CHAPTER VII

LITHOSTRATIGRAPHIC CLASSIFICATION AND DEPOSITIONAL ENVIRONMENT

7.1 Lithostratigraphic Correlation

Actually, the rock sequences of three measured sections are quite different, as described earlier. This fact makes it rather difficult to correlate among those sections if there is no key bed. Fortunately there are two distinct key beds for correlation in the three areas. However, some rock units have similar lithological characteristics which can be used as correlation criteria between measured sections. The key bed no. 1 is a dark grey, thinly-bedded, *Robustoschwagerina* sp. bearing biomicrudite bed, and the key bed no. 2 is the medium grey, thinly-bedded, packed biomicrudite containing abundant large gastropod and brachiopod shells with small fusulinid tests. The key bed no. 1 was found in the unit KD2 and unit KC1 but absent in the Pak Chong to Khao Yai area. The key bed no. 2 was discovered in the unit KD5 and unit PK1 but absent in the Khao Chan area.

The lowest rock units of measure rock sections in the Khao Khad, Khao Chan and Pak Chong to Khao Yai areas are mainly thin- to medium-bedded biomicrite but they are different in grain contents probably due to the difference in the stratigraphic location. To avoid this possible error, the author decided to use the key bed 1 as a reference time line in the measured sections of the Khao Khad and Khao Chan areas. The *Robustoschwagerina* sp. is locally present in the lower part of the unit KD2 of the Khao Khad and in the unit KC1 of Khao Chan areas. It was likely that the unit KD2 and unit KC1 were deposited at the same period of time with different lithology. As

the result, the unit KD1 should be placed as the lowest lithostratigraphic unit of the Khao Khad Formation (Figure 7.1).

In middle part of the Khao Khad Formation, the sections were correlated by using the key bed no. 2, the medium grey, thin-bedded, packed biomicrudite containing abundant large gastropod and brachiopod shells deposited together with small fusulinid tests. This lithological characteristic was recognized in the unit KD5 of the Khao Khad route and the unit PK1 of the Pak Chong to Khao Yai route. The rugose corals were exclusively present in both units. It is therefore likely that the unit KD5 is equivalent and can be correlated to the unit PK1 based on the above lithological characteristic and other similar criteria such as color, sedimentary structures and fossil contents (Figure 7.1).

The lithostratigraphic correlation among the three measured sections of the Khao Khad Formation gives fifteen different lithologic units which from now on will be called lithofacies (Figure 7.2). As such those fifteen lithofacies should be a better representation of the sedimentary sequence of the Khao Khad Formation than the previous reports.

Under the present study, the recognition of various depositional environments is based upon seven characteristic criteria, namely geometry of bedding, texture, sedimentary structure, mineral composition, special features, grain component and fossil contents. The interpretation of depositional environment of each lithofacies based upon these criteria has followed the mixed carbonate/clastic depositional model of Reeckmann and Friedman (1982) (Figure 7.3). The characteristics of each lithofacies are summarized as follows:

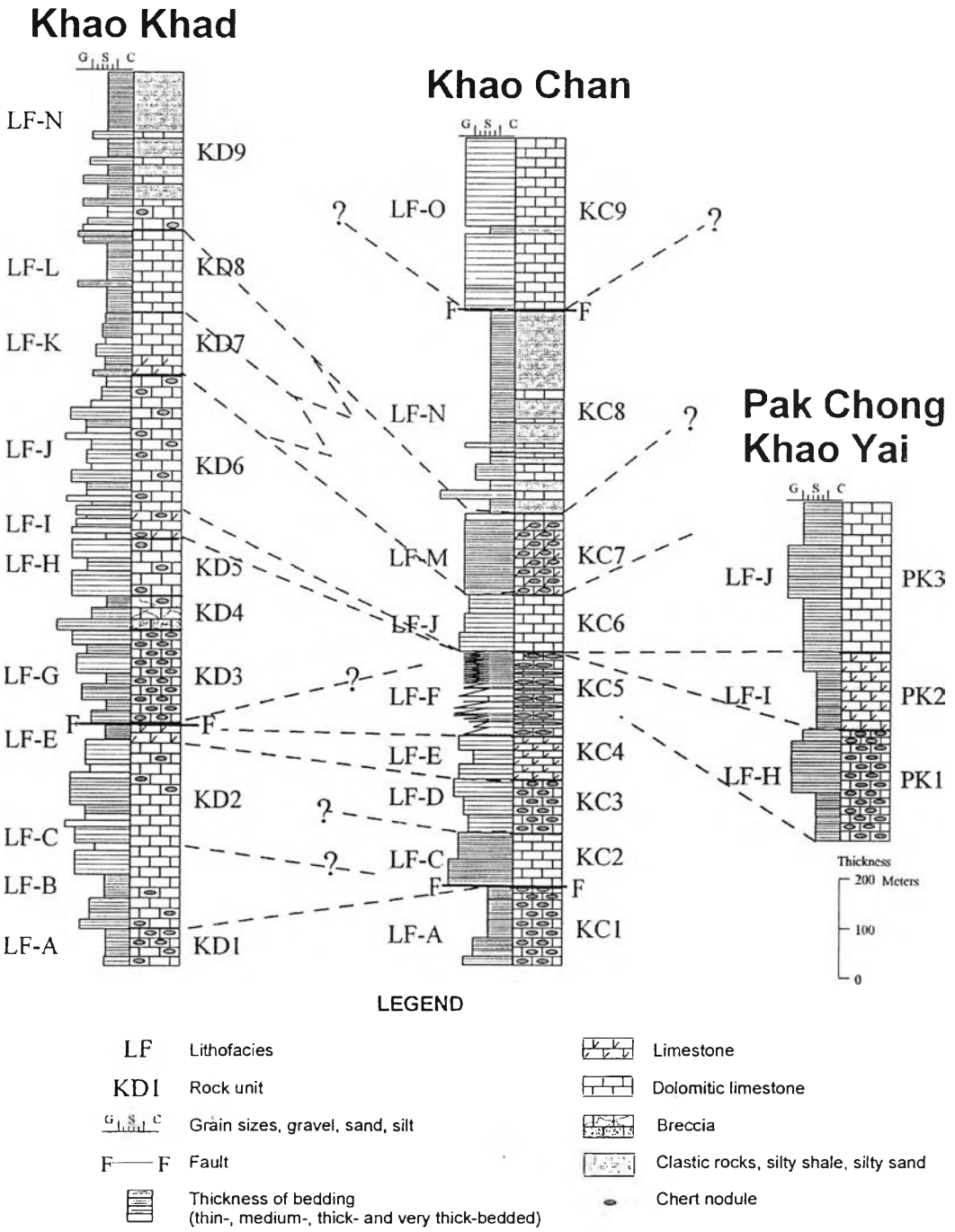


Figure 7.1 The stratigraphic correlation of the Khao Khad Formation from three measured section, Khao Khad, Khao Chan and Pak Chong to Khao Yai areas.

