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A remarkable end-Permian boulder bed of conglomeratic limestone at Nam Nao in NE Thailand: its biostratigraphical and environmental significance

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Abstract
Litho- and bio-stratigraphic analyses on the Lower Permian Khao Pa Khi and Middle-Upper Permian Khao Tham Yai limestones, and the siliciclastic Hua Na Kham Formation on clastic-dominant continental shelves in the western margin of the Indochina Block record important aspects of the extinction-related Guadalupian-Lopingian (G-LB) interval, and a large-scale sea-level drop of a global environmental change in the low-latitudes of the East Paleo-Tethys. Fusulinid and foraminifer species within the Khao Tham Yai Limestone record the abrupt disappearance of large-tested fusulines. The Khao Tham Yai Limestone above the G-LB is characterized by the sudden flourishing of a diverse range of smaller fusulinid and foraminifer species, together with the occurrence of a large number of broken fragments of diverse large-tested fusulinids. The second disappearance of smaller foraminifers occurred during the Wuchiapingian in the upper part of the Khao Tham Yai Limestone. These two phases of disappearance of fusulinid and foraminifer species on the continental margin of the Indochina Block likely appeared a little late compared to similar phases in the paleo-atolls of the mid-Panthalassa. The Wuchiapingian Hua Na Kham Formation unconformably onlaps the Khao Tham Yai Limestone replacing previous carbonate formation. These carbonate and siliciclastic formations are largely heteropic facies and possibly interfinger with each other. A remarkable boulder bed of fusulinids and conglomeratic limestones occurs on the top of the Hua Na Kham Formation. Fusulinid and foraminifer species in boulders indicate that they were eroded off the Khao Tham Yai barrier reef and transported by submarine debris flows that brought them to sites on the continental shelf where the Hua Na Kham Formation deposited. Such catastrophic events may have been caused by large-scale eustatic sea-level drop. The effects of this global environmental change on the continental margin of the Indochina Block may have occurred a little later in the Wuchiapingian compared with subaerial exposure and erosion reported from the G-LB interval in mid-oceanic seamounts that occur in mid-Panthalassa.

Key words: boulder bed of limestone, foraminifer species, Indochina Block, sea level drop, Upper Permian

1. Introduction

Since 2005, we have been carrying out geological and paleontological studies on a karstic mountain in Khao Tham Yai (Hill of the Large Cave), about 30 km NW of Nam Nao in eastern Phetchabun Province, NE Thailand in collaboration with the Department of Mineral Resources, Thailand. From a regional tectonic perspective, our research area is located along the western margin of the Indochina Block (Fig. 1). We have already published parts of a biostratigraphic investigation concentrating on the evolution and extinction of a Middle and Upper Permian fusulinid and foraminifer fauna from a single limestone unit named the Khao Tham Yai Limestone in the Nam Nao district (Hada et al., 2015). We have clarified the following aspects of evolutionary and extinction patterns of fusulinid species in the shallow-water Paleo-Tethyan shelf area in the western margin of the Indochina Block.

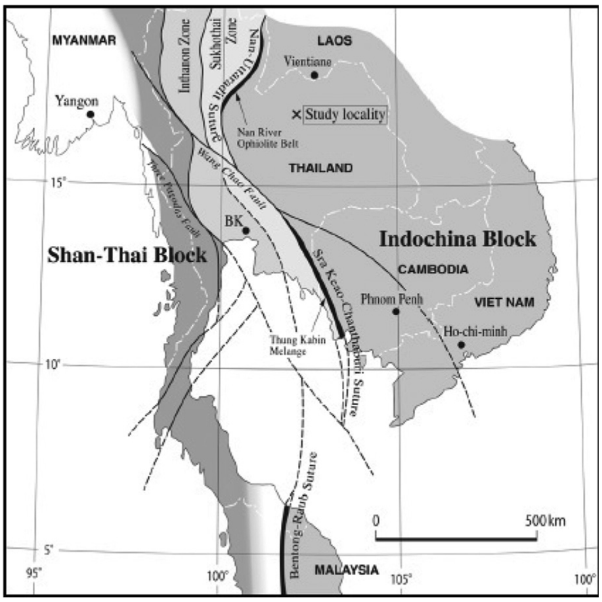

Figure 1: Index map showing the study locality and the tectonic subdivisions of Thailand and adjacent regions (Hada et al., 2015).

(1) The Khao Tham Yai Limestone ranges from the Wordian (middle Middle Permian) up to the Wuchiapingian (lower Upper Permian). The existence of the Wuchiapingian within a single continuous limestone section rangingfrom Middle to Upper Permian is confirmed for the first time in Thailand.

(2) Three fusulinid zones are differentiated in the Khao Tham Yai Limestone namely; *Colania, Lepidolina* and *Codonofusiella* zones in ascending order.

(3) Shell sizes of the fusulinid species in the *Lepidolina* Zone display continuous rapid morphological change along a one-way evolutionary path from small, primitive species with simple structure to large, highly evolved species having a complicated wall structure.

(4) The G-LB between the Guadalupian (Middle Permian) and Lopingian (Upper Permian) within the Khao Tham Yai Limestone is clearly defined as the boundary of the abrupt change in the fusulinid assemblages from the elimination of large-tested Verbeekinids and Schwagerinids to the domination of small-shelled Schubertellids with simple wall structure that underwent slower evolutionary morphological change than earlier fusulinids and persisted and expanded in the Wuchiapingian.

(5) Even smaller fusulinids abruptly become extinct near the top of the Khao Tham Yai Limestone during the Wuchiapingian.

(6) Eventually, clastic sediments unconformably onlap (abut) the Khao Tham Yai Limestone characterized by algae-foraminifera biota.

In this paper, we particularly provide details of our recent study on the Upper Permian siliciclastic formation onlapping the Khao Tham Yai Limestone and on a newly found boulder bed of fossiliferous and conglomeratic limestones on the top of the siliciclastic sequence focusing on a great variety of the fusulinid and foraminifer species identified from boulders, and their characteristic occurrence. In relation to this new data, the aim of this paper is also to reanalyze the biostratigraphic investigation of the smaller fusulinid and foraminifer species above the G-LB with special reference to remarkable facies change in the Khao Tham Yai Limestone.

2. Tectonic and geologic setting

Recently, Ridd et al. (2011) presented the widely available book entitled The Geology of Thailand in the English language that attempts to cover the wide range of Thai Geology. In this book Ueno and Charoentitirat (2011) provide an especially useful attempt to comprehensively review the Carboniferous and Permian systems of Thailand. They make great efforts to sort out the informal naming of many stratigraphic units based on available paleontological data that provide critical chronostratigraphic constraints. Following their synthesis, we firstly attempt to readjust the stratigraphic and geotectonic data presented by Hada et al. (2015), then move to the main issue.

Since the epoch-making proposal by Bunopas (1981), Thailand has come to be understood as being fundamentally comprised of two distinct continental blocks; the Indochina Block, which is regarded as a Cathaysian domain to the east and the Shan-Thai Block, which is a Gondwana-derived block associated with the eastern Cimmerian Continent to the west (Fig. 1).

