

# Depositional Environments of Permian Rocks of the Khao Khad Formation in Central Thailand

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**ABSTRACT:** The Khao Khad Formation of Saraburi Group in the central part of Thailand is the sequences of limestone, dolomitic limestone and silty shale with nodular and banded cherts. The investigation of the sedimentary sequences has been undertaken on the basis of lithological characteristics and sedimentary structures. Twenty nine measured sections were conducted in three study areas in the vicinity of Khao Khad, Khao Chan and areas along Pak Chong – Khao Yai route. Altogether 312 sampling locations and 539 rock specimens were examined in this study. Fifteen rock units can be distinguished from the sedimentary sequence including: a) calcilitite with nodular chert, b) algal biolithite, c) crinoidal calcirudite, d) crinoidal calcirudite with nodular chert, e) crinoidal calcirudite with banded dolomite, f) grade-bedded calcarenite with banded chert, g) fusulinid-bearing fine calcirudite, h) coral biolithite, i) laminated dolomitic calcarenite, j) fusulinid and intraclasts-bearing calcirudite, k) fenestral and disturbed dolomitic calcilitite, l) fusulinid bearing calcarenite, m) intraclasts-bearing calcarenite, n) argillaceous limestone with silty shale, and o) cross-laminated calcarenite. The Khao Khad Formation was most likely deposited during a major transgressive and regressive cycle of seawater during the Lower to Middle Permian time in the marine shelf condition under sub-environments of intertidal to subtidal zones near shore, subtidal zone of lagoon, shallow platform, barrier bar or shoal and foreslope of barrier bar.

**KEYWORDS:** sedimentology, lithostratigraphy, Permian, carbonate rocks, Khao Khad Formation.

## INTRODUCTION

The Permian carbonate rocks in central Thailand are an economically important source of industrial rocks and minerals. They are the major raw materials currently being used for Portland cement and stone industries of the country. Besides, they were anticipated and have been proved as a potential oil and gas reservoir<sup>1-2</sup>. A number of studies have addressed on the regional geology, structural geology, palaeontology, biostratigraphy and sedimentology of local areas<sup>3-11</sup>. However, there is still no comprehensive regional work done on detailed lithology, depositional environments and diagenetic history. Hence, the aim of this study is to focus on a detailed investigation on primary sedimentary features of Permian carbonate sequences near the Saraburi town and on the western part of Nakhon Ratchasima in central Thailand in order to decipher the depositional environment (Fig. 1). These localities were selected because they represent the well exposed Permian carbonate rocks mapped as the Khao Khad Formation in these areas.

## Geological Setting

The Permian carbonate rocks are widespread in Thailand. They are exposed as mountains with karstic topography in the northern and southern parts of the country including western part of the Khorat plateau. In central Thailand, the Permian carbonate rocks were named the 'Saraburi Group' by Bunopas<sup>12</sup>. Hinthong et al.<sup>4</sup> later divided it into six formal formations, namely, Phu Phe Formation, Khao Khwang Formation, Nong Pong Formation, Pang Asok Formation, Khao Khad Formation and Sab Bon Formation, in ascending order (Fig. 1). The carbonate rock of the Saraburi Group in this area is mainly the Khao Khad Formation, which is the main target of this study. It is underlain by shale and slaty shale of the Pang Asok Formation and overlain by gray to brown tuffaceous sandstone and shale of the Sab Bon Formation.

The area has undergone a complex geological history as a part of the western old Indochina land mass, which submerged as a shelf sea since Middle Carboniferous period<sup>13</sup>. The thick sequences of mixed carbonate-clastic sediments of the Saraburi Group were deposited in a marine shelf environment under tropical

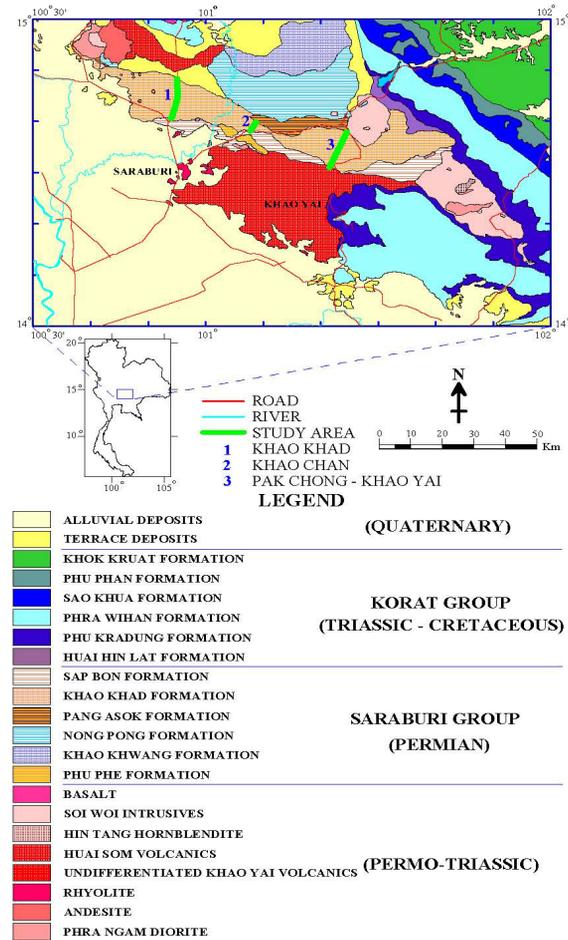


Fig 1. Geologic map of central Thailand showing location of study area (modified after Hinthong et al.<sup>4</sup>).

zone of the southern hemisphere. The paleolatitude depositional environment during the Permian period is nearly 10° south of the paleoequator<sup>11</sup>. Indosinian orogeny probably started since Late Permian where the convergence of the Shan-Thai and Indochina were eventually collided in Late Triassic<sup>13</sup>. This caused the emergence of the shelf followed by strong folding in the area, the Phetchabun Fold Belts. The post-collision igneous activities took place mostly during Late Triassic to Early Jurassic<sup>4</sup>.

**MATERIALS AND METHODS**

Field work was carried out on three localities in the vicinity of Khao Khad, Khao Chan and areas along Pak Chong–Khao Yai route (Fig. 1). Twenty nine measured sections were conducted to determine the lithological characteristics of sedimentary sequences. Rock sampling has been conducted from the sections for the detailed petrographic study. Altogether there are 312 sampling locations and 539 rock specimens.

