems **Figure 3**. This phase was followed by the rapid expansion of shelf environments in the Late Miocene [7] [13]. Strata in the southern Taranaki Basin experienced deformation and erosion during Late Miocene inversion along the Central Eastern Fault Zone and other structural features, before shelfful sedimentation resumed [10].

This reconstructed geological setting provides a glimpse into the dynamic history of the Taranaki Basin, highlighting the interplay of tectonic, sedimentary, and climatic factors that have shaped the region over millions of years (**Figure 3**).

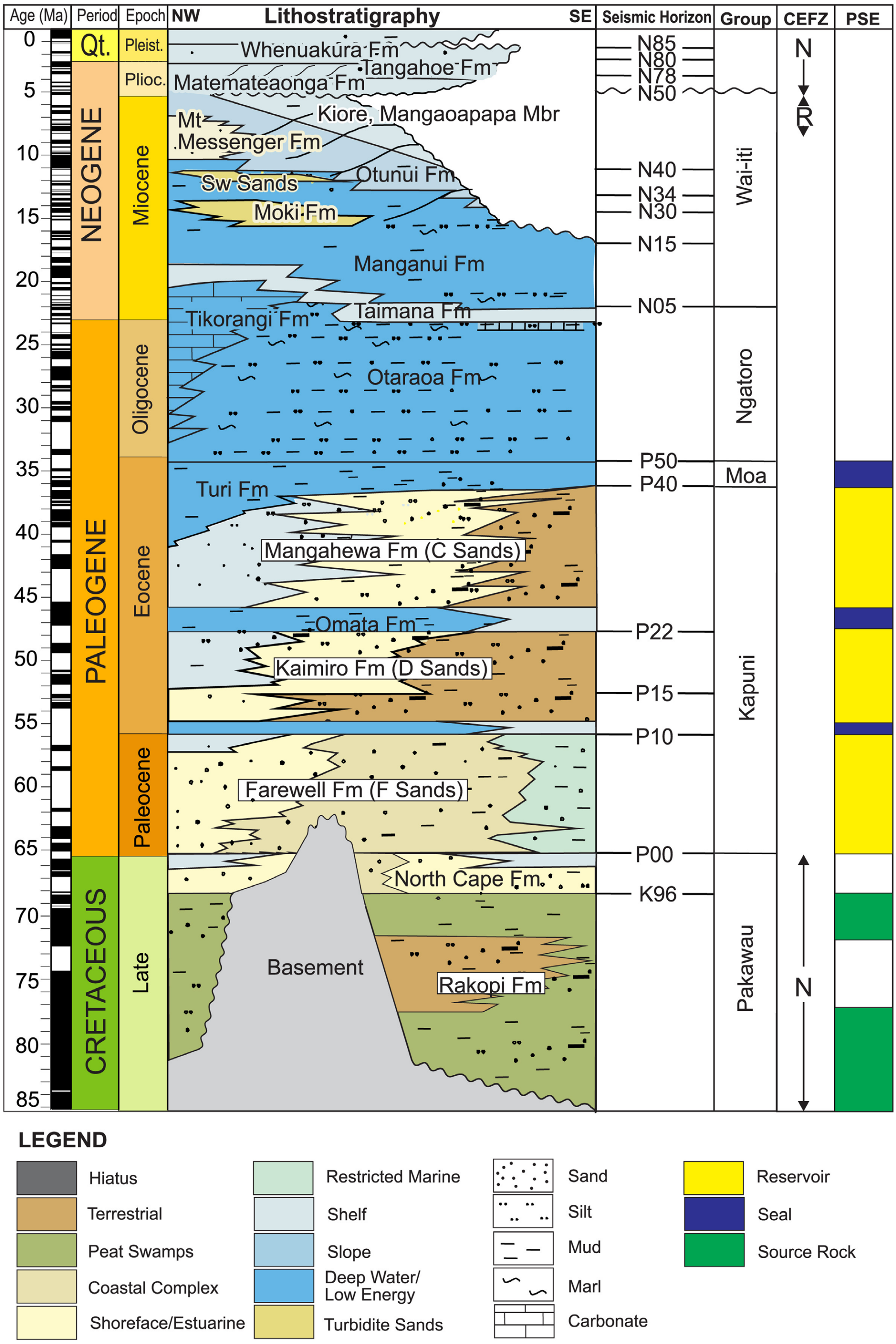

Figure 3. Stratigraphy of central southern Taranaki Basin after [13].

