Triassic carbonate rocks of Pha Kan and Doi Long Formations of Lampang Group consist mostly of carbonate successions deposited in the Sukhothai Zone, northern Thailand. These formations are mixed carbonate and siliciclastic sediments and widely exposed in the Lampang area. These deposits are important for the reconstruction of depositional environments and regional correlations of the Triassic carbonate rocks with respect to the volcanic arc of the Sukhothai Zone during the Triassic. The goal of this study is to analyze the lithology and microfacies of the carbonate rocks of the Pha Kan and Doi Long Formations and reevaluate the existing depositional models and carbonate settings. Both formations have diverse skeletal fossils, including foraminifers, sponges, calcimicrobes, calcareous algae, bivalves, echinoderm spines and fragments, ostracods, gastropods, and other fossils. Based on field observations and microfacies analysis, twelve major facies, corresponding to specific depositional environments within a carbonate setting, have been established. The inferred depositional environment is a carbonate platform with a well-developed lagoon, small-scale reefs, and bioclastic and oolitic shoals, as parts of a carbonate ramp. The microfacies and sedimentological study show that this carbonate system was influenced by the nearby volcanic arc. Consequently, our study shows that the Lampang Group in northern Thailand can be correlated with the Lincang Massif of the western Yunnan Province, PRC and the northwestern Lao PDR.

1. Introduction

Triassic sedimentary successions, which formed as intra-arc facies of the Sukhothai Zone, are widely distributed in northern Thailand. They are mainly sandstone, mudstone, and limestone, known as the Triassic Lampang Group (e.g., Charoenprawat et al., 1994; Chaodumrong and Burrett, 1997; Kobayashi et al., 2006; Chonglakmani, 2011; Ueno and Charoenprawat, 2011). The depositional age of the Lampang Group was assigned to Early to Late Triassic (Olenekian to Carnian age) based on ammonoids, bivalves, and foraminifers (Chonglakmani and Grant-Mackie, 1993; Carey et al., 1995; Kobayashi et al., 2006; Chonglakmani, 2011). The Triassic carbonate successions, including Pha Kan and Doi Long Formations, of the Lampang Group developed in response to volcanic arc activity of the Sukhothai Zone (Sone and Metcalfe, 2008; Hara et al., 2017). Reconstruction of carbonate depositional environment associated with arc development is important for understanding the paleoenvironment and volcanic arc activity that occurred in the Sukhothai Zone. However, the depositional model and the volcanic influence have not been clarified or reported in this area. In the Pha Kan and Doi Long Formations, sedimentology and microfacies from the carbonate rocks have only been done in the central and northern Lampang areas (e.g., Chaodumrong, 1992; Chaodumrong and Rao, 1992; Miyahigashi et al., 2012). Paleontological studies have provided some evidence of the depositional age and environment, but the sample areas in Chaodumrong and Rao (1992), Kobayashi et al. (2006), Miyahigashi et al. (2012), and Ketmuangmoon et al. (2018) are overlapping and only distributed in certain areas. There is no report or publication about the microfacies in the two formations located in the northeastern Mae Moh, southwestern Chae Hom, and Ngao areas.

The Lampang Group was interpreted to be deposited in two sub-basins, Lampang Sub-basin and Phrae Sub-basin. The Lampang Sub-basin comprises five formations of Lower to Upper Triassic, namely Phra That, Pha Kan, Hong Hoi, Doi Long, and Pha Daeng Formations (Bunopas, 1994; Chonglakmani, 2011). On the contrary, the younger Pha Daeng, Kang Pla, and Wang Chin Formations deposited in the Phrae Sub-basin are confined to the Upper Triassic (Chaodumrong, 1992; Chonglakmani, 2011). Chonglakmani (2011) established Song Group for the Upper Triassic rocks that deposited in the Phrae Sub-basin.
Thus, this study is emphasized on the Lampang Group in the Lampang Sub-basin. Among the five formations in the Lampang Sub-basin, the Pha Kan and Doi Long Formations consist mainly of carbonate rocks (Feng et al., 2005; Chonglakmani, 2011; Ueno and Charoentitirat, 2011) (Figure 1). The carbonate rocks of the Pha Kan and Doi Long Formations are of great interest to many geologists because they lead to a better understanding of depositional setting related to the major closure of the Paleo-Tethys and the development of a volcanic arc (Ueno, 1999; Ueno and Hisada, 2001; Sone and Metcalfe, 2008; Sone et al., 2012). This study focuses on microfacies of these carbonate sediments, as they preserve continuous records of carbonate build-up and volcanic influence on the carbonate deposition.

We have surveyed the Lower to Upper Triassic carbonate rocks in the Lampang Sub-basin, from multiple excursions between April, 2018 to January of 2020, and found new fossil-rich localities in the Pha Kan and Doi Long Formations in Doi Ton (DT), Ban Than (BT), Ban Mae Ang (MA), Doi Wiang Ho (DWH), Ban Khun Mae Huat (KMH), and Ban Sop Chang (SC) localities of the Lampang Province (Figure 2). Preliminary results from the petrographic study in February 2020 showed that these intervals offer sedimentological and paleontological data that reflect paleoenvironmental, paleoclimatic, and temporal changes during the Triassic time. The existing paleontological and sedimentological studies of Chaodumrong (1992), Chaodumrong and Rao (1992), Charusiri et al. (1994), Carey et al. (1995), and Miyahigashi et al. (2012) do not provide any evidence on carbonate deposition of both Pha Kan and Doi Long Formations, and there is only a few reports on the fossil faunas microfacies (e.g., Chonglakmani and Grant-Mackie, 1993; Kobayashi et al., 2006; Miyahigashi et al., 2012; Ketmuangmoon et al., 2018). The Triassic carbonate rocks of the Lampang Group are exposed within the Lampang Sub-basin in the Sukhothai Zone (Figures 2 and 3). However, the microfacies of the Triassic carbonate rocks of the Lampang Group reported in Chaodumrong and Rao (1992) and Kobayashi et al. (2006) are only from the central Lampang and a part of southern Ñao areas. To better understand the development of the Triassic forearc sediments, the depositional models are constructed from additional six new outcrops that have never been investigated before (Figure 2).

This research interprets the depositional paleoenvironment of the Pha Kan and Doi Long Formations from field observations, microfacies descriptions, fossils, and petrographic study, and reevaluates the existing depositional models which can be compared and supported the correlation with the other Triassic carbonate build-ups in the SE Asia.

2. Geological setting

Northern Thailand and its adjacent regions consist of tectonic terranes bounded by suture zones from the Paleo-Tethys. There are four tectonic subdivisions, from west to east (Figure 3): Sibumasu Block, Inthanon Suture Zone, Sukhothai Zone, and Indochina Block (Sone and Metcalfe 2008; Metcalfe, 2013, 2017). The Sukhothai Zone is considered to be an island-arc system developed along the western margin of the Indochina Block during the Permian to Triassic, and a part of the arc developed as a forearc basin (Barr and Macdonald, 1991; Ueno, 1999; Sone and Metcalfe, 2008; Chonglakmani, 2011; Har?, et al., 2017). The Sukhothai Zone includes a major Triassic sedimentary rock unit that is conventionally referred to as the Lampang Group (Chaodumrong and Burrett, 1997; Singharajwarapan and Berry, 2000; Kobayashi et al., 2006; Chonglakmani, 2011; Metcalfe, 2013, 2017) (Figure 2). General stratigraphy of the Triassic rocks within the Sukhothai Zone is shown in Figure 1. The basement rocks in the Lampang Sub-basin are low-grade Paleozoic metamorphic rocks, Permian sedimentary rocks of the Ngao Group, and Permo-Triassic volcanic rocks. The younger units

Figure 1. Stratigraphic chart of the Lampang and Song Groups. Ages and lithostratigraphic division are modified from Feng et al. (2005).
are consisting of Triassic granitoid rocks and Triassic-Jurassic red-beds sedimentary rocks (Department of Mineral Resources, 2006) (Figure 1).

The carbonate rocks of the Lampang Group namely Pha Kan and Doi Long Formations are relatively well exposed in the central and northern parts of the Lampang Province (Figure 2). The studied sections are distributed in Mae Tha and Mae Moh Districts, Ban Tha Si area, Chae Hom District, and the southern part of Ngao District of the Lampang Province (Figure 2). In general, the Pha Kan and Doi Long Formations at

Figure 2. Geological map of the Lampang and Phrae areas, northern Thailand and locations of the studied localities (black points) (modified from Hara et al., 2017). Dashed line is the boundary between the sub-basin modified from Feng et al. (2005).