The Indochina Continental Block is delineated to the west by the Nan Suture Zone (Nan-Uttaradit Suture in Fig.1) (Figs.1 and 2). The suture zone contains remnants of a now closed back-arc basin that once existed in the western flank of the Indochina Block (Ueno and Hisada, 2001). Upper Triassic red beds with red chert pebbles that yield Middle Triassic radiolarians disconformably overlies the serpentinite mélange of the Nan Suture Zone in the Nan Mine, N Thailand. This indicates that the back-arc basin closed during Late Triassic time (Hada et al., 1999). Red chert is an important constituent element of the back-arc basin (marginal sea) that opened in the Permian and closed in the Triassic.

Another enigmatic aspect of the Indochina Block is the origins of the Nam Duk Basin. This basin along the western margin of the Indochina Block separates the Pha Nok Khao Platform to the east from the Khao Khwang Platform to the west (Fig. 2). It has been variously interpreted as the Indosinian collisional orogen, the Loei Fold Belt (Helmcke and Lindenberg, 1983; Helmcke, 1994) or a suture, the Loei Suture (Chutakositkanon et al., 1999; Charusiri et al., 2002). Charusiri et al., (2002) suggested that it represents a suture zone based on the existence of older rocks ranging from Upper Silurian to Cretaceous including radiolarian chert as well as basic and ultrabasic igneous rocks, which represent scraped-off ocean-floor rocks. It extends from Loei to the east of the Nam Duk Basin. However, the Loei Suture is still the subject of much debate.

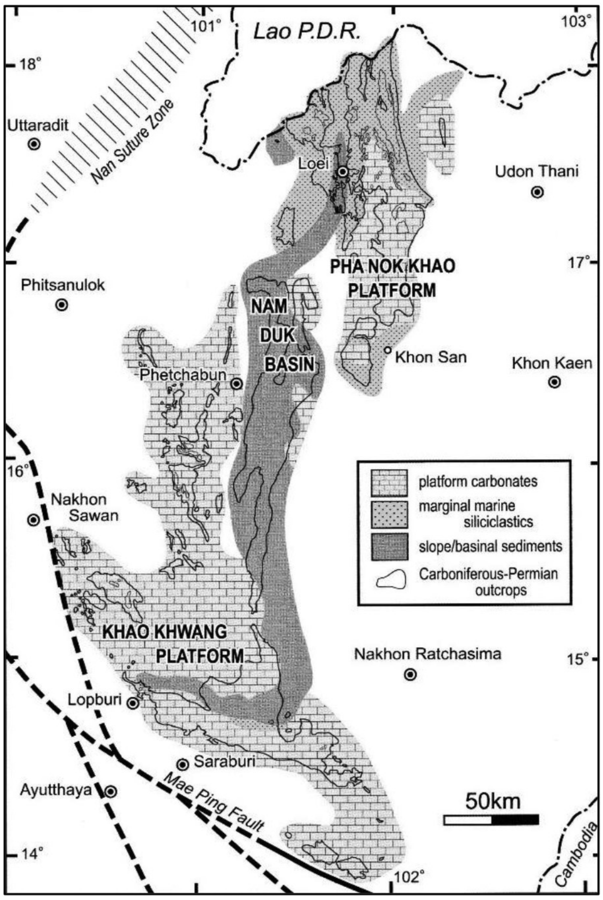

Figure 2: Major facies subdivisions for Late Paleozoic rocks on the western margin of the Indochina Block (Wielchowsky and Young, 1985; Ueno and Charoentitirat, 2011).

The Nam Duk Formation in the Nam Duk Basin is composed of siliciclastic dominant strata and has also been the subject of many studies in the context of the geotectonic evolution of Thailand. It has long been believed that the formation represents a typical pelagic flysch-molasse succession corresponding to pre-, syn- and post-orogenic stages of an 'Indosinian' collisional orogeny based on the classic 'geosynclinal model' (Loei Fold Belt) (Helmcke and Lindenberg, 1983; Helmcke, 1994). However, it is hard to draw any conclusions in the context of the formation's orogenic development in the view of the incomplete understanding of the stratigraphy and stratigraphic relations between the Nam Duk Formation and surrounding formations (Ueno and Charoentitirat, 2011). Evidence for the existence of a molasse sequence is also questionable. Ueno and Charoentitirat (2011) interpreted the Nam Duk Basin as an intracra tonic depression between two shallow platform areas on the margin of the Indochina Block and reported that the strata of the Nam Duk Basin are dominated by Permian slope-to-basin sediments and pre-dominantly consist of turbidites. We suggest that the Loei Suture is not a suture between two microcontinents inside the Indo china Block, nor is Loei Fold Belt a collisional orogeny. Rather it possibly originated as an intraplate strike-slip deformation belt, and the Nam Duk Basin is a basin related to intraplate strike-slip deformation. The northern extension of the Loei Suture or the Nam Duk Basin is largely concealed by Mesozoic sediments thus relations to the Nan Suture Zone remain unclear (Fig. 2).

Ueno and Charoentitirat (2011) formally introduced the term Loei Group for a succession of carbonate and siliciclastic Pennsylvanian-Permian strata associated with the Pha Nok Khao Platform on the eastern side of the Nam Duk Basin. In the southern part of Loei, this group is composed of the siliciclastic Huai Som (mostly Pennsylvanian), carbonate Pha Nok Khao (mainly Lower-Middle Permian) and siliciclastic Hua Na Kham (younger Permian) formations (Chonglakmani and Sattayarak, 1984).

The Khao Tham Yai Limestone (Hada et al., 2015) is extensively exposed in the Nam Nao district in NE Thailand and is assigned to the carbonate Pha Nok Khao Formation of the Loei Group on the Pha Nok Khao Platform. Fontaine and Salyapongse (2001) and Fontaine et al. (2002) first showed that the Khao Tham Yai Limestone ranges from Murgabian (middle Middle Permian) to the top of Median (upper Middle Permian). Later Hada et al. (2015) proved the age of the Khao Tham Yai Limestone extends to the Upper Permian (Wuchiapingian).

Fontaine and Salyapongse (2001) and Fontaine et al. (2002) reported a siliciclastic succession in the valley on the eastern side of the Khao Tham Yai Limestone. It appears to stratigraphically overlie the Khao Tham Yai Limestone. Although, it was previously assigned to the Nam Duk Formation, it bears similarity to the siliciclastic Hua Na Kham Formation of the Loei Group as noted by Ueno and Charoentitirat (2011).

Fontaine and Salyapongse (2001) also made a reference to the Khao Pa Khi Limestone that is in direct contact with the Hua Na Kham Formation. It is sparsely fossiliferous and was once regarded as Triassic, whereas Fontaine et al. (2002) later tentatively considered a Permian age. We recently found Lower Permian fusulinid species in the massive Khao Pa Khi Limestone and it is confirmed as Lower Permian (see below).

In the following, we describe the fusulinid and foraminifer species, and the relevant facies change of the Khao Tham Yai and Khao Pa Khi limestones of the Pha Nok Khao Formation of the Loei Group, and the boulder bed of fossiliferous and conglomeratic limestones at the top of the siliciclastic Hua Na Kham Formation of the Loei Group, which are distributed in the Pha Nok Khao Platform on the eastern side of the Nam Duk Basin on the western flank of the Indochina Block.

