Bulletin of the Geological Society of Malaysia, Volume 59, November 2013, pp. 59 – 66

Microfacies and diagenesis in the Setul Limestone in Langkawi and Perlis

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Abstract: The Setul limestone outcrops in Langkawi and Perlis show a variety of facies consisting of thickly bedded mudstone, wackestone, packstone, grainstone and dolomitic limestone. Seven microfacies have been recognized comprising of dolomicritic mudstone, bioclastic wackestone, peloidal wackestone, intraclastic wackestone, pelloidal packstone, pelloidal grainstone and dolomitic limestone. The presence of bioclasts such as brachiopods, trilobites, ostracods, bivalves, crinoids and the microfacies spectrum reflect that the sediments were deposited in broad environments ranging from tidal flats to lagoon and shallow subtidal of a carbonate ramp. The diagenetic processes that have taken place include cementation, dolomitization, stylolitization, neomorphism, dissolution, compaction and micritization. Petrographic studies show that diagenesis took place in wide digenetic environments including freshwater phreatic zone, marine phreatic zone, mixing zone and deep burial zone.

Keywords: carbonate sedimentology, carbonate diagenesis, Setul Formation, depositional environment

INTRODUCTION

The Setul Formation is widely distributed in the Northwestern part of the Peninsular Malaysia and southern Thailand (Figure 1). The limestone forms a broad range of hills extending up to 30 km from Kuala Perlis to Thailand. The Setul Formation was first described by Jones (1981) as a prominent limestone of considerable thickness forming the rugged karst topography the Setul Boundary Range in west Perlis and also occurs extensively in the eastern part of Langkawi Island. The same limestone is known as the Thung Song Limestone in Thailand. In the Kilim area of Langkawi, this limestone which forms picturesque tower karsts standing out from the dense green mangrove forests is a great tourist attraction. The landscape was carved by prolonged geomorphological processes especially dissolution that took place in a humid tropical climate when it was exposed to the atmosphere.

This paper will focus on describing the microfacies in this rock and also the diagenetic aspects which have not been described in detail before.

METHODOLOGY

Samples of the Setul Limestone were collected from Kilim area in Langkawi and close-spaced sampling was done at the Kang Giap Quarry in Perlis. About 200 samples from the quarry in Perlis and sea-cliffs in the Kilim area in Langkawi were thin-sectioned and studied under the polarizer microscope for detailed petrographic investigation to classify the limestone and diagenetic studies. Thin sections were stained prior to study under the petrographic microscope according to the procedure described by Friedman and Johnson (1992) in order to discriminate ferroan calcite, non-ferroan calcite and dolomite. The rock microfacies were classified according to Dunham (1962).

GEOLOGICAL SETTING

The study area covers a limestone quarry in Northern Perlis and limestone exposures in the western part of the Langkawi Island. Basically the geology of the northwestern part of the Malaysia Peninsula is dominated by a complete sequence of Paleozoic sedimentary rocks. The deposition started with an Upper Cambrian clastic Machinchang Formation deposited under fluviodeltaic conditions which was then followed by the deposition of the subsequence younger sedimentary sequence that was almost uninterrupted until the Upper Permian and Triassic time.

The Setul Limestone was deposited conformably on top of the clastic rock of the Machinchang Formation. This gradual change was suggested to be due to the reduction of clastic input as the source area was peneplained (Lee, 2005).

Gobbett in his chapter in Gobbet & Hutchison (1973) has interpreted the Setul Limestone to be Ordovician in age based on its fossil content. Jones (1981) however, has assigned the age of this rock formation to Ordovician – Lower Devonian. This is further confirmed by Lee (2001; 2005) who found *Scyphocrinites* loboliths in the upper part of the formation which he interpreted to represent the late Silurian – early Devonian time.

Jones (1981) has divided the Setul Formation into four units namely Lower Limestone Member, Lower Detrital Member, Upper Limestone Member and Upper Detrital Member. The base of the formation is not exposed but the passage beds are exposed at Kuala Kubang Badak inLangkawi while the top is exposed on Pulau Langgun where the Singa formation rests unconformably. The total thickness was estimated to be around 2000 meters.

The rock of the Setul Formation comprises crystalline, hard brittle, dark colored, thick bedded, variably impure, crystalline limestone with subordinate detrital facies

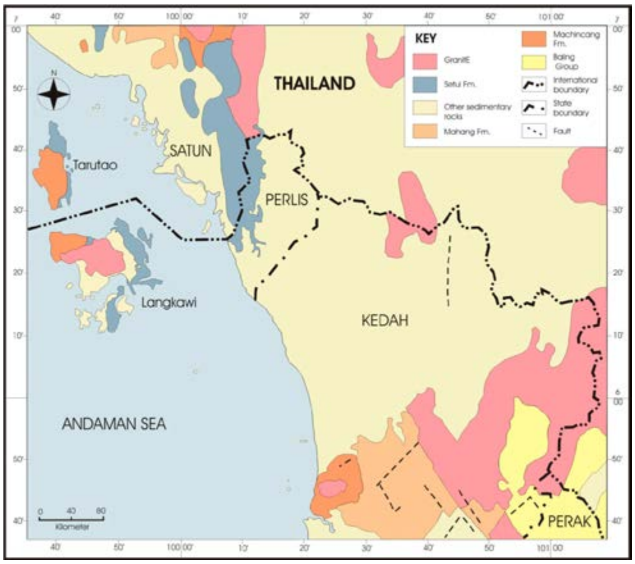

Figure 1. Distribution of the Setul Formation in Northwest Peninsular Malaysia and Thailand.