Figure 3. Geological setting and location of the studied area. a) Geotectonic subdivisions of Thailand that represent the orientation of the Sukhothai Arc Terrane in the northern Thailand. b) Locations of the studied area modified after Chonglakmani (2011) and Ueno and Charoenitittirat (2011).
the studied sections consist mainly of limestones interbedded with few siliciclastic shales, mudstones, and sandstones.

The geology of the Pha Kan and Doi Long Formations was mainly studied by Pitakpaivan (1965), Chaodumrong (1992), and Kobayashi et al. (2006). The Pha Kan Formation was named after Doi Pha Kan, north of Ban Thasi, Lampang Province (Piyasin, 1972). Most of the rocks in this formation are limestones. Sandstone and mudstone occur in the upper part of the formation (Chaodumrong and Burrett, 1997; Chonglakmani, 2011). Thickness of the formation varies from place to place (400–640 m). Limestones are gray to dark gray showing medium to thick bedding (10–60 cm). Oncoidal structures are common and distinctive (Chaodumrong and Burrett, 1997; Chonglakmani, 2011). Figure 4 shows the field photographs of the Pha Kan Formation in the Lampang area. Ammonoid fragments found in the Pha Kan limestone indicate Late Anisian (Chonglakmani and Grant-Mackie, 1993) and paleontological evidence in Charusiri et al. (1994) indicate Anisian to Carnian. Biostratigraphic study by Carey et al. (1995) showed that the lower part of this unit contains the Early Olenekian (Smithian) conodonts. Thus, the age of the Pha Kan limestone could extend back to the Early Olenekian. The study localities 2, 3, and 4 of Kobayashi et al. (2006) are in the Pha Kan Formation of Charoenprawat et al. (1994) and Chonglakmani (2011). The foraminiferal associations found in the three localities are Glomospirella lampangensis, n. sp., Pilammina densa, endothyroid foraminifers-Diplotremina astrofimbriata, and Aulotortus sinuosus microfaunas, indicating a biostratigraphic range from the Early Triassic to Carnian. Recently, Ketmuangmoon et al. (2018) classified 29 species of ostracods in the Pha Kan Formation and proposed the depositional age to be the Middle Triassic.

The shallow ramp platform and regressive platform environments of the Pha Kan Formation were firstly introduced by Chaodumrong (1992).
and Chaodumrong and Rao (1992) based on carbonate microfacies studies. Recently, Ketmuangmoon et al. (2018) analyzed Triassic ostracods in Phra That Muang Kham, Mae Tha District, Lampang Province, located in the Pha Kan Formation and interpreted the depositional environment to be a protected to an open marine.

The Doi Long Formation was named by Chonglakmani (1981) and comprises limestone beds underlying the Pha Daeng Formation and overlying the Hong Hoi Formation (Figure 1). Figure 5 shows the field photographs of the Doi Long Formation in the Lampang area. The thickness of this formation is 200 m. It consists of gray to light gray, fine-grained limestones (Figure 5). Numerous peloids and algae occur locally (Miyahigashi et al., 2012). Oncoids are also found but are less prominent than they are in the Pha Kan Formation (Chonglakmani, 2011). Massive beds in the lower part of the formation overlie the Hong Hoi mudstone (Figure 5e). Interbedded red to pink limestones occur at the top of the formation close to the Pha Daeng Formation (Figure 5f).

The geologic age of the Doi Long Formation is regarded in general as Carnian (Chonglakmani and Grant-Mackie, 1993; Miyahigashi et al., 2012). The Middle Carnian Hollandites-Balatonites fauna was found in this formation (Chonglakmani and Grant-Mackie, 1993). Miyahigashi et al. (2012) studied the foraminifers in the Doi Long Formation. The sample locations MT-5 and MT-6 of Miyahigashi et al. (2012) correspond to the localities 3 and 4 of Kobayashi et al. (2006). The foraminiferal assemblage at the locality 4 of Kobayashi et al. (2006) is from Ladinian because of the presence of the Diplotremina astrofimbriata and the lack of Carnian foraminifera such as Aulotortidae. However, Miyahigashi et al. (2012) reported that Aulotortus sinuosus and Aulotortus tumidus are found abundantly in MT-5 and MT-6 locations and proposed that the depositional age of the Doi Long Formation should be Carnian rather than Ladinian. The age assessment is consistent with the study of ammonoids in Chonglakmani and Grant-Mackie (1993). This study adopts the depositional age of the Pha Kan and Doi Long Formations based on the foraminiferal associations of Kobayashi et al. (2006) and Miyahigashi et al. (2012) (Figure 6).

The shallow-water limestones of the Doi Long Formation were deposited in a regressive platform (Chaodumrong, 1992; Chaodumrong and Rao, 1992). Chaodumrong (1992) concluded that the Doi Long Formation was deposited in a ramp setting mainly because of the absence of reef sediments. However, the recent study from Miyahigashi et al. (2012) proposed that the environment of deposition of the Doi Long Formation could be in a reef or bank setting because of the presence of sclerosponges, sphinctozoan sponges, microbes, and microproblematica (Shamovella, Bacinella, and Microtubus).

3. Investigation and methodology

This research includes the study of microfacies in hand samples collected from thirteen localities in the Lampang Province (Figure 2). The studied sections are from the Pha Kan and Doi Long Formations. Geographic positions of the studied sections can be divided into three regions, including the central area and the northern and northeastern parts of the Lampang Sub-basin (Figures 2, 4, and 5). The Lampang Sub-
| Period | Stage | Phra That | Phra That | Phratu Pha | Phratu Pha | Doi Wiang Ho | Doi Wiang Ho |
|--------|-------|-----------|-----------|------------|------------|-------------|-------------|
| Jurassic| Rhaetian | Muang Kham | Ban Tha Si | Phratu Pha | Shrine | Natural | Long |
| Late | Norian | Carnian | | | | | |
| Triassic | | Ladinian | | | | | |
| Middle | | Anisian | | | | | |
| Early | | Olenekian | | | | | |
| Permian | | Induan | | | | | |

**Figure 6.** Biostratigraphic summary of the studied sections in the Pha Kan and Doi Long Formations, defined on the basis of foraminiferal associations compared with the previous studies of Kobayashi et al. (2006) and Miyahigashi et al. (2012).

**Figure 7.** Lithostratigraphic columns and correlation of the studied sections of the Pha Kan Formation.
basin, in the west, is dominated by the Lower to lower Upper Triassic, whereas the Phrae Sub-basin, in the east, consists of the Upper Triassic sediments (Figures 1 and 2).

The investigations and reexaminations were carried out at the previous works’ localities (Chaodumrong, 1992; Kobayashi et al., 2006; Hara et al., 2017). These localities are Phra That Muang Kham Temple (MK), Mae Tha Railway station (NE of MK), Ban Pha Lad (PL), Ban Tha Si (TS), Phratu Pha Shrine (PP), Ban Khun Mae Huat (KMH), Doi Huai Long (DHL), Doi Wiang Ho (DWH), and the 434\textsuperscript{th} km of the National Highway 11 (southeast of DWH). Six new localities were investigated including Doi Ton (DT), Ban Than (BT), Ban Sop Chang (SC), Ban Mae Ang (MA), Doi Wiang Ho (DWH), and Ban Khun Mae Huat (KMH). Of these, limestones at MK, DT, BT, DWH, DHL, and SC are fossiliferous. Lithostratigraphic subdivision along with the lithological description and microfacies interpretation are from outcrop observation.

Lithostratigraphic columns and stratigraphic correlation of the studied sections are shown in Figures 7 and 8. The lithological details of each formation are observed and investigated for distinct facies, mainly focusing on the best-preserved areas with significant lithology, sedimentary structures, and biotic contents. Stratigraphic levels of the studied sections are based on the lithology, stratigraphic relationship, and biostratigraphy between the upper and lower stratigraphic units. Then, together with the existing literatures of the recognized biostratigraphy, the accurate stratigraphic level could be inferred. The major components of these formations are limestones with minor amount of siliciclastic rocks and non-skeletal grains, including ooids, oncoids, and peloids. The shallow-marine fossils observed here are sponges, microbes, bivalves, gastropods, foraminifers, calcareous algae, and ostracods, explained in further details in the subsection 4.1.

