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Landscape, Geology and Soils of the Malay Peninsula

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ABSTRACT

Intermittent climate change episodes since the Late Pleistocene resulted in decreasing or increasing the earth's temperature causing the global sea levels to drop or rise accordingly. These episodes had a remarkable impact on landscape and soils in the Malay Peninsula. The peninsula is characterised by the presence of steep highlands in the central region with the rest occupied by upland undulating terrains and flat alluvial areas. Major soils in the upland regions are formed from igneous, sedimentary and metamorphic rocks ranging in age from Mesozoic to Paleozoic. Most soils developed from those rocks are classified as Ultisols or Oxisols. Both soil types are acidic in nature, having low basic cations insufficient to sustain crop production. Three levels of riverine terraces are scattered sporadically in the peninsula. The age of the sediments forming the highest terraces is 40,000 years, while the lowest terraces are found in the present flood plains. The fluvial characters of the terraces are preserved in the sediments that can be observed and studied. Marine deposits are located along the low-lying coastal plains. The alluvium is divided into clayey sediments found mainly in the West coast and the sandy ones in the East coast of the peninsula. The former contains pyrite at certain locations that produces acidity on oxidation, while the latter have very high sand content. The pyritization of the sediments took place 4,300 years ago when the sea level in the peninsula rose by 3-5 m above the present level.

Key words: climate change, river capture, soil fertility, tropical weathering, Sundaland

INTRODUCTION

The Late Pleistocene (50,000-11,000 BP) was the geological epoch that registered intermittent climatic fluctuations in Southeast Asia. The decrease and increase in earth's temperature during the period had a remarkable influence or impact on the landscape, soil and agriculture in the region. It was during that time that the sea level in Southeast Asia was 100 m below, followed by a rise of 50 m above the present level (Molengraaff 1921; Scrivenor 1931). When the sea level was at its lowest, a large area which hitherto had been flooded by sea water was exposed to atmospheric conditions. The new land area resulting from the sea level drop was called 'Sundaland' by Molengraaff (1921).

The intermittent change in climate during the era impacted the Malay Peninsula in terms of landscape, geology, soil, agriculture and human civilization. According to Bird *et al.* (2005), during the Late Pleistocene, Southeast Asia was covered by Savanna Forest i.e., the area was dominated by a mixed woodland-grassland ecosystem. The objectives of this review paper are: 1) to explain the formation of and/or changes in landscape in the Malay Peninsula since the Late Pleistocene as affected by global climate change; and 2) to describe in detail the various geological processes and pedological attributes that influenced the formation of soils and their physico-chemical properties that impacted agricultural production.

GLOBAL DROP AND RISE IN TEMPERATURE

Geologists and soil scientists know with certainty that there was a period of global drop in earth's temperature, followed by a rise throughout the Late Pleistocene. The former is known as the Ice Age era (glacial), while the latter is the interglacial period. Studies conducted over 100 years ago reported that the Late Pleistocene was the geological epoch that registered intermittent climate fluctuations in Southeast Asia. The geological episode had a striking influence on landscape, geology and vegetation of the region (Bird *et al*. 2005).

Intermittent changes in climate during the Late Pleistocene had significant impact on the landform of the Malay Peninsula in terms of topography (due to deposition of riverine and marine sediments, erosion, river capture, etc.), soil development/formation and agriculture. The shallow seas surrounding the Malay Archipelago in ancient Southeast Asia, often regarded as 'Maritime Continent' by scholars and historians, had a rather warm climate. According to Bird *et al.* (2005), the area was then covered by a mixed woodland-grassland ecosystem.

THE EMERGENCE OF SUNDALAND

The Last Glacial Maximum (LGM) i.e., the Ice Age, was the most recent glacial period that occurred during the Late Pleistocene. One of the most extensive glaciations during the above-mentioned era that significantly impacted Southeast Asia took place 50,000-40,000 BP (Bird *et al.* 2005). Molengraaff (1921), a Dutch geologist working in the region, investigated and subsequently published a landmark paper on the ancient submerged system of the Pleistocene age in South China Sea and the adjoining landmasses.

It was postulated by Molengraaff (1921) and later confirmed by Bird *et al.* (2005) that during the Late Pleistocene, the sea level in Southeast Asia dropped to more than 100 m below the present level. The episode of sea level drop was closely related to the decrease in the earth's temperature that caused the Ice Age. The phenomenal drop of sea level in Southeast Asia at that time is consistent with the findings of studies conducted by a British geologist, working in pre-independent Malaya (Scrivenor 1931; Scrivenor 1949). The amazing geological event resulted in the exposure of a new large landmass in the region with a combined size of a small continent which Molengraaff (1921) termed 'Sundaland' (Figure 1).

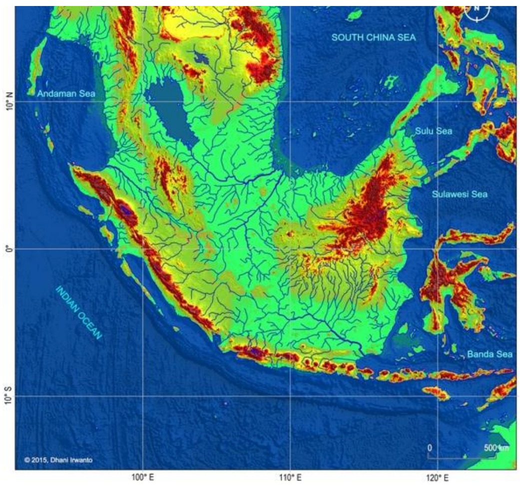

Figure 1. Sundaland during the Late Pleistocene with its complete river system (Courtesy of Reddit)

(https://www.reddit.com/r/worldbuilding/comments/4xjhvr/sundaland_looks_like_a_fantastic_invented_world/)

In a paper on the geology of Sundaland, Bird *et al.* (2005) reiterated that glacio-eustatic depression of the sea level by 100 m during the LGM fully exposed the Sunda Shelf, joining mainland Southeast Asia and Sumatra, Java and Borneo (Figure 1). Thus, Malaya (the Malay Peninsula), Sumatra, Java and Borneo, Thailand, Cambodia and Vietnam were connected. At that time, humans from the North migrated South to the regions of Southeast Asia looking for a better life. The main rivers that provided drainage for the region during that period of the geological history are shown in the above-mentioned figure.

A RIVER CAPTURE IN THE MALAY PENINSULA

Excess water from the highlands of Sundaland was drained into the South China Sea or Indian Ocean by an intricate system of rivers and waterways. Three main rivers in the Malay Peninsula are shown in Figure 1. The first is the Perak River located in the middle of the peninsula, which drains its water into the Straits of Melaka. The second is the Muar River (down south), which also drains its water into the Straits of Melaka. (The third big river, the Kelantan River flows into the South China Sea.

At the present time, tourists traveling in the vicinity of western Pahang (bordering Negeri Sembilan) in the Malay Peninsula will notice that the Pahang River and the Muar River are nearly connected at a location near Jempol or Bahau (in the state of Negeri Sembilan). Note that the Serting River in Negeri Sembilan flows into the Bera River in Pahang. The latter is believed to be a former tributary of the current Pahang River that discharges its water into the South China Sea. Today, we can see that the Jempol River flows into the Muar River in Johor state, which discharges its water into the Straits of Melaka.

