# CHAPTER II

# LITERATURE REVIEW

This chapter covers the fundamentals of ostracods, conodonts, tentaculitoids including their morphology and ecology, and offers a comprehensive overview of the Paleozoic geology in Satun Province, emphasizing the Silurian-Devonian rock formations. This information provides an essential foundation for understanding the geological context in the subsequent parts of the thesis.

## 2.1 Geology of Satun Province, Southern Thailand

Exposed rocks in Satun Province (Figure 2.1) according to geological map from Department of Mineral Resources (2013) range from Cambrian to Carboniferous-Permian and covered by Quaternary sediments with some Triassic granite intrusions. Most of the Cambrian rocks are exposed on Tarutao Island (Ko Tarutao), covering more than half of the area. Ordovician rocks are exposed in the northeast of Tarutao Island and in the north and east of mainland Satun. Silurian and Devonian rocks are difficult to distinguish precisely, so they are often grouped together as Silurian-Devonian rocks and are mostly exposed on the mainland of Satun. Carboniferous-Permian rocks are also grouped together and exposed in the lower to middle parts of mainland Satun. Quaternary sediments cover the middle and western parts of the mainland. Triassic granite is exposed on Ra Wi Island, Adang Island, and the eastern part of mainland Satun.

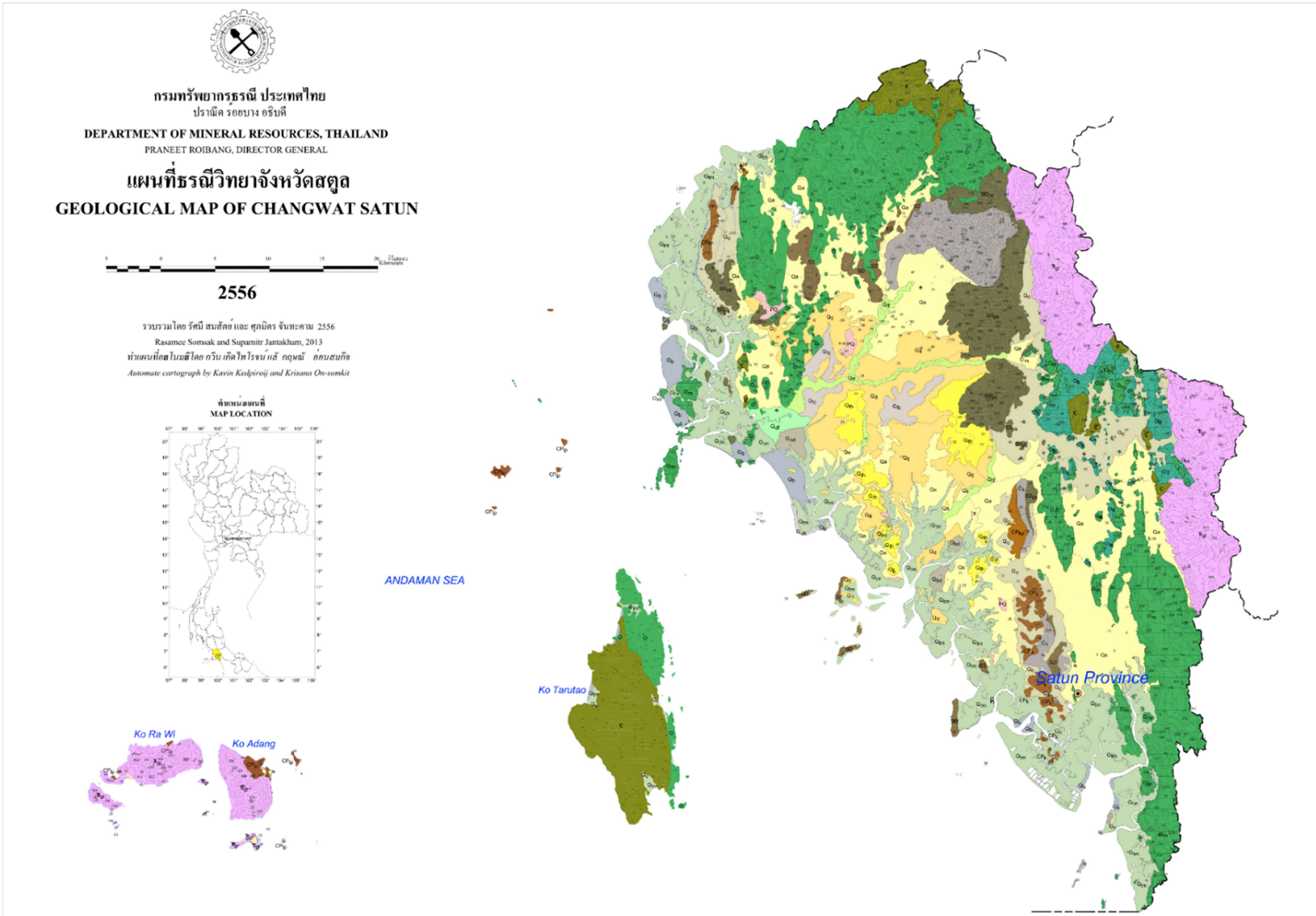


Figure 2.1 Geological map of Satun Province from Department of Mineral Resources (2013).

## EXPLANATION

| | SEDIMENT, SEDIMENTARY AND METAMORPHIC ROCKS | FORMATION/GROUP | PERIOD | AGE (my.) |
|---|---|---|---|---|
| Qa | Alluvial deposits : gravel, sand, silt and clay. | | | |
| Qb | Beach sand formation : sand, fine to coarse, well sorted, subrounded, light brown or light grey, quartz, loose. | | | |
| Qbd | Former beach ridges and dunes. (above high water spring tide) : Sand, fine-medium grained, well sorted. | | | |
| Qdf | Deltaic-flood plain : Fine sand stratied with clay and gravels. | | | |
| Qfc | Abandoned channels : Fine sand, silt and clay overlies stiff mottle clay. | | | |
| Qff | Flood plain : Fine grained sand and silt overlies the gravels. | | | |
| Qtm | Tidal flat vegetated with mangrove (In between high-low water spring tide) : peat, platy clay, fine sand, silty clay and sandy clay of intertidal flat. | | | |
| Qua | Accretionary plain, tidal delta and bar deposits. (Below-high water spring tide.) : Sand, silty sand, fine-medium grain, with well developed bedforms. | | QUATERNARY | 0.01-1.6 |
| Qtl | Lower terraces and undulating upland : elevation from 10-20 meters in the mainland, and 1-5 meters above mean sea levels in the islands : clayey sand, mottle clay, laterite and gravels overlain the weathered surface of bed rock. | | | |
| Qth | Higher terrace : well dissected surface with elevation from 20-50 maters above sea level. Laterite, gravels and rock fragments, thickness depends on the weathered surface of bed rock. | | | |
| Qc | Colluvial deposits : fine sand and clay, red, yellow, light brown and light gray, abundant mottled, loose, with some rock fragments and relic structure, partly lateric or lateritic layer. | | | |