All rock specimens were slab-cut, polished and subjected to various detailed macroscopic and microscopic examinations. Standard microscopy was carried out on 315 thin sections. The thin sections were stained with potassium ferricyanide and Alizarin Red S solutions to assist carbonate mineral identification as well as to detect their texture and composition<sup>14</sup>. The rock classification and nomenclature of Grabau<sup>15</sup> and Folk<sup>16</sup> were selected for this study as field name and petrographic name, respectively. The depositional textures of rocks in the study area are often obscured by complex diagenetic history.

**Lithostratigraphic sequence and depositional environment**

The sedimentary sequence of the Khao Khad Formation in the study area is composed of limestone, dolomitic limestone, argillaceous limestone and silty shale with nodular and banded cherts. The detailed lithostratigraphic correlation among the three measured sections of the Khao Khad Formation gives fifteen different rock units (Fig. 2), namely from Units A to O consecutively in ascending order, and are described as follows:

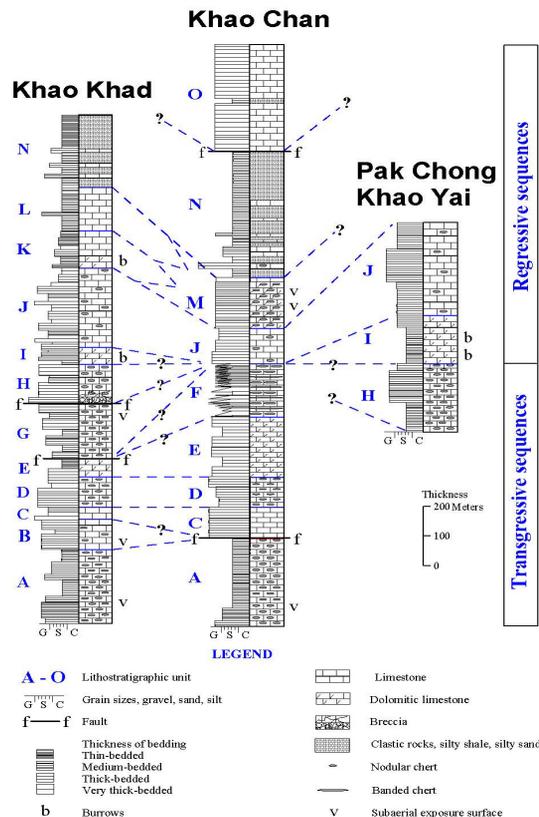
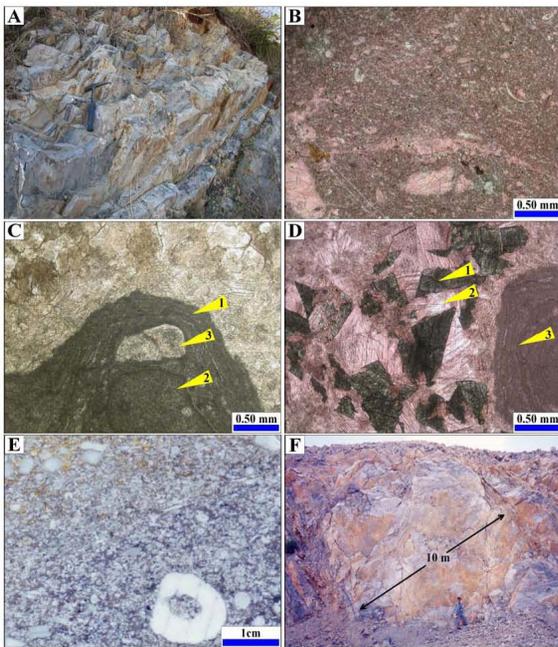


Fig 2. The lithostratigraphic correlation of the Khao Khad Formation from three measured sections, Khao Khad, Khao Chan and Pak Chong to Khao Yai areas.

### Unit A: Calcilutite with nodular chert

The lower most rock unit of the Khao Khad Formation is the calcilutite with nodular chert. It is exposed at both the Khao Khad and Khao Chan sections with the thickness of 251 to 294 m. This unit is characterized by medium light grey, thin- to medium-bedded calcilutite with dark grey chert nodules (Fig. 3A). Generally, bioturbation features are poor. However, three subunits can be distinguished on the basis of the type of bed and relative abundance of grain contents. The lower part of the unit is a parallel-bedded calcilutite rarely with skeleton grains. This is in contrast to the middle part which is dominated by wavy- and non-parallel-bedded calcilutite containing abundant algal mats, brachiopod shell fragments and fusulinid tests of mainly *Robustoschwagerina* sp. The upper part of the



**Fig 3.** **A:** An outcrop of the Unit A showing thin- to medium-bedded, parallel-bedded type, medium to dark grey calcilutite interbedded with dark grey nodular cherts. (UTM 706100E, 1634850N) **B:** Photomicrograph of packed biomicrite of the Unit A. (Stained, PPL, Sample no. L3/22) **C:** Photomicrograph of laminated algal stromatolite (1) accretion from the unidentified micritized grain (2) and dissolved grain (3) of the Unit B. (PPL, Sample no. 233/1) **D:** Photomicrograph depicting the macrocrystalline dolomite (1) associated with sparry calcite cement (2) in the central area of intergranular pore spaces of the algal stromatolite (3) buildup of the Unit B. (Stained, PPL, Sample no. 233/1) **E:** A rock slab of the Unit C showing poorly sorted crinoidal fragments. (Sample no. L17/7) **F:** An exposure of very-thick-bedded calcirudite, 10 m thick between a series of thin- to medium-bedded calcarenite to calcilutite, in the middle part of the Unit F (UTM 731000E, 1621200N).

unit is similar to the lower part and is a parallel-bedded calcilutite with relatively rare shell fragments and sparse fusulinid tests. The rocks are classified as finely laminated fossiliferous micrite, algal biomicrite, packed biomicrite and packed biomicrudite based on Folk<sup>16</sup> (Fig. 3B). Allochems are fusulinid tests, pellets, brachiopod and gastropod shell fragments, algal fragments and unidentified small micritized grains. Most of shells were completely micritized and some fusulinid tests and brachiopod shells are coated with micrite. The microcrystalline calcite cement can be recognized around pellets and around contact point area of allochems. The chert nodules vary in size from 5 to 10 cm and are composed mainly of microcrystalline quartz with some calcareous patches.