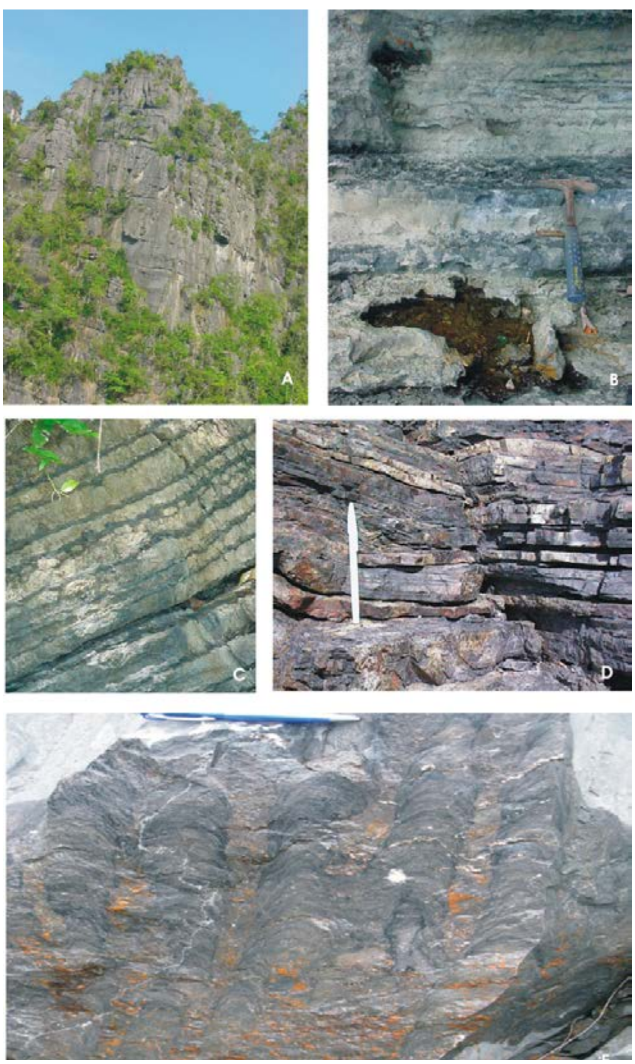

Figure 2: A. Karst morphology on the Setul Limestone. B. Color variation at outcrop related to mud content in the limestone. Muddier facies appears darker. C. Wavy stromatolites are common features in the limestone. D. The Detrital Member in the Setul limestone. E. Columnar stromatolite found at the quarry.

composed of quartzite, flagstone, carbonaceous shale, slate and black cherty mudstone (Jones, 1981). In the field (Figure 2) the Setul Formation appears dark grey in colour with massive and thick layers. Wavy stromatolites are common features in this rock formation and columnar stromatolites are also found at two localities in the Kang Giap Quarry in Perlis. Generally, the rock is devoid of sedimentary structures but in certain areas, weak evidence of rare current bedding occurs as shown by weak cross bedding.

CARBONATE MICROFACIES

The limestone is normally made up of allochems, matrix and cement. All these three components are found in most of the samples collected from the study areas. Allochems in the Setul Limestone comprise skeletal materials, peloids, ooid and some intraclasts. Skeletal and peloidal grains are widely distributed in the rock but ooids and intraclasts are rather limited. The main skeletal components found in this limestone are bivalves, tentaculites, pelecypods and some trilobite skeletal fragments. Micrite is also a major component in this rock consisting of microcrystalline carbonate material of less than 5µm in size. It normal forms the background material in most of the samples. Cement is another important component that binds the rock together. Different cement types occur in this rock and will be discussed in greater detail later.

Studies of thin sections of the rock samples from Langkawi and Perlis show that the the carbonate rocks of the Setul Formation can be divided into several microfacies based on Dunham's (1962) classification. The major microfacies are mudstone, wackestone, packstone, and grainstone (Figure 3). The microfacies have been either partly or fully dolomitized. The fully dolomitized rock has become a new microfacies called dolomite.

Mudstone

Description: The mudstone microfacies consists almost entirely of carbonate mud and the allochems do not exceed 5% (Figure 3A). The facies appears thickly bedded and dark grey at outcrops. The allochem comprises mainly of crinoids, shell fragments (of gastropods and brachiopods) and peloidal materials. This microfacies has been partly or fully dolomitized and turned into dolomicritic mudstone characterized by the presence of lime mud with dolomite crystals disseminated in the matrix. The well formed crystals are fine in size and show euhedral hipidiotopic texture.

Interpretation: At present, most of lime muds accumulate in a wide range of environments ranging from intertidal to lagoonal and basinal areas (Gischler et al, 2013; Adjas et al, 1990, Wright, 1990; Scoffin, 1987). In the Setul Limestone however, the microfacies is interpreted to have been deposited in a shallow but quite water setting as shown by the association of this microfacies with other shallow water facies. This condition might occur in protected areas of an open shelf.