1.2. Structural Setting

The structural setting of the Cape Egmont Fault Zone (CEFZ) is characterized by a series of geological features and tectonic events in the southern and central Taranaki Basin. Here is an overview of the structural setting:

Fault System: The CEFZ is a prominent fault system that extends for approximately 70 kilometers. It follows a specific orientation, striking between 035˚NE and 065˚ENE. This fault system has been extensively studied and documented by geologists [6] [14].

Regional Lineament: The CEFZ is part of a larger structural lineament that stretches over 200 kilometers in a NE-SW direction (**Figure 4**). This lineament runs through the central portion of the southern Taranaki Basin. It includes not only the CEFZ but also other faults, such as the Maari and Wakamarama faults located to the southwest of the CEFZ [6] [10].

Tectonic Phases: Late Cretaceous Extension (ca. 80 - 65 Ma): During this geological period, the central southern Taranaki Basin experienced a phase of extension. The CEFZ played a significant role during this time, forming the western boundary of a half graben. The fault system accumulated up to 3 kilometers of normal movement, contributing to the geological landscape of the region [10].

Late Miocene Contraction (ca. 7.5 - 5.5 Ma): Following a period of relative geological quiescence during the Paleogene and Neogene, the Late Miocene witnessed a phase of tectonic inversion. This inversion was a response to increased rates of shortening along the Hikurangi margin, resulting in erosion on the eastern hanging wall side of the CEFZ and uplift to the west. The Whitiki Fault, a smaller NW-SE oriented inversion structure, also played a role in this phase [15].

Pliocene-Recent Extension (ca. 5 - 0 Ma): In more recent past, the CEFZ experienced renewed normal movement. This extension phase, which began in the Pliocene and continues to the present, resulted in further geological changes, including the rapid burial of the Maui sub-basin [14].

Accommodation Zones and Offsets: The CEFZ is separated from the Maari and Wakamarama faults to the south by a synrift accommodation zone. Additionally, in the northern Taranaki Basin, there are extensional structures offset to the northwest at the Taranaki Peninsula.

Secondary Faults: Within the CEFZ, several secondary faults are present, and some of these have been mapped (**Figure 4**). These secondary faults add complexity to the structural setting and can influence local geological features.

1.3. Tectonic Setting

The formation of the Taranaki Basin played a crucial role in the breakup of the supercontinent Gondwana, leading to the separation of Zealandia from Antarctica and Australia. This geological event was marked by the deposition of substantial