The micrite is commonly present in a low-energy depositional environment<sup>17</sup> whereas the fecal pellets are usually deposited in moderate- to low-energy conditions in a basinal or lagoon environment<sup>18</sup>. Micritized and micrite-coated grains are commonly found in the bio-active zone on the sea floor both in the intertidal and subtidal environments<sup>19</sup>. However, the formation of microcrystalline calcite cement indicates that the sediments might have occasionally been exposed to marine vadose zone and frequently flushed by seawater or brine<sup>18</sup>. As such, the Unit A was most likely deposited in the subtidal zones of lagoon.

### Unit B: Algal biolithite

The algal biolithite of Unit B overlies conformably on the Unit A and is found only at the Khao Khad section with thickness of about 100 m. This unit is represented by light to medium grey, medium-bedded calcarenite to calcirudite associated with algal biolithite. The rocks show a grain-supported fabric of differing types and sizes of grain components. Allochems are algal encrustations, fusulinid tests, crinoid fragments, pellets, and shells of brachiopods, gastropods and cephalopods. The shell fragments are usually orientated parallel or sub-parallel to bedding plane. The rocks are classified as pelsparite, biopelsparite and biosparudite. All bioclasts were completely micritized and initially cemented by microcrystalline calcite. The detailed petrographic studies of algal stromatolite revealed that the pre-existing grains of pelsparite, biopelsparite and oncolite were encrusted with many algae (Fig. 3C). There was some braking period of algal encrustation which was separated by radial fibrous calcite cement. Many layers of the fibrous calcite cement are separated by microcrystalline dolomite layers. Some macrocrystalline dolomite rhombs occur in association with sparry calcite cement in the central area of intergranular pores (Fig. 3D).

Even though the micritized grains and pellets could occur in the intertidal or subtidal zone of a shallow

marine environment<sup>18, 19</sup>, the presence of algal stromatolite encrustation on those micritized grains and pelsparite grains suggested that the sediments of Unit B were rather deposited in low-energy intertidal environment (as seen in the modern analog at the Persian Gulf<sup>20</sup>). Furthermore, the occurrence of microcrystalline calcite cement on fecal pellets and bioclasts indicates that the sediments had been exposed to the marine vadose zone whereas the formation of microcrystalline dolomite interlayer further reinforced the deposition in upper intertidal environment<sup>21, 22, 23</sup>. It is therefore likely that the unit B was deposited in the intertidal.

#### **Unit C: Crinoidal calcirudite**

Overlying conformably on the Unit B is the crinoidal calcirudite of Unit C. This unit is well exposed at both the Khao Khad and Khao Chan sections with thickness of 32 to 116 m. This unit is light to medium grey, medium- to thick-bedded crinoidal calcirudite. The rocks contain more than 50 % of large (0.5 mm to 2 cm) crinoid stems (Fig. 3E). The beds are of parallel-bedded type with very thin bands of grayish black to reddish silty shale between each crinoidal bed. The rocks are classified as unsorted crinoidal biosparite and biosparudite. Allochems are mainly crinoidal and bryozoan fragments. They are cemented together by coarse sparry calcite. The fine-grained matrix is rarely recognized as micrite and pseudosparite with sparse dolomite rhombs in some parts. Most crinoidal fragments were overgrown by syntaxial calcite cement.

The Unit C was probably deposited in current- or wave-agitated shallow subtidal environment of barrier bar or shoal. This assumption is inferred by the abundant occurrence of cleanly-washed and large-sized crinoid fragments analogous to those found in the Betic Mountains, southern Spain<sup>24</sup>. The rather thick crinoidal calcirudite unit certainly requires the deposition under subsiding condition. The presence of thin bands of silty shale between crinoidal limestone beds however suggests a brief interrupt of the carbonate deposition by the influx of fine-grained siliciclastic sediments.

#### **Unit D: Crinoidal calcirudite with nodular chert**

The crinoidal calcirudite with nodular chert of Unit D overlies conformably on the Unit C at both the Khao Khad and Khao Chan sections with thickness of 57 to 117 m. This unit is characterized by grey to dark grey, medium- to thick-bedded crinoidal calcirudite with scattered dark grey elongated chert nodules. The beds are of parallel-bedded type and slightly dolomitic in the upper part of the unit. Allochems are crinoid stems, foraminifera, intraclasts and bryozoans, respectively in decreasing order of abundance. It is noted that the relicts of crinoid and foraminifera are also observed in

chert nodules. The rocks are classified as sorted biosparite and biosparudite. However, microcrystalline dolomite is locally present along the boundaries of carbonate grains as dark brown rhombs. The crinoid fragments show syntaxial overgrowth cement. The chert nodules vary in size from 5 to 30 cm and are mainly composed of microcrystalline quartz locally disseminated with calcite rhombs.

There seems to be a certain degree of similarity in lithology between the Unit C and the Unit D, except that the Unit D contains chert nodules and some foraminifera and intraclasts. Intraclasts are the former semi-consolidated sediments being ripped off in the high-energy intertidal zone near shore or barrier bar or shoal. They commonly re-accumulated in subtidal zone or on the back side of the bar together with other grain components as have been found in the Bahama Bank<sup>25</sup>. As such the depositional environment of the Unit D was probably a slowly subsiding back barrier.

#### **Unit E: Crinoidal calcirudite with banded dolomite**

The crinoidal calcirudite with banded dolomite of Unit E overlies conformably on the Unit D at both Khao Khad and Khao Chan sections with the thickness of 92 to 213 m. This unit is represented by light grey, medium- to thick-bedded, coarse calcarenite to fine calcirudite. The beds are of parallel-bedded type with thin bedded dolomite alternating with dolomitic limestone beds. Allochems of this unit are similar to those of the underlying Unit D. The rocks are quite similar to those of the Unit D but suffer higher degree of dolomitization. The Unit E comprises sorted biosparite, biosparudite, poorly-washed biosparite and finely to coarsely crystalline dolomite. Within the dolomitic limestone, dolomite rhombs are sparsely embedded in the blocky calcite cement, while in the dolomite bed the rock exclusively consists of finely to coarsely crystalline dolomite replacing both allochems and cements.

