Empirical Model of Thailand Shale Compaction Based on Geological Age Classification

Syukratun Nufus

A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of Master of Science in Earth System Science (International Program)

Prince of Songkla University

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ABSTRACT

Recently large sources of gas and oil have been found in shale, due to its organic-rich contain, acts as source rock, and a trap in the process of ordering oil and gas resources. Shale is a clastic rock formed from tiny particles of clay, the compaction can be defined as a process related to the pressure and burial depth of sedimentary. Shale compaction has been studied for many years. However, curves graphically showing relationships between shale porosity and burial depths are normally widely scattered. The variation in shale porosity decreases as the burial depth increases, this is known as the conventional compaction trend. Other main parameters that influence the changes of porosity during the compaction process are temperature, framework mineralogy, and geological time. This study aims to be refined the variation of the Thailand shale compaction, to estimate the geological of shale compaction from the burial depth using the velocity function based on the numerical analysis method, and to establish the empirical models of each geological age by the numerical methods. Thailand shale compaction data classifying into three geological ages (Paleozoic, Mesozoic, and Cenozoic) were collected and plotted as the conventional compaction curve, the graph shows scatter because the shale data are from a different location and lead to the variation of its geological age, the older of shale gives the lower porosity. Numerical analysis was conducted in this study to estimate the geological time of shale compaction from the burial depth using the velocity function. Then, the empirical models of each age were established by numerical methods. Finally, the three-dimension (3D) plot was carried out to demonstrate the compaction trends in each age. The findings in this study act as a

guide for future study of the standard curve of shale compaction. The reconstructed data plots on a porosity-depth graph of Thailand shales might be studied with compaction curves varying with time.

ACKNOWLEDGEMENT

First of everything, I would like to say Alhamdulillah and thank all those who have been involved and helped me complete this thesis. Sincerely, I would like to express my heartfelt gratitude to my advisors, Assoc. Prof.Thongchai Suteerasak and Asst. Prof. Dr. Avirut Puttiwongrak, who has guided from the beginning of writing this thesis to the end, and for their great help in planning and implementing this research until it can be completed on time, despite the many obstacles I faced before, thank you for continuing to support me.

My special gratitude to Asst. Prof. Dr. Chinnawat Surussavadee for his help during my study at Prince of Songkla University since my day one in Thailand. Further, I would like to thank all lectures, and staff of the Earth Systems Sciences program, Faculty of Technology and Environment, Prince of Songkla University, Phuket Campus for the wonderful education and helps during my study and stay in Thailand.

Financial support for my study and research was provided by the Andaman Environment and Natural Disaster research center (ANED) and the Graduate School of Prince of Songkla University.

I owe special gratitude to my number one support system, my parents and family, who never absent to give their wholehearted support and prayers for me and the patience during my journey to finish my master's studies.

I thank all my classmates for the supports, our long and interesting discussions, and last but not least for all my Thai friends, Indonesian friends, other international friends, and all the staffs of Prince of Songkla University, to those whose names have not been mentioned but always supported me in one way or the other. Thank you and I am very happy to have met and made friends with all of you.

Syukratun Nufus

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CHAPTER 1
INTRODUCTION

1.1 Problem Statement

Hydrocarbon resources are the most consumed energy source in the world. Demand for hydrocarbons will continue to increase every year, as predicted by EIA (2017) will increase by 28% in 2040. This fact makes the study of hydrocarbon resources important to study. Recently large sources of gas and oil have been found in shale, due to its organic-rich contain and shale plays a dual role in the process of ordering oil and gas resources, namely as a source rock which is where oil and gas are formed and shale acts as a trap where oil and gas are trapped, due to its low permeability. Not all shale rocks have oil and gas potential, several conditions, such as the level of maturity, the content of organic matter, the thickness of the source rock, mineralogy, pore pressure, and the rock brittleness also need to be considered.

The global distribution of Shale resources shows in Figure 1.1, the growth in shale gas production in the United States has led to increased interest in exploring shale resources in other regions of the world including Asia Pacific countries, as reported by Asia Pacific Research Center (2015) China, Australia, Pakistan, and India all have significant shale reserves. Then followed by Asian Pacific countries include Thailand, Indonesia, and Mongolia. Shale development in Thailand is still growing. Oil and gas productions in Thailand have been done for the past three decades until today. Almost 90% of the petroleum output comes from conventional sandstone and carbonate reservoirs in offshore fields in the Gulf of Thailand. The study from EIA/ARI (2013) suggested that Thailand's main onshore sedimentary basins in North-central and Northeastern Thailand include Khorat Basin, North Intermontane Basin, and Central Plain may contain unconventional oil and gas potential.

In addition, knowing the presence of shale in an area, the characteristics of shale also need to be studied because each sediment has its characteristics. The sediment that has been buried will undergo a diagenetic process, one of which is compaction, which plays a significant role in the process of changing porosity in sediment. Compaction generally occurs due to the influence of grain rearrangement, deformation, dissolution, and brittle fracturing. The compaction process causes the increase of velocity and density with the depth and the decreases of porosity, this is known as the conventional compaction trend.

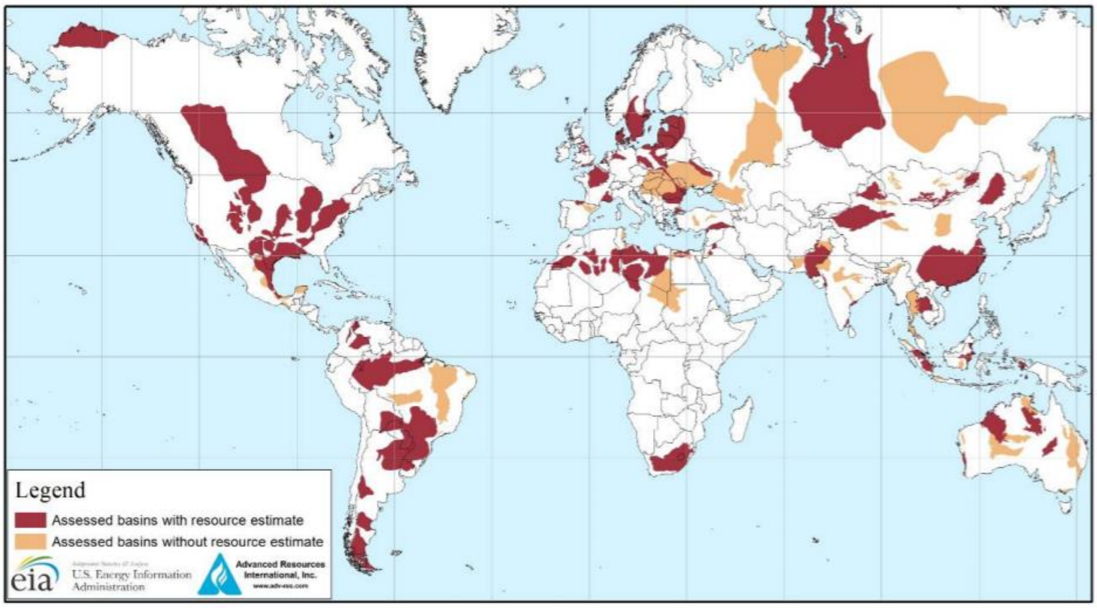


Figure 1.1 Global distribution of shale resources (EIA/ARI, 2013)

The main parameters influencing the changes of porosity during the compaction process are burial depth, temperature, framework mineralogy, and geological time. (Scherer, 1987, Giles et al., 1998, Bjørlykke et al., 2004, Walderhaug et al., 2001). Shale compaction has been studied for many years. However, shale compaction curves graphically showing relationships between shale porosity and burial depths are normally widely scattered. Shale compaction (porosity-depth) curves are essential for a variety of reasons in drilling, basin modeling, and seismic exploration: (Dutta, et al., 2009)

1. Using seismic velocity anomalies to discover and identify overpressure and hydrocarbon zones.
2. To determine interval velocities and depth conversion, using seismic data and Earth models.
3. To anticipate sand-shale interface seismic signals as a function of depth.
4. To identify zones that have been over-compacted due to uplift.

Athy's (1930) curve is the most used to define compaction. The compaction curve for Thailand shale data, using Athy's model indicates a tendency of scattered data points throughout the depth. The difference in area or basin causes the scattered porosity on the compaction curve to a difference of more than 20%. Shale data from different basins lead to the variation of its geological age (Giles, et al., 1998). So that one effective way to control the scattering data of the compaction curve by classifying the time of burial (Puttiwongrak, 2020), and the compaction curves varying with geological age has been demonstrated by Puttiwongrak, et al., (2020). The main focus of this study is to clarify the time factor for shale compactions in Thailand shales and this study suggests a multiple linear regression to establish the empirical relationships among porosity, depth, and time, of each age, based on the methods in Puttiwongrak et al. (2020). Geological ages used as references in this study are categorized into Cenozoic, Mesozoic, and Paleozoic ages. In comparison to Puttiwongrak et al. (2020) a three-dimensional (3D) model of typical compaction for Thailand shales is also discussed.

1.2 Objective

The following are the study's objectives:

1. This study first confirms that the porosity-depth curves of shales of the targeted locations are well expressed with regard to different geological ages, Cenozoic, Mesozoic, and Paleozoic ages.

2. To estimate the numerical of geological ages, velocity as a function of burial depth.
3. To establish an empirical link between porosity, depth, and time for each geological age of Thailand shales.
4. To analyze and compare the new three-dimensional (3D) model of standard compaction Thailand shale with previous work by Puttiwongrak et al., 2020.

1.3 Scope of Study

Method Scope:

The numerical method is used to analyze the relationship among the velocity, geological age (time), burial depth, and porosity as suggested by Faust,1951. The suggested model of Thailand shale datasets from this study will compare with the previous work of Puttiwongrak, et. al. (2020) using worldwide data. The method for time estimation in this study use the velocity and depth relationship to ages as suggested by (Faust, 1951) and the 3D shale compaction models, the empirical relationships among porosity, depth, and time, of each age, are proposed by this study using multiple linear regression methods as suggested in Puttiwongrak et al, 2020. The geological age for this study was classified into Cenozoic age (now – 65 Ma), Mesozoic age (65 – 250 Ma), and Paleozoic (upper than 250 Ma).

Area Scope:

The location of data is defined as the study's area scope. This study examined data from four local basins in North part of Thailand, including the Phetchabun basins in the north, Mukdahan, Kuchinarai, and Phu Din basins in the northeast. Each basin has different geological ages, which are listed in Table 3.1. The Department of Mineral and Fuel (DMF) of Thailand provided the data for this study, which was available for different geological ages (Cenozoic, Mesozoic, and Paleozoic).

Time Scope:

The time scope of working to carry out this research starts from April 2020 – May 2021 (13 Months).

1.4 Outcome

The expected outcome for this study is to gain an understanding of Thailand shale characteristic and the compaction, also the standard curve and the 3D (porosity-depth-geological age) model that has been established from this study can be a basis or reference for Thailand shale compaction in general.

CHAPTER 2
LITERATURE REVIEW

2.1 Shale Characterization

Shale is a clastic rock formed from small clay particles, most of the shales contain clay minerals with high presentation and basic types of clay that are contained in the shale are different, including kaolinite, illite, and montmorillonite clays, each type of clay has a different effect on the different reservoir and sources of different formations (Selley, et al, 2015). Shale is an important sedimentary rock because it is one of the source rocks where oil and gas formed and due to its low permeability, shale also acts as a trap where oil and gas are trapped. The presence of shale is also very abundant in most of the sedimentary basins (Bjørlykke, 2010). However, not all shales have oil and gas potential because other several conditions also need to be considered, such as the level of maturity, the organic matter content, the thickness of the source rock, mineralogy, pore pressure, and the rock brittleness (Deshpande, 2008).

Shale, a clastic rock that contains an amount of clay. The interaction of tiny particles with clay minerals has a significant impact on the sedimentation process, such as erosion, transport, deposition, and compaction due to the nature of the clay itself, as it can influence grain mechanical strength and pore fluid composition (Bjrlykke, 2010).