Sixty-eight samples from the selected studied sections were collected for the studies of microfacies and microfossils. Microfacies types and associations are interpreted from field observation, slabbed samples, and thin-sections, distributed throughout the two formations of the Lampang Group. All analyses were carried out at the Petrographic Laboratory in Department of Geological Sciences, Faculty of Science, Chiang Mai University, Thailand.

The microfacies are classified according to the classification of Dunham (1962), subsequently improved by Embry and Klovan (1971). Microfacies are interpreted according to the criteria of Flügel (2004, 2010), and the depositional is interpreted from Wilson's facies belt (Wilson, 1975).

4. Results

4.1. Fossils

In the Pha Kan Formation, the dominant fossils are foraminifers such as *Pilammina densa* Pantić (1965), *Glomospirella lampangensis* Kobayashi et al. (2006), and endothyroid foraminifers *Diplotrema* sp. (Figure 9a-b). These foraminiferal associations are shown in Figure 10. Kobayashi et al. (2006) interpreted them to be from the Early Triassic to Ladinian (Figure 6). This formation contains bivalves (Figure 9c), and ostracods including *Bairdia* sp., *Acratia* sp., and *Bairdiacypris* sp. Other commonly found fossils are corals, sponges, dasycladacean algae, gastropods, and echinoderm spines (Figure 9d-f).

In the Doi Long Formation, the significant fossils are foraminifers such as *Aulotortus sinuosus* Weynschenk, *Agathammina austroalpina* Kristan-Tollmann & Tollmann, *Endotriada tyrrhenica* Vachard, Martini, Rettori and Zaninetti, and *Ophthalmidium tori* Zaninetti and Brönnimann (Figure 11a-c). The foraminiferal associations are shown in Figure 10. They are typically from the Carnian (Miyahigashi et al., 2012) (Figure 6). Microbialite, calcareous algae, gastropods, encrusting foraminifera, and echinoderm spines, are common (Figure 11d-e).
Shamovella Tubiphytes (Riding, 1993; Senowbari-Daryan, 2013) is also found in the Doi Long Formation (Figure 11f).

4.2. Microfacies and lithological characteristics of Pha Kan Formation

In this study, twelve microfacies type are identified: Bioclastic grainstone (Bg), Dasycladacean algae grainstone (Dag), Oolitic grainstone (Og), Oncoidal peloidal packstone (Opp), Oncoidal wackestone (Ow), Peloidal packstone (Pg), Bioclastic wackestone (Bw), Lime mudstone or dolomitized mudstone (Lm), Siliciclastic wackestone (Sw), Calcareous siltstone (Cs), Oncoidal packstone (Op), and Sponge-microbe boundstone (Smb). Description of these microfacies types is summarized in Tables 1 and 2. In the Pha Kan Formation, nine microfacies types based on carbonate composition and relationship of grains are identified through the petrographic study (Table 1). Their distribution is not similar among the studied areas, which reflects the differences in depositional environment.

4.2.1. Central area

The microfacies in the central area are from four studied localities including Phra That Muang Kham (MK), Doi Ton (DT), Mae Tha Railway station (northeast of MK), and Ban Pha Lad (PL) (Figure 2). The Pha Kan Formation is exposed and continuous in the former three locations. Nine main microfacies have been recognized (Table 1).

Bioclastic grainstone (Bg) consists mainly of bioclasts and minor amounts of ooids and intraclasts (Figure 12a). Bioclasts are commonly rounded, disarticulated, and fragmented and consist mainly of foraminifers (Pilammina densa and Glomospirella lampangensis), dasycladacean algae, and (calcimicrobe Girvanella) with minor amount of echinoderms, bivalves, and ostracods (Figure 12a-b). In the Doi Ton locality, Dasycladacean algae grainstone (Dag) is vertically associated with Bg and composed mainly of corals and algae with minor numbers of peloids and intraclasts dispersed in calcite cement. In oolitic grainstone (Og), ooids are well-sorted with an average diameter of 0.46 ± 0.09 mm with few bioclasts and composite grains. The nuclei of ooids are mainly peloids and skeletal grains (Figure 12c). Sparry calcite cement dominates over micrite in this facies. Oncoidal peloidal packstone (Opp) consists mainly of peloids with subordinate oncoids and bioclasts (Figure 12d). Oncoids are spherical to subspherical and have well-developed lamination, which indicate a high degree of rolling (Figure 12e). This microfacies is often associated with oncoidal wackestone (Ow) and peloidal packstone (Pg). In Pg, peloids are densely arranged and form peloid assemblages while in some areas the peloids are often randomly distributed and are difficult to distinguish due to micritization (Figure 12f). Dolomites are minor components, inequigranular, anhedral to subhedral in shape, and appear to be tightly packed.

Dasycladacean algae grainstone (Dag) commonly occurs together with Bg in the Doi Ton (DT) locality. Dag consists mainly of dasycladacean algae (Dag) vertically associated with Bg and composed mainly of corals and algae with minor numbers of peloids and intraclasts dispersed in calcite cement. In oolitic grainstone (Og), ooids are well-sorted with an average diameter of 0.46 ± 0.09 mm with few bioclasts and composite grains. The nuclei of ooids are mainly peloids and skeletal grains (Figure 12c). Sparry calcite cement dominates over micrite in this facies. Oncoidal peloidal packstone (Opp) consists mainly of peloids with subordinate oncoids and bioclasts (Figure 12d). Oncoids are spherical to subspherical and have well-developed lamination, which indicate a high degree of rolling (Figure 12e). This microfacies is often associated with oncoidal wackestone (Ow) and peloidal packstone (Pg). In Pg, peloids are densely arranged and form peloid assemblages while in some areas the peloids are often randomly distributed and are difficult to distinguish due to micritization (Figure 12f). Dolomites are minor components, inequigranular, anhedral to subhedral in shape, and appear to be tightly packed.
siliciclastic minerals, such as quartz and feldspar that are mixed with carbonate minerals (Figure 12j). They are overlain by the basal conglomerate of Hong Hoi Formation (Figure 12k).

4.2.2. Northeastern area

The Ban Than locality (BT) is the only section logged in the northeastern Lampang area because the Pha Kan Formation is distributed in a narrow zone of the northeastern Lampang Sub-basin (Figure 2). It has the most diversified set of carbonate lithofacies and has never been studied before. Six distinctive microfacies are observed in this area, consisting mainly of oolitic grainstone (Og), bioclastic grainstone (Bg), oncoidal peloidal packstone (Opp), peloidal grainstone (Pg), bioclastic wackestone (Bw), and lime mudstone (Lm) (Figure 13). The lithology is mainly gray, medium-to thick-bedded limestone with minor dark gray to gray, thin-bedded limestone, and shale.

The nuclei of ooids in oolitic grainstone (Og) are mainly bioclasts such as foraminifers, bivalves, and gastropods (Figure 13a-b). All of the ooids are well-sorted with diameter ranging from 0.3-0.6 mm (Figure 13b). Cross-stratification is commonly observed. The interspaces of ooid grains are filled with sparry cement. Oncoidal peloidal packstone (Opp) is composed of dark micrite associated with oncocyst, algae, ooids, and micritized peloids (Figure 13c-d). Cyanobacteria and green algal fragments are dominant; few Shamovella are observed in bioclastic grainstone (Bg). Algal layers, algal fragments, and algal tubes are common; some of them have been micritized (Figure 13e). Rare echinoderms, dasycladacean algae, corals, bryozoans, foraminifers, and thin-encrusted shell debris are also found in Bg. Peloid grains in Opp are mainly discrete grains, rounded, and spherical to irregular in shape (Figure 13f).

Peloidal grainstone (Pg) has peloids associated with lump and bioclasts. Peloids are various in size and shape, such as fecal pellets, microbialite, and reworked mud grains or micritized clasts. Microbalite is mainly composed of sub-rounded or irregular grains and is moderately sorted (Figure 13g). Bioclastic wackestone (Bw) is locally observed in this area, which is associated with lime mudstone (Lm) and distributed near the clastic sediments of the Hong Hoi Formation.