It is known that at Jalan Penarikan located near Jempol, the locals were hired to pull boats overland for about 300 m to get across to a tributary of the Pahang River (Bera River), which was flowing into the South China Sea. It was a shorter route to Thailand, Cambodia, Vietnam or even China when the Melaka Empire reigned supreme in the region.

Currently, the Pahang River flows its water into the South China Sea, while the Muar River flows into the Straits of Melaka. Hutchison (1989) was convinced that a long time ago, water from the streams in the upper reaches of the current Pahang River could very well be flowing into the Muar River (Figure 1). The geological episode is termed ‘river capture’. It was plausible that the rivers in the upper reaches of the Muar River were captured by the Pahang River at a location near Bahau town in Negeri Sembilan. The river capture had probably taken place during the Late Pleistocene or the early Holocene. The geological phenomenon is in agreement with the results of the study conducted by Raj (2009) who provided extra field evidence.

As to when the river capture took place is uncertain. To give a convincing answer, we need to study the river system that existed during the Sundaland era (Figure 1). The longest river in the Malay Peninsula at that time was the Muar River, with its upper reaches in the highlands of the peninsula. Its water flowed into the Straits of Melaka, with the river mouth in Johor. As Figure 2 shows, Muar River is no longer the longest river in the Malay Peninsula. That position has been taken over by the Pahang River, which drains into the South China Sea.

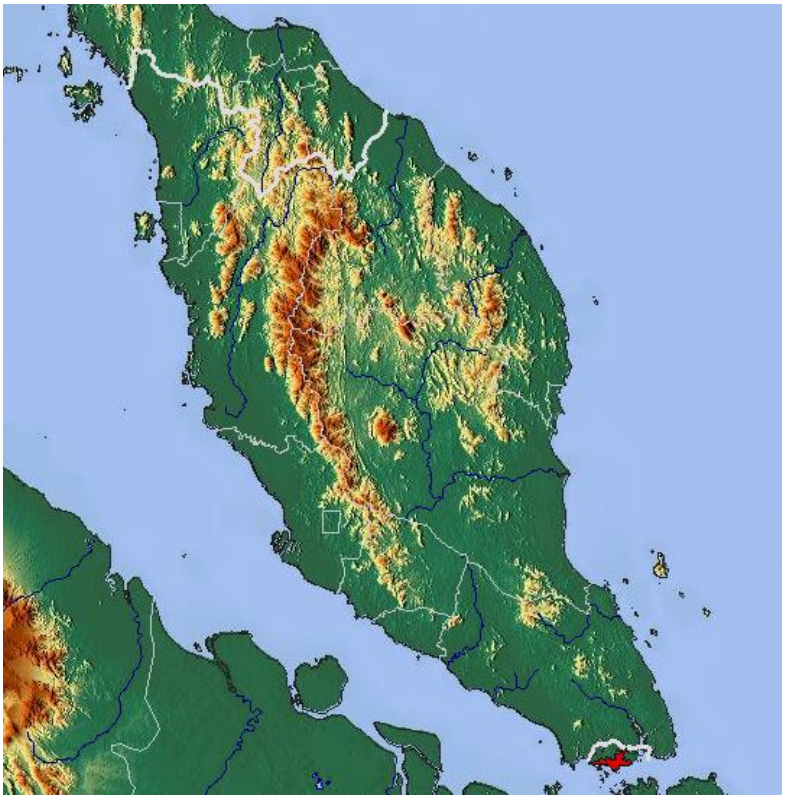

Figure 2. A map showing the current major rivers that control the drainage pattern in the Malay Peninsula
(Courtesy of Wikipedia Commons)
(https://en.wikipedia.org/wiki/Geography_of_Malaysia#/media/File:Location_map_Peninsula_Malaysia.png)

Currently, the Muar River is just a short river, originating from northern Negeri Sembilan and/or south-western Pahang state (Figure 2). Notwithstanding, the mouth of the Muar River in the state of Johor is very big, fitting the size of a major river it once was. So far, the available field data obtained from geological excursions in the area are not sufficient to determine the approximate date when the Muar River was captured by the Pahang River.

There is an area partly located in the state of Pahang with the rest in Negeri Sembilan that can be used to link the river capture discussed above. The area is termed as Cenozoic Basins (Figure 3). It is now covered by freshwater lakes, namely Lake Bera and Lake Chini, made well-known in Malaysia by word of mouth or legends. Perhaps, Lake Bera (a government conserved wetland) is one of the remnants of the area involved in the river capture.

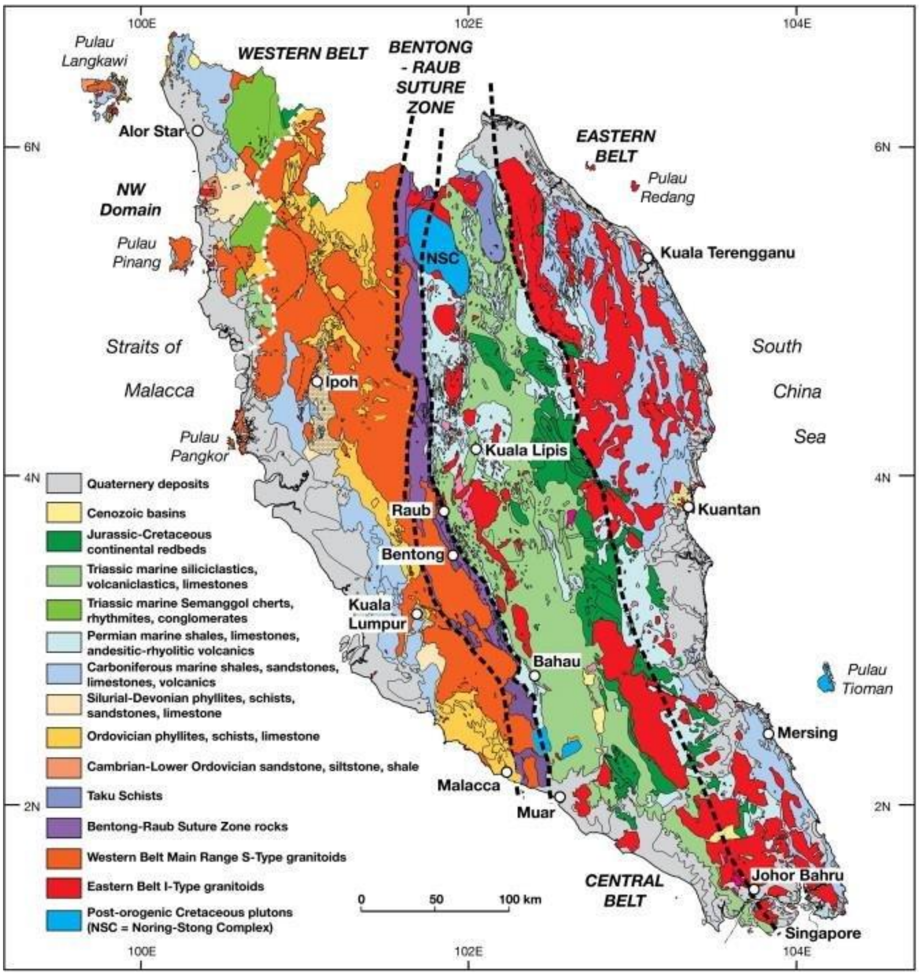

*Figure 3. A geology map of the Malay Peninsula**
(Courtesy of Google LLC)
(*S-Type granitoids are over-saturated with Al, while I-Type granitoids are saturated with Si, but under-saturated with Al)
(https://www.google.com/search?q=geological+map+of+peninsular+malaysia&tbm)

Lake Bera has been known for its beauty and splendour since the 14-15th century when the Melaka Empire in the Malay Archipelago was at its height. During the period of glory and splendour, sailors, merchants, Islamic scholars and others from many countries of the world came in droves to Melaka. Some could have passed through Lake Bera while on their way to the East coast states of the Malay Peninsula or even Thailand, Indochina and China.

