SEDIMENTOLOGY, DEPOSITIONAL ENVIRONMENT, AND ANCIENT RELATIVE SEA-LEVEL FLUCTUATIONS FOR PALEOZOIC SEDIMENTARY OUTCROPS IN LANGKAWI ISLAND, KEDAH, MALAYSIA

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UNIVERSITI SAINS MALAYSIA

2025

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by

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Thesis submitted in fulfilment of the requirements for the degree of Doctor of Philosophy

July 2025

ACKNOWLEDGEMENT

Alhamdulillah, all praise and thanks to Allah for His endless blessings throughout journey. I would like to express my deepest gratitude to my supervisor, Dr. Teoh Ying Jia, for her unwavering support, guidance, and expertise. I am equally grateful to my co-supervisor, Dr. Ismail Ahmad Abir, for his valuable insights and constructive feedback.

Special thanks to my beloved parents, Encik Abdul Rahman and Puan Rashidah, for their love and prayers. To my siblings, thank you for your constant support, including financial help.

To the Geophysics Team, including all lecturers, lab assistants, and the Geophysics Department, thank you for your support and dedication throughout this journey. I also extend my appreciation to the Fundamental Research Grant Scheme (FRGS) [FRGS/1/2020/STG08/USM/03/3] for the funding and resources that made this research possible.

To Zakwan and Thivi, I am truly grateful to both of you for standing by me from the beginning to the end. Zakwan, thank you for your patience, motivation, and support, especially during fieldwork, lab sessions, and my most difficult moments. Thivi, thank you for being the best PhD partner throughout this journey — from staying up late and handling fieldwork, to sharing doubts and pushing through together. This journey was tough, but we made it together, #topibulattogether.

To my postgraduate and undergraduate friends, including Alia, Khairi, Najwa, Bashir, Rasheed, Siraj, Farid, Sakinah, Izaty, Fatin, Syaf, Hayati, and Balqis, thank you for your support, ideas, and assistance. Special thanks to Jira, Kamek, Amirah, and Julia for your constant encouragement and companionship along the way.

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LIST OF SYMBOLS

d	Distance between planes in the crystal lattice (interplanar spacing)
θ	Glancing angle
λ	Wavelength of the incident wave
T	Sum of the thickness of the field section or well
i	Current cycle number
N	Total number of cycles
n	Positive integer (order of diffraction, n=1,2,3,…)
D_0	Depth of the base of the first cycle
D_N	Depth of the last cycle top
D_i	Actual depth of the i-th cycle top
x	Variable used in the derivation
Å	Ångström, a unit of length
%	Percentage

LIST OF ABBREVIATIONS

C	Calcite mineral
CaCO3	Cacium carbonate
CDMT	Cumulative Departure from Mean Thickness
D	Dolomite
F	Facies
FA	Facies Association
Fs	Feldspar mineral
Fr	Foraminifera
FRGS	Fundamental Research Grant Scheme
FSST	Falling stage system tract
He	Hematite mineral
H	Hummocky
HST	Highstand system tract
ICDD	International Centre of Diffraction Data
JMG	Jabatan Mineral dan Geosains
K	K-feldspar
L	Lithic fragments
Lv	Volcanic lithic fragments
M	Micrite
MFS	Maximum flooding surface
Mg	Magnesium
MgCO3	Magnesium carbonate
Oo	Ooids
Op	Opaque mineral

O	Outcrop
P	Peloid
Pe	Pellets
Pl	Plagioclase
PPL	Plane-polarized light
Q	Quartz mineral
Qch	Chert quartz
Qm	Monocrystalline quartz
Qm-u	Monocrystalline quartz with undulose extinction
Qp	Composite quartz (polycrystalline quartz)
RSL	Relative sea level
TST	Transgressive system tract
USA	United States of America
USM	Universiti Sains Malaysia
Vc	Calcite vein
XPL	Cross-polarized light
XRD	X-ray Diffraction

LIST OF APPENDICES

SEDIMENTOLOGI, PERSEKITARAN PEMENDAPAN, DAN FLUKTUASI RELATIF ARAS LAUT KUNO BAGI SINGKAPAN SEDIMEN PALEOZOIK DI PULAU LANGKAWI, KEDAH, MALAYSIA

ABSTRAK

Kajian ini meneliti sedimentologi, persekitaran pemendapan, dan perubahan aras laut kuno bagi formasi sedimen Paleozoik di Pulau Langkawi, Malaysia. Walaupun Pulau Langkawi dikenali sebagai kawasan singkapan Paleozoik yang penting, hubungan terperinci antara fasies, persekitaran pemendapan, dan perubahan aras laut kuno masih kurang difahami. Selain itu, walaupun Fischer plot merupakan kaedah yang berguna dalam menggambarkan perubahan aras laut relatif, kebanyakan kaedah sedia ada kurang dari segi aksesibiliti dan kesesuaian, terutamanya untuk aplikasi lapangan dan analisis stratigrafi tempatan. Pendekatan bersepadu yang merangkumi kerja lapangan, analisis petrografi, pemodelan Fischer plot, dan turutan stratigrafi digunakan untuk memberikan pemahaman menyeluruh tentang sejarah sedimen dan tektonik kawasan kajian. Kajian ini bertujuan mengenal pasti perubahan aras laut relatif serta hubungannya dengan persekitaran pemendapan, memberikan gambaran mendalam terhadap proses geologi serantau dan global. Sebanyak 15 fasies dan mikrofasies yang berbeza (F1-F15) dikenal pasti, menggambarkan persekitaran pemendapan seperti hadapan pantai, muka pantai, luar pesisir, dataran pasang surut, glasio-marin, dan pelantar karbonat. Analisis petrografi menunjukkan komposisi mineralogi yang didominasi oleh kuarza, kalsit, dan dolomit, dengan sampel klastik dikelaskan sebagai sublitharenit, mencerminkan asal usul kitar semula dan kematangan tekstur tinggi. Analisis mikrofasies batuan karbonat mengenal pasti packstone, grainstone, dan wackestone, yang mencerminkan dinamik sedimentologi