4.2.3. Northern area

The northern area has light gray to dark gray, thick-bedded to massive limestones in Ban Tha Si (TS), Phratu Pha Shrine (PP), and Ban Mae Ang (MA) localities (Figure 2). Six microfacies are recognized here.
They are oncoidal wackestone (Ow), oncoidal peloidal packstone (Opp), bioclastic wackestone (Bw), peloidal grainstone (Pg), dolomitized mudstone (Lm), and siliciclastic wackestone (Sw).

Oncoidal wackestone (Ow) is dominant in Ban Mae Ang and Pratu Pha Shrine localities (Figure 14a-b). Oncoids in Ow are rounded, sub-spherical to irregular in shape and floating in fine-grained micrite. Green algae and *Shamovella* are also found in Ow associated with calcimicrobes (Figure 14c). In oncoidal peloidal packstone (Opp), dark micrite has oncoids, calcareous algae, and micritized peloids (Figure 14c). Bioclastic wackestone (Bw) is mainly composed of dark micrite and bioclasts associated with oncoids. The most abundant bioclasts in Bw are foraminifers, echinoderms, corals, bryozoans, sponges, and ostracods (Figure 14d-e). The size of bioclasts varies from 0.15-0.7 mm. Bw is commonly associated with peloidal grainstone (Pg) (Figure 14f). Pg is abundant in Ban Tha Si and Phratu Pha Shrine areas and has been found in the Doi Pha Kan outcrops and road-cut outcrops at the 754th km of the National Highway 1 (Phaholyothin Road). Pg is dominated by peloids of various sizes and shapes including fecal pellets, microbial peloids, reworked mud grains or micritized clasts. Bioclastic grainstone (Bg) is mainly composed of foraminifers within sparry cement. The foraminiferal assemblage includes *Pilammina densa* and *Glomospirella lampangensis*. Other skeletal components are dasycladacean algae and calcimicrobes with minor amount of echinoderms, bivalves, green algal fragments, dasycladacean algae, corals, and ostracods.

Dolomite and calcite crystals are found in dolomitized mudstone (Lm) at Ban Mae Ang and Ban Tha Si. The dolomite and calcite grains range from 0.05-0.1 mm in size. They are equigranular, euhedral to subhedral in shape, and are tightly packed (Figure 14g). In the upper part of Pha Kan Formation, siliciclastic wackestone (Sw), shale, and mudstone are also observed in Ban Tha Si locality (Figure 14h). Sw gradually changes into the siliciclastic sediments of the overlying Hong Hoi Formation.

### Table 1. Microfacies of the Pha Kan Formation

| Microfacies               | Microfacies description                                                                 |
|--------------------------|----------------------------------------------------------------------------------------|
| Siliciclastic wackestone (Sw) | Mud-supported facies composed mainly of matrix with siliciclastic grains. Small bioclast fragments are bivalves and gastropods. Siliciclastic grains are lithic fragments, quartz, feldspars, and reworked carbonate clasts. |
| Lime mudstone and dolomitized mudstone (Lm) | Mud-supported facies composed mainly of lime mud matrix or dolomite matrix with rare skeletal grains. Smaller foraminifers, bivalve shells, and gastropods were observed in this facies. |
| Bioclastic wackestone (Bw) | Mud-supported facies composed mainly of micrite matrix with other skeletal grains. The skeletal components include fragments of echinoid spine and bivalves, algae, bryozoans, gastropods, smaller foraminifers, and ostracods. |
| Oolitic grainstone (Og) | Grain-supported texture composed mainly of ooids and sparry cement. Mud was not observed. |
| Dasycladacean algae grainstone (Dag) | Composed mainly of large dasycladacean fragments with other skeletal and non-skeletal components. Skeletal components include small foraminifers, bivalves, and algae fragments. Non-skeletal components are aggregate grains and intraclasts. |
| Bioclastic grainstone (Bg) | Grain-supported texture composed mainly of foraminifers within sparry cement. The foraminiferal assemblage includes *Pilammina densa* and *Glomospirella lampangensis*. Other skeletal components are dasycladacean algae and calcimicrobes with minor amount of echinoderms, bivalves, green algal fragments, dasycladacean algae, corals, and ostracods. |
| Oncoidal peloidal packstone (Opp) | Composed mainly of rounded clasts of muddy peloids with minor oncoids. The skeletal components of this facies are calcareous algae fragments, microbes, echinoderms, and foraminifers. |
| Peloidal grainstone (Pg) | Composed mainly of peloids with minor oncoids. Algae, bivalve shells, gastropods, and echinoderms are the skeletal components. Non-skeletal components are grapestone and lumps. |
| Oncoidal wackestone (Ow) | Mud-supported texture composed mainly of oncoids and coated skeletal grains dispersed within micrite matrix. Skeletal grains are foraminifers, algae, *Shamovella*, calcimicrobes, ostracods, bivalves, and echinoderms. |
4.3.1. Central area

Five main microfacies types in the central area are oolitic grainstone (Og), bioclastic grainstone (Bg), and oncoidal packstone (Op) associated with bioclastic wackestone (Bw). Micritic ooids are dominant due to the obliteration of original tangential or radial microfabrics by micritization and recrystallization of the micritic envelope. Some ooids partly preserve the original microstructures (Figure 15b). The interspace is filled with sparry cement and quartz grains. Low-angle cross-stratification is visible in some beds of Og (Figure 15c1-c2). Bioclastic grainstone (Bg) is also observed in the Doi Wang Ho locality. The major bioclasts are corals, sponges, *Shamovella*, bivalves, gastropods, foraminifers, and unidentified fossils (Figure 15d-e). *Shamovella* consists of algal groups, cyanobacteria as well as sponges, bryozoans, and foraminifers. Bg is commonly associated with oncoidal packstone (Op) (Figure 15f).
Sparry calcite is the main intergranular cement, filling 10%–20% of the total rock volume. Cyanobacterial encrustations envelop bioclast grains, calcareous algae, and peloid grains (Figure 15f).

The road-cut outcrops at the 434th km of the National Highway 11 (southeast of DWH) locality have oolitic grainstone (Og), bioclastic wackestone (Bw), and siliciclastic wackestone (Sw). Bw, which contains fragments of bivalves, gastropods, and foraminifers, is also recognized. Lime mud matrix accounts for over 70% of the total rock volume (Figure 15g-h). Moreover, the intercalation of Sw, shale, and sandstone indicates that the main lithology of this area is mixed siliciclastic-carbonate. Sw is abundant with quartz grains and ooid fragments (Figure 15i). Limestone is dominated by bioclast fragments and sub-rounded ooid fragments (Figure 15j). Carbonate grains are less abundant in limestones.

### 4.3.2. Northern area

In the northern area, we observed the limestone outcrops from three localities including Ban Sop Chang (SC), Doi Huai Long (DHL), and Ban Khun Mae Huat (KMH) (Figures 2 and 5). There are seven microfacies. The small sponge-microbe boundstone (Smb), peloidal grainstone (Pg), oncoidal peloidal packstone (Opp), and oncoidal wackestone (Ow) are dominant with minor amounts of bioclastic grainstone (Bg), siliciclastic wackestone (Sw), and calcareous siltstone (Cs).

Peloidal grainstone (Pg) is rich in peloids and micritized grains with minor amount of microporoblematica. This facies is always found adjacent to oncoidal wackestone (Ow) and oncoidal peloidal packstone (Opp) in the Doi Huai Long and Ban Khun Mae Huat localities (Figure 16a-b). The bioclasts in sponge-microbe boundstone (Smb) comprise sponges and microbes with a few numbers of problematic fossils, such as *Shamovella* (Figures 5d and 16c). Laminated filaments and micrite are also observed in Smb (Figure 16c). Most Smb samples have been found in Ban Sop Chang (valley and outcrops) and Doi Huai Long localities. Peloidal grainstone is characterized by peloids and micritized grains (Figure 16d).