3. Lithology and fossils below the G-LB within the Khao Tham Yai Limestone of the Pha Nok Khao Formation, Loei Group

This limestone sequence which is exposed extensively in the Nam Nao district, which has been regionally included in the Lower to Middle Permian Pha Nok Khao Formation of the Loei Group and is termed the Khao Tham Yai Limestone (Hada et al., 2015). We previously redefined the range of the Pha Nok Khao Formation from the Lower to Upper Permian on the basis of biostratigraphic data (Hada et al., 2015). Strata of the formation include carbonate materials that accumulated *in situ* on the shallow-water, low-latitude Paleo-Tethyan shelf area within the western margin of the Indochina Block.

The Khao Tham Yai Limestone crops out as a very large, elongated, N-S trending limestone hill about 10 km long in the Nam Nao National Park in NE Thailand. It is well exposed on steep slopes, cliffs and the crest of the limestone hill in the Nam Nao district, and forms a continuous, near homoclinal section estimated to be ca. 1700 m thick (Fig. 3). It strikes NNW-SSE to NW-SE and dips moderately to the east (Fig. 4). We subdivided the Khao Tham Yai Limestone into the Lower, Middle and Upper members (Hada et al., 2015). Figure 5 shows a composite stratigraphic column and fusuline distribution of the upper part of the Lower Member and the Middle and Upper members of the Khao Tham Yai Limestone (Hada et al., 2015). Fontaine et al. (2002) has divided the Khao Tham Yai Limestone into 8 horizons from the western side (base) to the eastern side (top) of the hill. Lower, Middle and Upper members of the Khao Tham Yai Limestone approximately correspond to their horizons 1 to 4, 5 to 7 and 8, respectively.

First, provide a summary of the limestone focusing on the evolutionary and extinction patterns of the larger fusulinid species of the Lower and Middle members of the KhaoTham Yai Limestone based on the findings of Hada et al. (2015)

3.1 Lower Member

The Lower Member is further subdivided into Units 1 and 2 in ascending order that correspond to the horizons 1 and 2, and 3 and 4 of Fontaine et al. (2002). Unit 1 is difficult to study because of widespread and dense tropical vegetation. Horizon 1 is also not rich in fossils and contains scattered corals that are not well preserved and commonly destroyed by recrystallization. The limestone of Horizon 2 is packstone containing algae, smaller

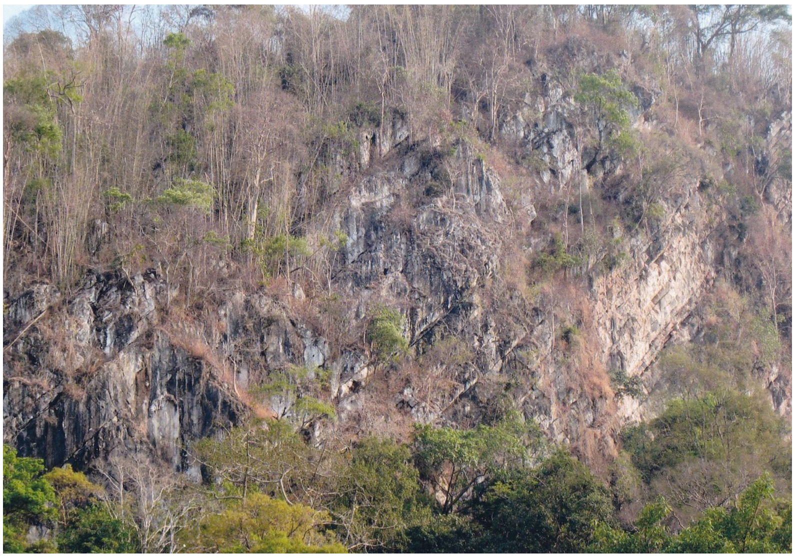

Figure 3: Field photograph of the Khao Tham Yai Limestone. The Limestone forms a continuous, near homoclinal section striking NNW-SSE to NW-SE and moderately dipping eastward.

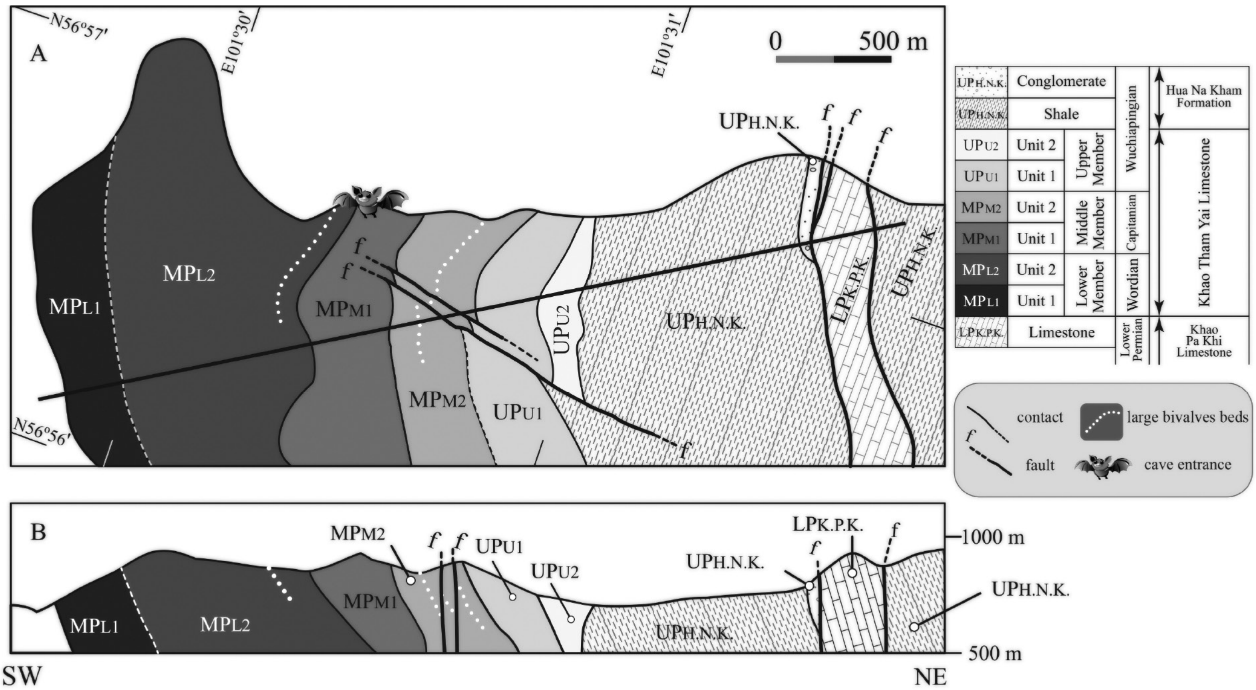

Figure 4. Geologic map (A) and structural cross-section (B) across the Khao Tham Yai Limestone, Hua Na Kham Formation and Khao Pa Khi Limestone in the Nam Nao district, NE Thailand.

foraminifers, abundant massive corals, bryozoans, and rarely brachiopod. Fusulinid fossils are extremely rare (Fontaine et al., 2002).

Unit 2 consists of mostly massive, dark gray limestone, commonly packstone rich in diverse fossils such as large fusulinids like *Colania douvillei* (Ozawa), smaller foraminifers, algae, and large bivalves (Alatconchidae), but corals are rare (Fontaine et al., 2002; Hada et al., 2015). *Colania douvillei,* which is prolific in some beds constitutes a transitional group between *Cancellina* and *Lepidolina* in phylogenic lineage; i.e., *Misellina-Cancellina-Colania-Lepidolina* evolutionary lineage (Ozawa, 1970). It occurs widely across SE Asia embracing Laos, Viet Nam, Thailand and Peninsula Malaysia. It is a typical fusulinid species of the Wordian (middle Middle Permian) of the *Colania* Zone in the Tethyan Province (e.g. Ozawa, 1970; Ota, 1977; Ingavat et al., 1980).