THE GEOLOGY OF THE MALAY PENINSULA

The physico-chemical properties of soils in the Malay Peninsula are related to a great extent to the main geological features existing in the area (Tessens and Shamshuddin 1983). To fully understand the pedogenesis of the soils in the Malay Peninsula that make a difference, its geology is briefly described in this paper. Tectonic evolution of the Malay Peninsula, explaining major geological events in the area before and during the Pleistocene epoch, has been extensively studied and subsequently written by many geologists (Hutchison1989; Hutchison 2007; Hutchison, 2009; Metcalfe 2013; Hutchison 2014). The tectonic activity was already active in the area during the Mesozoic Era. In essence, the Malay Peninsula is characterised by three North–South belts i.e., the Western, Central and Eastern belts, based on distinct differences in stratigraphy, structure, geophysical signatures and geological evolution (Figure 3).

Metcalfe (2013) found that the Western Belt of the Malay Peninsula formed part of the Sibumasu Terrane, derived from the NW Australian Gondwana margin in the early Permian. The Central and Eastern Belts represent the Sukhothai Arc, which were constructed in Late Carboniferous–early Permian on the margin of the Indochina Block.

According to Hutchison (1989), the Bentong-Raub suture zone formed the boundary between the Sibumasu Terrane (Western Belt) and Sukhothai Arc of the Central and Eastern Belts. The preserved remnants of the Devonian–Permian Ocean basin were destroyed by subduction beneath the Indochina Block/Sukhothai Arc. The geological phenomenon was assumed to have produced the Permian–Triassic andesitic volcanism and I-Type granitoids observed in the Central and Eastern Belts of the Malay Peninsula (Figure 3).

Hutchison (1989) and Hutchison (2014) reiterated that collisional crustal thickening that followed produced the Main Range S-Type granitoids that were found to have intruded the Western Belt as well as the Bentong-Raub suture zone (Figure 3). The S-Type granitoids are coarse grained igneous rock, composed mostly of quartz, K-feldspar (alkali-feldspar) and plagioclase. A significant Late Cretaceous tectono-thermal event affected the Malay Peninsula with major faulting, granitoid intrusion and re-setting of palaeomagnetic signatures.

The Malay Peninsula is geologically part of the Sunda Shelf in the South China Sea. Yeh (1968) wrote convincingly that with its complexity and splendour, the fold mountain system of Malaysia was the southerly continuation of that extending from Myanmar through Thailand, Bangka and Billiton Islands, and eastwards into Kalimantan (Indonesia) in Borneo.

As Figure 3 shows, all strata from the Cambrian to Quaternary age are found in the Malay Peninsula. Triassic and older rocks are marine in origin and include shale, sandstone, limestone and schist. However, the post-Triassic strata are characteristically non-marine and are presented by Riverine Alluvium of the Late Pleistocene and/or the early Holocene.

Figure 3 further shows that intrusive granite occupies almost half of the total land surface of the Malay Peninsula. As such, soils formed on granite occupy a large area of the peninsula. Such being the case, the soils are very crucial for agriculture in the region, especially for the cultivation of oil palm, rubber, cocoa and other tropical crops.

In essence, granite forms the compelling topographic highs of the Malay Peninsula, the largest of which is the Main Range (otherwise known as Central Range). The Main Range is about 480 km long, with an average width of 64-80 km and rising to more than 2,000 m above sea level at some places. As shown in Figure 3 more basic intrusions are also present in the Malay Peninsula, which are represented by basalt, gabbro and volcanic tuffs.

The oldest sedimentary formations are rocks of the Machinchang Formation, which is found in the North coast of the Langkawi Islands in the state of Kedah (northern region of the West coast of the Malay Peninsula). The sediments are predominantly arenaceous in character with minor beds of shale, sandstones and conglomerates.

Limestone beds are found as isolated hills in many parts of the Malay Peninsula, most particularly in Kedah-Perlis (northern), Ipoh in Perak and Kuala Lumpur (central) as well as the southern regions of Kelantan (northeast). Riverine and marine alluvial deposits of Quaternary age, with thickness varying from a few m to 150 m (Singh 1978), cover a large portion of the coastal plains in the Malay Peninsula. These are the areas where food crops such as rice, vegetables and fruit trees are mainly produced.

For all intents and purposes, Hutchison (1977) subdivided the Malay Peninsula into four tectonic regions. The proposed tectonic regions are:

1. The Western Stable Shelf
2. The Main Belt (Main Range)
3. The Central Graben
4. The Eastern Belt

Yeh (1968) believed that there were at least four major episodes of granitic emplacement in the Malay Peninsula. Much of the known mineralization in the peninsula occurred in the later episodes, commonly associated with faulting. Regional metamorphism is widespread and most of the Paleozoic and Mesozoic rocks show slight to moderate deformation. By and large, the older rocks show a greater degree of metamorphism than those of the younger ones.

Large granitic batholiths of predominantly Permian to Triassic age characterize the Main Belt and Eastern Belt of the Malay Peninsula. According to Hutchison (1977), granite of the Main Belt of the peninsula is described as mesozonal, which is coarsely porphyritic in nature. On the other hand, granite in the Eastern Belt is epizonal and is primarily characterized by an equigranular to weakly porphyritic texture. As such, the texture of the soils formed from the two granite types differs slightly.

Granite in the Malay Peninsula has undergone extensive physico-chemical weathering because of the long exposure to the tropical conditions, forming soils with sandy clay texture (Paramananthan 2000; Soil Survey Staff 2018). According to Paramananthan (1977) and Tessens and Shamshuddin (1983), the mineralogy of the clay fraction is dominated by kaolinite and sesquioxides (i.e., gibbsite, goethite and hematite).

Most of the soils in the Malay Peninsula formed on granite is classified as Ultisol (e.g., Rengam Series), which is found to be suitable for oil palm and rubber cultivation (Shamshuddin *et al.* 2018; Soil Survey Staff 2018). Rengam Series soil is dominantly scattered in the well-drained upland regions, having undulating to steep landscapes. Note that granite soils are acidic in nature, but with proper agro-management practices, they can be very productive.

According to Tjia (1973), the drainage system in the Malay Peninsula has morphologically evolved during the Cretaceous. The main rivers controlling the drainage pattern of the peninsula (Figure 2) are Pahang River (420 km), Perak River (350 km) and Kelantan River (280 km). Currently, the Kelantan River (located in the northeast) and Pahang River (middle) flow into the South China Sea, while the Perak River (middle) flows into the Straits of Melaka. A long time ago, water from the upper reaches of the present Pahang River is believed to have drained into the Straits of Melaka via the Muar River i.e., before a river capture took place.