berskala halus dalam persekitaran laut cetek. Proses diagnetik seperti dolomitisasi, pemadatan, dan penyimenan memberikan kesan signifikan terhadap ciri pasca-pemendapan, mengurangkan porositi dan mengubah komposisi mineral. Aplikasi berasaskan Python, stratFISCHER, untuk menghasilkan Fischer plot memberikan pemahaman terperinci mengenai perubahan aras laut relatif. Berbanding platform lain seperti kaedah Excel, FischerLab, dan pyFISCHERPLOT, stratFISCHER menawarkan fleksibiliti dan aksesibiliti tinggi, menjadikannya kaedah yang efektif untuk analisis stratigrafi. Analisis terhadap Formasi Machinchang mendedahkan perubahan aras laut relatif akibat peristiwa transgresif Furongian dan tektonik setempat, manakala Formasi Singa mencatatkan anggutan glasio-eustatik dengan turutan regresif, serpihan ais, dan diamiktit. Turutan stratigrafi mengenal pasti unit sistem—aras tinggi, fasa menurun, aras rendah, dan transgresif—yang mencerminkan dinamik ruang sedimentasi dipengaruhi oleh perubahan aras laut relatif. Sekutuan fasies (FA1-FA9) menunjukkan interaksi antara proses pasang surut, ombak, dan glasial dengan pemendapan sedimen, memperluaskan penafsiran stratigrafi formasi Paleozoik di Langkawi. Hasil kajian ini menyelaraskan rekod sedimen tempatan dengan peristiwa geologi global, menunjukkan tahap keselarasan tinggi serta menyediakan asas kukuh untuk membina semula persekitaran pemendapan kuno. Penyelidikan ini memperhalusi teknik dalam bidang sedimentologi dan turutan stratigrafi secara signifikan, dengan menyediakan kaedah yang inovatif untuk menganalisis perubahan aras laut relatif. Hasil kajian ini juga meningkatkan pemahaman tentang stratigrafi Paleozoik di kawasan kajian dan menyumbang kepada pengetahuan geologi yang lebih luas, dengan implikasi terhadap pembinaan semula paleo-persekitaran dan strategi pengurusan pantai. Integrasi perisian analisis yang canggih dengan kaedah sedimentologi tradisional menekankan kepentingan pendekatan pelbagai disiplin dalam menangani cabaran geologi.

SEDIMENTOLOGY, DEPOSITIONAL ENVIRONMENT, AND ANCIENT RELATIVE SEA-LEVEL FLUCTUATIONS FOR PALEOZOIC SEDIMENTARY OUTCROPS IN LANGKAWI ISLAND, KEDAH, MALAYSIA

ABSTRACT

This study investigates the sedimentology, depositional environments, and ancient sea-level fluctuations of Paleozoic sedimentary formations on Langkawi Island, Malaysia. Despite Langkawi's significance as a Paleozoic outcrop locality, there remains a gap in understanding the detailed relationship between its facies, depositional environments, and ancient sea-level changes. Furthermore, although Fischer plots are valuable tools for illustrating relative sea-level changes, existing methods often lack accessibility and suitability for diverse datasets, particularly in field-based stratigraphic studies. Utilizing an integrated approach that combines fieldwork, petrographic analyses, Fischer plot modeling, and sequence stratigraphy, the research offers a comprehensive understanding of the sedimentary and tectonic history of the study area. The study aims to delineate relative sea-level changes and their relationship with depositional environments, offering insights into regional and global geological processes. Fifteen distinct facies and microfacies (F1-F15) were identified, reflecting depositional settings such as foreshore, shoreface, offshore, tidal flats, glaciomarine and carbonate ramps. Detailed petrographic analysis revealed mineralogical compositions dominated by quartz, calcite, and dolomite, with clastic samples classified as sublitharenite, indicative of recycled provenance and high textural maturity. Microfacies analysis of carbonate rocks identified packstone, grainstone, and wackestone, capturing the fine-scale sedimentological dynamics of

shallow marine environments. Diagenetic processes, including dolomitization, compaction, and cementation, significantly influenced the post-depositional characteristics, reducing porosity and altering mineral composition. The application of a newly developed Python-based tool, stratFISCHER, for generating Fischer plots provided precise insights into sea-level fluctuations. Compared to other available platform such as Excel-based methods, FischerLab and pyFISCHERPLOT, stratFISCHER offers flexibility and accessibility, making it a powerful tool for stratigraphic analysis. Analysis of the Machinchang Formation revealed relative sea-level changes influenced by Furongian transgressive events and localized tectonics. The Singa Formation, spanning the Late Carboniferous to Early Permian, recorded glacio-eustatic fluctuations marked by regressive sequences, ice-rafted debris, and diamictites, indicating glacial influence. Sequence stratigraphy delineated system tracts—highstand, falling stage, lowstand, and transgressive—highlighting accommodation space dynamics driven by relative sea-level changes. Facies associations (FA1-FA9) demonstrated the interplay of tidal, wave, and glacial processes with sediment deposition, enriching the stratigraphic interpretation of Paleozoic formations in Langkawi. These findings align local sedimentary records and relative sea-level changes with global geological events, showing high synchronicity and offering a reliable framework for reconstructing ancient depositional environments. This research significantly advances the methodologies in sedimentology and sequence stratigraphy, providing innovative tools for analyzing relative sea-level changes. The findings enhance the understanding of Paleozoic stratigraphy in the study area and contribute to broader geological knowledge, with implications for paleoenvironmental reconstructions and coastal management strategies. The integration of advanced computational tools with traditional sedimentological methods underscores the importance of interdisciplinary approaches in addressing geological challenges.

CHAPTER 1

INTRODUCTION

1.1 Background

Sediments and sedimentary rocks cover most of the Earth, and weathering is occurring on the rest of which give a huge influence on the planet, affecting everything from the evolution of life to the tectonic of mountain ranges. People living on planet face a number of pressing issues that include climate change, food and energy security, natural resource management, human health, clean water management, sustainable use of the oceans, building resilient infrastructure, and responsible production and consumption (United Nations, 2015). Many of these issues involve a better understanding of ancient, modern, and future process interactions at and below the Earth’s surface. Particulate transport processes and fluxes are the key physical measures, and sedimentary successions form the critical archives, which permit investigations into the response of the planet’s interconnected systems to climate change, and the triggers, magnitudes, and frequency of natural hazards.

The interpretation of ancient environmental conditions in sediment source areas and depositional sites is important to sedimentological research. It is important to note, the large part of sedimentology is concerned with modern sediments and depositional processes. This is not just to better interpret ancient sedimentary rocks, but also to improve our understanding of present-day sedimentary processes. These studies are of vital importance in the manipulation of our environment. The aim of sedimentology, studying sediments, is to derive information on the depositional conditions which acted to deposit the rock unit, and the relation of the individual rock units in understanding of the evolution of the sedimentary and thus, the Earth's geological history as a whole.

1.2 Relative Sea-level Fluctuations

Paleo sea-level models are significantly useful for global correlation, interpreting bioevents, understanding regional tectonics, and understanding global paleoclimate (Brett et al., 2011). In general, the repetitive stacking of beds within carbonate deposits can provide great insight on the biological and physical processes occurring at the time of sedimentary deposition (Strasser, 2018). Gilbert (1985) was the first to interpret such alternations in the Late Cretaceous Benton, Niobrara and Pierre formations of Colorado, United State of America (USA) as being related to the precession cycle and thus could propose a time duration for these stratigraphic units. The thickness of the facies within these stacked deposits, which represent shallow to deep marine carbonate shelf deposits (Strasser, 2018), are primarily controlled by fluxes in regional tectonics and eustasy (Poole et al., 1977). These variations in facies reflect slight changes in proximity to land, and therefore fluctuations in water depth within a marine basin.

Fischer plot is one of the crucial tools for studying and understanding sea-level changes, including identifying long-term trends, variations, and potential acceleration of sea-level rise. It was first conceptualised by Fischer (1964). This graphical representation is a fundamental means of constructing vertical space-time diagrams, revealing the recurring phenomena within the calcareous Alps, especially in peritidal Lofer cyclothems. Fischer plots are essential in understanding relative sea-level curves through the complex interaction of thick and thin sedimentary cycles. This graphical technique serves as a method for characterising alterations in accommodation (comprising both sea level and tectonic subsidence) and, consequently, the identification of the sequences of deposits on cyclic carbonate platforms. It accomplishes this by plotting the cumulative departure from the mean cycle thickness against time (Goldhammer, 1987; Read & Goldhammer, 1988; Sadler et al., 1993).