2.2 Compaction Theory

Compaction is a process related to the pressure, burial depth, and porosity of sedimentary. It is also known as a process of porosity reduction due to grain rearrangement and compression of sediment, which is generally caused by geological, physical, chemical, and mineralogical factors in the subsurface (Magara, 1980). The compaction based on porosity for experimental and empirical equation has been purposed by Athy (1930) and confirmed by Rubbey and Hubbert (1959) that the equation is fit for general compaction conditions, which is at the compaction-equilibrium condition with fluid pressure is hydrostatic (eq. 1). It typically shows the exponential increasing porosity with decreasing depth. This condition is explained as the shale has lower permeability at the shallow depth, thereby increasing the ability of the shale to absorb fluid and, it will decrease as the burial depth increases. The porosity-depth relationship also known as the compaction equation:

$$\phi = \phi_o e^{-cz} \tag{1}$$

Where c is the compaction coefficient, z is burial depth, ϕ is porosity in the depth z, and ϕ_o is the initial porosity (at the surface). This function is an empirical function because there is no physical influence such as mechanical compaction that directly connects to porosity and depth (Giles et al., 1998). The exponential function of shale in (eq. 1) explains that at an earlier time (which used to in shallow depth) have lower porosity than in the older time. Besides the exponential trend, other studies also suggest different trends such as linear compaction trend (Bjørlykke et al., 1989), double-exponential trend (Kominz et al., 2011), and exponential-linear trending (Cao et al. 2017). Porosity-depth curves from identical lithology and depth but various locations generate porosity variances of more than 20%, this is due to differences in composition, age, geothermal gradient, and overpressure in each area (Giles et al., 1998).

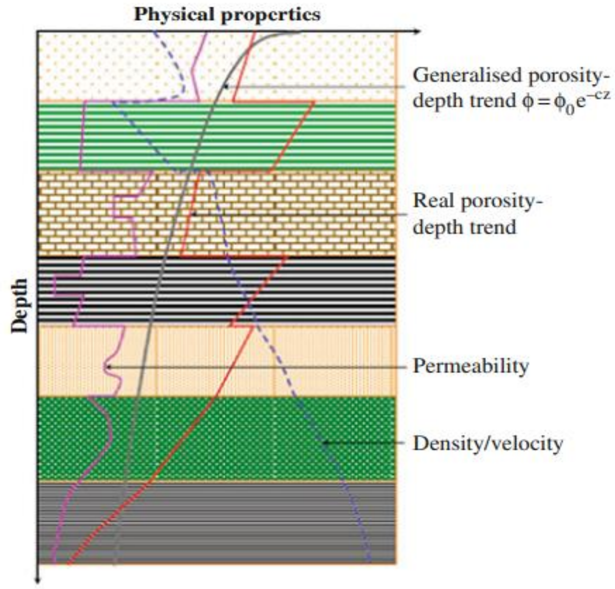


Figure 2.1 Principal aspects of sediment compaction (burial diagenesis) (Bjørlykke,2010)

The changes of sedimentary rocks during the burial in their physical properties are shown in Figure 2.1, due to the influence of increasing depth, stress, temperature, and geological time (low strain rates), and hydromechanical effects such as erosion and uplifting. The compaction process causes the increase of velocity and density with the depth and the decrease of porosity (Bjørlykke et al., 2004, Walderhaug et al., 2001).

Compaction occurs due to sediment packages being buried gradually by other, younger sediments and the overburden load (burial depth) increases due to the influence of lithostatic and hydrostatic pressures (Gretener, 1976). Figure 2.2 shows the illustration of the compaction process, i.e., deposition, mechanical compaction, and chemical compaction (Worden, et al, 2003). In the diagenetic process of sediment burial, mechanical and chemical compaction is the dominant process that causes changes in the porosity of the original sediment, compared to other processes, namely dissolving, cementation, recrystallization, etc.

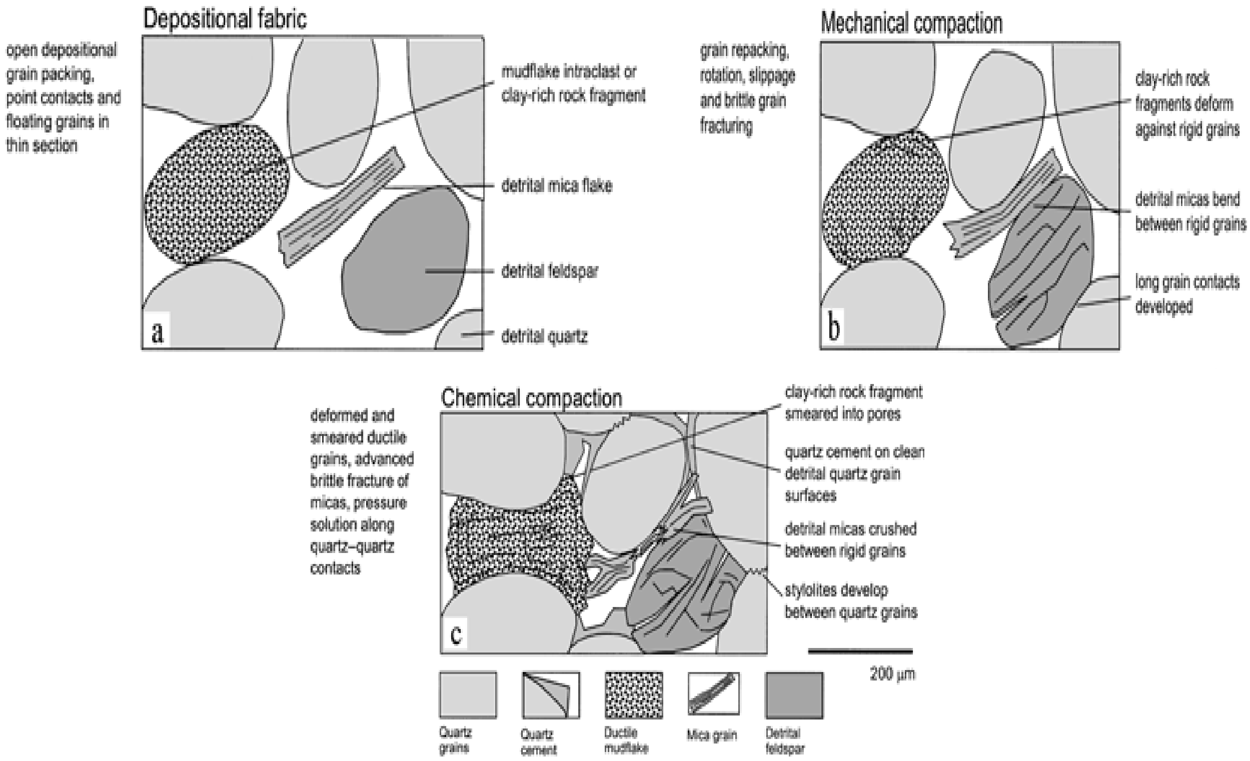


Figure 2.2 illustration of compaction processes (a) sediment that undergoes deposition, (b) the sediment structure after mechanical compaction, (c) after mechanical and chemical compaction (Worden and Burley, 2003).

2.2.1 Compaction Process in Sedimentary Basins

a. Mechanical Compaction

Effective stress (σ_v') is a factor in mechanical compaction, a reduction in porosity with the burial depth, by the contribution of vertical overburden stress (σ_v) and fluid (pore) pressure (p_p). The mechanical compaction occurs right after the deposition process and consequently increases the stiffness of the sediment. Mechanical compaction often occurs at shallow depths involving rearrangement and damage of grain (Puttiwongrak et al, 2020 and Mondol et al, 2007). The major processes of mechanical compaction are sedimentation, deformation of grain framework and porosity reduction, increase in pore pressure due to reduction of pore space, slightly over-pressured pore fluids move to a place with lower potential energy (Bjørlykke et al., 2004).

Diagenetic processes that cause changes in rock characteristics as burial depth increases have a significant impact on sediment texture (grain size), mineralogical composition, and fluid expulsion rate from compacting sediments (Bjrlykke et al., 2004). The weight of overburdened sediment and the weight of the fluid in the pore space of the sediment determine the vertical tension on mechanical compaction. Total vertical stress is calculated using the following equations:

$$\sigma_v = \rho_s g h \qquad (2)$$

Where: σ_v represents the total vertical stress, ρ_s represents the average bulk density of overburden sediments, g represents gravitational, and h represents burial sediment thickness. Effective vertical stress $\sigma v'$ has a significant influence in mechanical compaction but has a minor impact on chemical compaction. Effective stress ($\sigma_v{}'$) is the difference between the total vertical stress (σ_v) and the pore pressure (P_p), and it varies linearly with depth, this equation known as Terzaghi's Relationship (Terzaghi, 1925 and Terzaghi, 1936):

$$\sigma\_v' = \sigma\_v - P\_p \qquad (3)$$

The effective vertical stress is influenced by two phases, the fluid phase (pore pressure) and the solid phase (grain framework). Its illustration shows in Figure 2.3. The effective vertical stress, as well as the mechanical and chemical compaction effects, are reduced by increasing pore pressure. (Osborne and Swarbrick, 1999). The mechanical compaction as a function of effective vertical stress and depth and the chemical factor with increasing depth for chemical compaction are illustrated in Figure 2.4.

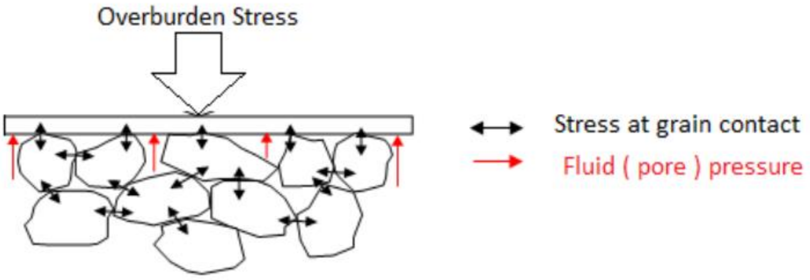


Figure 2.3 Schematic illustration of the pressures contribution to mechanical compaction (Ndingwan, 2011)

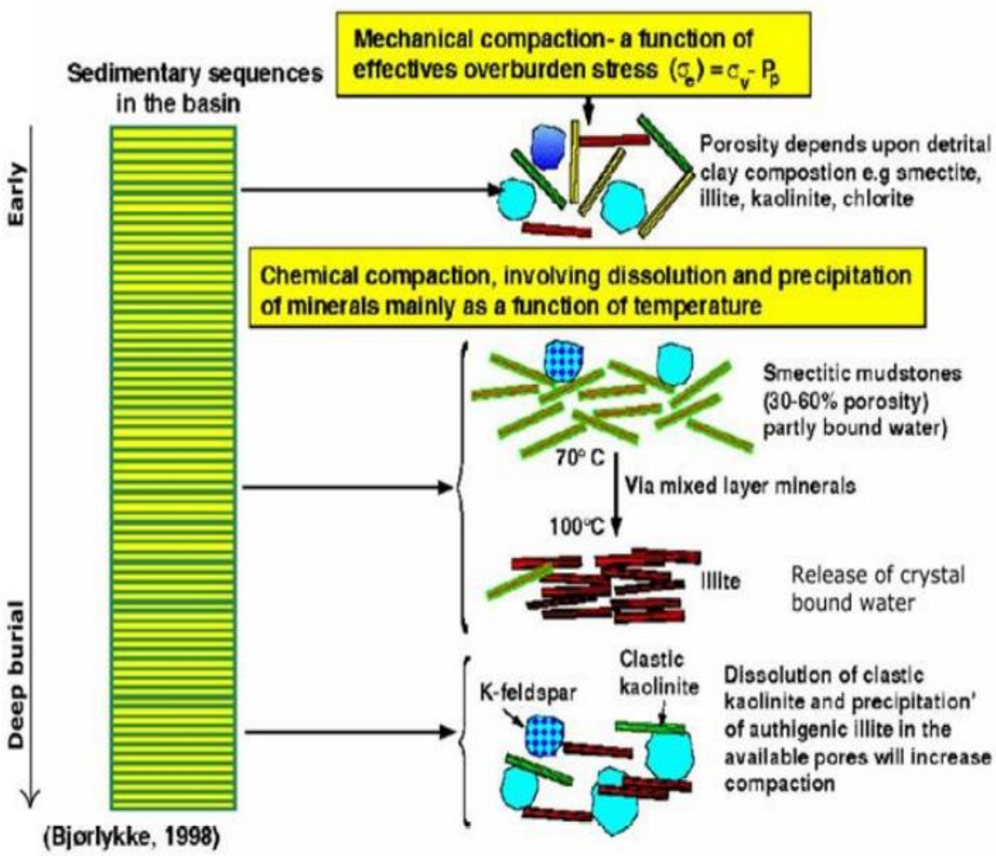


Figure 2.4 Schematic explanation of mechanical and chemical compaction of sediment, with increasing burial depth (Bjorlykke, 1998 and Ndingwan, 2011).

b. Chemical Compaction

Chemical compaction takes place in sedimentary basins at a deeper depth than mechanical compaction. The mechanical compaction must have ended as a result of the lower effective stress, but chemical compaction, which is less susceptible to stress, has proceeded. The mechanical compaction change to mostly chemical compaction is not set in stone and will be affected by mineralogy and burial history (Bjorlykke, 1998). On a grain size, chemical compaction involves mineral breakdown, which causes disequilibrium, and the precipitation of thermodynamically more stable mineral assemblages. It is determined by mineral stability and cement precipitation kinetics. Temperatures of 70^0 C–80^0 C have a big impact on these processes, and the burial depth is around 2 km (Mondol, et al., 2007). Grain size, grain boundary thickness, diffusion coefficient, and effective stress are all factors that affect this process. Chemical compaction is not aided by porosity. In the porosity-depth relationship, both mechanical and chemical compaction processes could be explained asshown in figure 3.5.