| PQ | Erosion surface of bed rocks : weathered bed rock in situ or bed rock with Quaternary sediment overlains less than 20 meters. | | | |
| P | Limestone : light gray, massive, fossils of brachiopods, corals and crinoids. | Ratburi Gp. | PERMIAN | 245-286 |
| CPkp | Mudstone : dark gray, thin bedded to massive, with silt lamination, weathering to reddish brown, interbedded with siltstone; lithic sandstone and pebbly mudstone; sandstone, fine-to medium-grained, thick bedded, moderately sorted, subrounded, pebbles composed of quartz, sandstone, chert and granite. | KHAO PHRA Fm., KAENG KRACHAN Gp. | | |
| CPlp | Mudstone : dense, black, thin bedded, well bedded, with silt lamination, intercalated with lithic sandstone; quartzitic sandstone and pebbly mudstone, black, reddish brown and gray, thin bedded to massive. | LAEM MAI PHAI Fm., KAENG KRACHAN Gp. | PERMIAN to CARBONIFEROUS | 245-360 |
| CPk | Mudstone, shale, siltstone, pebbly greywacke and pebbly mudstone : dark gray, thick-bedded with lamination and lens of siltstone, fine-to coarse- grained, poorly sorted, moderatly rounded. | KAENG KRACHAN Gp. | | |
| Ck | Mudstone, shale, sandstone and pebbly mudstone : white, light gray, dark gray, brown, reddish brown, yellowish brown, thin to thick-bedded, fine-to coarse-grained, poorly sorted, moderatly rounded, well cementation, with abundant bivalves, trilobites, cephalopods, brachiopods, crinoids and gastropods. | KUAN KLANG Fm. | CARBONIFEROUS | 286-360 |
| SDps | Siliceous mudstone : dark gray, greenish gray, thin to medium bedded, well bedded, interbedded with lilthic sandstone, siltstone and chert, dark gray, grayish brown and reddish brown. | PA SAMED Fm. | DEVONIAN to SILURIAN | 360-445 |
| SD | Siliceous mudstone, chert, shale, sandstone and pebbly mudstone : gray, light brown, dark gray, brown, reddish purple and greenish gray, thin-to medium-bedded; very coarse-grained sandstone, poorly sorted, moderatly rounded, well cementation, pebbles consist of sandstone and quartzite with abundant tentaculites, graptolites, trilobites, brachiopods, crinoids and cephalopods. | | | |
| Orn | Limestone, argillaceous limestone : gray to dark gray, thick bedded to massive, with argillaceous laminations and fossil of nautiloid. | RUNG NOK Fm., THUNG SONG Gp. | | |
| Olt | Shale, calcareous shale : reddish brown, brown and yellowish brown, thin bedded, interbedded with siltstone, lithic sandstone, fine-grained, well sorted, with limestone lenses at top. | LAE TONG Fm., THUNG SONG Gp. | ORDOVICIAN | 445-490 |
| O | Argillaceous limestone, limestone : grey and dark grey, and dolomitic limestone with abundant fossils. | THUNG SONG Gp. | | |
| Є | Sandstone, siltstone, shale and local quartzite : light brown, light gray, reddish brown yellow, thin-to thick-bed; sandstone showing cross-bedding, ripple cross-bedding, lamination and slump structure, with trilobite. | TARUTAO Gp. | CAMBRAIN | 490-540 |
| | **IGNEOUS ROCKS** | | **PERIOD** | |
| $TR_{gr}$ | Granite : biotite-muscovite granite, aplite and pegmatite, fine to coarse crystal, porphyritic texture, with feldspar phenocryst, euhedral crystal. | | TRIASSIC | 210-245 |