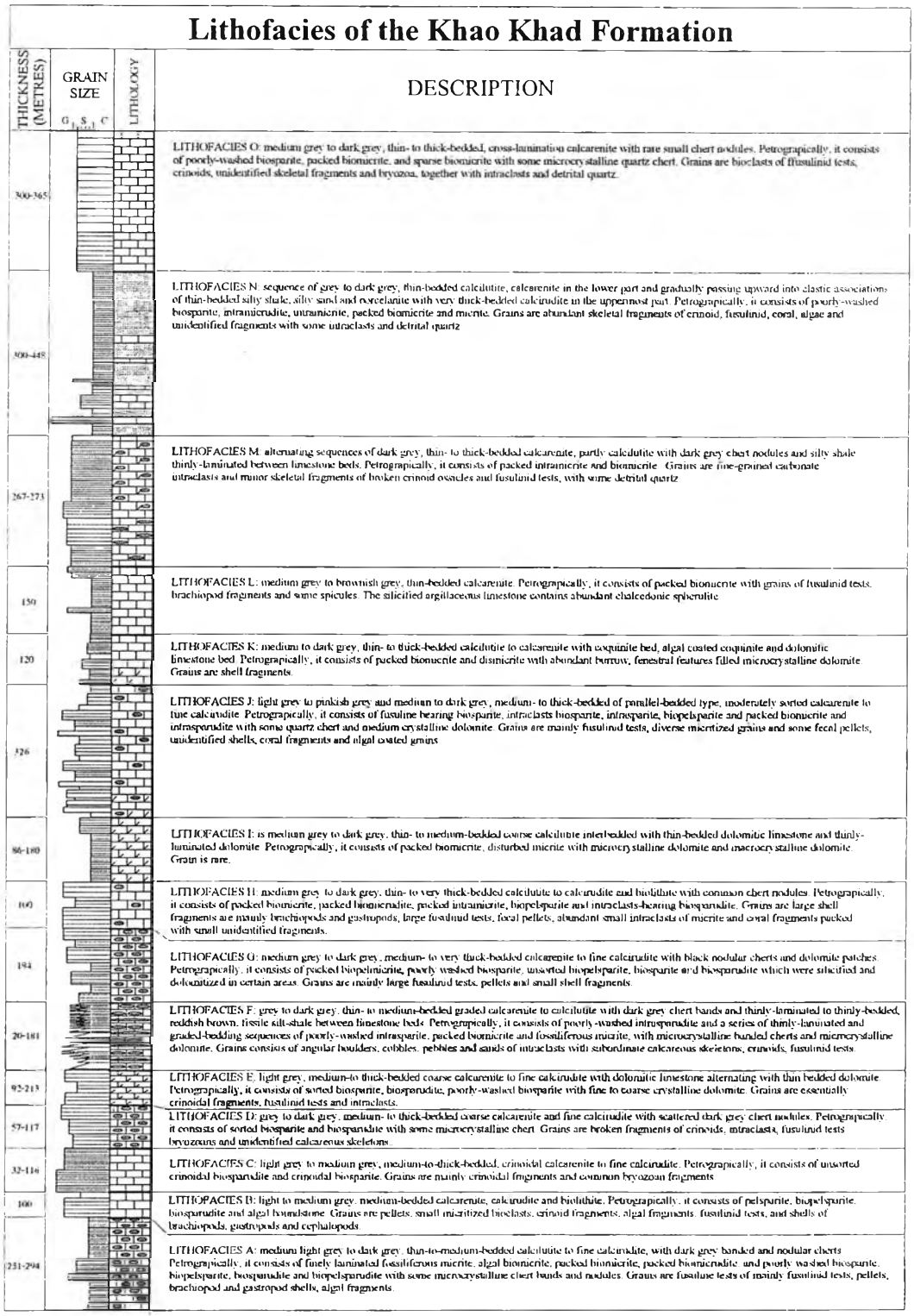


Figure 7.2 Stratigraphic columns of the representative sections of fifteen lithofacies of the Khao Khad Formation.

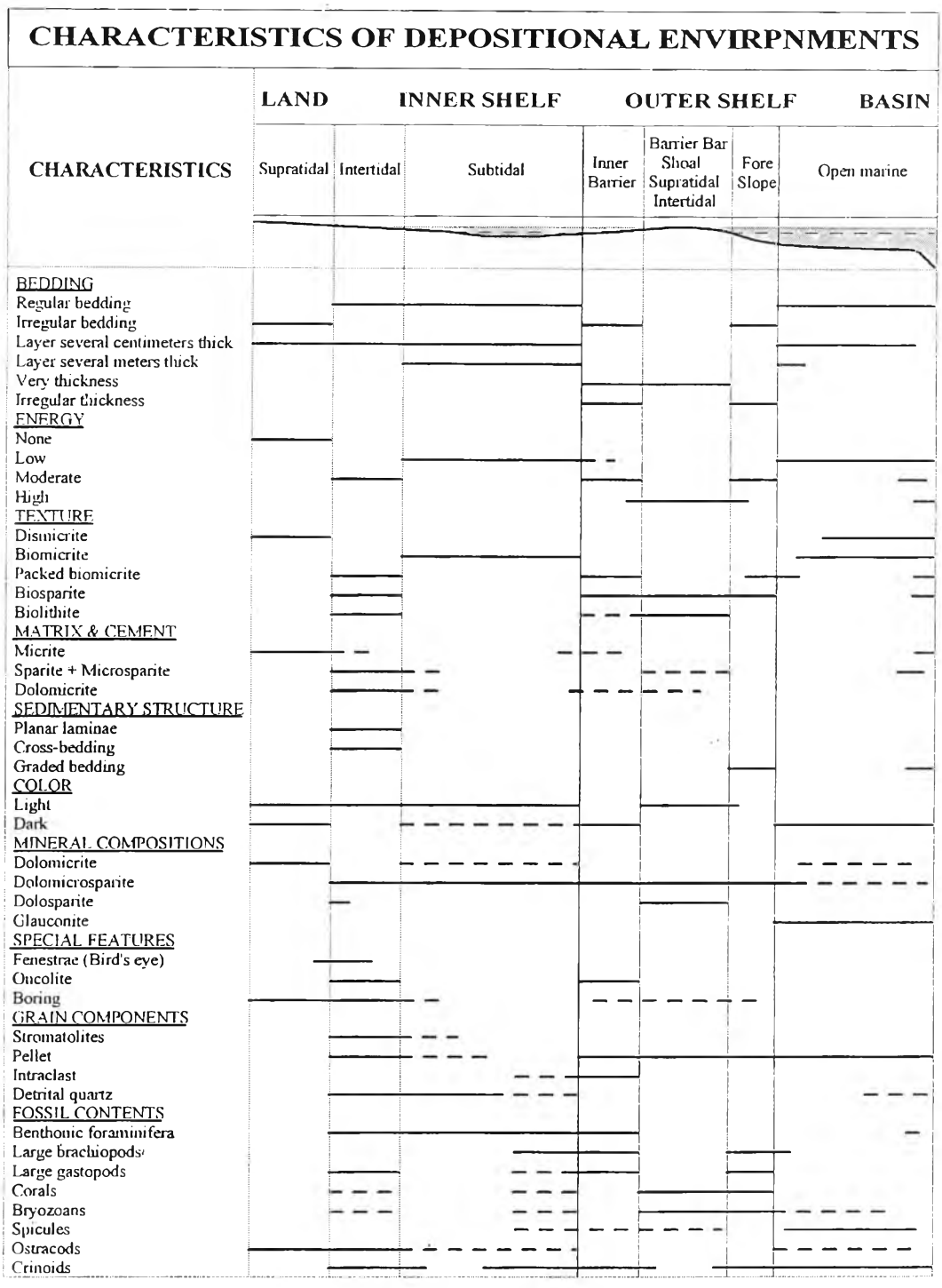


Figure 7.3 The characteristics of depositional environments of carbonate rocks (modified after Reeckmann and Friedman, 1982).