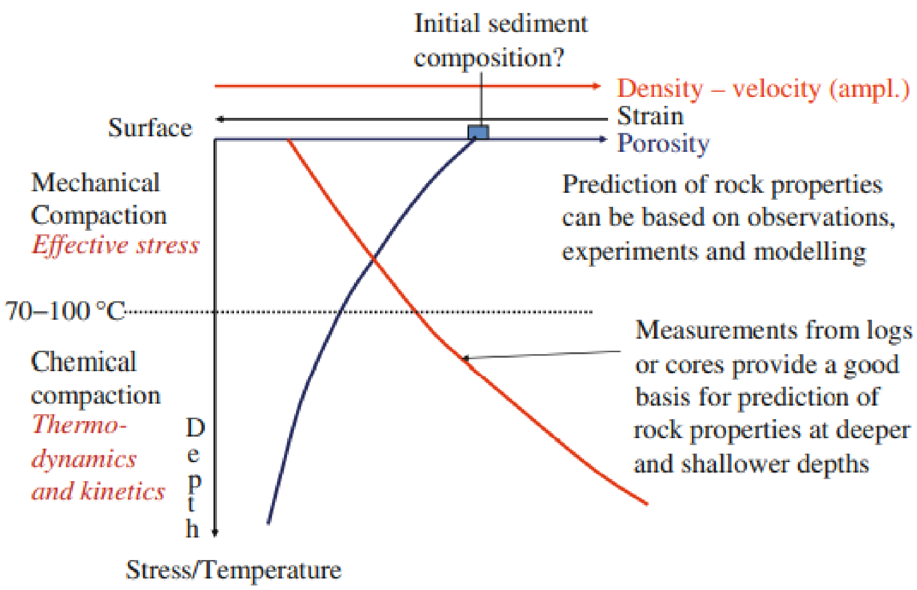


Figure 2.5 Depth-porosity function in burial compaction of sediment (Bjørlykke, K., 2010)

2.2.2 Compaction of Shale

Physical, chemical, and mineralogical events in subsurface shale produce compaction. When the fluid (pore) pressure is near hydrostatic, or the shales are close to compaction equilibrium, shale compaction is primarily regulated by burial depth, which is well understood in many places of the world. Shales compact less than those compacted ordinarily under hydrostatic pressure when the fluid pressure is higher than normal. Assume the area under investigation has been subjected to severe uplift and erosion. When compared to the tendency in an area with no erosion at any depth, the usual shale compaction trend is altered in the direction of higher compaction. As a result, based on shale compaction data, we can estimate the quantity of erosion and the maximum burial depth. The most significant factor to consider while studying shale compaction is porosity. Apart from porosity, various elements can influence the compaction process, including pressure, sedimentary burial depth, and many studies have found that compaction is significantly linked to burial period. (Xia et al, 2018, Scherer, 1987, Giles et al., 1998, and Issler, 1992).

Shales and other sediment have different compaction trends because they have principally different processes of their own. Shales compact mechanically as a function of effective stress until chemical compaction takes control, at which point subsequent compaction is mostly determined by temperature and time. For both shale and sandstone, the early mineralogical and textural composition is critical. Shales, which often make up the majority of the finest fractions, have a wide range of sizes. Some shales with small grain sizes and sensitive to chemical composition have a large specific surface area (hundreds m^2/g). The composition of shales is crucial for learning about the basin's environment, as well as the rock qualities that affect compressibility, density, seismic velocity, and resistivity. These variables have an essential role in seismic and electromagnetic data interpretation (Bjrlykke, K., 2010).

2.3 Thailand Geological Setting

Thailand is part of a geological unit that encompasses Southeast Asia's continental core, which includes several part in Indonesia, Sumatra, Java, and Borneo, and also west Malaysia, Thailand, eastern Myanmar, Vietnam, Laos, and Cambodia (Ridd et al., 2011) Shan Thai in the west and Indochina in the east can be understood geologically as two micro-continental chunks or terranes (Bunopas and Vella, 1983, Chonglakmani, 2011.). Northern Sumatra, western Peninsular Malaysia, western and peninsular Thailand, and eastern Myanmar were all covered by the Shan-Thai (also known as Sibumasu) terrane. Indochina included areas of Thailand, Laos, Cambodia, and Vietnam. Both terranes have their beginnings in the Paleozoic on the Gondwana border. Thailand's geological setting is separated into many regions with different geological and lithological histories ranging from the Precambrian, which follows the Paleozoic, to the Quaternary, which follows the early Cenozoic.

Late Carboniferous to Early Permian glacial-marine diamictite and Early Permian cool-water faunas found in northwest Australia are typical of the Shan-Thai terranes (Bunopas, 1981, 1992). The Indochina Block is an extended stable block made up primarily of Precambrian rocks with some Paleozoic shallow marine faunas and floras that were most likely deposited in a warm environment (Metcalfe, 1988). A geological map as provided by the Geological Survey Division and modified by Charusiri, et al., 2002 (Figure 2.6) shows the distribution of sediments of various ages, significant tectonic plates, and major sutures/fault systems.

2.3.1 The Precambrian

Thailand Precambrian sediments are exposed only in Shan-Thai terrane, included North, Upper West, East, Lower and Southern parts of Thailand. The common lithologic for Precambrian are high-grade metamorphic rocks of amphibolite facies and consist of a wide variety of types including paragneisses, mica schist, quartz schist, amphibolite, quartzite, and marble. The metamorphosed sedimentary rocks initially were shale, siltstone, sandstone (including arkose), and carbonate rocks (Shawe, 1984). The stratigraphy of metamorphic rocks in the Precambrian age in western Thailand was reported firstly by Brown, et al. (1951) and for the Northern part of Thailand, it was described for the first time by Baum, et al (1970).

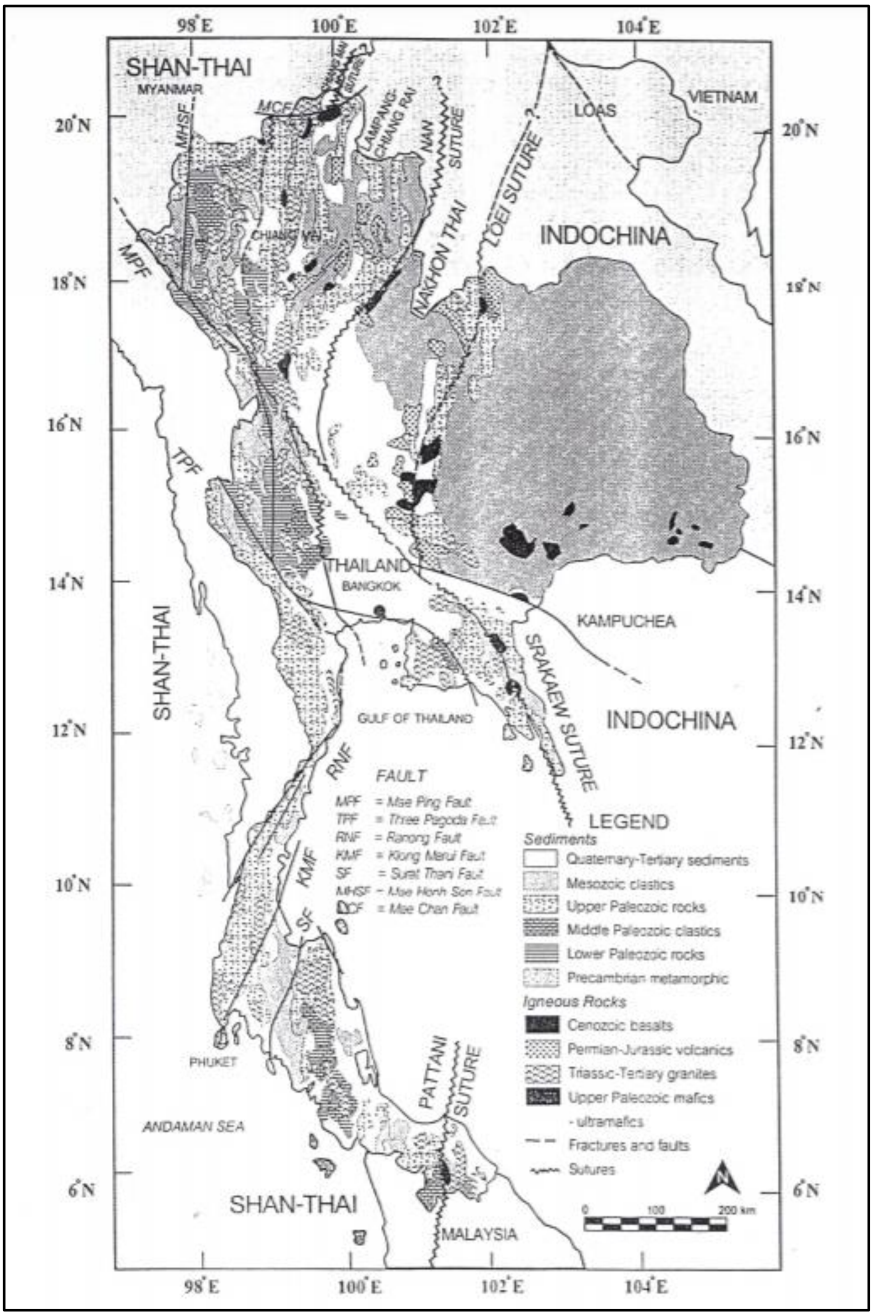


Figure 2.6 Simplified geological map of Thailand (Geological Survey Division Bangkok, 1987 and modified by Charusiri, et al., 2002)

2.3.2 The Paleozoic

Lower, medium, and upper Paleozoic sediments are the three types of Paleozoic sediments. Lower Paleozoic rocks of Cambrian to Ordovician age can be found in the south and western parts of the Shan Thai terrane, but no record mentions Lower Paleozoic rocks in the Indochina terrane in the country's northeast. Lower Paleozoic sediments from the Shan-Thai terrane are classified into two types of rock: the Tarutao Group's lower siliciclastic unit and the Thung Song Group's upper carbonate unit. Tarutao Group is the lowest unit in Lowe Paleozoic located in the island Ko Tarutao in Satun Province, southern peninsula. It contains very fine-grained sandstone, siltstone, and tuffaceous mudstone with minor limestone intercalations. Those sediments compound with rare acid tuff and heavy-mineral band (Lee, 1983). Whereas Thing Song Group in Satun Province contains more limestone, which is a shallow to deep carbonate ramp deposit (Wongwanich and Burrett, 1983; Wongwanich et al. 1983). Those lower Paleozoic sediments may display the same environment of deposition on the Precambrian basement through the whole length of the Western Province, and their general trends are mainly north-south (Bunopas and Vella, 1983).