3.2. Middle Member

The Middle Member consists of massive to poorly bedded, black limestone and thick-bedded dark gray limestone, commonly packstone and grainstone. It locally contains nodular or layered chert. This member is further subdivided into Units 1 and 2 in ascending order (Hada et al., 2015) that approximately correspond to the horizons 5 and 6, and 7 of Fontaine at al. (2002), respectively. The limestone contains abundant, diverse fossils consisting of fusulinids including abundant large fusulinid species, smaller foraminifers, calcareous algae, crinoids, brachiopods, bivalves that include extraordinarily large bivalves (Alatoconchidae), bryozoans and rare fragments of corals.

Unit 1 of the Middle Member is particularly characterized by *Lepidolina asiatica* (Ishii) and *L. columbian*a (Dawson). *L. asiatica* occurs in SE Asia including eastern Peninsular Malaysia (Jengka Pass and Pahang) and western Cambodia (Sisophon). It belongs to the primitive species of the genus *Lepidolina* that may most likely be evolved directly from *Colania douvillei* (Ishii, 1966). Although *L. columbiana* was originally reported as the genus *Yabeina* from the Cache Creek Terrane of British Columbia, Canada (Ross, 1995). Goto et al., (1986) have described it under the genus *Lepidolina* on the basis of a statistical study of specimens. Limestones of the Cache Creek Terrane formed at low-latitude in mid-Panthalassa and were later tectonically accreted to North America (Ross, 1995). *L. columbiana* is sometimes included in *L. asiatica* (ex. Rui, 1983), our specimens in Unit 1 are here referred to as more evolved, larger forms of *L. asiatica* on the basis of prolocular diameter as described by Goto et al. (1986). *L. columbiana* has been found in eastern Thailand, western Cambodia and eastern Peninsular Malaysia in SE Asia.

Unit 2 of the Middle Member is specifically characterized by *L. multiseptata shiraiwensis* (Ozawa) in the lower part, *L. multiseptata multiseptata* (Deprat) in the upper part, and *Lepidolina kumaensis* Kanmera in the top (Fig. 5). These fusulinids of the genus *Lepidolina* widely occur in the Middle Permian limestones of SE Asia including eastern Thailand, western Cambodia, Viet Nam, Laos and eastern Peninsular Malaysia. These are the characteristic species of limestones not only in the continental blocks like the Indochina and South China blocks, which were distributed in low-latitudes of the eastern Paleo-Tethys in Middle Permian time (Domeier and Torsvik, 2014) (Fig. 6), but also those of the circum-Pacific region. The latter are species occurring in the accretionary complexes originated on paleo-atolls surrounding paleo-seamounts in mid-Panthalassa such as the Cache Creek Terrane of British Columbia, Canada (Ross, 1995) and the Akiyoshi Terrane of Japan (Sano and Kanmera, 1991). Based on this evidence, Hada et al. (1996) proposed the mid-Permian *Colania-Lepidolina* Territory of the *Colania-Lepidolina* lineage in the paleo-equatorial area of East Paleo-Tethys and mid-Panthalassa. It is worth noting that distribution of *Colania* and *Lepidolina* is limited to the East Paleo-Tethys and Pan-thalassa region. Hada et al. (1996) also proposed another territory the mid-Permian *Neoschwagerina-Yabeina* Territory of the *Neoschwagerina-Yabeina* lineage on the southern side of the *Colania-Lepidolina* Territory at low-latitudes in the East Paleo-Tethys and mid-Panthalassa in the Southern Hemisphere. The habitat of *Neoschwagerina-Yabeina* stock characterizing the Sibumasu (Shan-Thai) Block is apparently different from that of the *Colania - Lepidolina* lineage (Ishii et al., 1985).

Unit 2 of the Middle Member also includes a layer with broken fragments of extra-ordinarily large Alatoconchidae bivalves. Isozaki and Aljinovic (2009) confirmed that Alatoconchidae are characterized by their co-occurrence with typical Tethyan faunal assemblages that include large-tested fusulinids. They also concluded that the distribution of Alatoconchidae was restricted to low-latitude (tropical) domains both in Paleo-Tethys and Panthalassa. Alatoconchidae started and evolved in the Early to Middle Permian and became extinct in the late Middle Permian. The stratigraphic range, their intimate association with large-tested fusulinids and timing of extinction of Alatoconchids are applicable to the example of the Nam Nao district in the western margin of the Indochina Block in East Paleo-Tethys.

To sum up, the Middle Member of the Khao Tham Yai Limestone records a remarkable example of the phyletic evolution in the genus *Lepidolina*. Notably, the genus *Lepidolina* apparently displays continuous and rapid morphological change along many one-way evolutionary trends from small, primitive species with simple structure to large, highly evolved species having a complicated wall structure at stratigraphically higher horizon levels (e.g. Ozawa, 1975; Kanmera et al., 1976; Hada et al., 2015). *Lepidolina kumaensis* is one of the most

