STRATIGRAPHIC CORRELATION AND FOSSIL ASSEMBLAGES BETWEEN THE TIMAH TASOH FORMATION AND THE PA SAMED FORMATION

by

The Malaysian-Thai Working Group

A joint project carried out by
Minerals and Geoscience Department, Malaysia
and
Department of Mineral Resources, Thailand

The Malaysia-Thailand Border Joint Geological Survey Committee (MT-JGSC)
2022

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PREFACE

This report on the stratigraphic correlation between the Timah Tasoh Formation and the Pa Samed Formation is the result of close co-operation between the Department of Mineral and Geoscience Malaysia and the Department of Mineral Resources, Thailand since the year 2000. The aim of this joint report is to resolve problems related to cross-border geological and stratigraphic correlations between Malaysia and Thailand. Fieldwork was carried out independently by geoscientists of the Department of Mineral and Geoscience Malaysia, and those of the Department of Mineral Resources, Thailand covering the individual territories in the years 2019 and 2020.

On the Malaysian side, several rock units were introduced by previous workers to represent transitional sequence of Devonian age that occurred between the Silurian and Carboniferous succession in northwest Peninsular Malaysia. This sequence represents shallow marine deposits of the continental margin of the Sibumasu Terrane during the Middle Palaeozoic Era. It is separated into several formations namely the Early Devonian Timah Tasoh Formation, Middle to Late Devonian Chepor Formation and Sanai Limestone of Famennian (late Upper Devonian) age. The Timah Tasoh Formation comprises mainly black shale with tentacullitids and graptolite fossils. The Chepor Formation consists mainly of thick red mudstone interbedded with sandstone beds. The Sanai limestone consists of limestone containing late Devonian conodonts.

On the Thai side, the Pa Samed Formation represent the Devonian to Lower Carboniferous sequence. It comprises predominantly sandstone with minor grey argillaceous limestone and black carbonaceous shales. This report will discuss in detail about the stratigraphic correlation and fossil assemblages between these rock units to resolve the problems on the correlation of the Devonian rock units along the Malaysia-Thailand border area.

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Thanks are extended to Assoc. Prof. Dr. Meor Hakif bin Amir Hassan, Department of Geology, University of Malaya for his full cooperation and technical input in writing this report. We would like to expresss our sincere gratitude to Prof. Dr. Che Aziz bin Ali and Assoc. Prof. Dr. Kamal Roslan bin Mohamed, Geology Programme, Universiti Kebangsaan Malaysia for their input, free consultation, and advice during fieldworks as well as during the writing and editing of this report.

Thanks also due to all staff of the Department of Mineral and Geoscience Malaysia and Department of Mineral Resources, Thailand for their involvement in this preparing this report either directly or indirectly.

Last but not least to all local residences along the common border of both countries for their support and assistance during the fieldworks.

Stratigraphic correlation and fossil assemblages between the Timah Tasoh Formation and the Pa Samed Formation

By

The Malaysia-Thailand Working Group

EXECUTIVE SUMMARY

On the Malaysian side, early work on the Devonian rock unit focused mainly on the well exposed outcrops on Langkawi Islands. The study on Devonian rock unit on the mainland begun in 1991 when the rock exposed in an earth quarry in Perlis. The findings led to the introduction of a new stratigraphic nomenclature for the Devonian–Carboniferous succession of northwest Peninsular Malaysia, and further resolve the Devonian–Carboniferous history of the Sibumasu Terrane.

The Timah Tasoh Formation is defined as the mainly black shale sequence conformably overlying the Upper Setul Limestone, and underlying the Rebak Formation. The formation is early Devonian in age. In Perlis, it is well exposed at hilly ridge known locally as Guar Sanai, Kampung Guar Jentik, Beseri District and separated into three small hills referred to as Hill A, B and C from south to north. The Timah Tasoh Formation can be separated into smaller informal units namely Unit 1 and Unit 2 in ascending order. Unit 1 comprises predominantly black carbonaceous shale, with some brown coloured beds. It contains a dacryoconarid-monogfaptid-*Plagiolaria* fossils assemblage of Early Devonian age. Unit 2 comprises light coloured argillo-arenites, predominantly arenaceous, with thick, flat bottomed, fine grained sandstone beds with subordinate thinly-bedded shales.

On the Thai side, the Devonian Pa Samed Formation overlies the Silurian Thung Song Group and underlain the Carboniferous Khuan Klang Formation. The rocks predominantly consist of black shale, chert, sandstone and limestone. They distribute in southern part of western region and central part of southern region from Khao Luang, Surat Thani Province to Nakhon Si Thammarat Province, and Satun Province. Pa Samed Formation contains abundant fossils such as; tentaculites, trilobites, brachiopods, and nautiloids. The age of this fossil assemblages indicated Early Devonian to Early Carboniferous.

The Pa Samed Formation can be divided into six members namely in ascending order Member One, Member Two, Member Three, Member Four, Member Five and Member Six. Member One comprises black, pyritic carbonaceous shale with fossils of *Nowakia acuaria, Metastyliolina, Styliolina, Echinocoeliopsis, Plagiolaria, Echinocoelia* and *Monograptus* that indicate an Early Devonian age. Member Two comprises thick-bedded to massive, grey feldspathic sandstone and grey shale grading upwards to red feldspathic sandstone and red shales with graded bedding and cross lamination of incomplete Bouma sequences, fine-medium grain sandstone interbedded with shale and light grey feldspathic sandstone with scattered well-rounded pebbles of quartz, quartzite, chert and slate on the top. Abundant goniatites occur in this member. Member Three comprises grey argillaceous limestone, very dark grey laminated shale with an abundant fauna including small Namurian brachiopods and goniatites. Member Four comprises grey to light brown,

massive fine-grained sandstone, occasionally pebbly. Member Five comprises reddish-brown, fine-grained feldspathic sandstone interbedded with laminated red. Small crinoid fragments and mud clasts present. Member Six comprises brownish-grey fine-grained feldspathic sandstone with grey shale lenses. Small fossil fragments present.

In term of stratigraphic correlation, based on lithology and fossil assemblages, the Malaysia-Thailand Working Group agreed that the Early Devonian Timah Tasoh Formation on the Malaysian side is correlatable with the lower part of the Early Devonian-Early Carboniferous Pa Samed Formation on the Thai side.

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1. INTRODUCTION

Through the close and continuous cooperation between the Department of Mineral and Geoscience Malaysia and the Department of Mineral Resources Thailand since the year 2000, the Malaysia-Thailand Working Group has successfully completed the geological correlation of rock units along the whole stretch of the Malaysia-Thailand border area. The Working Group also has successfully resolved problems related to cross-border geological correlation of Northern Peninsular Malaysia and Southern Thailand. However, detailed study on the stratigraphy of correlatable rock units still need to be done to better understand the environment of deposition or depositional basins of sedimentary rock units across the international border of the neighbouring countries. Stratigraphic correlation might lead to the economic minerals correlation that might occur within the correlatable rock units.

During the Thirteenth MT-JGSC Meeting that was held on 17th August 2016 at Krabi Front Bay Resort, Krabi Province, Thailand, the Malaysia-Thailand Border Joint Geological Survey Committee (MT-JGSC) had endorsed the proposal on the detailed study on stratigraphic correlation and fossil assemblages between the Jentik Formation and the Pa Samed Formation. This study was carried out in the year 2019-2021. However, after discussion with Assoc. Prof. Dr. Meor Hakif Amir Hassan, a Geology Lecturer for University of Malaya who did detail studies on the Devonian sequences in Perlis, the Malaysian Working Group has decided to revise the nomenclature of the Devonian rock unit exposed in Perlis and Langkawi Islands. Now the term Timah Tasoh Formation is used for the Lower Devonian succession exposed in Perlis and Langkawi Islands.

The Malaysia-Thailand Working Group (in manuscript) refers the Carboniferous rocks in the Perlis as the Rebak Formation that is well correlatable with the Khuan Klang Formation in Satun Province. Mat Niza bin Abdul Rahman *et al.* (2019) also use the term Rebak Formation for the Carboniferous rocks in Perlis. Therefore, in this report the term Rebak Formation is used to replaced the term Kubang Pasu Formation for the Carboniferous rocks that overlies conformably the Timah Tasoh Formation.

After thorough discussions, the Malaysia-Thailand Working Group agreed that the Early Devonian Timah Tasoh Formation on the Malaysian side is correlatable with the lower part of the Early Devonian-Early Carboniferous Pa Samed Formation on the Thai side. Correlation of the Ordovician-Carboniferous rock units along the Malaysia-Thailand border area is shown in Table 1 below.

Table 1: Correlation of the Ordovician-Carboniferous rock units along the Malaysia-Thailand border area

<table>
<tr><th>ERA</th><th>PERIOD</th><th colspan="2">MALAYSIAN SIDE</th><th colspan="2">THAI SIDE</th></tr>
<tr><td rowspan="6">PALAEOZOIC</td><td rowspan="2">CARBONIFEROUS</td><td colspan="2">Rebak Formation</td><td colspan="2" rowspan="2">Khuan Klang Formation</td></tr>
<tr><td colspan="2">Telaga Jatoh Formation</td></tr>
<tr><td rowspan="2">DEVONIAN</td><td colspan="2">Sanai Limestone</td><td rowspan="3">Thong Pha Phum Group</td><td>Pa Samed Formation</td></tr>
<tr><td colspan="2">Timah Tasoh Formation</td><td>Khuan Tang Formation</td></tr>
<tr><td>SILURIAN</td><td rowspan="2">Setul Group</td><td>Mempelam Formation</td><td>Wang Tong Formation</td></tr>
<tr><td rowspan="2">ORDOVICIAN</td><td>Tanjung Dendang Formation</td><td rowspan="2">Thung Song Group</td><td rowspan="2">Pa Kae Formation</td></tr>
<tr><td>Kaki Bukit Formation</td></tr>
</table>

2. PREVIOUS STUDY

2.1 TIMAH TASOH FORMATION

Extensive geological mapping of northwest Peninsular Malaysia was done in 1950 and early 1960 by the Geological Survey Department. Jones (1966, 1981) published the first comprehensive stratigraphic study for the Palaeozoic rocks of Langkawi, mainland Kedah and Perlis, in which he divided the sedimentary rocks into four main lithostratigraphic units: Machinchang Formation (oldest), Setul Limestone, Singa/Kubang Pasu Formation and Chuping Limestone (youngest). Rocks in the Langkawi Islands are dated from Cambrian to Recent.

These rocks were deposited in multiple paleoenvironments and conditions before it was deformed by tectonic and magmatic events. The geological structure of northeastern Peninsular Malaysia and Langkawi Islands correlates and lies conformably with the regional tectonic pattern in Malay-Thai Peninsular (Jones, 1981).

This classification was made before the discovery of Devonian rocks between the Setul Limestone and Singa/ Kubang Pasu Formations. This clastic sequence has since then been surrounded by controversy. Based on Jones (1981), this sequence is divided into two units, the black dacryoconarid shales of the Upper Detrital Member of the Upper Setul Limestone, and the red pebbly mudstones of the basal Singa Formation. Gobbett (1972) erected the name Rebanggun Beds for the red conglomeratic mudstones of the basal Singa Formation in Pulau Langgun, due to its distinct lithology. This unit is also known as the Langgun Red Beds in the literature and an extension of the redbeds in Perlis have been named the Wang Kelian Redbeds (Lee & Azhar, 1991). The existence of an unconformity between the Upper Detrital Member and the Rebanggun Beds was questioned by Ahmad Jantan (1973) and Yancey (1975).

The conformable contact between the two units led Yancey (1975) to combine both units into one Unnamed Devonian unit. The sedimentary strata of northwest Peninsular Malaysia actually extend into neighbouring southern Thailand. Detailed stratigraphic work on the Palaeozoic strata of southern Thailand indicates that the stratigraphy is more complex (Wongwanich *et at*., 1990). Yancey's Unnamed unit is here known as the Pa Samed Formation.

Meor and Lee (2002) introduced the term Jentik Formation for a Devonian rock unit that forms a transitional sequence from the Ordovician-Silurian Setul Formation to the Carboniferous Kubang Pasu Formation (later in this report it is referred to as Rebak Formation). The sequence is well exposed in earth quarries at a small hilly ridge in Kampung Guar Jentik, Beseri, Perlis, Malaysia. Later Cocks *et al*. (2005) introduced the terms Timah Tasoh Formation for strata directly overlying the Mempelam Limestone in Perlis and Langkawi. Lee (2009) considered the Timah Tasoh Formation as part of the carbonate-dominated Ordovician-Devonian Setul Group.

Ong and Basir (2007) however favoured the term Jentik Formation for the whole Lower Devonian to Lower Carboniferous succession exposed at Kampung Guar Jentik. The

Malaysian-Thai Working Group (2010) also retained the term Jentik Formation and reported it is correlatable with the upper part of the Pa Samed Formation in Thailand.

The Malaysia-Thailand Working Group (in manuscript) still retained the term Jentik Formation and reported it is equivalent to the Upper Detrital Member of Jones (1981) which is exposed at Pulau Langgun and Pulau Tuba of the Langkawi Islands. The Malaysia-Thailand Working Group (in manuscript) also proposed the term Jentik Formation be used to replace the term Upper Detrital Member of Jones (1981) for the clastic sediment that is conformably overlying the Upper Setul limestone in Langkawi Islands.

Between 2002 until recently, Meor, Cocks, Lee and other researchers did many detailed studies on the Devonian sequence in Perlis and Langkawi. They described in detail about the sequence and managed to divide the Jentik Formation of Meor and Lee (2002) into several formations based on lithostratigraphy and fossil content. Therefore, in this report the Malaysian-Working Group is of the opinion that it is more appropriate to adopt the term Timah Tasoh Fomation to replace the term Jentik Formation. Evolution of stratigraphic nomenclature in Perlis and Langkawi from 1981 until now is shown in Table 2.

Table 2: Evolution of stratigraphic nomenclature in Perlis and Langkawi, NW Peninsular Malaysia

<table>
<tr><th>ERA</th><th>PERIOD</th><th colspan="2">Jones (1981)</th><th colspan="2">Meor & Lee (2002)</th><th colspan="3">Meor et al (2002)
Cocks et al (2005)
Lee (2009)</th><th colspan="2">This Report
Meor et al (2021)
Meor et al (2014)</th></tr>
<tr><td rowspan="4">PALAEOZOIC</td><td rowspan="2">CARBONIFEROUS</td><td colspan="2" rowspan="3">Singa Formation & Kubang Pasu Formation (basal)</td><td colspan="2" rowspan="3">Jentik Formation</td><td colspan="3">Wang Kelian Formation</td><td colspan="2" rowspan="2">Rebak Formation</td></tr>
<tr><td colspan="3">Telaga Jatoh Formation</td></tr>
<tr><td rowspan="2">Binjal Formation</td><td rowspan="2">Telaga Jatoh Formation</td></tr>
<tr><td>DEVONIAN</td><td rowspan="2">Setul Limestone</td><td>Upper Detrital Member</td><td>Sanai Limestone</td><td>Chepor Formation</td><td>Sanai Limestone</td></tr>
<tr><td>SILURIAN</td><td>Upper Setul Limestone</td><td>Setul Limestone</td><td>Upper Setul Limestone</td><td>Timah Tasoh Formation</td><td>Setul Limestone</td><td>Mempelam Limestone</td><td>Timah Tasoh Formation</td><td>Setul Group</td><td>Mempelam Formation</td></tr>
</table>

Jones (1981) divided this rock unit, in ascending order; Basal Limestone, Lower Setul Limestone, Lower Detrital Member, Upper Setul Limestone, and Upper Detrital Member.

Lee (2009) proposed a Setul Group which comprises in ascending order; the Machinchang Formation, Kaki Bukit Limestone, Tanjong Dendang Formation, Mempelam Limestone and Timah Tasoh Formation.

Cocks *et al*. (2005) has proposed to rename the Lower Setul limestone to Kaki Bukit Limestone, the Lower Derital Member to Tanjong Dendang Formation, the Upper Setul limestone to Mempelam Limestone and the Upper Detrital Member to Timah Tasoh Formation.

Setul Formation was later upgraded into Setul Group by Lee (2009) for the Cambrian to Early Devonian succession in Langkawi Islands and Perlis. He proposed that the Setul Group to be comprised of (in ascending order), Cambrian Machinchang Formation, Middle to Late Ordovician Kaki Bukit Limestone, Lower Silurian Tanjong Dendang Formation, Late Silurian Mempelam Limestone and Early Devonian Timah Tasoh Formation.

In 2013, Malaysian Working Group has revised the stratigraphy of the Setul Formation and comprises in ascending order; Kaki Bukit Member, Tanjung Dendang Member and Mempelam Member. The Malaysia Working Group (2017), has identified the Upper Detrital Member equivalent with Timah Tasoh Formation, taken it out from the Setul Formation, however retained the term Jentik Formation of Meor & Lee (2002) for the Early Devonian succession.

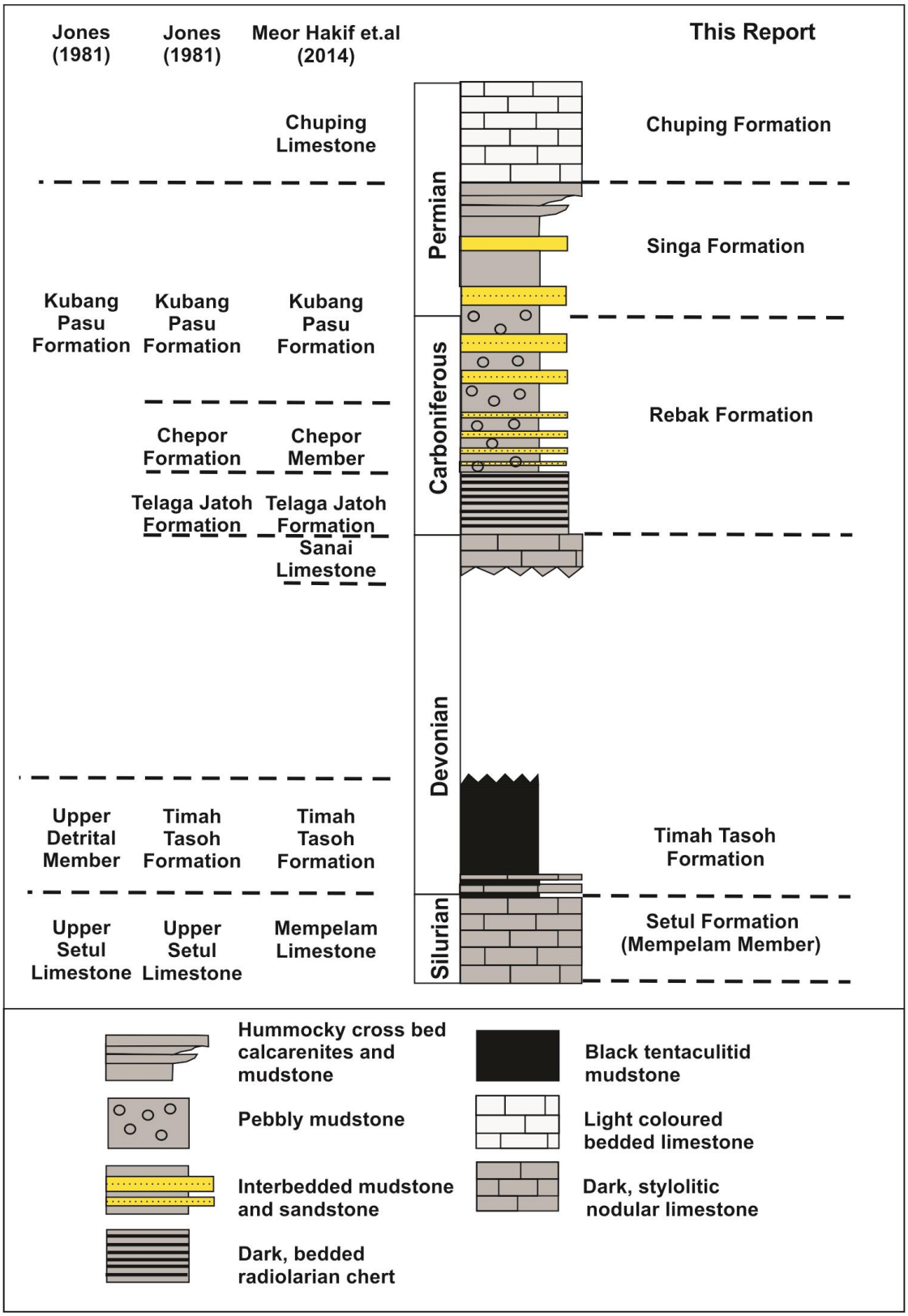

Figure 1: The stratigraphic column for the Timah Tasoh Formation from previous work

2.2 PA SAMED FORMATION

Pa Samed Formation was named by Tansuwan *et al.* (1980) after Ban Pa Samed, approximately 9 km north of La-ngu district, Satun province. Type section of this formation situated at km 9.7-9.8 on the road between La-ngu-Thung Wa districts by Wongwanich et al., (1990). In Satun Province, Tansuwan et al., (1985) reported Lower Carboniferous *Posidonomya* sp. From a 120 m thick sequence of reddish-brown weathering light grey to white shale intercalated with sandstone, siltstone and chert, apparently lying conformably above the Pa Samed Formation. They named these rocks the Kuan Klang Formation. This formation is possibly age-equivalent to the upper part of the Pa Samed Formation.

Boucot et al., (1999) described the first Devonian, probably early Emsian, brachiopods from Thailand. This fauna was collected from dacryoconarid-rich beds in black tentaculitic shale of the lowermost member of the Pa Samed Formation. Twelve brachiopod taxa were described, including one new genus and species, *Quasiprosserella samedensis*, and the new species *Plectodonta forteyi*, *Caplinoplia thailandensis* and *Clorunda wongwanichi*. They represent deepwater 'Bentihic Assemblage 5' (Wang et al., 1987; Boucot and Lowson, 1999), as shown by the associated abundant dacryoconarids and the trilobite *Plagiolaria.*

Wongwanich *et al*. (2004) reported that Namurian *Goniatites* and two brachiopod genera *Eileenella* Racheboeuf and *Plicambocoelia* Boucot and Brunton with five new species collected from fossil beds in the vicinity of Ban Pa Samet, La Ngu District, Satun Province are described. These brachiopods are unlike any known previously from Asia.

Cronier and Fortey (2006) reported morphology and ontogeny of an Early Devonian Phacopid trilobite with reduced-eyed species *Plagiolaria poothaii* Kobayashi and Hamada, 1986, from the shales and mudstone of the Pa Samed Formation of Southern Thailand, nort far from the border with Malaysia.

Agematsu et al., (2006) studied a siliciclastic sequence in the Satun area of southern peninsular Thailand contains a tentaculite bed of Pa Samed Formation that is composed of black shale and contains *Nowakia acuaria in* the lowermost part. Based on occurrences of *Nowakia acuaria* and correlations with surrounding areas, the depositional age of the tentaculite bed is earliest Emsian. A number of similar tentaculite-bearing beds are present over a wide area of northern, western, and southern Thailand and northwestern Malaysia. The depositional environments in which this tentaculite-bearing black shale accumulated prevailed from present northern Thailand to northwestern Malaysia during the earliest Emsian.

Agematsu *et al*. (2008) mentioned about paleogeography and the sea-level changes of the Sibumasu Block from the Ordovician to Early Devonian based on the conodont, graptolite, and tentaculitid biostratigraphy. Some results indicate that the Silurian and Lower Devonian rocks on those Block have been deposited under a deeper-water environment.

Tongtherm et al., (2017) reported Lower Carboniferous nautiloid from Pa Samed Formation, La-ngu district, Satun province, Sothern Thailand. Nuatiliod such as

Chidleyenoceras sp. Indet., Tainocerataceae gen. et sp. Indet. and Nautilaceae gen. et sp. Indet. All taxa of this paper were new records of cephalopod fossils from Thailand.

3. TIMAH TASOH FORMATION

The unit is well exposed at several earth quarries located in Kampung Guar Jentik, Beseri district, and Hutan Aji in Perlis. Meor and Lee (2002) originally referred this rock unit as the Jentik Formation. It is also well exposed on Pulau Langgun and Pulau Tuba of the Langkawi islands. The Malaysian-Thai Working Group (2010) also referred this rock unit as the Jentik Formation and reported it is correlatable with the Pa Samed Formation in Thailand, more specifically Member 1 of Wongwanich *et al*. (1990). Meor and Lee (2005) initially subdivided the Timah Tasoh Formation into 2 members, i.e. the Lalang and Bukit Raja members. This subdivision is now discarded, with the Lalang Member remaining in the Timah Tasoh Formation, while the Bukit Raja Member is now accepted as deformed strata of the overlying Kubang Pasu Formation (Meor *et al*., 2014; Meor, 2021). The Timah Tasoh Formation is equivalent to the Upper Detrital Member of Jones (1981) and was deposited during the Early Devonian.

The Timah Tasoh Formation consists mainly of black carbonaceous shale and mudstone, with minor thin intercalated lenses and beds of limestone. The rocks contain a rich Dacryoconarid-*Monograptus-Plagiolaria* fossil assemblage.

3.1 NOMENCLATURE

The term Timah Tasoh Formation was taken from name of the Timah Tasoh Dam in Perlis. The term was introduced by Cock *et al*. (2005). The term is use to describe a sequence of black mudstone with occasional chert that contain the dacryonorid tentaculitid Nowakia and also Early Devonian graptolites including *Monograptus* cf. *uniformis* and *M. langgunensis* of basal Lochkovian to perhap Pragian age in its lowest part (Lee, 2009).

3.2 DISTRIBUTION AND GEOLOGIC SETTING

The Timah Tasoh Formation is well exposed at Sanai Hill A, B and C in Kampung Guar Jentik, Beseri District and Hutan Aji near Kangar in Perlis, and on the NW coast of Pulau Langgun as well as on Pulau Tuba of the Langkawi islands. It is up to 40 m thick in Perlis and Langkawi (Meor Hakif Amir Hasan, pers. comm. 2022). Stratigraphically, the Timah Tasoh Formation conformably overlies the Silurian Mempelam Limestone. In most of the outcrop localities in Perlis, the Timah Tasoh Formation is unconformably overlain by Carboniferous cherts of the Telaga Jatoh Formation. However, at Sanai Hill B in Kampung Guar Jentik, the Timah Tasoh Formation is unconformably overlain the Late Devonian Sanai Limestone (Meor and Lee, 2003; Meor *et al.*, 2014; Meor, 2021). On Pulau Langgun in Langkawi, the Timah Tasoh Formation is unconformably overlain by the Carboniferous Rebak Formation. The complex nature of the contact may be due to the diachronous nature of the unconformity combined with shearing along bedding planes at the boundary between Devonian and Carboniferous strata (c.f. Meor, 2021).

3.3 LITHOLOGY

The Timah Tasoh Formation comprises dark grey to black coloured mudstone and shale. The black shales are rich in dacryoconarid fossils. In many intervals, the fossil composition appears to make up to roughly 90% of the rock volume. Finely dispersed pyrite is common, with fossils occasionally preserved through pyrite replacement. Rare thin lenses of black limestone are observed within the Timah Tasoh Formation at Sanai Hill C of Kampung Guar Jentik, Perlis. Thin limestone beds are also observed at the base of the formation near the boundary with the underlying Mempelam Limestone on Pulau Langgun in Langkawi.

3.4 STRATIGRAPHY

The Malaysian-Thai Working Group (2010) divided the Jentik Formation of Meor Hakif Amir Hassan & Lee (2002) into three units, namely in ascending order the Lower, Middle and Upper Units. The Lower unit consists of clastic sequence of black carbonaceous and reddish shale. It is equivalent with the Upper Detrital Member of the Setul Formation of Jones (1981) and Timah Tasoh Formation of Cocks *et al*. (2005). The Middle unit consists of medium- to thick-bedded light coloured areno-argilites with predominantly arenaceous sequence. The Upper unit consists predominantly of argillaceous, mainly of thick-bedded red mudstone with Late Devonian brachiopods-*Diacoryphe-Posidonomya* assemblage. It is correlatable with the Rebanggun beds (Gobbet, 1973) and Wang Kelian Member (Lee and Azhar, 1991). It can also be observed at Km 5.5 along the Kaki Bukit-Wang Kelian trunk road (N6º 40.156′, E100º 11.850′), the locality that was named as Wang Kelian Member by Lee and Azhar (1991).

Towards the top of the succession, the mudstone changes gradually to a sequence of thick sandstone beds interbedded with laminated mudstone containing fairly well preserved bivalve *Posidonomya* with occasional well-bedded limestone beds containing nautiloid fossils. Subsequently, Meor Hakif Hassan and Lee (2003) formalized this limestone unit as the Sanai Limestone Member. The occurrences of Devonian conodonts were reported in this limestone.

Cocks *et al*. (2005) has upgraded the Upper Detrital Member to Timah Tasoh Formation. Based on the Report of Geology Along the Malaysia-Thailand Border (2017), the Malaysian Working Group has revised the stratigraphy of the Setul Group of Lee (2009) and divided into three subunits with the Timah Tasoh Formation is taken out from the Setul Group and renamed as Jentik Formation. The Malaysian Working Group has decided to adopt the term Timah Tasoh Formation for a transitional sequence of Early Devonian sequenced well exposed at Guar Jentik area in Perlis.

3.5 LOWER AND UPPER CONTACT

3.5.1 Upper Contact with Sanai Limestone Formation

The black mudstones and shales of Timah Tasoh Formation is overlain by The Sanai Limestone Formation at Sanai Hill B, Kampung Guar Jentik. The contact is sharp and has

been interpreted as either a disconformity (Aung *et al*., 2013). The Sanai Limestone is then sharply overlain by the Telaga Jatoh Formation, with the contact being interpreted as a paraconformity (Meor, 2021). The Sanai Limestone section at Sanai Hill B, Kg Guar Jentik, Perlis is cut by bedding-parallel faults, which have produced a repeated section, with faulted Sanai Limestone blocks intercalated with slivers of the Timah Tasoh Formation (Meor, 2021).

The name Sanai Limestone was introduced by Meor and Lee (2003) to refer to a thin limestone unit exposed at Sanai Hill B, Kampung Guar Jentik, Perlis, which was younger than the Mempelam Limestone. It was included into the Setul Group by Meor *et al*. (2015). The unit was previously referred to as Unit 4 of the Jentik Formation (Meor and Lee, 2002), but this term has been discarded. The Sanai Limestone mainly consists of grey to black coloured, bedded micritic limestone, with thin intercalated shaly partings. The rocks contain a rich fossil assemblage, including cephalopods, conodonts and homoctenids.

The main lithology of the Sanai Limestone is grey-coloured, dm- to cm-thick (the exact thickness??), bedded, fine-grained stylolitic limestone, with subordinate intervals of black limestone. Thin (mm- to cm-thick) shaly partings (mm @ cm??) are common between limestone beds. Synaeresis cracks are also present on bedding planes (Meor and Lee, 2003). Thicker (dm- to m-thick) (mm @ cm??) intervals of black shales are also present. The grey bedded limestone is fine-grained and petrographically classified as mudstones and wackestones. However, thin sections of the black limestones show that they are rich with homoctenid tentaculitoids and can be classified as a grainstone of packstone (Meor *et al*., 2015).

The Sanai Limestone contains a rich invertebrate fossil assemblage. Conodonts have been recorded from the limestone. A spot sample from the topmost beds of the unit have uncovered a *Palmatolepis* and polygnathid conodont assemblage (Meor and Lee, 2003). Aung *et al*. (2013) conducted a more systematic biostratigraphic study and recovered a rich conodont assemblage including *Ancyrodella gigas, Ancyrodella nodosa, Ancyrognathus asymmetricus, Palmatolepis hassi, Palmatolepis jamieae, Palmatolepis rhenana, Palmatolepis linguiformis, Polygnathus decorosus, Polygnathus webbi, Icriodus alternatus, Ozarcodina* sp. and *Belodella* sp. Also associated with the conodonts are homoctenid tentaculitoids identified as *Homoctenus* sp. cf. *H. tenuicinctus* (Meor *et al*., 2015). Unidentified orthoconic nautiloids are also common in the limestone. Thin sections of the limestone also show the presence of small ostracods, syliolinid tentaculitoids, trilobites and crinoids. The conodonts of the Sanai Limestone are characteristic of the *linguiformi*s Zone and give a Late Devonian (Frasnian) age. The homoctenids are also consistent with a Late Devonian age.

The fine grained and bedded Sanai Limestone, containing abundant pelagic tentaculitoids and cephalopods, is interpreted as pelagic deposits associated with a carbonate platform depositional environment, below wave base (either carbonate slope or basin floor). Intervals of black limestone rich in pelagic tentaculitioids may indicate periods of high nutrient input with associated high organic productivity, possibly a result of algal blooms.

3.5.2 Upper Contact with Telaga Jatoh Formation

The name Telaga Jatoh Formation was introduced by Meor and Lee (2005) to refer to a thin chert unit directly overlying the Timah Tasoh and Sanai Formations in Perlis, as well as directly overlying the Mahang Formation in Kedah. The unit is well exposed at several earth quarries located in Perlis including Kampung Guar Jentik, Bukit Tuntung in Pauh and Hutan Aji, as well as several localities around Pokok Sena in north Kedah. It has been referred to by some workers as the base of the Kubang Pasu Formation (Basir Jasin, 1995; Basir Jasin and Zaiton Harun, 2001). The unit was also previously referred to as Unit 6 of the Jentik Formation (Meor and Lee, 2002). The Telaga Jatoh Formation was deposited during the Early Carboniferous. The Telaga Jatoh Formation consists of rhythmically alternating, cm-thick beds of grey chert and black to grey mudstone/shale. The rocks contain abundant fossil radiolarian.

The Telaga Jatoh Formation is well exposed at Sanai Hill B in Kampung Guat Jentik, Beseri District Perlis. Here, the unit is approximately 10 m thick and stratigraphically overlies the Late Devonian Sanai Limestone (Meor and Lee, 2005). The contact has been interpreted to be a paraconformity (Meor, 2021). The Telaga Jatoh Formation is present at Sanai Hill C and Hutan Aji of Perlis as thin deformed slivers directly overlying the Lower Devonian Timah Tasoh Formation. The deformed nature of the unit was probably due to faulting and intense shearing along the bedding plane contact between the Devonian and Carboniferous strata (Basir *et al*., 2010; Meor, 2021). The folded cherts of the Telaga Jatoh Formation at Sanai Hill B were previously interpreted as slump folds (Meor and Lee, 2005), but have recently been re-interpreted as representing deformation due to this tectonic shearing (Meor, 2021). In northern Kedah, the Telaga Jatoh Formation directly overlies black shales of the Mahang Formation (which is the southern extension of the Timah Tasoh Formation).

The Telaga Jatoh Formation comprises rhythmically alternating, cm-thick beds of grey chert and black to grey coloured shale/mudstone. Thin sections of the chert indicate that it is opaque but contain abundant radiolaria. The carbon content ranges between 1% – 2.5% (Basir *et al*., 2003). The intercalated black mudstone/shale has a slaty appearance, which is consistent with tectonic shearing along the Devonian-Carboniferous contact. Radiolarians extracted from the chert represent the Early Carboniferous *Albailella deflandrei* and *A. indensis* Zones, which correlate in Europe with the Mississippian, Late Tournaisian (Tn3) to lower Viséan (e.g., Braun and Gursky, 1991; Won and Seo, 2010).

The radiolarian-rich cherts of the Telaga Jatoh Formation may indicate marine pelagic deposition during periods of high nutrient input and high organic productivity, possibly associated with algal blooms. Basin and Zaiton (2011) interpret the depositional setting of the Telaga Jatoh Formation as ranging from outer shelf to deep marine continental rise (Basir and Zaiton, 2011b). There is a possible pattern of cherts deposited in outer shelf setting being restricted to west Perlis, while the deeper cherts deposited in deeper water being present in east Perlis and further south in Kedah (Meor *et al*., 2014).

3.5.3 Lower Contact with Mempelam Limestone Formation (Setul Group)

The exposed sections at Pulau Langgun and Kampung Guar Jentik, Perlis, clearly show that that the Timah Tasoh Formation overlies the Silurian Mempelam Limestone (previously known as the Upper Setul Limestone). The contact is well exposed on Pulau Langgun and is sharp and conformable, with the lithology abruptly changing from bedded limestone of the Mempelam Limestone into black shales of the Timah Tasoh Formation (Cocks et al., 2005). The Mempelam Limestone is 198 m thick at Pulau Langgun and comprises well-bedded, stylolitic, light grey, fine-grained limestone (micrite or mudstone-wackestone) with intercalated shale partings. The beds contain a rich celloni-amorphognathoides Zone conodont assemblage, which gives a Silurian (Llandovery, Telchyian) age (Igo and Koike, 1966, 1968; Idris, 1989). Igo and Koike (1973), Igo (1984) also report Wenlock and early Ludlow conodonts from 30 m above the base of the formation on Pulau Langgun. The topmost beds of the Mempelam Limestone are latest Silurian (Pridoli) in age based on conodonts from Pulau Langgun (Igo, 1984) and scyphocrinoid loboliths found in both Pulau Langgun and Kampung Guar Jentik (Lee, 2001, 2005; Cocks et al., 2005), with the contact between the Mempelam Limestone and Timah Tasoh Formation crossing the Silurian-Devonian boundary. The limestone is interpreted as pelagic limestone possibly deposited in an outer shelf setting (Lee, 2009).

3.6 THICKNESS

The exposure of Timah Tasoh Formation on Pulau Langgun (previously referred to as the Upper Detrital Member), Langkawi, reaches 170 m in thickness.

The exposed thickness in Hutan Aji, Perlis is estimated to be about 40 m. The succession is almost wholly argillaceous, made up mainly of black, grey and brown, laminated, dacryoconarid shale and siltstone. The unit is about 18 m thick at Kampung Guar Jentik, Perlis, but the exposures are strongly deformed.

The black shales of the Timah Tasoh Formation are rich in fossils, which is dominated by a dacryoconarid-monograptid assemblage. The monograptids include *Monograptus langgunensis* and are characteristic of the Early Devonian (Pragian or earliest Emsian) Monograptus yukonensis Zone (Jones, 1973; Meor et al., 2013). The dacryoconarids also indicate a Pragian or earliest Emsian age, and include taxa such as *Styliolina* sp., *Metastyliolina*? sp. cf. *M. lardeuxi*, *Nowakia (Turkestanella) acuaria acuaria*, *Nowakia (T.) acuaria posterior*, and *Nowakia (Alaina) matlockiensis* (Meor et al., 2013). Other fossils found in the Timah Tasoh include the trilobite *Plagiolaria* and the brachiopod *Plectodonta (P.) forteyi* (Meor and Lee, 2005). The predominance of pelagic fossils, which are almost rock-forming, the fine-grained texture of the sediment and the black colouration leads to a relatively deep marine, outer shelf depositional environment (Meor et al., 2014).

3.7 AGE AND FOSSIL ASSEMBLAGES

The black shales of the Timah Tasoh Formation contain a rich dacryoconarid – monograptid – trilobite – brachiopod fossil assemblage. The dacryoconarid tentaculitoids present are *Styliolina* sp., *Metastyliolina* sp. cf. *M. lardeuxi*, *Nowakia (Turkestanella) acuaria*

acuaria, *Nowakia (Turkestanella) acuaria posterior* and *Nowakia (Alaina) matlockiensis* (Meor et al., 2013). The graptolite *Monograptus langgunensis* is reported from the Hutan Aji, Perlis section as well as on Pulau Langgun (Jones, 1973; Meor et al., 2013). *Monograptus* sp. cf. *M. uniformis* is also reported from Pulau Langgun (Jones, 1973). Other fossils present include the brachiopod *Plectodonta (Plectodonta) forteyi* and the trilobite *Plagiolaria* (Meor and Lee, 2005).

The dacryoconarids and the monograptid *M. langgunensis*, which is characteristic of the *M. yukonensis* Zone, indicate an Early Devonian (late Pragian to earliest Emsian) age for the Timah Tasoh Formation (Meor et al., 2013). However, the presence of *M.* sp. cf. *M. uniformis* and the occurrence of Přídolí to Lochkovian age scyphocrinoids (Lee, 2005) and conodonts (Igo and Koike, 1973) near the boundary between the Mempelam Limestone and Timah Tasoh Formation indicates that the Timah Tasoh Formation extends downward into the earliest Devonian.

Figure 2: Dacryoconarid, Guar Jentik (6° 34.968 ´N, 100° 11.998´ E)

Figure 3: Graptolite, Guar Jentik (6° 34.968´ N, 100° 11.998´ E).

Figure 4: Straight cone nautiloid indicative of Devonian age, Hill C, Guar Jentik, Malaysia (6º 40.156´ N, 100º 11.850´ E)

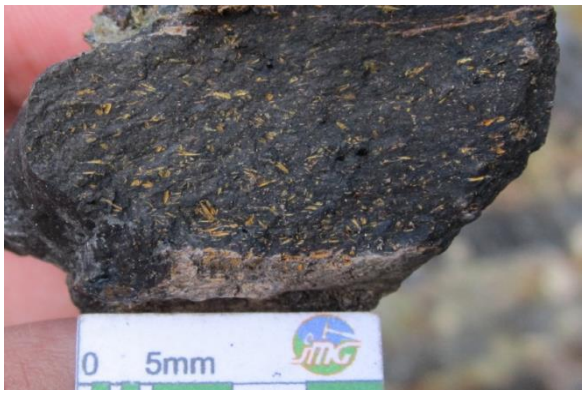

Figure 5: Dacryoconarid tentaculitoids-bearing dark grey shale at Teluk Mempelam, Pulau Langgun

3.8 TECTONIC AND DEPOSITIONAL ENVIRONMENT

According to Gobbett & Hutchison (1973), the Timah Tasoh Formation comprises of reddish-grey to grey mudstone, siltstone and quartzite due to the fact that the Timah Tasoh

Formation is slightly-to-not metamorphosed as explained by Jones (1976) that Pulau Langgun is situated away from the tectonic activities and thus are unaffected by the regional metamorphism. Jones (1976) has discovered an isolated fault on Pulau Langgun trending NE-SW with a dipping of apparently SE-NW. There is also a freshwater-filled sinkhole in the middle of the island, which is believed to be associated with the fault. In terms of the strata, the beds strike mainly SE-NW with a dipping of NE-SW.