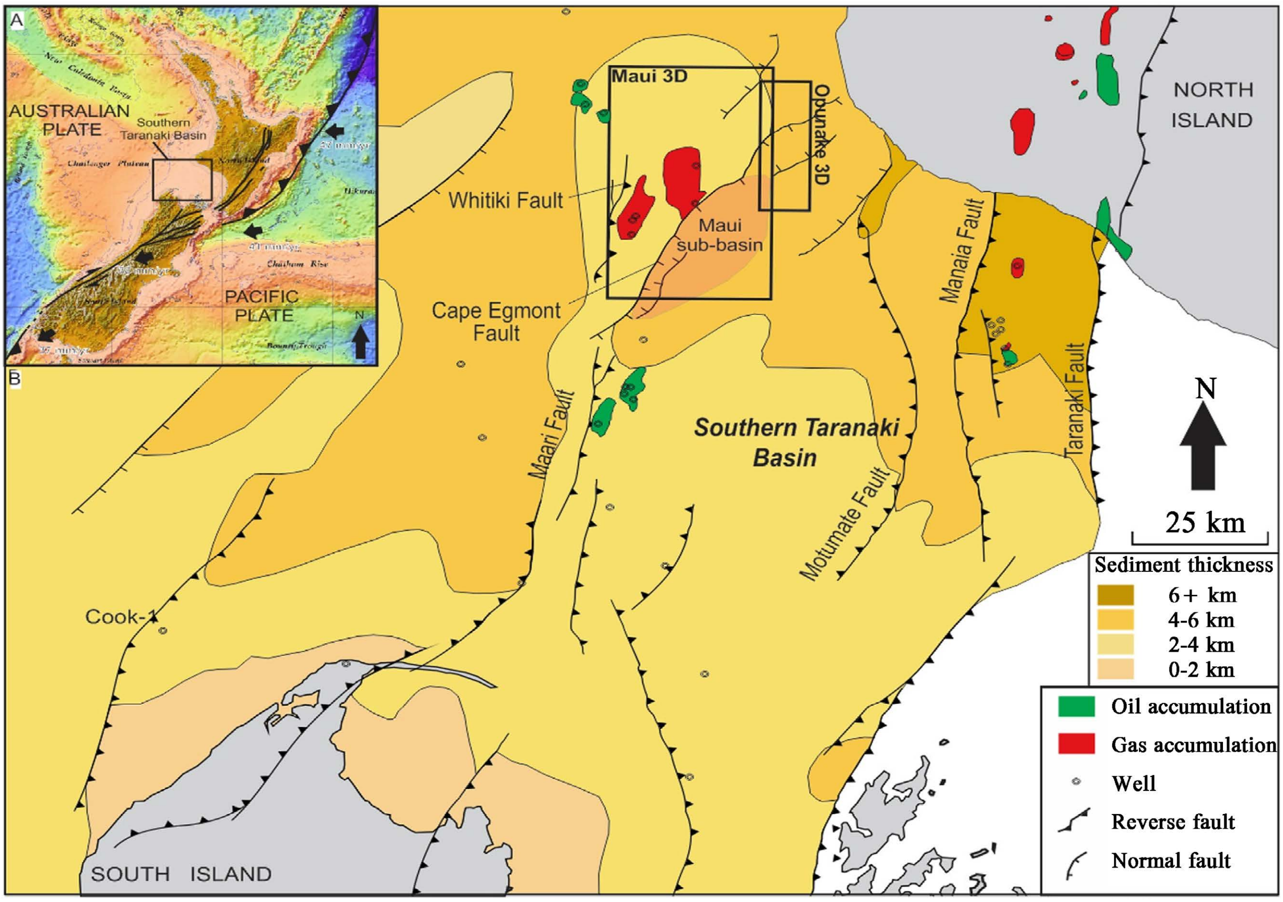

Figure 4. Map of the Southern Taranaki Basin, illustrating some of the basin's major structures [7] [16].

sedimentary layers during the Cretaceous and Paleogene-Neogene periods, which covered the pre-existing Jurassic metasediments and the ancient Precam brian basement [13]. While there has been considerable discussion about the Gondwana breakup and the key elements of the Cretaceous-Paleogene rifting phase in Zealandia [7] [13], less is known about the factors influencing the infill of such a massive basin with sediments over geological time.

The Taranaki Basin encompasses various tectonic elements, including rift-related transform faults, passive margins, subsidence linked to emerging subduction, foreland basins, subduction-related transform faults, volcanic arcs, fold-thrust belts, and back-arc rifts. During the Oligocene-Neogene period, plate boundary deformations mainly affected the southern and eastern regions of the Taranaki Basin, while the western parts remained relatively unaffected [3]. The Oligocene-Neogene convergence between the Pacific and Australian plates significantly modified the previous tectonic phases within the Taranaki Basin [10].

The primary hydrocarbon source rocks in the region date back to the Late Cretaceous, Paleocene, and Eocene periods and were mainly formed during a period of normal faulting. Interestingly, most hydrocarbon accumulations are found in fault-related anticlines that developed over the last 30 - 40 million years due to compressional forces associated with the subduction of the Pacific Plate east of New Zealand (**Figure 4**). These compressional structures were subsequently intersected by Late Miocene and more recent normal faults in many cases, possibly due to the eastward rollback of the Pacific Plate. Some of these later faults may have had adverse effects on seal integrity [7] [10].

Recent Tectonic Activity: Evidence of episodic failure and ongoing tectonic activity is observed on the seafloor, suggesting that the CEFZ continues to play a role in shaping the region's geology in recent times [14].

In summary, the structural setting of the Cape Egmont Fault Zone is characterized by its role in both extensional and contractional phases throughout its geological period, its association with a larger regional lineament, and its complex interaction with other fault systems and geological features in the Taranaki Basin (**Figure 4**).