The Silurian to Devonian Middle Paleozoic sediments of Thailand are classified into three geological types from west to east: the Thong Pha Phum Group, the Sukhothai Group (of the Shan-Thai terrane), and the Pak Chom Formation (Mantajit, 1997). The Thong Pha Phum Group is in Kanchanaburi which has an Ordovician Fauna and overlain by argillaceous and carbonate sequences and generated Silurian fossils (Ridd, 2011). The Sukhothai Group (in Sukhothai Fold Belt) is categorized as thick Middle Paleozoic sediments, the area is widely distributed by metamorphic and metavolcanic rocks including to the east of the western mountains in the Sukhothai Folding Belt. The Pak Chom Formation in the Loei fold belt (at Ban Nong, Sangkhom District, Nong Khai Province) is thinner Middle Paleozoic sediments contain Silurian schist, phyllite, quartzite, metatuff, and fossiliferous limestone and unconformably overlie Namo Group metamorphic rocks, with no significant volcanic activity (Bunopas, 1983). Nong Khai Province and Udon Thani Province (Ban Na Tum in Nam

Som District) are only the two provinces in NE Thailand where the middle Paleozoic rocks are found in the Thai part of the Indochina Terrane (Ridd, 2011).

The Upper Paleozoic sediments in Carboniferous and Permian age. Those sediments are the most widespread in all regions of Thailand and present both at Shan-Thai and Indochina terranes. Most of the Carboniferous sediments are siliciclastics and limestones (Ueno and Chareontitirat, 2011). The Ratburi Group, in the west and Peninsular, and the Ngao Group, in the north, are Permian karstic limestones. The Shan-Thai terrane is home to these two groups. At the western and southern edges of the Khorat Plateau, the Saraburi Group of the Indochina Terrane is made up of limestones interbedded with siliciclastic rocks and chert (Bunopas, 1992).

Lower Carboniferous fine-grained sediments are only found in the southern peninsula, containing *Posidonomya* sp. Sequences of reddish-brown weathering light grey to white shale intercalated with sandstone, these rocks named as Kuan Klang Formation. Mudstone and sandstone from Kaeng Krachan Group In the southern and south-western region represent the Carboniferous-Permian. The Permian sediment in the Northern and North-Western, Loei-Petchabun Ranges, Eastern, and Lower Western and Southern regions are from the Ngao, Saraburi, Chanthaburi and Ratburi Groups, respectively. (Ueno and Chareontitirat, 2011).

2.3.3 The Mesozoic

The marine and non-marine continental facies are Thailand's Mesozoic sediments, lithologically. Limestones, mudstones, sandstones, dolomites, and conglomerates make up the majority of marine sediments. Which can be found in the country's northern, western, and southern regions. These sediments which range in age from Lower Triassic to Early Middle Jurassic, and most of the western and southern regions are exposed by Jurassic Sediment. Non-marine is found primarily in the northeast (Khorat Plateau) and to a lesser extent in the southern peninsula. In the late Upper Triassic to Upper Cretaceous-Lower Tertiary, on the Khorat Plateau. Reddish-brown to light-grey sandstones, conglomeratic sandstones, siltstones, claystones, and conglomerates make up the majority of the sediments. Non-marine rocks in the southern peninsula include reddish-brown claystones, siltstones, sandstones, and conglomerates. Both flowing rivers and alluvial fans are thought to have deposited by these rocks. Other than the northeastern and southern regions, minor outcrops of non-marine rocks are also recorded (DMR, 1999).

2.3.4 The Cenozoic

Thailand Tertiary basins, including intermontane and rift basins, are frequently comparable in terms of origin, period, sedimentary settings, and basin structural types. Except in the northeastern part of the country, there are at least 70 Tertiary basins scattered around Thailand, both onshore and offshore, and organized into five primary regions: the Andaman Sea, Gulf of Thailand, Peninsular, Central and Northern Thailand (Chaodumrong et al., 1983; Polachan et al., 1991). See Figure 2.7. Petroleum, coal, oil shale, diatomite and clay are all frequent deposits in tertiary basins. These sediments are also known as oil and gas source rocks and reservoirs. The Mae Sod Basin (Basin No. 36 in Figure 2.7) is the most common oil shale deposit.

Climate change, sea-level rise, and altering landforms characterize the Quaternary geological epoch that spans 1.8 million years and continues to the present day. During this time, life migrated, and human evolution took place.

2.4 Thailand Basins and Regions

According to the Department of Mineral Fuel, by its regions the area of Thailand can be categorized into four areas, i.e., North-Central Area, Northeastern Area, Gulf Area, and Andaman Area, as shown in Figure 2.7 and based on the geological time and the hydrocarbon contain, Thailand basins can categorize into Tertiary Basins (late Cenozoic age), and Pre-Tertiary basins which are Triassic Basins (Mesozoic age), and Permian Basins (Paleozoic age), those basins shown in Figure 2.7 in green, purple, and yellow color, respectively. Tertiary basins are widespread in Thailand, onshore (North, Central and South) and offshore (the Gulf of Thailand and the Andaman Sea). The Triassic and Permian Basins make up the majority of the pre-tertiary basins in northeast Thailand.

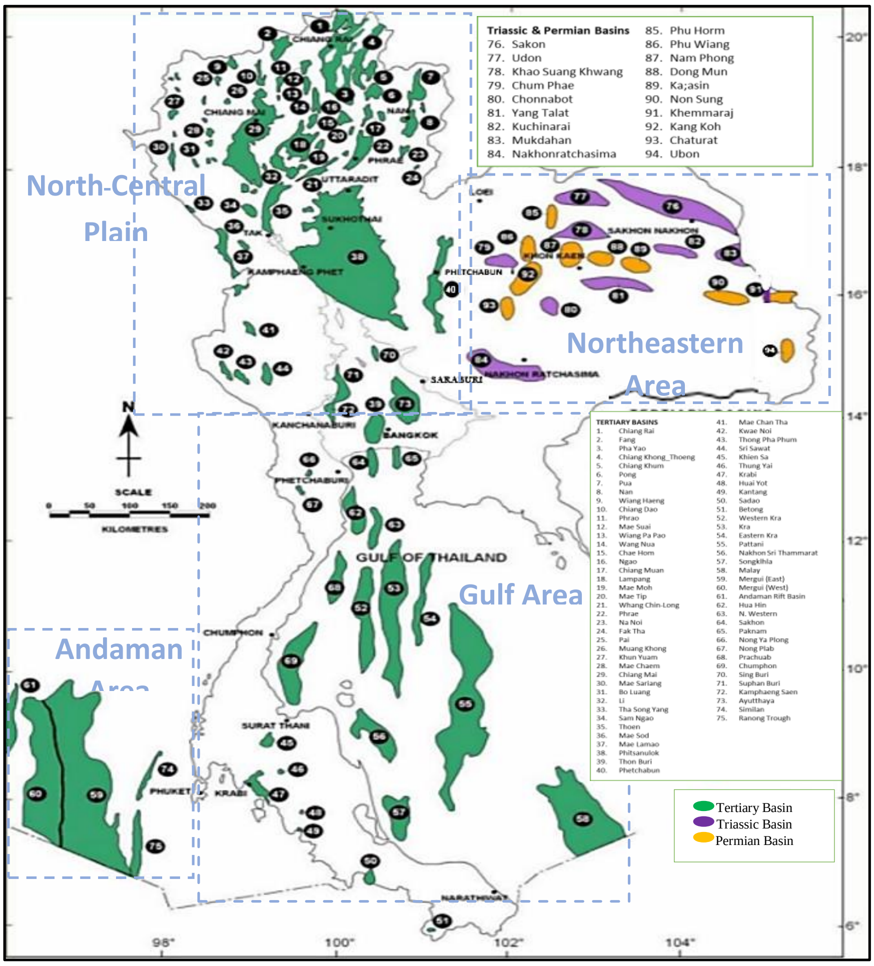
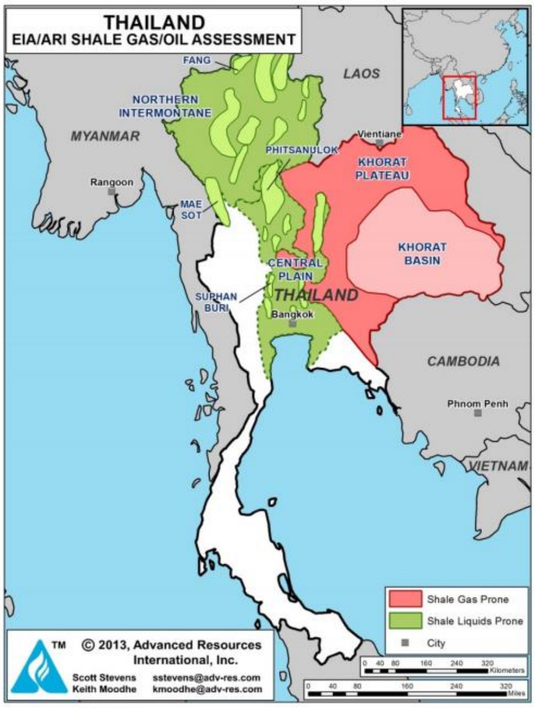


Figure 2.7 Map of basin in Thailand based on their Geological Time (period) at several regions of Thailand (Sources: Department of Mineral Fuel of Thailand)



Source: ARI, 2013

Figure 2.8 Thailand Shale Potential (EIA/ARI, 2013)

Thailand's shale potential is concentrated in the north-central and northeastern regions. Based on Advanced Resources International (ARI), the main sites of shale in Thailand are located at three main onshore sedimentary basins of Thailand in the North-Central and Northeastern region of Thailand (Figure 2.8), those sites potentially contain non-conventional oil and gas. These are the basins of the Khorat, North Intermontane, and Central Plain (EIA/ARI, 2013).

2.4.1 North-Central Plain

The north-central plain region is comprised of two major sedimentary basins: North Intermontane and Central Plain. Many intermontane Tertiary basins (subbasins) of varied sizes make up the North Intermontane Basin area. A series of north-south trending partial grabens pulled apart, forming the basins. Basins are normally narrow but deep, with a substantial heat flow on rare occasions. The exploration in the Fang area is highly active, whereas activity in the other areas is very restricted. The Fang, Phitsanulok, Suphan Buri, Kamphaeng Saen, and Phetchabun basins have all been successfully explored, indicating that Thailand's northern and central regions have a lot of oil potential. The largest basin in this area is Phitsanulok, with 8 kilometers of sediments. In the basin, ten oil fields have been discovered. The Phetchabun Basin is located in Thailand's central plan region, on the western boundary of the Indochina Terrane, within a fold belt. In the Late Oligocene, the basin was formed (Remus et al. 1993).

2.4.2 Northeastern Area

The Khorat basin is located in Southeast Asia and includes three countries: the biggest portion is in northeast Thailand, with the remainder in southern Laos and northern Cambodia. This basin is also known as the largest land-based sedimentary basin which has the best shale gas potential in Thailand. Figure 2.8 depicts a geological map of Northeast Thailand. The region in the Mesozoic sequence is known as "Khorat Basin," while in the upper Paleozoic sequence, it is known as "Isan Complex" (Booth and Sattayarak, 2011). In addition, Arsairai (2014) defines the Khorat Plateau Basin to be the higher Paleozoic (above the mid-Carbon mismatch) and all Mesozoic periods.

Northeastern Thailand mostly contains Permo-Carboniferous, Triassic, Mesozoic, and Tertiary basins. The Khorat Plateau is a very flat plain at 150-200 meters above sea level that descends gently north and west across the Mekong River into Laos, covering nearly the whole northeast Thailand region. It is split into two depositional basins by the Phu Phan Range, the Khorat in the south and the smaller Sakhon Nakhon in the north. Khorat Plateau seismic data and petroleum exploration wells show the presence of numerous Paleozoic and Triassic basins at depth, with outcrop analogs in the Loei-Phetchabun Foldbelt to the west (Löffler et al, 1984; Booth and Sattayarak, 2011).

Shallow marine siliciclastic and carbonate sediments make up the Permo-Carboniferous sequences. A sequence of half-graben basins formed intermittently throughout the Late Triassic. Lacustrine and fluviatile clastic sediments dominate the Triassic sequences. The region subsided during uplift and erosion in the late Triassic and was later overlain by thick non-marine Mesozoic Redbeds. The Tertiary sediments, which are made up of aeolian and alluvial sediments, are thin and localized. The gas-bearing reservoir is Permian carbonate, whereas probable source rocks are Permian shale and Triassic organic-rich shales.

2.4.3 Gulf Area

The majority of Thailand's petroleum comes from offshore Tertiary basins in the Gulf of Thailand, the most notable of which being the Pattani basin, which has been producing gas for the past 24 years. The Gulf is separated into two sections, one western and one eastern. Ten major basins of varying sizes can be found in the western part. In the Chumporn and Songkhla Basins, discoveries have been found. The Pattani, Khmer, and Malay Basins make up the eastern half.