Aggradation on the East coast shorelines seems to be predominant, particularly in the vicinity of large rivers such as the Pahang River and Kelantan River. The storm waves of the South China Sea account partly for the development of the conspicuous ridged beach landscapes in the East coast states of the Malay Peninsula (Shamshuddin *et al.* 2021a). The weaker wave action in the Straits of Melaka is reflected by the occurrence of the smaller beach ridges and muddy beaches along the west coast. Extensive drowning of the coastal regions is indicated by swamps at several places (Shamshuddin *et al.* 2021b). It appears that the longshore currents have a remarkable influence on the general direction of the river mouth.

The geomorphology of the West coast of the Malay Peninsula is characterized by flatland in the coastal regions. This is evidenced by the presence of coastal plains in the peninsula which are widest in the vicinity of the Perak River mouth (Figure 3), where they are about 45 km wide (Tjia 1973). On average, the coastal plains in the West coast have a width varying between 20 and 30 km. Alluvial terraces at various levels are found in this area (Shamshuddin 1982). The main constituents of the alluvial terraces are granite clasts and sand grains with some clayey materials.

According to Tjia (1973), the prevailing West-Northwest to Northwest longshore currents between 0° and 6°N latitude had resulted in the deflection of most river mouths to the Northwest. Beyond the 6°N, the resultant longshore current is towards the Southeast. So, the Kedah River (up north) has deflected in the same direction. The phenomenon of the movement of river mouths, resulting from the longshore current, was confirmed by Raj (2009). Koopmans (1964) estimated the rate of coastal accretion to be about 100 m in 80 years.

The eastern shoreline of the Malay Peninsula from Kelantan (Northeast of the peninsula, near Thailand) to Johor (South, close to Singapore) is about 640 km long. The occurrence of beach ridges and deltas in the coastal regions indicate pro-grading of the shoreline (Tjia 1973). These beach ridges formed about 160,000 ha of very sandy soils in the East coast. This landscape is found extensively in the East coast of the Malay Peninsula (Panton 1958; Panton 1960; Smallwood 1967; Abdul Halim 1978; Lim 1991) while on the west coast of the peninsula, it occurs as isolated ridges (Soo, 1968, 1976), except on the main island of Langkawi where it is well expressed (Lim *et al.* 1984; Lim 1991).

According to Roslan *et al.* (2010), the very sandy soils located along the coastlines are either classified as Entisols (young soils fringing the shorelines, without pedogenetic horizon) or Spodosols (soils having a diagnostic spodic horizon). The former is found extensively in the areas close to the shoreline, while the latter is located further inland (about 0.5 to a few km away from the coastline). The very sandy soils are locally known as BRIS soils – the term BRIS is the acronym for 'Beach Ridges Interspersed with Swales'. The first ever recorded mentioned term 'BRIS' is credited to Willimot (1948) in the Geological Map of Malaya (Lim 1991). BRIS is one of the most conspicuous landscapes in the East coast states of the Malay Peninsula (Shamshuddin *et al.* 2021a).

Tjia (1970) and Tjia (1973) noted that from the Thailand border down to Terengganu, the general shift of the river courses in the coastal plains is towards the Northwest (NW) or West Northwest (WNW), as indicated by a 35 km shift of the Kelantan River mouth towards the left of the former river. Figure 4 shows the current location of the Kelantan River. The shift in the course of the river mouth (from Pantai Senok) towards the Thailand border (to Pantai Mek Mas) is an ongoing process. From Kuantan (Pahang) to Pontian (Johor), the general shift is towards the right, following the direction of the longshore current (Tjia 1973; Raj 2009). This phenomenon has a great impact on soil formation and agriculture in the East coast states of the Malay Peninsula.

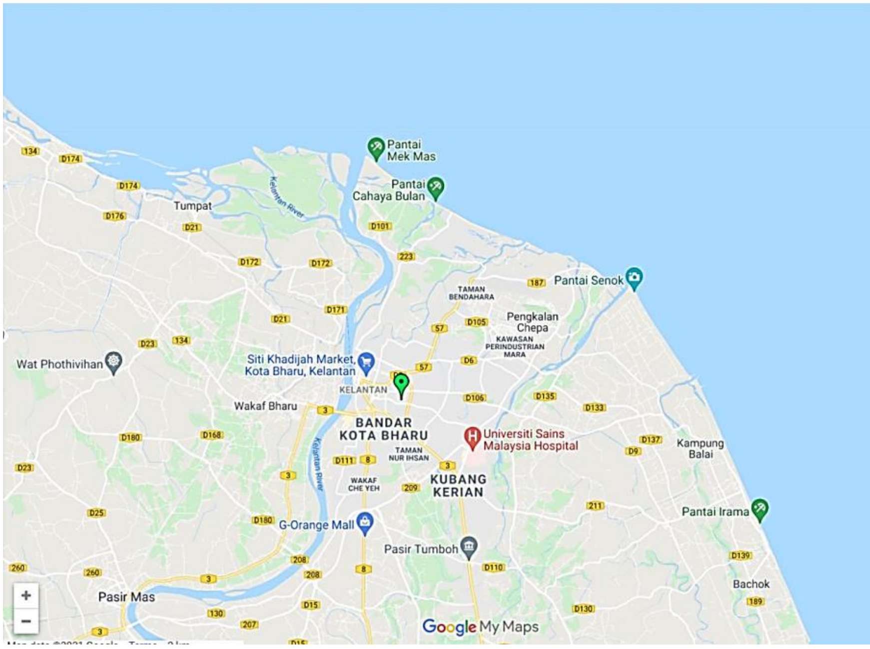

Figure 4. A Google map of the East coast of the Malay Peninsula bordering Thailand showing the current position of the Kelantan River
(Courtesy of Google LLC)

SOIL TYPE DISTRIBUTION IN THE MALAY PENINSULA

Soils in the Upland Regions

On weathering under a tropical environment, basalt and andesite in the Malay Peninsula normally give rise to Oxisols, while granite produces Ultisols (Tesssens and Shamshuddin 1983; Paramananthan 2000). Shale and schist, on the other hand, are weathered to form either Ultisols or Oxisols, depending on the local conditions where the rocks are located. Notwithstanding the close similarity in the climatic conditions, the formation of both soil types require a well-drained environment. As such, Ultisols and Oxisols are mostly found in the upland regions. These two types of soils occupy about 70 % of the country's land surface (Shamshuddin and Fauziah 2010). Typical profiles of the highly weathered soils are depicted in Figure 5 i.e., Rengam Series formed from granite and Segamat Series from andesite.

The type of shale, which is a function of the geological deposit that includes factors such as the amount of quartz, iron or carbon in the sediment together with physiographic position and the depth of the ground water table, will give rise to several types of soils (Noordin 1975). In general, illite and mica are typically more abundant in the clay fraction of soils formed from shale than in soils derived from other parent materials, especially at the inceptic stage (Inceptisols). However, with the progress of pedogenesis, there is a marked disappearance of illite and micaceous clay. The amount of kaolinite, gibbsite and goethite increases with the progress of pedogenesis. Hence, minerals dominate the entire clay fraction of the soils at the later stage of pedogenesis i.e., argillic (Ultisols) and oxic stage (Oxisols) (Noordin and Shafar 2017a).