According to Meor (2013), the Timah Tasoh Formation is overlain by folded and foliated flaggy rock and quartzite. The Rebak Formation comprises of red conglomeratic mudstone and light to grey quartzite and flaggy shale which overlies unconformably on the Timah Tasoh Formation (Jones, 1976).

The result of structural analysis showed that there are two major stress systems which had acted the outcrop in Hutan Aji, Perlis. The ST 1 stress acting with the main stresses ($\sigma 1$) from the northeast-southwest direction and the ST 2 stress system acted with the main stresses ($\sigma 1$) from the northwest-southeast affected the sequence of Setul Formation, Timah Tasoh Formation and Kubang Pasu Formation in Hutan Aji (Muhammad Ashahadi Dzulkafli, Nurasiah Sulaiman & Zaiton Harun, 2019).

Meor et.al. (2014) observed that the Timah Tasoh Formation is in fault contact with the overlying Sanai Limestone of Mempelam Member at Sanai Hill B, Perlis although in some localised parts of the Hill B exposure, the contact appears to be stratigraphic, with a sharp lithological change from black mudstone to limestone.

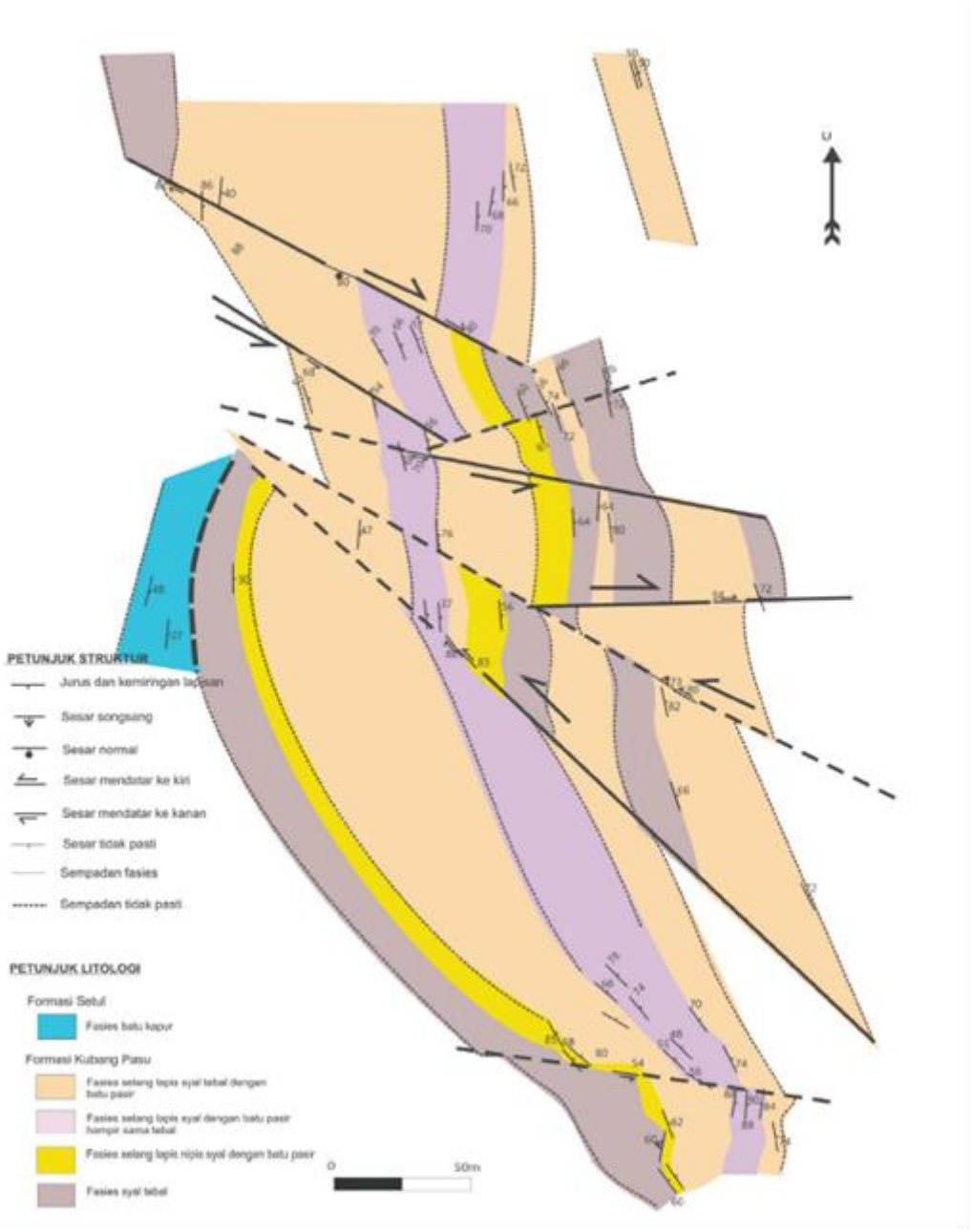

Figure 6: Geology and structure of Setul Formation, Timah Tasoh Formation and Kubang Pasu Formation at Hutan Aji, Perlis (Modified from Muhammad Ashahadi Dzulkafli, Nurasiah Sulaiman & Zaiton Harun, 2019)

The Timah Tasoh Formation is interpreted as being deposited in a marine outer shelf setting. The fossil composition of the Timah Tasoh Formation clearly indicates a marine depositional setting. The predominance of clay- and silt-sized clastic particles as well as the absence of sandy deposits and any wave/current generated structures can be interpreted as representing a more offshore position, either below wave base or in a restricted low energy basin. Abundant pelagic tentaculitoids and monograptids place the unit in Benthic Assemblage 4–5 of Boucot (1975), indicating water depths of between 150 m and 200 m (Brett et al., 1993). The black colour and high organic content have been interpreted as reflecting anoxic or dysoxic water conditions (Meor *et al*., 2014). However, the presence of

benthic fauna such as brachiopods and trilobites indicate the presence of free oxygen at the water-sediment interface, either for short or long periods of time. The dense dacryoconarid fossil assemblage may have been associated with periods of nutrient-enriched waters, high organic productivity and possible algal blooms.

During the earliest Devonian (Lochkovian), transgression in the areas of present-day Northwest Peninsular Malaysia resulted in gradual drowning of the carbonate platform and deposition of black mudstone (as marked by the gradational boundary between Mempelam Member and Timah Tasoh Formation in Perlis and Langkawi). Transgression occurred later in southern Peninsular Thailand, with carbonates of the Kuan Tung Formation being replaced by the Pa Samed Formation during the Early Devonian (Emsian) (Meor *et.al*., 2014).

3.9 REFERENCES SECTION

3.9.1 Guar Sanai Reference Section (Kampung Guar Jentik)

The Timah Tasoh Formation is exposed at several earth quarries in the Guar Sanai area, Perlis and generally dipping eastwards. There is a ridge locally known as Guar Sanai which consists of three small hills (guar) called Hill A, B and C by Meor and Lee (2002). Timah Tasoh Formation is underlain by the Mempelam Limestone in the west and overlain by the Sanai Limestone and Rebak Formation in the east which are cut by many thrust, lateral and normal faults.

The section at the northern part of Hill B comprises five lithofacies (in ascending order) i.e. limestone, dacryoconarid mudstone/shale, bedded chert, mudstone and fine sandstone. The rocks are tilted dipping northeast in normal position. For Hill C, the sequence is more complicated with lithofacies recognized in ascending order are; dacryoconarid black mudstone (oldest), very thinly bedded chert, sandstone, bedded chert, red mudstone, mudstone, black sandstone, interbedded sandstone and mudstone, sandstone (youngest).

The dacryoconarid bed at Hill B are very abundant and randomly oriented. The dacryoconarid beds are mainly composed of highly weathered mudstone and yellow in colour and approximately 4m thick with strike and dip of 348°/46°. The fossil composition in both dacryoconarid beds of Hill B and Hill C are essentially the same, indicating that both beds are correlatable and age equivalent.

The bedding has undergone great weathering as a result of exposure to the tropical climate. Quarrying activities here are expected to end with the rock outcrops were only small part remains. The contact of Timah Tasoh Formation (black shale and highly fossillerous) is still tracable, where it underlies chert beds of the Telaga Jatoh Formation at Hill C.

Several species and subspecies of dacryoconarid tentacultioids have been identified by Meor et al. (2013) from the dacryoconarid bed at Hill C represented by *Styliolina* sp., *Metastyliolina*? sp. cf. *M. lardeuxi*, *Nowakia (Turkestanella) acuaria acuaria*, *Nowakia (T.) acuaria posterior*, and *Nowakia (Alaina) matlockiensis*. The similarity of fossil content in the dacryoconarid beds of Hill B and Hill C indicates that both beds are of the same age (Early Devonian). The rock sequence at Hill B is comparable to the one at Teluk Mempelam, Pulau

Langgun. However, a major difference is the presence of the Late Devonian Sanai Limestone, which is absent from all other sections in Perlis and Langkawi.

Figure 7: The outcrop of black shale with Dacryoconarid bed of Timah Tasoh Formation at Hill B, Guar Sanai

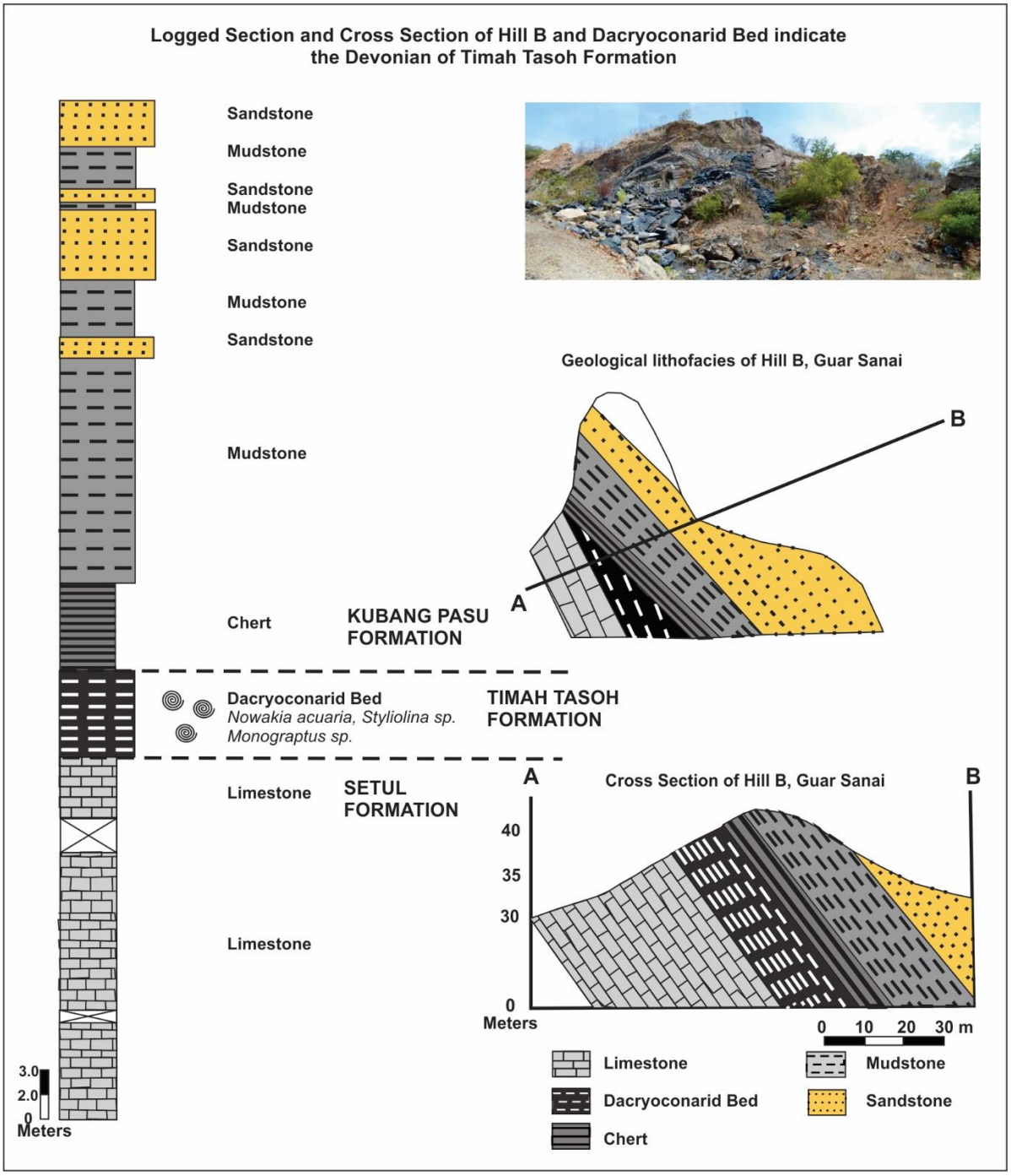

Figure 8: The reference section of black shale with Dacryoconarid bed of Timah Tasoh Formation at Hill B, Guar Sanai

The outcrop at Guar Sanai is almost in north-south direction. The black shale of Timah Tasoh Formation are clearly observed due to abundance of fossil occurences especially the tentaculites. The fossils in both dacryoconarid beds indicates the Early Devonian in age. The lithologic log sequence at Hill C shows the black shale of Timah Tasoh Formation overlain by the Kubang Pasu Formation, but with thin deformed chert lenses being preserved along the contact.

Figure 9: The scenery of hill formation at Guar Sanai, Kampung Guar Jentik

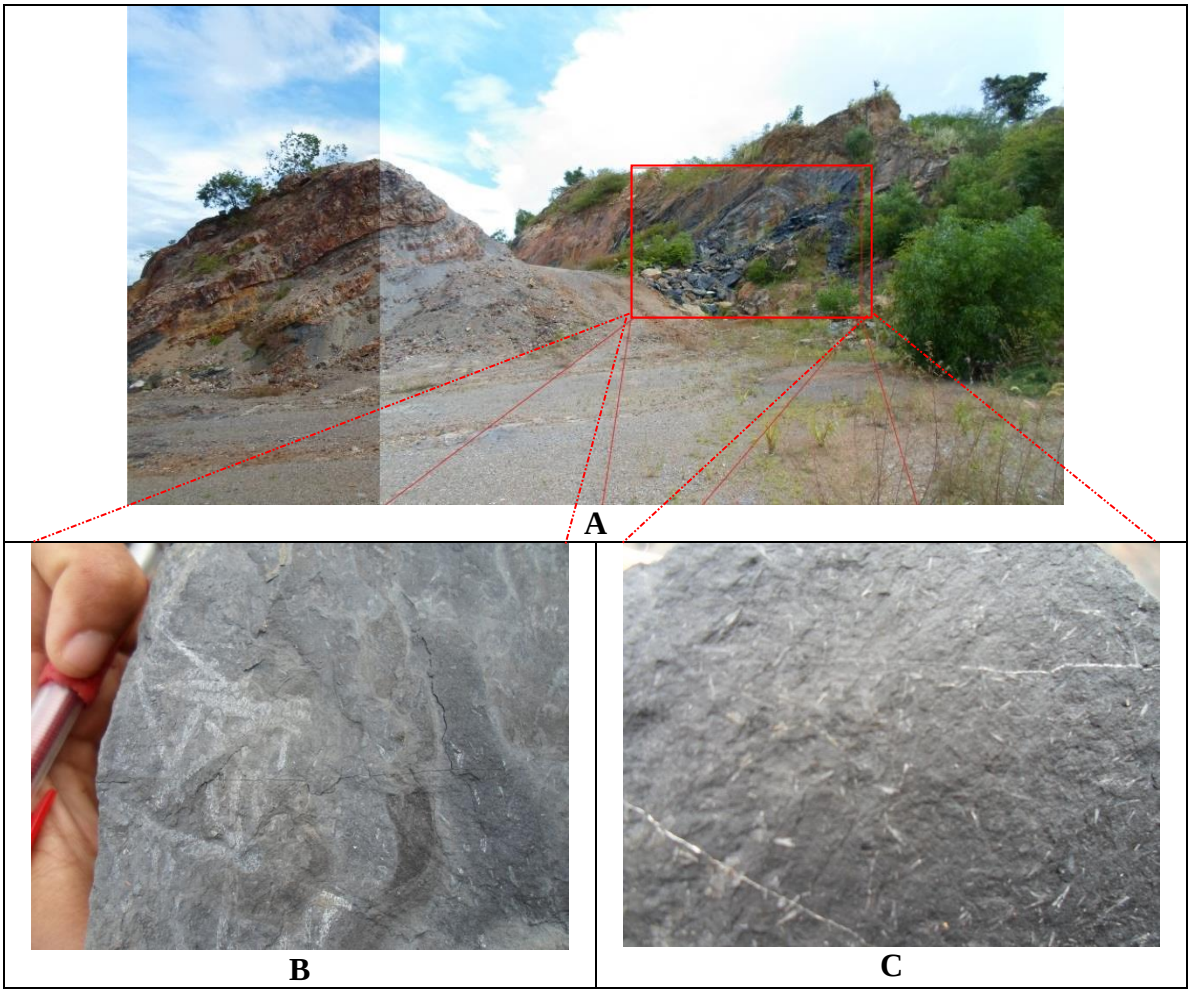

Figure 10: A – The outcrop of Timah Tasoh Formation at Hill B and Hill C at Guar Sanai, Kampung Guar Jentik. B & C – Several species and subspecies of dacryoconarids as well as graptolites have been identified from the dacryoconarid bed at Hill B and Hill C.

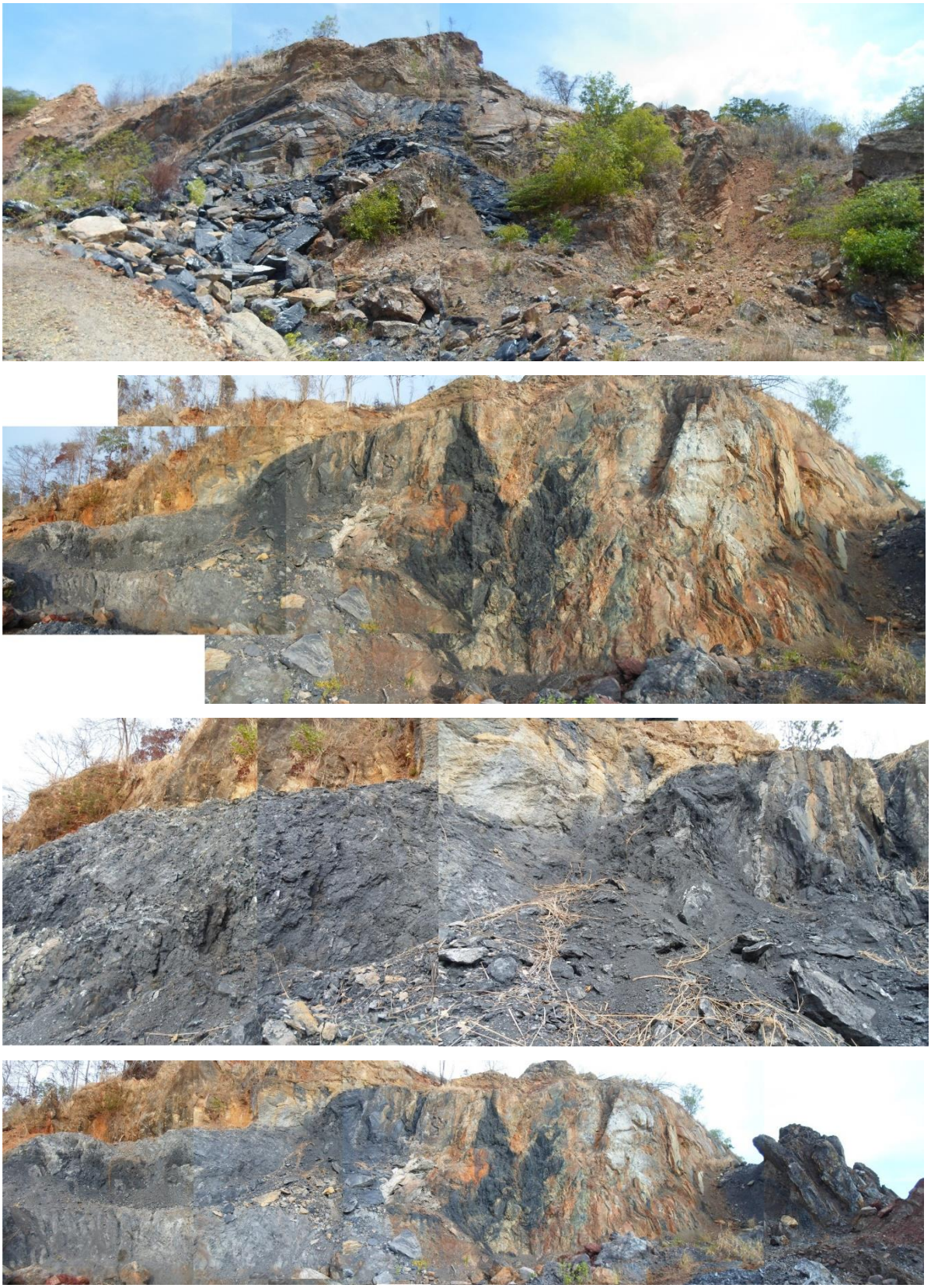

Figure 11:The outcrop of dacryoconarid black mudstone of Timah Tasoh Formation at Hill B at Guar Sanai, Kampung Guar Jentik.

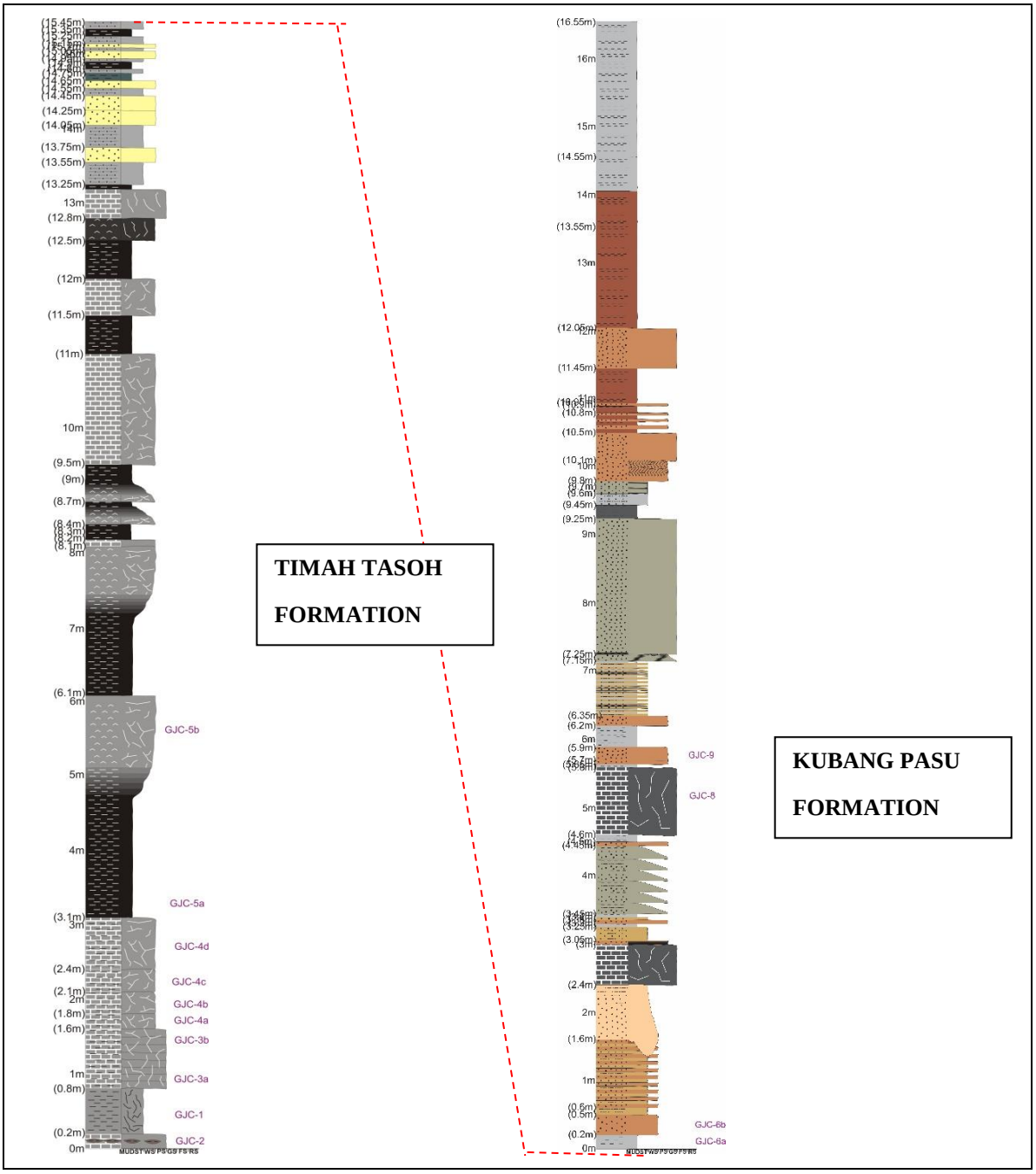

Figure 12:The details of lithology log of Hill B showing the Timah Tasoh Formation and Kubang Pasu Formation.

3.9.2 Teluk Mempelam Reference Section

The sedimentary log shows the variation of facies to the further north of Teluk Mempelam, Pulau Langgun. The sequence of the rocks can be seen to be coarsening upwards, which corresponds to its depositional environment i.e. from deep to shallow marine. From the log, it can be seen that the outcrops at the north of Teluk Mempelam is sandstone interbedded with shale. Towards the southern part, the units can be seen to have finer grains, almost black in color which referring to Timah Tasoh Formation.

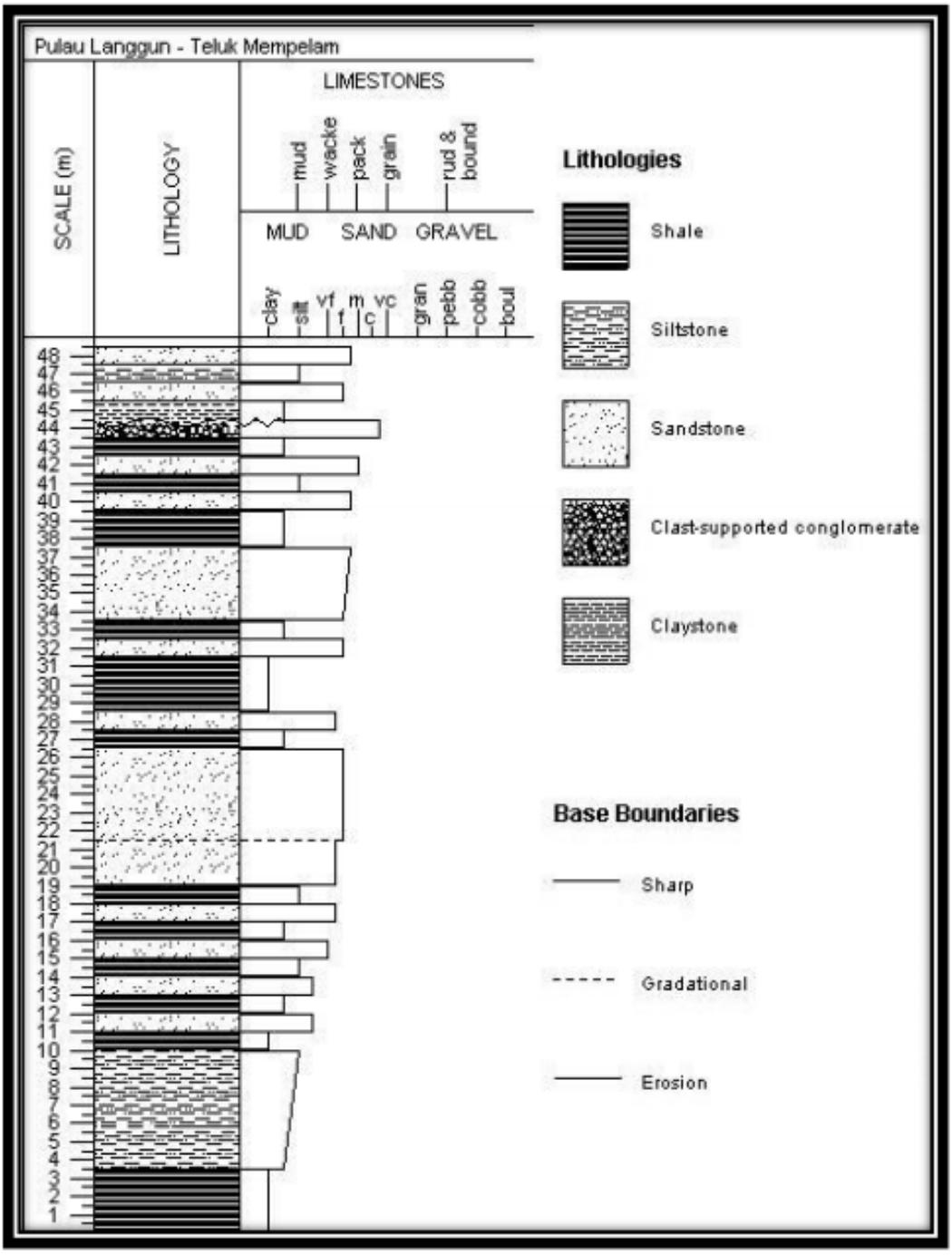

Figure 13:Sedimentary logging of the northern part of Teluk Mempelam. From 0 m – 44.5 m is the Timah Tasoh Formation, while from 44.5 m – 48.5 m is the Rebak Formation (Modified From Jones, 1981)

Rocks units in the Langgun reference section trend NW-SE with dips varying from 20° to 30°. There is an abrupt change from thick and massive limestone beds to thin laminations of limestone and to the finer black mudstone of Timah Tasoh Formation in an outcrop found along the coast of Pulau Langgun.

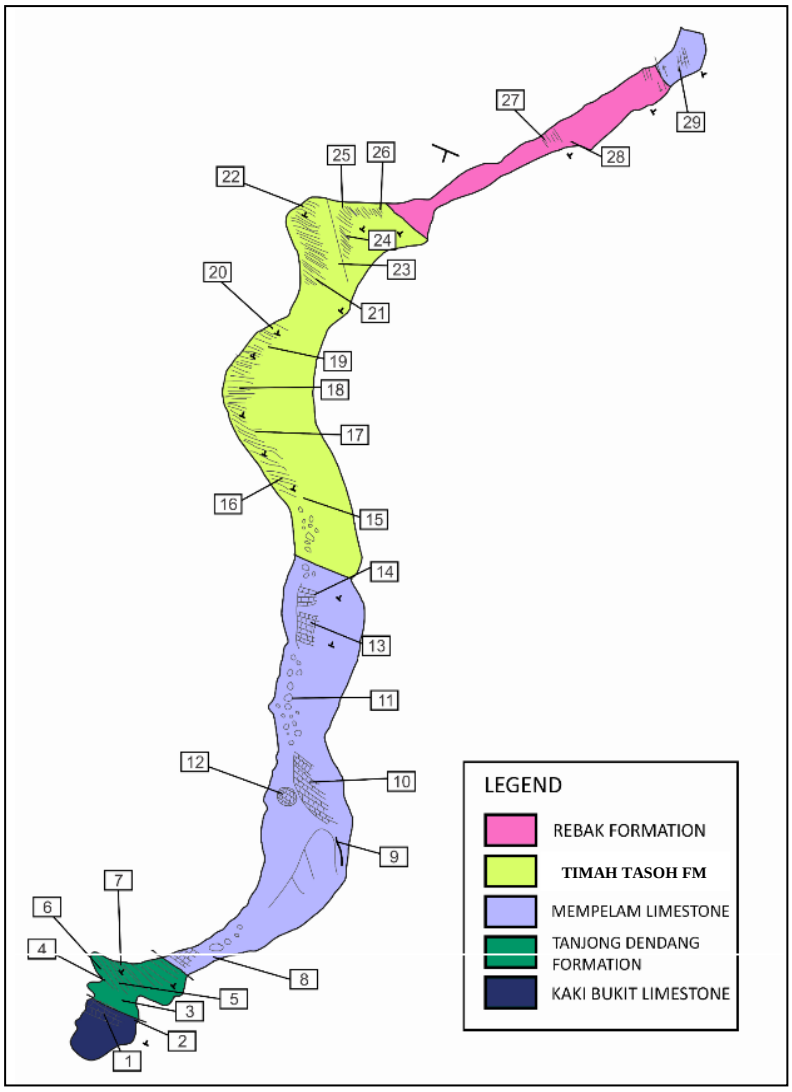

Figure 14: Geological map of Teluk Mempelam, Pulau Langkawi, Kedah. (Modified from Jones, 1981)

Explanation on lithology map (modified from Jones, 1981):

1. Limestone with light colour, fine texture and massive. Horizontal faulting between Kaki Bukit Limestone and Tanjong Dendang Formation. (308/22)
2. Clear boundary between Kaki Bukit Limestone and Tanjong Dendang Formation.
3. Bed of trilobite fossil, distributed randomly in black siltstone.
4. Bed of graptolite fossils in shale/mudstone.
5. Synclinal folding that is parallel with bedding.
6. Horizontal fault parallel to chert bedding.
7. Black chert with clear bedding that shows fining towards younging direction. (320/16)
8. Massive limestone with trace fossils parallel to bedding. (310/22)
9. Limestone edge showing parallel laminations. (320/26)
10. Stylolitic limestone with trace fossils present.
11. Boulders of mudstone with various shapes, which undergone transportation.
12. Limestone stump with visible bedding.
13. Limestone bedding with bioturbations. (290/20)
14. Limestone with light color, and having thin shale beddings.
15. Thin bedding of black and brown mudstones intercalated together.
16. Folding in mudstone.
17. Huge anticlinal and synclinal folding.
18. Clearer beddings of rocks. (310/20)

19. Parallel laminations in fine grained sandstone.
20. Sandstone with bright color with clear bedding. (312/24)
21. Anticlinal and synclinal folding, causing corrugation between sandstone.
22. Quarzite. (290/30)
23. Left horizontal faulting.
24. Parallel laminations in quartzite. (310/30)
25. Cross-laminations.
26. Beddings of red mudstones containing pebbles. (312/30) Conformable boundary of Timah Tasoh Formation with Rebak Formation.
27. Dark sandstones. (340/40)
28. Bright color sandstones. (320/20)
29. Limestone with parallel laminations. (350/38)

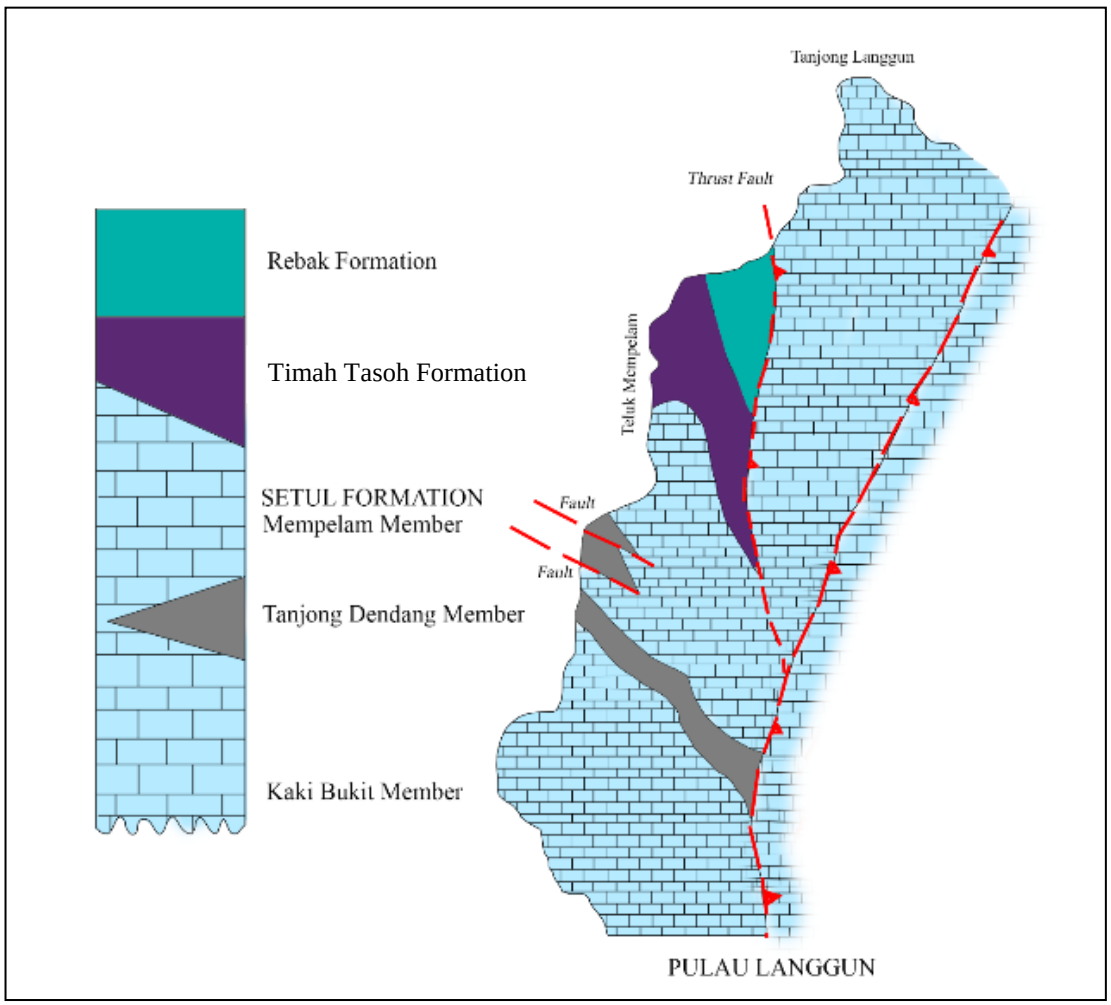

Figure 15: The Timah Tasoh Formation sequence with the fault contact to the Setul Formation in Langgun Island (modified from Malaysia-Thailand Working Group, 2013)

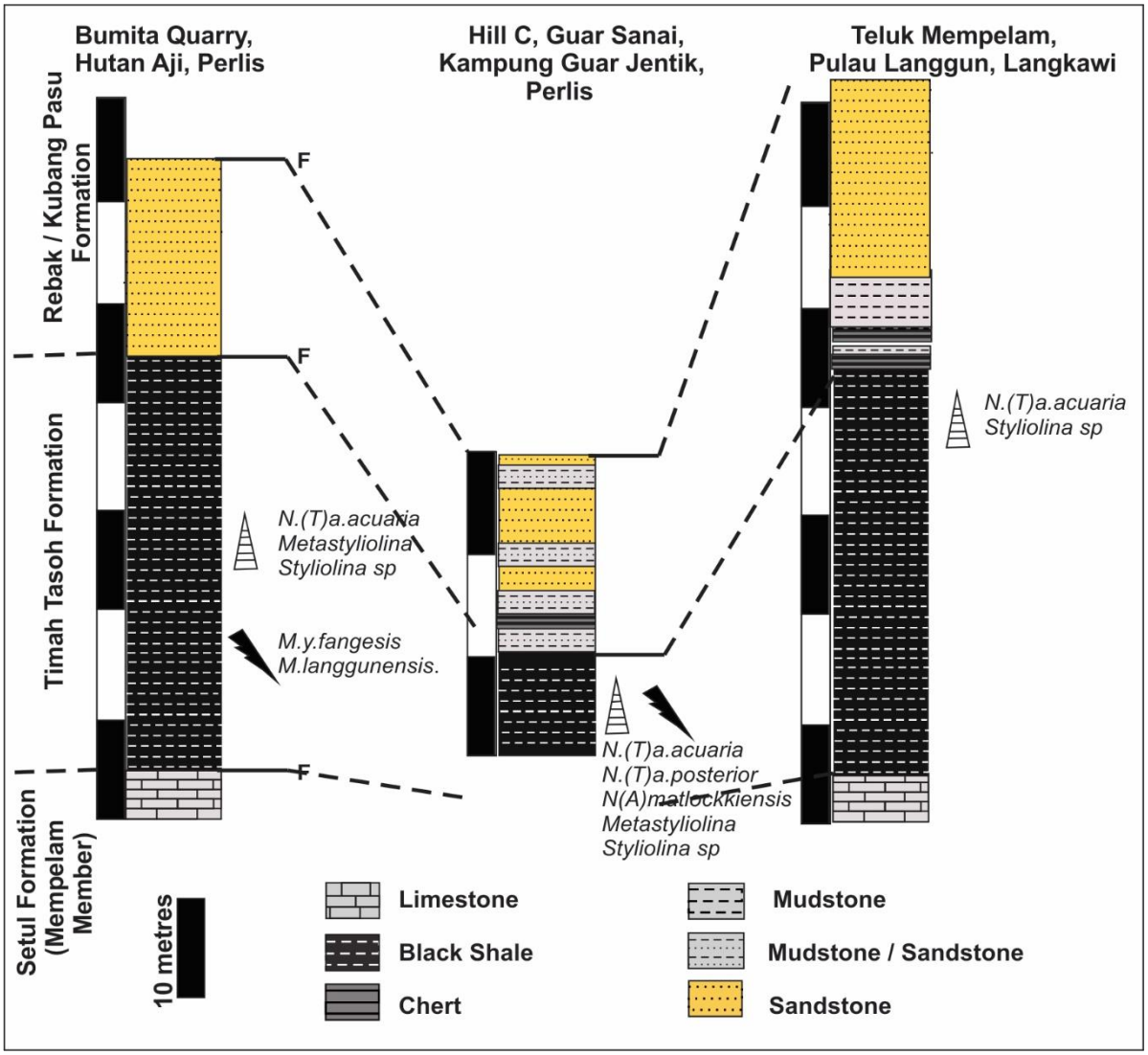

Figure 16: The correlation of the reference section of Timah Tasoh Formation at Hutan Aji, Guar Sanai and Teluk Mempelam (modified from Meor, 2003)

4. PA SAMED FORMATION

According to Department of Mineral Resources, Thailand (2014), Silurian-Devonian-Carboniferous rocks in southern region overlie the Thung Song Group and underlain the Khuan Klang Formation. The rocks predominantly consist of black shale, chert, sandstone and limestone. They distribute in southern part of western region and central part of southern region from Khao Luang, Surat Thani province to Nakhon Si Thammarat province, and Satun province. Wongwanich *et al.* (1990) made a detailed study of the rocks at km 10-11 along road between La-ngu-Thung Wa, north of Satun province and mapped four formations. Outcrop geological map in the Ban Pa Samet-Ban Pa Kae area by Wongwanich et al. (1990) shown in Figure 17. The sequence of these formations, starting from older to younger, comprises the Wang Tong, Kuan Tung, Pa Samed and Khao Chu Nong Formations. Later, conodonts at the Khao Chu Nong Formation were dated as Ordovician and are denoted fault contact rock with the underlying Pa Samed Formation. Therefore, the Thong Pha Phum Group in the southern region consists of only three formations.