The utilisation of thick and thin sedimentary cycles within Fischer plots reveals the complex dynamics of relative sea-level changes. Relative sea level refers to the vertical separation between the sea's surface and the solid Earth at a particular geographical location and time, as Kemp et al. (2015) describe. This concept is grounded in recognising that sea levels are not constant but exhibit variability over time. These fluctuations result from global factors such as eustatic sea level changes and localised factors such as land subsidence or uplift. The dynamics of relative sea level involve both rises and falls, contingent upon the equilibrium between eustatic sea level alterations, for instance, those stemming from climate-induced processes like ice melting and localised land movements, including subsidence due to geological processes or anthropogenic activities. It plays a vital role in furnishing a historical archive of past sea-level oscillations, facilitating the comprehension of enduring trends and patterns in sea-level transformations.

As Catuneanu (2022) discussed, relative sea-level oscillations initiate variations in the availability of accommodation spaces within coastal regions, which may subsequently accommodate the deposition of carbonate sediments. Consequently, these fluctuations generate fluctuating sedimentary cycle thicknesses in shallow-marine carbonate formations. Jervey (1988) suggested that a rise in relative sea level creates additional accommodation space for sedimentation, while a decrease in relative sea level or land uplift leads to a reduction of such space, as illustrated in Figure 1.1 (Al-Masgari et al., 2021). When sea level descends, formerly submerged areas become exposed to erosional processes, transitioning to terrestrial conditions, diminishing the expanse for sedimentary deposition. This situation may result in the erosion of previously deposited sediments. When considered alongside the geological and tectonic characteristics of the coastal landscape, the rate and magnitude of relative sea-level fluctuations significantly shape the formation or reduction of accommodation spaces for sediment deposition.

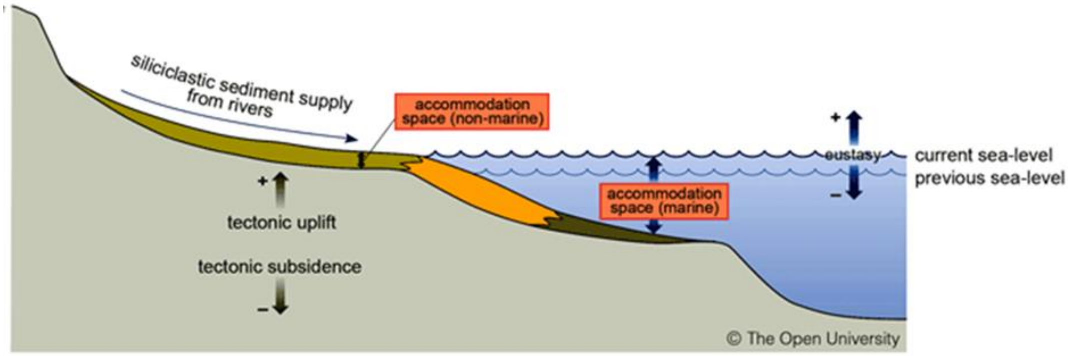

Figure 1.1 Represent the accommodation space in the marine and non-marine and the relationship between the tectonic movement and the sea-level change, after Al-Masgari et al. (2021).

1.3 Problem Statement

The coastal region of Langkawi, Kedah, Malaysia, presents a unique geological setting that remains underexplored in the context of sedimentology and sea-level fluctuations. The sedimentary deposits in this area hold invaluable information about both past and present environmental conditions, particularly in relation to sea-level changes during the Paleozoic era. Understanding ancient sea-level changes is crucial (Miller et al., 2020), as these fluctuations have shaped coastal landscapes and sedimentary processes, providing insights into Earth's climatic and geological history. Despite the critical role of ancient sea-level fluctuations in influencing sedimentary processes, there is a noticeable gap in our understanding of the intricate interplay between sedimentology and sea-level dynamics in Langkawi.

Furthermore, limited documentation of Paleozoic sea-level data poses a challenge in understanding and synthesizing ancient sea-level changes, especially when comparing global and local fluctuations. This gap highlights the need for more thorough investigation and analysis to provide a clearer picture of these past environments and their evolution over time. While only limited literature, such as Tjia (2013), addresses sea-level changes in Langkawi, the need to expand upon this understanding is evident.

Additionally, there are discrepancies in the methods used, particularly with Fischer plots (Yang et al., 2021), which are essential tools for representing sea-level changes. These discrepancies call for a deeper understanding of their accuracy and suitability for studying ancient geological changes, especially in the context of Langkawi's sedimentary record.

The existing literature on Langkawi's geology provides some insights into depositional environments and sedimentary facies; however, a comprehensive understanding of facies and depositional environments is still lacking. Integrating this with a more accurate model of sea-level changes would significantly enhance our ability to reconstruct past environments and better understand the sedimentary processes at work.

Finally, recognizing the importance of integrating local sea-level fluctuations with global Paleozoic records is crucial (Haq & Schutter, 2008). Such integration is essential to achieve a more holistic view of sea-level changes and to synchronize local data with broader geological trends. By addressing these data gaps, method discrepancies, and local-global integration, this study aims to bridge the gap in knowledge and offer a more comprehensive understanding of the Paleozoic era's sea-level changes as reflected in Langkawi's sedimentary record.

1.4 Objectives

The primary objectives of this study are:

i. To identify the sedimentary facies of outcrops based on the physical and chemical characteristics of sedimentary rocks in Langkawi.
ii. To develop the depositional environment model of the study area.
iii. To delineate the fluctuations in sea-level within the study area using a novel stratFISCHER approach.
iv. To correlate sea-level fluctuations with the sea-level history of other regions of comparable ages.

1.5 Research question

A number of questions arise in this study, for instance:

i. How do sedimentary structures and textures vary across different depositional environments in the study area, and what do these variations reveal about past processes?
ii. How do different sedimentary facies reflect changes in sea level?
iii. Can sedimentary archives in Langkawi provide insights into sea-level variations?

To address these questions, a deep understanding of sedimentology, stratigraphy and depositional environment is required.

1.6 Scope of Study

The scope of this study is to comprehensively investigate the sedimentological depositional environments spanning the Cambrian to Permian periods in Langkawi, with a specific emphasis on understanding the influence of sea-level fluctuations. Beyond the identification and description of sedimentary rocks, the study seeks to establish a systematic approach for classifying and correlating sedimentary units based on facies analysis and stratigraphic relationships. This includes a multidisciplinary integration of sedimentology, stratigraphy, petrography, geochemistry, and the incorporation of sea-level data to construct a cohesive depositional history.

The study focuses on the Machinchang, Setul, and Singa Formations as key stratigraphic units that preserve evidence of relative sea-level changes and varied depositional settings, including shallow marine, carbonate ramp, and glaciomarine environments. By combining facies interpretation, Fischer plot analysis, and sequence stratigraphy, the research reconstructs ancient sea-level trends and depositional processes during the Paleozoic, offering new insights into regional climatic and tectonic evolution.