7.1.1 Lithofacies A: Calcilutite with nodular chert

Description: The calcilutite with nodular chert lithofacies or lithofacies A is calcilutite to fine calcirudite, interbedded with dark grey nodular chert, partly banded chert and siliceous limestone (Figure 5.4A). The rocks are medium light grey to dark grey and thin-to-medium-bedded. The lower part of this lithofacies represents by thin-to-medium-bedded, medium light grey calcilutite with minor cherts (Figure 5.4B). The middle part of this lithofacies is dominated by thinly-to-thickly-laminated, wavy-and-nonparallel bed-type calcilutite and fine calcirudite containing abundant algal mats, brachiopod shell fragments and fusulinid tests of mainly *Robustoschwagerina* sp. (Figure 5.23B). In contrast, the upper parts are represented by medium-bedded calcilutite with relatively rare shell fragments and sparse fusulinid tests. The weathered surface is usually grey to light grey and smooth on this limestone, but it turns brownish grey to black and rough on the silicified part.

Petrographic studies show that the lithofacies A consists of finely laminated fossiliferous micrite, algal biomicrite, packed biomicrite, packed biomicrudite, poorly washed biosparite, biopelsparite, biosparudite and biopelsparudite with some cryptocrystalline dolomite, microcrystalline chert bands and nodules. Grains are fusulinid tests, pellets, brachiopod and gastropod shell fragments, algal fragments, and unidentified small micritized grains. Most of shells were completely micritized (Figure 5.4E) and some fusulinid tests and brachiopod shells are coated with micrite. The microcrystalline calcite cement can be recognized around pellets (Figure 5.4F) and around contact point area of brachiopod shells and fusulinid tests (Figure 5.5A). The internal pores of fusulinids are filled with finely crystalline sparry calcite cement. Nodular chert and silicified limestone are composed mainly of microcrystalline quartz with some calcareous patches (Figure 5.5B).

Interpretation: The presence of abundant micrite indicates a low energy index of depositional environment. The occurrence of poorly washed biosparite, however, indicates a slightly high energy index in which the energy might not be high enough to remove all micrite matrix. The fecal pellet distribution corresponded to moderate energy and deposited in low energy conditions in both basinal and protected shallow marine environments which were more amenable to extensive biogenic activities and preservation of fecal pellets. The biomicrudite also indicates the low energy condition of a restricted marine. Micritized and micrite-coated grains are commonly occurred in the bio-activated zone on the sea floor and in the intertidal to subtidal environments. The presence of microcrystalline calcite cement indicates that the sediments were exposed to marine vadose zone which frequently flushed by seawater or brine. The occurrences of microcrystalline quartz with some calcareous patches indicate replacement of silica-rich solution probably occurred after sediments were burial. As such the lithofacies A was most likely deposited in the subtidal zones of shallow restricted marine. The rather thick sequence of this lithofacies obviously indicates the gentle subsiding depositional environment with the rate of carbonate deposition almost equal to the rate of subsidence.

7.1.2 Lithofacies B: Algal biolithite

Description: The algal biolithite lithofacies or lithofacies B is calcarenite, calcirudite and biolithite that are light to medium grey and medium-bedded. The rocks show a grain-supported fabric of differing types and sizes of grain components. Grains are algal encrustations, fusulinid tests, crinoid fragments, pellets and shells of brachiopods, gastropods and cephalopods. The large shells of gastropods and brachiopods are commonly associated with carbonate buildup. The weathered surface is white to light grey and usually rough due to differential dissolution.

Petrographically the lithofacies B consists of pelsparite, biopelsparite, biosparudite. They are closely associated with carbonate buildup or algal biolithite (Figure 5.6C). Grains are abundant fecal pellets, small bioclasts of crinoid fragments, algal fragments, foraminiferal tests and unidentified grains. All bioclasts were completely micritized and initially cemented by microcrystalline calcite. The late sparry calcite cemented various types of grains, such as algal fragments, fusulinid tests and shell fragments of brachiopods, gastropods and cephalopods. The shell fragments are usually orientated parallel or sub-parallel to bedding plane. The detailed petrographic studies of algal stromatolite revealed that the pre-existing grains of pelsparite, biopelsparite and oncoilite were coated with many algae (Figure 5.7A). There was some braking period of algal coating which was separated by radiaxial fibrous calcite cement (Figure 5.7B). Many layers of the fibrous calcite cement are separated by microcrystalline dolomite layers (Figure 3.7C). Some macrocrystalline dolomite rhombs occur in association with sparry calcite cement in the central area of intergranular pores (Figure 5.7D).

Interpretation: The presence of algal stromatolites as stratiform layer is common in modern intertidal to supratidal at the Persian Gulf (Shinn, 1983) and Shark Bay (Logan et al., 1964; Logan, 1974). The associations of microcrystalline dolomite as interlayer or interlamination with limestones have been also commonly interpreted as tidal flat, upper intertidal to supratidal origins in the Ordovician of Western Marryland (Matter, 1967), the Lower Devonian of New York state (Laporte, 1967), the Silurian of Ohio (Textoris and Carozzi, 1966), the Visean of Canadian Maritime Province (Schenk, 1967) and in Ireland (West et al., 1968). In this study the presence of algal stromatolite coating on micritized grains and pelsparite grains of the lithofacies B indicates that the sediments were deposited in low-energy environment. The micritized grains and pellets commonly occur in the intertidal to subtidal zone of shallow marine. The occurrence of microcrystalline calcite cement on fecal pellets and

bioclasts indicates that the sediment had been exposed to the marine vadose zone. It is therefore likely that the lithofacies B was deposited in the intertidal zone of shallow marine.

7.1.3 Lithofacies C: Crinoidal calcirudite

Description: The crinoidal calcirudite lithofacies or lithofacies C is light grey to medium grey and medium- to thick-bedded (Figure 5.24A). The rocks contain more than 50 % fragments of large crinoid stems, between 0.5 mm to 2 cms in diameter (Figures 5.24B). The beds are of parallel-bedded type with very thin bands of grayish black to reddish silty shale in each crinoidal limestone beds.

Petrographically this lithofacies is unsorted crinoidal biosparudite and crinoidal biosparite. Grains are mainly crinoidal fragments and common bryozoan fragments. They are cemented together by coarsely crystalline and relatively clean sparry calcite. The fine-grained matrix is rarely recognized as micrite and pseudosparite with sparse dolomite rhombs in some parts. Most crinoid fragments were over-grown by syntaxial calcite cement (Figure 5.24C). It can be recognized that all grains were corroded before deposition. The dolomite rhombs are commonly found associated with fine-grained matrix as well as replace bryozoan fragments. The rhombs are subhedral to euhedral crystals of various sizes (50 to 300 μms) and some are corroded (Figure 5.24D).

Interpretation: The abundant cleanly-washed and large-sized crinoid fragments are commonly occurred in the agitated high energy environment of the barrier, as found in the Betic Mountains, southern Spain (Bustillo and Ruiz-Ortiz, 1987). Most of the crinoids were syntaxial overgrowth by calcite cement and showed corroded rims which indicated that grains were deposited and partially cemented before they were

transported and re-deposited again. The rather thick crinoidal calcarenite to fine calcirudite lithofacies certainly requires carbonate deposition under subsiding condition. The presence of thin bands of silty shale between crinoidal limestone beds indicates a small brake of carbonate deposition with the influx of terrestrial fine-grained clastic sediments. It is therefore concluded that the lithofacies C was deposited in high energy zone of the slightly subsiding barrier bar or shoal.

7.1.4 Lithofacies D: Crinoidal calcirudite with nodular chert

Description: The crinoidal calcirudite with nodular chert lithofacies or lithofacies D is coarse calcarenite and fine calcirudite that are grey to dark grey and medium- to thick-bedded with scattered dark grey chert nodules (Figures 5.25A). The nodules vary in size from a few cms to a few ten cms and partly elongated. The upper part of this lithofacies is slightly dolomitic. The major grain components are crinoid stems, foraminifera, intraclasts and bryozoans, respectively in decreasing order of abundance. It is noted that the skeletal remains of crinoid and foraminifera are also present in chert nodules.