Type section of Pa Samed Formation is situated at Km 9.7-9.8 on the road between La-ngu-Thung Wa districts. The lower part of the formation is black shale with numerous tentaculites. The middle part comprises brown and red sandstone exhibits Bouma sequences and conglomerate with many ammonoid beds. The upper part consists of thin laminations of grayish black shale becoming brown when weathered. Ammonoids and brachiopods were found in lower portion of the upper part of the formation. Thickness of the formation is 105 m. Depositional environment of the lower part of formation was interpreted to be in deep sea environment. The middle part deposited in shallower depth on continental slope. The upper part deposited in deep sea environment but shallower than that of the lower part. Rucha Ingawat and Benja Songsirikul in Wongwanich et al., (1990 p.7) identified a fauna occurring 10 m above the base of the formation, that includes *Nowakia, Metastyliolina, Styliolina, Echinocoeliopsis, Plagiolaria, Echinocoelia* and *Monograptus* indicating an age of Early to Middle Devonian.

Boucot *et al.* (1999) studied the brachiopods from the Pa Samed Formation, and described *Quasiprosserella samedensis, Plectodonta (Plectodonta) forteyi, Lissatrypa* sp., *Caplinoplia thailandensis, Plicanoplites?* and *Clorinda wongwanichi.* These are thought to represent a deep-water benthic assemblage. A trilobite with reduced sight belonging to *Plagiolaria poothaii* originally described by Kobayashi and Hamada (1968) from material collected between Trang and Phatthalung provinces is associated with the brachiopod fauna (Cronier and Fortey, 2006). Ruan Yi-ping in Boucot et al. (1999) identied the dacryoconarids in the Pa Samed Formation on the road side near Ban Tham Phra as *Nowakia acuaria, Nowakia* cf. *matlockiensis, Nowakia* cf. *hercyniana, Styliolina* sp., *Striasstyliolina* sp., *Viriatellina* sp., assigned them to the *Guerichina* Zone and suggested a Late Pragian age but that they may be as young as Early Emsian.

Late Carboniferous fauna occurs 44 m above the dacryonocarid beds in a siltstone and consists of an abundant but moderate diversity collection of kaolinized, brachiopods and goniatites (Wongwanich *et al.,* 2004). The goniatites include *Stenopronorites* cf., *uralensis, Syngastrioceras* sp. and *Glaphyritid* indet. and are definitely Namurian in age. The brachiopods include *Aseptella satunensis, Eileenella elegans, Tornquistia orthogona,*

Coledium satuni, Plicambocoelia tansathieni, Crurithyris sp., cf. *Martinia* sp., cf. *Reticularia* sp., and *Girtyella* sp. This brachiopod fauna is unlike any previously decribed fauna from Asia. The Kuan Tung and Pa Samed Formations both therefore contain Early Devonian faunas but so far, no Late Devonian or definite Early Carboniferous fossils have been found in the Pa Samed Formation. This may suggest a significant paraconformity within the Pa Samed or even a fault within a covered section above the dacryoconarid beds.

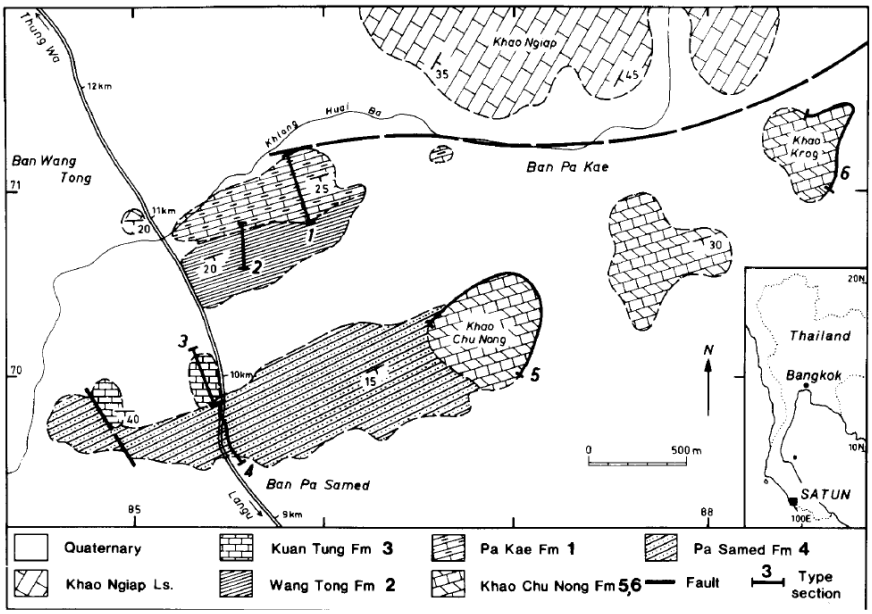

Figure 17: Outcrop geological map in the Ban Pa Samet-Ban Pa Kae area, Solid outcrop shown in separated by low lying areas with residual soils, laterite and alluvium. (After Wongwanich et al., 1990)

4.1 NOMENCLATURE

Pa Samed Formation was named by Tansuwan *et al.* (1980) after Ban Pa Samed, approximately 9 km north of La-ngu district, Satun province.

4.2 DISTRIBUTION AND GEOLOGIC SETTING

There is general agreement that Southeast Asia is a complex assembly of several continental blocks that rifted from Gondwanaland (e.g., Metcalfe, 1999). Thailand comprises two main continental blocks, the western Shan–Thai and eastern Indochina Blocks. These two blocks are separated by a suture zone made up of the northern Nan–Uttradit and southern Sra (Sa) Kaeo–Chanthaburi zones. The area is bordered to the west by the Sukhothai Fold Belt and to the east by the Loei–Petchabun Fold Belt (e.g., Bunopas, 1981). Bunopas (1992) recognized seven longitudinal stratigraphic belts, designated BS-1 to BS-5, that belong to the Shan–Thai Block, and belts BI-6 to BI-7 that belong to the Indochina Block. The Lower to Middle Paleozoic was divided into the following stratigraphic units by Bunopas (1992): the Cambrian Tarutao Group, Ordovician Thung Song Group, and Silurian to Carboniferous Thong Pha Phum Group (Figure 4.2). The Pa Samed Formation is distributed within belt BS-2 and 3.

Wongwanich et al. (1990) described the following lithostratigraphy in the Satun area: the Cambrian Tarutao Group, Ordovician Thung Song Group, and Silurian to Devonian Wang Tong, Kuan Tung, and Pa Samed Formations. The Silurian-Devonian-Carboniferous rock distribute in southern part of western region and central part of southern region from Khao Luang, Surat Thani province to Nakhon Si Thammarat province, and Satun province. Wongwanich et al., (1990) made a detailed study of the rocks at km 10-11 along road between La-ngu-Thung Wa, north of Satun province. Agematsu et al., (2006) studied a siliciclastic sequence in this type location of Pa Samed Formation, Satun province within Belt BS-3 (Figure 4.2). It contains a tentaculite bed from black shale and contains *Nowakia acuaria* in the lowermost part. Based on occurrences of *Nowakia acuaria*, the depositional age of the tentaculite bed is earliest Emsian.

Similar tentaculitid-bearing shales of the Pa Samed Formation are widespread in peninsular Thailand and Malaysia and further north in central western and northern Thailand and Burma (Brown et al. 1951, Kobayashi and Hamada 1968, 1972, Jones 1978, Burton 1967, Hagen and Kemper 1976, Burrett et al. 1986) and are mainly lower-Middle Devonian. The exact relationship of these shales to the Pa Samed Formation is not clear. However, the age of this formation is possibly Devonian.

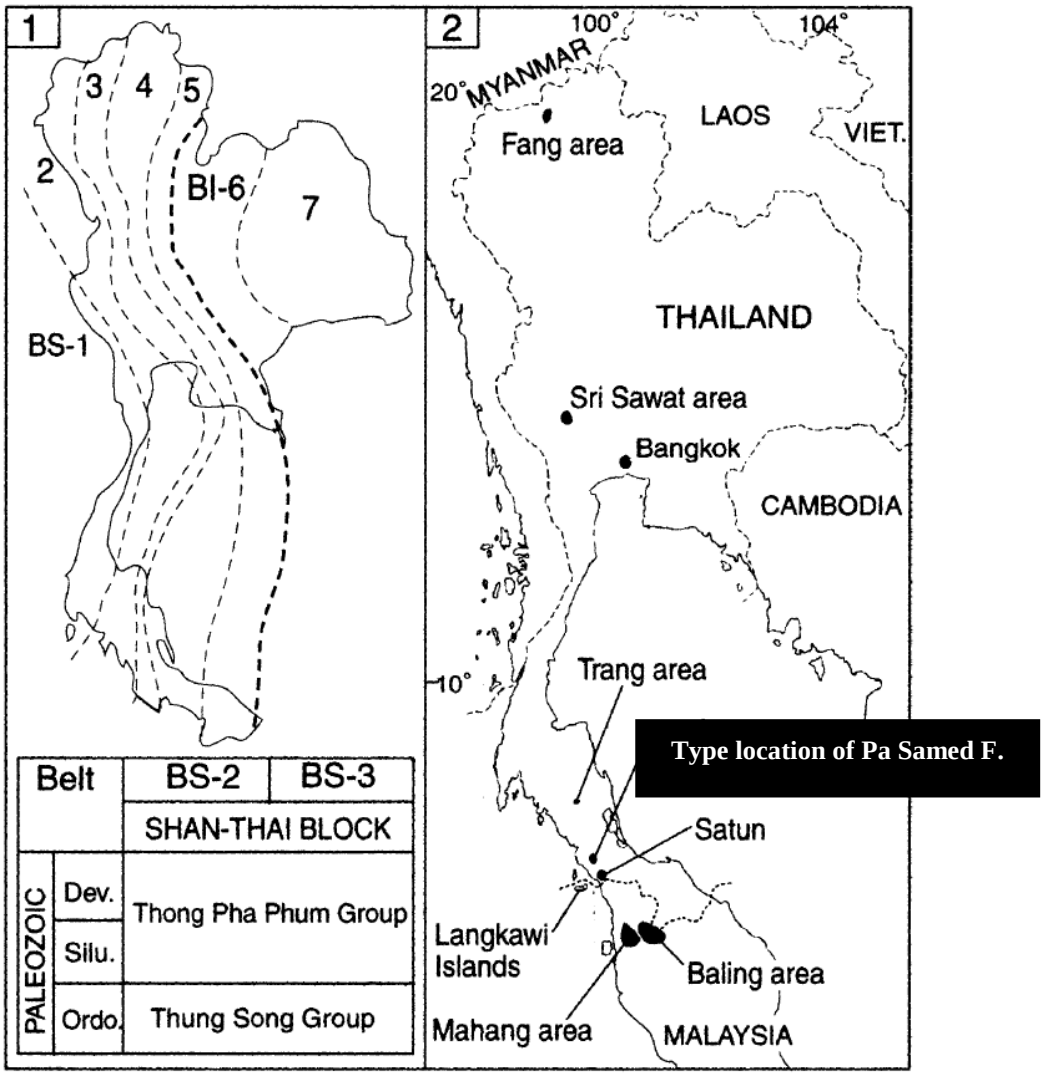

Figure 18: (1) Seven stratigraphic belts of Thailand and generalized stratigraphic nomenclature within the BS-2 and 3 belts (After Bunopas, 1992). (2) Index map showing the tentaculite beds distribution at several localities such as; the type location of Pa Samed Formation in Satun province and other areas. (After Agematsu et al., 2006)

4.3 LITHOLOGY

The Silurian-Devonian succession of the Pa Samed Formation, approximately 167 m thick, is dominantly siliciclastics (sandstone) with minor grey argillaceous limestone and black carbonaceous shales.

4.4 STRATIGRAPHY

According to Wongwanich and Boucot in Ridd et al., (2011), the Pa Samed Formation is redefined here from Wongwanich et al, (1990) as that 167 m thick sequence of dominantly siliciclastics (sandstone) with minor grey argillaceous limestone and black carbonaceous shales outcropping along the Langu-Thung Wa Road between 9.6 and 9.8 km from Amphoe Langu (Figure 4.2). It strikes N808E to 808W and dips 458 to the south (Agematsu et al., 2006). It conformably overlies the Kuan Tung Formation. In the type location of the Pa Samed Formation occurs over a stike lengths of about 2 km and extends to the Pa Kae Valley east of Amphoe Thung Wa. In this section, it can be divided into six members; in ascending order they are as follows.

Member One consists of 25 m of brown weathering black, pyritic carbonaceous shale. Small horizontal bioturbations(?) are common. Fossils include trilobites, brachiopods, cephalopods, graptolites, small nautiloids and tentaculitids. Abundant tentaculitids occur at 10 and 19 m above the base of the succession. Fossils from 10 m above the base of the member have been identified as species of *Nowakia, Metastyliolina, Styliolina, Echinocoeliopsis, Plagiolaria, Echinocoelia* and *Monograptus* and suggest an Early Devonian age by DMR palaeintologis. Agematsu et al., (2006) confirmed only *Nowakia acuaria* in the lowermost part of this unit.

Member Two consists of 35 m of fine-medium grain sandstone interbedded with shale. The basal part is thick-bedded to massive, grey feldspathic sandstone and grey shale grading upwards to red feldspathic sandstone and red shales with graded bedding and cross lamination of incomplete Bouma sequences. The uppermost 5 m consists of light grey feldspathic sandstone with scattered well rounded pebbles of (up to 100 mm diameter) quartz, quartzite, chert and slate on the top. Abundant goniatites occur at 4.5 m below the top of this member.

Member Three consists of 55 m of grey argillaceous limestone or decalcified brown decalcified shale with beds 20-50 mm thick, evenly laminated with a spheroidal weathering. It changes to very dark grey laminated shale with an abundant fauna including small Namurian brachiopods and goniates in the west.

Member Four is 8-10 m of grey to light brown, massively bedded fine sandstone. Sorting is poor and pebbles, up to 10 mm in diameter, are rarely present.

Member Five consists of 30 m of reddish-brown, fine feldspathic sandstone interbedded with laminated red shale in beds of between 100 and 200mm thickness. Small crinoid fragments and mud clasts are present.

The uppermost Member Six consists of 12 m of brownish-grey fine feldspathic sandstone with grey shale lenses. Bedding is 100-150 mm thick. Small fossil fragments are present.

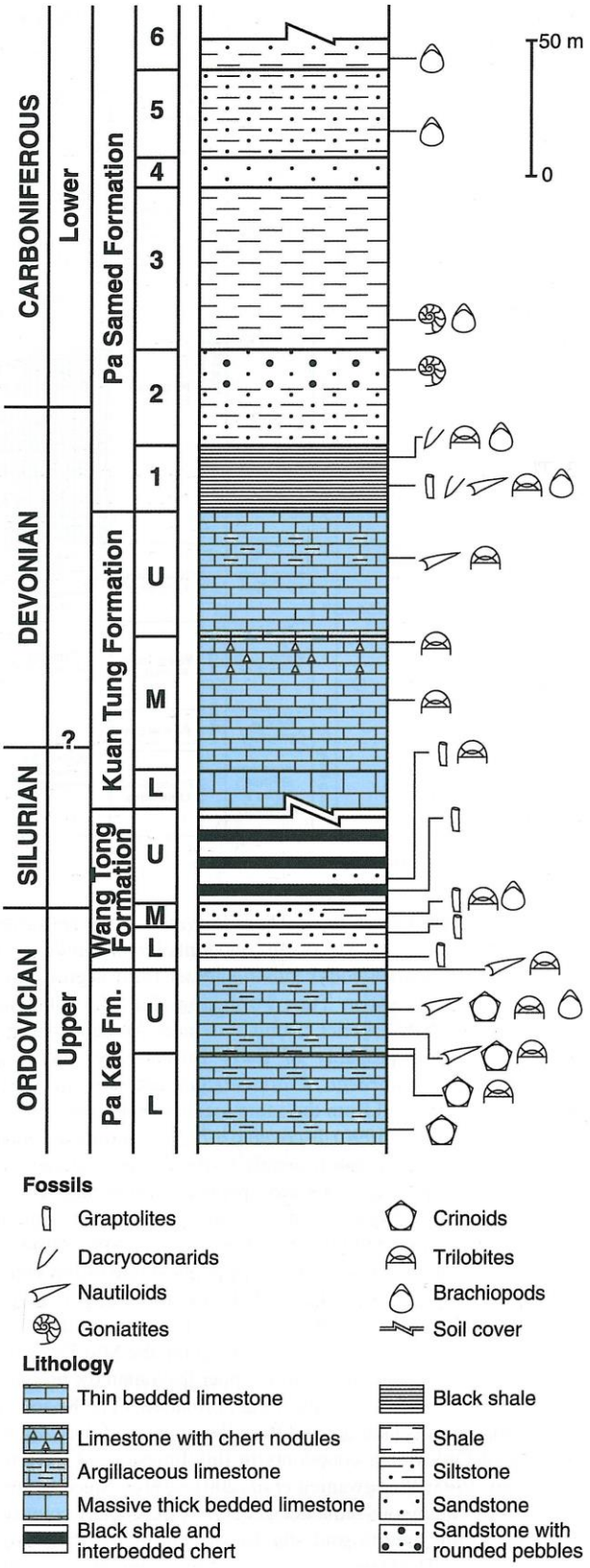

Figure 19: Composite stratigraphic column of the Upper Ordovician-Carboniferous between Km 9.5 and Km 11-kilometer posts beside the La Ngu to Tung Wa Road, Satun Province. A possible disconformity is inferred between the Carboniferous and Lower Devonian at about the level of unit 2 of the Pa Samed Formation (After Wongwanich and Boucot in Ridd et al., 2011)

4.5 LOWER AND UPPER CONTACT

Type area, The Pa Samed Formation conformably overlies the Kuan Tung Formation (Wongwanich et al., 1990). In Satun Province, Tansuwan et al., (1985) reported Lower Carboniferous *Posidonomya* sp. from 120 m thick sequence of reddish-brown weathering light grey to white shale intercalated with sandstone, siltstone and chert, apparently lying conformably above the Pa Samed Formation. They named these rocks the Khuan Klang Formation. This formation is possibly age-equivalent to the upper part of the Pa Samed Formation. The Malaysian-Thai Working Group (2012), the Khuan Klang Formation is continuously conformable with the underlying Pa Samed Formation in the vicinity of the northeastern part of Khuan Sung, Muang Satun District of Satun Province or at grid ref. 615658E 0731857N (Changwat Satun Quadrangle). The unit is grading gradually from dark grey, thin-bedded, carbonaceous mudstones containing abundant *Tentaculites* with, 30 cm thick, maroon, porous, hard pans, and bioturbated mudstones of the Pa Samed Formation. The sequence is grading to pale grey to light brown, powdered, thick-bedded mudstones and claystones of the Khuan Klang Formation. This indicates the change in depositional environment from the deeper to the shallower.

4.5.1 Kuan Tung Formation

Kuan Tung is the name of small hills trending on east-west and cutting across the Langu-Thung Wa Road between km 9 and 10 (Wongwanich et al., 1990). The area contains the bulk of the outcrop area of the Kuan Tung Formation and Pa Samed Formation. A reasonably well-exposed section of this formation is in a pararubber plantation at km posts 9.8-10.2, northwest side of Kuan Tung, commencing at grid reference 8531, 6985-8540, 6980; in 1:50,000 maps sheet 49221 Amphoe Langu. The formation is 105 m thick at the type section and up to 125 m thick to the west. It conformably overlies the Wang Tong Formation and conformably underlies the Pa Samed Formation.

The lower member is 15 m thick to massively bedded, grey to brownish-grey calcisiltite with thin (1-2mm) undulant argillaceous layers. The 44 m thick middle member consists of pink to red and grey caicisiltites and minor calcarenites with fine argillaceous layers. Bedding ranges from 100 to 500mm in thickness and chert nodules are observed in the top 10m of the member. The upper member consists of 46 m of red, well bedded, micrites interbedded with thin, brown to reddish-brown argillaceous layers. Small algal polygons are present at 26 m from the base of the member to the top of this unit.

The upper member of the sequence changes gradually westwards from the type section into a poorly fossiliferous red limestone with a very similar lithology to the Pa Kae Formation. The unit consists of 50m of red nodular limestone with argillaceous partings and coarser algal polygons of deep marine stromatolites. Bedding is 50-150 mm thick. The trilobites from a grey, thin bedded limestone close (3-5 m) to the top of the middle member as *Reedops, Cornuproetus, Decoroproetus* and *Platyscutellum.* These are associated with a species of *Polygnathus* closely related to the *P. perbonus P. labiosus* lineage of Mawson (1987) which suggests an Emsian-Eifelian age. Therefore, the age of this formation probably ranges from the late Silurian to the middle Devonian.

The Kuan Tung Formation is a biostratigraphic correlate of the Upper Setul Limestone of the Langkawi Islands, Malaysia (Jones, 1978) and the massively bedded grey limestone overlying black shale at Ban Na in central peninsular Thailand. Other Siluro-Devonian

limestone are known further north within Thailand at Thong Pha Phum, Kanchanaburi province, (Hagen and Kemper, 1976, Bunopas, 1982) and at Mae Ping National Park, Lumphun Province (Burrett et al., 1986), along the mountain range east of Amphoe Mae Sariang and Mae Lanoi, Mai Hong Son province.

4.5.2 Khuan Klang Formation

This formation was established by Tansuwan et al., (1985) in the Geologic Map of Changwat Satun with its type section at Khuan Klang *c.* 5 km west of Satun. It occurs mainly in Satun Province but has also been recognized locally in Songkhla and Phatthalung province. The formation is composed chiefly of grey and reddish shale with abundant fossil bivalves (*Posidonomya* sp.) in some beds, with intercalations of arkosic andquartzose sandstone, siltstone and chert. At its type section in a quarry at Bab Khuen Khan (probably inscribed as Khuan Klang originally), it is *c.* 150 m thick and passes down, apparently without a break, into tentaculite-bearing black shale of the Early Devonian Pa Samed Formation. It is overlain by grey mudstone probably belonging to the Kaeng Krachan Group. The Khuan klang Formation was originally thought to be the lower part of the Kaeng Krachan Group in the Satun area (Tansuwan et al., 1985), but the Geologic Map of Thailand (DMR, 1999) treats it as a distinct stratigraphic unit from the Kaeng Krachan Group.

At Ban Pa Samed in northwest Satun Province. Wongwanich et al., (2004) reported Namurian (late Missisippian to earliest Pennsylvanian) brachiopods and goniatites from Member 2 of the Pa Samed Formtaion. The fossil-bearing levels were originally assigned to the Early-Middle Devonian (Wongwanich et al., 1990). In the basal part of the formation (Menber One). Black shale contains abundant tentaculites of Early Devonian (Emsiam) age (Wongwanich et al., 2004; Agematsu et al., 2006). These data indicate a large hiatus between Member One and Member Two of the Pa Samed Formation. Moreover, the litho- and chronostratigraphic relationships observed at Ban Pa Samed are similar to those Ridd (2007) descried at the type section of the Khuan Klang Formation. Wongwanich et al. (1990) therefore presumed that at least Member Two of the Pa Samed Formation, and probably some of the overlying succession also, should be assigned to the Khuan Klang Formation, athough there are minor differences of lithofacies recogniszed between the Ban Pa Samed strata and those exposed at Ban Khuen Khan.

Sardsud and Saengsrichan (2002) descried the stratigraphy of the Khuan Klang Formation near Rattaphum in the Hat Yai area of Songkhla Province, where is *c.* 250 m thick and can be divided into two parts. The lower part consists of alternations of coarse-grained sandstone, siltstone and shale. The upper part is mainly light-coloured mudstone, yielding the bivalves *Posidonomya* sp. and *Edmondia* sp.

In the early days of palaeontological research in Thailand, Reed (1920) described of the ammonoid *Pronorites* aff. *Cyclolobus*, the gastropods *Pleurotomatia* (*Mourlonia*) aff. *conica* and *Euomphalus* cf. *subcircularis*, the bivalves *Parallelodon* aff. *corrugatus*, *Posidonomya becheri*, *Edmondia* sp. and *Aviculopecten* cf. *densistria*, the brachiopods *productus concentricus* and *Chonetes* cf. *rectispina* and trilobites *Phillipsia* aff. *silesiaca* and *Proetus* cf. *coddonensis* from a shale bed near Phatthalung. This shale probably

correlates with the bivalve-bearing part of the Khuan Klang Formation in the type and Rattaphum areas, and the fossil assemblage strengthens a Carboniferous age for the formation. The Mississippian, however, seems to be more likely than the Pennsylvanian based on the ammonoid. These age passements imply a large hiatus between the khuan Klang Formation and the overlying, chiefly Early Permian, Kaeng Krachan Group. Moreover, glacial sedimentation prevailed during the formation of the latter group, whereas is no sign of glacciogene sediments in the former formation. These lines of evidence strengthen the case for recognizing the Khuan Klang Formation as distinct from the Kaeng Krachan Group.

The Khuan Klang Formation suggests shallow-marine shelf deposition. Its lithology and fauna are unusual in the Carboniferous of the Sibumasu Block.

4.6 THICKNESS

The Pa Samed Formation is redefined here as that 167 m thick (Wongwanich et al., 1990, 2004). The type section outcropping along the Langu-Thung Wa Road between 9.6 and 9.8 km from Langu district, Satun province.

However, new excavations on the south side of the type section have revealed more than 400 m of greenish to dark grey laminated shale, mudstone, siltstone and some sandstone with trace fossils, more abundant in some beds than others, lying conformably above Member Six (Wongwanich et al., 2004). The total thickness of the Pa Samed Formation is therefore over 567 m (Wongwanich and Boucot in Ridd et al., 2011), but the Devonian part at the bottom of the Formation is probably only 25 m thick.

4.7 AGE AND FOSSIL ASSEMBLAGES

The Pa Samed Formation consists of abundant fossils reported by several previous studies. The list of fossils is shown in Table 4.1, such as; tentaculate, trilobite, brachiopod, and nautiloid. The age of this fossil assemblage indicated Early Devonian to Early Carboniferous. Boucot et al., (1999) established twelve brachiopod taxa that are described from the Early Devonian (probable early Emsian) Pa Samed Formation of southern Thailand in type area, including the new genus and species *Quasiprosserella samedensis* (Ambocoeliidae?) and the new species *Plectodonta forteyi, Caplinoplia thailandensis,* and *Clorinda wongwanichi* (Figures 4.3-4.5). They are the first undoubted Devonian brachiopods from Thailand. They represent the deeper-water Benthic Assemblages (Wang *et al*., 1987; Boucot and Lowson, 1999), as shown by the associated abundant dacryoconarids and the trilobite *Plagiolaria.*

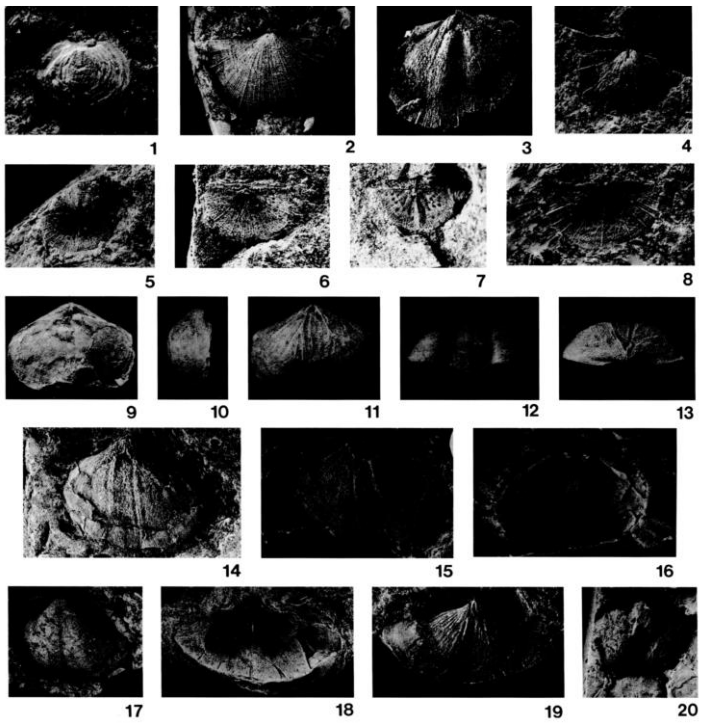

Figure 20: *Orbiculoideal* sp., 2-8, *Plectodonta (Plectodonta) forteyi* Boucot and Cocks n. sp.; 9-19, *Clorinda wongwanichi* Boucot and Cocks n. sp.; 20, Rhynchonellid indeterminate genus and species. (After Boucot et al., 1999)

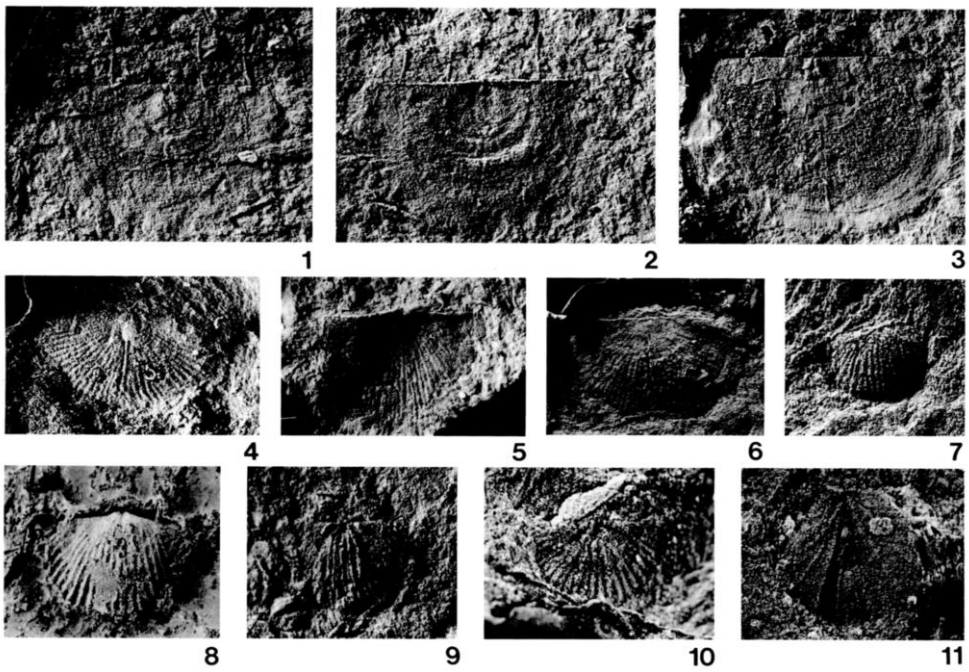

Figure 21: 1-3. Strophochonetidae? n. gen. and sp.; 4-6, *Philippotia?* sp.; 7-10, *Caplinoplia thailandensis* Racheboeuf n. sp.; 11, *Plicanoplitesl* sp. (After Boucot et al., 1999)

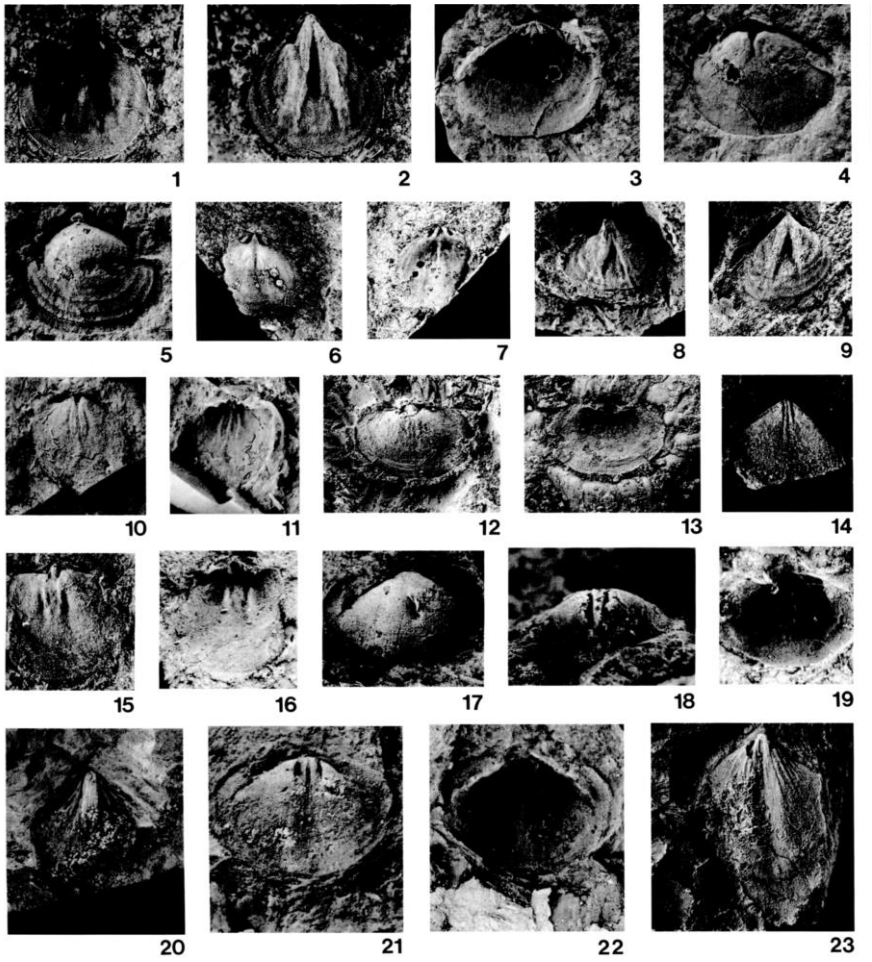

Figure 22: 1-9. *Lissatrypa* sp.; 10-19, 21, 22, *Quasiprosserella samedensis* Boucot and Cocks n. sp.; 20, Spiriferid indeterminate genus and species; 23, Athyridoid indeterminate genus and species. (After Boucot et al., 1999)

Wongwanich et al., (2004) discovered the richly fossiliferous early Namurian beds. These are packed with brachiopods and goniaties in the narrow transition zone between the sandstone of Member Two and the dark grey, laminated shale and mudstone of Member Three (Figure 4.6). This horizon (B 10 of Wongwanich et al., 2004) is about 40 m above the black dacryoconarid-rich beds. Below the Namurian beds there are varied siliciclastics of Member Well above the Namurian beds there are a few occurrences of scattered brachiopods that indicate an overall Carboniferous to lowest Permian age, with an upper age limit provided by the presence regionally of fossiliferous Permian Kaeng Krachan Group and Ratburi Limestone.

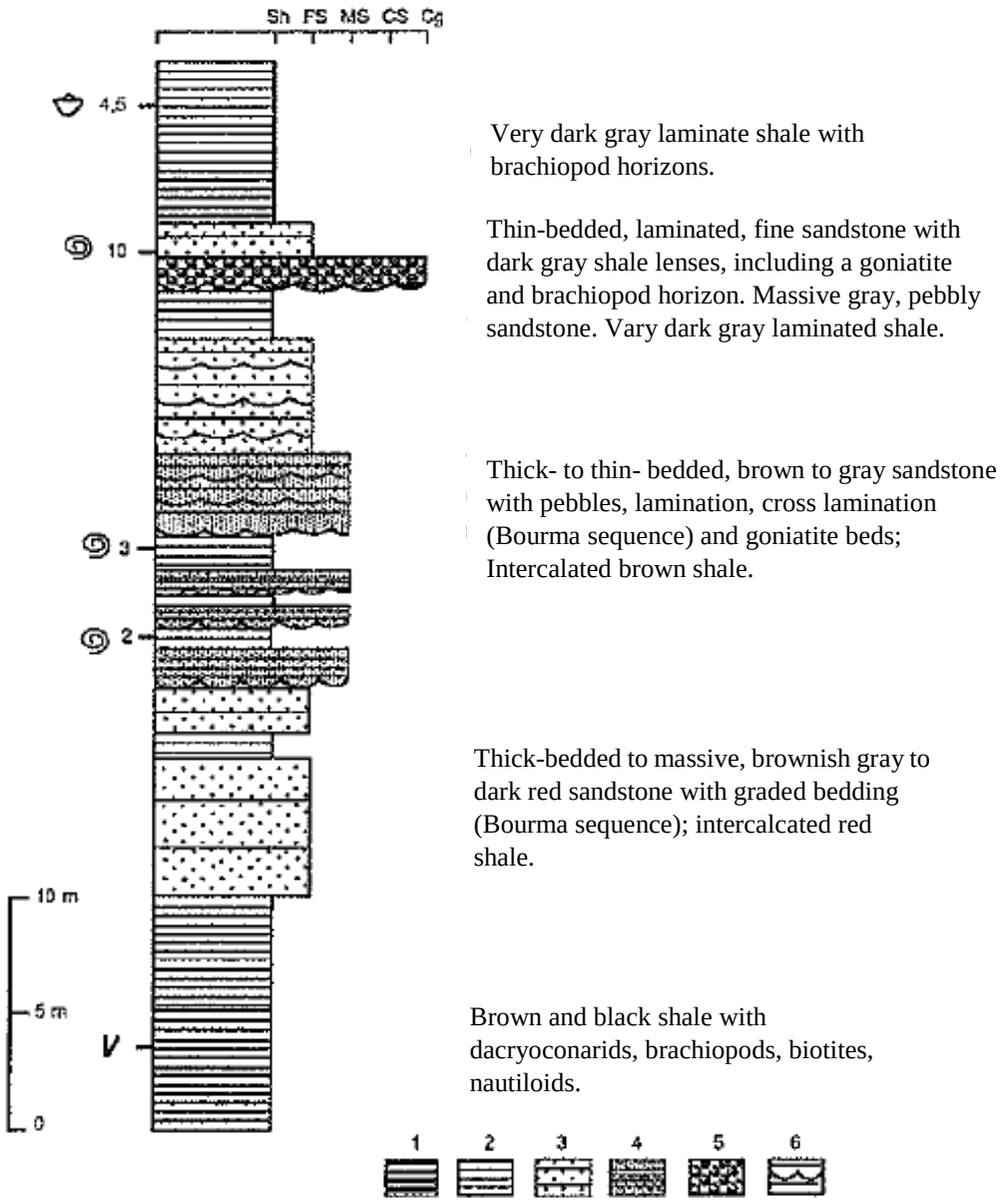

Figure 23: Detailed stratigraphic section of lower portion of Pa Samed Formation. Sh (shale), FS (fine-grained sandstone), MS (medium-grained sandstone), CS (coarse-grained sandstone), Cg (conglomerate); 1, black, tentaculitid shale; 2, brown shale; 3, thick to massive sandstone; 4, thick to thin-bedded sandstone; 5, pebbly sandstone; 6, wavy-based bedding. (After Wongwanich et al., 2004)

Two from which some beds have yielded rare Carboniferous goniatites (B-2, 3) (Figure 4.6). They reported two new brachiopod genera, *Eileenella* Racheboeuf and *Plicambocoelia* Boucot and Brunton. Moreover, five new species of brachiopod were discovered such as; *Aseptella satunensis* Brunton, *Eileenella elegans* Wongwanich et al., *Tornquistia orthogona* Wongwanich et al., *Coledium satuni* Boucot and Brunton and *Plicambocoelia tansathieni* Boucot and Brunton (Figures 4.7-4.12). **Therefore, the Pa Samed Formation ranges in age from late Early Devonian to Carboniferous.** Wongwanich et al., (2004) concluded that there may be a major disconformity between the Early Devonian, black, dacryoconarid-rich beds of Member One and the Carboniferous goniatite bed B-2 within Member Two, because there is no palaeontological evidence for the Mid- and Late

Devonian and there is no evidence of Carboniferous fossils older that Namurian in collections B-2 and B-3 (Member Two). The nature of this possible disconformity above the Emsian dacryoconarid-rich beds is uncertain; it is not known whether is represents a lengthy non-depositional interval of an interval of erosion or uplift. However, a concealed fault instead of a disconformity cannot be ruled out between the dacryoconaird-rich beds and the goniatite beds (B-2). Above the Nammurian B-10 beds to the south there is gradation to very thick, laminated, greenish grey to dark grey shale and siltstone and some sandstone over 400 m thick with very rare scattered fossils, with trace fossils abundant in some beds.