Wackestone

Description: The wackestone facies in the Setul Limestone is made up of allochems embedded in a matrix of lime mud (Figure 3B) and the rock appears fine to medium grained at outcrops. The allochems are represented by fragments of crinoids, bryozoans, trilobites, brachiopods, thin shelled bivalves and some peloidal materials. The grains made up about 10% of the rock volume. There are two types of wackestone microfacies found, namely bioclastic wackestone and peloidal wackestone depending on the major allochem present. Bioclastic wackestone in the Setul formation is characterized by the presence of fragments of various skeletal materials including trilobites, bivalves, crinoids and some brachiopods shells. Some peloidal materials are also present some of which could have been produced from the micritized skeletal fragments.

Peloidal wackestone on the other hand contains about 10 % of peloidal material embedded in micrite. There are also some minor amounts of skeletal material present in this microfacies. The peloids range from 0.05 to 3 mm in size and most of them are either rounded or elongated in shape. Some of these peloids could have originated from the micritization of skeletal grains while some others could represent fecal pellets.

Interpretation: This microfacies was deposited in a low energy environment but the allochem might have been derived from high energy areas as shown by the battered and fragmented nature of the grains. The grains could have been transported into deeper quiter water during storms or accumulated at the foot of gentle slopes.

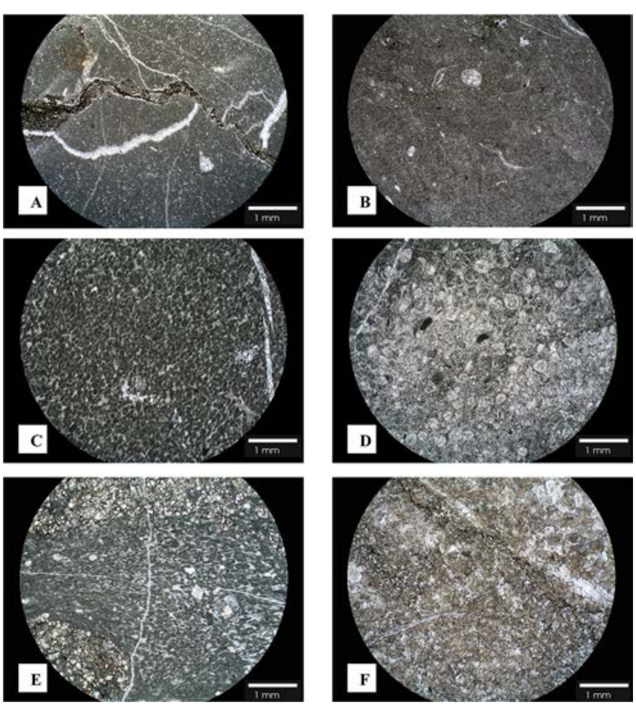

Figure 3: Microfacies in the Setul Limestone. A. Mudstone; B. Wackestone; C. Peloidal Packstone; D. Bioclastic Packstone; E. Peloidal Grainstone; F. Dolomite.

Packstone

Description: Packstone is a grain-supported microfacies consisting of a mixture of allochems and lime mud matrix (Figure 3C & D). Peloids and bioclastic tests are the main components that make up this microfacies producing two types of packstone *i.e.* peloidal packstone and bioclastic packstone. The bioclasts are represented by crinoids, bivalve shells and styliolinid tests. The presence of bioclasts is less than 25% while the percentage of peloids ranges from 10 to 45% in the samples. Some of the peloids had been compressed and aligned parallel to the bedding plane due to compaction while some other peloids have undergone dolomitization. The euhedral dolomite grains however were not compressed indicating that dolomitization took place after the sediment has been buried deeper in the subsurface.

The packstone microfacies is the most dominant facies representing about 43 percent of the total rock in the Kilim area.

Interpretation: The texture of this microfacies reflects deposition that took place under slightly higher energy conditions compared to the wackestone and mudstone microfacies. This is shown by the nature of the allochems that appear battered, broken and abraded reflecting the high energy condition closer to that of a skeletal shoal on a carbonate platform (Wilson, 1975).

Grainstone

Description: Grainstone is grain supported microfacies, with minimum amount of micrite present (less than 5%) and the rock is cemented by calcite cements. The amount of allochem is about 35% to 55% of the total rock volume, comprising peloids, bioclasts and some intraclasts (Figure 3E). In some samples, the pelloidal materials are so dominant that the rock can be classified as peloidal grainstone. The peloids were arranged parallel to the bedding plane during compaction. Calcite cements make up about 30% to 50% and dolomite is also present ranging from 1% to 10%. Figure 3E is a photomicrograph of the microfacies.

Interpretation: Its coarse grain texture and the lack of micritic material indicate that this microfacies was deposited in a high energy environment while peloids are derived from shallow water areas such as in the back barrier. The widespread cementation in the microfacies however indicates that the peloids and other allochems were deposited in rather open and agitated areas forming peloidal-skeletal shoals.