Resemble to the Unit D, the Unit E was probably deposited in a high-energy zone of back barrier bar in which the dolomitization could have been more favorable<sup>26</sup>.

#### **Unit F: Grade-bedded calcarenite with banded chert**

The grade-bedded calcarenite with banded chert of Unit F is only exposed at the Khao Chan section. It overlies conformably on the Unit E with the thickness of 181 m. This unit is a medium to dark grey, thin- to very-thick-bedded, calcilitite to calcarenite. The beds are of parallel-bedded type and show graded bedding with dark grey chert bands. The reddish brown fissile silty shale is often thinly-laminated to thinly-bedded between each limestone bed. In the middle part of the unit, there are four distinct calcirudite beds of 9-13 m thick (Fig. 3F). These four beds contain remarkably

large grain components (1 to 50 cm) of angular boulders, cobbles, pebbles and sands of intraclasts with subordinate calcareous skeletons, mostly crinoid ossicles, foraminiferal tests and other skeletons fragments. The rocks are classified as poorly-washed intrasparudite, poorly-washed intrasparite, packed intramicrite and fossiliferous micrite. The banded cherts (occasionally associated with packed intramicrite and fossiliferous micrite) consist mainly of microcrystalline quartz, subordinate chalcedonic and megacrystalline quartz, and sparse remnants of both calcareous and dolomite patches.

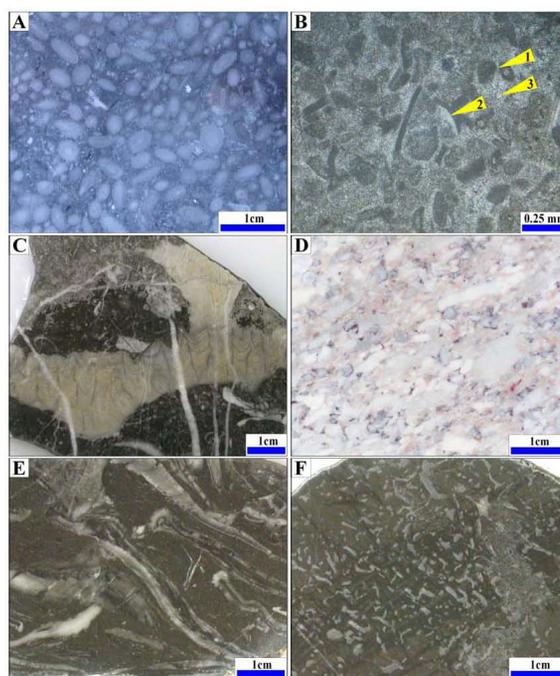
A sequence of thin and grade-bedded calcarenite to calcilutite is favor in the distal part of turbidity grain flows occurring in the foreslope of barrier bar<sup>27</sup>. As described in the final stage of evolution of the Niagaran buildup of Indiana<sup>23</sup>, the association of current swept platform 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 occurrences of the four thick calcirudite beds in this unit therefore suggest that the deposition could have taken place under exceptionally strong energy condition of presumably turbidite channel in the fore-slope of the barrier bar.

#### Unit G: Fusulinid-bearing fine calcirudite

The fusulinid-bearing fine calcirudite of Unit G is only exposed at the Khao Khad section with the thickness of 184 m. It overlies on the Unit E with fault contact. This unit is characterized by medium to dark grey, medium- to very-thick-bedded, grain-supported calcarenite to fine calcirudite. The beds are of parallel-bedded type. The chert nodules and dolomite patches (10 to 30 cm in size) are found scattering throughout the unit. Allochems are mainly fusulinid tests (1 to 5 mm in size) and the matrix is a mixture of pellets and small shell fragments (Fig. 4A). The rocks are poorly washed biosparite, unsorted biopelsparite and biosparudite. These rocks have been silicified and dolomitized in certain areas. Some pellets and contact point of grains were earlier cemented by thin-layer coating of light-colored microcrystalline calcite (Fig. 4B). The remaining intergranular and intragranular pore spaces were filled by 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. The nodular chert is mainly microcrystalline quartz with some scattered dolomite rhombs (10–300 µm in size) and calcareous patches (60–100 µm in size). Some parts of biosparite also contain scattered dolomite rhombs.

The Unit G contains various rock types indicating

both high and low-energy depositional environments. The grain-supported calcarenite to fine calcirudite were rather deposited in high-energy environment of intertidal zone. The packed biopelmicrite and poorly washed biosparite were probably formed in somewhat lower-energy condition in which micrite component has not been completely removed whereas the unsorted biopelsparite, biosparite and biosparudite indicate slightly higher energy to winnow all of the micrite. It is therefore likely that the Unit G was deposited in an intertidal to subtidal zone of lagoon similar to those found in the Middle Cambrian Daegi Formation<sup>28</sup>.



**Fig 4.** **A:** A fine calcirudite slab of the Unit G showing grain-supported fabrics of mainly fusulinid tests. (Sample no. 89/1) **B:** Photomicrograph of unsorted biopelsparite of the Unit G showing grain-supported fabrics. Grains were initially cemented by microcrystalline calcite (1), then by isopachous fibrous (2) and finally by sparry calcite (3). (PPL, Sample no. 87/3) **C:** A coral biolithite slab of the Unit H showing small coral colony in growth position (light grey) on hard ground calcilutite. (Sample no. 225/1) **D:** A rock slab of pinkish grey, moderately sorted, fusulinid and intraclast-bearing fine calcirudite of the Unit J. (Sample no. L1/1) **E:** A coquinite slab of the Unit K showing flattened broken shell fragments (white) embedded in the dark grey calcilutite matrix. (Sample no. 203/1) **F:** A medium grey calcilutite slab of the Unit K showing abundant burrows of *Chondrites* ichnosp. (white steaks) filled with microcrystalline dolomite. (Sample no. 210/1).