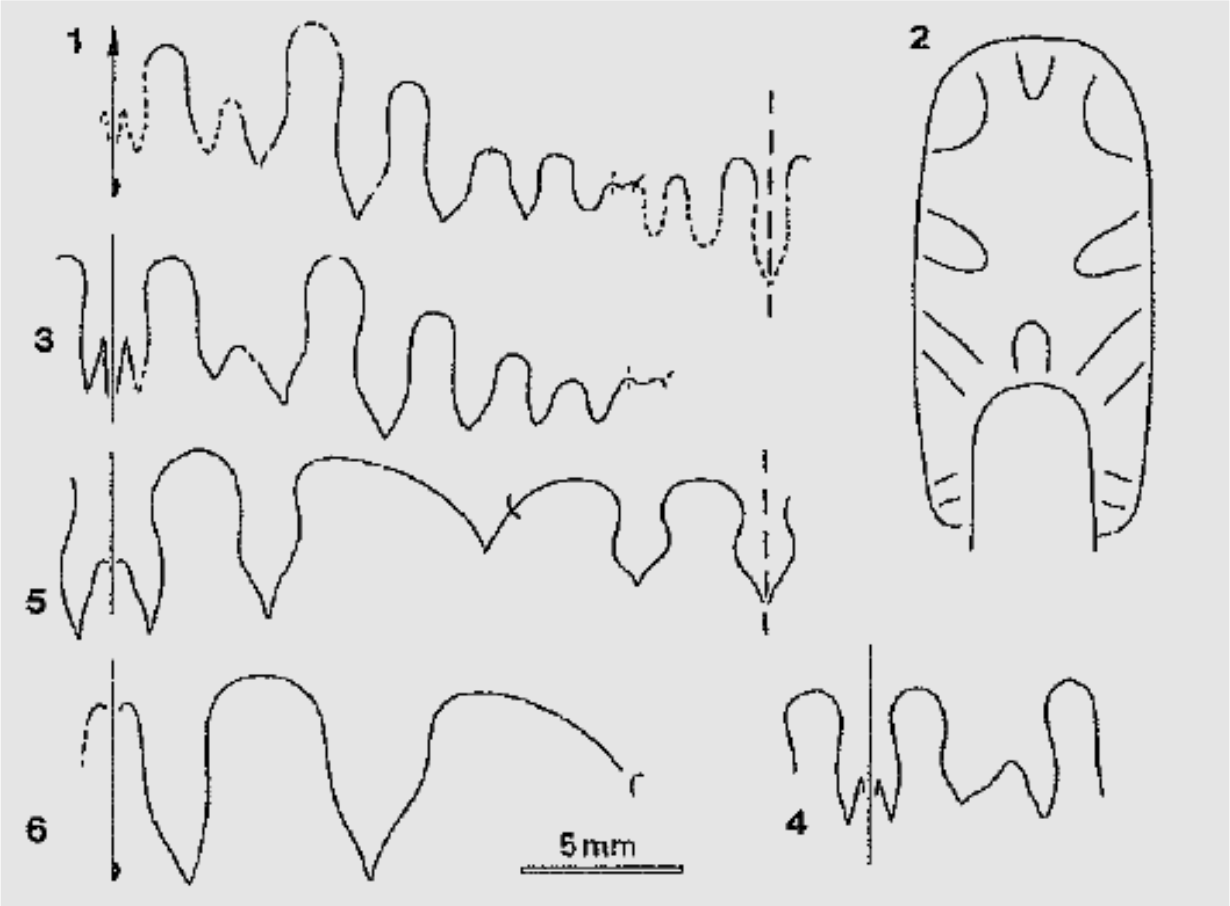

Figure 24: Namurian goniatite (suture and reconstruction of whorl section) from Ban Pa Samed. 1-3, *Stenopronorites* cf. *uralensis* (Karpinsky, 1889), 4. *Stenopronorites* aff. *uralensis* (Karpinsky, 1889), 5. *Syngastrioceras* sp. Indet., 6. ?Glaphyritid indet. (After Wongwanich et al., 2004)

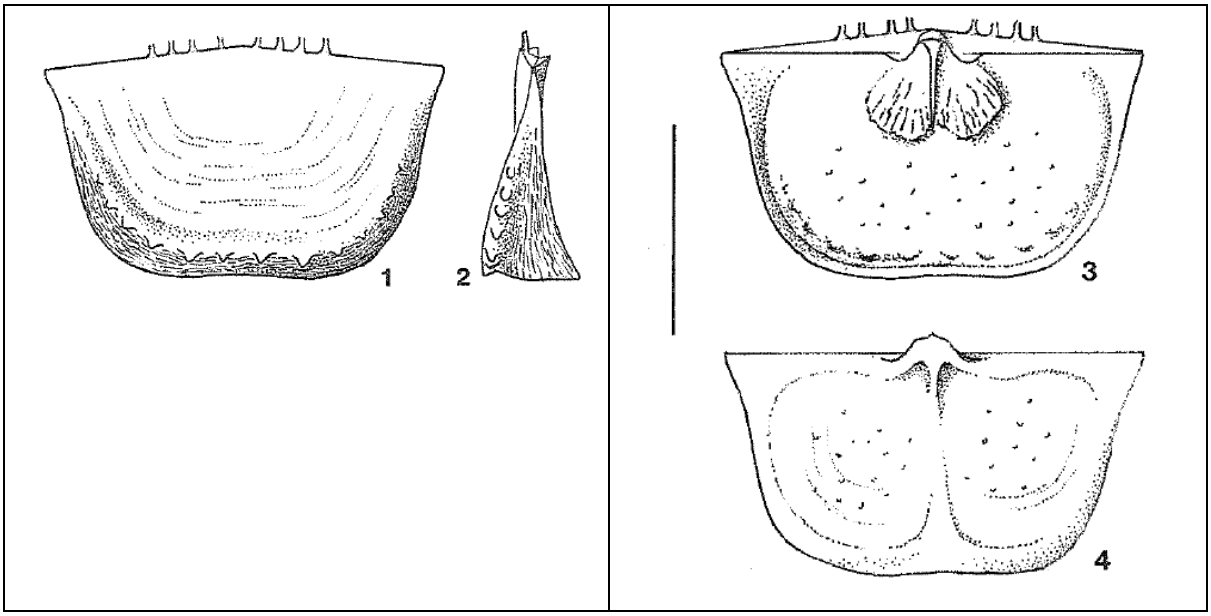

Figure 25: Namurian brachiopod from Pa Samed Formation. 1-4, Reconstruction of the shell of *Eileenella elegans* n. gen. and sp. 1, Ventral valve viewed ventrally; 2, articulated shell in lateral view; 3, ventral valve interior, 4, dorsal valve interior. Scal bar=5 mm. (After Wongwanich et al., 2004)

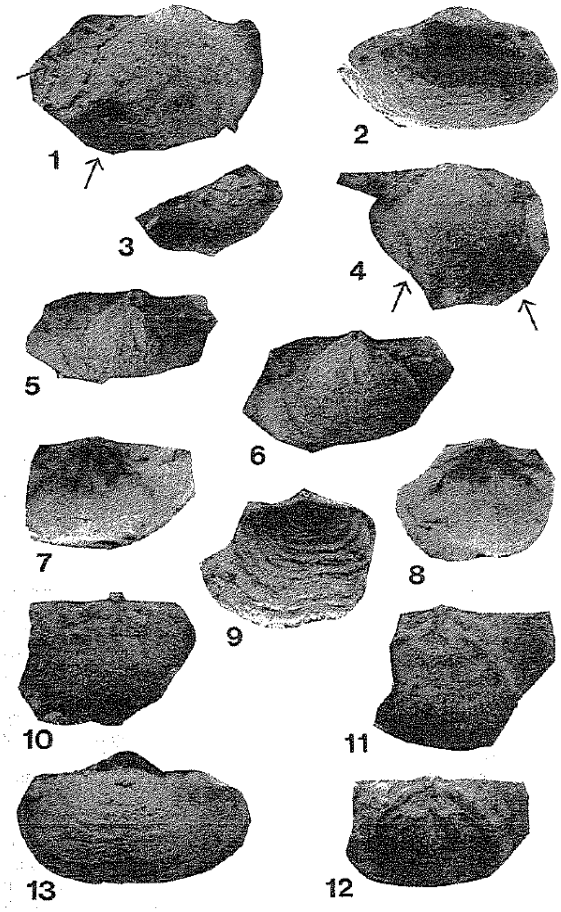

Figure 26: Namurian brachiopod from Pa Samed Formation. 1-13, *Aseptella satunensis* Brunton n. sp. (After Wongwanich et al., 2004)

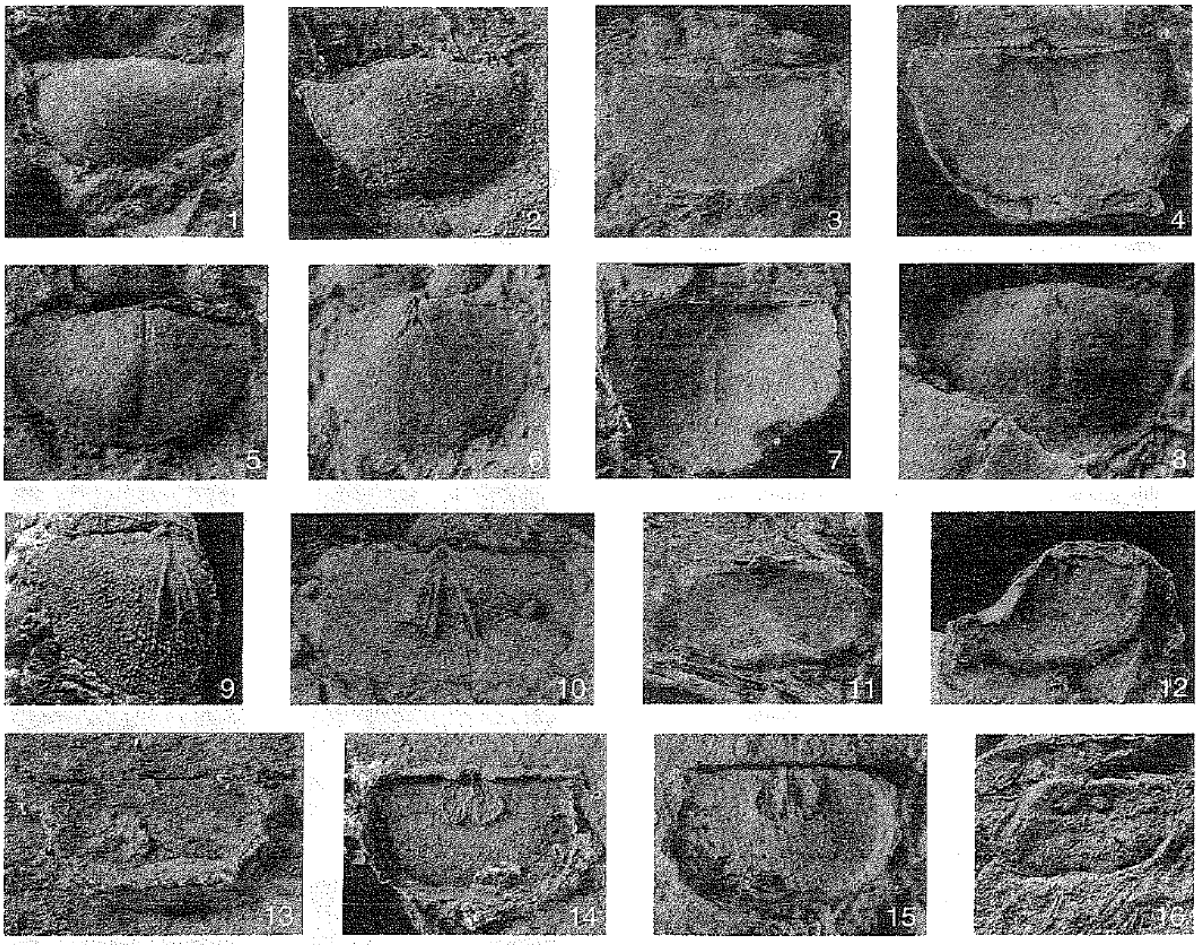

Figure 27: Namurian brachiopod from Pa Samed Formation. 1-10, *Tornquistia orthogona* n. sp., 11-16, *Eileenella elegans* n. gen. and sp. (After Wongwanich et al., 2004)

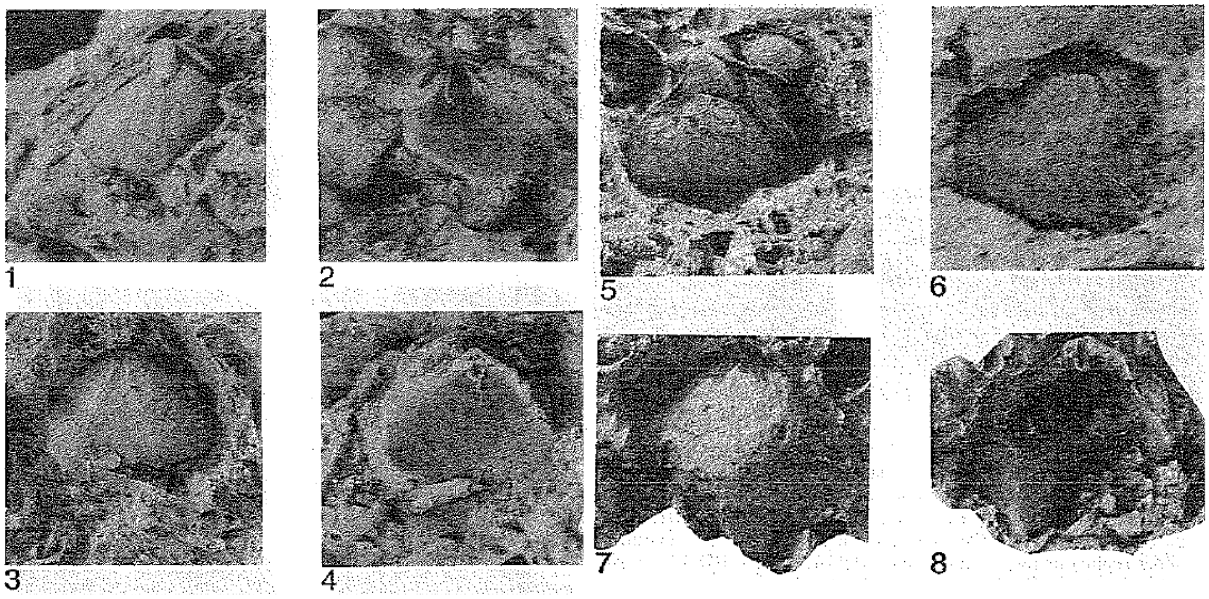

Figure 28: Namurian brachiopod from Pa Samed Formation. 1-6. *Coledium satuni* Boucot and Brunton, 7-8. cf. *Coledium satuni.* (After Wongwanich et al., 2004)

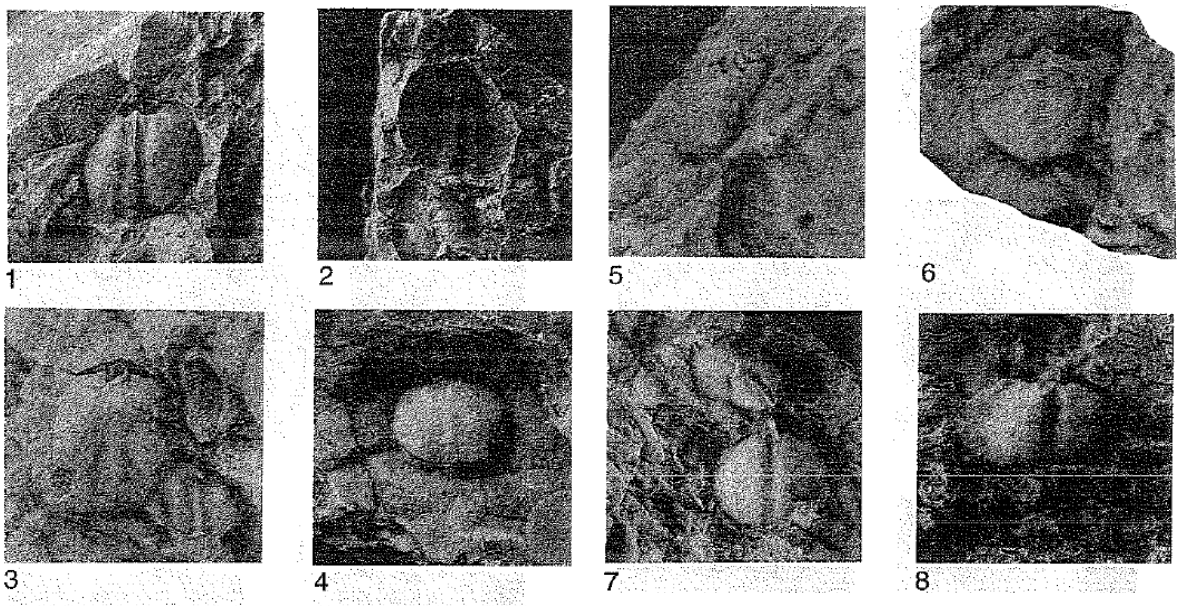

Figure 29: Namurian brachiopod from Pa Samed Formation. 1-8, *Plicambocoelia tansathieni* Boucot and Brunton. (After Wongwanich et al., 2004)

Cronier and Fortey (2006) reported morphology and ontogeny of an Early Devonian Phacopid trilobite with reduced-eyed species *Plagiolaria poothaii* Kobayashi and Hamada, 1986 (Figures 4.13 and 4.14), from the shales and mudstone of the Pa Samed Formation of Southern Thailand, not far from the border with Malaysia. The same locality yielded a brachiopod fauna described by Boucot et al. (1999), which provides full locality details. The most abundant fossils in the field are dacryoconarid tentaculites which indicate a late Pragian to earliest Emsian age. From the evidence of brachiopods and dacryoconarids, Boucot et al. (1999) concluded that the beds are "of definite later Early Devonian age, with the probability favoring early Emsian." The occurrence of *Plagiolaria* does not help to refine the age determination, but is consistent with it.

Moreover, they suggested that from the Silurian to Middle Devonian, the great majority of phacopid taxa show large, fully developed, kidney-shaped eyes with numerous lenses. These phacopids were adapted to shallow-water environments. Both blind and reduced-eyed phacopids with elliptical eyes occur occasionally from the Late Silurian onwards, such as *Struveaspis* H. Alberti, 1966 and *Plagiolaria*. During the Upper Devonian, the gradual regression of the visual complex leading to blindness is an evolutionary trend observed in different families, evolving simultaneously and correlating with analogous environmental factors. This feature generally seems to coincide with periods of pronounced eustatic deepening.

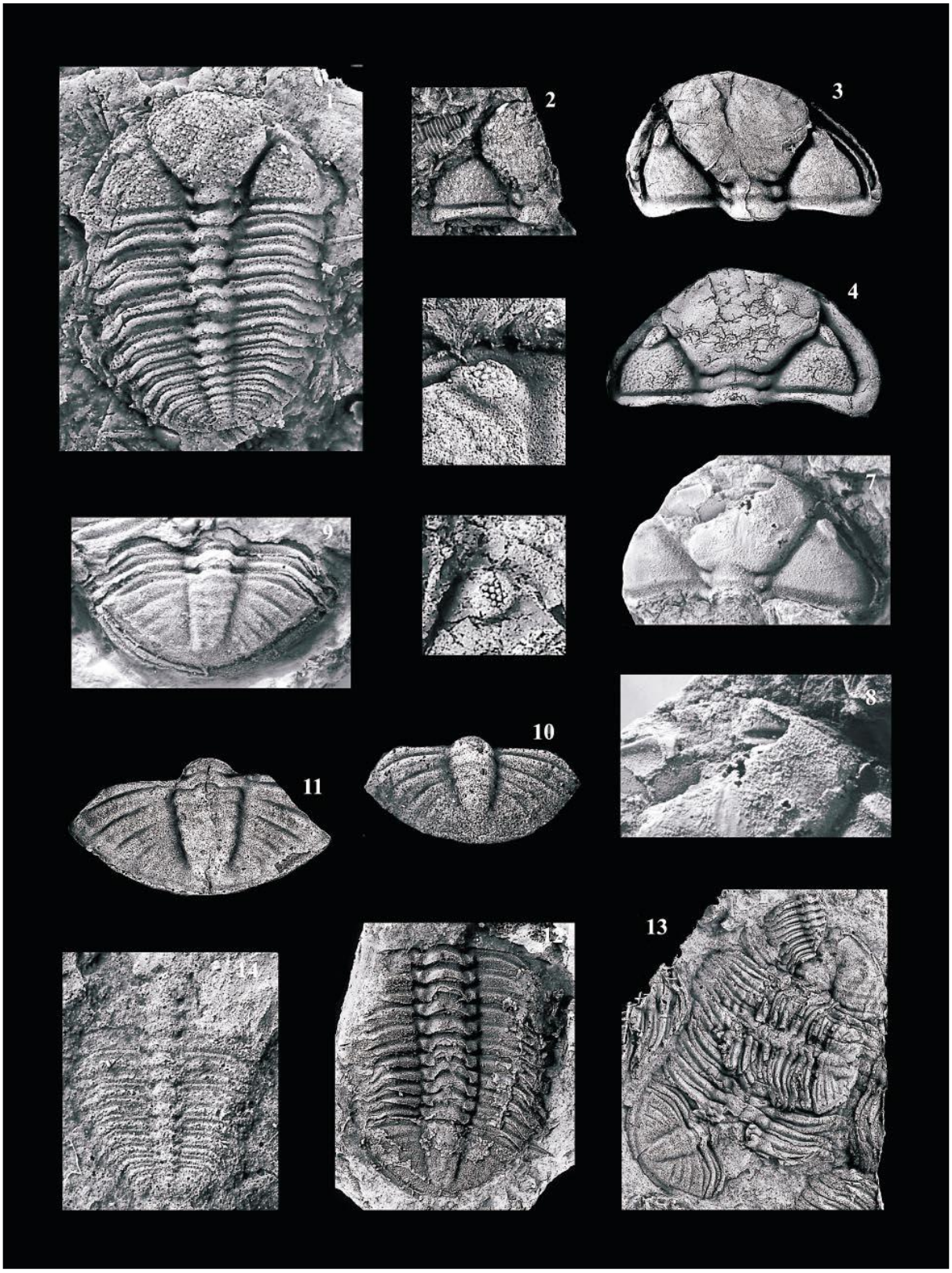

Figure 30: Early Devonian triobite from the Pa Samed Formation, Satun province, southern Thailand. 1-13, *Plagiolaria poothaii* Kobayashi and Hamada, 1968. (After Cronier and Fortey, 2006)

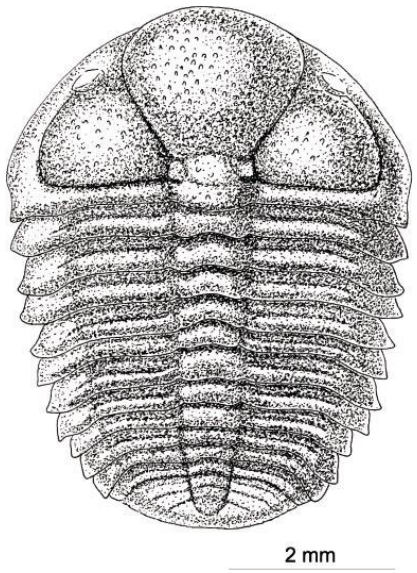

Figure 31: *Plagiolaria poothaii*, Satun Province, southern Thailand, Lower Devonian. Reconstruction of a meraspid exoskeleton, probable degree 10, in dorsal view. (After Cronier and Fortey, 2006)

Agematsu et al., (2006) studied a siliciclastic sequence in the Satun area of southern peninsular Thailand. These contain a tentaculite bed of Pa Samed Formation that is composed of black shale and contains *Nowakia acuaria in* the lowermost part. They study focuses on a stratigraphic sequence situated about 30 km north of Satun and exposed on the northwestern side of Route 4078 (Figure 4.15) at the type location of Pa Samed Formation (Wongwanich et al., 1990). This sequence is 250 m thick and composed of shale, mudstone, limestone, and sandstone. It strikes N808E to 808W and dips 458 to the south. The lower 170 m of this section is made up of alternating black to dark green shale and calcareous mudstone, and includes several limestone beds in its uppermost part. The upper 80 m of this section consists mainly of black to dark green shale, intercalated with sandstone beds in its lowermost part. The tentaculite bed, a basal part of this sequence, is a 5 m thick black shale bed containing many small, triangular shells. These siliciclastic rocks have been correlated with the Devonian Pa Samed Formation by Wongwanich et al. (1990). Although some horizons of the tentaculite bed contain concentrated tentaculites, other horizons yield sparse specimens. Nearly all shells lie horizontally on a bedding plane and orientations of their axes are variable (Figure 4.16 (1) and (2)). Moreover, these shells exhibit no characteristic trends in size, direction of axis, or abundance in each horizon. Fisher (1962) mentioned that tentaculites generally have two patterns of occurrence: the first exhibits many complete shells, whose longitudinal axes have a particular direction along a bedding plane; the second exhibits a few broken shell fragments, with no distinct orientation of the longitudinal axes. However, several horizons in this study bed contain abundant shells, but do not show these two patterns. Burton (1967a) stated that tentaculite beds with abundant fossils in Malaysia contain complete and incomplete shells of various sizes and show no uniformity in the orientation of their longitudinal axes. The occurrence of tentaculites in the Satun area is similar to that of Malaysia. Under microscopic observation, this black shale is seen to be composed mainly of quartz grains less than 0.03 mm in diameter, clay minerals, and black organic matter. The tentaculite shells have been replaced by silica. Based on occurrences of *Nowakia acuaria* (Figure 4.17) and correlations with surrounding areas, the depositional age of the **tentaculite bed is earliest Emsian**.

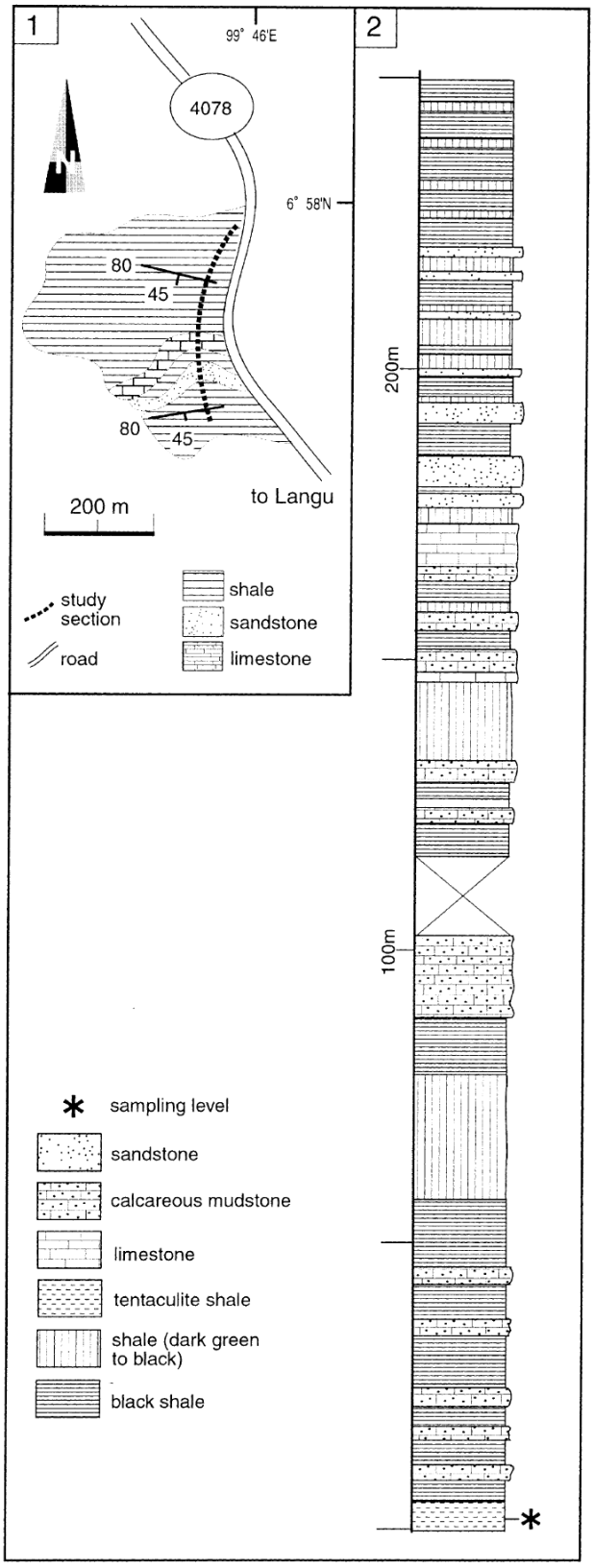

Figure 32: (1) Route map showing the section and the distribution of sedimentary rocks in the Satun area of southern peninsular Thailand. (2) Lithologic column of the study section. (After Agematsu et al., 2006)

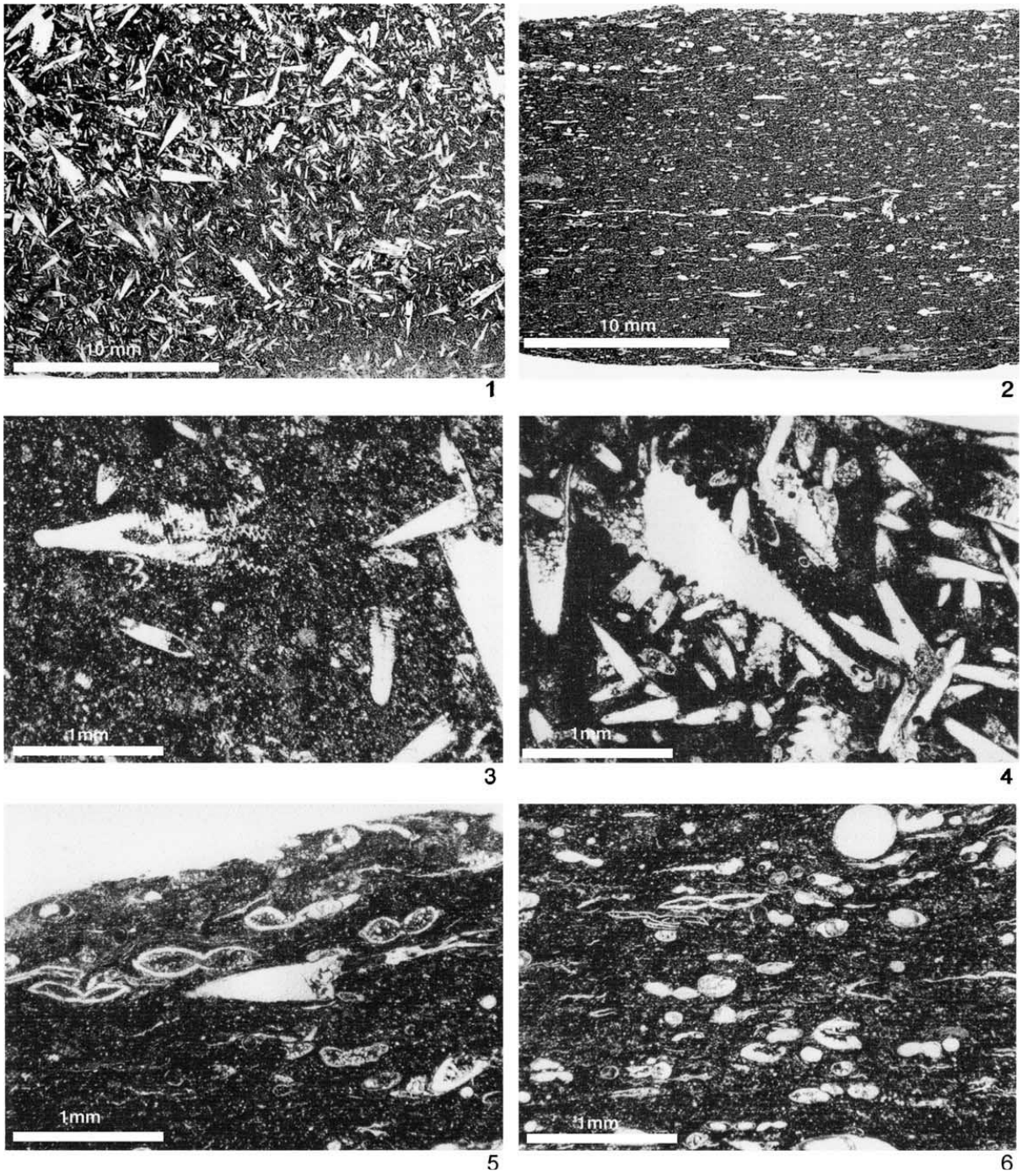

Figure 33: Photographs of thin sections of black shale in the tentaculite bed. (1) A parallel section with a bedding plane. Black shale includes many tentaculites. Scale bar indicates 10 mm. (2) A vertical section with a bedding plane. Most of white bodies are cross sections of entaculetes. (3) A parallel section with a bedding plane. Black shale is mainly composed of quartz grains and black matter. Some tentaculite specimens are completely preserved while others are broken or compressed. Scale bar indicates 1 mm. (4) A parallel section with a bedding plane. Scale bar is 1 mm. (5) A vertical section with a bedding plane. Black shale includes some compressed specimens that are shaped like a number eight and filled with matrix. Scale bar indicates 1 mm. (6) Avertical section with a bedding plane. White circles are cross sections of complete specimens. Inner side of white specimens are hollow. (After Agematsu et al., 2006)

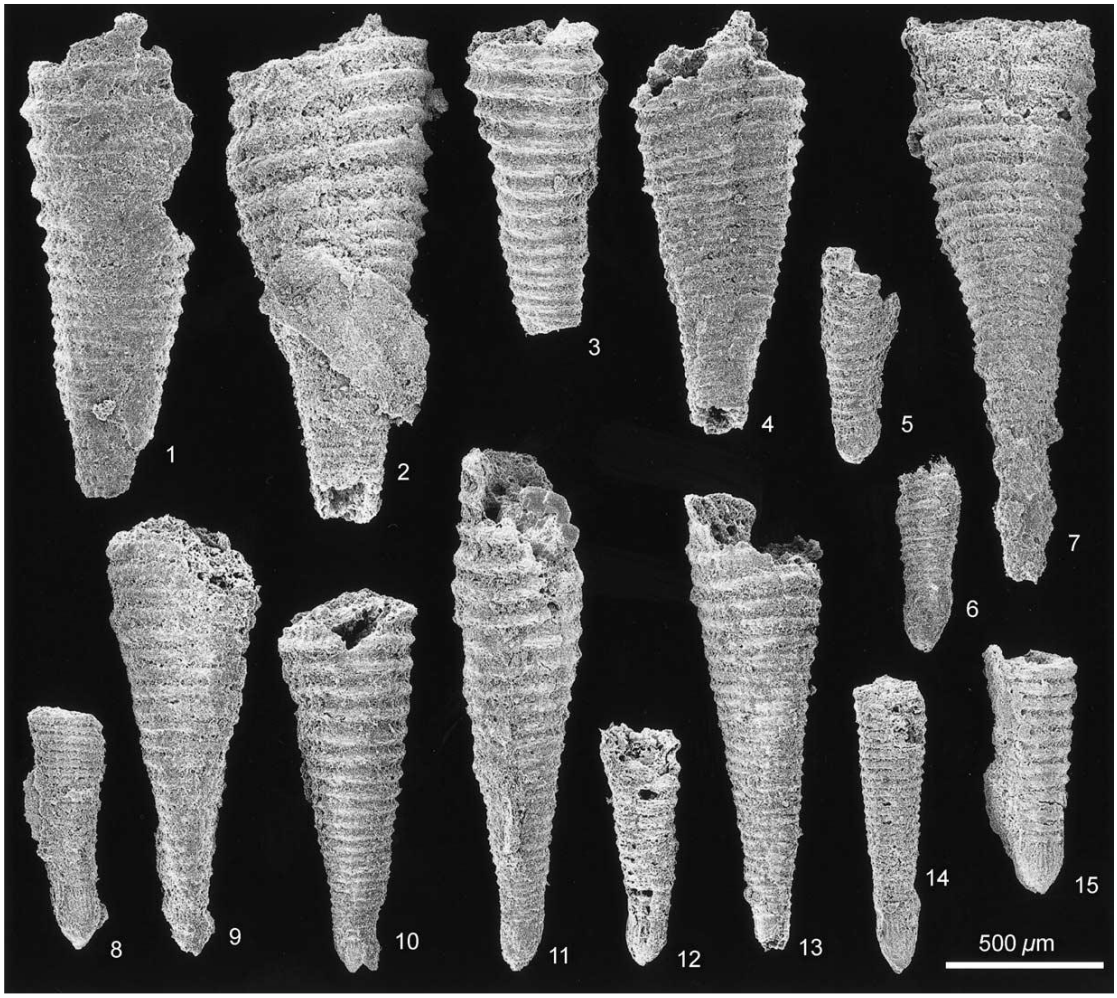

Figure 34: Photographs of isolated tentaculite specimens from Pa Samed Formation, Satun province. 1–15, *Nowakia acuaria* (Richer, 1854). (Agematsu et al., 2006)

Tongtherm *et al*., (2017) reported Lower Carboniferous nautiloid from Pa Samed Formation, La-ngu district, Satun province, Sothern Thailand. Nuatiliod such as Nautiloid gen. et sp. indet. I, *Chidleyenoceras* sp. Indet., Tainocerataceae gen. et sp. Indet. and Nautilaceae gen. et sp. Indet. Although most of the studied taxa were indeterminate species due to poor preservations of specimens. All taxa of this paper were new records of cephalopod fossils from Thailand.

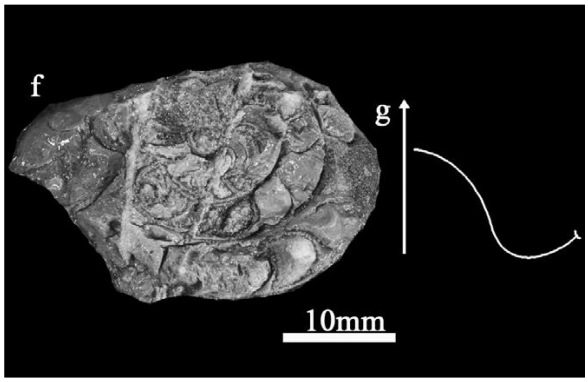

Figure 35: Lower Carboniferous nautiloid from Pa Samed Formation, La-ngu district, Satun province. f, g *Chidleyenoceras* sp .indet. (After Tongtherm et al., 2017)

Table 3: List of fossils from the Pa Samed Formation in Satun Province, southern Thailand.