Microscopically, the lithofacies D is designated as sorted biosparite and biosparudite with some microcrystalline chert. The biosparite and biosparudite (Figures 5.25B) consist of broken fragments of crinoids, bryozoans and unidentified calcareous skeletons, mixed in various proportions with intraclasts and complete foraminiferal tests. However, microcrystalline dolomite can be recognized as dark brown, dull color locally present between the boundaries of carbonate grains (Figures 5.25C and 5.25D). The crinoid fragments show syntaxial overgrowth calcite cement. The nodular chert is mainly microcrystalline quartz locally disseminated with calcite rhombs.

Interpretation: There seems to be a certain degree of similarity in lithology between the lithofacies C and D, except that the lithofacies D contains chert nodules and some foraminifera and intraclasts. The intraclasts are commonly present in high energy zone of barrier bar and usually accumulated on the back side of the bar. Therefore, it is likely that the depositional environment of the lithofacies D was a slowly subsiding back barrier.

7.1.5 Lithofacies E: Crinoidal calcirudite with banded dolomite

Description: The crinoidal calcirudite with banded dolomite lithofacies or lithofacies E is coarse calcarenite to fine calcirudite that are light grey and medium-to thick-bedded with dolomitic limestone alternating with thinly bedded dolomite (Figures 5.26B). The skeletal grain components of this lithofacies are similar to those of the underlying lithofacies D.

The petrographic studies of the lithofacies E revealed that the characteristic of this lithofacies is quite similar to those of the lithofacies D but with higher degree of dolomitization. The lithofacies E comprises mostly sorted biosparite, biosparudite, poorly-washed biosparite with fine to coarse crystalline dolomite. Grains are essentially crinoidal fragments, foraminiferal tests and intraclasts. These grains are closely packed in the form of grain-supported fabric with sparse micrite, and cemented by sparry calcite. Many parts of the rocks are thinly-bedded, and composed essentially of fine to coarse crystalline dolomite.

Interpretation: The presence of calcarenite to fine calcirudite indicates the moderately high energy index of depositional environment. Also the fact that the dolomitization could have been more favorable in the intertidal zone and barrier bar or shoal due to the seepage of Mg-rich brine in the lagoonal area towards the barrier bar

(Reeckman and Friedman, 1982). Therefore, it is likely that the fine calcirudite lithofacies were deposited in the intertidal zone of barrier bar.

7.1.6 Lithofacies F: Grade-bedded calcarenite with banded chert

Description: The grade-bedded calcarenite with banded chert lithofacies or lithofacies F is calcilutite to calcarenite with dark grey chert bands. The rocks are grey to dark grey, thin to medium and grade bedded. Abundant reddish brown fissile silty shales are thinly-laminated to thinly-bedded between the limestones beds of this unit (Figure 5.27A). It is noted that four calcirudite beds of 9-13 ms thick are present in the middle part of this lithofacies (Figures 5.27B). These four calcirudite beds contain remarkably large grain components. The grain components are intraclasts, crinoidal fragments, fusulinid tests and shell fragments, respectively in decreasing order of abundance.

Microscopically the rock comprises poorly-washed intrasparudite and a series of thinly-laminated and grade-bedded sequences of poorly-washed intrasparite, packed biomicrite and fossiliferous micrite, with microcrystalline banded cherts and microcrystalline dolomite. Grains consist of angular boulders, cobbles, pebbles and sands of intraclasts with subordinate calcareous skeletons, mostly crinoid ossicles, foraminiferal tests and other skeletons fragments. The boundary between the packed biomicrite and fossiliferous micrite is apparently transitional by which there is a progressive decrease of grain abundance in proportion to the increase of calcareous matrix. The banded cherts are occasionally associated with packed biomicrite and fossiliferous micrite and mainly consist of microcrystalline quartz, subordinately, chalcedonic and megacrystalline quartzs replacing carbonate matrix with sparse carbonate remnants (Figure 5.25E). The carbonate remnants are both calcareous patches and dolomite patches.

Interpretation: A sequence of thinly and grade-bedded calcarenite to calcilutite is favor in the distal part of turbidity grain flows occurring in the foreslope of the barrier bar. As described in the final stage of evolution of the Niagaran buildup of Indiana (Textoris and Carozzi,1964; Carozzi, 1989), the association of current swept platform morphology and an overproduction of crinoids created ideal conditions for the generation of slumping and turbidity currents which was a major mechanism for the radial distribution down the buildup flanks. The four thick calcirudite beds in the sequence therefore suggest the deposition under exceptionally strong energy index of presumably turbidite channel in the fore slope of the barrier bar of the open marine.

7.1.7 Lithofacies G: Fusulinid bearing fine calcirudite

Description: The fusulinid bearing fine calcirudite lithofacies or lithofacies G is calcarenite to fine calcirudite with black nodular cherts and dolomite patches (Figures 5.8A and 5.8B). The rocks are medium grey to dark grey and medium- to very thick-bedded. Grains are mainly fusulinid tests having the size from 1 to 5 mms and the matrix is a mixture of pellets, small shell fragments and cement. The chert nodules, varying in size from 10 to 30 cms, are found scattered throughout this lithofacies.

Microscopically the lithofacies G consists of packed biopelmicrite, poorly washed biosparite, unsorted biopelsparite, biosparite and biosparudite. These rocks have been silicified and dolomitized in certain areas. Grains are composed of randomly oriented fecal pellets and shell fragments. The internal pores of bioclast were earlier cemented by isopachous fibrous calcite fringing around the pore surface. It grows perpendicular to the pore surface. It was followed by sparry calcite cement filling the remaining pore spaces. The micrite was found as irregular patches filling in intergranular pores and fusulinid chambers. The remaining intergranular and intragranular pore spaces were filled with fine sparry calcite cement. It appears that the

outer surface of shell fragments had been coated with micrite before the fragments were broken. Some elongated shell fragments lie parallel or sub-parallel to the bedding plane.

In the zone of grain-supported calcarenite to fine calcirudite there is a lack of micrite remains in intergranular pore spaces. Grains were earlier cemented by thin-layer and light-colored microcrystalline calcite cement, coating around some pellet grains and around contact point of grains. Nodular chert is mainly composed of microcrystalline quartz with some scattered dolomite rhombs and calcareous patches (Figure 5.9C). The dolomite crystals vary in size from 10 to 300 μms whereas the calcareous patches vary in size from 60 to 100 μms. Some parts of biosparite contain scattered dolomite rhombs and calcareous grains (Figure 5.9D).

Interpretation: The presence of matrix-supported fine calcirudite indicates low energy index of depositional environment whereas the grain-supported calcarenite to fine calcirudite indicates high energy index of depositional environment. The pellets are abundant in the subtidal zone of restricted marine. The presence of packed biopelmicrite and poorly washed biosparite indicates that the energy was not high enough to winnow all of micrite. But the unsorted biopelsparite, biosparite and biosparudite indicate slightly higher energy to winnow all micrite. It was therefore likely that the lithofacies G was deposited in an intertidal to subtidal zone of restricted marine.

7.1.8 Lithofacies H: Coral biolithite

Description: The coral biolithite lithofacies or lithofacies H comprises calcilutite to calcirudite and biolithite that are medium grey to dark grey and thin- to very thick-bedded with common chert nodules (Figure 5.12A). The calcilutite usually

associates with coralline colonies in which their intergranular pores are filled with the dark grey calcilutite (Figure 5.12D). The calcarenite is coarse-grained and displays grain-supported texture. In hand-specimen, the rock contains many small elongate white spots (< 0.5 to 1 mm in size), and black fusulinids (1 to 1.5 mms in size) embedded in fine-grained micrite matrix. The white spots are uniformly scattered in the rock mass and orientated parallel or sub-parallel to the bedding plane. The biolithite is algal stromatolite and appears in the lower part of this lithofacies. It is a poorly sorted rock with diverse bioclasts, such as brachiopods, gastropods, fusulinids, algal fragments, branching corals and intraclasts (Figure 5.12E). It is the colonies of coral in growth positions. The weathered surface of the rocks is slightly rough and clearly reveals diverse types of grains such as brachiopods, gastropods and corals due to differential dissolution (Figure 5.12B). The chert nodules are variable both in shape (mostly elongate) and in size (mostly 10-20 cms in length) as shown in Figure 5.12C.