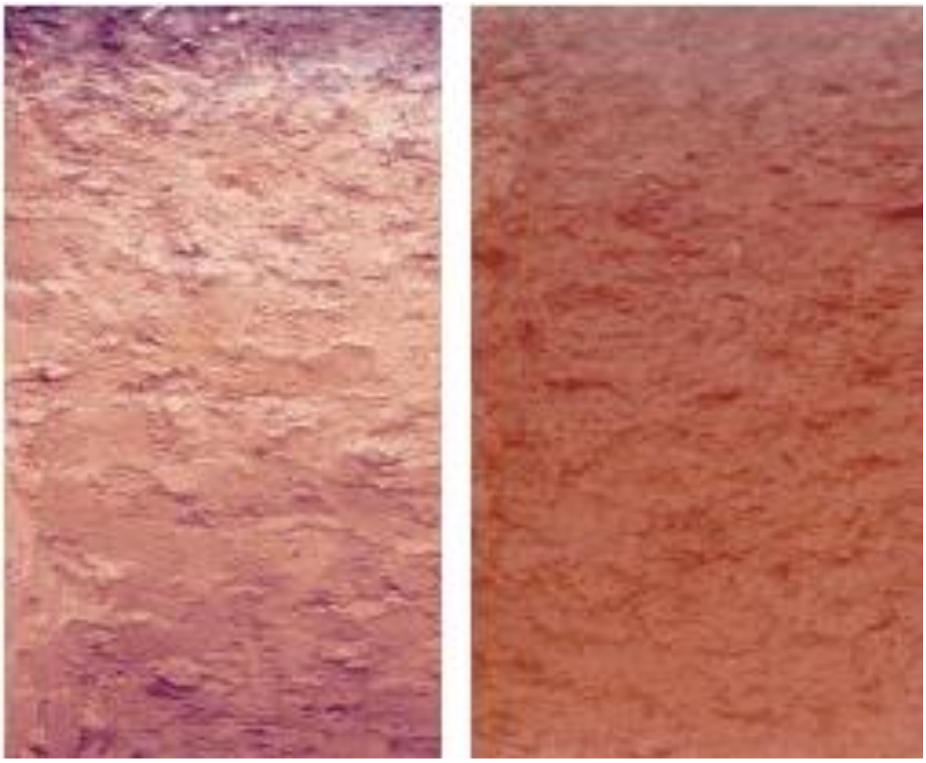

Figure 5. Typical Ultisol (Rengam Series, left) and Oxisol (Segamat Series, right) profiles found in the Malay Peninsula

Oxisols are usually assumed to be more weathered than the soils of the Ultisols (Shamshuddin *et al.* 2018; Soil Survey Staff 1999). The notion is based on the mineralogical composition of the soils and/or rocks from which they are formed. Basalt containing ferro-magnesium silicates (olivine and pyroxenes) plus feldspars weathers faster (and so does andesite) compared to granite, which is dominated by alumino-silicates (quartz, mica and feldspars). As such, weathering of basalt or andesite in a tropical environment results in the formation of Oxisols, while most granite forms Ultisols (Figure 5). The more weathered soils contain higher amounts of oxides of Fe (reddish hematite or goethite) and/or Al (gibbsite) as shown by the Segamat Series (Figure 5). Such being the case, Ultisols and Oxisols have significantly different physico-chemical properties.

Having being exposed to a tropical environment for a long period of time (since Late Pleistocene), rocks in the upland regions of the Malay Peninsula are weathered to form highly leached, acidic Ultisols and Oxisols (Tessens and Shamshuddin 1983; Shamshuddin and Fauziah,2010). Soil pH is low and basic cations are usually insufficient for crop requirements. Key characteristics of Ultisols and Oxisols in the peninsula are summarized in Table 1. The soils are mainly utilized for oil palm and rubber cultivation, with some areas reserved for cocoa. As the first two crops are known to be acid-tolerant, they are able to grow well below pH 5. Besides, physical properties of soil are of greater importance in soil evaluation because they are more essential and permanent than chemical properties which can be modified by management practices (Chan 1977; Noordin, 2013; Shamshuddin *et al.* 2018). That could be one of the reasons why most of the agricultural land in Malaysia is dominated by plantation crops (oil palm, rubber, cocoa and pepper), which account for about 84% of the total area (Noordin and Shafar 2017b).

TABLE 1
Common characteristics of Ultisols and Oxisols in the Malay Peninsula

Soil	Diagnostic Horizon	Soil pH	Clay Mineral*	CEC $cmol_c\ kg^{-1}$ clay	Colour
Ultisols	Bt	4.0-4.5	kn, gb, gt	>16	Yellowish
Oxisols	Bo	4.5-5.0	kn, gb, gt, ht	<16	Reddish

* kn = kaolinite; gb = gibbsite; gt = goethite; ht = hematite

In plantations, prolonged application of ammonium sulfate on Ultisols or Oxisols results in increased soil acidity that is known to affect crop productivity. However, an increase in soil acidity can, to a certain extent, be offset by the hydrolysis of Ca^{2+} from dissolution of applied phosphate rocks that produce some hydroxyls (Shamshuddin 2022). To increase soil pH to sustain crop production (e.g., corn) on Malaysian Ultisols, ground magnesium limestone (GML) can be applied at an appropriate rate and time (Shamshuddin *et al*. 1991). According to Shamshuddin and Fauziah (2010), the ameliorative impact of applying GML at 4 t/ha on Ultisols and Oxisols in the Malay Peninsula could last up to four years.

Soils in the Riverine Alluvial Plains

The phenomenal sea level drop in the Malay Peninsula during the Late Pleistocene resulted in the development of fluvial (riverine) terraces at different levels (Shamshuddin 1982). Gopinathan (1968) identified, studied and described in detail the characteristics of the above-mentioned fluvial terraces. The Malaysian pedologist divided fluvial terraces into: (i) High terraces; (ii) Intermediate terraces; and (iii) Low terraces of the present flood plains. A pictorial illustration of the existence of the fluvial terraces in the Malay Peninsula is shown in Figure 6, drawn according to the elevation and age of the alluvial deposits observed/recorded during the field work. In physiographic terms, they are known in the peninsula as T_3, T_2 and T_1 terraces, following the order of decreasing age (Figure 6).

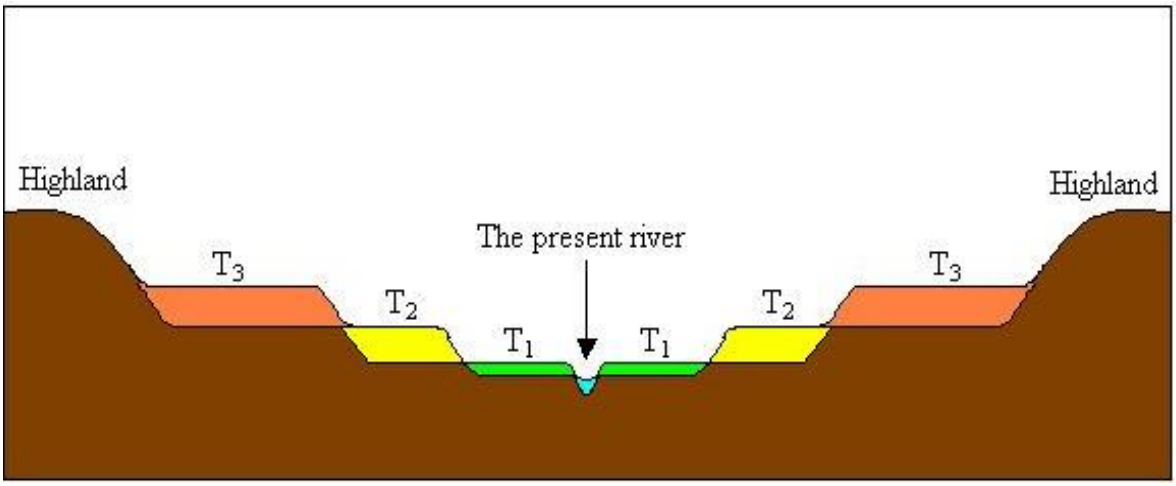

Figure 6. Artist impression of the fluvial terraces in the Malay Peninsula formed from the Late Pleistocene to the present time
[*Source*: Shamshuddin (1982); Shamshuddin and Tessens (1983)]

The Late Pleistocene sediments of varying thickness were identified and characterized in the alluvial plains of the Malay Peninsula by geologists and/or soil scientists in the 1960s. The alluvial sediments located in Johor state situated at an elevation of 45-70 msl were classified as Old Alluvium by Burton (1964); this is otherwise known as T_3 Terrace (Figure 6). According to Sivam (1969), the age of the Old Alluvium in Kinta Valley, Perak (in the middle of the Malay Peninsula) is about 40,000 years.