No.	Fossil	Species	Age	Reference
1	Tentaculite	*Nowakia acuaria* (Richer, 1854)	Early Devonian (Emsian)	Agematsu et al., 2006
2	Trilobite	*Plagiolaria poothaii* Kobayashi and Hamada, 1968	Early Devonian	Cronier et al., 2006
3	Brachiopod	*Orbiculoidea?* sp.	Early Devonian (probable early Emsian)	Boucot et al., 1999
4	Brachiopod	*Plectodonta (Plectodonta) Forteyi* Boucot and Cocks, in Boucot et al., 1999	Early Devonian (probable early Emsian)	Boucot et al., 1999
5	Brachiopod	Strophochonetidae Muir-Wood, 1962	Early Devonian (probable early Emsian)	Boucot et al., 1999
6	Brachiopod	*Philippotia* ? sp.	Early Devonian (probable early Emsian)	Boucot et al., 1999
7	Brachiopod	*Caplinoplia thailandensis* (Racheboeuf, 1999)	Early Devonian (probable early Emsian)	Boucot et al., 1999
8	Brachiopod	*Clorinda wongwanichi* Boucot and Cocks, in Boucot et al., 1999	Early Devonian (probable early Emsian)	Boucot et al., 1999
9	Brachiopod	Rhynchonellid indeterminate genus and species	Early Devonian (probable early Emsian)	Boucot et al., 1999
10	Brachiopod	*Lissatrypa* sp.	Early Devonian (probable early Emsian)	Boucot et al., 1999
11	Brachiopod	*Quasiprosserella samedensis* Boucot and Cocks, in Boucot et al., 1999	Early Devonian (probable early Emsian)	Boucot et al., 1999
12	Brachiopod	Athyridoid indeterminate genus and species	Early Devonian (probable early Emsian)	Boucot et al., 1999
13	Brachiopod	Spiriferid indeterminate genus and species	Early Devonian (probable early Emsian)	Boucot et al., 1999
14	Brachiopod	*Plicanoplites?* sp.	Early Devonian (probable early Emsian)	Boucot et al., 1999
15	Trilobite	*Decoroproetus* sp.	Early Devonian	Fortey, 1989
16	Trilobite	*Cornuproetus (Sculptoproetus) sculptus* (Barrande, 1846)	Early Devonian	Fortey, 1989
17	Trilobite	*Platyscutellum* sp. A Fortey, 1989	Early Devonian	Fortey, 1989
18	Trilobite	*Reedops magaphacos* Fortey, 1989	Early Devonian	Fortey, 1989
19	Trilobite	*Reedops seleniomma* Hass, 1968	Early Devonian	Fortey, 1989
20	Nautiloid	Nautiloid gen et sp. indet. I	Lower Carboniferous	Tongtherm et al., 2017
21	Nautiloid	*Chidleyenoceras* sp. indet.	Lower Carboniferous	Tongtherm et al., 2017
22	Nautiloid	Tainocerataceae gen. et sp. indet.	Lower Carboniferous	Tongtherm et al., 2017
23	Nautiloid	Nautilaceae gen. et sp. indet	Upper Carboniferous	Tongtherm et al., 2017
24	Amonoid	*Stenopronorites* cf. *uralensis* (Karpinsky, 1889)	Carboniferous (Namurian)	Wongwanich et al., 2004
25	Amonoid	*Stenopronorites* aff. *uralensis* (Karpinsky, 1889)	Carboniferous (Namurian)	Wongwanich et al., 2004
26	Brachiopod	*Aseptella satunensis* Brunton, in Wongwanich et al., 2004	Carboniferous (Namurian)	Wongwanich et al., 2004
27	Brachiopod	*Eileenella elegans* Racheboeuf, in Wongwanich et al.,	Carboniferous (Namurian)	Wongwanich et al., 2004

No.	Fossil	Species	Age	Reference
		2004		
28	Brachiopod	*Tornquistia orthogona* Racheboeuf, in Wongwanich et al., 2004	Carboniferous (Namurian)	Wongwanich et al., 2004
29	Brachiopod	*Coledium satuni* Boucot and Brunton, in Wongwanich et al., 2004	Carboniferous (Namurian)	Wongwanich et al., 2004
30	Brachiopod	*Plicambocoelia tansathieni* Boucot and Brunton, in Wongwanich et al., 2004	Carboniferous (Namurian)	Wongwanich et al., 2004
31	Brachiopod	*Crurithyris* species indeterminate	Carboniferous (Namurian)	Wongwanich et al., 2004
32	Brachiopod	cf. *Martinia* sp.	Carboniferous (Namurian)	Wongwanich et al., 2004
33	Brachiopod	cf. *Reticularia* M'Coy, 1842	Carboniferous (Namurian)	Wongwanich et al., 2004
34	Brachiopod	*Girtyella* sp.	Carboniferous (Namurian)	Wongwanich et al., 2004

4.8 TECTONIC AND DEPOSITIONAL ENVIRONMENT

There is general agreement that Southeast Asia is a complex assembly of several continental blocks that rifted from Gondwanaland (e.g., Metcalfe, 1999). Thailand comprises two main continental blocks, the western Shan–Thai and eastern Indochina Blocks. These two blocks are separated by a suture zone made up of the northern Nan–Uttradit and southern Sra (Sa) Kaeo–Chanthaburi zones. The area is bordered to the west by the Sukhothai Fold Belt and to the east by the Loei–Petchabun Fold Belt (e.g., Bunopas, 1981). Bunopas (1992) recognized seven longitudinal stratigraphic belts, designated BS-1 to BS-5, that belong to the Shan–Thai Block, and belts BI-6 to BI-7 that belong to the Indochina Block. The Lower to Middle Paleozoic was divided into the following stratigraphic units by Bunopas (1992): the Cambrian Tarutao Group, Ordovician Thung Song Group, and Silurian to Carboniferous Thong Pha Phum Group (Figure 4.19). The Pa Samed Formation is distributed within belt BS-2 and 3.

In Belt 2, Lower Devonian variegated nodular limestone and black tentaculitic shale occur in siliciclastic and carbonate sequence, the Thong Pha Phum Group, and can be correlated throughout the belt from Satun Province in the south to the type area at Thong Pha Phum, Kanchanaburi Province, and further north to Mae Hong Son Province (Wongwanich and Boucot, in Ridd et al., 2011). In the Southern Peninsula Thailand, the Lower Devonian limestone of the Kuan Tung Formation can be correlated with the Upper Setul Limeston of the Langkawi Islands, west Malaysia (Jone, 1981), while dacryoconarids in black tentaculitic shale of the Pa Samed Formation can be correlated with the Upper Detrital Member of the Langkawi Islands (Jone, 1981) and either the Jentic Formation in Perlis (west Kedah, Malaysia) (Cocks *et al*., 2005) or the Timah Tosah Formation

According to Wongwanich and Boucot, in Ridd *et al*. (2011), they suggested that the tentaculitic shale is the key unit for correlation throughout Belt 3 because these dacryoconarid-rich beds of Emsian age are widespread and occur not only in black shale but also in brown, red and grey shale and chert. The reddish brown tentaculitic shale of the Betong Formation, between Bannung Sata and Betong in lower Peninsular Thailand, can be

correlated with black and brown tentaculitic shale further north between Trang and Phattalung Provinces,

Wongwanich *et al*. (1990), a deep water euxinic marine environment is suggested by the black graptolitic shale and bedded chert of the Wang Tong Formation. These were successively overlain by the shallow water limestone of the lower Kuan Tung, the deeper water red nodular limestone of the upper Kuan Tung and the black tentaculitic shale and other clastic rocks of the Pa Samed Formation.

The total thickness of the Pa Samed Formation is 167 m. The sequence is interpreted as deposited in a deep-water euxinic marine basin (Member One) to slope channels (Member Two) and deeper water (Member Three-Six) (Wongwanich and Boucot in Ridd et al., 2011). The red sandstone and shale within Member Two and Five may be the result of the deep-water deposition of weathering products.

Wongwanich *et al*., (2004) interpreted the Emsian dacryoconarid-rich bed (Member One) as representing the deepest deposits. Above these, bed deposited in shallower water with channels containing pebbly sandstones (Member Two) occur, followed by deeper-water laminated shale and siltstones (Member Three). The pelagic, siliciclastic (Silurian) Wang Tong Formation, the deeper water carbonate (Silurian-Devonian) Kuan Tung Formation and the pelagic, slope of deeper-water (Devonian-Carboniferous) Pa Samed Formation were assigned to the Thong Pha Phum Group by Wongwanich et al., (2004), a unite whose type locality is in Kanchanaburi Province.

According to Agematsu *et al*. (2006), tentaculite beds yielding the *Nowakia–Styliolina* fauna have been reported from the following areas of Thailand and Malaysia: The Fang (e.g., Hamada, 1968), Sri Sawat (e.g., Brown et al., 1951), Trang (Kobayashi and Hamada, 1968), and Satun areas of Thailand, the Langkawi Islands (e.g., Jones, 1978) and the Mahang and Baling areas (e.g., Burton, 1967; Hamada et al., 1975) of northwestern Malaysia. There are many reports that merely refer to occurrences of this fauna in the northern to western areas of Thailand (e.g., Hahn and Siebenhüner, 1982). On the basis of graptolites and trilobites coexisting with tentaculites and their ages, Hamada et al. (1975) subdivided the Devonian tentaculite faunas in Thailand and Malaysia into four faunal units, labeled TN1 to TN4. They are assigned Lochkovian, early Emsian (Early Devonian), Emsian to Eifelian (Early to Middle Devonian), and Eifelian (Middle Devonian) ages, respectively.

The TN1 fauna corresponds to the fauna of Langkawi Islands. The TN2 fauna is known from the Fang, Sri Sawat, Trang, and Baling areas. The TN3 fauna occurs in the Trang and Baling areas. The TN4 fauna correlates with a part of the tentaculite beds in the Fang and Sri Sawat areas (Hamada et al., 1975) (Figure 4.20). The faunal composition of the tentaculite bed from Pa Samed Formation in the Satun fauna area is compared with that of the Trang area, and the depositional age of the Satun fauna is earliest Emsian. Therefore, the tentaculite bed from Pa Samed Formation in the Satun fauna area belongs to TN2. Although some Devonian tentaculite beds consist of black limestone within calcareous strata in western Thailand (Hagen and Kemper, 1976), other tentaculite beds are common in black shale. Burton (1967) discussed a depositional environment for tentaculite beds in Malaysia and suggested that a euxinic environment may have spread to these basins. It is difficult to know the duration in time and space of the depositional environment for the black shale,

owing to a lack of data about the lithologies and fossils of the strata overlying and underlying each tentaculite bed. In the earliest Emsian, at least, a uniform depositional environment covered a wide area of northern, western, and southern Thailand and northwestern Malaysia. Similar sediments with tentaculite fauna TN2 accumulated in these basins.

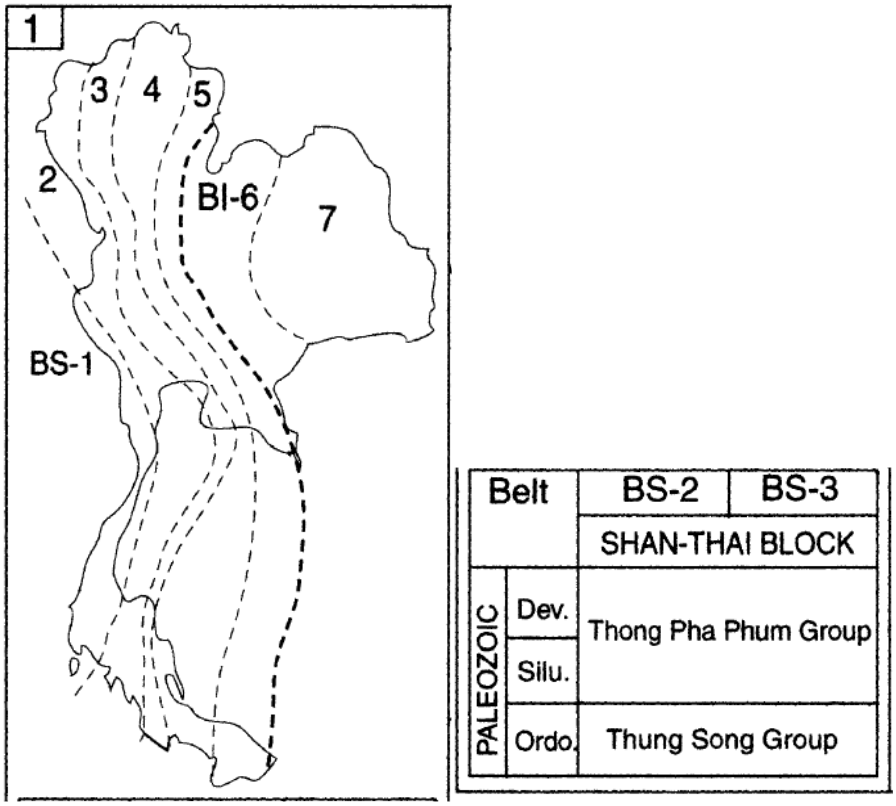

Figure 36: Seven stratigraphic belts of Thailand and generalized stratigraphic nomenclature within the BS-2 and 3 belts (After Bunopas, 1992).

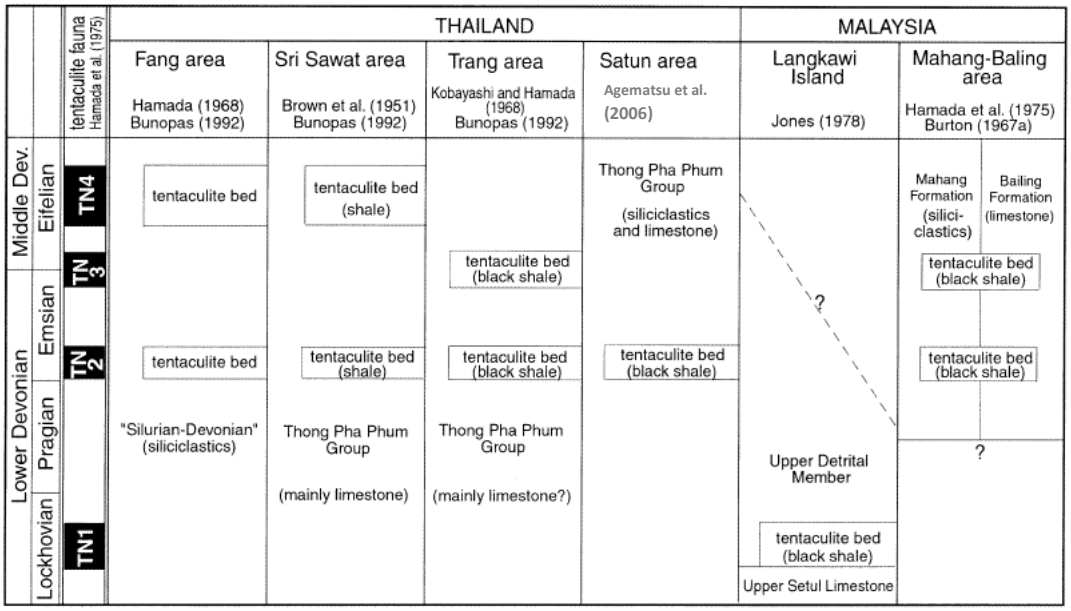

Figure 37: Correlation among tentaculate beds of the Fang, Sri Sawat, Trang and Satun areas in Thailand and The Majhang and Baling areas in Malaysia. (After Agematsu *et al*., 2006).

4.9 REFERENCES SECTION

4.9.1 Type location of Pa Samed Formation

Location

According to The Malaysian-Thai Working Group (2012), this reference section of the Pa Samed Formation is located in an abandoned mine at the small hill, western part of Km 10 road from Langu-Thung Wa Road no 4078, Ban Pa Samet, Langu District, Satun Province around the type location of Pa Samed Formation (Wongwanich et al., 1990). Grid reference of the section is 0585066E, 0769957N in Amphoe La Ngu 4922I Sheet on the scale 1:50,000. However, this area was reconstructed road many times over several years. The type section of Pa Samed Formation maybe changes from the original. In 2012, The Malaysian-Thai Working Group studied stratigraphy in this type location and reported follows as;

Exposure

The reference section has continuous exposure 300 m in an abandoned mine within the hill. Another section is a natural outcrop and roadcut at Km 10 road no. 4078 with 100 m wide exposure. Good exposures of fresh rocks having continuous sequence with only one fault disturbance and variable fossil assemblages are superb for studying characteristics of the rock units (Figure 38).

Figure 38: Outcrop exposures at the type area reference section. (After The Malaysian-Thai Working Group, 2012)

General Geology

Rocks units in this reference section have generally E-W trending with southward dipping. Generally, azimuth of beds varies from 45/170 to 60/190. Characteristics of strata are very smooth, continuous condensed sequence with slightly movement of beds by reverse faults, especially in the northern part.

Faulting and jointing occurred in the area are characterized by the only oblique strike-slip fault trending E-W direction especially near the Devonian and Carboniferous rocks. Cleavages are well developed particularly in argillite strata. The direction is parallel to the strata.

Four formations of rock units recognized in this reference section (118 m in thickness) are described in detail, in ascending order, as follows:

a. Devonian Khuan Tang Formation

The exposures of this formation are represented by natural outcrops located in the northern part of the main abandoned mines. The other exposure is well exposed in the northern part of the roadcut outcrop. The composite sequence is measured to be more than 11.0-11.5 m thick.

The rock units comprise limestones interbedded by shales. Limestones are generally biomicrite, dark grey (80%) and light grey to pinkish grey and pink (20%) with white colour when weathered. Beds are characterized by thin-bedded (5-20cm), well-bedded, almost even. Stylolite, stromatolite and lamination are common. Complete nautiloids, crinoids, coral especially in stramatolitic limestone and fragments of various fossil assemblages are found in pink limestone strata. Shales are dark grey, very thin-bedded (1-2 cm). Bioturbation on shale surface is usually found (Figure 39).

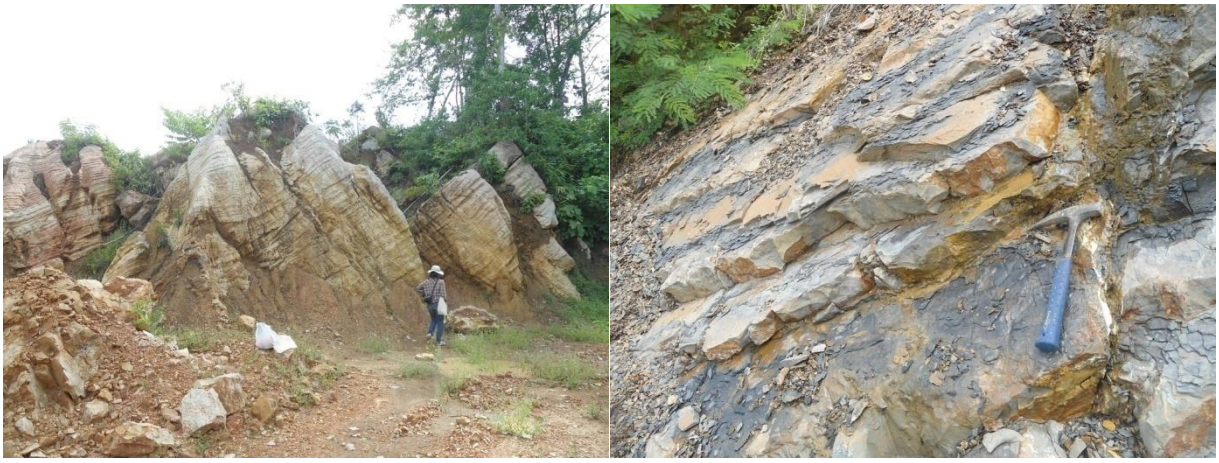

Figure 39: Outcrop and fossil assemblages within the Khuan Tang Formation. (After The Malaysian-Thai Working Group, 2012)

b. Devonian Pa Samed Formation

The exposures of this formation are represented by natural outcrops located in the northern part of the main abandoned mine. The other exposure is well exposed in the central part of the roadcut outcrop. The composite sequence is measured to be 8.5-9.0 m thick.

The rock units comprise two lithofacies. Lithofacies 1 is represented by shales interbedded with fossiliferous shale. Shales are dark grey to black and fissile, very thin-bedded (1-10 cm). Fossiliferous shales are pale purplish red, purplish white and yellow, laminated, thin-bedded (5-10 cm). *Tentaculites elegan*s, *Nowakia* sp., and bioturbation is abundant in these shales. Lithofacies 2 is laminated shale, lenses, sharp, wavy, dark grey to black, thin- to medium-bedded (5-20cm) intercalated with sandstones, very fine-grained, thin-bedded, lamination. Dirty medium-grained, poorly sorted

sandstone and lenses of yellowish grey, sandy siltstone with ostracod, brachiopod and *Tentaculites* sp. are sometime intercalated (Figures 40).

The Pa Samed Formation is continuously conformable with the overlying Khuan Klang Formation .The unit is grading gradually from interbeds of laminated, dark grey to black shale with ostracods, brachiopods and *Tentaculites* sp. and dirty, thin-bedded, very fine-grained sandstone, dark brown to greenish grey of the Pa Samed Formation .The sequence is grading to micaceous lithic sandstone, dark grey to dark brown, thick bed, medium-to coarse-grained, laminated, followed by interbeds of lamianated shale interbedded with lithic and quartzitic sandstones of the Khuan Klang Formation .This indicates the change in depositional environment from the deeper to the shallower.

Figure 40: Outcrop and fossil assemblages within the Pa Samed Formation (*Tentaculites elegans*, *Nowakia* sp.) (sfter the Malaysian-Thai Working Group, 2012)

c. Lower to Middle? Carboniferous Khuan Klang Formation

The exposures of this formation are represented by natural outcrops and quarries in the central part of the main quarry and southern part of the road cut. The sequence was measured to be 37.75 m thick. The Khuan Klang Formation at the reference section can be divided into four subunits.

(1) Lower clastic member

The lowest member is continuously exposed from thin-bedded shales interbedded with sandstone of the Pa Samed Formation north of the mine .General structures of rocks are trending approximately 45/180 .The rock sequence is generally characterized by the presence of interbeds of sandstones, mudstones and shale with 22 m in thickness .The outcrops, lithology and fossils of the Lower clastic member are shown Figure 41.

Figure 41: The outcrops and lithology of the Lower clastic member of Khuan Klang Formation. (After The Malaysian-Thai Working Group, 2012)

(2) Middle red clastic member

The Middle red clastic member is continuously exposed in the main abandoned quarries at the north-central part of the mine .General structures of rocks are trending approximately 40/175 .The rock sequence is generally characterized by the presence of interbeds of red mudstones and red sandstones, with 5.5 m in thickness)units 18-19 in Figure 78 .(The outcrops, lithology and fossils of the Middle red clastic member are shown in Figure 4.25.

Figure 42: The outcrops and lithology of the Middle red clastic member of Khuan Klang Formation. (After The Malaysian-Thai Working Group, 2012)

(3) Middle clastic member

The Middle clastic member is continuously exposed on the main abandoned quarries at the central part of the mine. General structures of rocks are trending approximately 40/175. The rock sequence is generally characterized by the presence of interbeds of laminated shales, sandy mudstones and stringering of sandstones, with 6.2 m in thickness. Complete *Posidonomya* sp. and other fossil assemblages are recorded. The outcrops, lithology and fossils of the Middle red clastic member are shown Figure 4.26.

Figure 43: The outcrops and lithology of the Middle clastic member of Khuan Klang Formation. (After The Malaysian-Thai Working Group, 2012)

(4) Upper clastic member

The Middle clastic member is continuously exposed south of the abandoned quarries. They are continuously exposed to the Kaeng Krachan Group in the south. General structures of rocks are trending approximately 40/170. The rock sequence is generally characterized by the presence of interbeds of mudstones, sandy mudstones and sandstones with 12.5 m in thickness. Carbonaceous shale and peat with bioturbation and worm burrows are occasionally found as lenses. The outcrops, lithology and fossils of the Upper clastic member are shown in Figure 4.27.

Figure 44: The outcrops and lithology of the Upper clastic member of Khuan Klang Formation. (After The Malaysian-Thai Working Group, 2012)

d. Lower Permian Kaeng Krachan Group

The exposures of this formation are represented by natural outcrops and quarries located in the southern part of the main abandoned mine (Figures 4.28). Thickness of this group in the section area exceeds 60 m. The rock unit consists of two lithofacies. Lithofacies 1 is represented by shales or mudstones intercalated with sandstones. Shales are dark grey to black and fissile, thick-bedded, laminated with generally convoluted and graded beds. Sandstones are lithic, greenish grey to grey, thin-bedded, very fine-grained. Load casts and slump structures are revealed in the lower part of beds. Lithofacies 2 is represented by shale or mudstones with lens of fossiliferous sandy mudstone. Shales are dark grey to black, medium- to thick-bedded, lamination and graded beds with some ammonoids and trilobites. Sandy mudstones are lenses and thin beds near the upper part of the formation. They are characterized by yellowish brown, porous, friable, dirty and heterogeneous. *Spinomartinia* sp., trilobites, ammonites are found in several strata.

Figure 45: Outcrops and fossil assemblages within the Kaeng Krachan Group (*Spinomartinia* sp., trilobites and ammonites). (After The Malaysian-Thai Working Group, 2012)

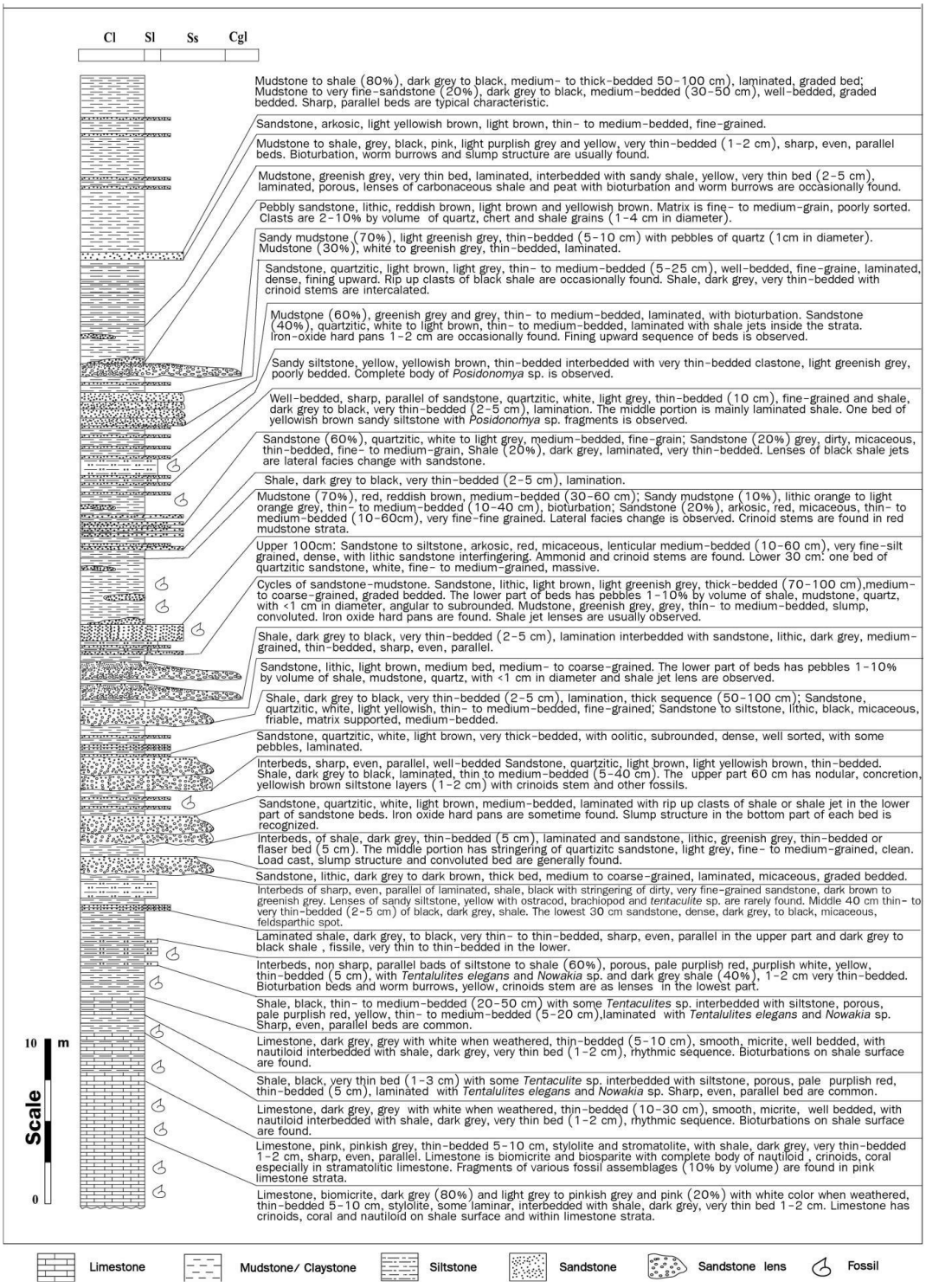

Figure 46: Stratigraphic column of the type location of Pa Samed Formation, abandoned quarry at Ban Pa Samet, La Ngu District, Satun Province. (After The Malaysian-Thai Working Group, 2012)

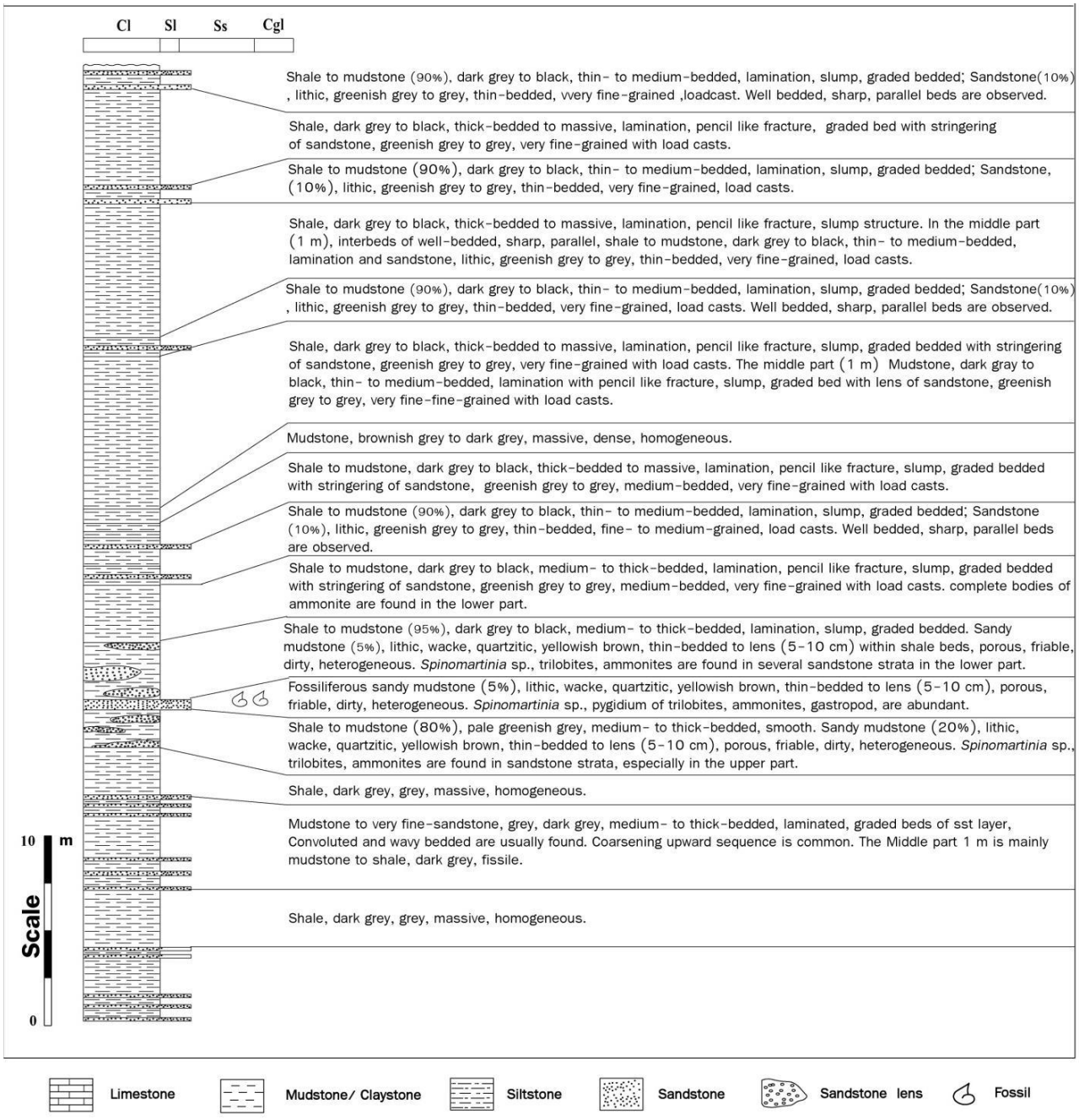

Figure 46: (*continuous)*

4.9.2 Khuan Sung Reference Section

Location

This section is a type section of the Khuan Klang Formation which were reported by The Malaysian-Thai Working Group (2012). It is located at a large quarry currently mined at Khuan Sung, Si-ngam village, Khuan Kat Urban, Muang District, Satun Province. The section can be accessed by road no 4 0 5 1 (Muang-Ban Khuan Mai). Grid reference of the section is 615552E 0731806N in Changwat Satun)5022 III) sheet at scale1:50,000.

Exposure

The section has continuous exposure (500 m) currently mined in the eastern part of the hill. Good exposures of fresh rocks and continuous sequence without break are superb for studying characteristics of the rock units (Figure 4.30).

Figure 47: Good exposures of the Khuan Sung Reference Section. (After The Malaysian-Thai Working Group, 2012)

General Geology

Generally, rock units at the type section show E-W trending with southward dipping. Azimuth of beds varies from 25/155 to 50/225. Characteristics of strata are very smooth having a continuous sequence without movement of beds by faulting. However, in the northern part of the main quarry (Grid reference 615658E 0731857N), this sequence is affected by a thrust fault (85/250 in azimuth) with close and tight folds.

Faulting and jointing occurred in the area is characterized by the two directions of oblique strike-slip faults trending NE-SW and NW-SE directions. Cleavages are well developed particularly in argillite strata with general 45/165 and 60/220 directions.

Three formations of rock units, approximately 213 m thick, recognized in this type section are described in detail, in ascending order, as follows:

a. Devonian Pa Samed Formation

The exposures of this formation are represented by natural outcrops at the lower level located in the northeastern part of the main quarry. The sequence is measured to be more than 33.5 m thick.

The rock units comprise two lithofacies. Lithofacies 1 is represented by shales interbedded with mudstones. Shales are light brown and fissile. Mudstones are reddish brown, pale reddish brown and white, laminated, thin-bedded (5-10 cm). *Tentaculites elegan*s, *Nowakia* sp., trilobites and bioturbation are abundant in mudstone. Lithofacies 2 is carbonaceous shale, lenses, sharp, wavy, dark grey to black, thin- to medium-bedded (5-20cm) intercalated with light brown, very thin-bedded, laminated claystone. *Tentaculites elegans, Nowakia* sp. and graptolites are abundant in carbonaceous shale. It is recognized that the *Tentaculites* was filled with pyrite (Figures 4.31 and 4.32).

Figure 48: Outcrop of Pa Samed Formation. (After The Malaysian-Thai Working Group, 2012)

Figure 49: Fossil assemblages within the Pa Samed Formation (*Tentaculites elegans, Nowakia* sp.). (After the Malaysian-Thai Working Group, 2012)

The upper is continuously conformable with the overlying Khaun Klang Formation in the vicinity of the northeastern part of Khuan Sung, Muang Satun District of Satun Province or at grid ref .615658E 0731857N)Changwat Satun Quadrangle .(The unit is grading gradually from dark grey, thin-bedded, carbonaceous mudstones containing abundant *Tentaculites* with, 30 cm thick, maroon, porous, hard pans, and bioturbated mudstones of the Pa Samed Formation .The sequence is grading to pale grey to light brown, powdered, thick-bedded mudstones and claystones of the Khuan Klang Formation . This indicates the change in depositional environment from the deeper to the shallower.

a. Lower to Middle? Carboniferous Khuan Klang Formation

The exposures of this formation are represented by natural outcrops, road cuts and quarries in the northern and central parts of the main quarry. The sequence was measured to be more than 150.65 m thick. The Khuan Klang Formation at the type section can be divided into 5 subunits.

(1) Lower clastic member

The lowest member is continuously exposed from the foot to the top of the hill in the northeastern portion of the quarry (Figure 36). Grid reference of this member is ranging from 615658E 0731857N to 615552E 0731806N. General structures of rocks are trending approximately 5/243, 10/225, 25/170 and 30/225. The rock sequence is continuously underlain by the carbonaceous shale of the Pa Samed Formation (Figure 4.33). The member A is generally characterized by the presence of interbeds of sandstones, mudstones and claystones with 64.95 m in thickness. *Posidonomya* sp. and fossil assemblages are occasionally found (Figure 4.34).

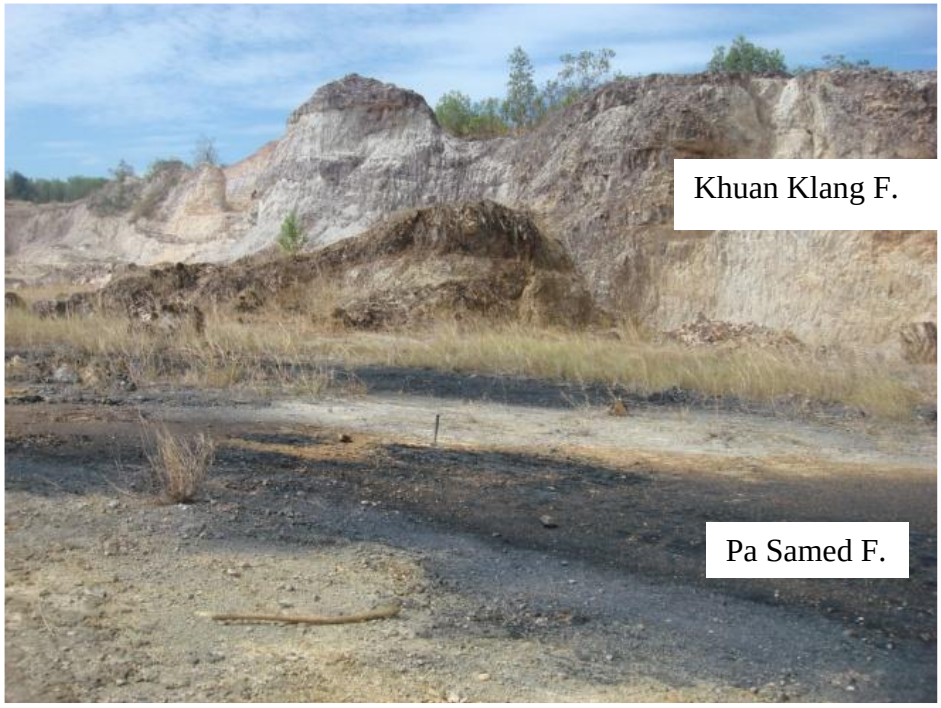

Figure 50: The contact zone of the lower Khuan Klang and Pa Samed Formations at Khuan Song Reference Section. (After The Malaysian-Thai Working Group, 2012)

Figure 51: *Posidonomya* sp. from the fossilliferous bed of the middle portion of this Lower clastic member at Khuan Song Reference Section. (After The Malaysian-Thai Working Group, 2012)

(2) Siliceous rocks member

The member is located along the intermitted road north of an active quarry or at grid reference 615577E, 0731809N .The sequence shows tight and recumbent folds within the mudstones and claystones in the upper portion)Figure 4.35 .(Theis is generally characterized by the presence of ribbon chert or siliceous rocks with 2-2.5 m in thickness)Figure 4.36.(

Figure 52: Recumbent folds in the chert beds at Khuan Song Reference Section. (After The Malaysian-Thai Working Group, 2012)

Figure 53: Closed-up of the ribbon chert at Khuan Song Reference Section. (After The Malaysian-Thai Working Group, 2012)

(3) Middle mudstone and claystone member

The member is widely exposed in the currently mined quarry or at grid reference between 615552E 0731806N to 615405E 0731639N. General structures of rocks are trending 30/ 165 30/ 190 10-20/ 235 and 30-45/ 225. The rock sequences are characterized by light colour, thick to massive mudstones and claystones, and some lenses of sandstones beds with 38.50 m thick (Figures 4.37 and 4.38). Fossilifeous beds of *Posidonomya* sp are occasionally found.

Figure 54: Well-bedded, laminated mudstone in the upper portion of the Middle mudstone and claystone member. (After The Malaysian-Thai Working Group, 2012)

Figure 55: Closed-up of the laminated mudstone to claystone of the Middle mudstone and claystone member. (After The Malaysian-Thai Working Group, 2012)

(4) Upper lithic sandstone member

The member is distributed in the southern portion of the currently mined quarry or at grid reference at 615452E 0731706N. General structures of rocks are trending approximately 30/ 165. The rock sequences are characterized by cycles of conglomerates-pebbly sandstones-sandstones-mudstones with 6 m thick (Figure 4.39) . Fossil fragments and plant remains are occasionally found in mudstone strata.

Figure 56: Outcrops of the Upper lithic sandstone member. (After The Malaysian-Thai Working Group, 2012)

(5) Upper mudstone member

The uppermost member is continuously exposed at the top of the hill, south of the quarry. Grid reference of this member is ranging from 615452E 0731706N to 615254E 0731650N. General structures of rocks are trending approximately 30/165, 28/180 and 30/155. The rocks sequence is continuously overlain by the slaty shale of the Kaeng Krachan Group. This member is generally characterized by the presence of mudstones intercalated with sandy siltstone and sandstones with 37.00 m in thickness. Outcrops, lithology and fossils of the Upper mudstone member are shown in Figure 57. Well preserved *Posidonomya* sp., ammonites, trilobite, bivalves, crinoid stems and lignite jet are usually found (Figure 58).

Figure 57: Outcrop exposure of interbeds or cycles of quartzitic sandstone, sandy siltstone and mudstone in the Upper mudstone member. (After the Malaysian-Thai Working Group, 2012)

Figure 58: *Posidonomya* sp. is abundant in fossilliferous sandy siltstone strata of the Upper mudstone member. (After The Malaysian-Thai Working Group, 2012)

b. Lower Permian Kaeng Krachan Group

The exposures of this formation are represented by natural outcrops and quarries located in the southern part of the main quarry. Thickness of this group in the type section area exceeds to 26.5 m. The sequence consists of interbeds of slaty shales, sandstones and paraconglomerates. Generally, beds of rock are well-bedded, sharp, wavy, non-parallel. Slaty shales are dark grey to dark greenish grey, very thin- to very thick-bedded. Lamination, load cast and graded bedding are commonly found (Figure 59). It is remarked that the developed cleavages are strongly affected in these argillites. Sandstones are greenish grey, fine- to coarse-grained, lithic, wacke and thin- to thick-bedded. Discontinuous lamination and graded bedding are very common. Paraconglomerates are occasionally found and characterized by greenish grey, medium-bedded, poorly sorted. Clasts are quartz, chert, and pebbles of rock fragments.