Under a microscope the lithofacies H can be classified as packed biomicrite, packed biomicrudite, packed intramicrite, biopelsparite and intraclast-bearing biosparudite. Grains are large shell fragments of mainly brachiopods and gastropods, large fusulinid tests, fecal pellets, abundant small intraclasts of micrite and coral fragments packed with small unidentified fragments (Figure 5.13B). There are abundant dolomite rhombs disseminated in packed intramicrite and usually show micro-stylolite around grain contact. The nodular chert is essentially microcrystalline quartz.

Interpretation: The presence of coarsely grain-supported calcarenite to finely matrix-supported calcirudite indicates slightly high energy index of depositional environment. The diverse bioclasts, such as brachiopods, gastropods, fusulinids, algal fragments, branching corals and intraclasts together with the colonies of coral in growth positions indicate bioaccumulation buildup. It is therefore likely that the

lithofacies H was deposited in the intertidal to subtidal zone of shallow platform buildup.

7.1.9 Lithofacies I: Laminated dolomitic calcarenite

Description: The laminated dolomitic calcarenite lithofacies or lithofacies I is coarse calcilutite thinly-interbedded with dolomitic limestone and dolomite. The calcilutite is medium grey to dark grey and thin- to medium-bedded. The dolomitic limestone and dolomite appear in the fields as bands of white to light grey 'elephant skin' texture on the weathered surface that marks the difference from the other lithofacies (Figure 5.36A). In the hand specimen the dolomitic limestone is white, thinly-bedded to thinly-laminated without significant grains. This is quite in contrast to medium grey to dark grey coarse calcilutite (Figure 5.36B). The cross lamination is also present in the dolomitic limestone.

Petrographically, the lithofacies I is packed biomicrite, disturbed micrite with microcrystalline dolomite and macrocrystalline dolomite. The packed biomicrite consists of diverse small bioclasts (10 to 500 μms in size) embedded in micrite matrix (Figure 5.36C). The disturbed micrite is characterized by abundant bioturbations, probably burrow, in micrite matrix (Figure 5.36D). There are many phases of burrow and burrow filling. Burrows are filled with micrite, finely crystalline dolomite and sparry calcite cement (Figures 5.36E to 5.37A). The dolomite beds are essentially medium crystalline dolomite replacing the pre-existing calcareous parts (Figure 5.36F).

Interpretation: The presence of calcilutite indicates low energy index of depositional environment. The cross lamination and bioturbations are usually dominant

in the intertidal zone of restricted marine. It is therefore likely that the lithofacies I was deposited in the intertidal zone of restricted marine.

7.1.10 Lithofacies J: Fusulinid and intraclasts bearing calcirudite

Description: The fusulinid and intraclasts bearing calcirudite lithofacies or lithofacies J is characterized by moderately sorted calcarenite to fine calcirudite that are light grey to pinkish grey and medium to dark grey, medium- to thick-bedded of parallel-bedded type (Figures 5.28A and 5.28B). The grain components are fusulinids, crinoidal stems, intraclasts, bryozoans and unidentified skeletal fragments. It is noted that there is reddish brown silty shale thinly-laminated between limestone beds, especially, in the upper part of the lithofacies. The banded argillaceous calcilutite with laminated silty shale has the thickness varying from a few cms to a few ten cms. This lithofacies comprises both grain-supported and matrix-supported calcirudite with some nodular cherts and dolomitic patches (Figure 5.14B). The weathered surface is usually light grey and slightly rough. The chert nodules are usually dark grey and protrude from the surface due to differential weathering. Grains are mainly fusulinid tests of 1 to 10 mms sizes, intraclasts and pellets (Figure 5.14C).

Petrographically, the lithofacies J is fusulinid bearing biosparite, intraclasts biosparite, intrasparite, biopelsparite, packed biomicrite and intrasparudite with some quartz chert and medium crystalline dolomite. Grains are mainly fusulinid tests, diverse micritized grains, some fecal pellets, unidentified shells, coral fragments and algal coated grains. They are completely micritized and the internal pores are occluded by sparry calcite cement (Figure 5.14D). Some grains and pellets show microcrystalline calcite cement near the grain contact. The broken shell shows complete micrite-coating before broken. It is revealed that some fusulinid tests were broken after sediments were indurated. The internal pores of some fusulinid test were

lack of cement before broken then occluded by radiaxial fibrous calcite cement (Figure 5.15A). The nodular chert is mainly microcrystalline quartz with minor chalcedonic quartz and crystalline quartz (Figure 5.15B).

Interpretation: The presence of finely matrix-supported calcirudite indicates low energy index of depositional environment whereas the grain-supported calcarenite to fine calcirudite indicates high energy index of depositional environment. The occurrences of biopelmicrite and packed biomicrite suggest the energy was not too high to winnow all micrite. But the fusulinid biosparite indicates slightly high energy to winnow all micrite. The pellets commonly deposit in the subtidal zone of restricted marine. As such there seems to be some alternating change in condition between low and high energy environments. Therefore, it is likely that the lithofacies J was deposited under the intertidal to subtidal zones of restricted marine or inner shelf behind the barrier bar or shoal.

7.1.11 Lithofacies K: Fenestral and disturbed dolomitic micrite

Description: The fenestral and disturbed dolomitic micrite lithofacies or lithofacies K is calcilutite to calcarenite with coquinite bed, algal coated coquinite and many dolomitic limestone beds (Figures 5.16A and 5.16B). The rocks are medium to dark grey and thin- to thick-bedded. There are some large shell fragments embedded in the calcilutite matrix (Figure 5.16C). Some calcilutite beds were intensely disturbed by burrows (Figure 5.16D). The burrows were generally filled with microcrystalline dolomite.

Petrographically, the lithofacies K consists of packed biomicrite and dismicrite. They contain abundant small shell fragments (a few μms to several hundred μms in size) packed together and embedded in micrite matrix (Figure 5.16F). The dismicrite

or disturbed micrite is characterized by lesser amount of grains in micrite matrix. Also in the micrite matrix there are abundant burrows (Figure 5.17A), bird's eye structure (Figure 5.17B and 5.17C) and fenestral feature (Figure 5.17D) which partially filled by microcrystalline and mesocrystalline dolomite and sparry calcite cement.

Interpretation: The presence of abundant micrite indicates low energy index of the depositional environments. The disturbed micrite by bioturbations such as burrow usually occurs in the intertidal zone. The occurrence of fenestral feature also indicates that the sediments were exposed in the intertidal zone. It is hence likely that the lithofacies K was deposited in the intertidal zone of shallow restricted marine environment.

7.1.12 Lithofacies L: Fusulinid bearing calcarenite

Description: The fusulinid bearing calcarenite lithofacies or lithofacies L is medium grey to brownish grey, thin-bedded calcarenite (Figure 5.18A). The large grains consist exclusively of fusulinid tests ranging in size from 1 to 2 mms (Figure 5.18B). Most of this lithofacies has been weathered into friable siliceous matter.