Dolomite

Description: This facies consists entirely of coarse grained replacive dolomite. It is quite impossible to recognize the original facies and grain type in this facies due to extensive dolomitization that had taken place and obliterated the original texture and fabrics of the rocks. Judging from the evenness of the dolomite grains however, we can deduce that the original microfacies could be lime mudstone with no significant amounts of allochem presents.

Interpretation: The evenness of the crystal sizes, together with some large and well formed crystals produced by extensive dolomitization indicate that dolomitization occurred late during diagenesis. Dolomitization in this microfacies had almost completely replaced both the grains and matrix. This process normally occurs deep in the subsurface where all crystals have enough time to grow and form euhedral texture.

Microfacies distribution

This facies is not evenly distributed laterally and vertically in the Kilim area. Since no sedimentary logging was carried out in Kilim area, the distribution can only be mapped laterally as shown in Figure 4. The mudstone and wackestone make up the bulk of the facies found in Kilim and they represent about 43 percent of the total sample collected in Langkawi. Meanwhile, the sequence at the Kang Giap Quarry is dominated by packstone and grainstone. Packstone is the second largest facies representing about 33 percent of the total samples collected whilst grain stone is the least with an amount of about 5 percent. About 18 percent of the total samples collected are represented by dolomite. The dolomite microfacies is seen to be associated with or to occur close to the mudstone microfacies. This phenomenon might indicate that a close genetic relationship for these two microfacies.

Detailed logging and mapping was at the Kang Giap Quarry have resulted in the lateral and vertical facies distributions presented in Figures 5 & 6. The microfacies changes from mudstone and wackestone into packstone and grainstone and continue further up with bioclastic wackestone and dolomitic limestone from bottom to top. The original texture of the microfacies cannot be ascertained due to pervasive dolomitization in the samples examined. Wavy stromatolites can be seen dominating this facies in the outcrop.

DIAGENESIS

Diagenesis involves processes that caused the physical, chemical and mineralogical changes in limestone. These processes had occurred since the sediment was deposited and normally it would lead to a more stable condition.

Factors that control the digenetic processes include the original composition of the sediment, pore water chemistry and its movements in the subsurface and also the time involved (Scoffin, 1987). Diagenesis can occur in various environment such as vadose, freshwater phreatic, sea water

Table 1: Microfacies percentage in the Setul Limestone from the Kilim area, Langkawi.

Mudstone-wackestone	43 %
Packstone	33 %
Grainstone	5 %
Dolomite	18 %

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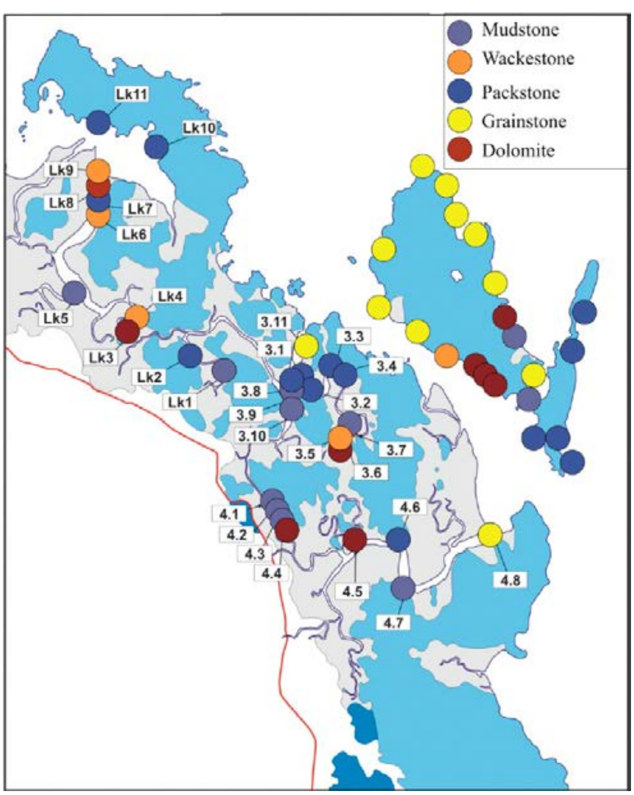


Figure 4: Microfacies distribution in Kilim Langkawi.