### Unit H: Coral biolithite

The coral biolithite of Unit H overlies on Unit G with fault contact and is exposed at both the Khao Khad and Pak Chong to Khao Yai sections with thickness of 123 to 211 m. This unit is characterized by medium to dark grey, thin- to very-thick-bedded calcilutite to calcirudite associated with coral biolithite. In hand-specimen, the rock contains many small elongate fusulinid tests (0.5 to 1.5 mm in size) embedded in fine-grained micrite matrix. The coral biolithite is the colonies of coral in growth positions (10 to 50 cm in size) and usually associated with poorly sorted rocks with diverse bioclasts (Fig. 4C). The dark grey calcilutite usually associates with coralline colonies by filling in their intergranular pores. Chert nodules are also common in this unit and mostly form elongate shape (10 to 20 cm long). The rocks are classified as biopelmicrite, packed biomicrite, packed biomicrudite, packed intramicrite and intraclast-bearing biomicrudite. Allochems 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. The packed intramicrite also contains many dolomite rhombs having micro-stylolitic grain contact. The nodular chert is essentially microcrystalline quartz.

The presence of the coral colonies in growth positions together with diverse bioclasts and intraclasts, as mentioned above, shows that the Unit H was a carbonate buildup, caused by active growth of colonial sedentary organisms. The accumulation of carbonate probably occurred in the intertidal to subtidal zone of shallow platform, analogous to those found in the Duranguesado carbonate platform in the northern Spain<sup>29</sup>.

### Unit I: Laminated dolomitic calcarenite

The laminated dolomitic calcarenite of Unit I overlies conformably on the Unit H and is exposed at both the Khao Khad and Pak Chong to Khao Yai sections with thickness of 86 to 180 m. This unit is represented by medium to dark grey, thin- to medium-bedded calcilutite interbedded with thinly-bedded dolomitic limestone and dolomite beds. 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 unit. This is quite in contrast to medium to dark grey calcilutite. The cross lamination is also present in the dolomitic limestone. The rocks are classified as packed biomicrite, disturbed micrite containing microcrystalline and macrocrystalline dolomite. The packed biomicrite comprises diverse small bioclasts (10 to 500  $\mu\text{m}$  in size) embedded in micrite matrix. The disturbed micrite is characterized by abundant burrows in micrite matrix.

Many burrow phases of *Diplocraterions* ichnosp., *Planolites* ichnosp. and *Skolithos* ichnosp. are filled with micrite, finely crystalline dolomite and sparry calcite cement. The dolomite beds are essentially medium crystalline dolomite replacing the pre-existing calcareous parts.

The laminated dolomitic calcarenite was probably deposited in the intertidal zone of lagoon. This interpretation is inferred by the abundant occurrence of burrows filled with micrite and finely crystalline dolomite. The presence of *Diplocraterions* ichnosp. is a good indicator of tidal flat<sup>30</sup> while the *Planolites* ichnosp. and *Skolithos* ichnosp. are known as feeding and dwelling burrows. They are also common in the intertidal zone of lagoon<sup>30</sup>.

### Unit J: Fusulinid and intraclasts-bearing fine calcirudite

Overlying conformably on the Unit I is the fusulinid and intraclasts-bearing fine calcirudite of Unit J. It is well exposed in all sections with thickness of 122 to 322 m. This unit is light to pinkish grey, medium- to thick-bedded, moderately sorted calcarenite to fine calcirudite (Fig. 4D). The beds are of parallel-bedded type. The fine calcirudite shows both grain-supported and matrix-supported fabric with some nodular cherts and dolomitic patches. The rocks are fusulinid-bearing biosparite, intrasparite, biopelsparite, packed biomicrite and intrasparudite. Allochems are fusulinids, crinoid stems, intraclasts, bryozoans, pellets and unidentified skeletal fragments. Grains are completely micritized and the internal pores are occluded by sparry calcite cement. Some grains and pellets show microcrystalline calcite cement near the grain contact. The nodular chert is mainly microcrystalline quartz with minor chalcedonic quartz and macrocrystalline quartz.

The Unit J, similar to that of the Unit G, comprises various rock types indicating both high and low-energy depositional environments. There seems to be some changes between low and high-energy conditions. The presence of intraclast indicates that the sediments were ripped off in the intertidal zone and re-deposited in the subtidal zone as mentioned earlier. As such, the Unit J was probably deposited under the intertidal to subtidal zones of lagoon or inner shelf behind the barrier bars or shoal.

### Unit K: Fenestral and disturbed dolomitic calcilutite

The fenestral and disturbed dolomitic calcilutite of Unit K overlies conformably on the Unit J and is only exposed at the Khao Khad section with thickness of about 120 m. This unit is medium to dark grey, thin- to thick-bedded calcilutite to calcarenite with coquinite,

algal encrusted coquinite and many dolomitic limestone beds. This unit contains some large shell fragments in the calcilutite matrix (Fig. 4E), and shows bird's eye structures, fenestral features and burrows of *Chondrites* ichnosp. (Fig. 4F), *Planolites* ichnosp., *Skolithos* ichnosp. and *Trichichnus* ichnosp. The rocks are packed biomicrite and dismicrite. Small shell fragments (10 to 600 mm in size) are abundant and packed together in micrite matrix. The bio-disturbed micrite such as burrow is partially filled with microcrystalline and mesocrystalline dolomite and sparry calcite cement (Fig. 5A).

The fenestral and disturbed dolomitic calcilutite of the Unit K was probably deposited in the intertidal

zone of lagoon environment. The abundant occurrences of bio-disturbed micrite and fenestral features are usually found in the intertidal to subtidal zones<sup>30, 31</sup>.