The basins of Pattani and Malay are rich in hydrocarbons. As source rocks, hydrocarbons can be discovered in Oligocene and Miocene sandstones. In the Pattani and North Malay Basins, certain oil and gas reserves have been identified. The majority of the gas resources are scattered throughout the Pattani basin's center region, while the oil fields are concentrated around the basin's shallower coast. Bidding is open on blocks all throughout the Gulf, but mainly in the north and south.

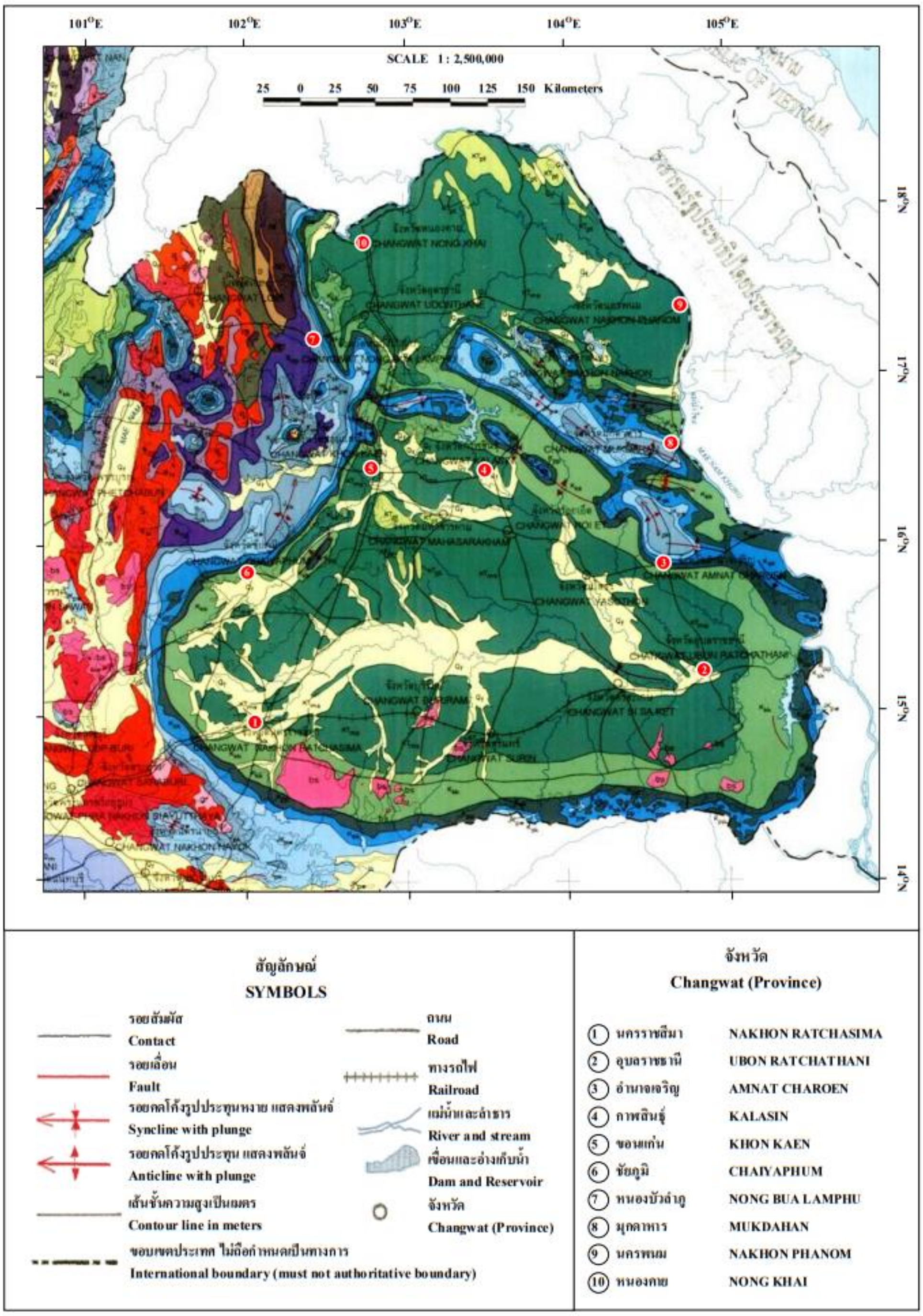


Figure 2.9 Geological map of Northeastern Thailand (DMR, 1999)

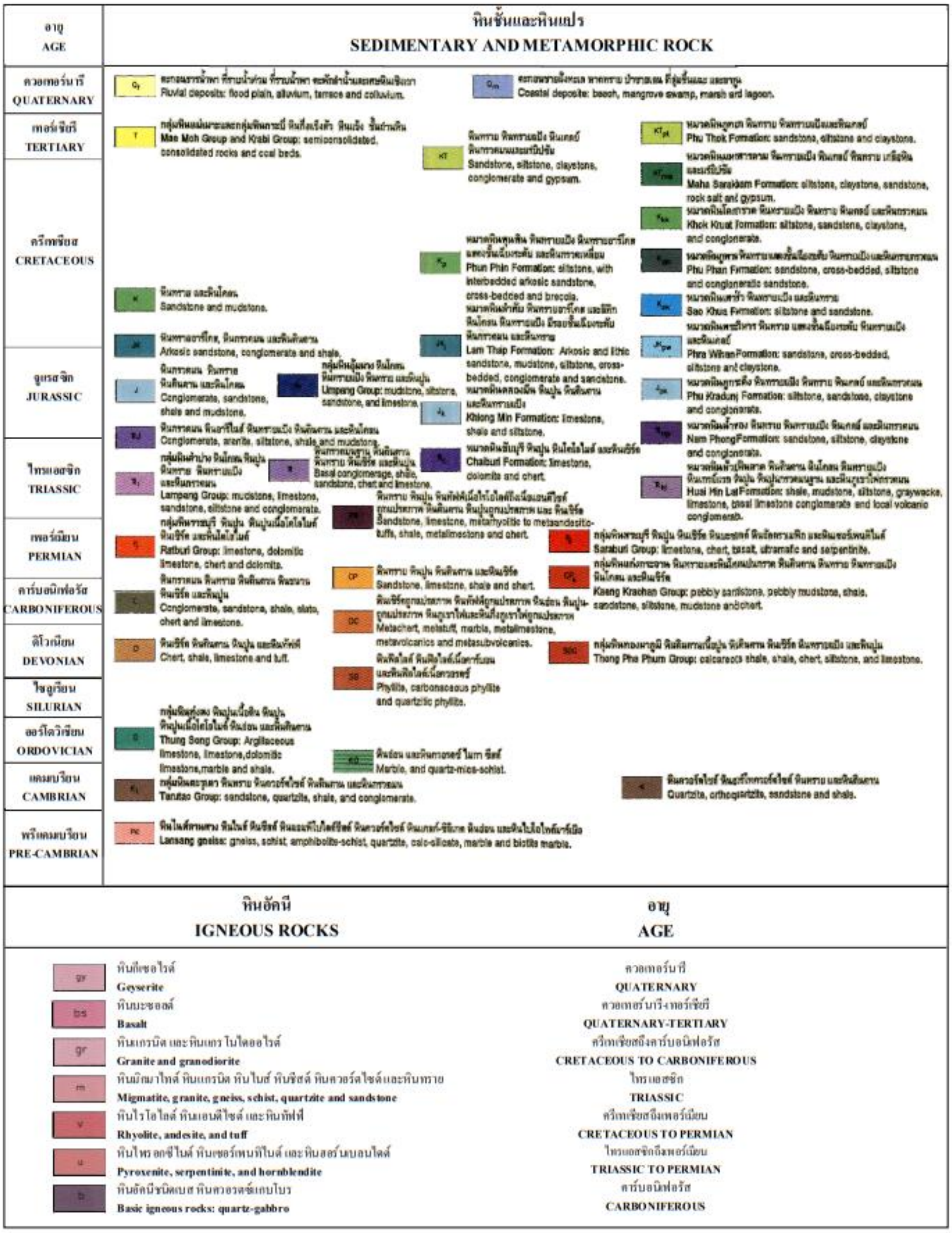


Figure 2.9 Geological map of Northeastern Thailand (DMR, 1999) (Continued)

2.4.4 Andaman Area

In western Thailand, the Andaman Sea is home to the Andaman area. The shallow and deep-water areas of the region are separated by the shelf margin. The Mergui, also called the trans-tensional back-arc basin, is mostly submerged. The basin is an extension of the North Sumatra Basin to the north. The Mergui Basin is the only Tertiary basin with genuine marine sediments. Two undiscovered gas prospects, as well as multiple gas shows, were located in the Oligocene sandstones.

Early Miocene sandstones and carbonate build-ups generated on the horst and shelf margin are of exceptional quality, and they could be potential reservoirs. Oligocene and Early Miocene sandstones and shale containing a lot of organic matter could be used as oil and gas source rocks. The maturity of the source rocks, as well as their ability to operate as a trap, are also factors that come into play in this exploration.

2.5 Geological Age

Earth's geological time scale is needed to determine the age of the physical geography of the earth. The evolution of life on earth has occurred over billions of years and the age of the earth starts from the Big-Bang event till the present day or about 4.65 billion years. The time frame of the Earth's evolution is very extensive, such as the evolution of life, the evolution of continents, the evolution of ocean and basins, and their constituents. The ancient time frame of the earth is formulated into:

- EON is a mega unit with a duration of half a billion years (or) more time.
- ERA refers to a period of time that occurred more than hundreds of millions of years ago.
- PERIOD refers to hundreds of millions of years.
- EPOCH is used to represent the duration of Tens of Millions of years, and
- AGE is used to represent Millions of years in the earth's history.

The geological time scale (Table 2.1) is a timeline that takes up an entire history of the Earth. It converts information about life types and specific geological events from Earth's past into usable time units. Since the beginning of time, time has been flowing. Long after the current generation has passed, time will continue to flow. The time scale was created by studying rock levels and fossils all throughout the world. One of the most essential aspects of Earth Science investigations is the age of the earth (Balasubramanian, 2014).

Table 2.1 Geological time scale (*NPS Geologic Resources Inventory, 2018*)

Eon	Era	Period	Epoch	MYA		Life Forms	North American Events
Phanerozoic	Cenozoic (CZ)	Quaternary (Q)	Holocene (H)	0.01	Age of Mammals	Extinction of large mammals and birds; Modern humans	Ice age glaciations; glacial outburst floods
			Pleistocene (PE)	2.6			
		Tertiary (T) Neogene (N)	Pliocene (PL)	5.3		Spread of grassy ecosystems	Cascade volcanoes (W); Linking of North and South America (Isthmus of Panama); Columbia River Basalt eruptions (NW); Basin and Range extension (W)
			Miocene (MI)	23.0			
		Paleogene (PG)	Oligocene (OL)	33.9			
			Eocene (E)	56.0			Laramide Orogeny ends (W)
			Paleocene (EP)	66.0		Early primates; Mass extinction	
	Mesozoic (MZ)	Cretaceous (K)		145.0	Age of Reptiles	Placental mammals; Early flowering plants	Laramide Orogeny (W); Western Interior Seaway (W); Sevier Orogeny (W)
		Jurassic (J)		201.3		Dinosaurs diverse and abundant	Nevadan Orogeny (W); Elko Orogeny (W)
		Triassic (TR)		251.9		Mass extinction; First dinosaurs; first mammals; Flying reptiles; Mass extinction	Breakup of Pangaea begins; Sonoma Orogeny (W)
	Paleozoic (PZ)	Permian (P)		298.9			Supercontinent Pangaea intact
		Pennsylvanian (PN)		323.2	Age of Amphibians	Coal-forming swamps; Sharks abundant; First reptiles	Ouachita Orogeny (S); Alleghany (Appalachian) Orogeny (E)
		Mississippian (M)		358.9			Ancestral Rocky Mountains (W)
		Devonian (D)		419.2	Fishes	Mass extinction; First amphibians; First forests (evergreens)	Antler Orogeny (W); Acadian Orogeny (E-NE)
		Silurian (S)		443.8		First land plants; Mass extinction	
		Ordovician (O)		485.4	Marine Invertebrates	Primitive fish; Trilobite maximum; Rise of corals	Taconic Orogeny (E-NE)
		Cambrian (C)		541.0		Early shelled organisms	Extensive oceans cover most of proto-North America (Laurentia)
Proterozoic		Precambrian (PC, W, X, Y, Z)		2500		Complex multicelled organisms; Simple multicelled organisms	Supercontinent rifted apart; Formation of early supercontinent; Grenville Orogeny (E); First iron deposits; Abundant carbonate rocks
Archean				4000		Early bacteria and algae (stromatolites)	Oldest known Earth rocks
Hadean				4600		Origin of life; Formation of the Earth	Formation of Earth's crust

2.6 Effect of Time of Shale Compaction Curve

There are several previous studies have been published on the issue of sedimentary compaction and suggested some equations about the compaction and its relationship for porosity and depth. However, few studies that detailed it for shale compaction. The most used shale compaction equation for the porosity and depth is Athy's (1930). Because Athy's exponential function (eq. 1) it is the that come closest to the compaction equilibrium circumstances when pore pressure reaches normal hydrostatic pressure. The shale porosity-dept connection can be approximated by and axponential function for a section of normal-hydrostatic pressure when compaction equilibrium has been reached even in relatively young sedimentary basins (Rubey and Hubbert) (1959).