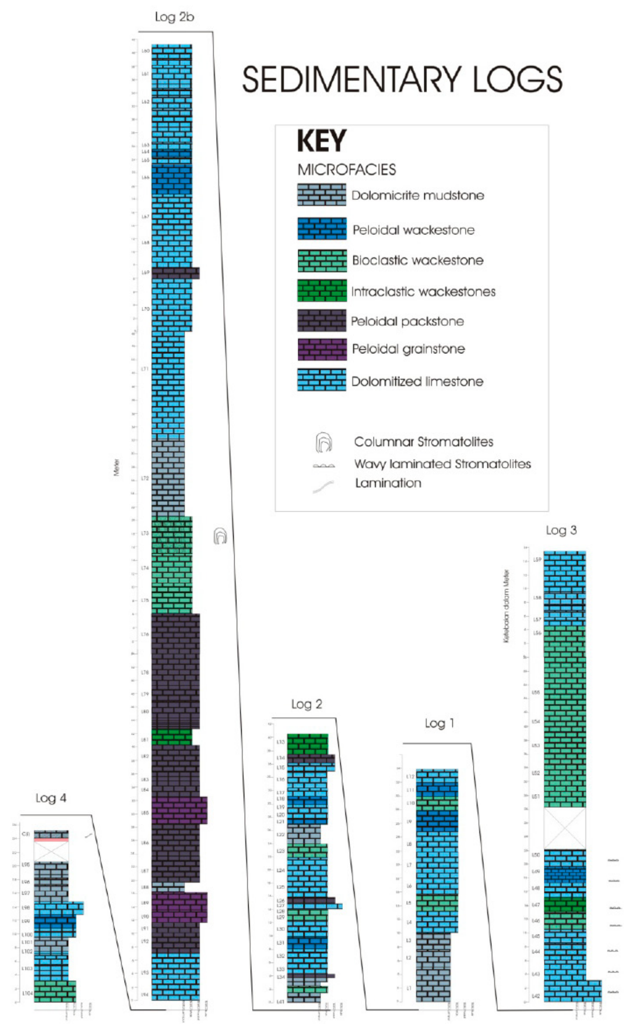


Figure 5: Limestone sequence logged at the Kang Giap Quarry.

phreatic and in the deep burial environment in the subsurface. Each of the environments will produce different diagenetic textures and fabrics.

Diagenesis in the Setul Limestone occurred very early even during deposition as shown by the presence of early marine cements. The various effects of diagenesis can be observed in the samples collected from Kilim and Kang Giap Quarry such as micritization, cementation, compaction, dissolution, neomorphism, dolomitization and silicification (Figure 7).

Cementation

Cementation was not a dominant diagenetic process in the Setul Limestone. Only minor amounts of calcite cementation are observed in the samples collected. Two generations of cement are observed in the Setul Limestone. The first generation is represented by fibrous isopachous calcite rim. This cement was superseded by the second generation cement consisting of blocky calcite cement.

The fibrous cement can be recognized from the presence of radiaxial fibrous calcite which had evolved from the originally microfibrous calcite cement. The cement was precipitated early during diagenesis when the sediment was still in a marine phreatic condition at or near the surface (Kendall, 1985). Another type of early generation cement occurs in the form of syntaxial overgrowth that affects mostly crinoid grains where the grain is now enveloped by a large calcite crystal. This type of cementation normally occurs in freshwater phreatic condition or deep in the subsurface when there is fresh water recharge to the environment. The final stage of cementation took place in deep burial in reducing conditions. This has brought about the precipitation of ferroan calcite as shown in Figure 7D

Dolomitization

Dolomitization is another dominant process that took place in the limestone. About half of the rock volume in the Setul Formation has been dolomitized. It involves direct precipitation of dolomite minerals and also replacement of calcite by dolomite. Early dolomitization occurs in discontinuity in the rock mass such as stylolites. Most dolomite in stylolites show fine and well formed crystals. Meanwhile the replacive dolomite tends to occur everywhere in the rock replacing matrix, grains and calcite cements.

Almost all samples contain some amount of dolomites. The dolomite crystals show subhedral to euhedral rhombohedron crystals with idiotopic texture. There is also some hipidiotopic dolomite texture found in the samples.

Large dolomite crystals that were produced during late stage deep burial diagenesis can also be found in the samples. They are represented by baroque dolomites or saddle dolomites. This type of dolomite is characterized by big crystals with curved boundaries and showing undulose extinction. Petrographic evidence clearly shows that there

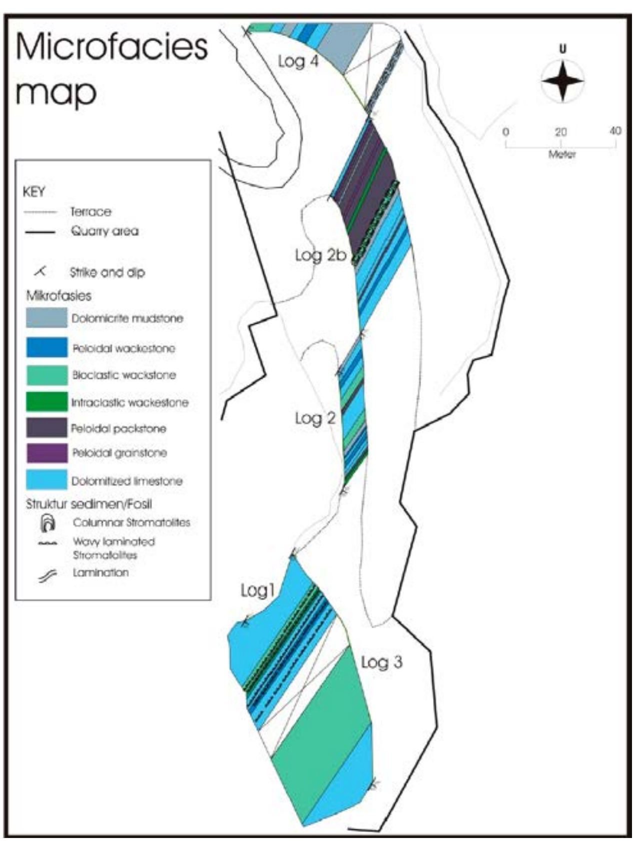


Figure 6: Microfacies distribution at Kang Giap Kuari in Perlis.