Bioclastic grainstone (Bg) is observed in the local area, especially in Ban Sop Chang. Bioclasts in Bg mainly consist of calcareous algae, sponges, benthic foraminifers, echinoderm fragments and spines, bivalves, and *Shamovella* (Figure 16e). In Doi Huai Long, quartz grains in siliciclastic wackestone (Sw) are angular and moderately sorted with diameters ranging from 0.05-0.1 mm. At the top of the Doi Long Formation, near the contact with the reddish-brown sandstone and siltstone of the Pha Daeng Formation, quartz grains are randomly distributed in the matrix. Quartz grains account for 14% of the total rock volume, and few lithic fragments are observed (Figure 16f). Sw facies indicates the transition between carbonate and terrigenous clastic rocks. The cement is mainly carbonate and Fe-oxide compounds. Foraminiferal fragments are the most common bioclasts in Sw (Figures 11c and 16f). Calcareous siltstone (Cs) is observed in the lower part, near the contact with the Hong Hoi Formation. Quartz grains in the Cs are well-sorted but angular (Figure 16g). They range in size from 0.008-0.016 mm. Fragments of foraminifers are also found in the clay matrix (Figure 11b).

### 5. Discussion

The Pha Kan and Doi Long Formations in the central, northern, and northeastern areas have different facies types and interpretations as summarized in Table 3. The sedimentary environment of each sub-area is interpreted based on lithology, facies distribution, and microfacies analysis.
5.1. Sedimentary environment of the Pha Kan Formation

5.1.1. Central area

Two studied localities—Phra That Muang Kham (MK) and Doi Ton (DT)—represent the Pha Kan Formation because the lower and upper boundaries of the formation are observed here. Mae Tha Railway Station (NE of MK) and Ban Pha Lad (PL) show the upper part of the formation because the intercalation between the clastic sediments and the basal limestone conglomerate of the Hong Hoi Formation are observed. The central area is dominated by oncoidal peloidal packstone (Opp) and peloidal grainstone (Pg) with few bioclastic grainstone (Bg) and oncoidal peloidal packstone (Opp) (Table 3). Oncoids are weakly laminated and exhibit random growth, representing less frequent rolling. Such oncoids occur in a low-energy environment (Flügel, 2004) (Figure 12d-e). Small (<200 μm in diameter) radial peloids, likewise, form in a very calm and stagnant environment with very low energy (Carozzi, 1961; Conley, 1961).

Table 2. Microfacies of the Doi Long Formation.

| Microfacies                      | Microfacies description                                                                 |
|---------------------------------|----------------------------------------------------------------------------------------|
| Siliciclastic wackestone (Sw)   | Mud-supported facies composed mainly of micrite matrix with siliciclastic grains. Siliciclastic grains are quartz, feldspars, volcanic lithic fragments, and reworked carbonate clasts (ooid and bioclast fragments). Fragments of skeletal components are foraminifers and bivalves. |
| Bioclastic wackestone (Bw)      | Composed of skeletal grains scattered within mud-supported texture that contains mud (lime mud). Skeletal grains include bivalves, gastropods, and foraminifers. |
| Oolitic grainstone (Og)         | Grain-supported texture composed mainly of ooids and other coated grains (oncoids and grapestones). Other skeletal components are fragments of bivalves and foraminifers. |
| Oncoidal packstone (Op)         | Composed mainly of oncoids and micritized grains. Skeletal components include cyanobacterial encrustations, enveloped bioclastic grains, and calcareous algae. |
| Bioclastic grainstone (Bg)      | Grain-supported texture composed mainly of skeletal grains. The skeletal grains include coral fragments, sponges, 
Shamovella
, calcareous algae, bivalves, gastropods, foraminifers, and echinoderm fragments and spines. |
| Sponge-microbe boundstone (Smb) | Composed of abundant sponge and large microbes. Calcareous sponges (spinhirsan, inassan, and scherziniun), algal-microbial crusts, calcimicrobes (Cayeuxia), and microbial laminated stromatolites or spongiosstromata crusts are dominant with other skeletal components including fragments of algae, Tubiphytes sp., and microproblematica such as Microtubus sp., and foraminifers. |
| Oncoidal peloidal packstone (Opp)| Composed mainly of peloids and oncoids. The skeletal components of this facies are calcareous algae, microbes, bivalves, echinoderms, and foraminifers. |
| Peloidal grainstone (Pg)        | Composed mainly of peloids and coated grains. Echinoid fragments, spines, bivalves, foraminifers, and gastropods are the skeletal components. |
| Oncoidal wackestone (Ow)        | Mud-supported texture composed mainly of oncoids and algae dispersed within matrix. Other skeletal grains are 
Shamovella
 and foraminifers. |
| Calcareous siltstone (Cs)       | Composed mainly of quartz grains within mud-supported texture with rare foraminifers and intracrysts. |
In addition, shells, echinoderms, and other bioclasts are coated by a micritic rim related to algal-fungi activities forming constructive and destructive cortoids, which are characteristics of stable shallow-water environment, up to 20-m deep (Swinchatt, 1969), with a low sedimentation rate. Therefore, this section of the Pha Kan Formation was deposited in a shallow lagoon environment. This interpretation is supported by the occurrence of rare evaporites such as dolomite and gypsum and is in accordance with the previous interpretation of Chaimongkol and Charoentitirat (2011) and Ketmuangmoon et al. (2018).

Bioclastic grainstone (Bg) is associated with oncoidal peloidal packstone (Opp). They formed in bioclastic shoal/sandbar depositional environment, depending on the abundance of bioclast grains within...
large-isopachous blocky cement (Tucker, 1984; Flügel, 2010; Haas et al., 2010) (Figure 17). Dasycladacean algae grainstone (Dag) is dominant and composed of well-sorted dasycladacean algae and calcimicrobes associated with foraminifers, aggregate grains, and bivalve fragments (Figure 12g). Dag facies forms landward in the channel of a restricted marine shoal environment because of the abundance of shallow-marine dasyclad fragments (Tucker and Wright, 1990; Parente and Climaco, 1999) (Figure 17). Other carbonate clasts such as ooids, echinoderms, bivalves, and gastropod-echinoderm debris are from localized relatively higher energy deposits. Bioclastic grainstone (Bg) in this area is interpreted to be a sandbar deposit because bioclasts such as echinoderms, gastropods, foraminifers, and ostracods are abundant in such setting (Hine, 1977; Haas et al., 2010). Ooids have not been reported in this area. Thus, the environments of deposition of this area are bioclastic shoal and channels of restricted marine shoal.

Bioclastic wackestone (Bw), siliciclastic wackestone (Sw), and lime mudstone (Lm) represent the upper part of the Pha Kan Formation (Figure 12h-j). These correspond to a deep ramp/slope depositional environment where there is a mixture between siliciclastic and carbonate sediments supply. The occurrence of thin- and parallel-bedded Lm, Bw, Sw, and interbedded mudstone suggests the lack of features indicative of shallow-water deposition. In addition, benthic fauna (bivalve) association indicates that this microfacies may have formed under relatively quiet conditions, in a slope/deep ramp environment (Figure 17) (Wilson, 1975; Tucker and Wright, 1990). The shallow-water clasts (i.e., ooids, brachiopods, echinoderms, ostracods, and foraminifers) could be transported from the platform to a deeper environment by gravity flow.

5.1.2. Northeastern area

The Ban Than (BT) locality is characterized by the presence of oolitic limestones with minor mudstone and shale. The two outcrops of this locality have been investigated for the first time in this study and assigned to be the Pha Kan Formation based on the presence of the lithological contacts between the Phra That, Pha Kan, and Hong Hoi Formations. Three microfacies types, including oolitic grainstone (Og), bioclastic grainstone (Bg), and peloidal grainstone (Pg), of this area are different from the other areas (Table 3). Ooids grains are broken from wave and current reworking (Tucker, 1984; Komatsu et al., 2014) (Figure 13a-b). In addition, the interspace of ooid grains in Og is filled with sparry calcite cement, indicating high-energy and moving water conditions (Figure 13a). A few parts of Bg are bioclast-rich, including calcimicrobes, echinoderms, dasycladacean algae, corals, gastropods, and foraminifers from high-energy environments. This area represents the reefs in the protected intertidal zone such as the edge of a carbonate ramp (Spence and Tucker, 1999; Flügel, 2004). Due to the lack of continuous reef barriers in the northeastern area, shoals could act as barriers protecting the lagoonal part from the open ocean. Therefore, this section of the Pha Kan Formation underwent sea-level fluctuations and changes in energy regimes (Figure 17).

Further to the north of the northeastern area, Opp and Pg are dominated by well-sorted peloid grains, associated with autochthonous calcimicrobes and ooids (Figure 13c-g). These facies formed in the upper photic zone of open-lagoon environments, where regular changes in water energy led to the absence of mud, and the lack of micritization indicates a rapid-cementation in an active circulating water environment (Kiessling and Flügel, 2000) (Figure 17).