A detailed study on the pedological characteristics of the soils on T_2 terraces was carried out by Shamshuddin (1982), with the aim of determining their genesis and physico-chemical properties. Sivam (1969) reported that primary sedimentary structures of fluvial character were found abundantly in the Young Alluvium of the present floodplains. The age of the Young Alluvium (T_1 terrace) in the same vicinity is less than 3,000 years.

The older deposits are usually characterized by a regular decrease in organic carbon in relation to soil depth. In recent deposits, the distribution of organic carbon is erratic with depth (Shafar 2017). Another notable feature in the older deposits is that clay has moved with the formation of an argillic horizon. This feature is lacking in recent deposits, indicating that insufficient time has elapsed for clay illuviation (Noordin 1980; Soil Survey Staff 1999).

Soils in the Marine Alluvial Plains

Pyritization of the coastal plains

Figure 3 shows the aerial distribution of the Marine Alluvial Deposits of the Quaternary age in the Malay Peninsula. A significant area of the marine alluvium contains pyrite (FeS_2), which is a prerequisite to the development of acid sulfate soils. The mineralization of pyrite in the sediments of the coastal plains of the countries in Southeast Asia can be used as solid evidence for the sea level rise (or higher sea level) during the Holocene (Shamshuddin 2017; Shamshuddin *et al.* 2017). This notion was confirmed by Enio *et al.* (2011) who studied pyrite distribution in the coastal plains of Kelantan in the Malay Peninsula (Figure 4).

A detailed study of the Perak plains by Noordin (1980) found new evidence of deposits on coastal plains originating from the sea where he found diatoms, sponge spicules and phytolite sea microorganisms. Diatoms are characteristically absent in the soils on riverine deposits.

The areas in the Kelantan Plains where pyrite was identified/found and those without were delineated by Enio *et al.* (2011); the line separating them is shown in Figure 7. The said line represents the predicted shoreline when the sea level was at its highest during the mid-Holocene i.e., about 4,300 years ago. The coastline in the Kelantan Plains 4,300 BP was a few km inland. When the sea level successively dropped to the present level due to climate change, the sea-water flooded lands were exposed to the atmosphere, forming the present conspicuous BRIS landscape. This landscape will be explained/discussed later.

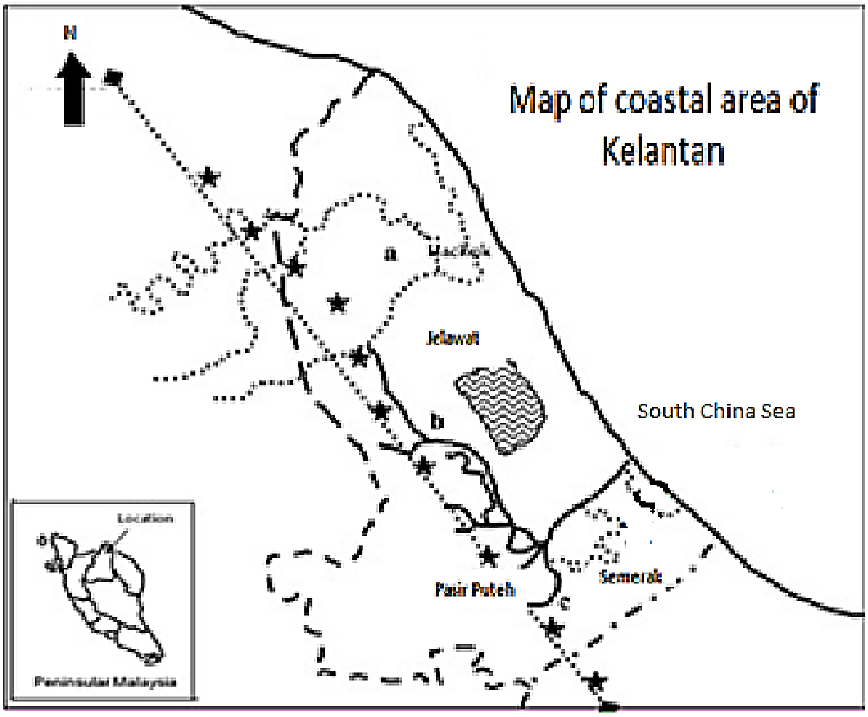

Figure 7. Map showing the predicted coastline in the Kelantan Plains of the Malay Peninsula when the sea level was 3-5 m above the present level
[Courtesy of Enio *et al.* (2011)]

According to Tjia *et al.* (1977), the sea level about 4,300 years ago was 3-5 m above the present level, The Malay Peninsula was seemingly smaller than what it is today. The sea level in Southeast Asia of 3-5 m above the present level was confirmed by a study conducted in Thailand (Sathiamurthy and Voris 2006). The rise in sea level during the mid-Holocene is consistent with the results of a study conducted by Azmi (1982). He found that rice fields in the Kedah-Perlis Plains (in the northern region of the peninsula) were once under the sea, as evidenced by sporadic occurrence of pyrite in the sediments/soils (Figure 8).