To support this analysis, a Python-based tool named stratFISCHER was developed as part of this study to improve the generation, visualization, and interpretability of Fischer plots. This tool enhances the reproducibility and clarity of sea-level analysis by automating key stages in the plotting process and integrating well with stratigraphic datasets. Its open-source design and adaptability make it suitable for broader applications beyond this case study.

The identification and interpretation of critical facies associations such as dropstones, diamictites, and other glaciomarine indicators allow for the reconstruction of past transgressive-regressive sequences and their links to climatic events. In doing so, the study contributes to documenting underexplored Paleozoic stratigraphy in Southeast Asia and provides a replicable model for facies-based sea-level interpretation.

More broadly, this research demonstrates how Fischer plots can be used not only for stratigraphic interpretation but also to understand the broader implications of ancient sea-level changes. These insights are increasingly important in present-day contexts, as they help provide geological analogues for how coastal environments may respond to modern and future sea-level rise. The outcomes of this study may therefore inform long-term coastal and environmental management by linking the ancient record with current challenges.

In summary, the scope of this study is to investigate sedimentological depositional environments from the Cambrian to Permian periods in Langkawi, with a particular focus on the influence of sea-level fluctuations. Through the integration of facies analysis, Fischer plot interpretation, and the development of stratFISCHER, the study offers both methodological and scientific contributions. It bridges local stratigraphy with global sea-level patterns and highlights the relevance of ancient records in supporting future geological and environmental decision-making. Novelty and Significance of the Research

This research unfolds as a pivotal exploration at the crossroads of sedimentology, sea-level fluctuations, and geological modeling in Langkawi, Kedah, Malaysia. A distinctive facet of this study lies in its concerted effort to bridge a critical gap in existing research. While prior studies have delved into the sedimentological characteristics of Langkawi, the dynamic interplay between sedimentology and sea-level fluctuations remains uncharted territory. This research addresses this gap by intricately weaving data on past and present sea-level variations into the fabric of sedimentological analysis. Augmented by the limited existing literature on sea-level changes in Langkawi, notably by Tjia (2013), this study marks a significant stride in understanding the sedimentary record's response to dynamic sea-level fluctuations.

An innovative as aspect of this research lies in the introduction of a Python code methodology for constructing Fischer plots. This computational tool stands as a groundbreaking addition, facilitating a meticulous analysis of sea-level fluctuations with unparalleled precision and efficiency. The Fischer plot, a cornerstone of this study, emerges as a visual representation of sea-level variations over time, presenting a powerful analytical tool for researchers and practitioners alike.

This study aspires not only to expand the scientific understanding of Langkawi's geological evolution but also to contribute to the development of accurate depositional history models for the region. By transcending the limitations of existing models and introducing innovative methodologies, this research aims to provide a nuanced and reliable representation of the geological processes that have shaped the landscape.

In the broader context, the outcomes of this research carry profound implications for environmental management and coastal adaptation in Langkawi. By uncovering the historical context of sedimentation and sea-level fluctuations, the study provides valuable insights into the vulnerability of coastal areas. This information is poised to inform sustainable development practices and resilient strategies in the face of changing environmental conditions, setting the stage for future advancements in the field.

1.7 Thesis Layout

The thesis unfolds across five chapters, each thoughtfully crafted to provide a comprehensive exploration of Langkawi Island's sedimentology. The layout is organized as follows:

Chapter 2 is split into two parts. The first part delves into Langkawi Island's geological context and introduces the theoretical foundations of the research methods. The second part focuses on reviewing past studies, particularly those pertaining to sedimentology in Langkawi Island.

Chapter 3 is dedicated to outlining the research methodology. It begins with an exploration of the island's geological setting through on-site visits. Fieldwork selection is explained, guided by the objective of correlating geological outcrops using geological maps. The collection of fresh rock samples is discussed, setting the stage for subsequent laboratory investigations. This chapter also details the acquisition of data, where physical and chemical properties undergo testing to reinforce and enrich the results.

Chapter 4 is a key section, focusing on the outcomes and interpretations derived from the study. A thorough examination and comparison between fieldwork data and laboratory studies are conducted, revealing correlations between the various methodologies employed.

The final chapter, Chapter 5, provides a synthesis of the sedimentary exploration of Langkawi Island. It summarizes key findings, including the physical and chemical properties of sedimentary rocks to establish correlations. Additionally, this chapter offers recommendations for future research, contributing to ongoing scholarly advancements in the field.

This structured layout adheres to academic conventions, ensuring a logical and accessible progression of information for a thorough exploration of sedimentology in Langkawi Island.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Peninsular Malaysia assumes a pivotal role within the intricate framework of the Eurasian plate, particularly in the context of Sundaland, the South-East Asian extension recognized by Hutchison (1989, 1996). This extension encompasses the Sunda Shelf, extending seamlessly eastwards and southwards to encapsulate territories such as Sumatra, Natuna, and Western Borneo. The contiguous nature of these regions, interconnected by the Sunda Shelf (depicted in Figure 2.1), substantiates their shared geological affiliation with the Eurasian plate. The shelf's boundary extends in a north-south orientation, reaching a short distance east of Vietnam before curving eastwards up to the West Baram Line (Hutchison, 2004, 2005). Beyond this boundary lies the continental slope-rose, a topographical feature constituted by continental crust that gradually thins towards the east. On maritime charts, this region is labeled as 'Dangerous Grounds,' signifying the presence of deep waters harboring a myriad of reefs.

It is noteworthy that the Straits of Malacca, while shallow, lacks tectonic significance, and the geological features of Peninsular Malaysia seamlessly transition into the contiguous Sumatra. A crucial aspect of the geological narrative lies in the convergence of the India-Indian Ocean-Australia Plate with Sundaland, an event occurring approximately at N15°E, marked by a rate of 55±3 mm-a according to Milsom (2005). This convergence, occurring at the Sumatran Trench (Sunda Trench), manifests as a highly oblique process, resulting in Sumatra Island being dominated by right-lateral wrench faults. These faults extend southwards, forming the Sumatran Fault System, and northwards into Myanmar as the Sagaing Fault.