Petrographically, the lithofacies L consists of packed biomicrite in which the grains are mainly fusulinid tests with minor brachiopod fragments (Figure 5.18C). The micritized shells of fusulinid were transformed into microsparite. As such the internal pores were filled with coarse sparry calcite cement. Some of the packed biomicrite also contain spicules embedded in the micrite matrix (Figure 5.18D). The silicified argillaceous limestone contains abundant chalcedonic spherulite (Figure 5.18E).

Interpretation: The occurrences of abundant micrite indicate a low energy index of depositional environment whereas arenaceous fusulinids are abundant in the

restricted marine. Micrite coating usually occurs in low energy conditions in both basinal and protected shallow marine environments which are more amenable to extensive biogenic activities. The spicules are abundant in the shelf of open marine and also common in restricted marine. It is therefore likely that the lithofacies L was deposited in the subtidal zone of restricted marine.

7.1.13 Lithofacies M: Intraclasts bearing calcarenite

Description: The intraclast bearing calcarenite lithofacies or lithofacies M is an alternating sequence of calcarenite (partly calcilutite) and silty shale. The calcarenite is dark grey and thin- to thick-bedded. The silty shale is thinly-laminated between limestone beds. Some parts of this lithofacies were patchily dolomitized. The elongate nodular cherts of a few cms in size are scattered throughout this lithofacies. In addition, the nodular cherts are also associated with some dolomitic limestone (Figure 5.29B).

Microscopically the lithofacies M consists of packed intramicrite and biomicrite. Grains are fine-grained carbonate intraclasts, minor broken crinoid ossicles and foraminiferal tests with some detrital quartz grains. The detrital quartz grains are 10 to 100 μms in size and probably laid on formerly hardground surface of biomicrite. The dolomite patches comprise abundant small dolomite grains deposited together with calcareous grains. They are packed together and cemented by ferroan sparry calcite (Figure 5.29E). The nodular chert is microcrystalline quartz with abundant calcareous remnants and microcrystalline dolomite. Some parts of nodular chert contain carbonate silts (Figure 5.29F).

Interpretation: The occurrences of detrital quartz, detrital dolomite and intraclasts are preferably restricted to the inner shelf, especially in the intertidal and

subtidal zones near the shoreline. Similarly, the presence of calcarenite is also recognized in the intertidal zone of moderately high energy index of depositional environment. On the contrary, the occurrences of micrite and thinly-laminated silty shale indicate slightly low energy index of depositional environment. The presence of vadose silt indicates that the sediments were exposed and affected by meteoric water. Thus, it is likely that the lithofacies M was deposited in subtidal and intertidal zones near shore.

7.1.14 Lithofacies N: Argillaceous limestone with silty shale

Description: The argillaceous limestone with silty shale lithofacies or lithofacies N is a sequence of grey to dark grey, thin-bedded calcilutite and calcarenite in the lower part, gradually passing upward into clastic associations of thin-bedded silty shale, silty sandstone and porcelanite with very thick-bedded calcirudite in the uppermost part (Figures 5.30A). The silicified calcilutite usually appears as dark grey to black on fresh surface or as yellowish brown on the weathered surface (Figure 5.19B). The cumulative thickness ratio of carbonates/clastics of this lithofacies is approximately 4:1. The uppermost calcirudite beds are 1 to 2 meters thick and comprise essentially compacted intraclasts having the size from 1 to 10 cms are significant features of the limeclast conglomerate (Figure 5.30B).

Petrographically the lithofacies N consists of poorly-washed biosparite, intramicrudite, intramicrite, packed biomicrite and micrite. Grains are abundant skeletal fragments of crinoid, foraminifera, coral, algae and unidentified fragments with some intraclasts and detrital quartz. Some grains are rounded to sub-rounded and appear as micrite-coated or completely micritized grains (hence unable to identify) (Figure 5.19C). The elongate grains are usually oriented subparallel to the bedding plane. In part, the carbonate has been silicified which appears as microcrystalline

quartz, as well as minor chalcedonic quartz and crystalline quartz. Also in the fine-grained chert matrix there are some of both non-ferroan calcite remnants (red-stained in Figure 5.19E) and ferroan calcite remnants (purple-stained in Figure 5.19F). There are also some ferroan microcrystalline dolomites disseminated in the fine-grained chert matrix. The porcelanite contains abundant sponge spicules of 10 to 100 μms in size mixed with silicified argillaceous matter (Figure 5.30F).

Interpretation: There seems to be a certain degree of gradually passing upward sequence from lithofacies M to lithofacies N because of the increasing of the proportion of intraclasts and clastic sediments in the sequence. The sequence of thinly-bedded limestone, dolomitic limestone, argillaceous limestone and shale were found to deposit in shallow to deep ramp in the Dumugol Formation (Lee and Kim, 1992; and Kim and Lee, 1998, 2003). The packed intraclastic calcirudites were found in the Chanda Limestone, Penganda Group, of India (Bose and Sarkar, 1991; Bandopadhyay, 1996; and Mukhopadhyay, 1999) and the Kelley-Snyder Field in West Texas (Schatzinger, 1983). These sediments have been interpreted as debris-flows representing a redeposition of semi-consolidated sediments (Mullins and Cook, 1986). Therefore, the depositional environment of this lithofacies should be high energy intertidal and subtidal zones. Because of the gradual increasing of clastic sediments, detrital quartz, intraclasts and micrite in the upper part of the sequence; it is therefore likely that the depth of the depositional basin was decreasing. This might be due to either the marine regression or the rate of deposition was greater than the rate of subsidence. The presence of remarkable intramicrudite in the upper part of this lithofacies indicates that energy condition in the intertidal and subtidal zones might have been very high. As such it could rework the semi-consolidated sediments and formed the intraclasts to be deposited in sub-wave bed zone.

7.1.15 Lithofacies O: Cross-laminated calcarenite

Description: This cross-laminated calcarenite lithofacies or lithofacies O is medium grey to dark grey, thin- to thick-bedded calcarenite rarely with small chert nodules. Cross-lamination can be recognized in the lower part of the sequence.

Petrographically, the lithofacies O consists of poorly-washed biosparite, packed biomicrite and sparse biomicrite with some microcrystalline quartz chert. The grains are bioclasts of foraminiferal tests, crinoids, unidentified skeletal fragments and bryozoa together with intraclasts and detrital quartz. The small chert nodule is made up essentially of microcrystalline quartz with some calcareous patches (Figure 5.31D).

Interpretation: The presence of calcarenite indicates slightly high energy index of depositional environment. But the occurrence of micrite in poorly-washed biosparite and packed biomicrite indicates that the energy index might not be high enough to remove the entire carbonate mud matrix. In addition, the cross-lamination usually formed in the intertidal zone of restricted inner shelf. Therefore, it is likely that this lithofacies was deposited in the intertidal and subtidal zones of inner shelf.