Figure 2.2 Explanation of rock units in Satun Province from Department of Mineral Resources (2013).

The lithology of rocks in Satun Province, as studied here, is based on the works of Suphakdee (2017), who summarized the lithology and fauna assemblage of the Pa Samet area (Ban Thung Samed). This includes the works of Bunopas (1981) for the Tarutao Group (Cambrian-Ordovician), Wongwanich (1990) and Wongwanich et al. (1990) for establishing the Thung Song Group (Ordovician) and Thong Pha Phum Group (Ordovician-Carboniferous) respectively, and Chaodumrong et al. (2004, 2007) for the Kaeng Krachan Group. The information of Quaternary sediments is adopted from Department of Mineral Resources (2013).

### 2.1.1 Tarutao Group

This group's type section, situated on Tarutao Island composed of the sequences of siliciclastic rocks including fine-grained sandstone, siltstone, shale, minor limestone, conglomerate, and minor volcaniclastics (Department of Mineral Resources, 2018). Notably, this group contains fossils of brachiopod, conodont and trilobites such as *Pagodiathaiensis*, "*Eosaukia*" *buravasi* (Kobayashi, 1957), and *Coreanocephalus phanulatus* (Kobayashi, 1957) which are typically late Cambrian species.

### 2.1.2 Thung Song Group

Thung Song Group which overlies Tarutao Group is predominant by limestone with some siliciclastic which includes bedded limestone, nodular limestone, cross-bedded limestone, calcisiltite, calcarenite, graptolitic shale but most distinguish of this group is red stromatolitic limestone which is the topmost of the sequence. The fauna in this group is typically carbonate-platform fauna such as gastropods, brachiopods, bivalves, sponges, trilobites, conodonts, nautiloids, graptolites and stromatolites. Thung Song Group is mostly Ordovician (Wongwanich, 1990; 2001).