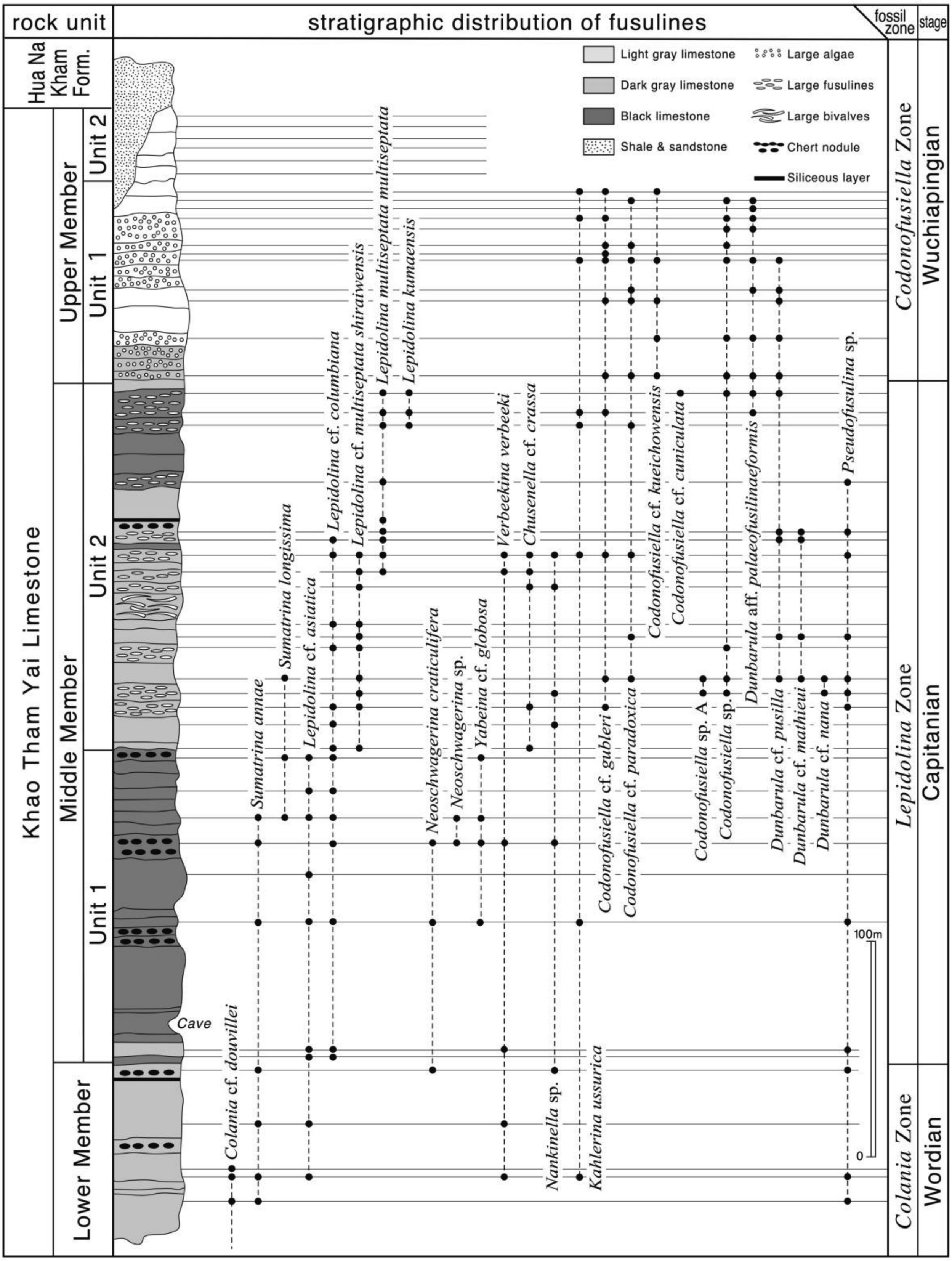

Figure 5: Composite stratigraphic column and fusuline distribution of the upper part of the Lower Member and Middle and Upper members of the Khao Tham Yai Limestone (slightly modified from Hada et al., 2015).

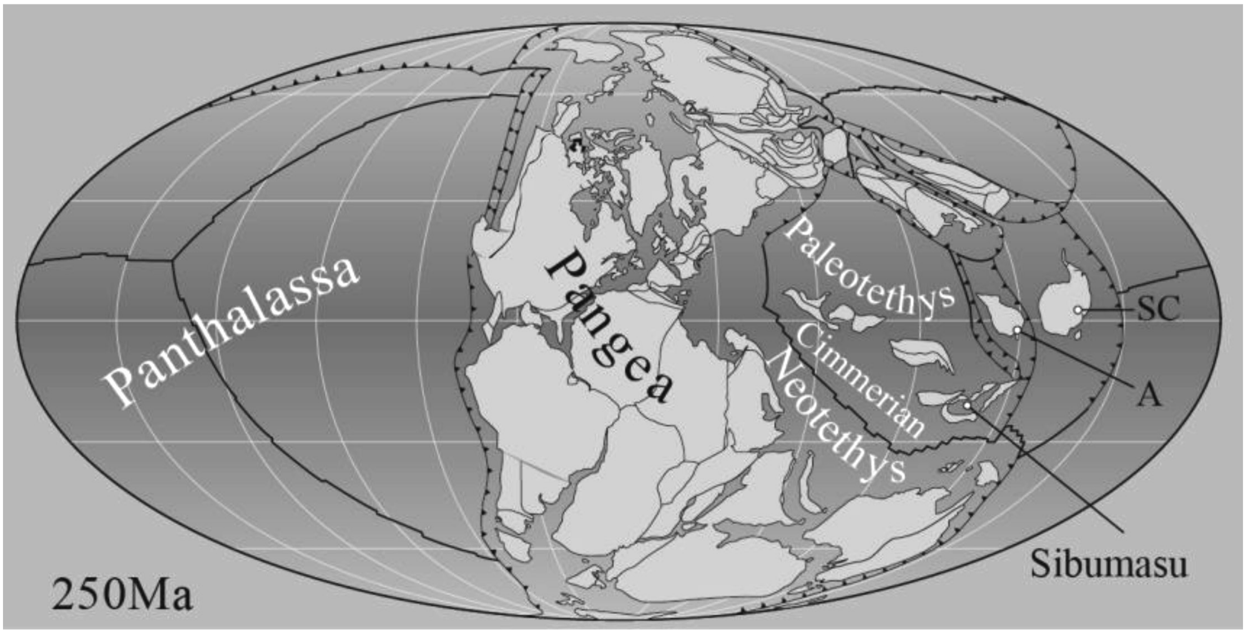

Figure 6: 250 Ma (Permo-Triassic) paleogeographic reconstruction showing simplified plate boundaries and with some major features labeled (modified from Domeier and Torsvik, 2014): A, Annamia (Indochina); SC, South China; Sibumasu constituted part of the eastern Cimmerian Continent.

advanced forms of Verbeekinidae and, recently, Kasuya et al. (2012) confirmed its termination by the end of the Capitanian (late Middle Permian). Our study of fusulinid faunas confirms that the Middle Member covers the Lepidolina Zone and can be assigned to the Capitanian (upper Maokoan) in South China (Sheng, 1963).

In conclusion, after marking the ultimate phase of their phyletic evolution of Permian fusulinid faunas in the top of Unit 2 of the Middle Member, the fusulinid assemblage characterized by long-ranging, large-tested Verbeekinids and Schwagerinids abruptly became totally extinct below the Guadalupian (Middle Permian)-Lopingian (Upper Permian) boundary (G-LB). Our study documents a remarkable horizon where the abrupt disappearance of large-tested fusulinids together with large bivalves occurred at the G-LB. The so-called end-Paleozoic mass extinction is the largest in Phanerozoic and has been considered to have occurred in two-phases (Jin et al., 1994): first, extinction at the Guadalupian-Lopingian boundary (G-LB; ca. 260 Ma) and second, at the Permo-Triassic boundary (P-TB; ca. 252 Ma). The importance of the most remarkable mass extinctions at the G-LB rather than the P-TB is emphasized repeatedly (e.g. Isozaki and Ota, 2001; Isozaki, 2007; Kofukuda et al., 2014).

4. Lithology and fossils above the G-LB with in the Khao Tham Yai Limestone of the Pha Nok Khao Formation, Loei Group

First, we provide a summary and re-examination of the smaller fusulinid and foraminifer species of the Upper Member of the Khao Tham Yai Limestone based on the findings of Hada et al. (2015) focusing in particular on their occurrence in relation to lithological change.

The boundary between the Middle and Upper members is clearly located between black limestones in the Middle Member and an overlying light gray limestone in the Upper Member. It is also clearly defined as the boundary of the abrupt change in the fusulinid assemblage from large-tested Verbeekinids and Schwagerinids to the small-shelled Schubertellids as mentioned above. The Upper Member is divided into Units 1 and 2 in ascending order, and the former approximately corresponds to the horizon 8 of Fontaine et al. (2002). Unit 2 is newly distinguished as a unit separated from the horizon 8 of Fontaine et al. (2002) and it forms the uppermost unit of the Khao Tham Yai Limestone.

Unit 1 of the Upper Member is mainly composed of thick-bedded, light gray limestone, commonly grainstone that characteristically contains small-shelled fusulinids and smaller foraminifers, abundant green algae, and totally lacks in situ (autochthonous) large-tested fusulinids (see below). The abrupt domination of small-shelled fusulinids, smaller foraminifers and green algae is accompanied by a remarkable lithological change from black carbonaceous limestone to light gray crystalline, dolomitic limestone.