1.4. Petroleum System

The central Taranaki Basin is home to a number of producing oil and gas fields (**Figure 4**). Fluids in these fields have been typed back to coaly source rocks of the Late Cretaceous Rakopi Formation [17]. Oil and gas are produced from Paleogene nearshore intervals. Paleocene and Eocene shoreface, estuarine, and coastal plain sandstones are interbedded with shallow marine and estuarine/coastal mudstones and siltstones (**Figure 4**) reflecting intermittent shoreline transgression and regression and change in sedimentary environments [7] [11]. Oil discovered in the overlying Miocene deepwater Moki Formation sands is also typed to the Rakopi Formation [17]. The Maui Field was discovered in 1969 and, at that time was considered to be one of the largest offshore gas fields in the world. The main accumulations of the field reside in two broad anticlinal closures, Maui "B" in the southwest and Maui "A" to the northeast [16]. The Maui B area is bound to the southwest by the Whitiki Fault, a Late Miocene reverse fault and associated hanging wall anticline that inverted a Cretaceous normal fault [7] [10]. Specifically, the Tui Area oils exhibited significantly higher (more radiogenic) Osi values, indicating that they probably originated predominantly from the Rakopi Formation in the Kahurangi Trough. In contrast, the Maui and Maari-Manaia oils had less radiogenic Osi values, suggesting a greater contribution from the North Cape Formation in the Maui sub-basin. However, it's important to note that further samples are required to validate and strengthen this hypothesis.

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The review article encompasses a thorough analysis of various facets of the Maui Field's geological and petroleum system, shedding light on crucial aspects influencing hydrocarbon reserves. The comprehensive examination of the geohistory, structural setting, tectonic evolution, petroleum system, seal rocks, hydrocarbon migration, and prospects offers an insightful overview of the field's significance within the Taranaki Basin [18].

The implications drawn for future exploration and production activities underscore the need to reconsider established models and geological concepts, potentially leading to the discovery of new hydrocarbon reserves. The complex hydrocarbon distribution and charge model developed offer a comprehensive framework for understanding the field's history and can serve as a template for similar studies elsewhere [18].

The review also presents a well-structured hypothesis regarding hydrocarbon migration and accumulation in the Maui Field. It discusses the geological barriers and continuous migration pathways influencing hydrocarbon movement, featuring contrasting viewpoints such as Thrasher's theory and Funnell's barrier proposition [2].

Furthermore, the support from regional migration evidence aligns with proposed charge directions, contributing to a more comprehensive understanding of hydrocarbon movement within the basin [19].

Overall, this systematic literature review offers valuable insights into the complex petroleum system of the Maui Field. It not only enhances existing knowledge but also provides guidance for exploration efforts, regulatory considerations, and encourages further research in the hydrocarbon exploration and production domain within the Taranaki Basin, benefiting scholars and industry professionals alike.

To conduct a thorough and efficient systematic literature review, it is crucial to develop Specific research questions. For this review, the following questions were formulated:

- What are the key uncertainties and knowledge gaps in understanding the petroleum system of the Maui Field, including hydrocarbon generation, migration, and charging processes?
- How can the findings from this systematic literature review benefit scholars and industry professionals?

2. Methodology

A systematic literature review is conducted in this study to address the persistent uncertainties surrounding the petroleum system of the Maui Field within the Taranaki Basin, New Zealand, **Figure 5**. Despite being the country's largest petroleum producer, the historical narrative of hydrocarbon formation, migration, and charging in this field remains shrouded in mystery. This systematic literature review aims to provide a comprehensive summary of recent advancements and diverse scenarios related to hydrocarbon accumulation and migration in the Maui Field.