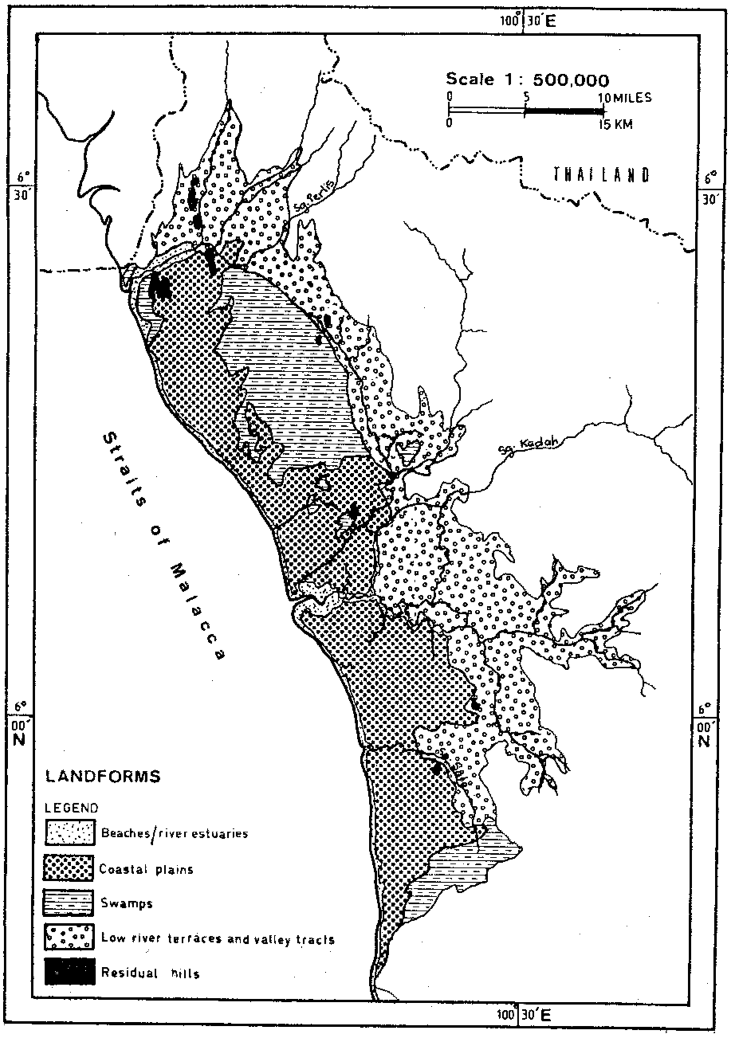

Figure 8. Major landforms in the Kedah-Perlis coastal plains
of the Malay Peninsula
[*Source*: Azmi (1982)]

Marine alluvium in the Kedah-Perlis Plains was found to have extended >10 km inwards i.e., into the upland region (Figure 8). Elsewhere in the peninsula, marine alluvium is also found a few km inland (Figure 3). According to Enio *et al.* (2011) and Shamshuddin *et al.* (2021b), marine alluvium had cut across the Quaternary sediments as in the case of the Kelantan Plains or Kedah-Perlis Plains. When the sea level was higher than that of the present level, much of the landmass then in the Malay Peninsula was inundated by sea water. This inundation accounts for the mineralization of pyrite in areas found many km away from the present coastline. It was the time when pyrite in the soils far away from the present coastline in the Kedah-Perlis Plains was formed or mineralized. Soils containing pyrite are classified as acid sulfate soils, which are not suitable for crop cultivation without undergoing alleviation.

A study in Kedah-Perlis Plains by Lim (1991) reported some differences in soil characteristics that developed on marine and riverine alluvium. The CEC of the marine alluvial soils is higher than that of the riverine derived soils, indicating the presence of 2:1 clay mineral (smectite) in the former. The presence of the 2:1 clay minerals result in the formation of cracks and gypsum during a distinct dry season that normally extends from December to March.

The coastal plains in the Malay Peninsula are partly occupied by swampy depressions, with a permanent high water table level. These are the areas where organic materials have accumulated over the years, forming vast peatlands, sometimes containing pyrite. Peatlands are sporadically distributed in the state of Selangor, Johor, Perak, Pahang, Terengganu and Kelantan in the Malay Peninsula. The area covered by peatlands in Malaysia is about 2,457,730 ha, with 642,918 ha (26.16%) in the peninsula, 116,965 ha (4.76%) in Sabah and 1,697,847 ha (69.08%) in Sarawak (Wetland International 2010).

Peat soils are organic soils containing more than 65% organic matter with a minimum thickness of 50 cm to 100 cm, or with more than half of it being lithic/paralithic or terric layer. According to Wong (1986), the capability of peatlands to support agriculture is very low. This is due among others to the problems of a high water table level, high acidity, insufficient nutrients and the presence of wood in the soil profile and above the ground. However, with proper soil, agronomic and water management, numerous economic crops such as oil palm and pineapple can be grown with satisfactory yields (As'ari *et al.* 2016; Paramananthan 2016).

Due to drainage or other reasons, pyrite in the sediments (Figure 9) is oxidized, producing a high level of acidity that significantly affects crop growth and/or production (Shamshuddin *et al.* 2014; Shamshuddin *et al.* 2021b). Under a low pH environment, alumino-silicates present in the coastal sediments are disintegrated and eventually dissolve releasing acid metals (Al and/or Fe) that cause toxicity to crops such as rice, cocoa or even oil palm. Therefore, in preparing the soils for cultivation, it is recommended that the drains be deepened gradually to wash away the excess acids formed to avoid sudden changes in acidity, which may have detrimental effects on plant growth (Chan *et al*. 1977; Noordin, 1980).

Figure 9. Oxidation of pyrite (left) results in the formation of jarosite (right)

According to Shamshuddin *et al.* (2014) and Shamshuddin *et al.* (2017), pyrite (Figure 9, left) oxidation produces a mineral called jarosite which is characteristically straw-yellow in colour (Figure 9, right). Al and Fe released into the soils will seriously pollute the environment in the vicinity of the acid sulfate soil areas as observed in the Kelantan Plains (Figure 7) and the Kedah-Perlis Plains (Figure 8).

A high level of Fe in the acid sulfate soils of the Kelantan Plains is often observed when land is flooded for rice cultivation. The presence of a high amount of Fe in the water of the rice fields is evidenced by its red colour. The low pH of <4 is consistent with the presence of a high concentration of Fe and Al in the water. It has been established that Fe^{2+} and Al^{3+} are toxic to rice plants growing in the fields (Shamshuddin *et al.* 2014; Shamshuddin *et al.* 2021b). The problem of Fe^{2+} and/or Al^{3+} toxicities can be alleviated effectively by applying an adequate amount of lime (Elisa *et al.* 2014) or lime in combination with a bio-fertilizer, fortified with phosphate-solubilizing bacteria (Panhwar *et al*. 2014a; Panhwar *et al.* 2014b).

a) Development of BRIS landscape

During the mid-Holocene, a large areas of the coastal plains in the countries of Southeast Asia were inundated by sea water from the South China Sea. At that time of the geological history, the coastal zones in the region had undergone progressive progradation (Tjia *et al.* 1977). A study by Bird and Teh (1990) concluded that the coastal zone progradation led to the formation of plains with wide beach ridges scattered sporadically along the coast, which are commonly observed in the Malay Peninsula, Thailand, Indonesia and even Cambodia.

Occurrence of the conspicuous sandy beach ridges in the East coast of the Malay Peninsula is indicative of a recession of the sea, beginning about 6,000 years ago. Based on geological and pedological evidence, the formation of the beach ridges at various elevations is related to the progressive lowering of sea level of many meters since then (Roslan *et al.* 2010; Shamshuddin *et al.* 2021a). Using field evidence gathered by Roslan *et al.* (2010) in the Kelantan-Terengganu Plains and the laboratory investigations that followed, it was concluded that the younger ridges were subsequently created as the sea level fell, with their elevation getting lower. The notion on the occurrence and distribution of the beach ridges is consistent with the results of the studies conducted by Raj *et al.* (2007) and Raj (2009).

Nossin (1965) believed that the whole length of the low-lying coastal regions in the East coast of the Malay Peninsula has recently been added to the old land; this was confirmed by Tjia *et al.* (1977). As mentioned earlier, the conspicuous landscape formed in this manner is termed as ‘Beach Ridges Interspersed with Swales, with BRIS as the acronym. Soils formed from the sandy beach ridges are called BRIS Soils (Shamshuddin *et al.* 2021a).