Figure 59: Dark grey to black, slaty shale with well-developed cleavages of the Kaeng Krachan Group. (After The Malaysian-Thai Working Group, 2012).

The Khaun Sung Reference Section is a type section of the Khuan Klang Formation which were reported by The Malaysian-Thai Working Group (2012). It is located at a large quarry currently mined at Khuan Sung, Si-ngam village, Khuan Kat Urban, Muang District, Satun Province. Three formations of rock units, approximately 213 m thick, stratigraphic column in this section are described in detail, in ascending order as in Figure 60.

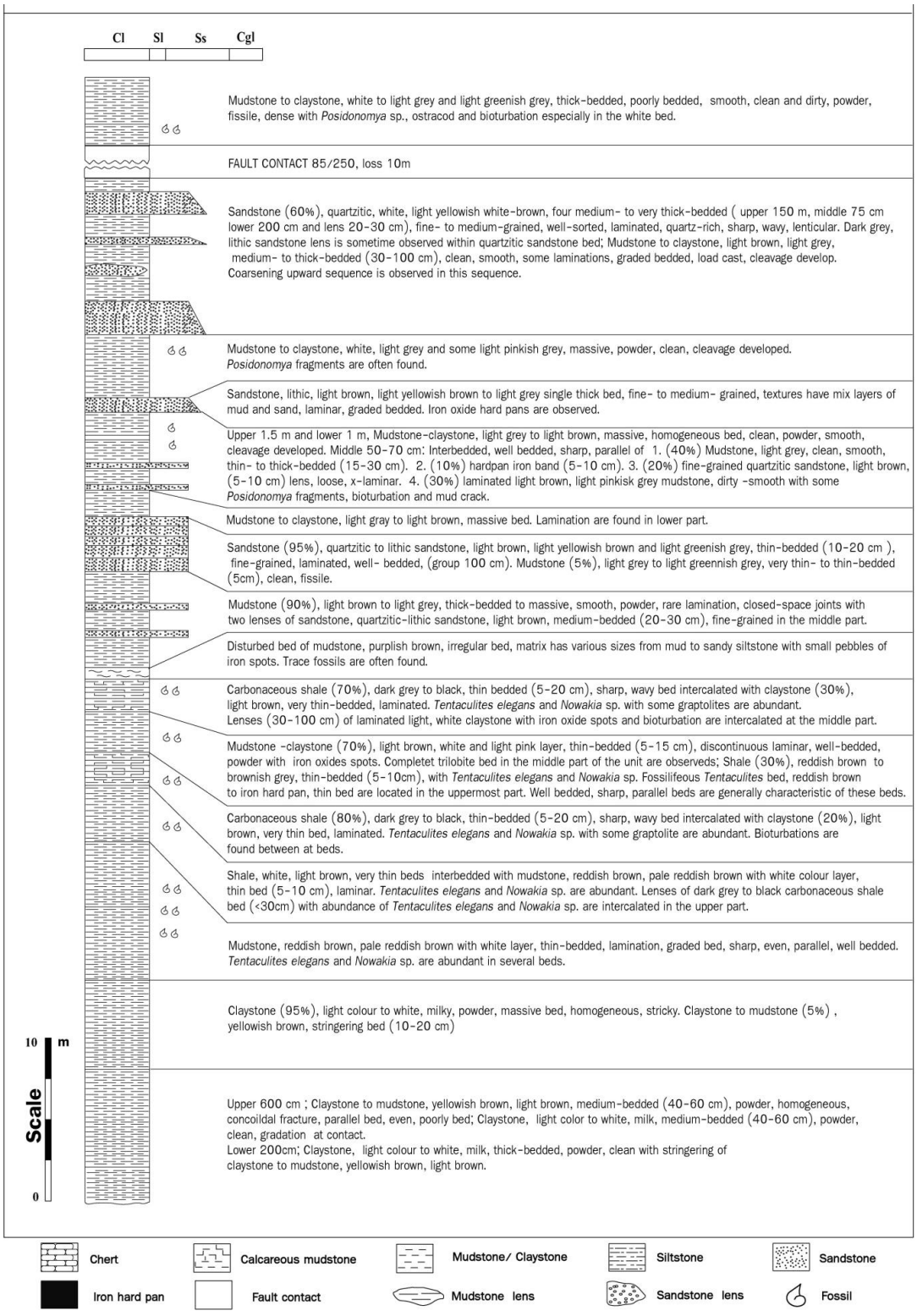

Figure 60: Stratigraphic column of the Khuan Sung Reference Section at the large quarry currently mined, Khuan Sung, Si-ngam village, Khuan Kat Urban, Muang District, Satun Province. (After The Malaysian-Thai Working Group, 2012)

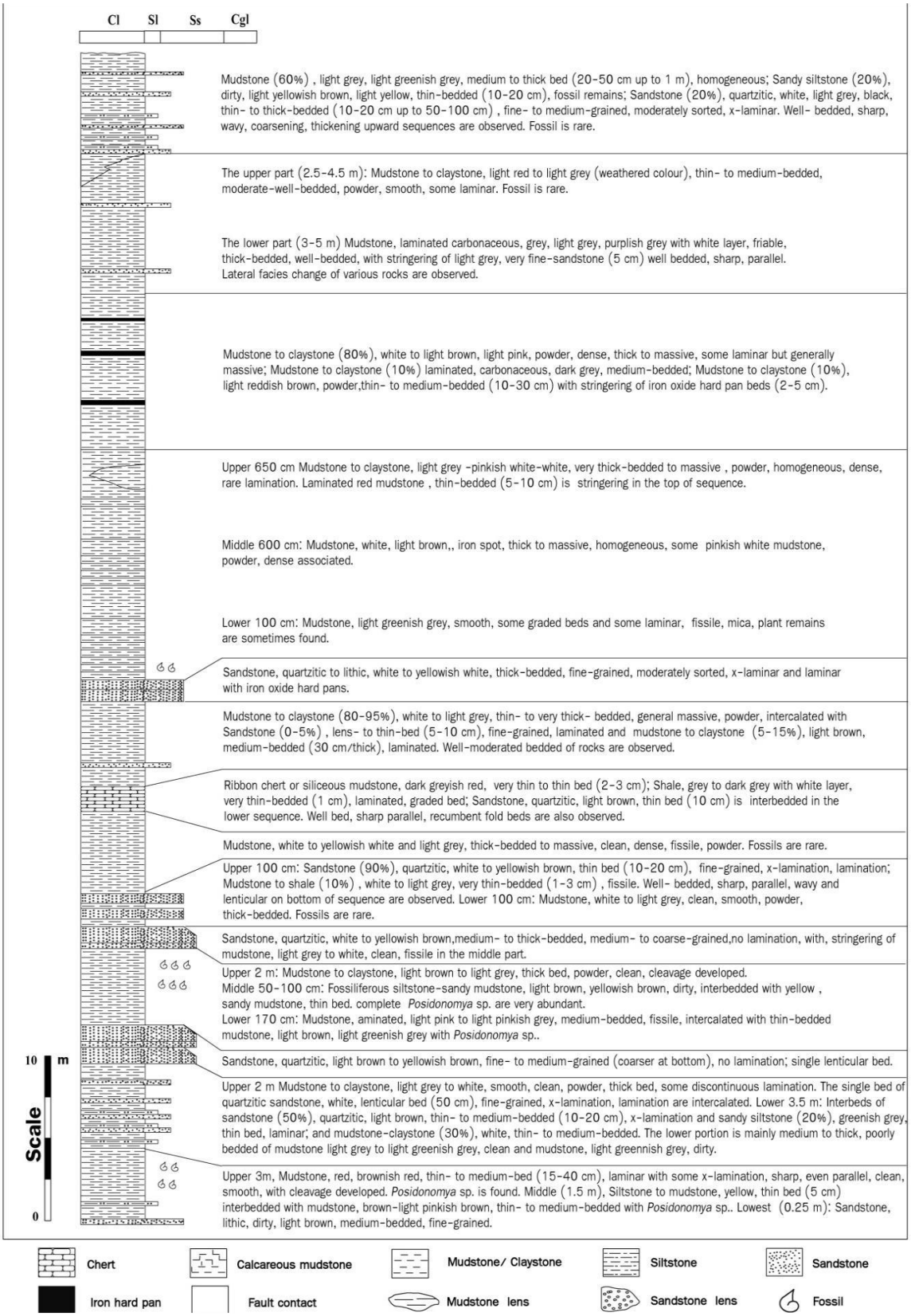

Figure 60 *(continuous)*

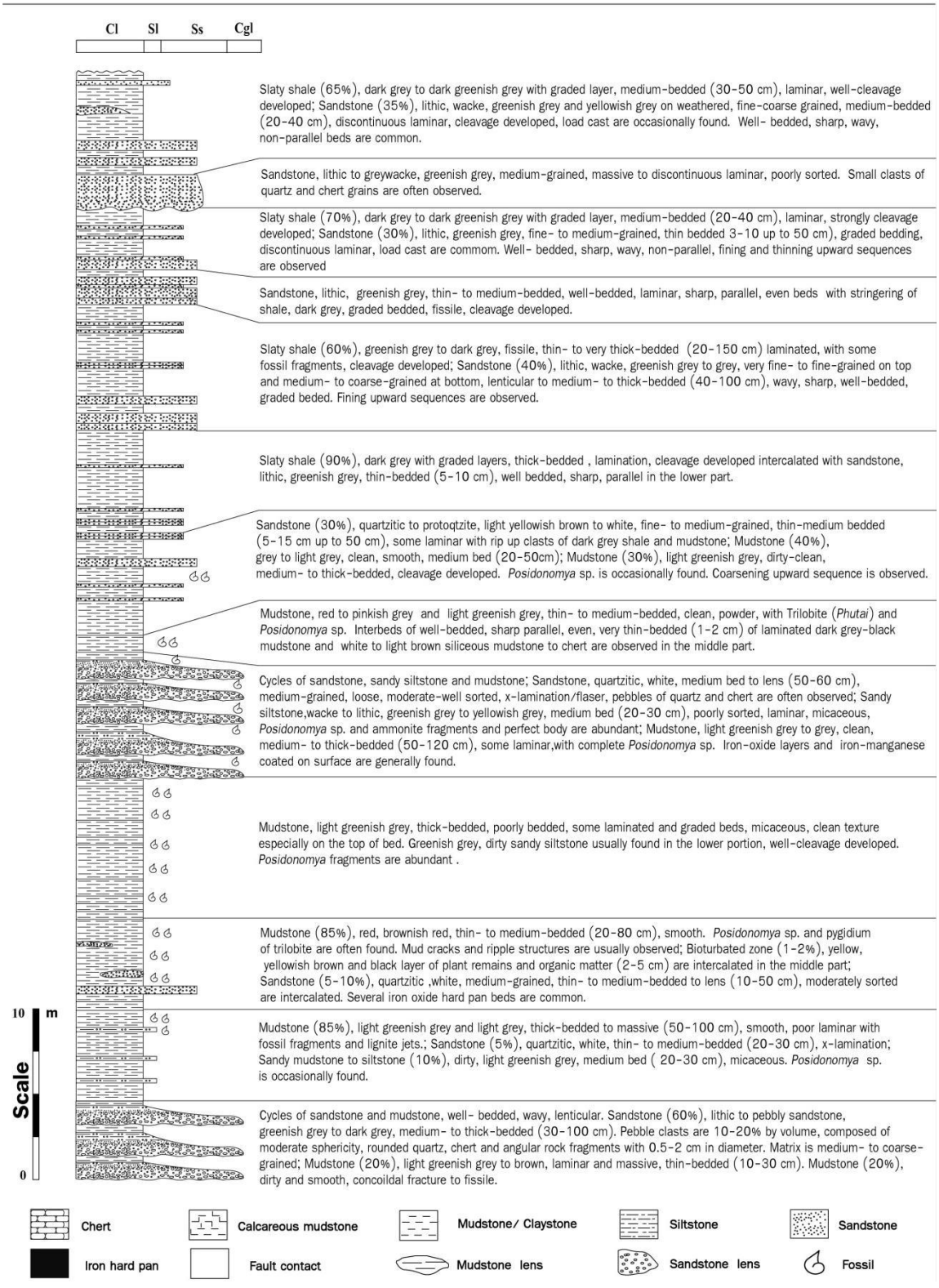

Figure 60 *(continuous)*

4.9.3 Khao Noi Reference Section

There are many Ordovician-Silurian-Devonian sequences cropping out in the vicinity of Ban Pa Samet-Ban Thung Samet area, La Ngu District, Satun Province. Most of which

are either road-cut outcrops or rock quarries excavated for construction. Meesook (2014) studied a quarry situated between Ban Pa Samet and Ban Thung Samet. This area is selected for detailed study based on its good accessibility and succession (Figure 61). This Ordovician-Silurian-Devonian sequence is located at a quarry situated between Ban Pa Samet and Ban Thung Samet, Kamphaeng Subdistrict, La Ngu District, Satun Province, Peninsular Thailand or at Latitude: 06.9752 Longitude: 099.7752, UTM 47N 585296 E 0771076 N (Figure 62). This outcrop is exposed besides a road constructed by local administrative office approximately 1 km east of Highway No. 416 (original, no. 4078) from La Ngu to Thung Wa. The site is situated as an abandoned quarry besides a small hill bounded by small hills to the north and east. The rest is undulating terrains covered by Quaternary deposits (Figure 63).

However, this area in the same rock quarries excavated were studied stratigraphy of rocks sequence by Wongwanich et al., (1990). They suggested that consists of two formations such as the Pa Kae Formation and the Wang Tong Formation. The Pa Kae Formation (Upper Ordovician) is proposed here as the uppermost formation of the Thung Song Group in Satun province and the overlying Wang Tong Formation (Latest Ordovician to Late Silurian).

Figure 61: The outcrop at the study area located in the vicinity of the Ban Pa Samet-Ban Thung Samet area, La Ngu District, Satun Province, Peninsular Thailand. (After Meesook, 2014)

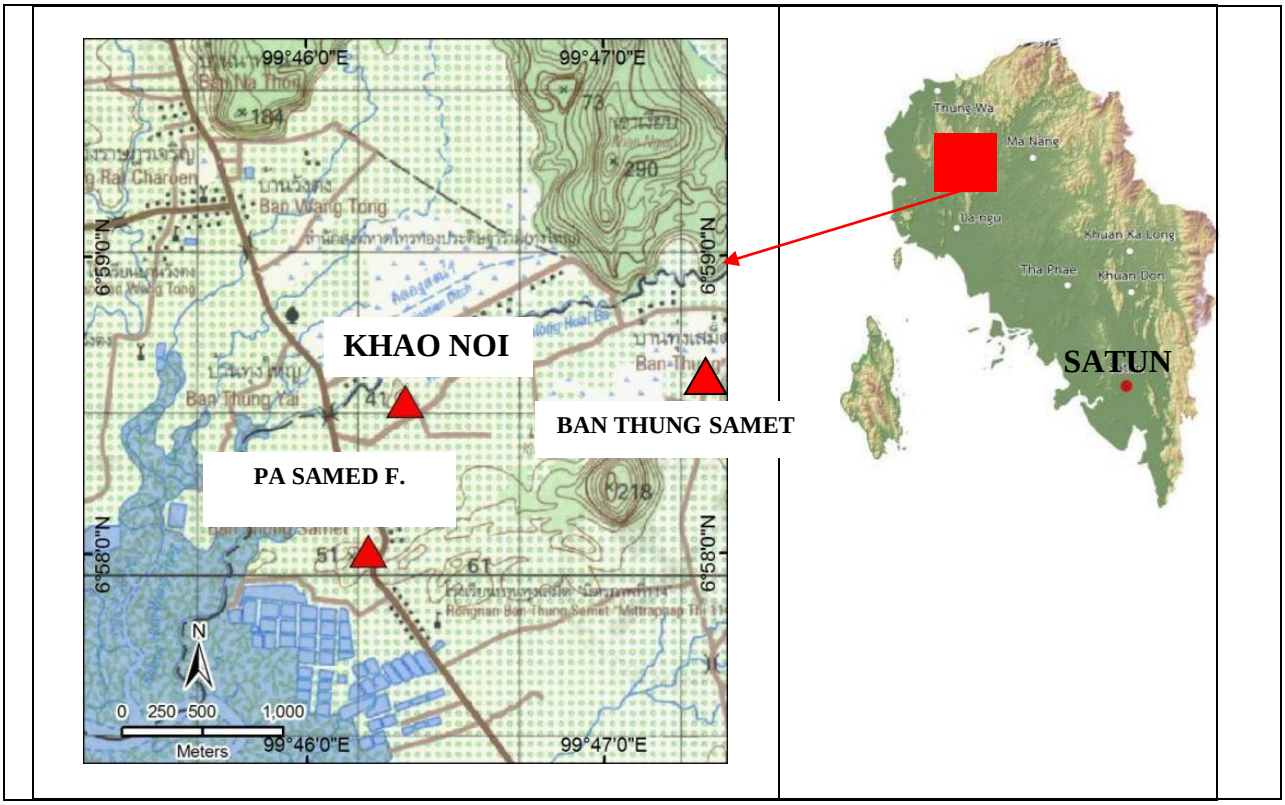

Figure 62: Topographic map showing the study area located in the vicinity of the Ban Pa Samet-Ban Thung Samet area, La Ngu District, Satun Province within the topographic map (scale 1:50,000): Amphoe La Ngu Quadrangle (4922 I). (After Meesook, 2014)

The following is the summary of each stratigraphic unit presented by Meesook (2014) and surrounding areas as shown in Figure 4.46. Most information is selected and compiled from the Transect area (on the Thai side i.e., Satun) called "Bukit Batu Puteh-Satun Transect" and "Langawi-Tatutao Transect" which has been carried out by geoscientists from Malaysia and Thailand (The Malaysian and Thai Working Group, 2013). Some exposures in the surrounding areas of each unit are also added for a better understanding in terms of rock distribution, and stratigraphic correlation particularly on the Malaysian side. Description of each unit including additional data is as follows (in ascending order):

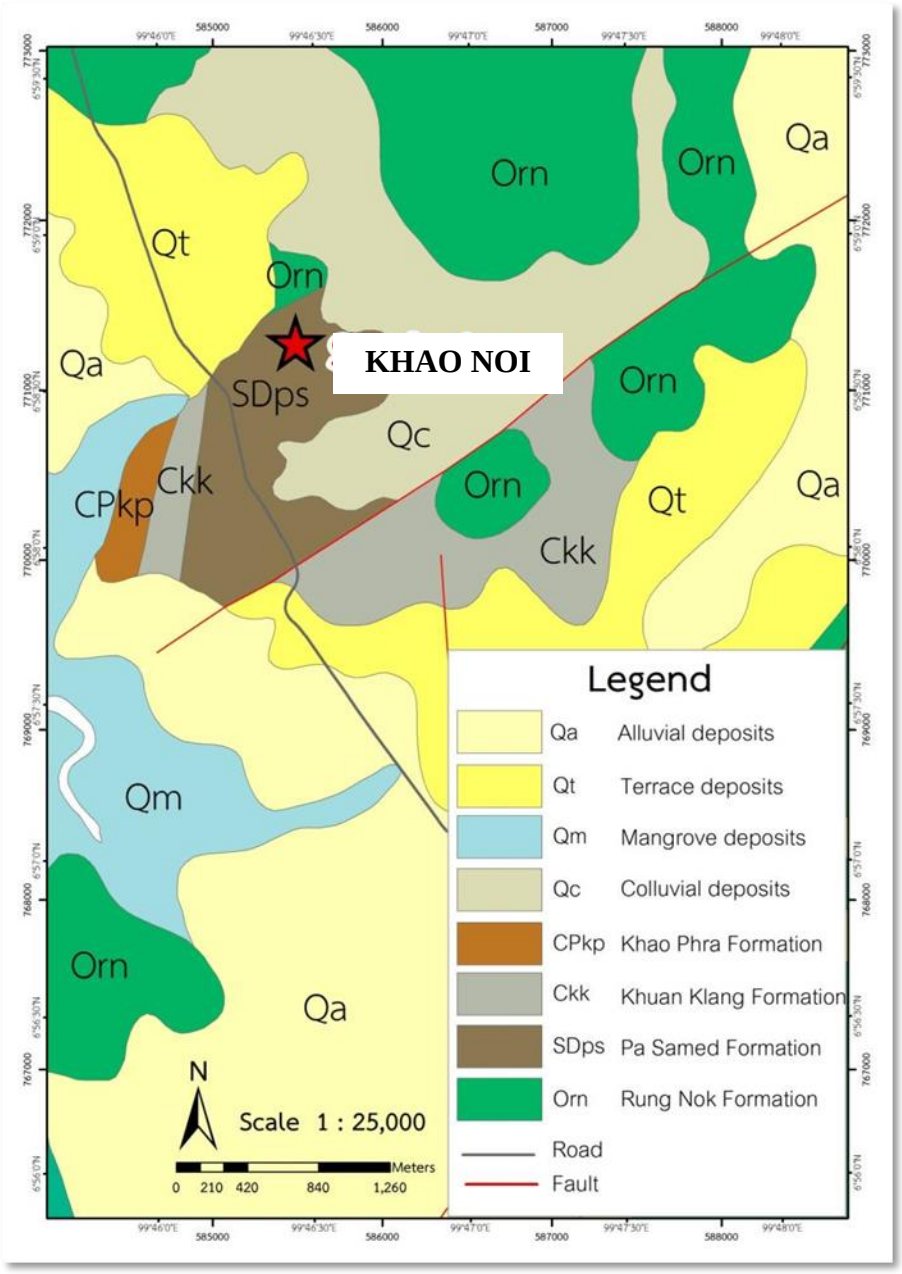

Figure 63: Geological map of the Ban Pa Samet-Ban Thung Samet area around Khao Noi Reference Section and its vicinity, La Ngu District, Satun Province, Peninsular Thailand (After Meesook, 2014).

Pa Samed Formation (SDps)

Distribution

The Pa Samed Formation (SD_{ps}) is confined to the western part of the Transect area in the vicinities of Mueang, La Ngu and Thung Wa Districts of Satun Province, Thailand. The upper part of this formation is correlatable with the Jentik Formation (D_{jt}) in Malaysia.

Lithology

The Silurian-Devonian succession of the Pa Samed Formation (SD_{ps}), approximately 120 m thick, is represented by grey to light grey, thin-bedded mudstone, chert and siliceous mudstone.

Age and correlation

At Khuan Klang of Mueang District, Satun Province, the Pa Samed Formation is conformably overlain by the Carboniferous Khuan Klang Formation. Abundant tentaculitids *Tentaculites* sp., *Nowakia* sp. and a few graptolites, brachiopods, and the trilobite *Plagiolaria poothaii* are found in this unit. The presence of these faunas indicates that the formation ranges in age from Silurian-Devonian.

Depositional environment

The Pa Samed Formation (SD_{ps}) was deposited in low-oxygenated deeper sea environment as a condensed sequence indicated by the presence of black shale and siltstone including graptolites and *Tentaculites* sp.

This Khao Noi Reference Section, the rocks cropping out at this fossil site consist mainly of the rocks ranging in age from Ordovician to Silurian-Devonian with Quaternary flood plain and alluvial deposits (Figure 64). In the northern part of this quarry, the rocks consist of grey, styliolitic, argillaceous limestones of the Rung Nok Formation followed by stromatolitic limestones of the Pa Kae Formation. These limestones are partly offset by two main N-S and E-W faults. Dark grey mudstones with coarsening-upward sequence to grey, siltstones and fine-grained sandstones of the Pa Samed Formation are conformably underlain by the Pa Kae Formation (Figure 65A). The lower part of the sequence consists of grey to dark grey mudstones, siltstones rich in graptolites (Figure 65B). The middle part is composed of thick-bedded sandstones and the upper part comprises grey, thin-bedded siltstones interbedded with mudstones having abundant and diverse graptolites and some tentaculitids (Figure 65C-D).

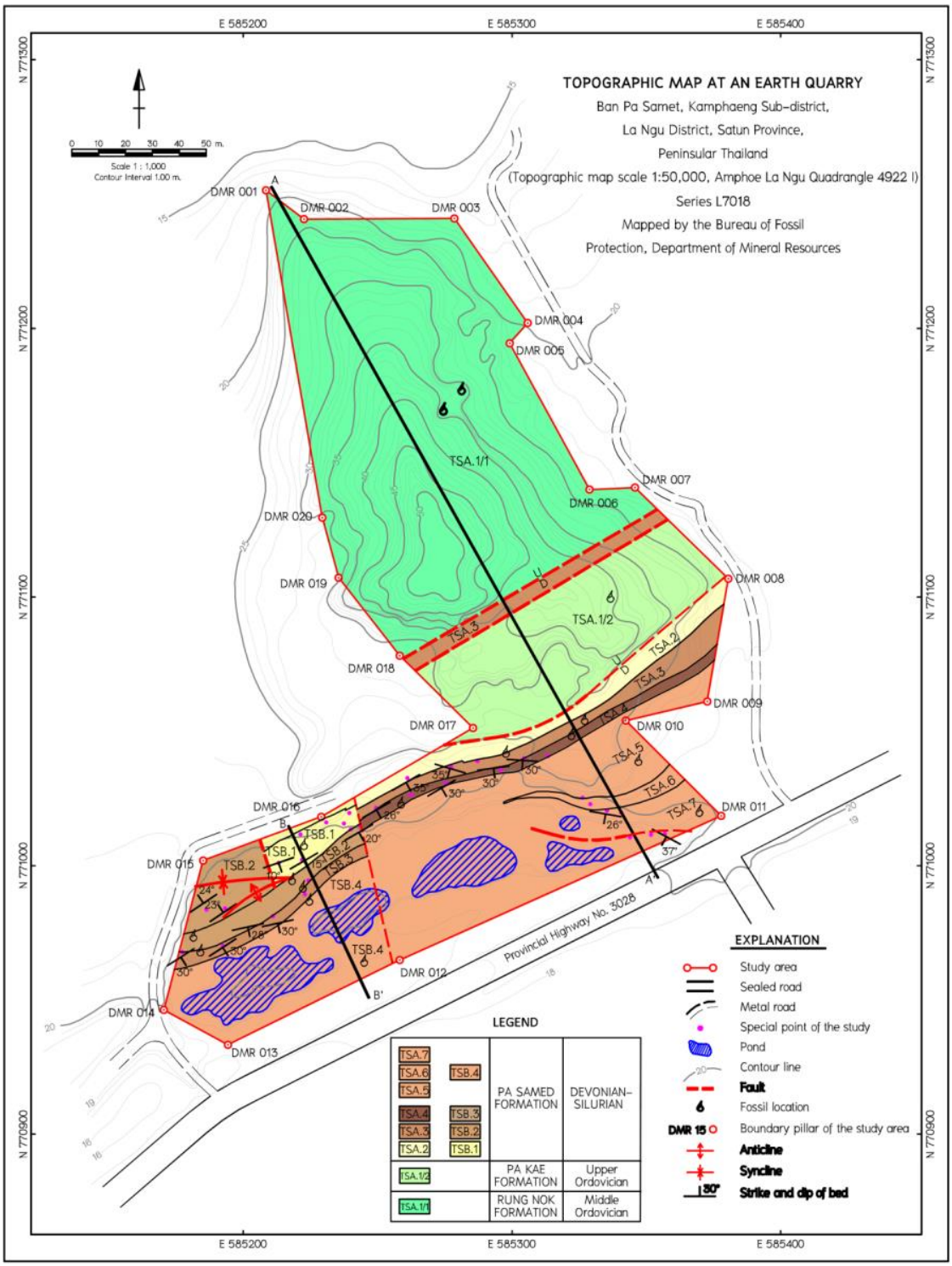

Figure 64: Detailed geological map covering the study area (fossil site at an earth quarry) located in the vicinity of the Ban Pa Samet-Ban Thung Samet area, La Ngu District, Satun Province, Peninsular Thailand. Two lines of Section A-A′ (TSA) and Section B-B′ (TSB) are indicated. (After Meesook, 2014)

Figure 65: Outcrops of a quarry belonging to the Rung Nok, Pa Kae and Pa Samed Formations exposed at the fossil site located in the Ban Pa Samet-Ban Thung Samet area, La Ngu District, Satun Province. A: Exposure of the the Rung Nok and Pa Kae Formation at the quarry. B: Exposure of the lower part of the Pa Samed Formation. C-D: The upper part of the Pa Samed Formation. (After Meesook, 2014)

Detailed stratigraphic columns in the Ban Pa Samet-Ban Thung Samet area (active excavated quarry) can be divided into two study lines, A-A′ and B-B′; TSA and TSB are lithostratigraphic rock units along lines A-A′ and B-B′, respectively (see Figure 4.47). Firstly, the sequence along line A-A′, approximately 64.8 m thick, consists of seven lithostratigraphic rock units (TSA.1-TSA.7 in ascending order). The section is represented by the sequence of the Rung Nok, Pa Kae and **Pa Samed Formations.** Secondly, the sequence along line B-B′, approximately 15.0 m thick, consists of four lithostratigraphic rock units (TSB.1-TSB.4 in ascending order). The section is represented by the sequence of the Pa Samed Formation. Details of lithologic description of each unit of the TSA and TSB sections are shown in Figures 66 and 67 respectively.

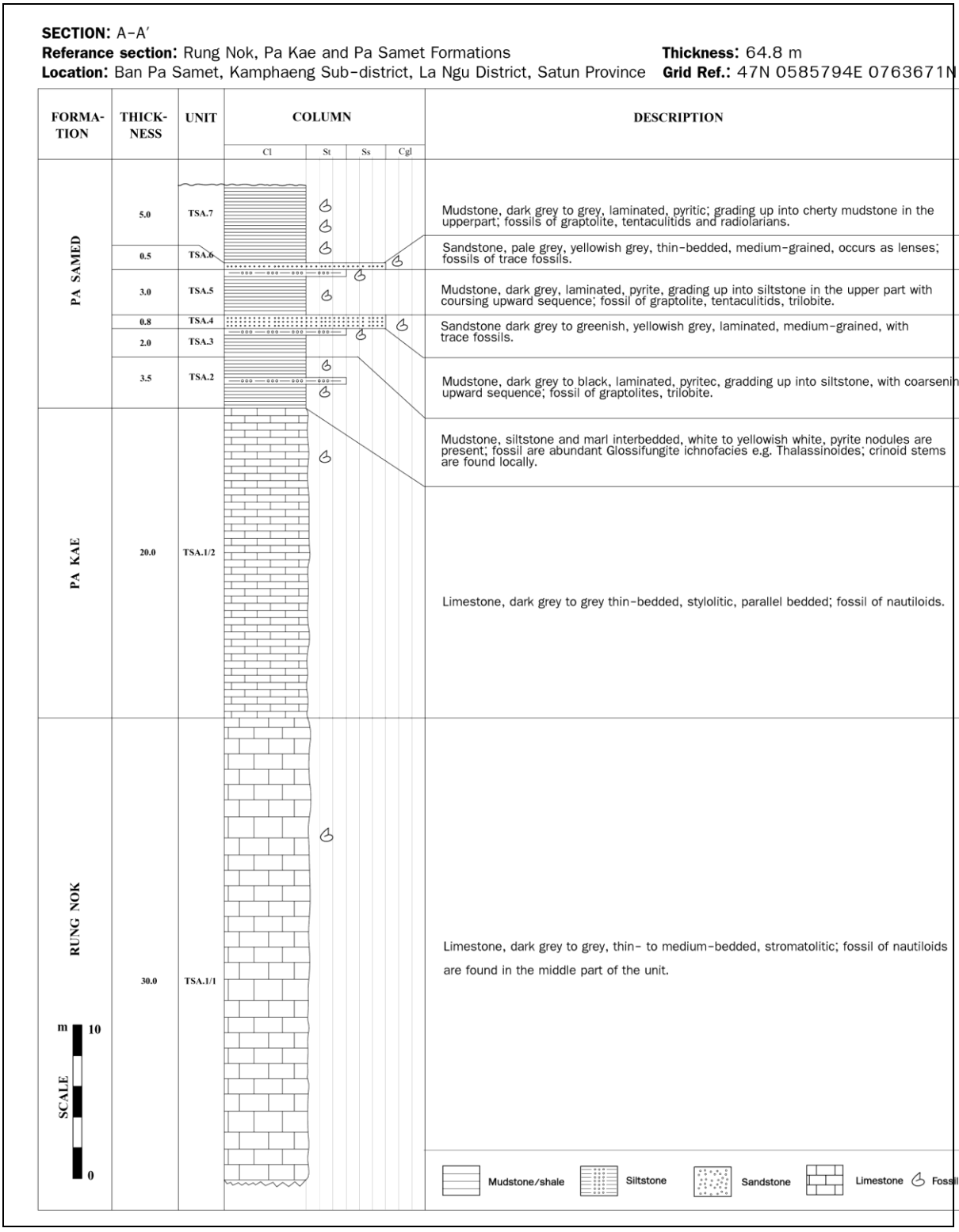

Figure 66: Stratigraphic column of the Rung Nok, Pa Kae and Pa Samed Formations (Section TSA, line A-A′) exposed at the study area located in the vicinity of the Ban Pa Samet-Ban Thung Samet area, La Ngu District, Satun Province, Peninsular Thailand. (After Meesook, 2014)

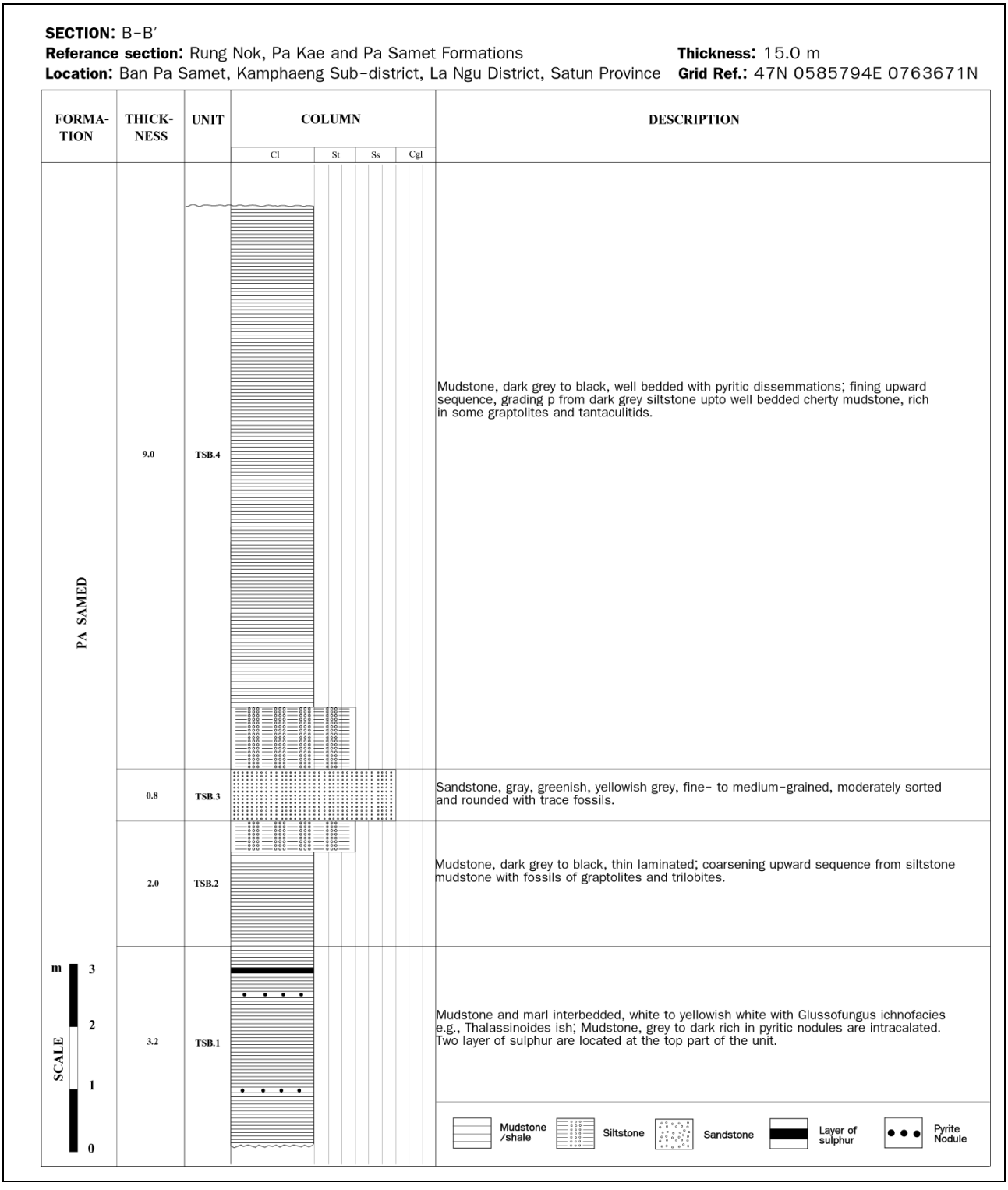

Figure 67: Stratigraphic column of the Pa Samed Formation (Section TSB, line B-B′) exposed at the study area located in the vicinity of the Ban Pa Samet-Ban Thung Samet area, La Ngu District, Satun Province, Peninsular Thailand. (After Meesook, 2014)

1. TSA Section (line A-A′)

The following is detailed description of lithostratigraphic units (TSA.1-TSA.7) along line A-A′ in ascending order (see Figure 4.47).

Description of UNIT TSA.1/1

(a) Definition: Unit TSA.1/1 is the lowest unit of the sequence lying between the unknown rocks and grey to dark grey, stromatolitic limestones.

(b) Lithology: The unit is characterised by grey to dark grey, thin- to medium-bedded, stromatolitic limestones of the Rung Nok Formation (Figure 4.51 A-F, see also Figure 4.49).

(c) Thickness: Unit TSA.1/1 is approximately 30 m thick.

(d) Contact: The lower contact of Unit TSA.1/1 is unknown covered by thick overburden; the upper contact is conformably overlain by thin-bedded limestones of the lower part of Unit TSA.1/2.

(e) Paleontology: Fossils of this unit contain common nautiloids particularly in the middle part of the unit.

Figure 68: Photographs showing lithologies and boundaries of Unit TSA.1/1 of the Ordovician-Silurian-Devonian sequence exposed in the Ban Pa Samet-Ban Thung Samet area, La Ngu District, Satun Province, Peninsular Thailand along line A-A′. A-B: The Ordovician stylolitic limestones of the Rung Nok Formation in the lower part. Limestones in the upper part of Unit TSA.1/1 containing some nautiloids in the lowermost part. (After Meesook, 2014)

Description of UNIT TSA.1/2

(a) Definition: Unit TSA.1/2 is conformably underlain by limestones of Unit TSA.1/1 and overlain by marly mudstones of Unit TSA.2.

(b) Lithology: The unit is characterized by dark grey to grey, thin-bedded, parallel bedded, stylolitic limestones of the Pa Kae Formation (Figure 69).

(c) Thickness: Unit TSA.1/2 is approximately 20 m thick.

(d) Contact: The lower and upper contacts of Unit TSA.1/2 are conformably underlain and overlain by limestones of Unit TSA.1/1 and marl of Unit TSA.2, respectively.

(e) Paleontology: Fossils of this unit are a few nautiloids.

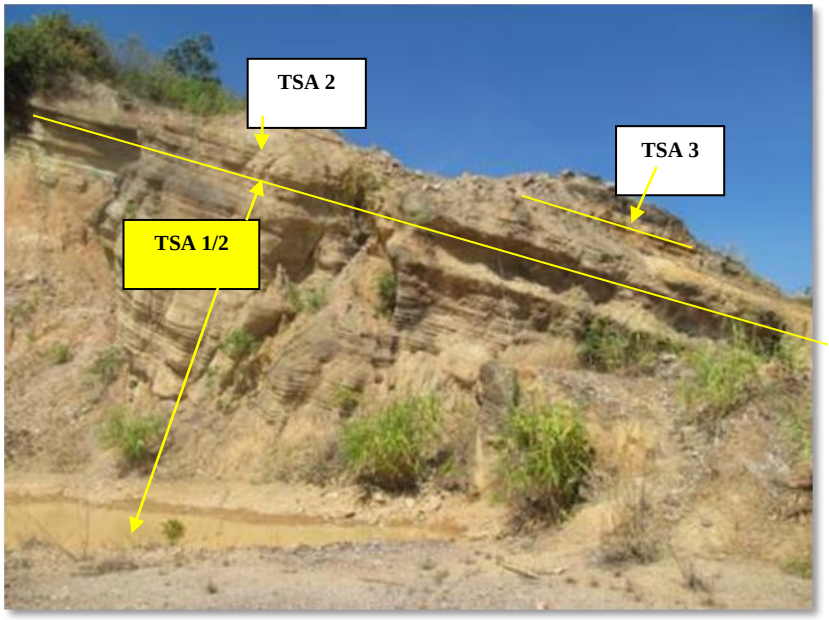

Figure 69: Photographs showing lithologies and boundaries of Unit TSA.1/2 of the Ordovician-Silurian-Devonian sequence exposed in the Ban Pa Samet-Ban Thung Samet area, La Ngu District, Satun Province, Peninsular Thailand along line A-A′. A-F: The Ordovician styliolitic limestones of the Pa Kae Formation. (After Meesook, 2014)

Description of UNIT TSA.2

(a) Definition: Unit TSA.2 is conformably underlain and overlain by marly mudstone of Unit TSA.1/2 and mudstone of Unit TSA.3.

(b) Lithology: The unit is characterized by white to yellowish white marls and siltstones, intercalated with thin-bedded, calcareous mudstone particularly in the top part of the unit (Figure 70); pyrite nodules are present.