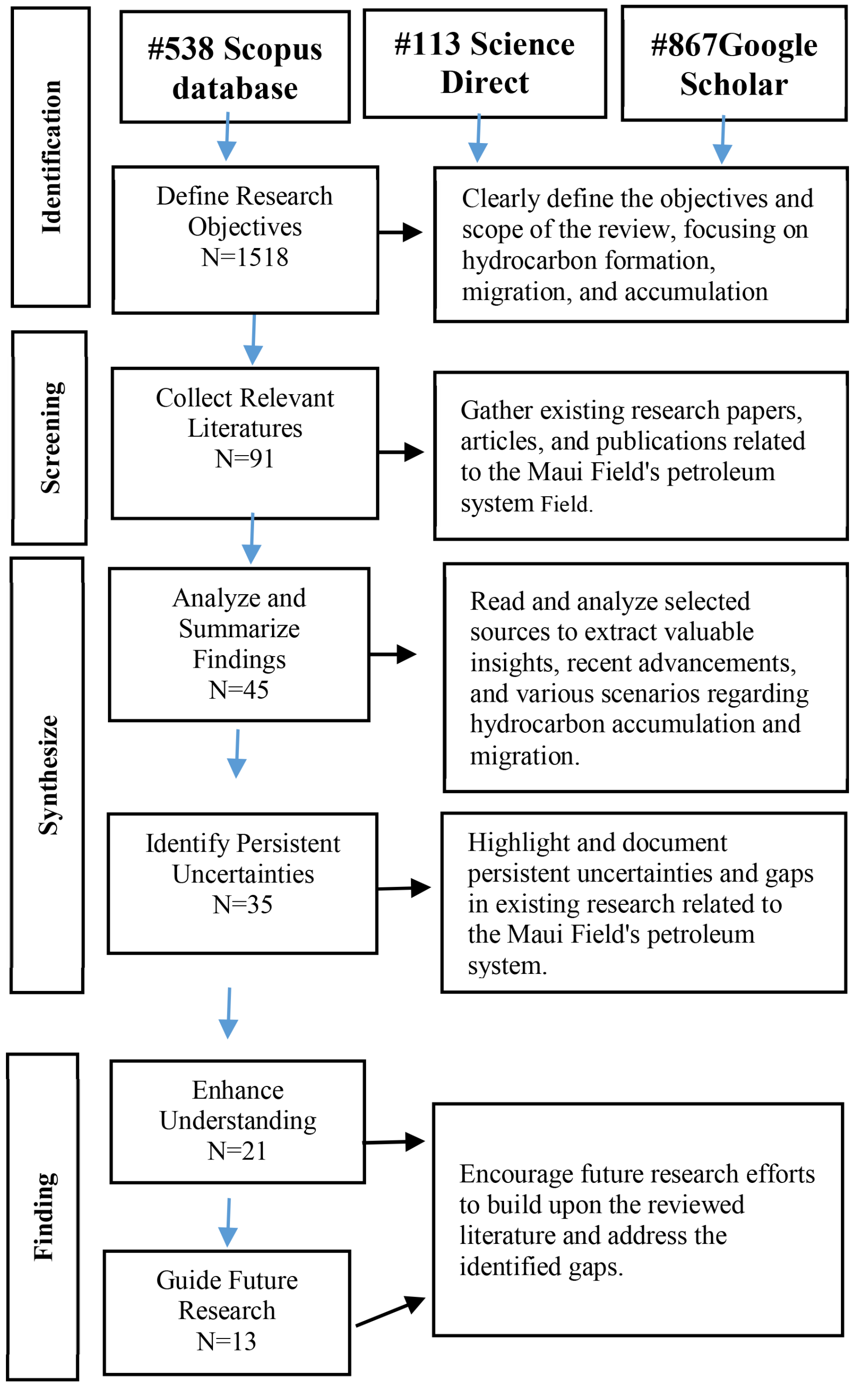

Figure 5. Flowchart outlines the key steps involved in a systematic literature review process.

2.1. Data Collection

The systematic literature review presented in this study involved a comprehensive search for relevant academic articles, reports, and industry publications related to the petroleum system of the Maui Field in the Taranaki Basin, New Zealand. The data collection process followed these key steps:

Database Selection: We conducted searches on various academic databases, including but not limited to Scopus, Web of Science, and Google Scholar. A combination of controlled vocabulary terms and free-text keywords was used to maximize the scope of the search. These terms included "Maui Field", "hydrocarbon generation", "petroleum migration" and related variations.

Inclusion and Exclusion Criteria: To ensure the relevance and quality of the selected literature, we established specific inclusion and exclusion criteria. Included sources had to be peer-reviewed articles, reports from reputable geological agencies, and industry publications related to the Maui Field's petroleum geology. Non-English publications were translated when necessary.

Data Extraction: A structured data extraction form was used to collect essential information from each selected source, including publication details, study objectives, methodologies employed, key findings, and any scenarios or models related to hydrocarbon generation, migration, and accumulation in the Maui Field.