### 2.1.3 Thong Pha Phum Group

The Thong Pha Phum Group was renamed by Bunopas (1981) from the Tanaosi Group of Javanaphet (1969). The type section of this group is exposed along the banks of Huai Thong Pha Phum in Amphoe Thong Pha Phum, Kanchanaburi Province (Bunopas, 1981). In the Satun area, this group was found and redefined by

Wongwanich et al. (1990) in the area between kilometers 9-11 on the side of La-Ngu to Thung Wa Road, known as Ban Pa Samed and Ban Pa Kae. This area (km 9–11) has been named Ban Pa Samed by later researchers, is in fact located at Ban Thung Samed village. Ban Pa Samed village also exists but is located further south of Wongwanich et al, (1990) studied area. The Thong Pha Phum Group consists of three formations: Wang Tong Formation, Kuan Tung Formation, and Pa Samed Formation (Wongwanich 2001; Wongwanich et al., 2002; Wongwanich and Boucot, 2011).

**2.1.3.1 Wang Tong Formation**

Wang Tong Formation has 50-110 meters thick and can be recognized by graptolitic black shale to dark grey siltstone in the lowermost part and changes into well bedded dark grey-brownish-grey muddy siltstone and very fine grained feldspathic sandstone with a lenticular layer of black graptolite-rich shale in the middle part of formation and the top is consists of thick sequence of grey, well bedded chert with black shale. The fauna of this formation consists of brachiopods and trilobites in the middle part and very abundant graptolites in the top of the Formation (Wongwanich et al., 1990). In sandstone beds of the middle parts contains Hirnantian (Latest Ordovician) brachiopod-trilobite fauna consisting of *Hirnantia sagittifera* (McCoy, 1851), *Onnia*? *Yichangensis* Zeng in Wang 1983, *Aegiromena planissima* (Reed, 1915), *Mirorthis mira* Zeng in Wang 1983, *Cliftonia* sp., *Paramalomena* sp., *Eospirigerina* sp., and *Mucronaspis mucronata* Brongniart (Cocks and Fortey, 1997). Beneath the sandstone beds found trilobites, *Mucranaspis* sp. and *Normalograptus medius*, *N. normalis*, *N. modestus* and *Pseudoclimacograptus* sp., *Parakidinograptus acuminatus*. The graptolite in the top of the Formation are identified as *Normalograptus persculptus* (Wongwanich et al., 1990) and *N. pseudovenustus pseudovenustus* Legrand, 1986 which represents the Uppermost Ordovician (Agematsu et al., 2006b). Therefore, Wang Tong Formation ranges from Late Ordovician to Early Silurian.

#### 2.1.3.2 Kuan Tung Formation

Kuan Tung Formation is approximately 105 meters thick and predominant by limestone. The lower member of this unit is massively bedded, grey calcisiltites with thin argillaceous layers. The middle member consists of calcisiltites that range in color from pink to red and grey with fossils and minor calcarenite with some chert nodule. The upper unit is red, well-bedded micrite, interbedded with thin reddish brown argillaceous layers and small algal polygons of stromatolite (Wongwanich et al., 1990). Based on Emsian trilobites in the lower part, *Reedops megaphacos, R. seleniomma, Decoroproetus* sp., *Cornuproetus (Sculptoproetus) sculptus* and *Platyscutellum* sp. (Fortey, 1989) and Early Devonian conodonts in the upper part, *Pandorinella steinhornensis steinhornensis* Ziegler, 1956, *Polygnathus labiosus mawsonae* Long and Burrett, 1989 and *Pseudooneotodus kuangtungensis* Long and Burrett, 1989 and the formation conformably overlies Upper Silurian Wang Tong Formation (Wongwanich et al., 1990), the age of Kuan Tung Formation is probably Late Silurian to Early Devonian (Wongwanich and Boucot, 2011).

Agematsu et al. (2017) redefined the rock units in this group due to numerous unclear boundaries and discontinuities. The redefined Kuan Tung Formation comprises lower, middle, and upper members. Where the lower member is the whole original Kuan Tung Formation of Wongwanich et al. (1990). The middle member is black tentaculitic shale which is the old member 1 of Pa Samed Formation of Wongwanich et al. (1990). The upper member is nodular limestone overlies unconformably middle member with fault contact. Agematsu et al. (2017) suggested that the Kuan Tung Formation ranges from the Latest Silurian to the Middle Devonian, based on the presence of Late Silurian to earliest Devonian conodonts in the lower member and Givetian conodonts in the upper member.