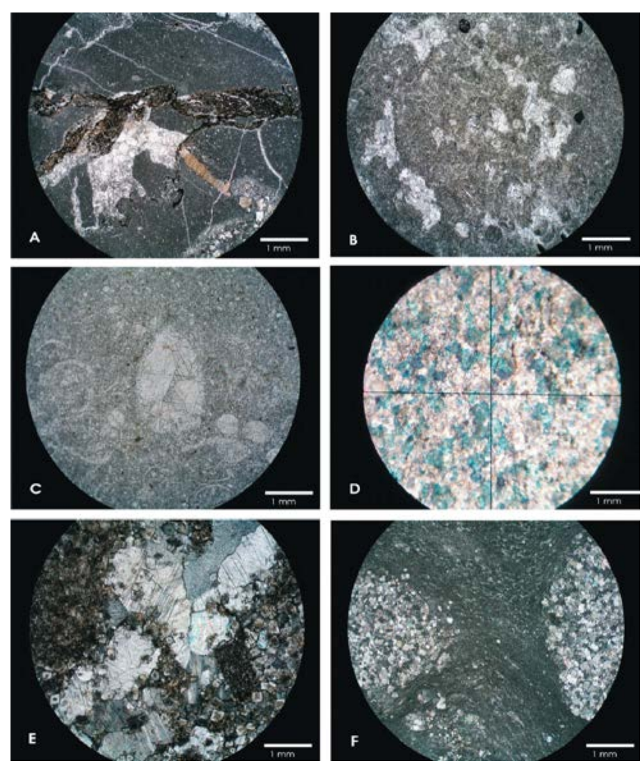


Figure 7: Diagenesis in the Setul Limestone. A. Compaction often produces fracture fabric in the rock. B. Loosely packed fabric produced by dissolution in the limestone. C. Cementation has plugged up all interparticle porosities. D. Late stage calcite cementation precipitated ferroan calcite in the remaining pore spaces. E. Replacive dolomitization produced dolomite crystals seen floating in calcite cements. F. Late stage compaction postdates cementation as seen in this image.

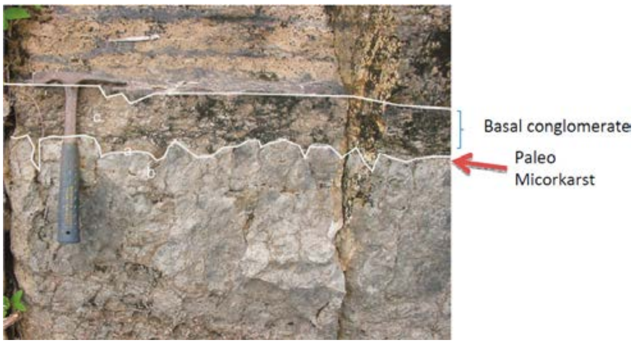


Figure 8: Paleokarst as seen in a sequence on Pulau Langgun Langkawi.

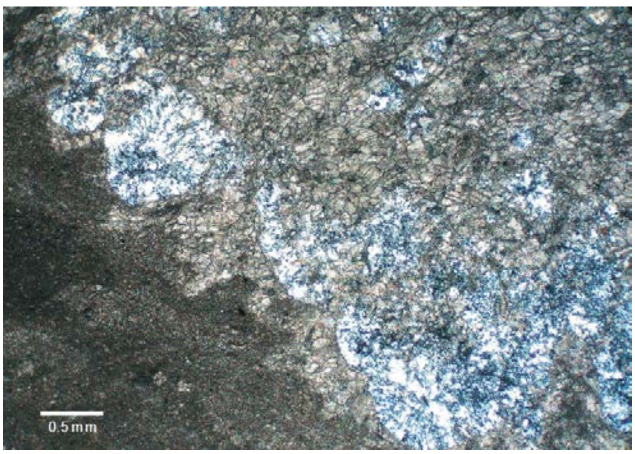


Figure 9: A late stage silica replacement found in a sample from Kang Giap Quarry.

is a mutual exclusion between saddle dolomite and other dolomite types

Compaction

It is a widely accepted fact that, increasing overburden stresses on carbonate sediment will lead to compaction. In the Setul Limestone, mechanical compaction which involves rearrangement of particles and closer grain packing began as soon as there is any overlying sediment. The effects of compaction are more noticeable in more muddy sediments where labile grains such as peloids have been compressed.

Chemical compaction and pressure solution are also very common in the muddy sediment of the Setul Limestone. The effect of chemical compaction is shown by the presence of dissolution seams and stylolites. Dissolution seams which lack the distinctive sutures of stylolites mostly go around and between grains. It is assumed that dissolution seams were formed at a very early stage during shallow burial as they have low amplitude and no accumulated clay seams. This phenomenon is common and has been widely described by earlier workers (e.g. Bathurst, 1971; Rickens, 1985; Koch & Schorr, 1986).

Unlike dissolution seams, stylolites are normally seen in tightly cemented grainy limestone (packstone). Some of them are seen cross-cutting the cements, indicating that their formation postdate calcite cementations (Figure 13).