2.2. Data Analysis

The collected data were systematically analyzed to identify trends, common themes, and variations in the understanding of the petroleum system in the Maui Field. This involved the following steps:

Categorization: Literature was categorized based on thematic areas, such as hydrocarbon migration pathways and historical geological context.

Synthesis: Key findings, hypotheses, and models presented in the selected literature were synthesized to provide a comprehensive overview of the current state of knowledge regarding the Maui Field's petroleum system.

2.3. Quality Assessment

To ensure the reliability and rigor of the literature included in this review, a quality assessment was conducted. This assessment considered factors such as the methodology employed, data sources, and the credibility of the authors and institutions involved.

2.4. Presentation of Results

The results of the systematic literature review are presented in a structured manner, highlighting key advancements, uncertainties, and various scenarios related to hydrocarbon accumulation and migration in the Maui Field. The findings are organized thematically to provide clarity and facilitate the extraction of insights.

This "Materials and Methods" section outlines the systematic approach taken to collect, analyze, and present the relevant literature for the review, ensuring transparency and rigor in the research process. Researchers can adapt and expand upon these methods to conduct their systematic literature reviews effectively.

3. Results and Discussion

Our research provides a comprehensive overview of the geological and petroleum system aspects of the Maui Field in the Taranaki Basin, New Zealand. It delves into several key areas, highlighting the field's geologic as well as structural setting, tectonic evolution, and the associated petroleum system (**Table 1**).

Table 1. Provides a concise overview of the main points and references related to the hydrocarbon migration in the Maui Field.

Aspect of hydrocarbon migration	Description	Reference
Geological "Kitchen" for Hydrocarbons	The initial oil charge may have originated from the Pihama or Maui sub-basin	[2]
Temporal change	The petroleum flow through the fault zone and a transition to shallower strata during the Pleistocene, indicating evolving hydrocarbon flow patterns.	[16]
Thrasher's Theory	Proposed hydrocarbon flow during Late Miocene and Early Pliocene	[13]
Vertical Migration	Describes the movement of hydrocarbons vertically along fault surfaces, potentially by passing the sealing capacity of the fault to prevent horizontal (cross-fault) flow.	[17]
Supporting Evidence for Regional Migration	Proposed charge directions align with regional up-dip migration patterns from the Pihama sub-basin.	[20]
Faults and Hydrocarbon Migration	Faults in geological formations can act as both conduits and barriers for the migration of hydrocarbons.	[21]

3.1. Petroleum System

The review article encompasses a thorough analysis of various facets of the Maui Field's geological and petroleum system, shedding light on crucial aspects influencing hydrocarbon reserves. The comprehensive examination of the geology, structural setting, tectonic evolution, petroleum system, seal rocks, hydrocarbon migration, and prospects offers an insightful overview of the field's significance within the Taranaki Basin [18].

The investigation into the timing of closure and rapid migration elucidates critical phases in the reservoir's history, indicating cessation of hydrocarbon influx and subsequent dynamic geological processes. Highlighting fault zones' role in hydrocarbon migration challenges conventional assumptions, potentially reshaping exploration strategies in similar geological settings.

The implications drawn for future exploration and production activities underscore the need to reconsider established models and geological concepts, potentially leading to the discovery of new hydrocarbon reserves. The complex hydrocarbon distribution and charge model developed offer a comprehensive framework for understanding the field's history and can serve as a template for similar studies elsewhere [18].

The review also presents a well-structured hypothesis regarding hydrocarbon migration and accumulation in the Maui Field. It discusses the geological barriers and continuous migration pathways influencing hydrocarbon movement, featuring contrasting viewpoints such as Thrasher's theory and Funnell's barrier proposition [2].

Furthermore, the support from regional migration evidence aligns with proposed charge directions, contributing to a more comprehensive understanding of hydrocarbon movement within the basin [19].

Overall, this systematic literature review offers valuable insights into the complex petroleum system of the Maui Field. It not only enhances existing knowledge but also provides guidance for exploration efforts, regulatory considerations, and encourages further research in the hydrocarbon exploration and production domain within the Taranaki Basin, benefiting scholars and industry professionals alike.

3.2. Timing of Geological Events

Understanding the timing of geological events is essential for deciphering the history and formation of the Maui Field:

Tectonic Evolution: The timing of tectonic events, including plate movements and regional geological activities, is crucial for understanding how the geological features of the Taranaki Basin and the Maui Field were shaped over time. This information helps establish the context for hydrocarbon reservoir developmentand the influence of geological processes [16].