In a recent study, Itsarapong et al. (2023) conducted a detailed investigation at the study section of this thesis and revised the Kuan Tung Formation (Figure 2.3). The formation is divided into three members. The lower member consists of medium to thick-bedded grey limestone, overlain by thin to medium-bedded limestone interbedded with black shale. The middle member is composed of thick-bedded black shale and siltstone interbedded with medium-bedded limestone, with pyrite found in the limestone. This member is unconformably overlain by black shale containing abundant fossils. The upper member consists of grey to pink, thin to thick-bedded limestone with observed laminations and argillaceous bands. According to Itsarapong et al. (2023), the upper member is overlain by red sandstone, which could potentially belong to either the Kuan Klang Formation (Suphakdee, 2017) or the Pa Samed Formation (Wongwanich et al., 1990).

**2.1.3.3 Pa Samed Formation**

Tansuwan et al. (1979) named the discovered black tentaculitic shale in Satun Province as the Pa Samed Formation, which dates from the Silurian to Devonian periods. Wongwanich et al. (1990) redefined Pa Samed Formation as mostly siliciclastic with some grey argillaceous limestone and black carbonaceous shales. The Formation consists of 6 members (Wongwanich et al., 1990) but later has been simplified into 3 units (Department of Mineral Resources, 2018). The lower part (member 1 of Wongwanich et al., 1990) consists of black tentaculitic shale containing abundant dacryoconarids, *Nowakia* (*Turkestanella*) *acuaria acuaria* (Richter), *Striatostyliolina* sp. and *Viriatellina* sp. and suggested a Late Pragian to possibly earliest Emsian age (Boucot et al., 1999). Agematsu et al. (2006a) only recognized *Nowakia acuaria* and interpreted as Emsian. The middle part (members 2–4 of Wongwanich et al., 1990) comprises sandstone interbedded with shale exhibiting Bouma sequences. Its age is interpreted as Carboniferous, based on brachiopods and goniatites reported by Wongwanich et al. (2004), including *Aseptella satunensis* Brunton, *Tornquistia orthogona* Racheboeuf, *Colodium satuni* Boucot and Brunton, *Girtyella* sp., *Crurithyris* sp., *Reticularia* sp., *Plicambocoelia tansathieni* Boucot and Brunton, *Eileenella elegans* Racheboeuf, and goniatites such as *Stenopronorites* cf. *uralensis* (Karpinsky) and