(c) Thickness: Unit TSA.2 is approximately 3.5 m thick.

(d) Contact: The lower contact of Unit TSA.2 is conformably underlain by pale grey limestones of Unit TSA.1/2; the upper contact is conformably overlain by dark grey mudstones of the lower part of Unit TSA.3.

(e) Paleontology: *Glossifungi* Ichnofacies is dominant trace fossils in this unit.

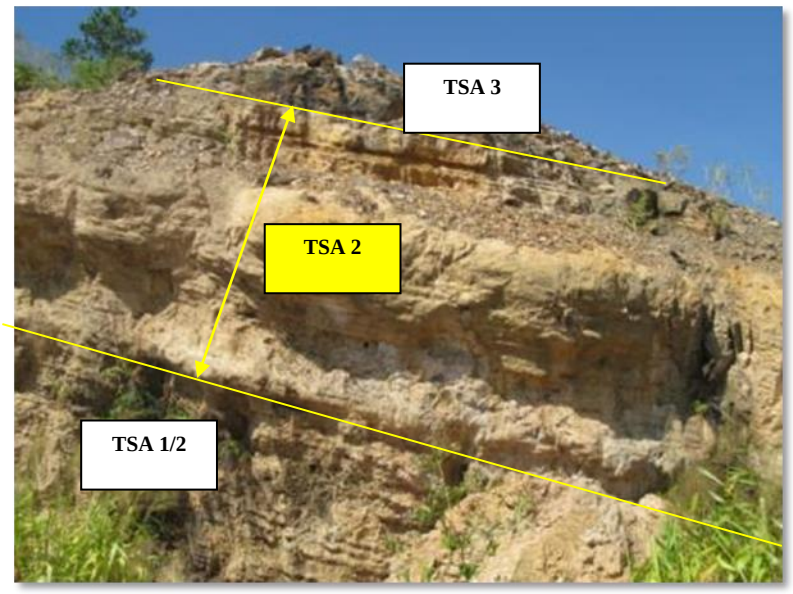

Figure 70: Photographs showing lithologies and boundaries of Unit TSA.2 of the Ordovician-Silurian-Devonian sequence exposed in the Ban Pa Samet-Ban Thung Samet area, La Ngu District, Satun Province, Peninsular Thailand along line A-A′. The marl-mudstone-siltstone-dominated sequence of Unit TSA.2. (After Meesook, 2014)

Description of UNIT TSA.3

(a) Definition: Unit TSA.3 is conformably underlain and overlain by marls and mudstones of Unit TSA.2 and mudstones of Unit TSA.4.

(b) Lithology: The unit is characterized by grey to dark grey, laminated, pyritic mudstones grading up to siltstones with coarsening upward sequence. Various views of mudstone-siltstone (coarsening upward) sequence are shown in Figure 71.

(c) Thickness: Unit TSA.3 is approximately 2.0 m thick.

(d) Contact: The lower contact of Unit TSA.3 is conformably underlain by marls and mudstones of Unit TSA.2; the upper contact is conformably overlain by sandstones of the lower part of Unit TSA.4.

(e) Paleontology: Fossils of this unit contain graptolites and trilobites.

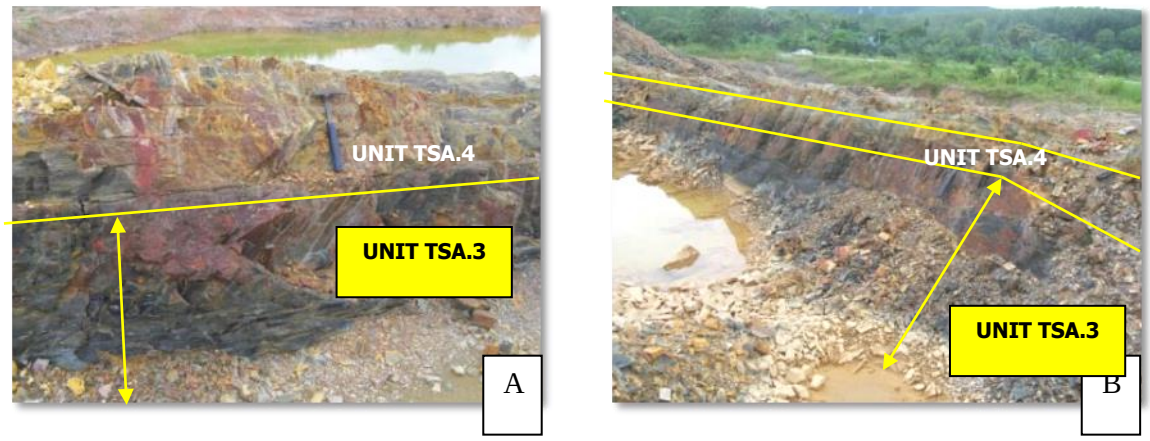

Figure 71: Photographs showing lithologies and boundaries of Unit TSA.3 of the Ordovician-Silurian-Devonian sequence exposed in the Ban Pa Samet-Ban Thung Samet area, La Ngu District, Satun Province, Peninsular Thailand along line A-A′. A-B: Various views of mudstone to siltstone (coarsening upward) sequence of Unit TSA.3. (After Meesook, 2014)

Description of UNIT TSA.4

(a) Definition: Unit TSA.4 is conformably underlain and overlain by siltstones of Unit TSA.3 and mudstones of Unit TSA.5.

(b) Lithology: The unit is characterized by greenish grey, yellowish grey and grey, laminated, medium-grained sandstones showing various views of the sandstone bed (Figure 72). Coarsening upward sequences were found in siltstones to sandstones.

(c) Thickness: Unit TSA.4 is approximately 0.8 m thick.

(d) Contact: The lower contact of Unit TSA.4 is thickening upward sequence from Unit TSA.3 i.e., from siltstones to sandstones; the upper contact is conformably overlain by mudstones of the lower part of Unit TSA.5.

(e) Paleontology: Trace fossils are found in this unit.

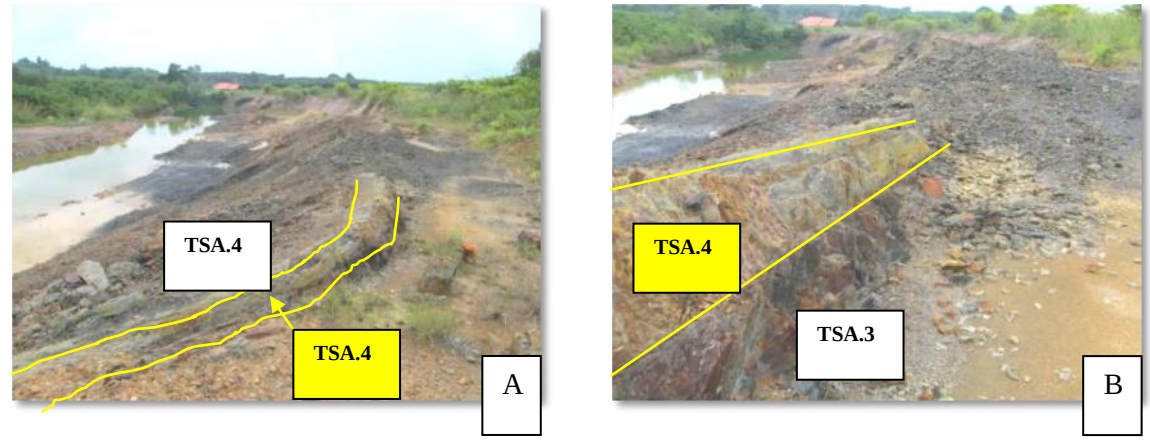

Figure 72: Photographs showing the sandstone bed of the Pa Samet Formation of Unit TSA.4 of the Ordovician-Silurian-Devonian sequence exposed in the Ban Pa Samet-Ban Thung Samet area, La Ngu District,

Satun Province, Peninsular Thailand along line A-A′. A-B: Various views of the sandstone bed of Unit TSA.4. (After Meesook, 2014)

Description of UNIT TSA.5

(a) Definition: Unit TSA.5 is conformably underlain and overlain by sandstones of Unit TSA.4 and sandstones of Unit TSA.6, respectively.

(b) Lithology: The unit is characterized by dark grey, laminated, pyritic mudstones grading up to siltstones in the upper part with coarsening upward sequence from mudstones to siltstones (Figure 73).

(c) Thickness: Unit TSA.5 is approximately 3.0 m thick.

(d) Contact: The lower contact of Unit TSA.5 is marked by the first appearance of mudstones of Unit TSA.5; the upper contact is conformably overlain by sandstones of the lower part of Unit TSA.6.

(e) Paleontology: Fossils of this unit are common consisting of graptolites, tentaculitids and trilobites.

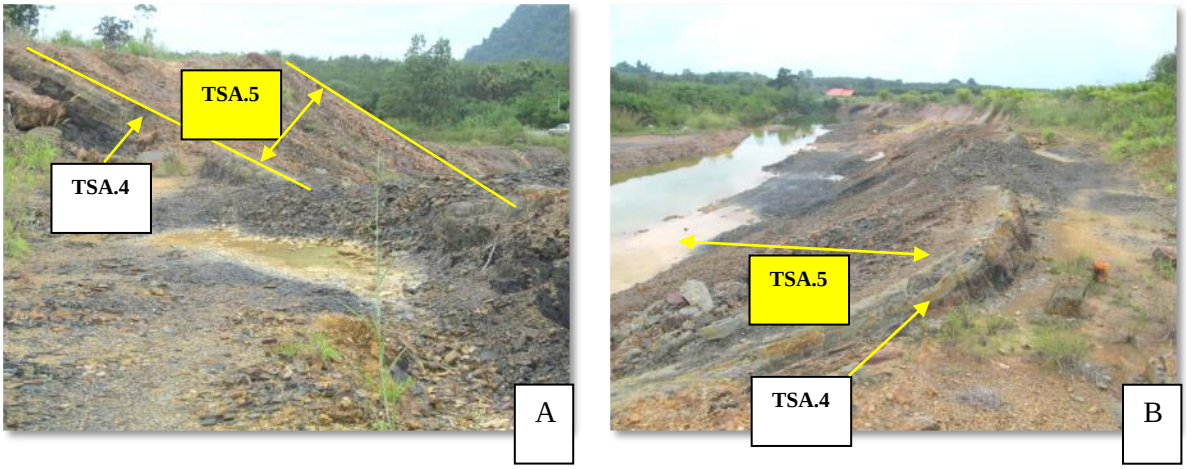

Figure 73: Photographs showing lithologies and boundaries of Unit TSA.5 of the Ordovician-Silurian-Devonian sequence exposed in the Ban Pa Samet-Ban Thung Samet area, La Ngu District, Satun Province, Peninsular Thailand along line A-A′. A-B: Various views of coarsening upward sequence from mudstones to siltstones of Unit TSA.5. (After Meesook, 2014)

Description of UNIT TSA.6

(a) Definition: Unit TSA.6 is conformably underlain and overlain by mudstones of Unit TSA.5 and Unit TSA.7, respectively.

(b) Lithology: The unit is characterized by pale grey to yellowish grey, thin-bedded, medium-grained sandstones occurring as lenses within mudstones (Figure 74).

(c) Thickness: Unit TSA.6 is approximately 0.5 m thick.

(d) Contact: The lower and upper contacts of Unit TSA.7 are conformably underlain and overlain by mudstones of Units TSA5 and TSA 7, respectively.

(e) Paleontology: Trace fossils are found in this unit.

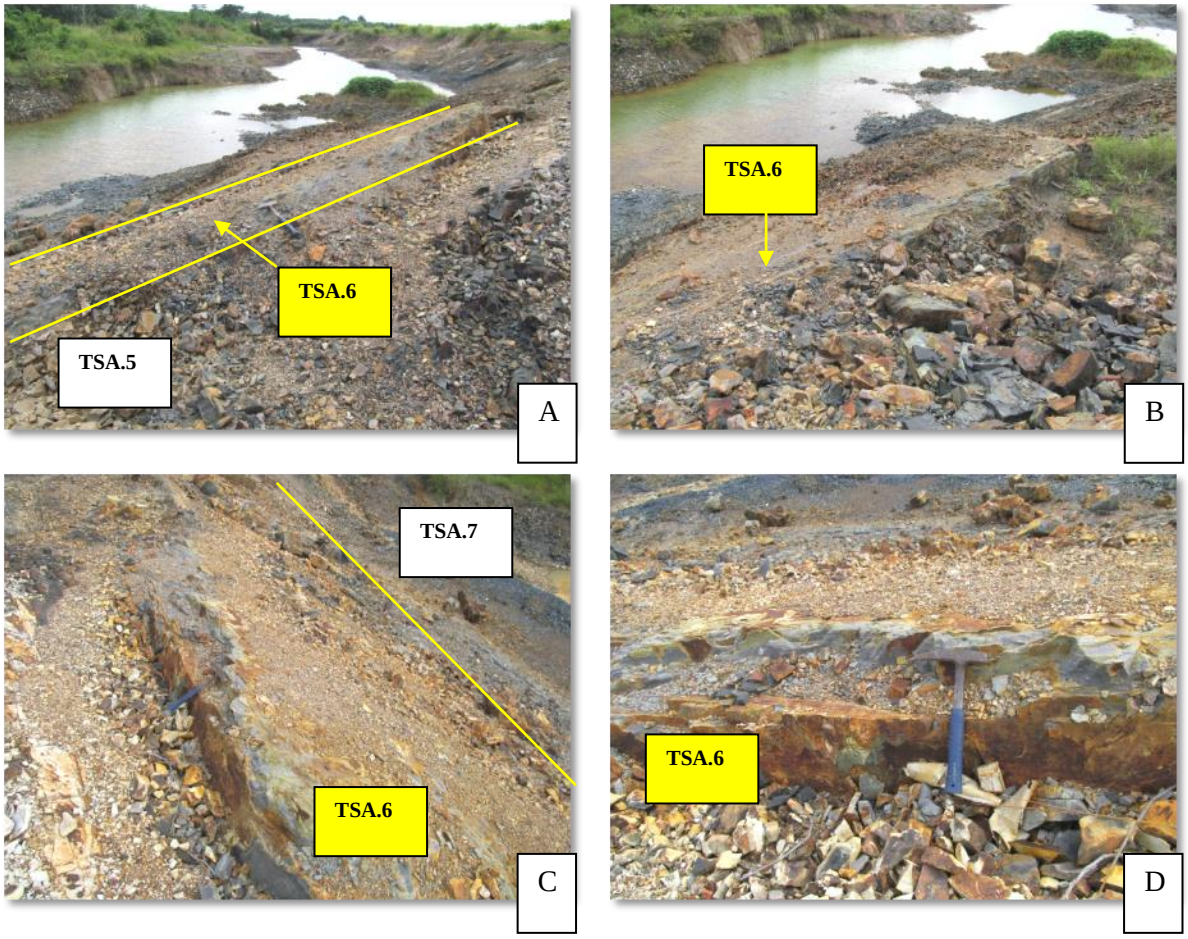

Figure 74: Photographs showing lithologies and boundaries of Unit TSA.7 of the Ordovician-Silurian-Devonian sequence exposed in the Ban Pa Samet-Ban Thung Samet area, La Ngu District, Satun Province, Peninsular Thailand along line A-A′. A-D: Various views of the sandstone bed occurring as lenses of Unit TSA.6. (After Meesook, 2014)

Description of UNIT TSA.7

(a) Definition: Unit TSA.7 is conformably underlain by marls of Unit TSA.6 and is overlain by overburden.

(b) Lithology: The unit is characterized by grey to dark grey, laminated, pyritic mudstones. Mudstones are dominated in the lower part of the unit (Figure 75A-B). The mudstones are grading up into cherty mudstones in the upper part (Figure 75C-F).

(c) Thickness: Unit TSA.7 is approximately 5.0 m thick.

(d) Contact: The lower contact of Unit TSA.7 is conformably underlain by sandstones of Unit TSA.6 and the upper contact is unknown.

(e) Paleontology: Fossils of this unit contain graptolites, tentaculitids and poorly preserved radiolarians.

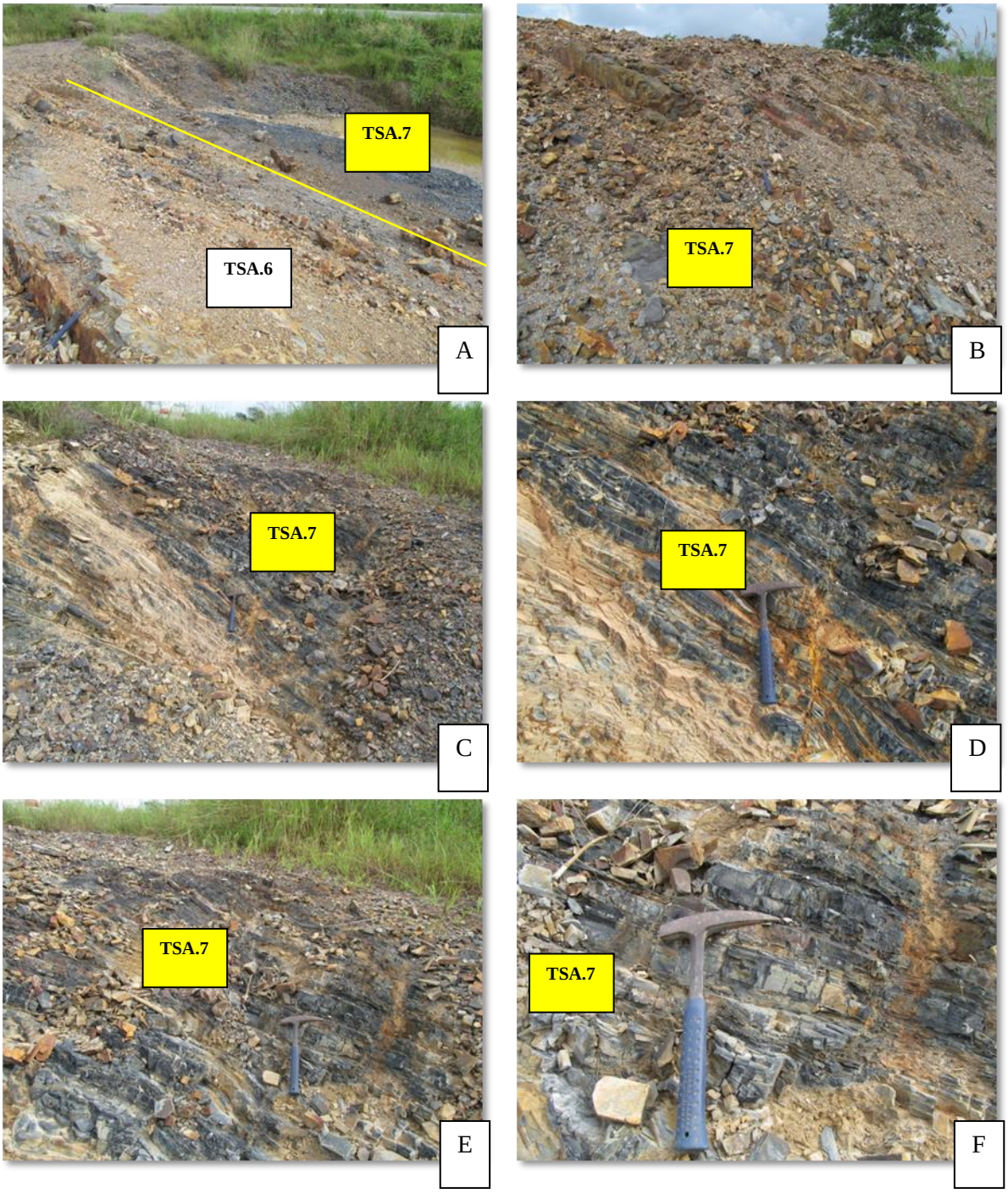

Figure 75: Photographs showing lithologies and boundaries of Unit TSA.7 of the Ordovician-Silurian-Devonian sequence exposed in the Ban Pa Samet-Ban Thung Samet area, La Ngu District, Satun Province, Peninsular Thailand along line A-A′. A-B: The dark grey mudstones in the lower part. C-F: Cherty mudstones of the upper part of Unit TSA.7. (After Meesook, 2014)

TSB Section (line B-B′)

This section consists of four lithostratigraphic units (TSB.1-4). Details of each unit are described as follows:

Description of UNIT TSB.1

(a) Definition: Unit TSB.1 is conformably overlain by mudstones of Unit TSB. 2 and is underlain by unknown rocks due to fault offset.

(b) Lithology: The unit is characterized by white to yellowish white mudstones interbedded with marls. Grey mudstones rich in pyritic nodules are intercalated. Two layers of sulphur are located in the top part of the unit (Figure 76).

(c) Thickness: Unit TSB.1 is approximately 3.2 m thick.

(d) Contact: The lower part of Unit TSB.1 is unknown and upper contact is conformably overlain by mudstones of Unit TSB.2.

(e) Paleontology: Fossils of this unit are abundant consisting of the trace fossil *Thalassinoides* isp.

Description of UNIT TSB.2

(a) Definition: Unit TSB.2 is conformably underlain and overlain by mudstones and marls of Unit TSB.1 and sandstones of Unit TSB.3.

(b) Lithology: The unit is characterized mainly by dark grey to black, thin laminated mudstones with coarsening upward sequence from mudstones to siltstones (Figure 77). In the lower part of the unit the rocks are grading up from marly mudstones of Unit TSB.1 to dark grey mudstones. Siltstones in the upper part of the unit are grading up to sandstones of Unit TSB.3.

(c) Thickness: Unit TSB.2 is approximately 2.0 m thick.

(d) Contact: The lower contact of Unit TSB.2 is conformably underlain by mudstones and marls of Unit TSB.1 and overlain by sandstones of the lower part of Unit TSB.3.

(e) Paleontology: Fossils of this unit are slightly abundant containing graptolites and trilobites particularly in dark grey mudstones.

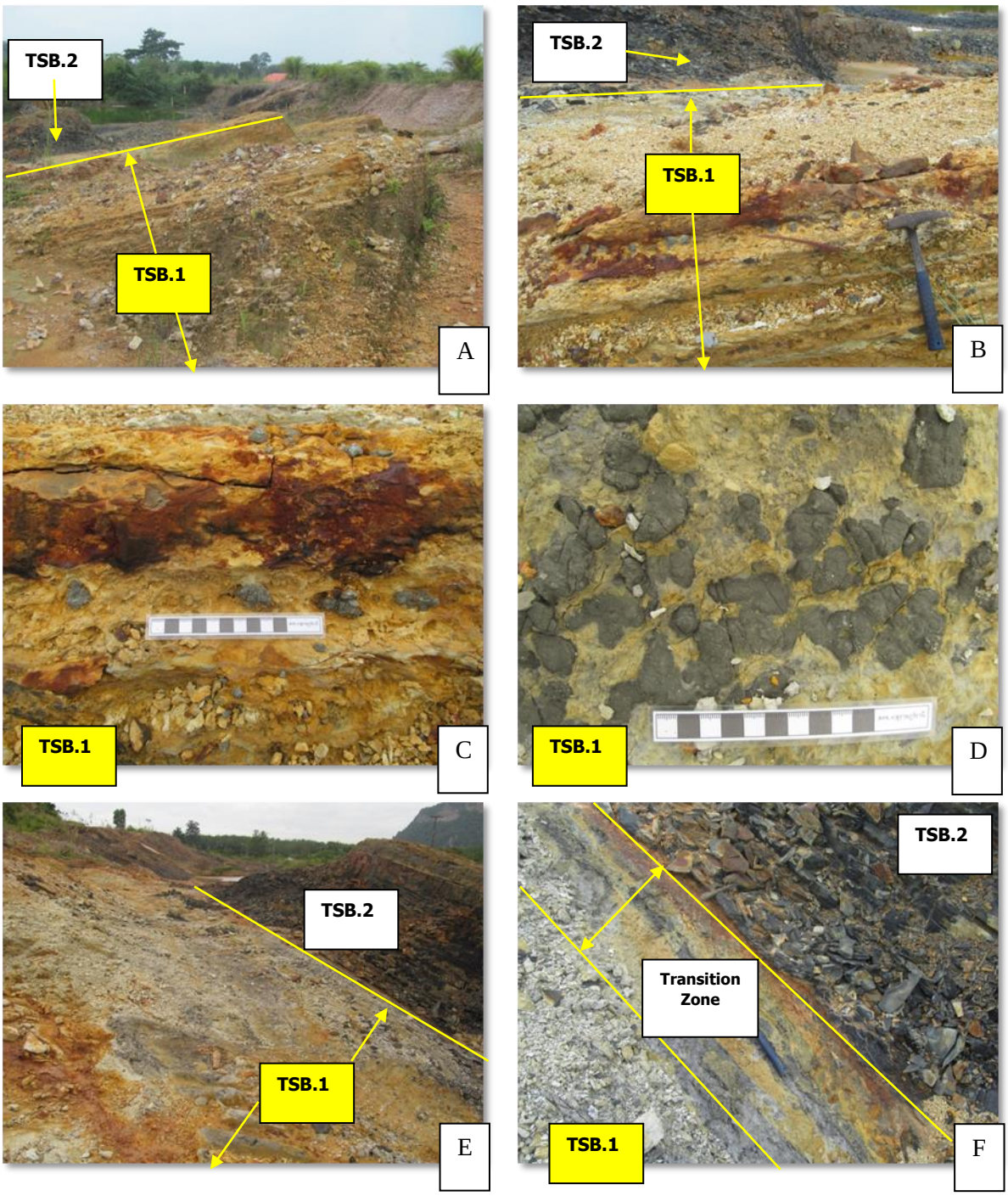

Figure 76: Photographs showing lithologies and boundaries of Unit TSB.1 of the Silurian-Devonian sequence of the Pa Samed Formation exposed in the Ban Pa Samet-Ban Thung Samet area, La Ngu District, Satun Province, Peninsular Thailand along line B-B′. A: The mudstone-marl-dominated sequence in the lower part. B: Close-up photograph of A. C-D: Pyrite nodules in mudstones and marls in the middle part. E: Whitish marls in the upper part of the unit consisting of trace fossils and pyrite nodules. F: Gradational contact between Unit TSB.1 and Unit TSB.2 (After Meesook, 2014)

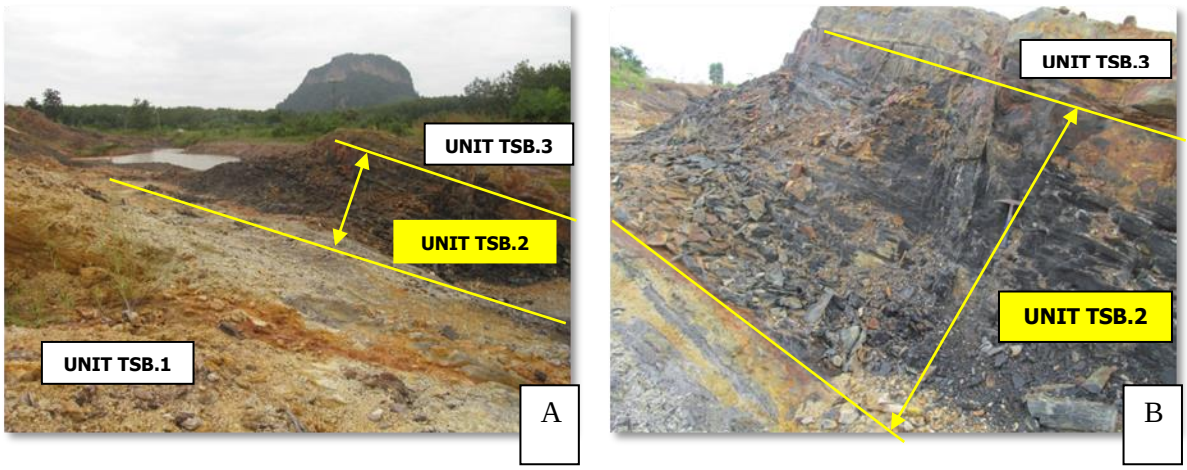

Figure 77: Photographs showing lithologies and boundaries of Unit TSB.2 of the Ordovician-Silurian-Devonian sequence exposed in the Ban Pa Samet-Ban Thung Samet area, La Ngu District, Satun Province, Peninsular Thailand along line B-B′. A-B: Dark grey mudstones of the Pa Samed Formation in the lower part. (After Meesook, 2014)

Description of UNIT TSB.3

(a) Definition: Unit TSB.3 is conformably underlain and overlain by siltstones of Unit TSB.2 and Unit TSB.4, respectively.

(b) Lithology: The unit is characterized by greenish grey to yellowish grey, fine- to medium-grained, poorly to moderately sorted and subrounded sandstones (arkosic wacke). Various views of sandstone beds of Unit TSB.3 are shown in Figure 78. The sandstone bed of Unit TSB.2 is underlain by siltstones of Unit TSB.2 displaying coarsening upward sequence from Unit TSB.2 to Unit TSB.3.

(c) Thickness: Unit TSB.3 is approximately 0.8 m thick.

(d) Contact: The lower and upper contacts of Unit TSB.3 are conformably underlain and overlain by mudstones of Units TSB.2 and TSB.4, respectively.

(e) Paleontology: Trace fossils are rich in this unit.

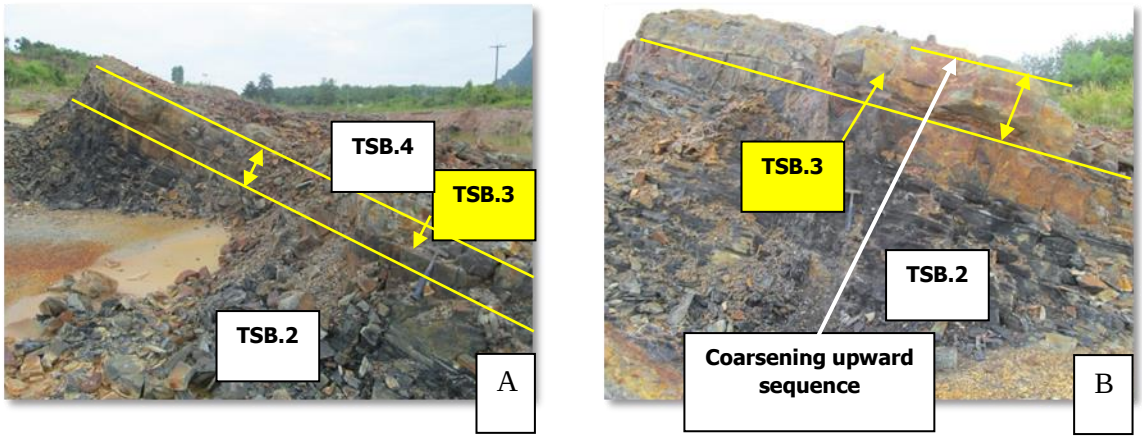

Figure 78: Photographs showing sandstone (Arkosic wacke) beds of Unit TSB.3 of the Silurian-Devonian sequence exposed along Line B-B′ in the Ban Pa Samet-Ban Thung Samet area, La Ngu District, Satun Province, Peninsular Thailand. A-B: The Silurian-Devonian sandstones of the Pa Samed Formation in various views. (After Meesook, 2014)

Petrographically, the selected sample *Sample number TSB3T* (TSB.3) is sandstone which has greyish olive colour on its fresh surface. The sample rather shows matrix-supported texture (amount of grains is approximately 60%). It is fine- to lower coarse-grained with an average grain size of 0.1-0.6 mm, poorly sorted. Its roundness is subrounded (3.5 according to the AGI scale) with the sphericity of subdiscoidal (2.5 according to the AGI scale). Detrital components are quartz (50%), feldspar (5%) and rock fragments (3%). Types of rock fragment are either chert or siltstone (Figure 3.17). Authigenic minerals present in this sample are quartz and sericite. Since abundant of authigenic sericitic mica present, the stage of textural maturity is, therefore, immature. On the basis of sandstone classification of Pettijohn *et al.* (1987), the sample is arkosic wacke (Figure 79).

Description of UNIT TSB.4

(a) Definition: Unit TSB.4 is conformably underlain by marly sandstones of Unit TSB.3.

(b) Lithology: The unit is characterized by dark grey to black, well bedded mudstones with pyrite disseminations. Fining and thinning upward sequences are observed in this unit which grade up from dark grey siltstones to dark grey, well bedded cherty mudstones in the topmost part of the unit (Figure 80).

(c) Thickness: Unit TSB.4 is approximately 9.0 m thick.

(d) Contact: The lower contact of Unit TSB.4 is starting from a thinning and fining upward sequences (siltstones to mudstones) until cherty mudstones in the uppermost part of the unit where the overlying sequence is unknown.

(e) Paleontology: Fossils of this unit are very abundant containing mixed faunas of graptolites and tentaculitids.

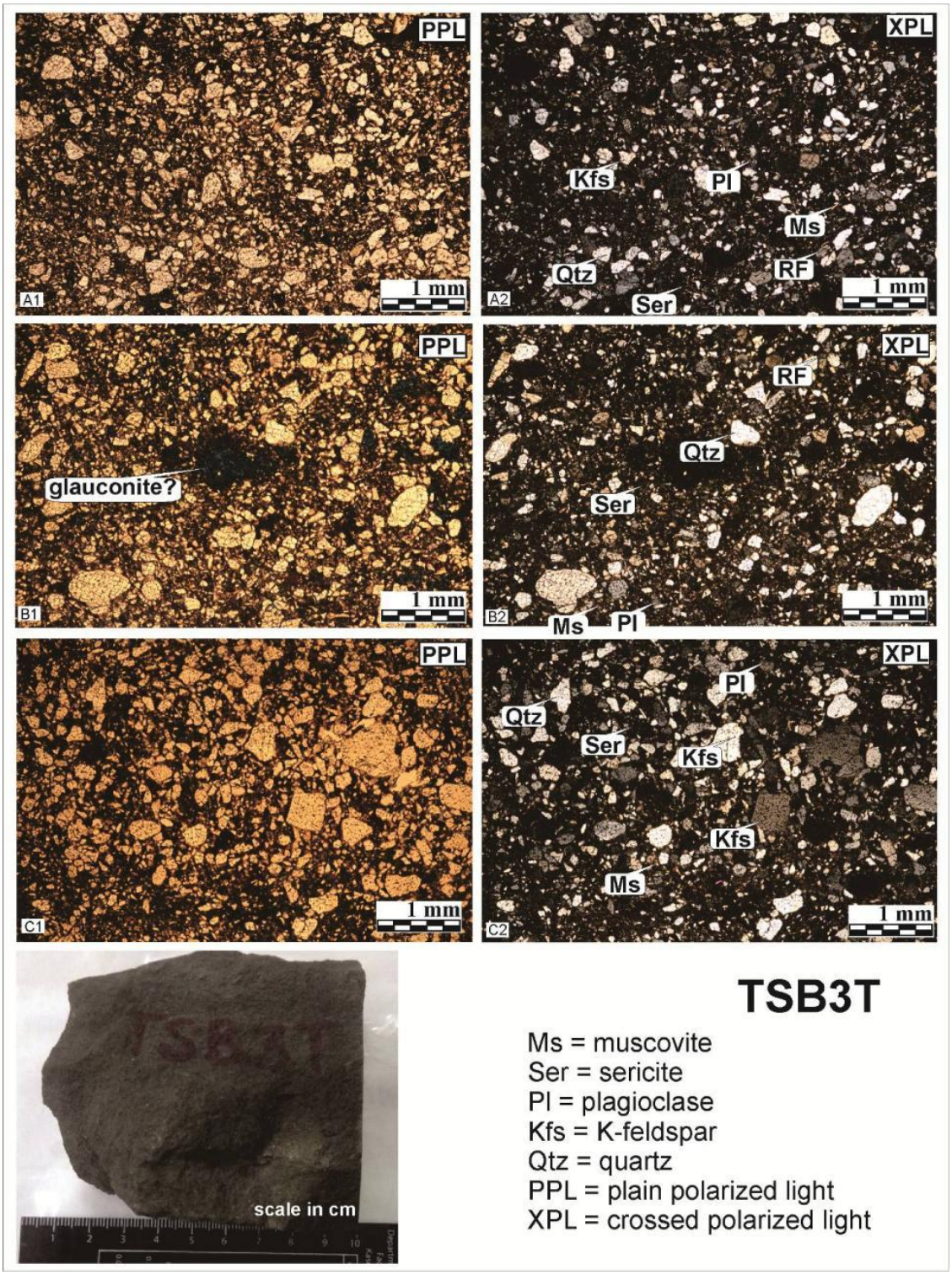

Figure 79: Photograph and microphotographs of sample number TSB3T (TSB 3) showing both macroscopic and microscopic characteristics of the sample, A1, B1 and C1 were taken under plain polarized light while A2, B2 and C2 were taken under cross polarized light. (After Meesook, 2014)

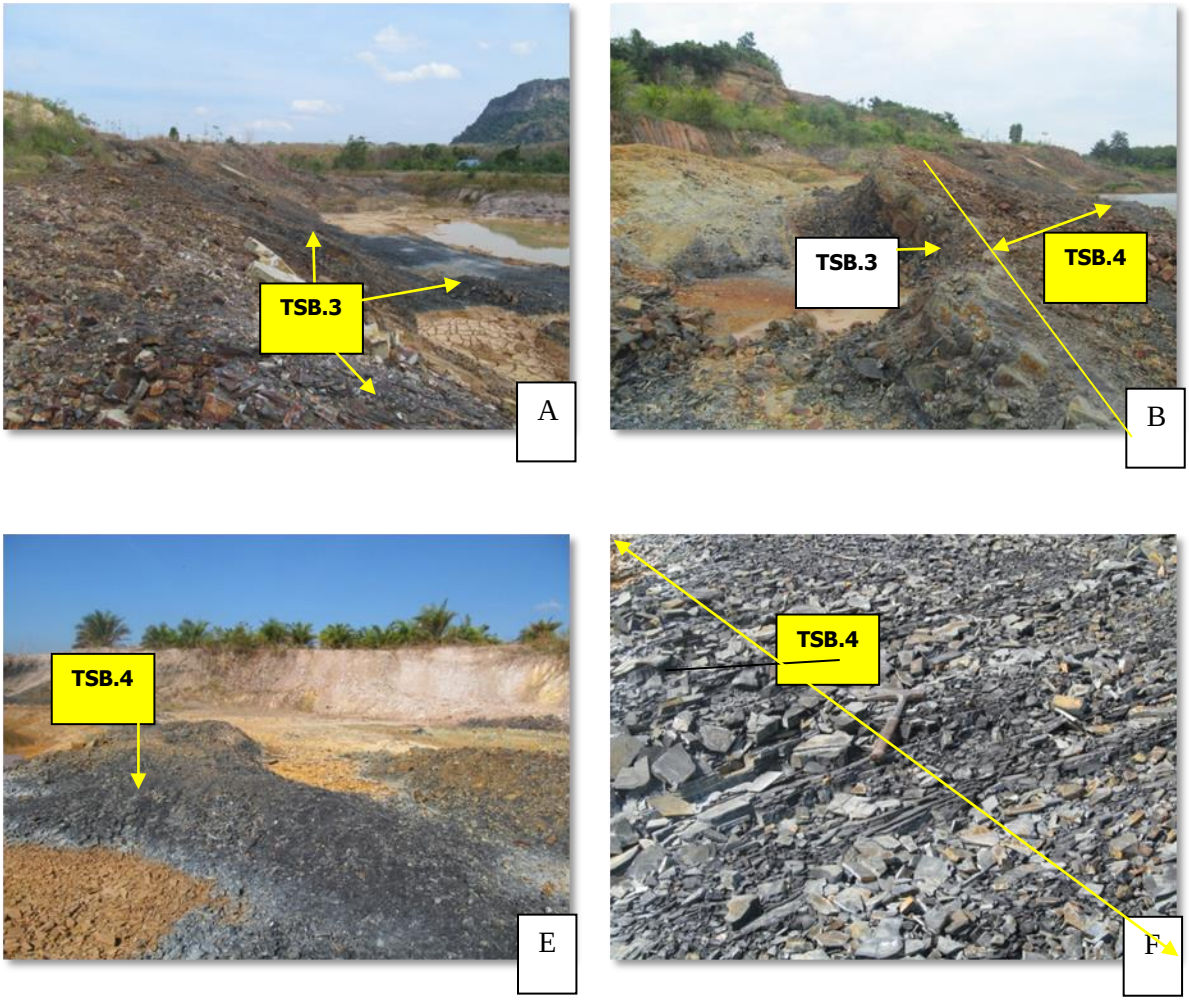

Figure 80: Photographs showing lithologies and boundaries of Unit TSB.4 of the Ordovician-Silurian-Devonian sequence exposed in the Ban Pa Samet-Ban Thung Samet area, La Ngu District, Satun Province, Peninsular Thailand along line B-B′. A-F: Various views of siltstone to mudstone sequence with cherty mudstones in the topmost part. (After Meesook, 2014)

Fauna Assemblages

Faunas of TSA Section (along line A-A′)

Faunas of TSA section along line A-A′ are found from the lowest unit (TSA.1/1) containing some nautiloids in the Ordovician Rung Nok Formation. A few poorly preserved nautiloids are also found in stylolitic limestones of the overlying Pa Kae Formation. Whilst the mudstones and marly mudstones is grading up from the Pa Kae Formation, abundant trace fossils i.e., *Thalassinoides* sp. occur in such rocks indicating transgression of sea water. Accordingly, fine sediments were deposited in deeper water giving rise to the deposition of dark grey to black, pyritic mudstones rich in fossils of graptolites in the Silurian Period. The Silurian-Devonian sequence is represented by the coarsening and fining upward sequences as indicated by the presence of rock types from mudstone-siltstone-sandstone-siltstone-mudstone-cherty mudstone-dominated sequence. Some genera of graptolites and trilobites are present in this sequence. In the upper part

tentaculitids are abundant in mudstones and cherty mudstones. Details of faunas found in each unit are described as follows:

Faunas of Unit TSA.2

Faunas of TSA.2 contain the trace fossil *Thalassinoides* isp. found in marly mudstones rich in pyrite nodules (Figure 81).