5.1.3. Northern area

The Ban Tha Si (TS) locality is represented by limestone with packed oncoid beds. This is in accordance with the facies that, in this area, is likely close to the stratigraphic level of the Pha Kan Formation (Figures 4a-e and 14). The Phra That, Pha Kan, and Hong Hoi Formations. Three microfacies types, including oolitic grainstone (Og), bioclastic grainstone (Bg), and peloidal grainstone (Pg), of this area are different from the other areas (Table 3). Ooids grains are broken from wave and current reworking (Tucker, 1984; Komatsu et al., 2014) (Figure 13a-b). In addition, the interspace of ooid grains in Og is filled with sparry calcite cement, indicating high-energy and moving water conditions (Figure 13a). A few parts of Bg are bioclast-rich, including calcimicrobes, echinoderms, dasycladacean algae, corals, gastropods, and foraminifers from high-energy environments. This area represents the reefs in the protected intertidal zone such as the edge of a carbonate ramp (Spence and Tucker, 1999; Flügel, 2004). Due to the lack of continuous reef barriers in the northeastern area, shoals could act as barriers protecting the lagoonal part from the open ocean. Therefore, this section of the Pha Kan Formation underwent sea-level fluctuations and changes in energy regimes (Figure 17).
Table 3. Summary of microfacies types, associated localities and interpretations of the Pha Kan and Doi Long Formations.

| Microfacies Type                  | Localities                                                                 | Interpretations                                      |
|-----------------------------------|-----------------------------------------------------------------------------|------------------------------------------------------|
| Siliciclastic wackestone (Sw)     | Mae Tha Railway Station (northeast of MK), the 434th km of the National Highway 11 (southeast of DWH), Ban Tha Si (TS), Phratu Pha Shrine (PP), Doi Wiang Ho (DWH), Doi Huai Long (DHL), Ban Sob Chang (SC) | Slope to deep                                        |
|                                   | Mixed-siliciclastic and carbonate sediments (volcanic activity)              |                                                      |
| Bioclastic wackestone (Bw)        | Mae Tha Railway Station (northeast of MK), Ban Pha Lad (PL), the 434th km of the National Highway 11 (southeast of DWH), Ban Than (BT), Ban Tha Si (TS), Ban Mae Ang (MA) | Slope to deep                                        |
|                                   | Lagoon                                                                      |                                                      |
| Oolitic grainstone (Og)           | Phra That Muang Kham (MK), Doi Ton (DT), Ban Than (BT), the 434th km of the National Highway 11 (southeast of DWH), Doi Wiang Ho (DWH), Doi Huai Long (DHL), Ban Khun Mae Huat (KMH) | Oolitic shoal                                        |
| Oncoidal packstone (Op)           | The 434th km of the National Highway 11 (southeast of DWH), Doi Wiang Ho (DWH), Ban Khun Mae Huat (KMH) | Channel of shoal                                     |
| Bioclastic grainstone (Bg)        | Phra That Muang Kham (MK), Doi Ton (DT), Ban Than (BT), Doi Wiang Ho (DWH) | Bioclastic shoal                                     |
| Dasyycladacean grainstone (Dag)   | Doi Ton (DT)                                                                | Channel of shoal                                     |
| Sponge-microbe boundstone (Smb)   | Ban Sop Chang (SC), Doi Huai Long (DHL)                                     | Reef                                                 |
| Oncoidal peloidal packstone (Opp) | Phra That Muang Kham (MK), Ban Than (BT), Ban Tha Si (TS), Phratu Pha Shrine (PP), Doi Huai Long (DHL), Ban Khun Mae Huat (KMH) | Lagoon                                              |
| Peloidal grainstone (Pg)          | Ban Than (BT), Ban Tha Si (TS), Phratu Pha Shrine (PP), Doi Huai Long (DHL), Ban Khun Mae Huat (KMH) | Lagoon                                              |
| Oncoidal wackestone (Ow)          | Phra That Muang Kham (MK), Ban Tha Si (TS), Ban Mae Ang (MA), Ban Than, Doi Huai Long (DHL), Ban Khun Mae Huat (KMH) | Lagoon                                              |
| Calcareaeous siltstone (Cs)       | Doi Huai Long (DHL)                                                        | Mixed-siliciclastic and carbonate sediments, lagoon to peritidal zone |
| Lime mudstone and Dolomitized mudstone and (Lm) | Ban Tha Si (TS), Ban Mae Ang (MA), Ban Than, Doi Huai Long (DHL), Ban Sob Chang (SC), Ban Khun Mae Huat (KMH) | Lagoon to peritidal zone                             |
|                                   | Mae Tha Railway Station (northeast of MK)                                   | Deep                                                 |

packstone (Opp), peloidal grainstone (Pg), and oncoidal wackestone (Ow) with a low amount of lime mudstone and dolomitized mudstone (Lm) are observed in the northern area (Table 3). Opp, Pg, and Ow accumulated in a lagoon environment due to the abundance of algae and oncos (Wilson, 1975; Senowhri-Daryan et al., 1993; Flügel, 2004) (Figures 14 and 17).

Lm and Ow facies formed in shallow water under a weak hydrodynamic level in the peritidal zone due to the dominance of dolomite crystals and intercrystalline recrystallized calcite and dolomite cements (Figure 14g). Alternation between fine-crystalline carbonate (limestone and dolomite) layers, which might be microbially induced and diagenetically deformed, and evaporite crystals (gypsum) layers could form in the intertidal zone of coastal plains and evaporitic lacustrine basins (Flügel, 2010). Thus, the northern area is a large platform of a shallow-marine lagoon environment (Figure 17). In addition, the volcanolithic fragments and feldspars preserved within the siliciclastic wackestone (Sw) indicate that the Pha Kan Formation was deposited near the volcanic arc of the Sukhothermal Zone (Figure 14h).

5.2. Sedimentary environment of the Doi Long Formation

5.2.1. Central area

The Doi Wiang Ho (DWH) and km 434th of the National Highway 11 localities are characterized by massive gray to light gray bedded limestone intercalated with mudstone, exhibiting a discordant contact with the underlying siliciclastic rocks of the Hong Hoi Formation. In addition, limestone in these localities is dominated by foraminifers including Aulotortus sinusuosus, Endoteba bithynica, and involutinitis (Aulotortus sp.). This association indicates Carnian age (Kobayashi et al., 2006; Miyahigashi et al., 2012). By combining our and the previous studies, we can assume that the investigated localities are closely stratigraphic level to the Doi Long Formation based on the lithologies, stratigraphic relationships, and fossils. Bioclastic grainstone (Bg) is dominated by corals, sponges, Shanovella, bivalves, gastropods, foraminifers, associated with algae and calcimicrobes (Figure 15d-e) and has well-developed pachyous marine cement. Hence, Bg facies is formed in a small reef environment (Wilson, 1975; Boggs, 2012). The absence of peloids and micritization of grains suggests that the Bg facies is thus a high-energy facies that deposited in shoal or sandbar where sediments were transported elsewhere.

Ooids in Oolitic grainstone (Og) are spherical to concentric, indicating high-energy open marine conditions. The presence of cross-lamination within the Og facies supports the interpretation that this deposit can be related to wave action (Flügel, 2004) (Figure 15c1-c2). The lack of fossils is also typical of ooids developed in open marine environments dominated by constant water flow, which is favorable to the precipitation of ooids. Some samples are oncoidal packstone (Op); they are from a protected area in contact with shoal or a lower energy area located near shoal or in the channel of shoal environments (Wilson, 1975) (Figure 18).

The association of bioclastic wackestone, siliciclastic wackestone, and clastic sedimentary rocks such as shale, mudstone, and sandstone is characteristic of deep ramp/slope environments (Wilson, 1975; Tucker and Wright, 1990; Boggs, 2012) (Figures 15p-j and 18). The clastic sedimentary rocks could be turbidity current deposits. Grains of shallow-water organisms could be derived from the active edge of the platform.