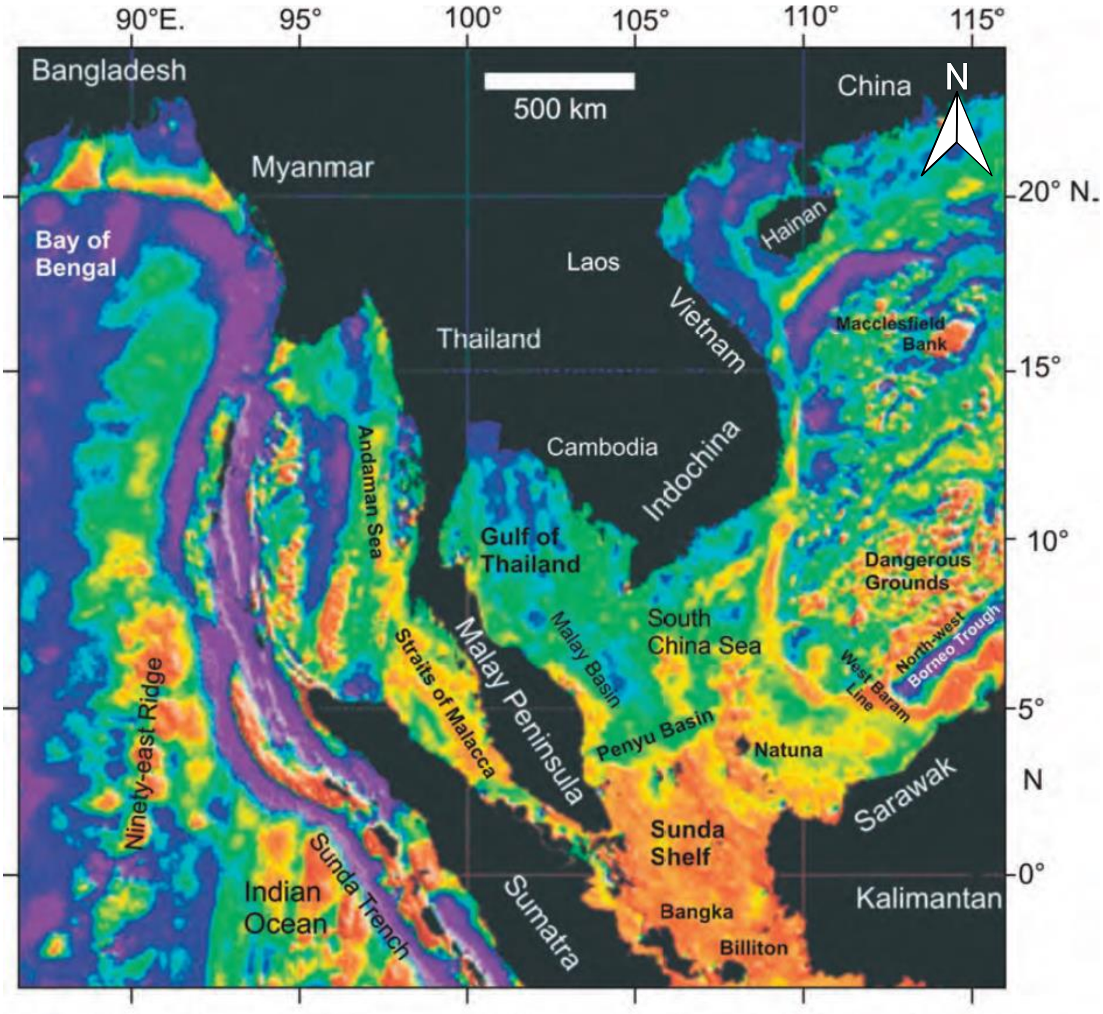

Figure 2.1 Global marine gravity anomalies of Southeast.

Transitioning to the geological structure of Peninsular Malaysia, it is characterized by three distinct sedimentary basins, each demarcated by two major granitic batholiths—namely, the Main Range belt and Eastern Belt. These basins, identified as the Western Basin, Central Basin, and Eastern Basin, hold specific mineralization characteristics, earning them designations such as the Western Tin Belt, Central Gold Belt, and Eastern Tin Belt, respectively (Tan, 1984). The Western Basin, situated between the Straits of Malacca to the west and the Bentong Line to the east, is defined by the eastern foothills of the granitic Main Range. The Bentong Line, alternatively known as the Bentong–Raub Ophiolite Line, is interpreted by (Haile, et al. (1977) as a Lower Paleozoic Subduction zone, characterized by a phyllitic mélange housing blocks of serpentinite, ophiolite, metabasic rocks, radiolarian chert, and conglomerate.

The Central Basin, on the other hand, is constrained by the Lebir fault zone to the east, with Basori et al. (2018), Hutchison (1973) and Metcalfe (2017) postulating the Lebir fault zone's potential left lateral displacement along the Kuala Lumpur–Endau fault zone into the South China Sea east of the Johor shoreline (Gobbett & Hutchison, 1973; Kasim, et al., 2020). The Eastern Basin extends eastwards from the Lebir fault zone, contributing to the comprehensive geological diversity of Peninsular Malaysia.

Delving into the geological timeline, the Phanerozoic eon, segmented into Paleozoic, Mesozoic, and Cenozoic eras (Metcalfe, 2011), features the Paleozoic era characterized by profound geological, climatic, and evolutionary transformations. This era is further divided into six periods—Cambrian, Ordovician, Silurian, Devonian, Carboniferous, and Permian (Metcalfe, 2011). In the context of Peninsular Malaysia, the oldest sedimentary sequences are concentrated in the northwest portion, revealing a Late Cambrian age. These sequences, typified by bedded sands intermixed with mud, silts, and pebbles, denote a shallow water depositional environment.

The Silurian era witnessed a transgressive movement of the sea southwards, leading to the deposition of thick successions of limestone and graptolitic shale under conditions resembling a deeper shelf. The subsequent Upper Silurian to Lower Devonian period experienced a mild orogeny, leaving behind post-orogenic sedimentary sequences marked by unconformities in the Western Basin. In contrast, other basins showcased uninterrupted sedimentation from the Devonian until the Carboniferous period, characterized by predominantly limestone in the south and non-calcareous material in the north (Mou & et al., 2023; Tan, 1984).

The Upper Carboniferous-Lower Permian interval introduced an orogenic phase that disrupted deposition, leading to granitic emplacement across various parts of Peninsular Malaysia. Permian sediments, mainly calcareous, indicate a restricted sedimentation during the Lower Permian. The Middle Permian witnessed a transgression of the sea to the southern part of Peninsular Malaysia, with sedimentary sequences in the Central and Eastern Basins featuring tuff and lesser flows of acid to intermediate composition towards the Late Permian.

The Upper Permian marked a return to restricted sedimentation, signifying the onset of another orogenic episode reaching its peak during the Lower Triassic. This period witnessed large-scale granitic intrusions and the emergence of a volcanic island arc during the Upper Permian-Lower Triassic orogeny (Tan, 1984). The geological narrative of Peninsular Malaysia unfolds as a rich pattern, interweaving tectonic events, sedimentary basins, and chronological milestones that collectively contribute to its multifaceted geological history. This geological saga reflects the intricate dynamics and complexities of the region's geological evolution, providing a comprehensive understanding of Peninsular Malaysia's geological framework.

2.2 Geology of Langkawi Island

Langkawi Island, situated in the Andaman Sea, is a geologically captivating landmass shaped by intricate tectonic and erosional processes, resulting in a complex geological history. Located within the North-western Domain of the Western Belt of Peninsular Malaysia, Langkawi Island is a part of Sundaland and consists predominantly of Paleozoic sedimentary rocks, ranging in age from the Cambrian to the Permian (Lee, 2009). These sedimentary formations encompass a variety of clastic and carbonate rocks, deposited in diverse paleoenvironments and under varying paleoclimatic conditions, leading to a rich array of rocks. The island's geological formations contribute significantly to its diverse topography and rock assemblages.