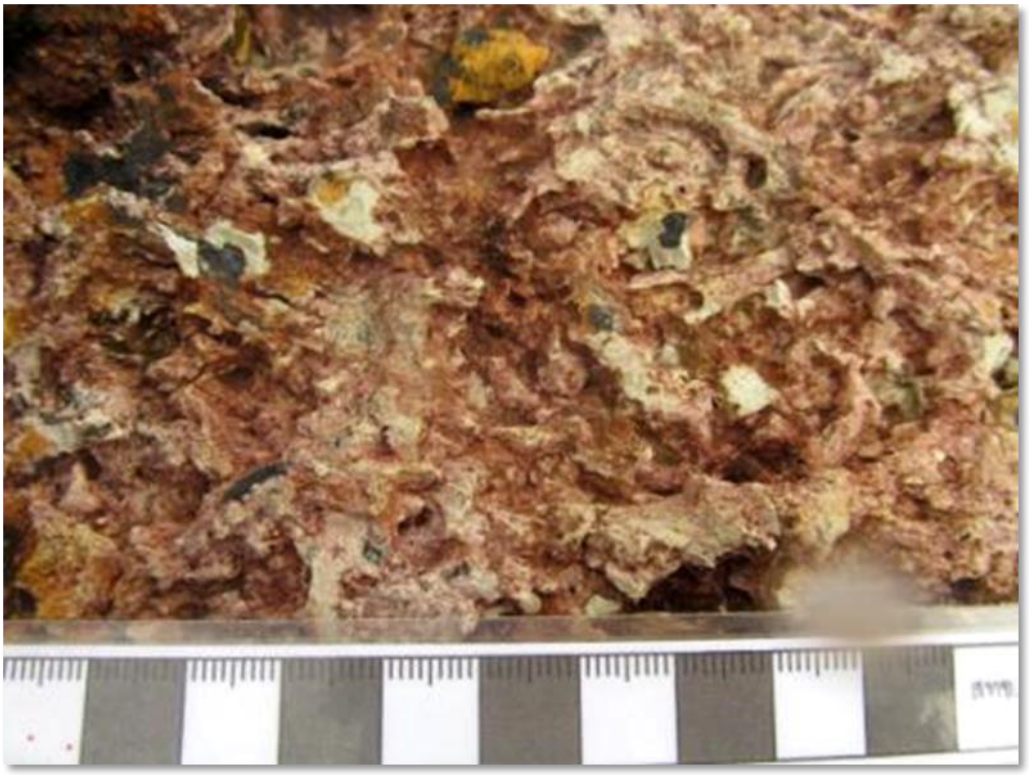

Figure 81: A-B: Photographs showing trace fossils *Thalassinoides* isp. collected from Unit TSA.2 along line A-A′ located in the Ban Pa Samet-Ban Thung Samet area, La Ngu District, Satun Province. (After Meesook, 2014)

Faunas of Unit TSA.3

Faunas of TSA.3 contain the graptolite *Diplograptus* sp. This graptolite is abundant in dark grey to black mudstones of the Pa Samed Formation (Figure 82).

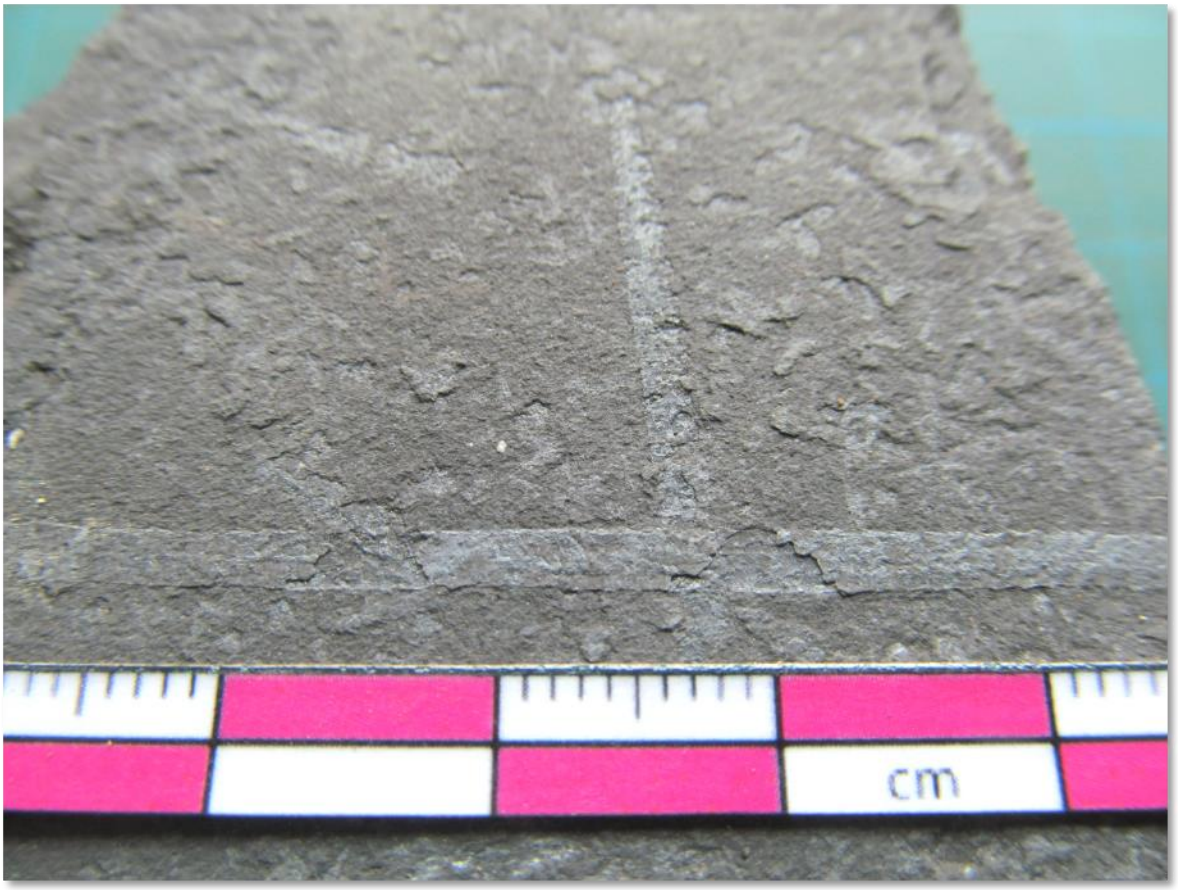

Figure 82: Photographs showing fossils of the graptolite *Diplograptus* sp. collected from Unit TSA.3 along line A-A′ located in the Ban Pa Samet-Ban Thung Samet area, La Ngu District, Satun Province. (After Meesook, 2014)

Faunas of Unit TSA.4

Fossils are not abundant in this unit. Only very poorly preserved trace fossil *Thalassinoides* sp. are found locally on the sandstone bed of Unit TSA.4.

Faunas of Unit TSA.5

Faunas of Unit TSA.5 contain the trilobite *Dalmanitina* sp. (cephalon) (Figure 83A-C), the *Dalmanitina* sp. (pygidium) (Figure 83D-F), and the graptolites *Normalograptus* sp. (Figure 84A-B), and *Diplograptus* sp. (Figure 84 C-F).

Figure 83: Photographs showing fossils of trilobites collected from Unit TSA.5 along line A-A′ located in the Ban Pa Samet-Ban Thung Samet area, La Ngu District, Satun Province. A-C: the trilobite *Dalmanitina* sp. (cephalon); D-F: the trilobite *Dalmanitina* sp. (pygidium). (After Meesook, 2014)

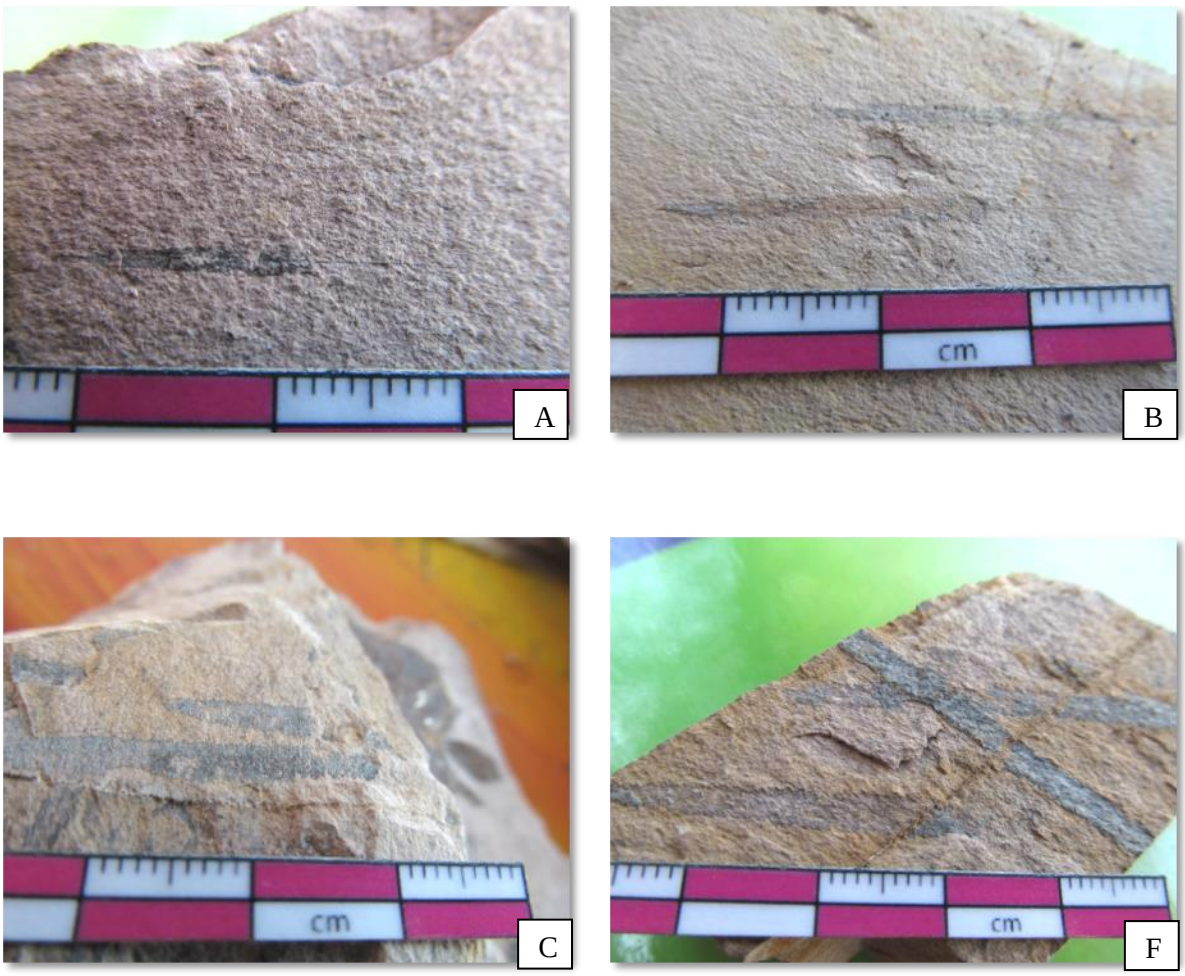

Figure 84: Photographs showing fossils of graptolites collected from Unit TSA.5 along line A-A′ located in the Ban Pa Samet-Ban Thung Samet area, La Ngu District, Satun Province. A-B: the graptolite *Normalograptus* sp. C-F: the graptolite *Diplograptus* sp. (After Meesook, 2014)

Faunas of Unit TSA.6

Faunas of Unit TSA.6 contain the trace fossil *Thalassinoides* isp. This fauna is usually found on the grey sandstone bed of the Silurian-Devonian Pa Samed Formation (Figure 85).

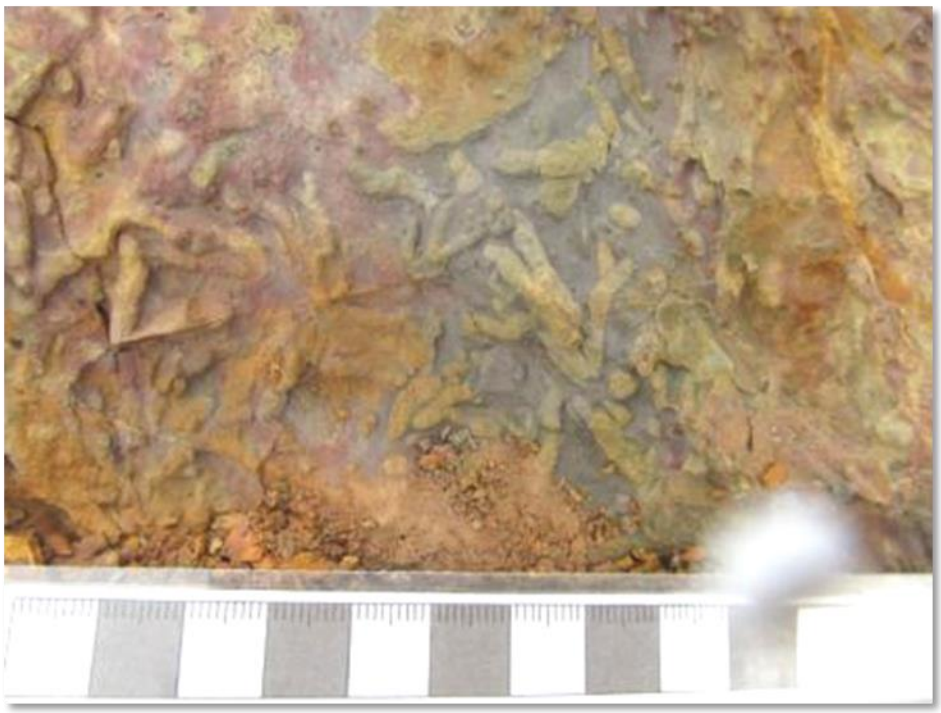

Figure 85: Photographs showing the trace fossil *Thalassinoides* isp. collected from Unit TSA.6 along line A-A′ located in the Ban Pa Samet-Ban Thung Samet area, La Ngu District, Satun Province. (After Meesook, 2014)

4.2.7 Faunas of Unit TSA.7

Faunas of Unit TSA.7 contain the graptolites *Normalograptus* sp. (Figure 86A) and *Diplograptus* sp. (Figure 86 B), and tentaculitids (Figure 87). These faunas are usually found in dark grey to grey siltstones and mudstones of the Silurian-Devonian Pa Samed Formation

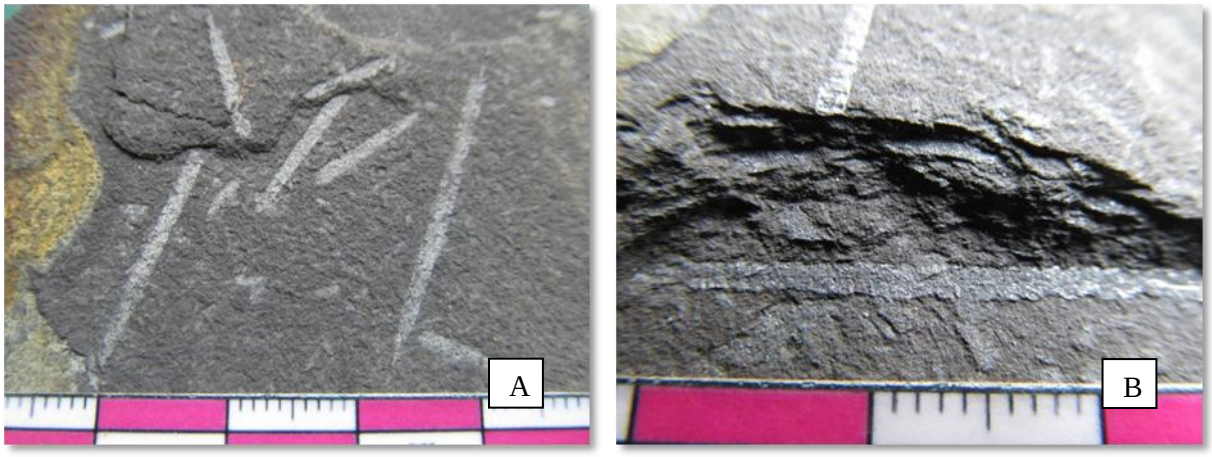

Figure 86: Photographs showing fossils of graptolites collected from Unit TSA.7 along line A-A′ located in the Ban Pa Samet-Ban Thung Samet area, La Ngu District, Satun Province. A: *Normalograptus* sp., B: *Diplograptus* sp. (After Meesook, 2014)

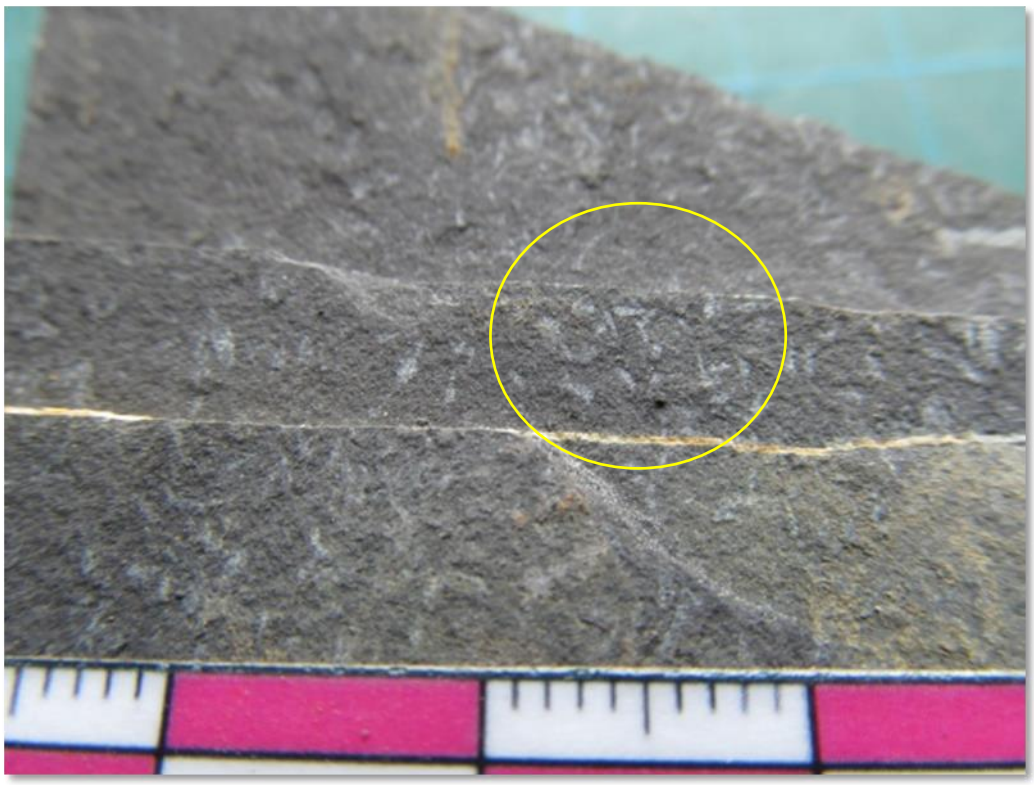

Figure 87: A-D: Photographs showing fossils of tentaculitids collected from Unit TSA.7 along line A-A′ located in the Ban Pa Samet-Ban Thung Samet area, La Ngu District, Satun Province. (After Meesook, 2014)

Faunas of TSB Section along line B-B′

Faunas of TSB section along line B-B′ are found from the lowest unit (TSB.1) containing abundant trace fossils i.e., *Thalassinoides* sp. This indicates transgression of sea water. This sequence is similar to that of TSA section. Accordingly, fine sediments were deposited in deeper water giving rise to the deposition of dark grey to black, pyritic mudstones rich in fossils of graptolites in the Silurian Period. The Silurian-Devonian sequence is represented by the coarsening and fining upward sequences as indicated by the presence of rock types from mudstone-siltstone-sandstone-siltstone-mudstone-cherty mudstone-dominated sequence. Some genera of graptolites and trilobites are present in this sequence. In the upper part tentaculitids are abundant in mudstones and cherty mudstones. Details of faunas found in each unit of TSB section are described as follows:

Faunas of Unit TSB.1

Faunas of Unit TSB.1 contain the trace fossil *Thalassinoides* isp. (Figure 88) This fauna is abundant in yellowish white marly mudstones having pyritic nodules.

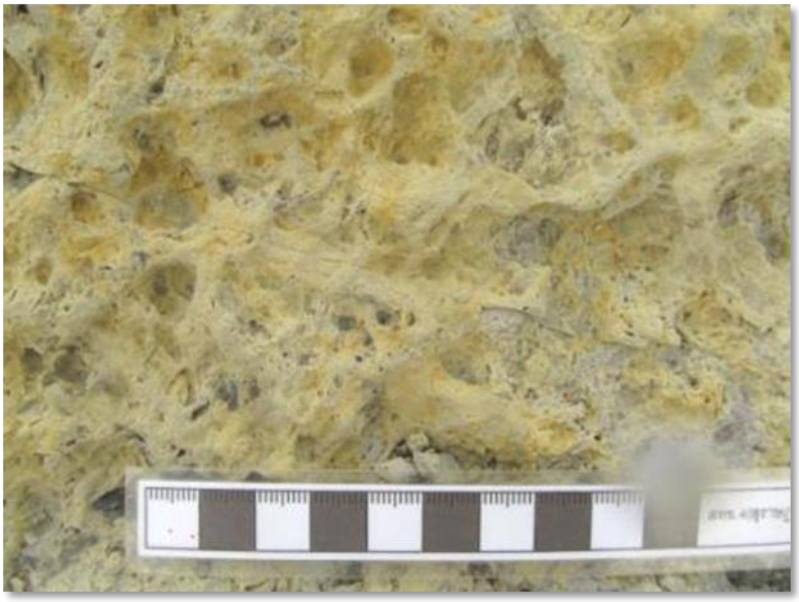

Figure 88: Photographs showing the trace fossil *Thalassinoides* isp. collected from Unit TSB.1 along line B-B′ located in the Ban Pa Samet-Ban Thung Samet area, La Ngu District, Satun Province. (After Meesook, 2014)

Faunas of Unit TSB.2

Faunas of Unit TSB.2 contain the graptolite *Diplograptus* sp. (Figure 89). This fauna is abundant in dark grey to black mudstones and siltstones of the Silurian-Devonian Pa Samed Formation.

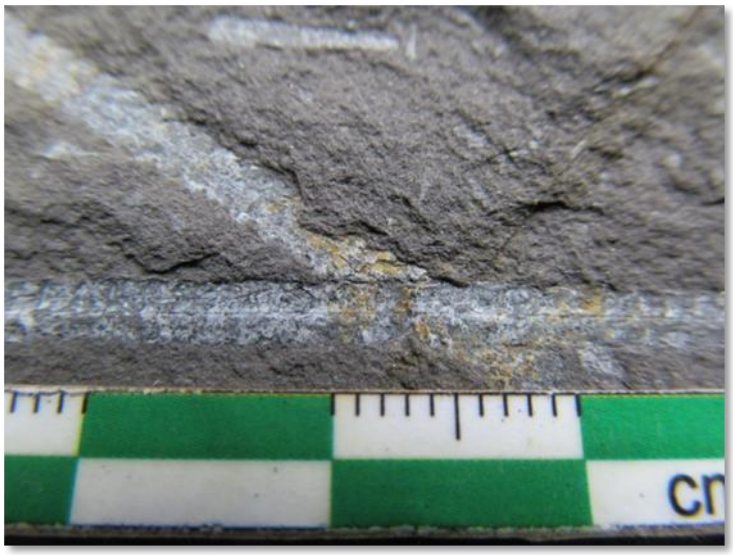

Figure 89: Photographs showing fossils of the graptolite *Diplograptus* sp. collected from Unit TSB.2 along line B-B′ located in the Ban Pa Samet-Ban Thung Samet area, La Ngu District, Satun Province (Photographers: A. Meesook, R. Somsat, and J. Nedphab). (After Meesook, 2014)

Faunas of Unit TSB.3

Faunas of Unit TSB.3 contain the trace fossil *Thalassinoides* isp. (Figure 90). This fauna is usually found in dark grey to grey sandstones of the Silurian-Devonian Pa Samed Formation.

Figure 90: Photographs showing the trace fossil *Thalassinoides* isp. collected from Unit TSB.3 along line B-B′ located in the Ban Pa Samet-Ban Thung Samet area, La Ngu District, Satun Province (After Meesook, 2014)

Faunas of Unit TSB.4

Faunas of Unit TSB.4 contain the graptolites *Monograptus* sp. (Figure 91), *Diplograptus* sp. (Figure 92), *Normalograptus* sp. (Figure 93), *Cyrtograptus* sp. (Figure 94), and the tentaculitids (Figure 95). These faunas are abundant in dark grey to black siltstones, mudstones and cherty mudstones of the Silurian-Devonian Pa Samed Formation.

Figure 91: Photograph showing fossils of the graptolite *Monograptus* sp. collected from the lower part of Unit TSB. 4 along line B-B′ located in the Ban Pa Samet-Ban Thung Samet area, La Ngu District, Satun Province. (After Meesook, 2014)

Figure 92: Photographs showing the graptolite *Diplograptus* sp. collected from the lower-middle part of Unit TSB.4 along line B-B′ located in the Ban Pa Samet-Ban Thung Samet area, La Ngu District, Satun Province. (After Meesook, 2014)

Figure 93: Photographs showing the graptolite *Normalograptus* sp. collected from the middle part of Unit TSB.4 along line B-B′ located in the Ban Pa Samet-Ban Thung Samet area, La Ngu District, Satun Province. (After Meesook, 2014)

Figure 94: Photographs showing the graptolite *Cyrtograptus* sp. collected from the upper part of Unit TSB.4 along line B-B′ located in the Ban Pa Samet-Ban Thung Samet area, La Ngu District, Satun Province. (After Meesook, 2014)

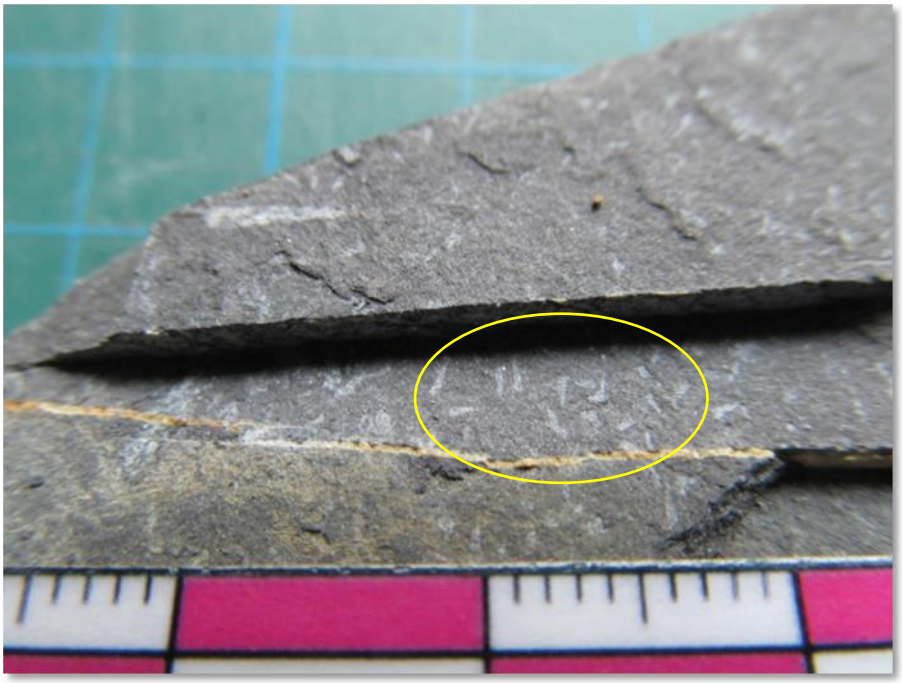

Figure 95: Photographs showing fossils of tentaculitids (in yellow circle) collected from the upper part of Unit TSB. 4 along line B-B′ located in the Ban Pa Samet-Ban Thung Samet area, La Ngu District, Satun Province. (After Meesook, 2014)

According to Meesook (2014), this concluded the Ordovician-Silurian-Devonian sequence of Peninsular Thailand is well exposed at a quarry in the Ban Pa Samet-Ban Thung Samet area, La Ngu District, Satun Province. The Ordovician-Silurian-Devonian

sequence in this area consists of a sequence of the Rung Nok, Pa Kae and Pa Samed Formations. This rock section represents coarsening and fining upward sequence as indicated by the presence of dark grey mudstone-siltstone-sandstone-siltstone-cherty mudstone succession. Based on faunal assemblages of nautiloids, trilobites, graptolites, and tentaculitids, the rocks in this area should be assigned as Ordovician-Silurian-Devonian in age. The presence of *Thalassionoides* isp. in two layers of yellowish white marly mudstones indicates two short-time span transgression of sea water into the basin. This was followed by the deeper water environment as shown by the presence of various genera of graptolites and tentaculitids. Based on mentioned lithostratigraphy and faunal assemblages, the rocks in this area are interpreted as having been deposited conformably as a condensed sequence. Moreover, the rocks and fossils found in the Ban Pa Samet-Ban Thung Samet area are very important in terms of condensed sequence, fluctuation of sea level, and faunal assemblages. Accordingly, this area should be conserved for more detailed study and be promoted as a fossil site for academic references and geo-tourism.

5 LITHOSTRATIGRAPHIC CORRELATION

The Timah Tasoh Formation is age-equivalent to the Pa Samed Formation, which is also composed of black tentaculitid-bearing mudstone. Fossils also indicate an earliest Emsian age for the Pa Samed Formation (Boucot et al., 1999; Agematsu et al., 2006). The faunal assemblages of the Timah Tasoh Formation is similar to Pa Samed Formation and includes tentaculitoids such as *Nowakia acuaria*, *Styliolina*, *Metastyliolina*, the graptolite *Monograptus* and the trilobite *Plagiolaria* (Meor and Lee, 2005; Meor et al., 2013a).

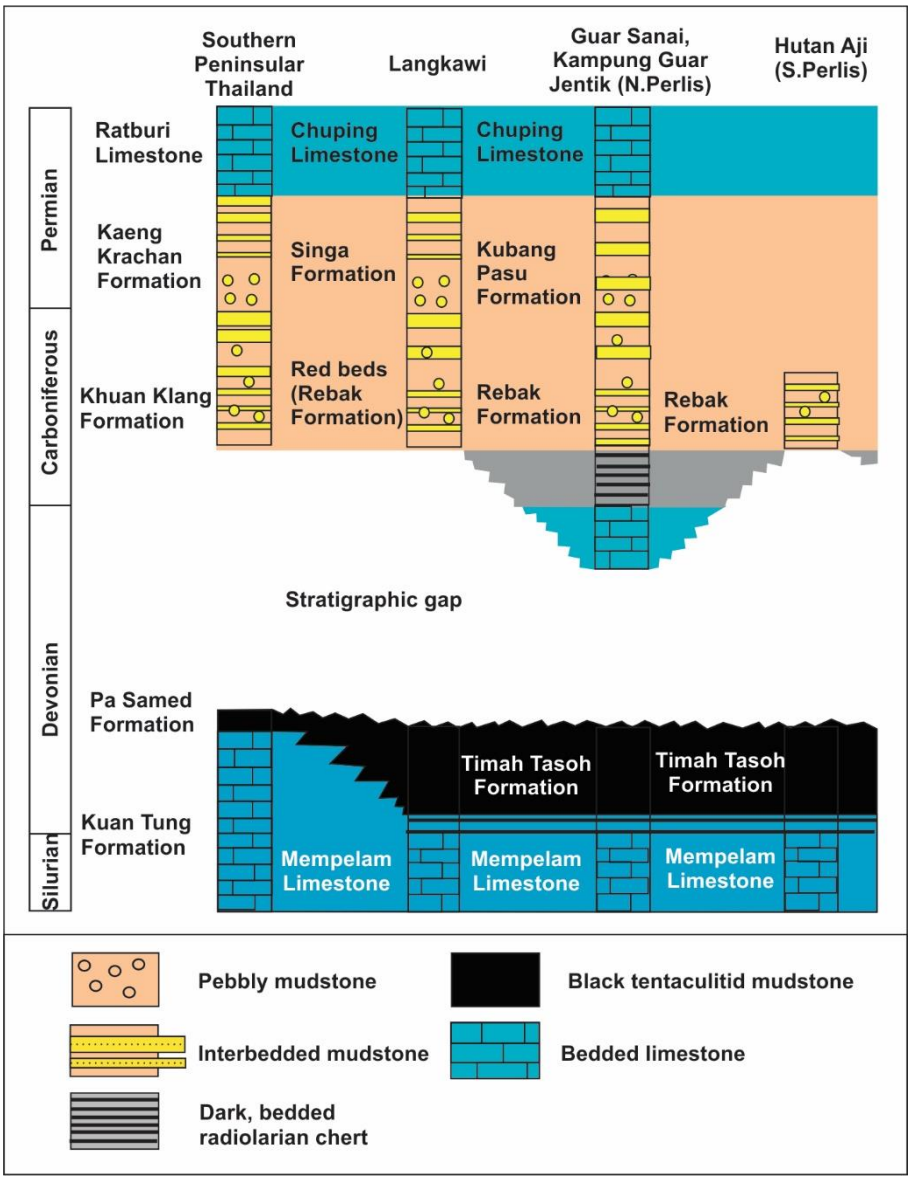

Figure 96: Stratigraphic correlation of the Timah Tasoh Formation to the Pa Samed Formation (Edited from Meor Hakif Amir Hassan *et al*., 2014)

The Lower Devonian dacryoconarid beds have been reported as Tentaculite-beds in several parts of Thailand, Malaysia, Myanmar, and Yunnan in southwestern China (Kobayashi & Hamada, 1968). Meor Hakif and Lee (2005) discovered Tentaculite bearing black mudstone from Guar Sanai, Kampung Guar Jentik, Perlis.

The outcrops of Guar Sanai have enabled us to resolve the transitional sequence between the Setul Limestone and Kubang Pasu Formation, and have also allowed us to correlate these rocks with those in southern Thailand. A sequence similar to the Timah Tasoh has been reported by Wongwanich et al. (1990), in Satun Province, where the unit is called the Pa Samed Formation.

The Timah Tasoh Formation is defined as the mainly black shale sequence conformably overlying the Upper Setul Limestone, and underlying the Kubang Pasu Formation. The formation is early Devonian in age. The study area is a hilly ridge known locally as Guar Sanai, Kampung Guar Jentik, Beseri District, Perlis and separated into three small hills, here referred to as Hill A, B and C from south to north. The Timah Tasoh Formation can be separated into smaller informal units as follows:

i) Unit 1 (oldest)

The lithology is mainly argillaceous, predominantly black carbonaceous shale, with some brown coloured beds. It contains a dacryoconarid-monogfaptid-*Plagiolaria* fossil assemblage, giving an early Devonian.

ii) Unit 2

The lithology consists of light coloured argillo-arenites, predominantly arenaceous, with thick, flat bottomed, fine grained sandstone beds. Shales· make up about 15% of the unit, and are thin bedded.

Unit 1 can be biostratigraphically and lithostratigraphically correlated to Member 1 of the Pa Samed Formation, whose black shales also contain monograptids, *Nowakia, Styliolina* and *Plagiolaria*. Unit 2 is similar to Member 2 of Pa Samed Formation, which is also composed of white sandstones and shales.

According to Wongwanich and Boucot in Ridd et al., (2011), the Pa Samed Formation is redefined here from Wongwanich et al, (1990) as that 167 m thick sequence of dominantly siliciclastics (sandstone) with minor grey argillaceous limestone and black carbonaceous shales outcropping along the Langu-Thung Wa Road between 9.6 and 9.8 km from Amphoe Langu. It conformably overlies the Kuan Tung Formation. In the type location of the Pa Samed Formation occurs over a stike lengths of about 2 km and extends to the Pa Kae Valley east of Amphoe Thung Wa. In this section, it can be divided into six members.

Member One consists of 25 m of brown weathering black, pyritic carbonaceous shale. Small horizontal bioturbations(?) are common. Fossils include trilobites, brachiopods, cephalopods, graptolites, small nautiloids and tentaculitids. Abundant tentaculitids occur at 10 and 19 m above the base of the succession. Fossils from 10 m above the base of the member have been identified as species of *Nowakia, Metastyliolina, Styliolina, Echinocoeliopsis, Plagiolaria, Echinocoelia* and *Monograptus* and suggest an Early Devonian age by DMR palaeintologis. Moreover, Agematsu et al., (2006) confirmed only *Nowakia acuaria* in the lowermost part of this unit which was indicated in Emsian age (Lower Devonian). This sequence is interpreted as deposited in a deep-water euxinic marine basin (Wongwanich and Boucot in Ridd et al., 2011).

Based on the lithology, stratigraphy and fossil assemblage of Lower Devonian, the Member One of Pa Samed Formation can be correlated to the upper part of Timah Tasok Formation.

6. DISCUSSION AND CONCLUSION

- The Early Dvonian Timah Tasoh Formation comprises predominantly black carbonaceous shale and mudstone, with minor thin intercalated lenses and beds of limestone. The rocks contain a rich Dacryoconarid-*Monograptus*-*Plagiolaria* fossil assemblages.
- It can devided into two subunits.
- Unit 1 comprises predominantly black carbonaceous shale, with some brown coloured beds. It contains a dacryoconarid-monogfaptid-*Plagiolaria* fossils assemblage of Early Devonian age. Unit 2 comprises light coloured argillo-arenites, predominantly arenaceous, with thick, flat bottomed, fine grained sandstone beds with subordinate thinly-bedded shales
- In this report the term Rebak Formation is used to replaced the term Kubang Pasu Formation for the Carboniferous rocks in Perlis.
- The Timah Tasoh Formation conformably overlies the Silurian Setul Formation and underlies the Carboniferous Rebak Formation.
- The Early Devonian to Early Carboniferous succession of the Pa Samed Formation is dominantly siliciclastics (sandstone) with minor grey argillaceous limestone and black carbonaceous shales.
- The Pa Samed Formation can be divided into six members.
- Type location of the Pa Samed Formation conformably overlies the Kuan Tung Formation (Wongwanich et al., 1990). In Satun Province, Tansuwan et al., (1985) reported Lower Carboniferous *Posidonomya* sp. from Khuan Klang Formation, 120 m thick sequence of reddish-brown weathering light grey to white shale intercalated with sandstone, siltstone and chert, apparently lying conformably above the Pa Samed Formation. The Khuan Klang formation is possibly age-equivalent to the upper part of the Pa Samed Formation. The Malaysian-Thai Working Group (2012), the Khuan Klang Formation is continuously conformable with the underlying Pa Samed Formation in the vicinity of the northeastern part of Khuan Sung, Muang Satun District of Satun Province. The unit is grading gradually from dark grey, thin-bedded, carbonaceous mudstones containing abundant *Tentaculites* with, maroon, porous, hard pans, and bioturbated mudstones of the Pa Samed Formation. The sequence is grading to pale grey to light brown, powdered, thick-bedded mudstones and claystones of the Khuan Klang Formation. This indicates the change in depositional environment from the deeper to the shallower.
- The Pa Samed Formation consists of abundant fossils reported by several previous studies. Fossils are tentaculate, trilobite, brachiopod, and nautiloid. The age of this fossil assemblage indicated Lower Devonian to Lower Carboniferous.
- Member One of the Pa Samed Formation comprises black, pyritic carbonaceous shale with fossils of *Nowakia acuaria, Metastyliolina, Styliolina, Echinocoeliopsis, Plagiolaria, Echinocoelia* and *Monograptus* that indicate an Early Devonian age. Member Two comprises thick-bedded to massive, grey feldspathic sandstone and grey shale grading upwards to red feldspathic sandstone and red shales with graded bedding and cross lamination of incomplete Bouma sequences, fine-medium grain sandstone interbedded with shale and light grey feldspathic sandstone with scattered well-rounded pebbles of quartz, quartzite, chert and slate on the top. Abundant goniatites occur in this member.

- The Emsian dacryoconarid-rich bed (Member One of Pa Samed Formation) as representing the deepest deposits. Above these, bed deposited in shallower water with channels containing pebbly sandstones (Member Two) occur, followed by deeper-water laminated shale and siltstones (Member Three). The pelagic, siliciclastic (Silurian) Wang Tong Formation, the deeper water carbonate (Silurian-Devonian) Kuan Tung Formation and the pelagic, slope of deeper-water (Devonian-Carboniferous) Pa Samed Formation were assigned to the Thong Pha Phum Group by Wongwanich et al., (2004), a unite whose type locality is in Kanchanaburi Province.
- Based on lihology and fossil assemblages, it is clear that the Timah Tasoh Formation is correlateble with Member One and Member Two in the lower part of the Pa Samed Formation.
- On the Malaysian side, the stratigraphy of the Devonian rocks in Langkawi and Perlis needs to be revised to solve the problems especially on the nomenclatures used for the small and unamapable rock units in those areas.

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