Rapid Migration: The rapid migration of hydrocarbons within a relatively short timeframe after reservoir closure, estimated to be 5 million years or less, highlights the dynamic nature of the migration process. This rapid migration suggests the presence of efficient pathways for hydrocarbon movement. Understanding this timing provides insights into the geohistory of the field and the efficiency of migration pathways [15].

Structural Changes: Timing is essential when considering the impact of structural changes on hydrocarbon accumulation and migration. For instance, the timing of structural changes, such as those in the Late Pliocene, significantly influenced the oil column heights and subsequent leakage. This temporal aspect emphasizes the importance of considering structural factors when assessing hydrocarbon prospects [16].

3.3. The Uncertainties and Knowledge Gaps

The uncertainties and knowledge gaps in understanding the petroleum system of the Maui Field are multifaceted, encompassing various critical aspects. Firstly, source rock development remains uncertain, with questions surrounding the characteristics and distribution of source rocks. These uncertainties hinder a comprehensive understanding of hydrocarbon generation processes within the field.

Another significant knowledge gap relates to migration pathways. Despite the study highlighting the rapid migration of hydrocarbons, the specific pathways and mechanisms involved remain poorly understood. Identifying and characterizing these pathways is essential for effective reservoir management and exploration strategies.

The structural complexity of the Maui Field, particularly the role of fault systems, challenges conventional assumptions. The study suggests that fault transmissibility is influenced not only by fault rock properties but also by host rock permeability. Further research is necessary to unravel the complexities of these structural elements in hydrocarbon migration.

Additionally, the timing of geological events, such as tectonic movements and structural changes, plays a fundamental role in the field's evolution. However, more precise timelines and their impacts on the petroleum system need to be established.

To address these uncertainties, comparing the findings of the Maui Field with other geological settings can be illuminating. Such a comparative analysis can help identify common patterns and unique characteristics, potentially offering insights to clarify uncertainties in the petroleum system.

The systematic literature review offers several benefits to scholars and industry professionals. It enhances knowledge by providing a comprehensive understanding of the geological and petroleum system aspects of the Maui Field, serving as a valuable reference for future research in similar geological settings. Industry professionals can use these findings to make informed decisions about exploration, drilling, and reservoir management. The research challenges existing assumptions, potentially leading to more effective exploration strategies. It encourages the optimization of exploration efforts, particularly in regions with similar geological characteristics, reshaping exploration strategies by identifying efficient migration pathways. Moreover, it fosters innovation in the oil and gas industry by challenging traditional concepts and models, potentially uncovering new opportunities for hydrocarbon discoveries and improved reservoir management. The study also highlights the value of collaboration between academia and industry, promoting future partnerships for research and resource provision.

4. Recommendations and Conclusion

This review article outlines key findings and hypotheses related to the hydrocarbon dynamics in the Maui Field of which the major observations are as follows:

Two-Stage Charge Model: The hypothesis proposes a two-stage model for hydrocarbon charging. In the first stage, oil entered the reservoirs during Miocene tectonic events, likely from the Maui sub-basin. In the second stage, gas was introduced during renewed tectonic activity.

Structural Controls: Structural changes, including normal and reverse faulting, played a crucial role in controlling when and where hydrocarbons accumulated in the reservoirs.

Alternative Hypotheses: An alternative hypothesis suggests ongoing hydrocarbon migration from the Northern Graben to the south, involving oil spillage between designated areas based on current structural trends.

Complexity and Research Need: The presence of multiple hypotheses highlights the complexity of the Maui Field's geology, emphasizing the importance of ongoing research and exploration for a comprehensive understanding.

Based on the observations, there are some potential recommendations that have been made, which are:

Future Geochemical Analysis: Conduct comprehensive geochemical analyses of hydrocarbon samples from the Maui Field to trace their origins, timing, and compositional changes over geological time scales.

Potential for Advanced Basin Modeling: Employ advanced geological and reservoir modeling techniques to simulate and validate the proposed hydrocarbon migration scenarios. Incorporate data from seismic studies, well logs, and geological surveys for a comprehensive understanding.

Conflicts of Interest

The authors declare no conflicts of interest.

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