The categorization of the Paleozoic sedimentary rocks of Langkawi includes the Machinchang, Setul, Singa, and Chuping formations, listed chronologically by age (Tjia, 1992). Additionally, the Paleozoic sedimentary rocks have been intruded by younger granites, leaving distinctive metamorphic imprints at their contacts (Ribeiro da Costa et al., 2018).

The geological history of Langkawi, as summarized in Figure 2.2 and based on studies by Jones (1981), Shafeea et al. (2007), and Abdul Rahman et al. (2022), reveals that the sedimentary rock formations are generally younger towards the east, with the Kisap Thrust Fault disrupting this pattern in the eastern part of the island. The Kisap Thrust Fault plays a crucial role in the geological dynamics of Langkawi, introducing westward transport that brings older Setul (and possibly Machinchang) Formations from the east to overlay the younger Chuping and Singa Formations in the central axis of Langkawi Island. This fault activity adds a layer of complexity to the island's geological evolution, emphasizing the significance of structural features in shaping the landscape and rock formations of Langkawi.

The geological history of Langkawi Island showcases the interplay of tectonic forces, erosional processes, and structural features that have shaped its unique geological landscape over millions of years. Understanding the island's geological formations is crucial for unraveling its geological history and conserving its geological heritage for future generations.

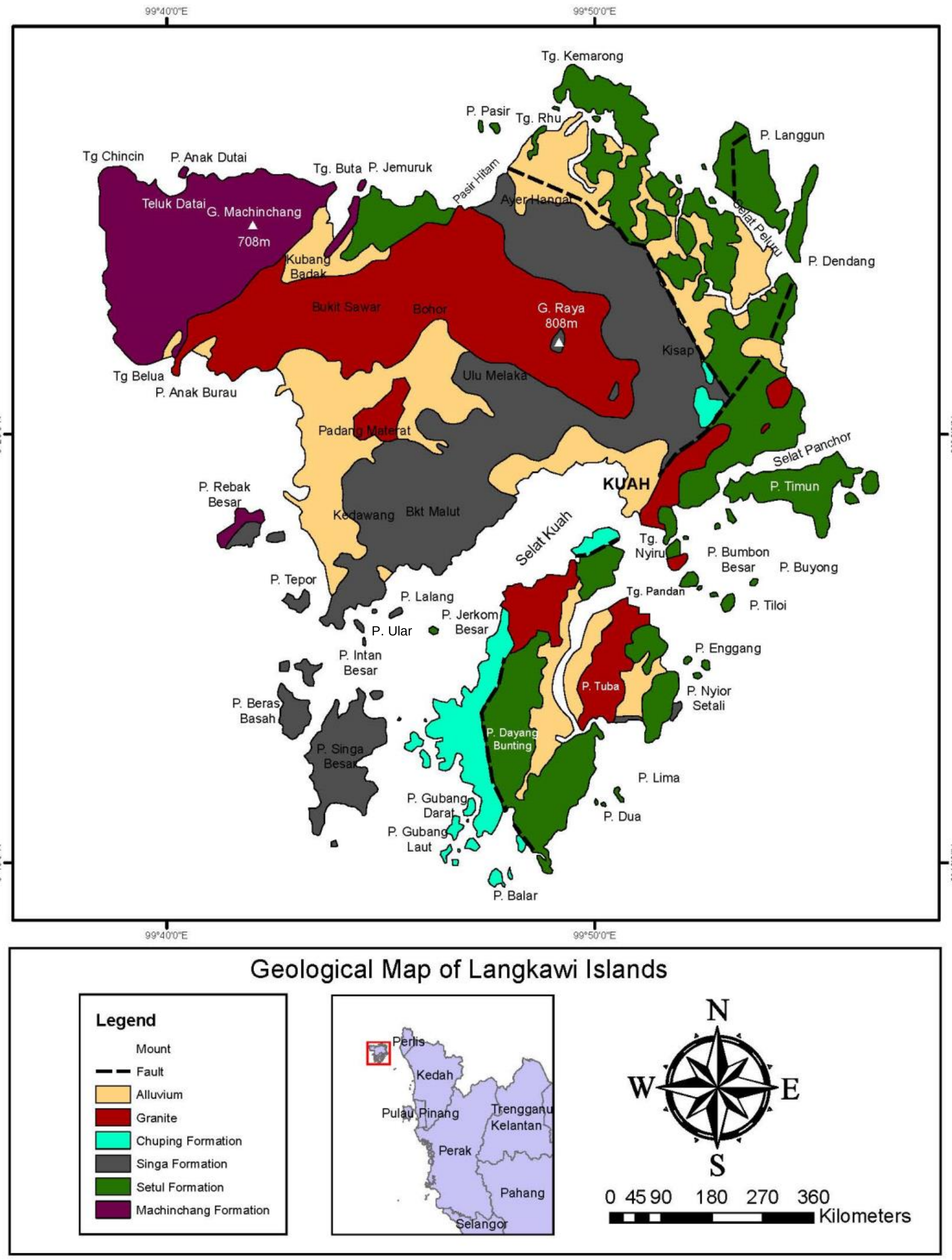

Figure 2.2 Geological map of Langkawi Island (Abdul Rahman et al., 2022).

2.2.1 Machinchang Formation

The meticulous examination of the Machinchang Formation by Lee (2006) has brought to light crucial insights into its stratigraphic intricacies. This formation, along with its Thai counterpart, the Tarutoa Formation, has been informally classified into three members, with the middle member further delineated into three submembers.