The lower half of Unit 1 is characterized by a sudden flourishing of diverse species of *Codonofusiella* and *Dunbarula,* such as *Codonofusiella* cf. *gubleri* (Tien), *C. kuwangsiana* Sheng, *C. kueichowensis* Sheng, *C. paradoxica* Dunbar and Skinner, *Dunbarula paleofusilinaeformis* Sheng, *D.* cf. *pusilla* Skinner, *Colaniella minima* Wang, *Reichelina* cf. *media* Maclay, *R.* sp., *Sichotenella orientalis* Toumanskaya, *Nanlingella* cf. *meridionalis* Rui and Sheng, *N.* sp., *Kahlerina* cf. *ussurica* Sosnina, *K.* sp., and abundant green algae.

In contrast, the upper half of Unit 1 is particularly notable for the occurrence of a large number of broken fragments of diverse large-tested fusulinids having abraded outer volutions with iron-oxide-stained zones and abundant green algae accompanied by smaller foraminifers the same as those in the lower part of Unit 1. Fusulinid bioclasts contained in this lithofacies are of the same genus, *Lepidolina,* but include species at different stages of phyletic evolution, such as *Lepidolina asiatica, L. multiseptata, L. multiseptata multiseptata* or *L. kumaensis.* Their sizes are remarkably smaller than typical sizes of the species because of abrasion. Other broken fusulinid fossils include *Pseudofusulina* sp., *Sumatrina* sp., etc. It is noteworthy that the limestones appear to contain bioclasts exhibiting different degree of diagenesis (S. Mizutani, personal communication). Moreover, fossils of the Khao Tham Yai Limestone are more or less broken reflecting an energetic environment. The facies rich in elongated-type of *Dunbarula* have also been considered reflecting an energetic environment. Broken fragments of large-tested fusulinids undeniably represent a reworked fauna based on the mode of occurrence of large-shelled fusulinids together with the small-shelled fusulinids and green algae.

Unit 1 of the Upper Member is replete with diverse species of *Codonofusiella* and *Dunbarula.* Specifically, *Codonofusiella* cf. *kueichowensis, C. paradoxica* Dunbar and Skinner and *Dunbarula paleofusulinaeformis* that characterize the Wuchiaping Limestone in low-latitudes of Tethyan domains in Kwangsi, Kueichou and Szechuan in South China (Sheng, 1963) occur in Unit 1. Based upon these observations, Unit 1 most likely corresponds to the *Codonofusiella* Zone of Sheng (1963) in South China. Thus, the age of Unit 1 of the Upper Member is considered to be Wuchiapingian. In our recent investigation of Unit 1, we found additional small fusulinid species as *Nanlingella* cf. *meridiionalis* Rui and Sheng, and *Reichelina* cf. *media* Maclay. Those fusulinids appear in the upper part of the *Codonofusiella* Zone and flourished in the lower and middle part of the *Paleofusulina* Zone. So, it is possible that the age of the upper part of Unit 1 and Unit 2 of the Upper Member extends to the *Changhsingian* although no typical *Changhsingian* (uppermost Permian) *Paleofusu lina-Reichelina* assemblage has been recognized from the Khao Tham Yai Limestone. Existence of the Wuchiapingian within a single continuous limestone section ranging from Middle to Upper Permian is confirmed for the first time in Thailand (Hada et al., 2015).

The newly differentiated Unit 2 of the Upper Member is the stratigraphically highest unit of the Khao Tham Yai Limestone. It is mainly composed of massive, crystalline light gray limestone commonly grainstone in which large algae are locally abundant, and fusulinid faunas are totally absent. Small foraminifers are all broken, fragmented species of *Codonofusiella, Reichelina* and *Colaniella.* The age of Unit 2 seems most likely to be Wuchiapingian based on its stratigraphic position. Unit 2 of the Upper Member is possibly comparable to a “barren interval” reported by Ota and Isozaki (2006) and assigned to shallow marine limestone in mid-Panthalassa below the G-LB. In more detail, Kofukuda et al. (2014) documented that the disappearance of major taxa at the end of the Capitanian occur in two steps in the barren interval in mid-Panthalassa; i.e., first the disappearance of large-tested fusulines in the upper Capitanian, and then a second episode involving smaller foraminifers also in the upper Capitanian, although smaller foraminifers reappeared above the GL-B. On the other hand, in the Nam Nao district, the abrupt disappearance of large-tested fusulines and a sudden flourishing of smaller fusulinid and foraminifer species clearly occurred across the G-LB, and the second disappearance of smaller foraminifers was registered during the Wuchiapingian in Unit 1 of the Upper Member of the Khao Tham Yai Limestone. Kofukuda et al. (2014) also reported the subaerial exposure and erosion of mid-oceanic seamounts that occurred in the topmost barren interval across the G-LB in mid-Panthalassa. While, in the Nam Nao district, Unit 1 and the topmost barren interval of the Khao Tham Yai Limestone is disconformably overlain by the siliciclastic Hua Na Kham Formation and the top bed of the Hua Na Kham Formation is characterized by remarkable boulder bed of fusulinid and conglomeratic limestones derived from the Khao Tham Yai Limestone (see below). Namely, the two phases of the disappearance of major taxa and a large-scale sea-level drop started above the G-LB and occurred a little later during the Wuchiapingian on the continental margin of the Indochina Block. Large-scale sea-level drop at the end of Capitanian has been globally recognized through analyses of continental shelf areas around Tethys. The sea-level drop detected around Paleo-Tethys and mid-Panthalassa during the late Middle to early Late Permian likely reflected a global cooling, which caused a large-scale eustatic regression (e.g. Haq and Schutter, 2008). Although the possible cause of a global cooling is still not definite, Isozaki (2009) recently proposed that a change in the core's geodynamo might have played an important role in determining the course of the Earth's surface climate and biotic extinction/ evolution.

5. The Hua Na Kham Formation of the Loei Group with special reference to the boulder bed of conglomeratic limestone

In the valley on the eastern side of the Khao Tham Yai Limestone, Fontaine and Salyapongse, (2001) and Fontaine et al. (2002) reported a siliciclastic succession consisting of shale, cleaved siltstone, minor sandstone and rare thin beds of argillaceous limestone approximately 1000 m thick, and stratigraphically overlying the Khao Tham Yai Limestone. Although the succession is intensely weathered and exposed only in scattered small outcrops, it is attributed to the Upper Permian Hua Na Kham Formation of the Loei Group (Ueno and Charoentitirat, 2011). Little has been known about the fossil content of the Hua Na Kham Formation, but Fontaine et al. (2002) reported poorly preserved fusulinaceans as *Codonofusiella, Dunbarula, Reichelina* and *Lepidolina* from loose blocks of argillaceous limestone. This assemblage is similar to some beds in the eastern part of the Khao Tham Yai Limestone and they suggested a Midian (upper Middle Permian) age.