5.2.2. Northern area

In the northern area, Ban Sop Chang (SC), Doi Huai Long (DHL), and Ban Khun Mae Huat (KMH) localities are characterized by limestones with abundant algalstromatolite, peloids, and bioclasts. Sponge and microbe features and oncos are observed in SC and DHL localities. All studied localities show the contacts between the carbonate rocks of the Doi Long Formation with the turbiditic sediments of the Hong Hoi Formation and the red-beds clastic sediments of the Pha Dang Formation, respectively (Figure 8). In addition, the foraminifers in the northern area indicate Late Triassic, corresponding with the previous study from Miyahigashi et al. (2012) (Figures 10 and 11). Peloidal grainstone (Pg) and oncoidal wackestone (Ow) are dominant (Figure 16a, d) (Table 3). This formation is rich in Foraminifers such as Aulotortus sinusuos micro-fauna (Kobayashi et al., 2006; Miyahigashi and Ueno, 2015) and is associated with Tubiphytes (which is sponge-microbial reefal sediments (Miyahigashi and Ueno, 2015)). Pg is a mud-rich packstone to grainstone, which is formed in a low energy depositional setting (Flügel, 2004, 2010) (Figures 16d and 18). Oocs in Ow have irregular random growth which are typically formed in a low-current energy, where the current was not strong enough to create good concentrical lamination in the cortices (Wright, 1983) (Figures 16a and 18). Hence, the association of
Figure 17. Schematic depositional model of the Pha Kan Formation (see text for description). The abbreviations of each locality are MK for Phra That Muang Kham, NE of MK for Mae Tha Railway Station, DT for Doi Ton, PL for Ban Pha Lad, BT for Ban Than, TS for Ban Tha Si, MA for Ban Mae Ang, and PP for Phratu Pha Shrine.

Figure 18. Schematic depositional model of the Doi Long Formation (see text for description). The abbreviations of each locality are DWH for Doi Wiang Ho, SC for Ban Sop Chang, DHL for Doi Huai Long, and KMH for Ban Khun Mae Huat.
Pg and Ow is a characteristic of a shallow lagoon environment due to the presence of algae, calcimicrobes, and bioclast assemblages (Tucker and Wright, 1990; Flügel, 2004; El-Yamani et al., 2018).

The abundance of peloids, oncoinds, and algae fauna in oncoindal peloidal packstone (Opp) and peloidal grainstone (Pg) facies suggests that they formed in a photic zone. The absence of characteristics derived from a high-energy and wave action, such as broken bioclast, ooid grains, and cross-stratification, indicates that Opp and Pg developed in a low-energy condition (Figure 16b). Sponge-microbe boundstone (Smb) facies shows binding textures, which are formed by Shanomella, calcimicrobes, and minor skeletal organisms such as foraminifers, algae, corals, and bryozoans (Figure 16e). Thus, Smb facies developed in a small-scale reef environment. In addition, reefal cavities with large isotopachous and blocky sparry cement in Smb facies indicate rapid cementation in an open marine and circulating water condition (Flügel, 2010) (Figure 16e-d) (Table 3).

Therefore, the Doi Long Formation of this area represents a shallow lagoon with small-scale reefs (e.g., Flügel, 2004, 2010; Reid and McIntyre, 2012) (Figure 18). The facies association in this area is similar to that in Popa et al. (2014) in which the carbonate environment was interpreted to be cement-dominated upper-slope Tuhiphytes reef. In addition, siliciclastic wackestone (Sw) in the upper part of the Doi Long Formation contains abundant quartz and volcanic fragments (Figure 8). This suggests that the Doi Long Formation limestone deposition was strongly influenced by a supply of volcanic materials from the volcanic arc of the Sukhothai Zone.

The evidence of the main reef builders are various microbial crusts, algae, microproblematica Shanomella, and oncoinds in sponge-microbe boundstone facies (Smb) (Figure 16e). However, large continuous corall-sponger rudstone/framework is not observed. These reef builders are, thus, formed as patch reefs or small-sized bioherms in the reef environment (Embry and Klován, 1971). Calcimicrobes found within Smb facies is an indicator of lagoon and reef environments (Riding, 2000).

5.3. Mixed carbonate and siliciclastic sediments in limestones of the Lampang Group

Several previous studies have suggested that volcanic activity in the Sukhothai Zone started during the Late Carboniferous (Barr and MacDonald, 1991; Ueno and Hisada, 2001; Sone and Metcalfe, 2008; Metcalfe, 2011, 2013). From the U-Pb dating of zircons in volcanic rocks, the volcanic belts within the Sukhothai Zone, namely Chiang Khong and Lampang volcanic belts, occurred in the Middle to Late Triassic (e.g., Barr et al., 2000; Srichan et al., 2009; Qian et al., 2017). Recent U-Pb dating of clastic sedimentary rocks shows that the volcanic activity in the Sukhothai Zone occurred in the Early to early Late Triassic, corresponding the depositional age of the Phra That, Hong Hoi, and Pha Daeng Formations (Hara et al., 2017). In addition, U-Pb dating studies of volcanic rocks reported that the volcanic activity of the Lampang volcanic belt occurred around the Middle Triassic (Ladinian), 241-240 Ma ago, which is during the deposition of the Hong Hoi Formation (Barr et al., 2000; Qian et al., 2017). This finding is corresponding with the U-Pb ages of detrital zircon of Hara et al. (2017), indicating the sediment sources of the Hong Hoi and Pha Daeng Formations were the older basaltic-felsic volcanic rocks from intensive igneous activity of the Sukhothai Zone. Based on the stratigraphic studies, the Early-Late Triassic Lampang Group can be subdivided into the Phra That, Pha Kan, Hong Hoi, and Pha Daeng Formations, representing the succession of repeated carbonate- and turbidite-dominated facies (Chaoerdumrong, 1992; Chonglakmani, 2011). The Hong Hoi Formation contains intercalations of limestone bodies and clastic sedimentary rocks while the Pha Kan and Doi Long Formations comprise mainly of limestones, indicating the lateral facies change between the formations (Chonglakmani, 2011; Feng et al., 2005; Kamata et al., 2016). From the combination between the previous studies and this study, the siliciclastic materials in the Pha Kan and Doi Long Formations are from the volcanic arc of the Sukhothai Zone, resulted from the volcanic activity during the Triassic (Barr et al., 2000; Srichan et al., 2009; Hara et al., 2017; Qian et al., 2017).

The Pha Kan and Doi Long Formations contain siliciclastic wackestone (Sw) microfacies within the carbonate rocks. Sw microfacies, composed of volcanic lithic fragments, angular quartz, and feldspar grains resulted from volcanic activity, occurs in various areas (Figures 4e, 14h and 16f). This microfacies was found in multiple localities, which include Ban Tha Si (TS), Phrathu Pha Shrine (PP), Doi Hual Long (DHL), Ban Sop Chang (SC), and Doi Wiang Ho (DWH) (Figure 2). In addition, the volcanic grains in some samples contribute up to 10% of the total rock volume and are either scattered or locally assembled into flat, lenticular laminae as observed in the field (Figure 4e). This confirms that the Lampang Sub-basin was deposited closed to the volcanic arc of the Sukhothai Zone (Chonglakmani, 2011; Kamata et al., 2016; Hara et al., 2017) and the forearc basin (Singharajarwapan and Berry, 2000).

5.4. Depositional model

The depositional environment of the Pha Kan and Doi Long Formations is interpreted based on microfacies type and association and lithological characteristics that have been determined through slabbased and thin-section under the petrographic microscope. The depositional environments interpreted here are based on the criteria described by Wilson (1975), James and Mountjoy (1984), McBreath and James (1984), Read (1985), Chaoerdumrong and Rao (1992), Flügel (2010), Miyahigashi et al. (2012). The spatial distribution of microfacies association is also considered when constructing the depositional models shown in Figures 17 and 18.

The depositional models have been created based on the distribution of microfacies in the thirteen studied localities, and the models have been compared with previous studies also. In the field, the facies distribution and their transitional contacts within each area are observed (Figures 4d and 5f), whereas the vertical change in facies succession from shallow marine facies to deep marine facies is only observed in MK, PL, PP, and km 434th of the National Highway 11 localities (Figures 7 and 8). Thus, the change in depositional environment is mainly observed in lateral directions (Figures 17 and 18). This could be induced by diverse factors such as sea level, energy, salinity, temperature, nutrient supply, turbidity, and platform morphology (Flügel, 2004). The Triassic Pha Kan and Doi Long limestones show characteristics of shallow-water ramp carbonate platforms and reef/bank settings, respectively (Figures 17 and 18). The slope of the carbonate system is represented by Sw and Bw microfacies that are typical of a shallow-to-deep-water environment influenced by elastic influx that is originated from the platform margin (Figures 12h, i and 15i, j). Skeletal or oolitic sand shoal facies are observed along the rim of the platform which is highly dominated by winds and waves (Figures 12a-c, 13a, b and 15a, b). Opp, Pg, Ow, Bw, Lm, and Bm microfacies developed in the platform interior (Figures 15e-g, 14a-f and 16a-d). Ow, Lm, and Bw locally associated with Opp were formed in low-energy protected parts of the lagoon where water circulation is restricted, and mud is dominated. Smb is reef deposits, probably located within lagoon environment (Figure 16b, c, e). The lack of a continuous barrier reef suggests that the depositional setting is a ramp carbonate platform (Wilson, 1975; Read, 1985; Flügel, 2010).