Besides the exponential trend from Athy (1930) and Rubey and Hubbert (1959), other studies also suggest different compaction trends such as linear compaction trend (Bjørlykke et al., 1989), double-exponential trend (Kominz et al., 2011), and exponential-linear trending (Cao, et al. 2017), regardless of geological time effects.

Burst (1969), a study that plotted porosity versus geological time by modifying shale compaction data published by Manger (1963) from several places and concluded that shale porosity decreases with increasing time or geological age, was a pioneer in quantitatively investigating the effect of geological time on the compaction process. Other studies have also reviewed the effects of geological time on the compaction process and suggested several equations that show the relationship of time into the compaction process, but most of these studies have focused on sandstones, as has been done by Scherer (1987), Ehrenberg, et al., (2009), and Xia, et al., (2018). The equations suggested by these studies give a high correlation trend up to 0.85.

Recently in 2007, Mondol, et al., re-plotted the published depth-porosity trends for shale from several parts of the world and explains that published data trends varied the greatest at shallow burial depths, and the differences decrease dramatically at nearly 2000 m. This study also found that there was a large difference in the initial porosity in the published porosity depth data, but most of them had an initial porosity value lower than 60%.

The study from Puttiwongrak, et al., (2013) compared, revised, and reconstructed the published porosity-burial depth data of mudstone from several locations, geologic ages, and geothermal gradients. This study classified all the data based on their geological time (young and old mudstone) and temperature (high and low), which are a major factor influence the mudstone compaction. For the time effect on mechanical compaction, this study showed porosity declines with increasing time at constant depth (or overburden pressure). For temperature effect, this study showed a decrease in low porosity due to an increase in geothermal energy.

Another currently published study from Puttiwongrak, et al., (2020), used the shale compaction data from various published data of several sedimentary basins around the world. They suggested a mathematical expression of porosity change with depth and geological time as follows, with $R^2 = 0.70$:

$$\ln \phi = 4.023 - 0.4z - 0.0042t \qquad (4)$$

where z is the depth of shale in km^{-1}, t is geological time in Million age.

An easy approach to determine the geologic time of sedimentary burials with respect to depth and time, is to look at their relationship to seismic velocities. This can be done by following the equation proposed by Faust (1951). Where assumes that velocity is a function $v = f\,(Z, T, L)$, where Z is depth, T is elapsed time since deposition and L is another lithology variation (limestone, shale, and sandstone). The velocity data on Faust's study are from 500 well surveys in the United States and Canada. They proposed the following equation to describe the link between velocity, depth, and geological time (age) in years:

$$v = \alpha\,(TZ)^{1/6} \qquad (5)$$

Where v denotes seismic velocity in meters per second, Z denotes depth in meters, T denotes geological time in years, and α is currently 46.55 and is numerically equal to velocity in meters per second when $TZ = 1$.

CHAPTER 3
METHODOLOGY

3.1 Research Framework

The research framework of this study is shown in Figure 3.1, the process is starting with collecting data and doing some reviews for the previous studies regarding the relationship of geological age and burial depth to estimate the numerical geological age of Thailand Shale data.

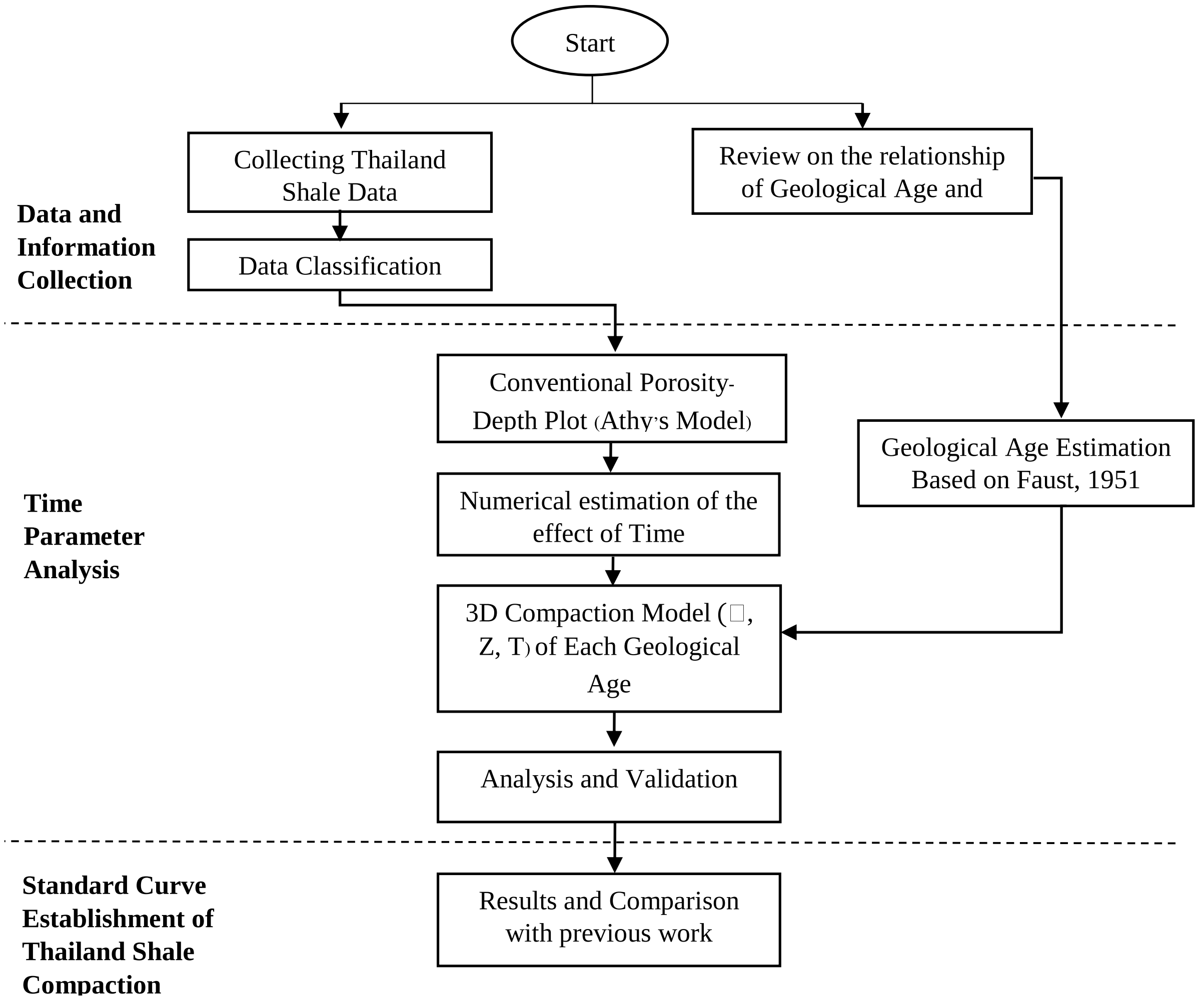


Figure 3.1 Research framework of this study

3.2 Data Collection and Study Area

The data for this study came from four separate local basins with varying geological ages, including the Phetchabun basins in North Thailand, which are part of the Central Plain basin, and the Mukdahan, Kuchinarai, and Phu Din basins in Northeast Thailand, which are part of the Khorat Basin. Figure 3.2 depicts the location of this research area. The collection contains 176 shale data points with a common mechanical compaction parameter, such as porosity, depth below the surface, and geological age. Furthermore, the geological age of the data for this study ranges from Paleozoic to Mesozoic to Cenozoic, the burial depths available from 280 to 1432 m. Paleozoic data dates from more than 250 million years ago (Ma), Cenozoic data dates from 250 to 65 Ma, and Cenozoic shales date from 65 Ma to the present day. Table 3.1 provides a summary of the dataset's details. The Department of Mineral and Fuel (DMF) of Thailand collected all the data used in this study.

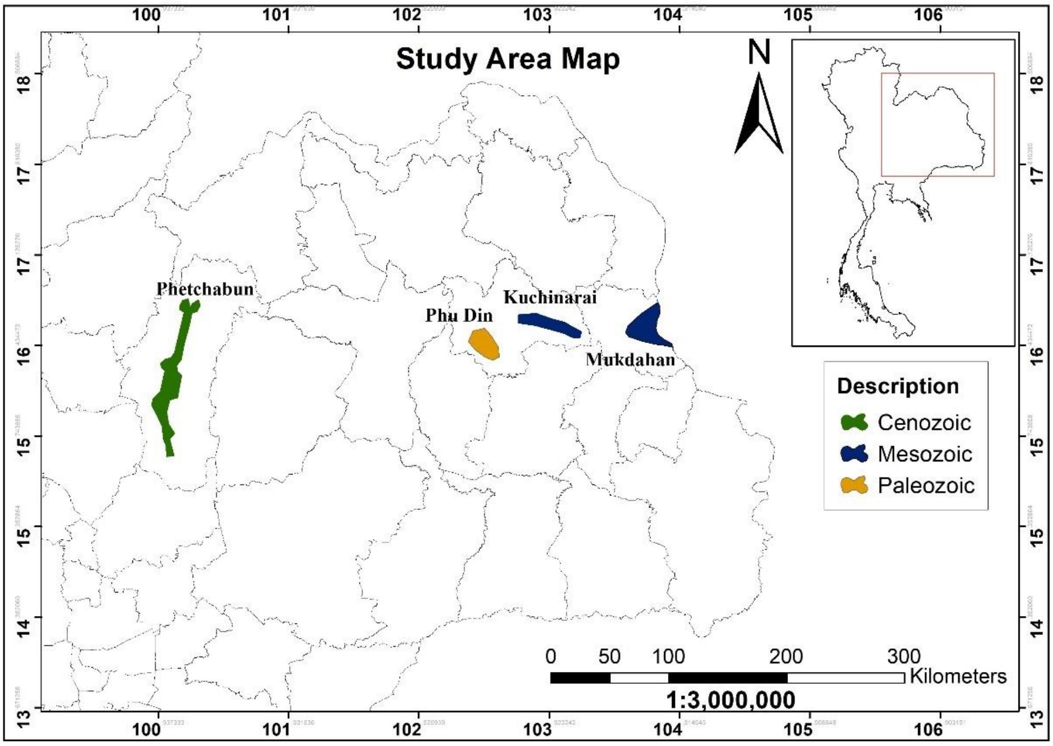


Figure 3.2 The map of data collection for this study

3.3 Porosity-Depth Plot Using Conventional Model

Athy's Model is the exponential function for compaction curve plot, which is the most used in several compaction research. The equation of Athy's is described in Eq. (1) and the details about the compaction curve (porosity-depth plot) purposed by Athy (1930) has been explained in section 2.2 and 2.6.

The dataset of this study was plotted in exponential trend as purposed by Athy also known as the conventional compaction trend, the porosity-depth plot is shown in Figure 3.3. Figure 3.3 demonstrates that Thailand shale compaction data is excessively scattered, which explains why Athy's Model (r-square = 0.0406) was not fitted to the Thailand shale data to yield compaction curves (r-square = 0.0406).