#### Unit L: Fusulinid-bearing calcarenite

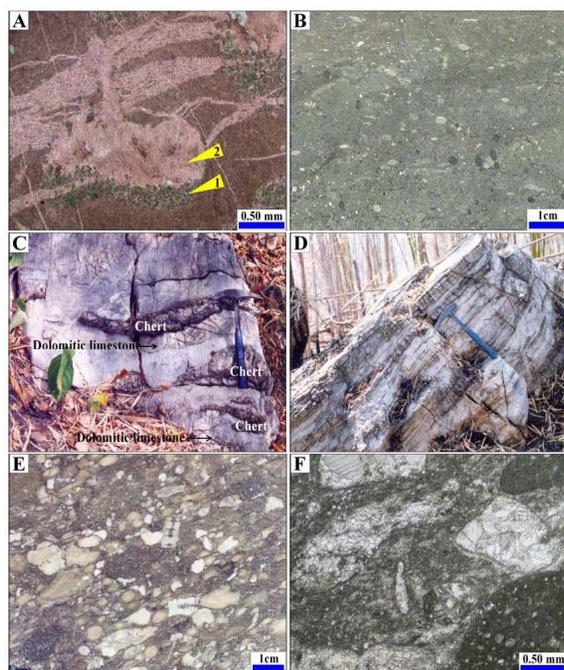
The fusulinid-bearing calcarenite of Unit L overlies conformably the Unit K and is exposed only at the Khao Khad section with the thickness of about 150 m. This unit is characterized by medium to brownish grey, thin-bedded calcarenite. Allochems are mainly of fusulinid tests (1 to 2 mm in size) and some brachiopod shell fragments (Fig. 5B). Most of this unit has been silicified and weathered into friable siliceous matter. The rocks are classified as packed biomicrite. The micritized fusulinids were transformed into microsparite. As such the internal pores were filled with coarse sparry calcite cement. The silicified packed biomicrite contains abundant chalcedonic spherulite.

As has been repeatedly mentioned micrite usually occurs in low-energy depositional environments<sup>17</sup> and arenaceous fusulinids are also abundant in the lagoon environment. It is therefore likely that the Unit L was deposited in the subtidal zone of lagoon similar to those found in the Lower Member of the Khuff Formation in Saudi Arabia<sup>31</sup>.

#### Unit M: Intraclast-bearing calcarenite

The intraclast-bearing calcarenite of Unit M overlies conformably the Unit J and is exposed only at the Khao Chan section with the thickness of about 159 m. This unit is characterized by dark grey and thin- to thick-bedded calcarenite (partly calcilutite) alternating with reddish brown silty shale. Some parts of this unit were patchily dolomitized. The elongate nodular cherts of less than 20 cm in size are scattered throughout this unit. In addition, the nodular cherts are also associated with some dolomitic limestone (Fig. 5C). The rocks are packed intramicrite and biomicrite. Allochems are intraclasts, minor broken crinoid ossicles, and foraminiferal tests. There are some detrital quartz and dolomite grains (10 to 100  $\mu\text{m}$  in size) deposited with calcareous grains. They are packed together and cemented by ferroan sparry calcite. The nodular chert is microcrystalline quartz with abundant calcareous remnants and microcrystalline dolomite. Some parts of nodular chert contain carbonate vadose silts.

The detrital quartz, dolomite grains, and intraclasts occur preferably in restricted zone of inner shelf, especially in the intertidal and subtidal zones near the shoreline. Similarly, calcarenite is also common in the intertidal zone of moderately high-energy. On the contrary, the occurrences of micrite and thinly-laminated silty shale indicate low-energy environment while the presence of vadose silt suggests the sediments



**Fig 5.** **A:** Photomicrograph of disturbed micrite of the Unit K. The burrows of *Chondrites* ichnosp. were earlier filled by microcrystalline dolomite (1) and later cemented by sparry calcite (2). (Stained, PPL, Sample no. 210/1) **B:** A calcarenite slab of the Unit L showing matrix-supported fabric of fusulinid test. (Sample no. 201/1) **C:** An exposure of medium-bedded, dark grey calcarenite of the Unit M showing elongate chert nodules and dolomitic limestone patches embedded in limestone beds. (UTM 731100E, 1620500N) **D:** An outcrop of thin-bedded, dark grey mixed calcarenite and argillaceous limestone of the Unit N. (UTM 732000E, 1620000N) **E:** A rock slab of calcirudite of the uppermost part of the Unit N showing abundant intraclasts packed with foraminiferal tests and crinoidal fragments. (Sample no. L24/6) **F:** Photomicrograph of rounded packed biomicrite of the Unit N showing micrite coated grains with rounded rims. Grains were completely replaced by sparry calcite. (PPL, Sample no. 119/1).

were exposed and affected by meteoric water. Thus, it is likely that the Unit M was deposited in intertidal and subtidal zones near shore.

#### **Unit N: Argillaceous limestone with silty shale**

The argillaceous limestone with silty shale of Unit N is exposed at both the Khao Khad and Khao Chan sections. It overlies conformably on the Unit M with the thickness of 239 to 435 m. This unit is represented by a sequence of medium 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. The calcilutite and calcarenite usually contain abundant argillaceous matter (Fig. 5D). The uppermost calcirudite beds are 1 to 2 m thick and comprise essentially compacted intraclasts (1 to 10 cm in size, Fig. 5E). The cumulative thickness ratio of carbonates and siliciclastics of this unit is approximately 4:1. The rocks are poorly-washed biosparite, packed intramicrudite, packed biomicrite and micrite. Allochems are abundant skeletal fragments of crinoid and foraminifera with some algal and coral fragments, unidentified grains, intraclast and detrital quartz. Some grains are rounded to sub-rounded and appear as micrite-coated or completely micritized grains (hence unable to identify, Fig. 5F). 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 megacrystalline quartz. Also in the fine-grained chert matrix there are some of both non-ferroan and ferroan calcite remnants. There are also some ferroan microcrystalline dolomites disseminated in the fine-grained chert matrix. The porcelanite contains abundant sponge spicules of 10 to 100  $\mu\text{m}$  in size mixed with silicified argillaceous matter.

There seems to be a certain degree of gradually passing upward sequence from Unit M to Unit N because of the increasing of the proportion of intraclasts and siliciclastic sediments in the sequence. As previously been documented, 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<sup>32</sup>. The packed intraclastic calcirudites or packed intramicrudite were found in the Chanda limestone, Penganda Group, of India<sup>33</sup> and the Kelley-Snyder Field in West Texas<sup>34</sup>. These sediments have been interpreted as debris flows representing a re-deposition of semi-consolidated sediments<sup>35</sup>. Therefore, the depositional environment of this unit could be high-energy intertidal and subtidal zones.