Micritization

Micritization is a process that took place soon after the sediment was deposited. Observations in samples from the Setul Formation show that most shelly materials and algae have undergone micritization. Some peloids may have resulted from prolonged micritization processes. Micritization normally take place in quiet environment such as lagoon or back reef areas.

Dissolution and neomorphism

Dissolution is not a common feature found in this rock. Where it is present dissolution is normally shown by the poorly packed fabric with a lot of pore space. Dissolution involves matrix and bioclasts especially bivalve and other shell fragments. The pore spaces produced during dissolution were later plugged up by calcite cement during deeper burial diagenesis. Dissolution is normally related to the invasion of fresh water into the rock formation especially when the rock was exposed to the atmosphere during low sea-level. This kind of dissolution normally produces micro karsts as shown by a section on Pulau Langgun in Langkawi (Figure 8).

In contrasts to dissolution which involves destruction of depositional fabrics, neomorphism often led to preservation of the original structure of skeletal material. A considerable portion of skeletal materials were altered into low Mg-Fe-calcite. This type of neomorphism normally produced a non-ferroan microspar mosaic. Neomorphism also occurs in matrix and produced microspars.

Silicification

Silicification was also observed in the samples from the Setul Limestone. Like dolomitization, silicification can take place during early or late diagenesis (Tucker, 1991). In the Setul Limestone silicification takes the form of pervasive replacement. The silica occurs as microquartz and calcedonic quartz replacing grains cement and matrix. The nature of replacement indicates that silicification processes took place very late in the diagenetic sequence of the Setul Limestone (Figure 9).

Diagenetic sequence

The Setul Limestone has a long and complicated diagenetic history. A wide spectrum of diagenetic processes and products has been recognized including cementation, near surface dissolution, dolomite precipitation and burial calcite precipitation. Some of the processes were controlled by relative sea-level changes.

The Setul Limestone diagenetic spectrum can be subdivided into three stages: 1) early marine, 2) near surface and 3) deep burial. The diagenetic sequence is depicted in Table 2.

Early marine diagenesis is recorded by the presence of fibrous cements. The fibrous cements grew in interskeletal and intraskeletal pores. The cements were later stabilized, recrystalized and evolved into bladed cements. The presence of these cements seems to be very important in consolidating the sediments.

Meteoric diagenetic processes occurred during the relative sea-level lowstands and were only detected from one locality on Pulau Langgun in Langkawi just below the transgressive sequence. The second diagenetic stage took place in the deeper burial environments and involved late stage cement precipitation including blocky calcite and saddle dolomite. Some of these diagenetic features were later obliterated by the silicification processes that took place at the latest stage.

DEPOSITIONAL ENVIRONMENT

Various environments of deposition in the Setul Limestone have been identified. These include tidal flat, lagoon or protected environment, skeletal shoal and deeper outer ramp. Muddy microfacies with wavy stromatolites laminae or laterally linked hemispheroids can be interpreted to represent tidal flat deposits or on protected shorelines (Hoffman, 1976). Most of the other fine grained facies including mudstone and wackestone were deposited either in protected environments or deepwater outer ramp areas. Coarse-grained microfacies such as packstone and grainstone could represent higher energy setting in shallower water areas such as skeletal banks. The abundance of peloidal materials in the limestone again reflects the quietness of the depositional environment in general during the deposition of the Setul Limestone

According to Wright (1990) stromatolites morphology can be used as an indicator of energy condition. The presence of columnar stromatolites in the Kang Giap Quarry in Perlis (Figure 2E) reflects deeper water condition with high energy setting. In Shark Bay, this type of stromatolites occurs on headlands fully exposed to waves.

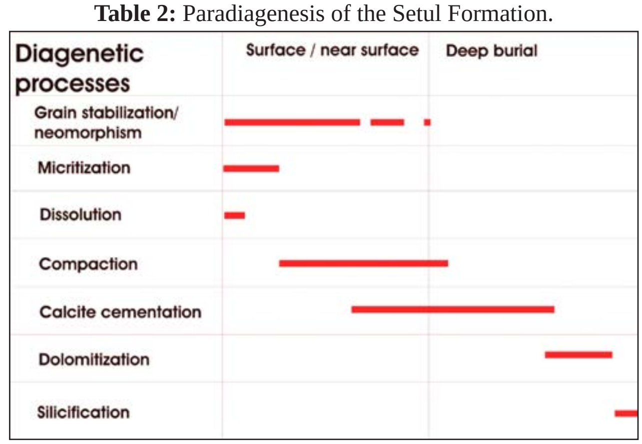
The overall facies indicates the changes in environment of deposition that might have been controlled by the sea-level changes. The relationship between the facies and the sea-level changes is shown in Figure 10.