Table 3.1 The list of datasets for each location of this study

Location	**Porosity**	**Depth (m)**	**Geological Age**	**Total Data**	**Estimation Ages (Ma)**
Petchabun	12.1 – 29.4%	285 -1100	Cenozoic	136	24.4 – 40.6
Kuchinarai	3.2 – 14.5%	503 – 869	Mesozoic	15	73.5 – 78.1
Mukdahan	4.8 – 8.0%	996- 1432	Mesozoic	9	75.7 – 88.9
Phu Din	2.2 – 4.8%	280 - 970	Paleozoic	16	231.8 - 478.9

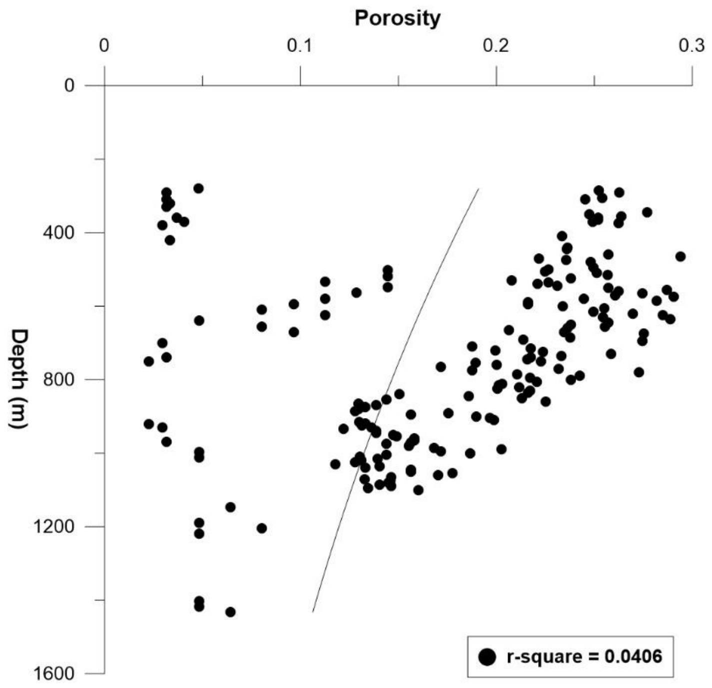


Figure 3.3 Thailand Shale porosity-depth in exponential trend of compaction curve.

3.4 Numerical Estimation of Geological Age Data and Geological Time Classification

The data in this study is divided into three geological eras: Cenozoic, Mesozoic, and Paleozoic. The assessment of geological age in numerical data from those groupings of geological ages must be done by looking at the link between seismic velocity, burial depth, and geological age in years, as recommended by Faust (1951). For the Cenozoic, Mesozoic, and Paleozoic datasets, respectively, the velocity data were derived utilizing the link between velocity (v) and depth (z) using Eqs. (6), (7), and (8), which were acquired from modified velocity-depth plots of Faust (1951)'s data (Figure 3.4). Figure 3.4 shows the link between velocity and depth for each geological age, with r-squares of 0.9414, 0.7701, and 0.6253 for each ages, Cenozoic, Mesozoic, and Paleozoic, respectively.

The velocity as a function of depth for Cenozoic, Mesozoic, and Paleozoic equations are given here,

$$v_C = 0.434z + 3269.4 \tag{6}$$

$$v_M = 0.6325z + 2396 \tag{7}$$

$$v_P = 0.412z + 2096.5 \tag{8}$$

Faust (1951) proposed the relationship of velocity, depth, and geological time as shown in equation (5), for time estimation in each age the equation used in this study is expressed as below:

$$\mathrm{T} = \left(\frac{v}{a}\right)^6 \times \frac{1}{Z} \tag{9}$$

Where v is from v_C 〖, v〗 $\_m$ 〖, v〗 $\_p$ which are velocity for Cenozoic, Mesozoic, and Paleozoic ages, z is depth, and α is given presently the value of 46.55 When TZ = 1, it is numerically equal to velocity in meters per second, where z is depth in meter. Finally, using Table 3.1's depth data, Eq. (9) was used to determine the estimation of each geological age in numerical data (T).

Where v is v_C, v_m, v_p are velocity in every age (Cenozoic, Mesozoic, and Paleozoic ages), z is depth, and the value of α is given 46.55 and when TZ = 1 and velocity numerically equal in meter per second, where z is depth in meter. Finally, the estimation of each geological age in numerical data (T) was calculated by Eq. (9) using the burial depth data as shown in Table 3.1.

From Table 3.1, the estimation age (T) in each geological age is matched well for this study, as we can see that the range years of Cenozoic data is less than 50 Ma, and Mesozoic data ranges from 65 - 100 Ma, and for Paleozoic data the range is broadly above 230 Ma. The value of the calculation of geologic time that is carried out here is in conforms with the range of geological time given by geoscientists as shown in Table 2.1. However, in this study the amount of data used at each age has a large enough difference from one another. This also needs to be considered in future research

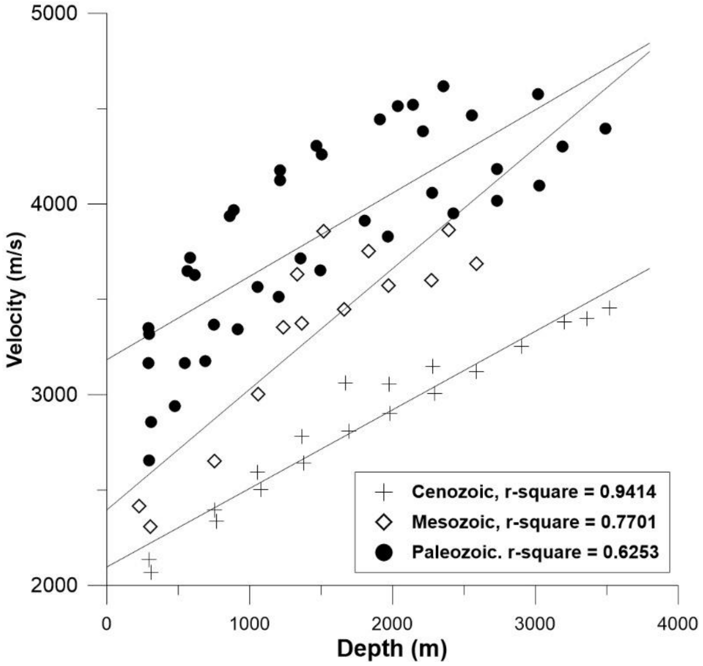


Figure 3.4 Modified plots from Faust (1951) velocity as a linear function for each geological age, Cenozoic, Mesozoic, and Paleozoic.

3.5 Multiple Linear Regression Method

This study suggests a multiple linear regression for porosity, depth, and geological age for Thailand shale compaction instead of exponential trend (Athy's model), to increase the r-square of shale compaction curve. Regression analysis is a mathematical method used for modelling and analyzing the relationships among variables that have reason and result relation. Specifically, the relationship between a dependent variable and one or more independent variables. When the study variable depends on one independent variable is named the simple linear regression model and for more than one independent variables is known as the multiple linear regression model. Multiple linear regression allows the user to account for multiple independent variables and therefore to create a model that predicts the specific outcome being researched. This method is suitable for use in this study to establish a compaction model of Thailand shale for porosity, depth and time variables.

$$y = \beta_0 + \beta_1 x_1 + \dots + \beta_n x_n + \in \quad (10)$$

y : dependent variable

x : independent variable

β : parameter

$\in$: error

A statistical technique was utilized to investigate the correlation of the 3D empirical models given by this study (porosity, depth, and geological age) for the Cenozoic, Mesozoic, and Paleozoic datasets. Matlab 2015 was used for analysis and validation. The coefficient of determination (r-square) can be calculated as follows.

$$r - square = \frac{\Sigma(\phi_{data} - \phi_{model})^2}{\Sigma(\phi_{data} - \bar{\phi})^2} \quad (11)$$

Where ϕ_data refers to the porosity data in Table 1, ϕ*_model* refers to the anticipated porosity from the compaction model, and $\bar{\square}$ represents the statistical variable's mean value. The r-square is always in the range of 0 to 1. The greater the correlation between data from observation and model data, the higher the value. Finally, the new compaction model for all datasets was fitted, in terms of porosity as a function of depth and geological age, after the model was categorized based on each geological.

CHAPTER 4
RESULTS AND DISCUSSION

4.1 Effect of Time on Thailand Shale Compaction

The conventional compaction curve from Figure 3.3 is classified into three geological ages (Cenozoic, Mesozoic, and Paleozoic) representing the effect of time on porosity-depth as the shale compaction curve (Figure 4.1). In the porosity-depth plots, the data fits better with Athy's model thanks to the time categorization in Figure 4.1. This link quantitatively backs up the findings of Puttiwongrak et alprior .'s study (2020). For Athy's Cenozoic, Mesozoic, and Paleozoic ages, there is a variation in initial porosity (ϕ_0) of 40.11%, 16.59%, and 4.00%, respectively. Despite the low r-square values in some geological ages (0.6572, 0.5100, and 0.3613, respectively) this categorization shows a quantitative empirical relationship between geological ages and porosity-depth plots. As a result, as detailed in the next sections, this relationship is quite useful in examining the empirical model between porosity, depth, and geological age.

Overall, the porosity of shale decreases with increasing depth and decreased more slowly in the deeper burial. Figure 4.1 also shows that the older shale (Paleozoic and Mesozoic) has lower porosity compared to the younger shale (Cenozoic). The porosity of shale in Cenozoic and Mesozoic ages has a wider range of porosity values than the Paleozoic, and the decrease in porosity value is slower at the older shale age.

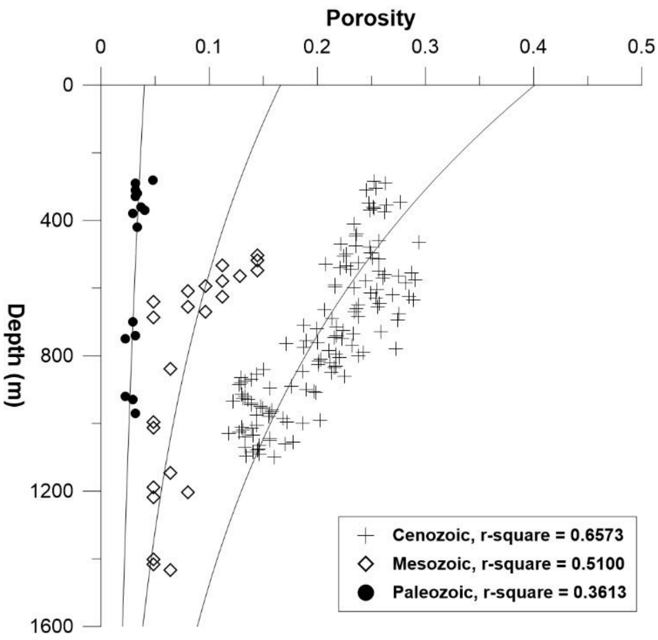


Figure 4.1 Thailand Shale porosity-depth classified in Cenozoic, Mesozoic, and Paleozoic ages

Exponential Plotted as suggested by Athy's model shown in figure 4.1 give the equations for porosity in Cenozoic, Mesozoic and Paleozoic, respectively:

$$\phi_C = \phi_0 e^{-0.00094z} \tag{12}$$

$$\phi_M = \phi_0 e^{-0.00091z} \tag{13}$$

$$\phi_P = \phi_0 e^{-0.00107z} \tag{14}$$

4.2 Thailand Shale Compaction: An Empirical Model of Geological Age Classification

The geological age categorization is required to construct an empirical relationship between porosity, depth, and geological age based on the porosity and depth depicted above. This study suggests a multiple linear regression for porosity, depth, and geological age for Thailand shale compaction (Figure 4.2) instead of an exponential trend (Athy's model). Multiple linear regression is a mathematical function of several variables that is a linear function of each variable when the other variables are given fixed values, it is suitable for use in this case. The empirical compaction model for each geological age classification is expressed as below:

- Cenozoic Age (T < 65M years ago):

$$\phi_C = \phi_0 e^{-0.0014z-0.0342T} \tag{15}$$

- Mesozoic Age (65M < T < 250M years ago):

$$\phi_M = \phi_0 e^{-0.0017z-0.0700T} \tag{16}$$

- Paleozoic Age (T > 250M years ago):

$$\phi_P = \phi_0 e^{-0.0012z-0.0066T} \tag{17}$$

Where ϕ is porosity for each geological age, T is time in million years ago, and z is depth in meter.