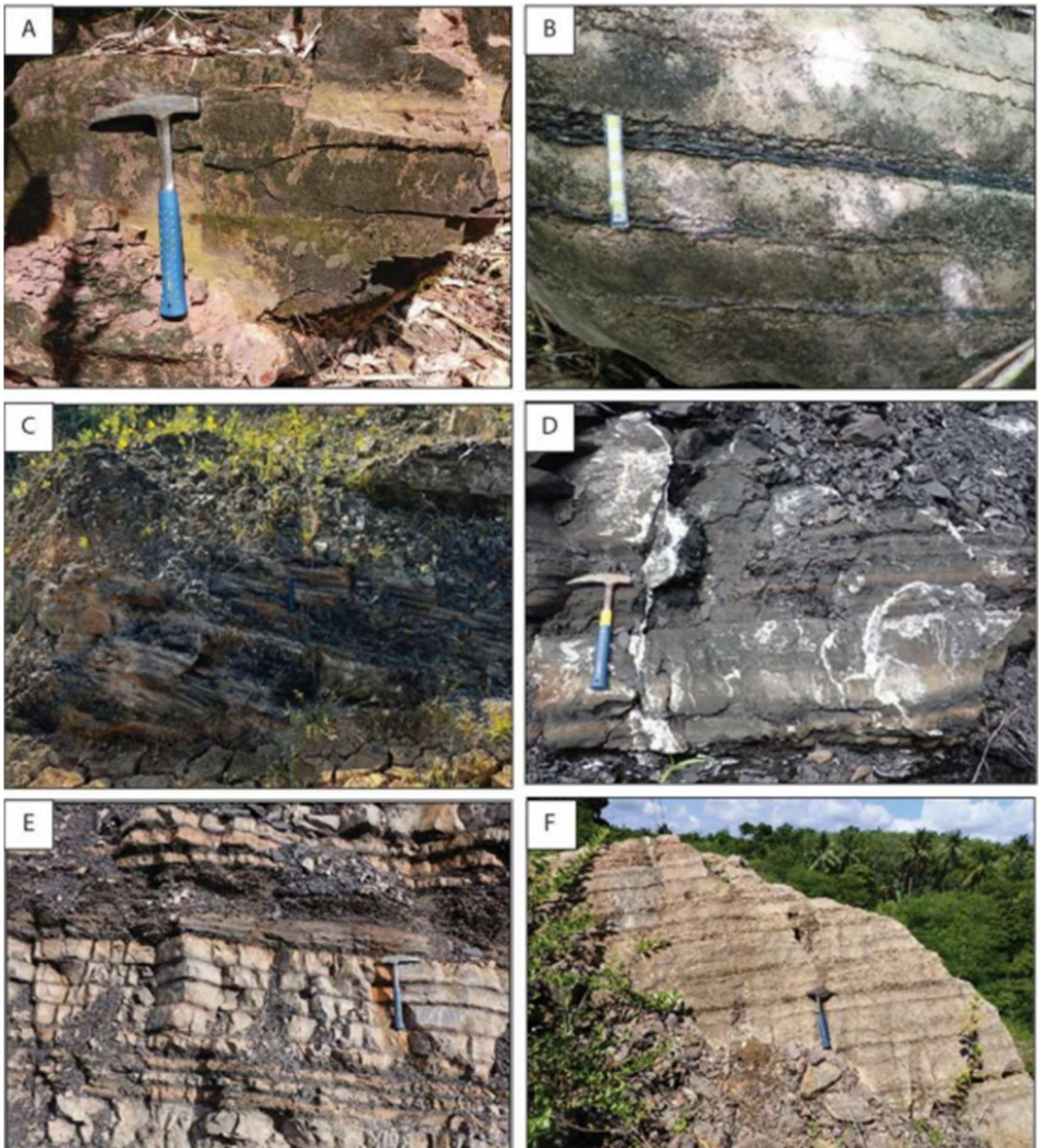


Figure 2.3 Kuan Tung Formation, A. Contact between Upper member and sandstone. B. Upper member. C. Middle member upper part. D. Middle member lower part. E. Lower member upper part. F. Lower member lower part. (Itsarapong et al., 2023).

*Syngastrioceras* sp. The upper part of the formation (member 5-6 of Wongwanich et al., 1990) consists of grey fine-grained sandstone intercalated by thinly laminated black shales. Therefore, Pa Samad Formation ranges from Early Devonian to Carboniferous.

There is disconformity between the Member 1 (Early Devonian) and Member 2 (Carboniferous), or this could represent a concealed fault (Wongwanich et al., 2004).

### 2.1.4 Kuan Klang Formation

Kuan Klang Formation is approximately 210 m thick scattered in Satun, characterized by grey, reddish brown to red mudstones and cross bedded sandstones and a 15 m thick dark grey chert at bottom part with cross cutting quartz veins, grey and reddish-brown shale with bivalve (*Posidonomya* sp.), brachiopods and fragments of trilobites. It is interbedded with sandstone, siltstone and chert beds. The ammonoids *Agathiceras* sp. and *Pronorites* sp., which concurrence with *Posidonomya* sp. in upper part suggests Pennsylvanian age with the founding of Tournaisian radiolarian fauna in 2.5 m thick chert located 65 m above its base (Saesaengseerung and Saiid, 2016) which similar to Kubang Pasu Formation of Malaysia suggests Mississippian age (Jasin, 2015). Therefore, this formation possibly ranges from Mississippian to Pennsylvanian (Carboniferous).

### 2.1.5 Kaeng Krachan Group

Kaeng Krachan Group has been defined by Chaodumrong et al. (2004, 2007) and established 5 formations. In Satun province, this Group exposed inconsistency around the islands and only 3 out of 5 were identified, Laem Mai Phai Formation, Khao Phra Formation, and Khao Chao Formation (Department of Mineral Resources, 2018). Laem Mai Phai Formation is exposed at Ko Bu Lon and its vicinity consists of thin bedded, black mudstone and laminated siltstone with some intercalated sandstone (Tiyapairat, 2004). Khao Phra Formation is characterized by interbedded shales and grey sandstones, well exposed in Adang-Rawi Islands. On mainland Satun, this formation exposed at Khuan Pho, near Satun City contains *Spinomartinia* sp. suggests Sakmarian age (Meesook, 2014). Lastly, Khao Chao Formation is mainly grey to light brown sandstone with some shales exposed on Ko Bitsi, Ko Ta Mui, Ko Lan Ja and north of Ko Adang. The age of this group is probably Early Permian.