7.2 Reconstruction of Depositional Environment

Based on the analysis of those 15 lithofacies it can generally be summarized that the carbonate/clastic sequences of the Khao Khad Formation were deposited in the shelf marine condition under sub-environments of intertidal to subtidal zones near shore, subtidal zone of shallow restricted marine, shallow platform, barrier bar or shoal and foreslope of outer shelf (Table 7.1, Figure 7.4). By careful examination of the vertical succession of lithofacies and associated environments in the measured

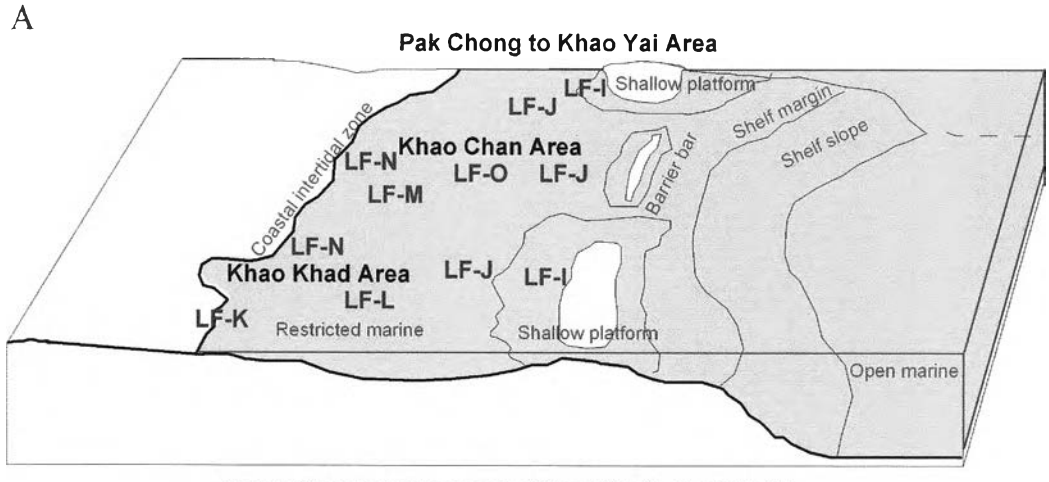
Table 7.1 The lithologic descriptions and depositional environments of lithofacies of the Khao Khad Formation.

Litholfacies	Thickness (meters)	Lithological Characteristics	Depositional environment
Litholfacies G	184	Medium grey to dark grey, medium- to very thick-bedded calcarenite to fine calcirudite with black nodular cherts and dolomite patches. Petrographically, it consists of packed biopelmicrite, poorly washed biosparite, unsorted biopelsparite, biosparite and biosparudite which were silicified and dolomitized in certain areas. Grains are mainly large fusulinid tests, pellets and small shell fragments.	Intertidal to subtidal zone of restricted marine.
Litholfacies F	20-181	Grey to dark grey, thin- to medium-bedded graded calcarenite to calcilutite with dark grey chert bands and thinly-laminated to thinly-bedded, reddish brown, fissile silty shale between limestone beds. Petrographically, it consists of poorly-washed intrasparudite and a series of thinly-laminated and graded-bedding sequences of poorly-washed intrasparite, packed biomicrite and fossiliferous micrite, with microcrystalline banded cherts and microcrystalline dolomite. Grains consists of angular boulders, cobbles, pebbles and sands of intraclasts with subordinate calcareous skeletons of crinoid fragments and fusulinid tests.	Foreslope of barrier bar of the open marine.
Litholfacies E	92-213	Light grey, medium-to thick-bedded coarse calcarenite to fine calcirudite with dolomitic limestone alternating with thin bedded dolomite. Petrographically, it consists of sorted biosparite, biosparudite, poorly-washed biosparite with fine to coarse crystalline dolomite. Grains are essentially crinoidal fragments, fusulinid tests and intraclasts.	Intertidal zone of barrier bar.
Litholfacies D	57-117	Grey to dark grey, medium- to thick-bedded coarse calcarenite and fine calcirudite with scattered dark grey chert nodules. Petrographically, it consists of sorted biosparite and biosparudite with some microcrystalline chert. Grains are broken fragments of crinoids, intraclasts, fusulinid tests, bryozoans and unidentified calcareous skeletons.	Back barrier bar.
Litholfacies C	32-116	Light grey to medium grey, medium- to thick-bedded, crinoidal calcarenite to fine calcirudite. Petrographically, it consists of unsorted crinoidal biosparudite and crinoidal biosparite. Grains are mainly crinoidal fragments and common bryozoan fragments.	Barrier bar or shoal.
Litholfacies B	100	Light to medium grey, medium-bedded calcarenite, calcirudite and biolithite. Petrographically, it consists of pelsparite, biopelsparite, biosparudite and algal boundstone. Grains are pellets, small micritized bioclasts, crinoid fragments, algal fragments, fusulinid tests, and shells of brachiopods, gastropods and cephalopods.	Intertidal zone of shallow marine.
Litholfacies A	251-294	Medium light grey to dark grey, thin- to medium-bedded calcilutite to fine calcirudite, with dark grey banded and nodular cherts. Petrographically, it consists of finely laminated fossiliferous micrite, algal biomicrite, packed biomicrite, packed biomicrudite, and poorly washed biosparite, biopelsparite, biosparudite and biopelsparudite with some microcrystalline chert bands and nodules. Grains are mainly fusulinid tests, pellets, brachiopod and gastropod shells and algal fragments.	Subtidal zones of shallow restricted marine.

Table 7.1 The lithologic descriptions and depositional environments of lithofacies of the Khao Khad Formation (continue).

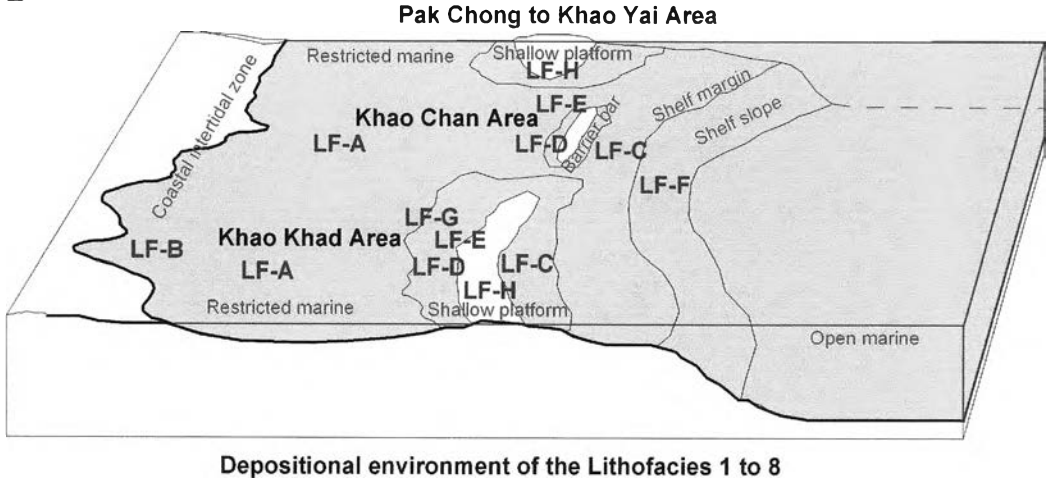
Litholfacies	Thickness (meters)	Lithological Characteristics	Depositional environment
Litholfacies O	300-365	Medium grey to dark grey, thin- to thick-bedded, cross-lamination calcarenite with rare small chert nodules. Petrographically, it consists of poorly-washed biosparite, packed biomicrite, and sparse biomicrite with some microcrystalline quartz chert. Grains are bioclasts of fusulinid tests, crinoids, unidentified skeletal fragments and bryozoa, together with intraclasts, detrital quartz.	Intertidal and subtidal zone of inner shelf
Litholfacies N	300-448	Sequence of grey to dark grey, thin-bedded calcilutite, calcarenite in the lower part and gradually passing upward into clastic associations of thin-bedded silty shale, silty sand and porcelanite with very thick-bedded calcirudite in the uppermost part. Petrographically, it consists of poorly-washed biosparite, intramicrudite, intramicrite, packed biomicrite and micrite. Grains are abundant skeletal fragments of crinoid, fusulinid tests, coral, algae and unidentified fragments with some intraclasts, detrital quartz.	High energy intertidal and subtidal zones.
Litholfacies M	267-273	Alternating sequences of dark grey, thin- to thick-bedded calcarenite, partly calcilutite with dark grey chert nodules and silt-shale thinly-laminated between limestone beds. Petrographically, it consists of packed intramicrite and biomicrite. Grains are fine-grained carbonate intraclasts and minor skeletal fragments of broken crinoid ossicles and fusulinid tests, with some detrital quartz.	Subtidal and intertidal zones near shore.
Litholfacies L	150	Medium grey to brownish grey, thin-bedded calcarenite. Petrographically, it consists of packed biomicrite with grains of fusulinid tests, brachiopod fragments and some spicules. The silicified argillaceous limestone contains abundant chalcedonic spherulite.	Subtidal zone of restricted marine.
Litholfacies K	120	Medium to dark grey, thin- to thick-bedded calcilutite to calcarenite with coquinite bed, algal coated coquinite and dolomitic limestone bed. Petrographically, it consists of packed biomicrite and dismicrite with abundant burrow, fenestral features filled microcrystalline dolomite. Grains are shell fragments.	Intertidal zone of shallow restricted marine.
Litholfacies J	326	Light grey to pinkish grey and medium to dark grey, medium- to thick-bedded of parallel-bedded type, moderately sorted calcarenite to fine calcirudite. Petrographically, it consists of fusulinid bearing biosparite, intraclasts biosparite, intrasparite, biopelsparite and packed biomicrite and intrasparudite with some quartz chert and medium crystalline dolomite. Grains are mainly fusulinid tests, diverse micritized grains and some fecal pellets, unidentified shells, coral fragments and algal coated grains.	Intertidal to subtidal zone of restricted marine.
Litholfacies I	86-180	Medium grey to dark grey, thin- to medium-bedded coarse calcilutite interbedded with thin-bedded dolomitic limestone and thinly-laminated dolomite. Petrographically, it consists of packed biomicrite, disturbed micrite with microcrystallme dolomite and macrocrystalline dolomite. Grain is rare.	Intertidal zone of restricted marine.
Litholfacies H	100	Medium grey to dark grey, thin- to very thick-bedded calcilutite to calcirudite and biolithite with common chert nodules. Petrographically, it consists of packed biomicrite, packed biomicrudite, packed intramicrite, biopelsparite and intraclasts-bearing biosparudite. Grains are large shell fragments are mainly brachiopods and gastropods, large fusulinid tests, fecal pellets, abundant small intraclasts of micrite and coral fragments packed with small unidentified fragments.	Shallow platform buildup.