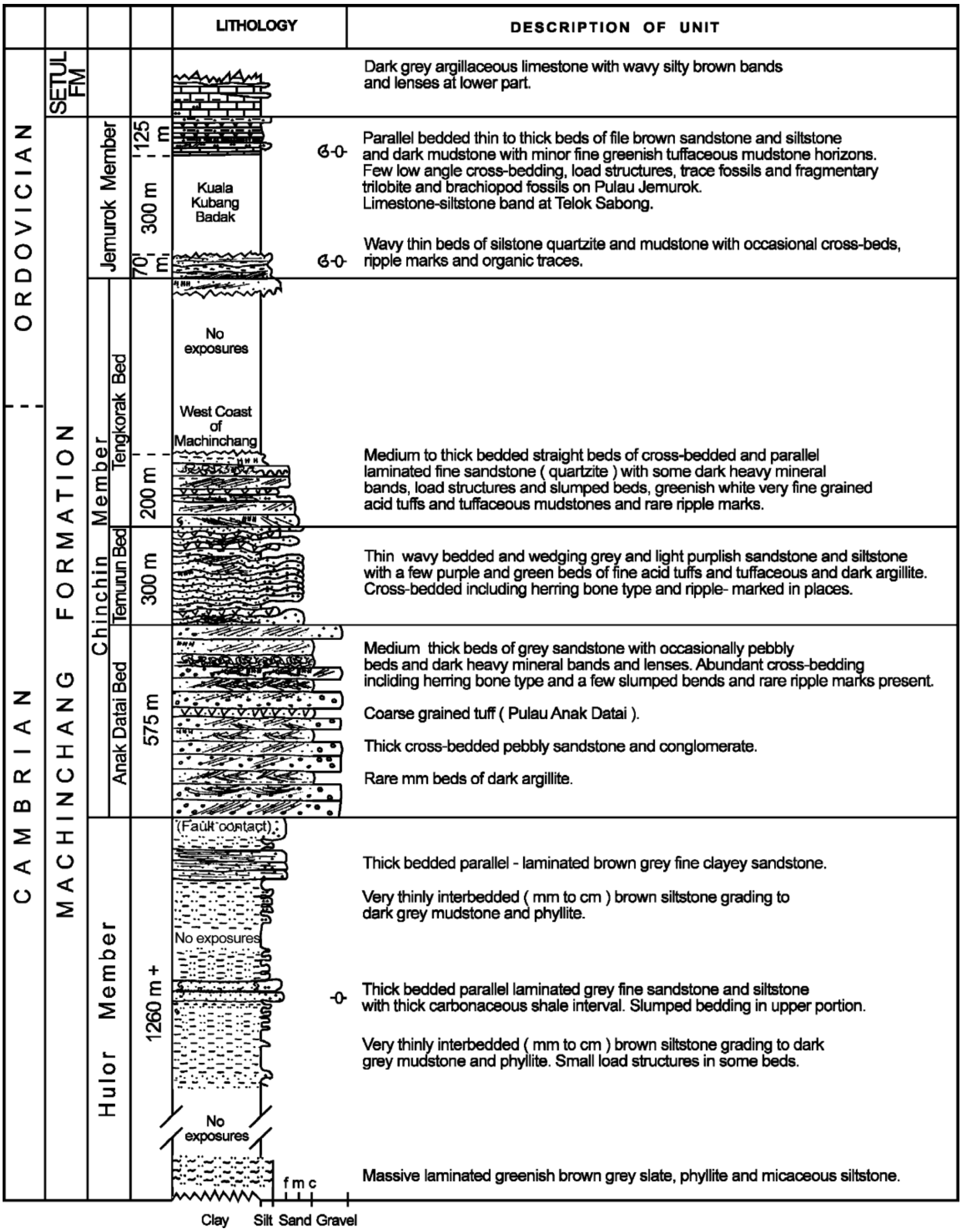

Figure 2.3 Stratigraphy of Machinchang Formation as a whole (Lee, 2006).

Lee's investigation reveals a dynamic depositional environment characterized by a highly destructive, wave-influenced delta deposit, featuring preserved beach-ridge complexes. The study underscores the impact of peneplanation on the source area, resulting in a nuanced sequence transition from coarser to finer beds, culminating in limestone deposition (Lee, 2006). Figure 2.3 provides a composite stratigraphic illustration encompassing all members and submembers of the Machinchang Formation.

2.2.1(a) Hulor Member:

The Hulor Member, representing the oldest sedimentary rock within the Machinchang Formation, emerges as a substantial geological entity with a thickness surpassing 1260m at the core of the Machinchang Anticline around Datai Bay. Comprising sandstone, siltstone, and shale, this member presents a coarsening upward succession. Lee (2006) discerns four distinctive facies within the Hulor Member, each revealing specific sedimentary nuances. These include mm to cm interbedded rhythmite deposits, cm to dm bedded fine argillaceous sandstones, slumped facies of very thick, poorly bedded to massive fine argillaceous sandstone, and a distinct 5m thick interval of black carbonaceous and pyritiferous silty shale indicative of reducing conditions.

2.2.1(b) Chinchin Member

The Chinchin Member, situated at the extreme northwest of the Machinchang area, unfolds as a stratigraphic giant with an estimated thickness exceeding 1575m. This member demonstrates a fining upward succession, further subdivided into three beds—Anak Datai Bed, Temurun Bed, and Tengkorak Bed. Anak Datai Bed spans 575m and features graded lenticular beds of cross-bedded pebbly sandstone and conglomerate. Temurun Bed, with a thickness of 300m, exhibits a wavy-bedded sequence of fine sandstone facies with intriguing similarities to certain Upper Cambrian to Lower Ordovician strata in the Snowy Range Formation (Myrow et al., 2004). Tengkorak Bed, the topmost layer exceeding 200m, is characterized by fine to very fine, thick bedded sandstone facies with intermittent intervals of fine rippled sandstone, acid tuff, and mudstone.

2.2.1(c) Jemurok Member

As the youngest member of the Machinchang Formation, the Jemurok Member unfolds with a thickness exceeding 420m. Lee (2006) categorizes three facies within this member: thick-bedded mudstone, thin to thick-bedded very fine sandstone and siltstone with trace fossils, and thin wedging beds and lenses of impure limestone. The second facies is notable for its parallel lamination, low-angle planar cross bedding, hummocky cross bedding, and the presence of trace fossils such as Dictyodora and Chondrites.

In conclusion, Lee's (2006) comprehensive investigation into the Machinchang Formation not only reveals the intricate stratigraphic details but also offers a critical perspective on the sedimentary dynamics and depositional environments. The detailed analysis of each member provides a robust foundation for understanding the geological evolution encapsulated within this formation, paving the way for further exploration into the complex interplay between sedimentary processes and regional tectonics.

2.2.2 Setul Formation

The Setul Formation, situated along the eastern littoral of Langkawi Island in Kedah, Malaysia, constitutes a paramount geological archive dating from 490 to 370 million years ago. As the preeminent carbonate lithological unit in Langkawi and the broader region, it serves as a pivotal conduit for delving into the stratigraphic intricacies of the Silurian and Devonian epochs in Southeast Asia.

Comprising predominantly dark-hued, thin- to thick-bedded limestones, as elucidated by (Ali & Mohamed, 2013), the Setul Formation also encompasses captivating intervals of detrital rocks, notably sandstones and shales, manifesting the temporal evolution of depositional environments.

Initially named by Jones (1981), the members were later revised by Cocks et al. (2005), enhancing the understanding of the formation's stratigraphy. Jones (1981) initially characterized the Setul Formation as a significant geological entity located in northwestern Peninsular Malaysia. According to his classification, this formation comprised limestone and detrital units. The limestone components were further segregated into distinct lower and upper members, distinguished by their specific attributes such as crystallinity, coloration, and fossil composition. Meanwhile, the detrital units encompassed materials such as quartzite, carbonaceous shale, slate, and black cherty mudstone.

The formation is subdivided into four distinct members. The Lower Limestone Member, distinguished by abundant micrite and bioclastic limestone, signifies a tranquil shallow marine depositional setting. Subsequent to this is the Lower Detrital Member, characterized by black flaggy shales and minor sandstones, indicative of heightened terrigenous input and sea-level fluctuations. The Upper Limestone Member, marked by a resurgence of limestone dominance, denotes a return to placid, clear marine conditions. Concluding this sequence is the Upper Detrital Member, featuring sandstones and minor argillaceous beds, signaling a renewed clastic influence and marking the transition to the overlying Singa Formation.

In the revised classification introduced by Cocks et al. (2005) in Figure 2.4, there emerged a recognition of the necessity for a more intricate classification system tailored to the geological units prevalent in the region. Their extensive study prompted a reevaluation of the Setul Formation, resulting in its subdivision into four distinct formations characterized by their lithological properties:

1. The Kaki Bukit Formation (Lower Setul Member), representing the lower limestone unit initially identified by Jones (1981).