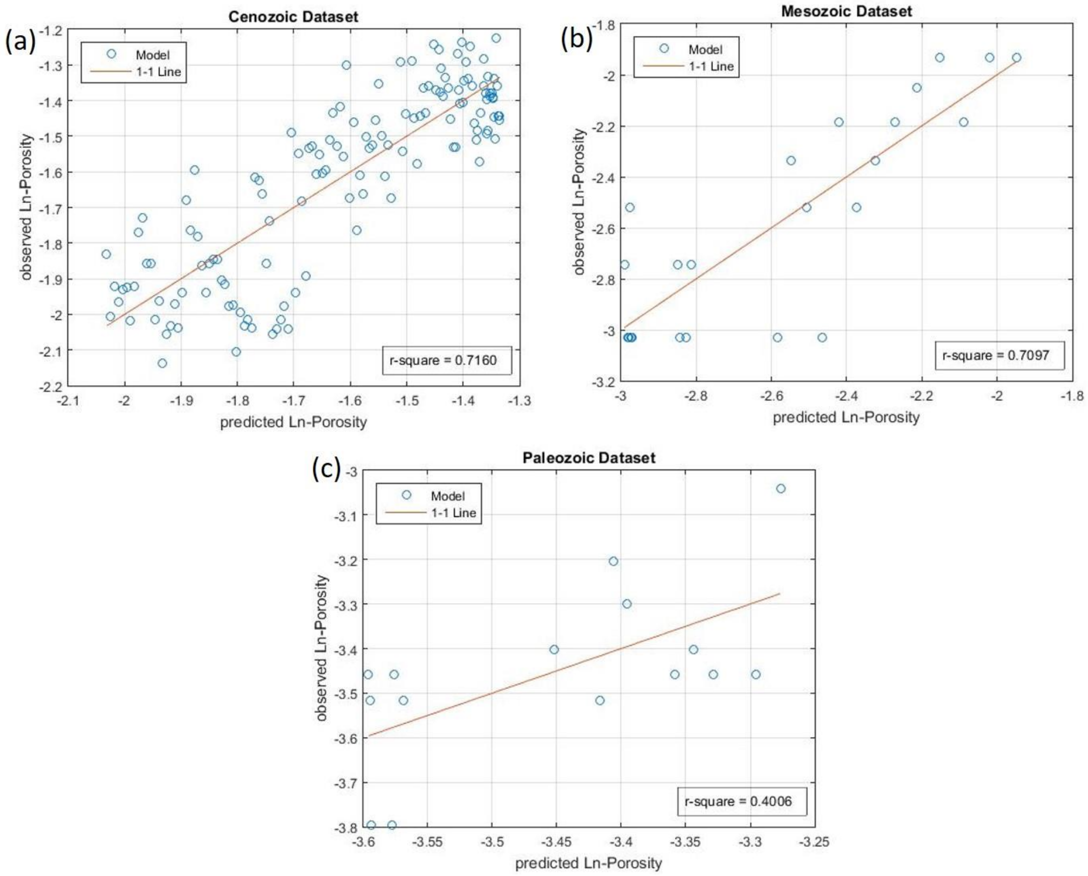


Figure 4.2 Validation of new empirical model for each geological age, (a) Cenozoic Dataset, (b) Mesozoic Dataset, and (c) Paleozoic Dataset

The dataset with geological age classification was fitted to equations (15), (16), and (17), which result in a good association of porosities as a function of depth and time, with r-squares of 0.7160, 0.7097, and 0.4006 for Cenozoic, Mesozoic, and Paleozoic data, respectively (Figures 4.2). (a,b, and c). As shown in the figure, the r-squared for the Cenozoic and Mesozoic fittings has a higher value than the Paleozoic, this may be because the total paleozoic data is in the least amount compared to the two ages. It is recommended that in the future the gap between the total data for each age is not too wide.

The comparison of models of Eqs. (15-17) as shown in Figure 4.2 and the Athy's model in each geological age (Figure 4.1) show that (Figures 4.2 (a,b, and c) has the higher r-squares in every geological age. Long geological processes (deposition, diagenesis, erosion-uplift, etc.) result in lower first porosities in older shales, therefore they will likewise contribute to lower initial porosities. The coefficients take into account the effect of time on shale compaction.

4.3 Standard Compaction Model in Three Dimensions (3D) for Thailand Shales

It is crucial to classify geological age on shale compaction because it appears that geological age has a significant impact on Thai shale compaction data (Figure 4.2). Because a typical model of Athy fails to account for porosity-depth changes, this study used a 3D model of conventional shale compaction (porosity as a function of depth and geological time) for all datasets, as shown in Figure 4.3. The empirical equation for a 3D standard model of shale compaction in Thailand is as follows:

$$\boldsymbol{\phi = \phi_0 e^{-0.0012z-0.0066T}} \tag{18}$$

With an r-square of 0.8372, equation (18) best matches all data (Figure 4.3). The proposed model of Puttiwongrak et al. (2020) was supported by a typical model of shale compaction in this work. The findings of this study are in line with those of Puttiwongrak et al. (2020), whose claim that shales require geological age data as a parameter of compaction data in order to better fit the compaction model. The initial porosity of Eq. (18) was 55.95 percent, which is extremely close the initial porosity of Puttiwongrak et al., 2020, other model parameters, as stated in Table 4.2, are compared to the Puttiwongrak's investigation. Except for the compaction coefficient of burial depth, the comparative result is considered acceptable when the original porosity and compaction coefficients are close to one another. As a result, it may be concluded that the burial depth alone is insufficient to define the shape of the shale compaction curve.

In a three-dimensional (3D) plot, the measured porosity and burial depth data were displayed with geological age data computed using equation (9) as shown in Figure 4.4. The initial porosity calculated by the 3D curve fitting is 55.95 percent, and the r-square is 0.8372, which is extremely comparable to the value calculated by Eq. (18).

Table 4.1 shows the comparison of three-dimensional compaction models.

Parameter	**The model purposed by this study**	**The model of Puttiwongrak et al. (2020)**
Initial porosity, ϕ_0	55.95%	55.90%
Compaction Coefficient of Burial Depth	0.0012	0.4000
Compaction Coefficient of Geologic Time	0.0066	0.0042
r-square	0.8376	0.7000

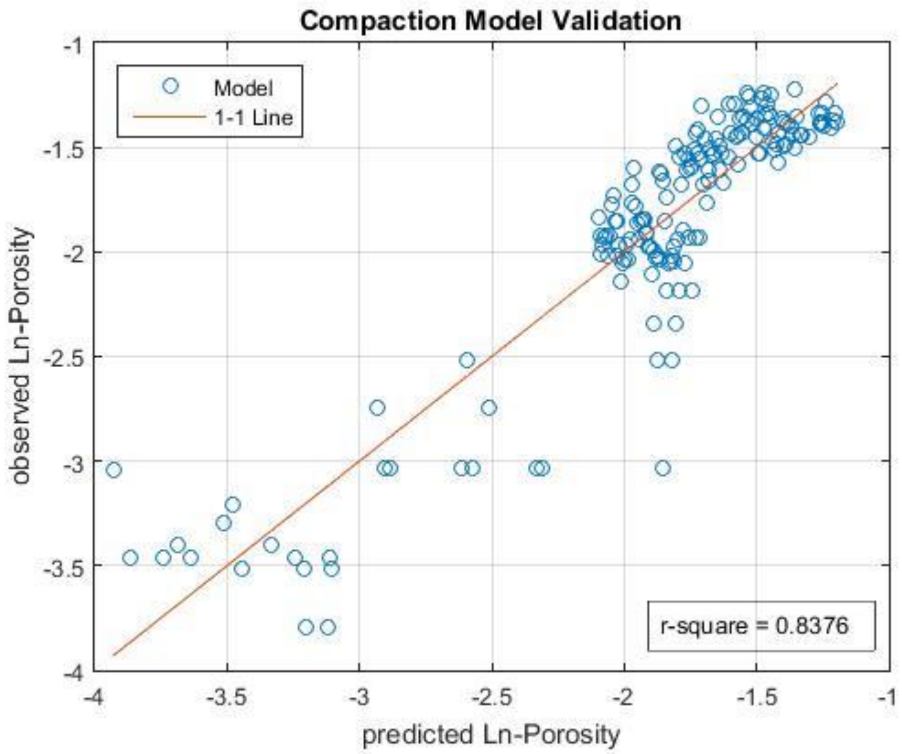


Figure 4. 3 The validation of the empirical model for all datasets

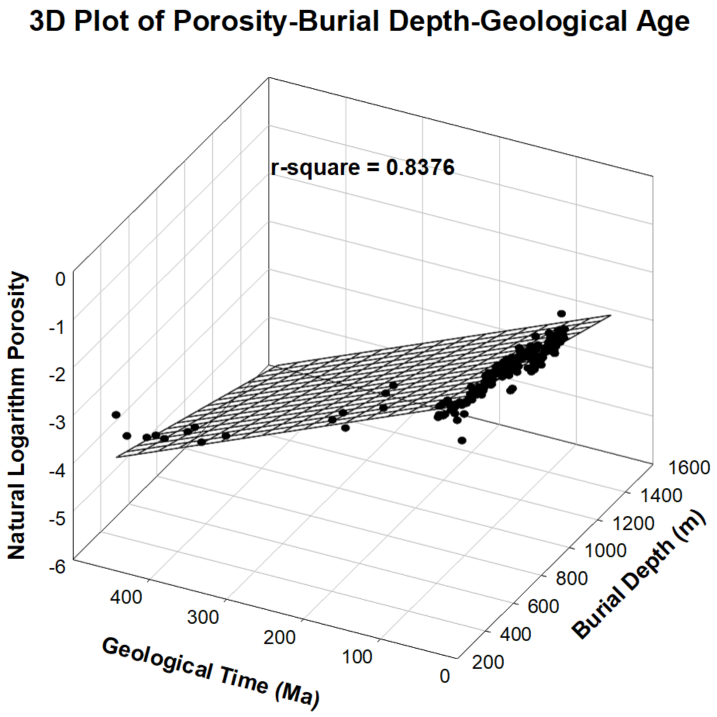


Figure 4.4 three-dimensional plot for porosity change with depth and geological time.

CHAPTER 5
CONCLUSIONS

5.1 Conclusions

The conclusion for this study we know that both the increasing of depth and geological time have a high contribution on the decreasing of porosity during the compaction, particularly at the shallower depth and younger age. The empirical function of porosity and depth only cannot represent the compaction curve of the Thailand shales, the geological time needs to be taken into account in the shale compaction function. The findings of this study reveal that the empirical function of Thailand shales is expected to be established based on the geological ages of the Cenozoic, Mesozoic, and Paleozoic periods. Using multiple linear regression, empirical models of Thailand shale were built for each geological era in terms of porosity, depth, and geological period.

From the examination of thailand's datasets, this study examined and emphasized on the 3D empirical model in the relationship between porosity, burial depth, and geological age in the shaly formation of northeastern Thailand. The following are the study's key findings:

- Although numeric data on geological age in a shaly deposit is difficult to collect, it is obtained from Faust's hypothesized link between velocity, depth, and geological age (Faust, 1951).
- The traditional Athy (1930) exponentially model of shale compaction was not fitted to the data in order to get a compaction curve without a geological age classification study.
- According to the conclusions of this study, the compaction trend of porosity decrease in shales varies by geological age, notably in the shallow region.

- A framework for the compaction curve of the influence of geological time is provided by the substantial link between porosity, burial depth, and geological age of the shaly formation over the study area.
- Empirical analysis of the relationship between porosity, burial depth, and geological age can be used to develop the 3D mathematical model for shale compaction.
- A 3D empirical model of the relationship between porosity, burial depth, and geological age was used to find the standard curve of compaction data for northeastern Thailand shales; this has been explained in full in the study that has been carried out by Puttiwongrak et al (2020).

5.2 Research Gaps and Recommendations for Further Research

Despite the fact that this study establishes a clear link between porosity, burial depth, and geological age in northeastern Thailand, the suggested compaction model is fitted to the data rather than the traditional paradigm (Athy, 1930). However, in this study the amount of data used at each age has a large enough difference from one another. This also needs to be considered in future research and due to the rarity of laboratory measurements of the influence of time on shale compaction due to the lack of advanced experiments and techniques, future research should focus on the effect of time on a laboratory scale.

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