Hada et al. (2015) demonstrated that onlap of the clastic formation onto the Khao Tham Yai Limestone occurred on a larger scale replacing previous carbonate formation characterized by algae-foraminiferal biotas. In detail, the onlap of siliciclastic rocks onto Unit 1 of the Upper Member of the Khao Tham Yai Limestone to the south of the fault identified by a marker bed of Alatocon-

Figure 7: Field photograph of the Hua Na Kham Formation and the Khao Pa Khi Limestone. A: A distance view. Boulders dispersed at the foot of the Khao Pa Ki Limestone hill just like loose blocks are outcrops of the boulder bed at the top of the Hua Na Kham Formation. B: Close-up view of the boulder bed of the Hua Na Kham Formation.

Figure 8: Field occurrence of boulders of fusulinids and conglomeratic limestone at the top of the Hua Na Kham Formation. (A) Fusulinid limestone. (B) An enlarged view of the fusulinid boulder. (C) Bioclastic limestone (rudstone) (D) Brecciated limestone. (E) Bioclastic limestone accompaning chert band.

chidae and onto its Unit 2 (barren interval) to the north of the fault is regionally recognized (Fig. 4). The strike of siliciclastic Hua Na Kham Formation is NW-SE and is the same as the Khao Tham Yai Limestone, but steeply dipping towards the west. As repeatedly emphasized by Ueno and Charoentitirat (2011), siliciclastic formations and carbonate formations having similar ages in some areas are largely heteropic facies and possibly interfinger with each other. The relationship between the Khao Tham Yai Limestone and the siliciclastic Hua Na Kham Formation of the Loei Group in the Nam Nao district shows that both formations are heteropic and the latter finally overlies the Khao Tham Yai Limestone.

Recently, we discovered a remarkable boulder bed of fossiliferous and conglomeratic limestones at the top of the Hua Na Kham Formation. Large boulders of a large-tested fusulinid limestone and a remarkable conglomeratic limestone having various lithologies have been dispersed at the top of a rather steep slope under the Khao Pa Khi Limestone hill just like loose blocks on the slope. Siltstones surrounding boulders are so strongly weathered that it is remarkably difficult to judge in the field whether boulders are loose blocks or lie within a siltstone matrix of the Hua Na Kham Formation. Fossils yielded from boulders match those of the Upper Member of the Khao Tham Yai Limestone, whereas totally different fossils characterize the Lower Permian Khao Pa Khi Limestone in direct contact to the east with the Hua Na Kham Formation (see below). At the same time, it is regarded as most unlikely that boulders were accumulated by farmers working in cornfields in the valley considering its topographic position, their number and size. In conclusion, the large boulders of fossiliferous conglomeratic limestones that appear to be loose blocks are interpreted as constituent rocks of the uppermost strata of the Hua Na Kham Formation (Fig. 7A and B). Boulders are composed of a brecciated limestone with or without fusulinid fossils, large-tested fusulinid limestone, and bio-clastic limestone (rudstone). Those boulders are sometimes accompanied by chert nodules and bands. All these conglomeratic limestones are regarded as part of an intrafor mational conglomerate and breccia in origin. The shape of boulders is subangular, tabular and disc-shaped, and the sizes of major axes of most boulders are approximately 1-3 m (Fig. 8A, B, C, D and E). Boulders of fusulinacean limestone contain *Lepidolina* cf. *multiseptata, Verbeekina verbeeki, Sumatrina* sp., *Pseudofusulina* sp., and conglomeratic limestone boulders yield abundant broken or fragmented and abraded fusulinid species such as *Lepidolina multiseptata mulutiseptata, L. asiatica, L.* sp., *Colania douvillei, Sumatrina* sp., *Pseudofusulina crassa, P. padangensis, P.* sp., *Neoschwagerina* sp. and *Verbeekina verbeeki,* and fusulinacean species such as *Pseudofusulina* sp., *Sichotenella* sp., *Codonofusiella* sp., *Dunbarula* sp., *Kahllerina* sp., and *Reichelina* sp. These fusulinid and fusulinacean species are surprisingly similar to those of the Khao Tham Yai Limestone.

In conclusion, boulders of fossiliferous and conglomeratic limestones are interpreted to have eroded off from the Khao Tham Yai Limestone and brought to the Hua Na Kham Formation based on the fusulinids and foraminiferal fauna they contain. Boulders may be transported by large-scale submarine debris flow from a Khao Tham Yai barrier reef developed on clastic-dominant continental shelves (Fig. 9). The occurrence of conglomeratic limestone boulders in a siliciclastic matrix indicates that the carbonate sedments were lithified before they were enveloped by the flow of terrigenous mud. This is a reason that the limestones appear to contain bioclasts showing different degree of diagenesis mentioned above.

Similar large boulders beds of limestone are known within the uppermost Jurassic-lowermost Cretaceous Torinosu Group on Shikoku Island of southwest Japan. Thepresence of limestone boulders derived from the mounds has been interpreted as indicating that cessation of carbonate deposition may have been associated with catastrophic events (Kano, 1988). Terrigenous sediments flowed over the carbonate deposits, killing the colonial organisms and stopping carbonate sedimentation possibly indicating that the cessation of the carbonate deposition may have been associated with a large-scale eustatic sea-level drop. The Ordovician Cow Head Breccia in the Appalachian Orogen in Canada is also an example of mixed angular breccia and softly deformed tabular blocks of limestone showing different degrees of diagenesis and typically developed off the edge of the carbonate bank at the ancient continental margin (James and Stevens, 1986). Similar coarse carbonate Upper Devonian debris was deposited along the base of a steep-walled platform as talus breccias (via rockfall) and debris-flow breccias in the Napier Range of the Canning Basin of NW

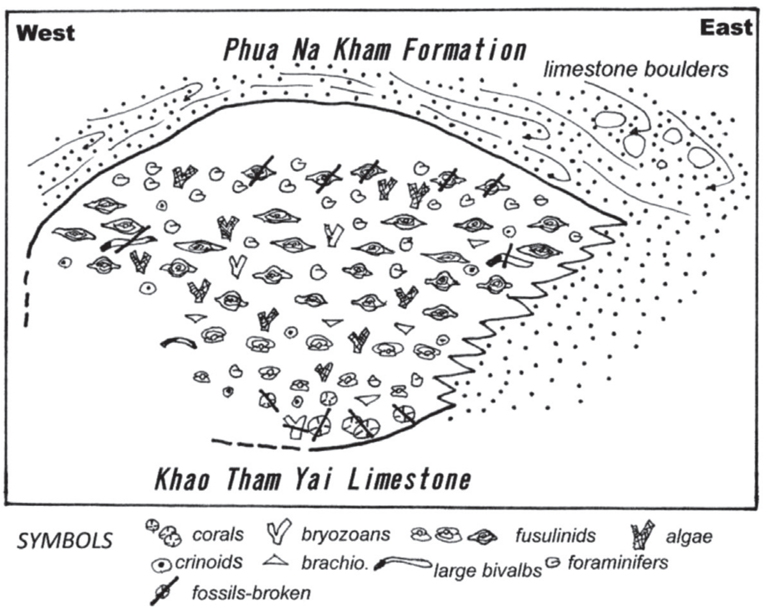

Figure 9: Model illustrating possible development of the Khao Tham Yai barrier reef (transverse section) on the continental shelf of the western margin of the Indochina Block. Limestone boulders were transported by submarine debris flow from the Khao Tham Yai barrier reef to sites on the continental shelf where the Hua Na Kham Formation was deposited (modified after Kano, 1988).