#### **Unit O: Cross-laminated calcarenite**

The cross-laminated calcarenite of Unit O is the uppermost unit of the Khao Khad Formation. It overlies on the Unit N with fault contact and is exposed only at the Khao Chan section with the thickness of about 365 m. This unit is characterized by medium to dark grey, thin- to thick-bedded calcarenite rarely with small chert nodules. Cross-lamination can be recognized in the lower part of the unit. The rocks are poorly-washed biosparite, packed biomicrite and sparse biomicrite. Allochems are bioclasts of foraminiferal tests, crinoids, unidentified skeletal fragments and bryozoans together with intraclasts and detrital quartz. The chert nodule is made up essentially of microcrystalline quartz with some calcareous patches.

The formation of calcarenite from diverse grain components by itself suggests that the rock represents a slightly high-energy zone of shallow marine. However, the presence of micrite in poorly-washed biosparite and packed biomicrite seems to indicate a low-energy environment. In addition, the cross-lamination usually formed in the intertidal zone of restricted inner shelf. As such this unit was probably deposited in the intertidal and subtidal zones of inner shelf.

#### **Reconstruction of Depositional Model**

Based on the analysis of those 15 rock units, it can be summarized that the carbonate and siliciclastic sequences of the Khao Khad Formation were deposited in the marine shelf condition under sub-environments of intertidal to subtidal zones near shore, subtidal zone of lagoon, shallow platform, barrier bar or shoal and foreslope of outer shelf. By careful examination of the vertical succession of lithostratigraphic units and associated environments in the measured sections, there appears to be a major transgressive and regressive cycle of seawater during the Lower to Middle Permian time.

#### **The Transgressive Sequences**

The transgressive sequences probably occurred during the deposition of Unit A to H in which the sub-environments might have varied from intertidal and subtidal zones of lagoon to barrier bars (Fig. 6A). The sequence started with the Unit A which was the subtidal zone of lagoon at both Khao Khad and Khao Chan areas (might be absent or not exposed in the Pak Chong to Khao Yai area). The Khao Chan area seemed to have higher amount of micrite deposition than that at the Khao Khad area. The Unit B, which is locally present in the Khao Khad area, was algal stromatolites in the intertidal zone. It probably represented a minor regression or progradation. The Unit C to E were barrier bar or shoal at the Khao Khad and Khao Chan areas contained various proportion of grain components of

**Table 1.** Summary of lithological characteristics and depositional environments from lower to upper units.

Unit	Thickness (meters)	Lithological Characteristics	Depositional environment
O	365	Medium to dark grey, thin- to thick-bedded, cross-lamination calcarenite with rare small chert nodules. The rocks are poorly-washed biosparite, packed biomicrite, and sparse biomicrite and with some microcrystalline quartz. Allochems are foraminiferal tests, crinoid stems, bryozoan and intraclasts with some detrital quartz. It overlies on the Unit N with fault contact.	Intertidal zone of inner shelf
N	239-435	Sequences of medium to dark grey, thin-bedded calcilutite to 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. The rocks are poorly-washed biosparite, packed intramicrite, packed biomicrite and micrite. Allochems are crinoidal and algal fragments, fusulinid tests and intraclasts with some coral and detrital quartz. The unit rests conformably on the Unit M.	High energy intertidal and subtidal zones
M	159	Dark grey, thin- to thick-bedded calcarenite, partly calcilutite with dark grey chert nodules and silt-shale between limestone beds. The rocks are packed intramicrite and biomicrite. Allochems are intraclasts, crinoid ossicles and fusulinid tests with some detrital quartz. The unit rests conformably on the Unit J.	Subtidal and intertidal zones near shore
L	150	Medium to brownish grey, thin-bedded calcarenite. The rock is packed biomicrite with grains of fusulinid tests and brachiopod fragments. The silicified argillaceous limestone contains abundant chalcedonic spherulite. The unit rests conformably on the Unit K.	Subtidal zone of lagoon
K	120	Medium to dark grey, thin- to thick-bedded calcilutite to calcarenite with coquinite, algal encrusted coquinite and dolomitic limestone beds. The rocks are packed biomicrite and dismicrite with abundant burrows and fenestral features. Allochems are shell fragments. The unit rests conformably on the Unit J.	Intertidal zone of lagoon
J	122-322	Light to pinkish grey, medium- to thick-bedded, calcarenite to fine calcirudite with nodular cherts. The rocks are fusulinid bearing biosparite, intrasparite, biopelsparite, packed biomicrite and intrasparudite with microcrystalline, macrocrystalline and chalcedonic quartz. Allochems are fusulinid tests, crinoidal and bryozoan fragments, intraclast and pellets. The unit rests conformably on the Unit I.	Intertidal to subtidal zone of lagoon
I	86-180	Medium to dark grey, thin- to medium-bedded calcilutite interbedded with thin-bedded dolomitic limestone and dolomite beds. The rocks are packed biomicrite, disturbed micrite with some burrows. Allochem is rare. The unit rests conformably on the Unit H.	Intertidal zone of lagoon
H	123-211	Medium to dark grey, thin- to very-thick-bedded calcilutite to calcirudite and coral biolithite with nodular cherts. The rocks are classified as biopelmicrite, packed biomicrite, packed biomicrudite, packed intramicrite and intraclasts-bearing biosparudite. Allochems are brachiopods and gastropods shells, fusulinid tests, fecal pellets and intraclasts with coral fragments. It overlies on the Unit G with fault contact.	Shallow platform buildup
G	184	Medium to dark grey, medium- to very-thick-bedded, parallel-bedded type, calcarenite to fine calcirudite with nodular cherts and dolomite patches. The rocks are poorly washed biosparite, unsorted biopelsparite and biosparudite with microcrystalline quartz and macrocrystalline dolomite. Allochems are mainly large fusulinid tests, pellets and small shell fragments. It overlies on the Unit E with fault contact.	Intertidal to subtidal zone of lagoon.
F	181	Medium to dark grey, thin- to very-thick-bedded, parallel-bedded type, graded calcarenite to calcilutite with dark grey banded chert and thinly-laminated to thinly-bedded, reddish brown, fissile silty shale between each limestone bed. The rocks are poorly-washed intrasparudite, poorly-washed intrasparite, packed intramicrite and fossiliferous micrite. The banded cherts consist of microcrystalline, megacrystalline and chalcedonic quartz. Allochems consist of angular boulders, cobbles, pebbles and sands of intraclasts, crinoid stems and fusulinid tests. The unit rests conformably on the Unit E.	Foreslope of barrier bar
E	92-213	Light grey, medium- to thick-bedded, parallel-bedded type, coarse calcarenite to fine calcirudite with dolomitic limestone beds. The rocks are sorted biosparite, biosparudite, poorly-washed biosparite with finely to coarsely crystalline dolomite. Allochems are crinoid stems, fusulinid tests, intraclasts and bryozoans. The unit rests conformably on the Unit D.	Back barrier bar
D	57-117	Grey to dark grey, medium- to thick-bedded, parallel-bedded type, crinoidal calcirudite with dark grey chert nodules. The rocks are sorted biosparite and biosparudite with some microcrystalline quartz and microcrystalline dolomite. Allochems are crinoid stems, fusulinid tests, intraclasts and bryozoans. The unit rests conformably on the Unit C.	Back barrier bar
C	32-116	Light to medium grey, medium- to thick-bedded, parallel-bedded type, crinoidal calcirudite. The rocks are unsorted crinoidal biosparite and biosparudite. Allochems are crinoidal and bryozoan fragments. The unit rests conformably on the Unit B.	Barrier bar or shoal
B	100	Light to medium grey, medium-bedded calcarenite to calcirudite and algal biolithite. The rocks are pelsparite, biopelsparite and biosparudite. Allochems are algal and crinoid stems, pellets, fusulinid tests, and shells of brachiopods, gastropods and cephalopods. It overlies conformably on the Unit A.	Intertidal zone of shallow marine
A	251-294	Medium light grey, thin- to medium-bedded, parallel- to wavy-bedded types, calcilutite with dark grey chert nodules. The rocks are classified as finely laminated fossiliferous micrite, algal biomicrite, packed biomicrite and packed biomicrudite with some microcrystalline quartz. Allochems are fusulinid tests, pellets, brachiopod and gastropod shells and algal fragments.	Subtidal zones of lagoon