Most of the soils utilized for agriculture in the BRIS landscape occur on the three ridges, running parallel to the present shoreline, but having different elevations. The ridge closest to the shoreline is about 1 m above the present sea level, while the next ridge is slightly higher, mostly at about 2 m (Figure 10). At specific locations in the Kelantan-Terengganu Plains, the former is about 2 km wide, while the latter is about 0.5 km (Roslan *et al.* 2010). In between the conspicuous sandy ridges occur slightly depressed areas (mostly at 1-2 m above the present sea level), which are usually under a permanent high water table. These are the so-called swales (lakes) that dominate the littoral landscape of the East coast states of the Malay Peninsula. According to Shamshuddin *et al.* (2021a), soils of this nature are also found extensively in other parts of Southeast Asia such as Thailand and West Kalimantan (Indonesia).

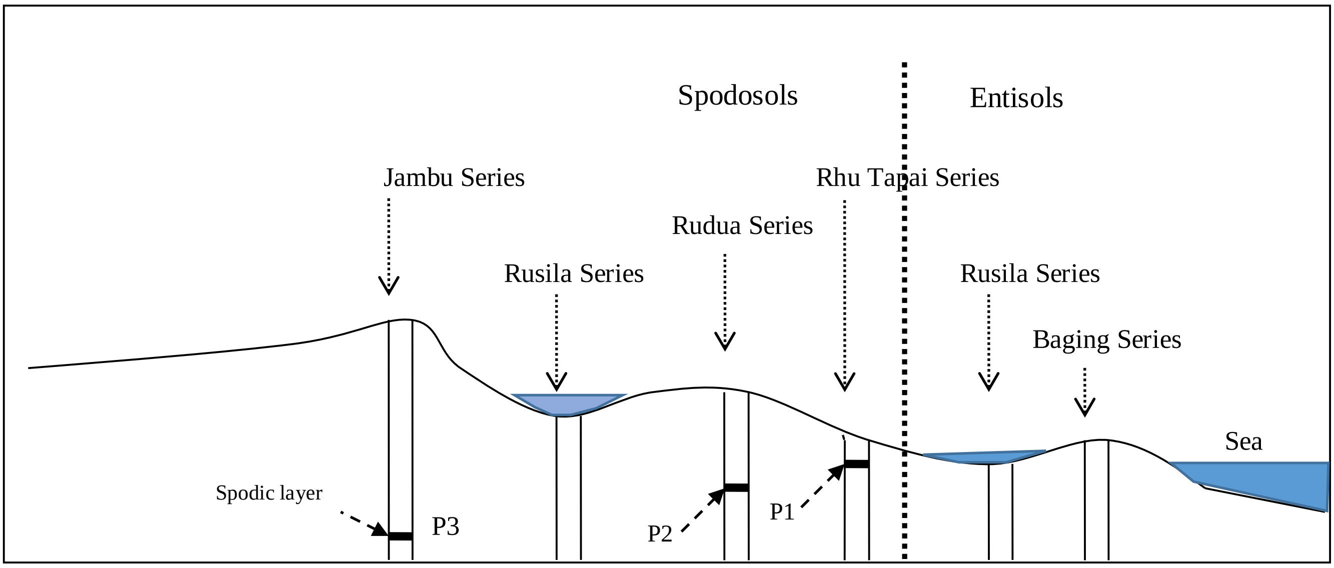

Figure 10. Spatial distribution of BRIS Soils in the Kelantan-Terengganu coastal plains (P1, P2 and P3 occurs at 0-50, 50-100 and > 100 cm below soil surface, respectively)
[Source: Roslan *et al.* (2010)]

Soils on another ridge can occasionally be identified, occurring at an elevation of 5-7 m above the present sea level. This ridge is exclusively located farthest away from the present shoreline. According to Raj *et al.* (2007) and Raj (2009), the ridge (which is mostly about 0.5 km wide) is located some 4 km away from the present shoreline. Whenever this happens, a second swale is almost certainly found, which also runs parallel with the other ridges. It appears that every time the sea level drops, a new ridge adjacent to the shoreline would be formed. As three sets of sandy ridges can be observed in the Kelantan-Terengganu Plains, the sea level in the Malay Peninsula could have dropped at the least three times during the Holocene.

The evidence so mentioned seemingly suggests that there is no doubt that the sea level at the Kelantan-Terengganu Plains in the past was higher than at the present level. This is in agreement with the findings of the studies conducted by Haile (1970), Haile (1971), Tjia *et al.* *(*1977) and Enio *et al.* *(*2011). Thus, the sea level in Southeast Asia during the mid-Holocene was a few meters above the present level. Other studies conducted in the coastal regions of the Malay Peninsula (Nossin 1961; Nossin 1964) and Thailand (Sathiamurthy and Voris 2006) provide further evidence on the sea level rise in the region during the period.

It is schematically shown in Figure 10 that the oldest ridge (R3 where P3 is sited), located at the farthest distance from the shoreline, is sitting at the highest elevation of 5-7 meters above the present sea level. The youngest ridge (R1 where P1 is sited), the one closest to the shorelines, is at the lowest elevation of about 1 m above the sea level.

In between the ridges occur swales either at 1-2 or 2-3 m above the present sea level. The depression can either be occupied by acid sulfate soils, peat soils or even normal soils. The hydromorphic soils are sometimes drained to make way for agriculture such as for the cultivation of rice and/or vegetables. Figure 10 shows that the Jambu, Rudua and Rhu Tapai Series occurring in the BRIS landscape are taxonomically classified as Spodosols, while the Baging Series is an Entisol. The sandy nature of the soils makes it impossible for farmers to sustain crop production without undergoing proper or innovative agro-tech practices.

CONCLUSION

The present landscape, geology and soils in the Malay Peninsula are partly a consequence of climate change that took place in the region since the Late Pleistocene. During that era, the earth's temperature intermittently decreased or increased, causing global sea levels to drop and rise, respectively. This had a profound impact on soils in the peninsula. The landscape of the peninsula is characterised by the presence of steep highlands in the central region with upland undulating terrains and flat alluvial areas along the coast.

Major soils in the upland regions are formed from igneous, sedimentary and metamorphic rocks, with their age ranging from Mesozoic to Paleozoic. Under a tropical environment, sedimentary rocks are usually weathered to form soils classified as Ultisols or Oxisols, while those developed from igneous rocks are Oxisols. Both soil types are acidic in nature, having low basic cations, and are mostly insufficient in nutrients to sustain crop production.

Climate change resulted in the development of three levels of riverine terraces, found sporadically in the Malay Peninsula. Sediments forming the highest terrace are 40,000 years, old while the lowest terrace is found in the present flood plains. The riverine terraces are occupied by soils with slightly different physico-chemical characteristics compared to those formed from igneous, sedimentary or metamorphic rocks.

Marine alluvial deposits are found abundantly along the low-lying coastal regions of the Malay Peninsula. The alluvium is divided into clayey sediments (sometimes containing pyrite) mostly deposited in the West coast and the sandy sediments occur predominantly in the East coast. The pyritization of the coastal plains took place about 4,300 years ago when the sea level in the peninsula rose by 3-5 m above the present level. Pyrite in the sediments produces acidity on oxidation that negatively impacts crop production. The lands so formed are occupied by acid sulfate soils. The progressive drop in sea level since mid-Holocene resulted in the development of the conspicuous BRIS landscape, having three beach ridges, with different elevations, running parallel to the present coastlines – i.e., the youngest ridge is located closest to the beach. Acid sulfate soils and BRIS Soils are not productive without proper agro-management practises derived from innovative research.

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