2. The Tanjung Dendang Formation (Lower Detrital Member), encompassing the detrital unit positioned beneath the limestone strata.

3. The Mempelam Formation (Upper Setul Member), signifying the upper limestone unit delineated within the original Setul Formation.

4. The Timah Tasoh Formation (Upper Detrital Member), comprising the detrital unit overlaying the upper limestone stratum.

The depositional settings of the Setul Formation have been a focal point of scholarly interest. Initial interpretations posited a deep marine environment (Jones, 1961), yet subsequent investigations by Lee (2006) and Hassan et al. (2013) advocate for a shallower platform setting characterized by intermittent fluctuations in sea level and terrigenous input. These nuanced dynamics are elucidated through the alternating stratigraphic sequences of limestone and detrital rocks, offering insights into the intricate geological history.

Despite the limited presence of fossils, the Setul Formation retains paleontological significance. Trace fossils, including burrows and stromatolites, provide glimpses into early life forms. Noteworthy discoveries of brachiopods, trilobites, and conodonts, particularly within the Lower Detrital Member, contribute invaluable insights into the evolutionary trajectory of marine fauna during the Silurian and Devonian periods (Cocks et al., 2005).

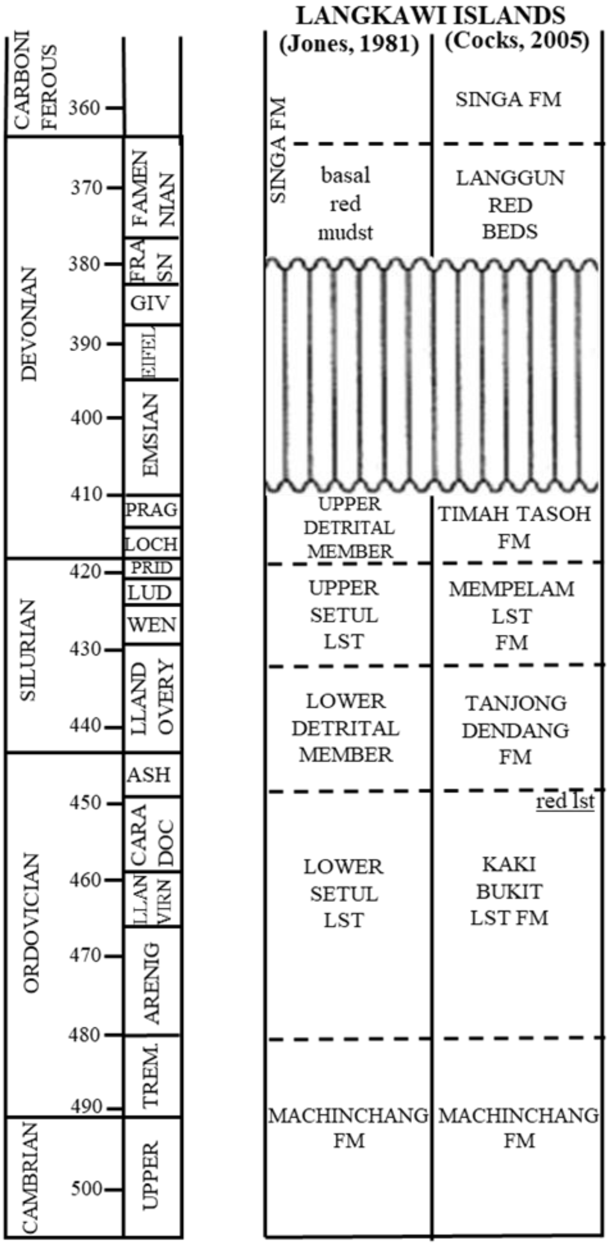

Figure 2.4 Stratigraphic column of the Setul Formation in Langkawi Islands, as originally described by Jones (1981) and revised by Cocks et al. (2005).

The Setul Formation has undergone significant geological upheaval characterized by tectonic activities, notably during the Cretaceous period with the intrusion of the Gunung Raya massif. This intrusion initiated folding and faulting processes that have shaped the present-day terrain. The imposing limestone hills, accompanied by distinctive karst formations such as sea caves, arches, and pinnacles, serve as enduring evidence of both the formation's durability and the profound impact of weathering and erosion mechanisms.

2.2.3 Singa Formation

The Singa Formation, located along the southwestern margins of Langkawi Island, Kedah, Malaysia, unfolds a comprehensive geological narrative spanning the late Devonian to the early Permian period, approximately 370 to 290 million years ago. As the predominant geological unit on the island, the Singa Formation provides a nuanced insight into a dynamic geological past, revealing the evolution of environments and paleoecosystems. This thorough review engages with the intricate geology of the Singa Formation, assimilating pertinent elements from existing geological literature for seamless integration into a doctoral thesis, complemented by visual representations to elucidate the geological framework.

The lithological composition of the Singa Formation is characterized by dark grey to black mudstone and siltstone, occasionally featuring dispersed pebbles of diverse morphologies and provenances. These distinct clasts, identified as glacially derived dropstones, imply environmental conditions that were colder and shallower compared to its precursor, the Setul Formation. With a thickness of approximately 2100 meters, the formation is stratified into four members.

The Lower Member is marked by red mudstone intercalated with sandstone beds, signifying the initiation of the transition from the late Devonian to the Carboniferous period. Subsequently, the Kentut Member is dominated by black mudstone with sporadic occurrences of sandstone and conglomerate layers, indicating a resurgence of deeper marine conditions. The Ular Member is characterized by alternating sequences of black mudstone and siltstone, interspersed with light-colored quartzite, reflecting dynamic shifts in sea levels and sporadic shallow-water settings.

The Selang Member is distinguished by the emergence of limestone lenses within the dark mudstone, suggesting a gradual transition towards shallower marine conditions and the eventual deposition of the overlying Chuping Limestone Formation.

Deciphering the depositional settings of the Singa Formation has been a subject of rigorous geological discourse. Initial interpretations proposed a deep marine setting, while subsequent studies advocated a more dynamic perspective, indicating a transition from deep marine conditions to shallower coastal and prodelta environments. Evidences such as dropstones, Bouma sequences in sandstones, and micro-sedimentary structures substantiate the diverse depositional settings postulated.

Although the Singa Formation exhibits limited fossiliferous content, it preserves notable paleontological specimens. Microfossils, particularly conodonts, provide invaluable insights into both the chronologic framework and prevailing paleoenvironmental conditions. Additionally, the identification of brachiopods, notably those indicative of cold-water environments, contributes substantially to the understanding of the paleobiota within the formation, enriching our comprehension of marine life evolution during the late Paleozoic era.

The geological history of the Singa Formation is marked by episodes of folding and faulting attributable to tectonic processes. These forces have sculpted the contemporary landscape of Langkawi, influencing the spatial distribution of the formation's outcrops and contributing to the formation of conspicuous geological features, including dramatic cliffs, scenic beaches, and picturesque coves that typify the island's geomorphology.

2.2.4 Chuping Formation

The Chuping Formation, located on the northwestern shores of Langkawi Island, Kedah, Malaysia, encapsulates a captivating chronicle of geological evolution spanning