crinoid fragments, intraclasts, some fusulinid tests, bryozoans and shell fragments. The Unit F was the foreslope of barrier bar as indicated by the repetitive sequence of graded calcarenite to calcilitite with abundant intraclasts. This unit was only exposed at the Khao Chan area. The Unit G was deposited in intertidal to subtidal zones of lagoon at the Khao Khad area and contained abundant fusulinid tests. The Unit H was deposited in the shallow platform or bioconstructed buildup zone, approximately 100 m wide, at the Khao Khad and Pak Chong to Khao Yai areas. This environment might be initiated during low stand of shallow outer shelf which was quite different from crinoidal barrier bar of the Unit C. In this shallow platform area there were abundant buildups of corals or patch reef, large brachiopods and gastropods without crinoids. The buildups were probably acting as the barrier separated the lagoon from open marine conditions.

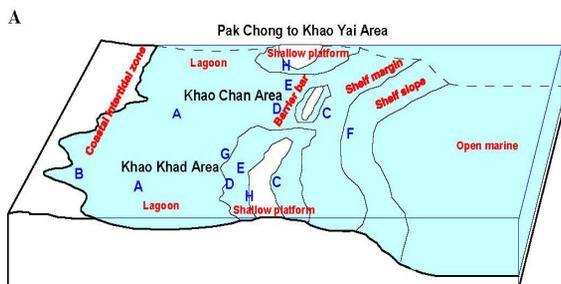
### The Regressive Sequences

The regressive sequences probably occurred during the deposition of the Unit I to O. The depositional environments change from intertidal and subtidal zones of back barrier bar to intertidal zone of near shore (Fig. 6B). The regression probably started from the Unit I and J which deposited in the intertidal to subtidal zone of lagoon probably related to subsequent exposure of shallow platform buildup. After that sea level fell down

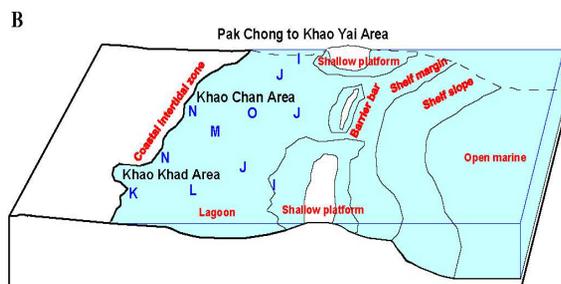
then unit K was deposited in the intertidal zone of lagoon with abundant bioturbation and fenestral features forming by processes such as upward escape of gas bubbles. The Unit L was deposited in the area slightly deeper in subtidal zone of lagoon. During the deposition of Unit M and N, there was the increasing influx of terrigenous sediments into the intertidal and subtidal zones near shore. The siliciclastic sediments were deposited together with fine-grained intraclasts and minor skeleton fragments of crinoids and fusulinids. Subsequently, the supply of terrigenous sediments was decreasing and the Unit O was deposited in the intertidal to subtidal zones of inner shelf with slightly high-energy condition.

### CONCLUSION

The depositional model of the Khao Khad Formation is represented by the lagoon of inner shelf with barrier bar or shallow platform in outer shelf and foreslope. The barrier bar and shallow platform environments protected the inner shelf from the open marine wave energy and promoted diverse bio-communities on the back side. The situation may vary from low to slightly high-energy conditions probably related to the variation of paleogeography of the sea floor. The low-energy condition was dominated by the deposition of abundant micrite with large allochems such as fusulinid tests and brachiopod and gastropod shells. 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-water carbonate platform at the Khao Khad and Pak Chong to Khao Yai areas into crinoidal barrier bar at the Khao Khad area. There might have been some channels cross-cutting the barrier bar by which the turbidity current could transport the carbonate sediments into the foreslope. The overall lithostratigraphic sequence indicates that the Khao Khad Formation was deposited during the transgression and regression of the Lower to Middle Permian sea.



Depositional environment of the transgressive sequence, units A to H



Depositional environment of the regressive sequence, units I to O

**Fig 6.** Schematic block diagram illustrating the depositional environments of the rock units of the Khao Khad Formation. A: During transgression period. B: During regression period.

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