A



Depositional environment of the Lithofacies 9 to 15

B



Depositional environment of the Lithofacies 1 to 8

Figure 7.4 The schematic block diagram representing the depositional model of the Khad Formation. A: During regression period. B: During transgression period.

sections, there appears to be a major transgressive and regressive cycle of seawater during the Lower Middle Permian time.

7.2.1 The Transgressive Sequences

The transgressive sequences probably occurred during the deposition of lithofacies A to H in which the sub-environments might have varied from subtidal and intertidal zones of restricted marine to barrier bars (Figure 7.4B).

The sequence started with the lithofacies A which was deposited in the subtidal zone of restricted marine at both Khao Khad and Khao Chan areas (might be absent or not exposed in the Pak Chong to Khao Yai area). The grain components deposited in this zone were fusulinid tests (of mainly *Robustoschwagerina* sp.), pellets, brachiopod and gastropod shell fragments, algal fragments and unidentified small micritized grains. The Khao Chan area seemed to have higher amount of micrite deposition than that at the Khao Khad area.

The lithofacies B is locally present in the Khao Khad area and was probably deposited in the intertidal zone of restricted marine. The grain components deposited in this zone were algal stromatolites, fusulinid tests, crinoid fragments, pellets and shells of brachiopods, gastropods and cephalopods. It probably represents a minor regression or the decreasing of basin depth by the accumulation of sediments in the stable shelf.

The lithofacies C was deposited in the barrier bar or shoal at the Khao Khad and Khao Chan areas but absent at the Pak Chong to Khao Yai area. The grain components deposited in this zone were abundant crinoid fragments and some bryozoa fragments.

The lithofacies D was deposited in the back barrier at the Khao Khad and Khao Chan areas but absent at the Pak Chong to Khao Yai areas. The grain components deposited in this zone were abundant crinoid fragments, intraclasts, some fusulinid tests, bryozoa and shell fragments.

The lithofacies E was deposited in the intertidal zone of barrier bar at the Khao Khad and Khao Chan areas but absent at the Pak Chong to Khao Yai areas. The grain components deposited in this zone were crinoid fragments, fusulinid tests and intraclasts.

The lithofacies F was probably deposited in the foreslope of barrier bar as indicated by the repetitive sequence of graded calcarenite to calcilutite with abundant intraclasts. This lithofacies was only deposited at the Khao Chan area but absent at the Khao Khad and Pak Chong to Khao Yai areas.

The lithofacies G was probably deposited in intertidal to subtidal zones of restricted marine at the Khao Khad area but absent in the Khao Chan and Pak Chong to Khao Yai area. In these zones there was abundant deposition of fusulinid tests.

The lithofacies H was deposited in the shallow platform or bioconstructed buildup zone at the Khao Khad and Pak Chong to Khao Yai areas but absent in the Khao Chan area. This environment might be initiated during low stand of shallow outer shelf which was quite different from crinoidal barrier bar of the lithofacies C. In this shallow platform area there were abundant buildup of corals or patch reef, large brachiopods and gastropods without crinoids. The buildup was probably acting as barrier separated the restricted marine from open marine.

7.2.2 The Regressive Sequence

The regressive sequences probably occurred during the deposition of the lithofacies I to O. The depositional environments change from intertidal to subtidal zones of back barrier bar to intertidal zone of near shore (Figure 7.4A).

The lithofacies I was deposited in the intertidal zone of restricted marine, (probably related to subsequent exposure of shallow platform buildup) at both the Khao Khad and Pak Chong to Khao Yai area. Grains deposited in this zone were minor amount of small shell fragments.

The lithofacies J of quite similar lithology was deposited in the intertidal to subtidal zones of restricted marine at all three areas. Most of the grain components deposited in these zones was fusulinid tests, diverse micritized grains, some fecal pellets, unidentified shells, coral fragments, algal coated grains and intraclasts with some micrite.

The lithofacies K was deposited in the intertidal zone of restricted marine at the Khao Khad area but absent in the Khao Chan and Pak Chong to Khao Yai areas. In this environment there were probably abundant bioturbation and fenestral activities.

The lithofacies L was deposited in the subtidal zone of restricted marine with low energy of depositional environment at Khao Khad area but absent at the Khao Chan and Pak Chong to Khao Yai areas. The large grain components deposited in this zone were exclusively fusulinid tests.

The lithofacies M was deposited in subtidal and intertidal zones of near shore at the Khao Chan area. The grain components are mainly fine-grained intraclasts and minor skeleton fragments of crinoids and fusulinids with some detrital quartz.

The lithofacies N was deposited in the high energy intertidal and subtidal zones of near shore at the Khao Khad and Khao Chan areas. The major grain components deposited in this zone were skeleton fragments of crinoids, fusulinids, corals, algae and intraclasts with some detrital quartz.

The lithofacies O was deposited in the intertidal to subtidal zones of inner shelf with slightly high energy of depositional environment only at the Khao Chan area. The grain components deposited in these zones were foraminiferal tests, crinoids, unidentified skeletal fragments and bryozoa, intraclasts and detrital quartz.

7.2.3 Conclusion

The depositional model of the Khao Khad Formation is represented by the shallow restricted marine of inner shelf with barrier bar or shallow platform in the open shelf. The situation may vary from low energy to slightly high energy conditions. The low energy condition was dominated by the deposition of micrite and large fusulinid tests. The high energy condition was dominated by the deposition of crinoid fragments and intraclasts. The barrier bar in the outer shelf was changed from shallow bioaccumulated platform at the Khao Khad and Pak Chong to Khao Yai areas into crinoidal barrier bar at the Khao Khad area.