CONCLUSION

Generally, the rock of the Setul Formation is muddy in nature as shown by the presence of abundant muddy microfacies. The rock also contains both shallow and deep marine elements. The presence of tentatculites, graptolites and loboliths indicates that there were times when the limestone was deposited in deeper marine condition as shown in Figure 10. In contrast, there are also evidences that point to very shallow water conditions as shown by the presence of shallow marine benthic fossils such as brachiopods and trilobites. At a locality on the Langgun island there is even an indication of sub-aerial dissolution preserved in the sequence. In conclusion, it can be said that the Setul Limestone was deposited in a ramp setting with depositional environments ranging from intertidal to deep open marine. The limestone is also rich in peloidal and algal materials. In places peloids become the main component in this limestone and it could be related in origin to coccoidal microbes. Normally peloids collect in lagoons and shallow intertidal zones where they are protected from rough ocean currents. Sun and Wright (1989) who studied the limestone in the Weald Basin have interpreted that peloids were produced microbially either by direct precipitation or by induction in areas which had relatively low framework growth rate, low sedimentation rate and moderate energy level.

The limestone has undergone complete diagenetic processes right from the time of deposition at the surface up to the time when it was buried deep in the subsurface. Petrographic evidences show that during deposition and near surface burial the sediment was affected by very little early marine cementation as shown by the rare occurrence

Table 2: Paradiagenesis of the Setul Formation.



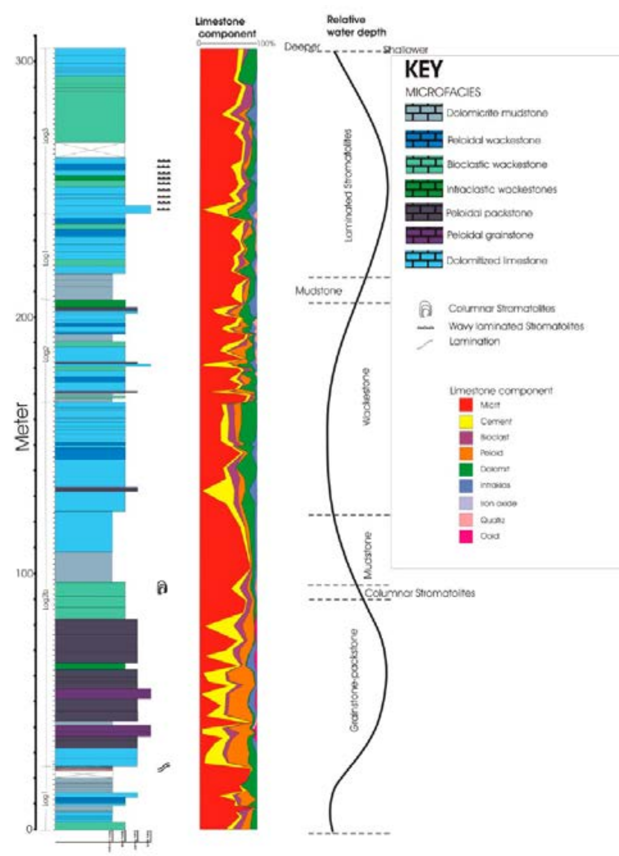


Figure 10.: A composite log measured at the Kang giap Quarry showing the facies changes, major limestone components and the interpretation of the relative sea-level during deposition.

of early marine cementation in the rock sequence. This evidence together with the fossil occurrence support the earlier interpretation that most of the sediment was deposited in deeper water setting except for the algal rich part of the limestone facies. Soon after deposition, the sediment was subjected to compaction that resulted in development dissolution seams and distortion of labile grains such as peloids. During the depositional processes there were times when the area was subject to the sub aerial exposure due the lowering of sea-level. This has resulted in the formation of the karstic surface. Further burial processes have produced late stage calcite cementation represented by large crystal calcite mosaic crystals followed by dolomitization. Dolomitization took place in two phases. The first phase of dolomitization occurred mainly through stylolites and spread outwards replacing whatever material that contain high amount of magnesium (high magnesium calcite) whilst the second phase occurred very late and produced large crystals of saddle dolomite. All in all, the Setul Limestone was deposited in a broad depositional setting ranging from shallow to deep marine condition and experienced all stage of diagenetic sequence in it history. The Lower Setul Limestone was basically deposited in shallow marine conditions. At one stage there are areas where the sediments were exposed to the atmosphere. This phenomenon marked the end the deposition of the Lower Setul Limestone. It was then transgressed by the sea water leaving behind an evidence of shallow water inundation as shown by the presence of the trilobite layer in the lower part of the Lower Clastic Member. The environmental deposition of the Lower Detrital Member was then drastically change to deep marine as shown by the occurrence of thinly bedded cherty mudstone in the top of this sequence. Then suddenly the area once again witnessed the change of sediment type to generally muddy carbonates in the area during the deposition of the Upper Setul Limestone. This limestone member was deposited in deeper marine conditions as shown by the presence of *Scypocrinites* lobolith and tentaculites in this part of the Setul Limestone. It was then followed by the deposition of another clastic interval of the Upper Detrital Member which also occurred in deep marine conditions. Evidence of deep marine again was shown by the presence of tentaculites in this member.

ACKNOWLEDGEMENT

We wish to thank Lee, C.P for his critical revision of the manuscript. This paper was produced from the fieldwork funded by grants from GUP (DPP-2013-065) and PIP-2013-001 of Universiti Kebangsaan Malaysia.

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Manuscript received 21 January 2010
Revised manuscript received 23 October 2013