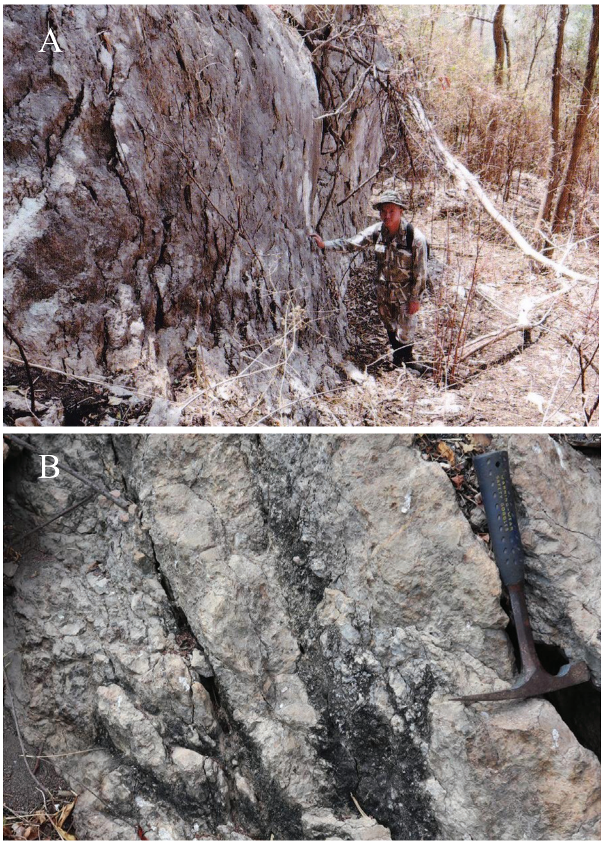

Figure 10. Field photographs of a fault scarp between the Khao Pa Khi Limestone and the Hua Na Kham Formation (A) and Riedel shear in its fault breccia indicate a reverse sense of slip (B).

Australia. Changes in sedimentary style on the slope, reflecting differing rates of carbonate production on the platform, are linked to relative sea-level fluctuations (George et al., 1997). The broken limestone and limestone breccias have been also reported from the reef-capped Akiyoshi seamount in the accretionary complex of Japan. In this case, large-scale collapse of the seamount and limestone cap was caused as the result of the encroachment of the seamount into a trench area (Sano and Kanmera, 1991).

The age of the Hua Na Kham Formation in the Loei Group can be defined as Wuchiapingian and possibly extends to Changhsingian considering its stratigraphic relation with the Khao Tham Yai Limestone, fossils of conglomeratic limestone boulders and argillaceous limestone.

6. The age of the Khao Pa Khi Limestone of the Pha Nok Khao Formation, Loei Group

The Khao Pa Khi Limestone is a continuous succession of narrow hills aligned in a north-south direction. The limestone is pale gray or whitish gray, massive, vertically dipping, approximately 250 m thick (Fig. 8A). Stylolites commonly observed in the limestone occur as single low amplitude suture planes. It is in direct contact to the west with the siliciclastic Hua Na Kham Formation. It is sparsely fossiliferous and was once regarded as Triassic (Fontaine and Salyapongse, 2001). Fontaine et al. (2002) later suggested a Permian age for the Khao Pa Khi Limestone based on foraminifers, and corals (from loose blocks). Fontaine et al. (2002) commented that if the corals belong to the Khao Pa Khi Limestone, they show that an inconsistent Upper Permian or Triassic age and also suggested the existence of fault between the Khao Pa Khi Limestone and the siliciclastic Hua Na Kham Formation. Recently, we found fusulinid fossils in outcrops of the Khao Pa Khi Limestone. Those are *Misellina* cf. *otai, Sakaguchi* and *Sugano, M.* sp. and *Para-schwagerina* cf. *fosteri* (Thompson and Miller). *Misellina otai* is the most primitive representative of the genus (Sakagami and Sugano, 1966). In late Early Permian time *Misellina* spread throughout Paleo-Tethys, although the occurrence of localities, yielding this genus, are sporadic (Ishii et al., 1985). *Misellina* gave rise to the *Misellina-Cancellina-Colania-Lepidolina* and the *Misellina-Maklaya–Neoschwagerina-Yabeina* evolutionary lineages (Ozawa, 1970). The Khao Tham Yai Limestone that is supposed to be developed in the same continental shelves as the Khao Pa Khi Limestone on the western margin of the Indochina Block is characterized by the former evolutionary lineage.

Our study of the fusulinid fauna confirms the *Misellina* Zone of the Lower Permian for the Khao Pa Khi Limestone of the Pha Nok Khao Formation. The fault between the Khao Pa Khi Limestone and the Hua Na Kham Formation is confirmed at the bottom of the Khao Pa Khi Limestone. It is N-S trending and dips steeply east to vertical. Discontinuous shear plane and foliation plane Riedel shear indicate a reverse sense of slip consistent with uplift of the Khao Pa Khi Limestone against the Hua Na Kham Formation (Fig. 10A and B).

7. Concluding remarks

Litho- and bio-stratigraphic analyses of the Lower Permian Khao Pa Khi and Middle-Upper

Permian Khao Tham Yai limestones, and the heteropic siliciclastic Hua Na Kham Formation indicate they accumulated on a clastic-dominant continental shelf at low-latitude on the western margin of the Indochina Block. We have clarified the following matters. (1) The abrupt disappearance of large-tested fusulines with large bivalves clearly occurred at G-LB within the Khao Tham Yai Limestone, and they never returned. (2) The Khao Tham Yai Limestone above the G-LB is characterized by sudden proliferation of a diverse range of species of smaller foraminifers and the occurrence of a large number of broken fragments of diverse large-tested fusulinids and abundant green algae. Broken fragments of large-tested fusulinids undeniably represent a reworked fauna from (3) The first disappearance of large-tested fusulines and the proliferation of smaller fusulinid and foraminifer species clearly occurred across the G-LB, and the second disappearance of smaller foraminifers was registered during the Wuchiapingian. These two phases of dis-appearance of fusulinid and foraminifer species on the continental margin of the Indochina Block have likely occurred a little later comparing to the phases on the paleo-atoll in mid-Panthalassa. (4) The Wuchia-pingian siliciclastic Hua Na Kham Formation unconformably onlaps the Khao Tham Yai Limestone replacing previous carbonate formation characterized by algae-foraminiferal biotas. A remarkable boulder bed of fusulinids and conglomer atic limestones occurs at the top of the Hua Na Kham Formation. The fusulinacean assemblage yielded within boulders undoubtedly compares to that of the Middle and Upper members of the Khao Tham Yai Limestone. Therefore, it is reasonable to consider that these boulders were eroded from the Khao Tham Yai Limestone and brought to the Hua Na Kham Formation. Boulders may be transported by large-scale submarine debris flow originating from the Khao Tham Yai barrier reef and developed on a clastic-dominant continental shelf. Terrigenous sediments flowed over the carbonate deposits, possibly indicating that the cessation of the carbonate deposition may have been associated with catastrophic events like a large-scale eustatic sea-level drop. (5) Although the subaerial exposure and erosion reported from mid-oceanic seamounts occurred across the G-LB in the uppermost barren interval in mid-Panthalassa, a large-scale sea-level drop associated with global environ-mental change inside the continental margin of the Indochina Block occurred a little later during the Wuchiapingian. (6) Our recent study of the fusulinid fauna confirms the Misellina Zone of the Lower Permian for the Khao Pa Khi Limestone of the Pha Nok Khao Formation.

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