Chaoerdumrong and Rao (1992) proposed that the Pha Kan Formation formed in a ramp platform and the platform margin is dominated by shoal intercalated with high amount of oncoinds, corresponding to Og and Op microfacies of this study (Figure 12a-d). The platform interior is represented by a wide variety of low to high energy facies within the lagoon (Figure 14a-f). The differences between our model and that of Chaoerdumrong and Rao (1992) are (1) the ramp platform has peritidal zone and siliciclastic wackestone (Sw) as observed in the northern area (Figure 14g, h) and (2) the platform margin is dominated by bioclastic and oolitic shoals with small-scale channels of shoal (Figure 17). The Bg with Pilammina densa, Glomospirella lampangensis foraminifers and Dag
facies found mostly in the central area (MK and DT) (Figures 9a, f and 12a, b and g) are common in such environments. Slope to deep environments of the carbonate system are represented by Bw, Sw, and Lm microfacies in the PL and NE of MK localities (Figure 12h-j), underlying the basal limestone conglomerate of the Hong Hoi Formation (Figure 12k). In addition, limestone of the Pha Kan Formation in the BT locality in the northeastern Lampang area is studied for the first time (Figures 2 and 13). Here, the oolitic grainstone (Og) is dominated (Figure 13a, b) with minor amount of platform interior facies (Figure 13c-g). Therefore, this locality deposited in a shoal environment and minor lagoon (Figure 17).

The environment of depositional model of the Doi Long Formation of this study (Figure 18) is in agreement with that of Miyahigashi et al. (2012) in that the formation formed as shoal deposits on the rim of a platform and small patch reefs in the platform. Microfacies type oolitic grainstone (Og) and bioclastic grainstone (Bg) from locality km 434th of the National Highway 11 (this study) and MT-2-MT-7 and MT-11-MT-13 of Miyahigashi et al. (2012) show characters of shallow-water reef/bank setting. However, our study area extends further to the north of that of Miyahigashi et al. (2012) (Figure 2). In the northern area, siliciclastic wackestone (Sw), calcareous siltstone (Cs), oncoidal wackestone (Ow), and oncoidal peloidal packstone (Opp) have been reported in this study for the first time. Oncoidal wackestone (Ow) and oncoidal peloidal packstone (Opp) are characteristic of stable shallow-water environment where the water is calm and stagnant with very low water circulation, lacking high-energy wave and current (Swinchatt, 1969; Carozzi, 1961; Conley, 1977) (Figure 16a, d). Microbial features (algal structures, microbial peloids, and oncoid) associated with ooids are also well presented in Opp (Figure 16b), suggesting stable shallow-water environments. No ooids have been found in the northern area. Oolitic grainstone (Og) is only found at the km 434th of the National Highway 11 in the central area (Figures 15a-c and 18).

6. Conclusion

This study integrates the sedimentological data and microfacies and fossil associations of the Lampang limestone located in the Sukhothai Zone, northern Thailand. The study area extends further to the north of the former studies of Chaodumrong and Rao (1992), Kobayashi et al. (2006), and Miyahigashi et al. (2012). Six localities (DT, BT, SC, KMH, DWH, and MA) of this work have never been previously studied. Peritidal zone and mixed carbonate and siliciclastic sediments are also investigated for the first time here. Figure 6 summarizes the foraminiferal assemblages of both Pha Kan and Doi Long Formations from this study and those from the previous studies of Kobayashi et al. (2006) and Miyahigashi et al. (2012) and refines the depositional age of the formations. The foraminiferal assemblages clearly indicate that the Pha Kan Formation is the Early Triassic to Ladinian and the Doi Long Formation is Carnian.

The detailed study of the Pha Kan and Doi Long Formations in terms of microfacies, sedimentology, and paleoenvironment reconstruction revealed that:

(1) The Pha Kan and Doi Long Formations in Lampang Sub-basin represent the shallow-water carbonate platform.

(2) The carbonate rocks consist of twelve microfacies ranging from peritidal to a shallow lagoon, small-scale reef, shoals, and deep ramp to slope environments.

(3) In the Pha Kan Formation, the platform margin is dominated by two main environments, the oolitic and bioclastic shoals and deep ramp environments (Figure 17). The platform interior is represented by a wide variety of low-energy facies such as those developed in the channel of shoal, reef, and lagoon environments to peritidal zone.

(4) Four depositional environments in the Doi Long Formation are lagoon, reef, shoal, and slope facies (Figure 18). Thus, this formation is more likely to be deposited in a platform setting rather than a reef or bank setting, as previously proposed by Miyahigashi et al. (2012).

(5) Clastic minerals (e.g., quartz, feldspars, and zircon) and volcanic lithic fragments have been observed in both formations. This suggests that the volcanic arc system was providing an influx of volcanic materials into the platform at the time of the carbonate sedimentation.

Our findings provide better understanding of the regional stratigraphic correlation and lithostratigraphy of the Triassic carbonate rocks in Thailand, Lao People’s Democratic Republic, and People’s Republic of China. According to the regional biostratigraphic correlation and foraminifer’s studies of Ueno et al. (2018) and the results from this study, the Lampang Group in northern Thailand can be correlated with the Lincang Massif of western Yunnan through a part of the northwestern Laos. These provide a firm basis for supporting the tectonostratigraphic correlation across the Sukhothai Zone in northern Thailand. Consequently, our study reveals critical details of the microfacies and sedimentological records explaining the environment and geologic settings of the Triassic carbonate rocks of the northern Thailand in the Sukhothai Zone, which is one of the major tectonostratigraphic units comprising mainland Southeast Asia.

Declarations

Author contribution statement

Kritsada Moonpa: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Kannipa Motanated: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Funding statement

This work was supported by Science Achievement Scholarship of Thailand (SAST) and the Shell Centennial Education Foundation, Shell Company of Thailand.

Data availability statement

Data included in article supplementary material/referenced in article.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

Acknowledgements

The authors would like to thank Assoc. Prof. Dr. Thasinee Charoenitirat for valuable suggestions on the stratigraphy of the carbonate rocks in Lampang area. We thank Assoc. Prof. Dr. Niti Mankhemthong, Assist. Prof. Dr. Wecrapan Srichan, and Dr. Pitaksit Ditbanjong for the discussions related to the geological background of the study area. We thank Chanawut Sooksabai for technical assistance and Chuwit Thaimai, Thikapong Thata, Sathit Kanthata, and students from the Department of Geological Sciences, Chiang Mai University (CMU) for their help in the field sessions.
Ueno, K., Hisada, K., 2001. The Nan-Uttaradit-Sra Kaeo Suture as a main Paleo-Tethyan suture in Thailand: is it real? Gondwana Res. 4, 804–806.

Ueno, K., Charoentitirat, T., 2011. Carboniferous and Permian. In: Ridd, M.F., Barber, A.J., Crow, M.J. (Eds.), The Geology of Thailand. Geological Society, London, pp. 71–135.

Ueno, K., Kamata, Y., Uno, K., Charoentitirat, T., Charusiri, P., Vilaykham, K., Martini, R., 2018. The Sukhothai zone (Permian–Triassic island-arc domain of Southeast Asia) in northern Laos: insights from Triassic carbonates and foraminifers. Gondwana Res. 61, 88–99.

Wilson, J.L., 1975. Carbonate Facies in Geologic History. Springer-Verlag, Berlin.

Wright, V.P., 1983. Morphogenesis of oncoids in the lower Carboniferous Llanelly Formation of south Wales. In: Peryt, T.M. (Ed.), Coated Grains. Springer, Berlin, pp. 424–434.