### 2.1.6 Ratburi Group

Ratburi Group lies conformably on the Kaeng Krachan Group and is primarily composed of fossiliferous limestone, predominantly found in western Thailand. In Satun Province, it occurs in Khao Thanan, Ko Taban, and Ko Lidi, where Middle to Late Permian fusulinids have been identified.

### 2.1.7 Quaternary Sediments

Quaternary sediments cover all undulating terrains in Satun Province. This sequence consists of loose sediments, including clay, silt, sand, and gravel. These sediments can be divided into 11 main units: colluvial, alluvial, mangrove and beach deposits, former beach ridges and dunes, deltaic flood plain, abandoned channels, flood plain, high terrace, low terrace, accretionary plain, and tidal delta and bar deposits (Department of Mineral Resources, 2013).

### 2.1.8 Igneous Rock

Igneous rocks in Satun Province are predominantly granite, which intruded into Paleozoic rock sequences in Triassic. The granites are exposed in the northern and eastern parts of Khuan Kalong District, extending to the east of Khuan Don District. On the islands, granites are visible at Ko Adang, Ko Lipe, and others. These granites commonly consist of biotite granite, biotite-muscovite granite, aplite, and pegmatite, with fine- to coarse-grained porphyritic textures and feldspar phenocrysts (Department of Mineral Resources, 2013).

## 2.2 Paleoenvironment of Satun Province

Satun Province offers a detailed record of Paleozoic environmental changes, spanning from Late Cambrian to Permian, based on extensive research. The Department of Mineral Resources (2018) summarized these findings from the accumulated works of many researchers. The deposition of the Tarutao Group during the Upper Cambrian to Lower Tremadoc shows a sandy, barrier-beach complex in shallow tropical seas. During the Lower Ordovician of the Thung Song Group, sedimentation occurred on a homoclinal ramp in predominantly very shallow tropical sea, characterized by tidal flats, which transitioned to slightly deeper subtidal environments in the Middle Ordovician. By the Late Ordovician of the Thung Song Group, sedimentation took place in deep (approximately 200 meters) and cool (around 15°C) tropical sea, indicated by the presence of large-eyed trilobites, cool-water conodonts, and specific isotopic signatures. These deep-water or deep subtidal conditions persisted through much of the Silurian and Devonian of the Thong Pha Phum Group and likely extended into the Carboniferous. This inference is supported by the brachiopod communities, trilobites with reduced eyes (such as *Plagiolaria* sp.), and the pelagic faunas of graptolites, ammonoids, and radiolarians. The Late Carboniferous to Permian of Satun is correlated to the sediments of Phuket, Krabi, and Langkawi, where there is abundant evidence of deposition near or under glaciers.

## 2.3 Ostracod

### 2.3.1 Overview

Ostracods are small, bivalve crustaceans, typically microscopic in size. Most adult ostracods range from 0.5 to 2 mm in length, though certain freshwater species can grow as large as 8 mm. The pelagic marine species *Gigantocypris*, a member of the Myodocopida order, can reach an impressive 32 mm in size (Horne, 2005). Ostracods can be documented as far back as the Early Ordovician (Siveter, 2008; Williams et al., 2008). Renowned for their adaptability, survival, demonstrate vulnerability to environmental factors such as temperature, salinity, substrate, hydrodynamics, and oxygen levels (Jones, 2010; Maillet et al., 2013; Racheboeuf et al., 2012; Song et al., 2019). Despite these sensitivities, ostracods have displayed an impressive capacity for adaptation, facilitating their widespread distribution across ecosystems worldwide. Therefore, the more discoveries of fossil ostracods, the more applications on paleoenvironmental interpretation and paleogeographic reconstructions can be carried out (e.g., Maillet et al., 2016; Meidla et al., 2013; Olempska et al., 2015; Perrier and Siveter, 2013; Schallreuter et al., 1996; Song et al., 2022).

### 2.3.2 Morphology of ostracod

The ostracod carapace (Figure 2.4) is made up of two valves that encase its body and limbs. It consists of two layers: a rigid outer calcified layer and a soft epidermis layer. During their lifetime, the ostracod's hard layer is covered with a chitinous layer, while the epidermis is enclosed in chitin. The hard layer consists of an inner lamella and an outer lamella. The outer surface of the carapace is mostly made up of the outer lamella, which is calcified and usually remains as a fossil.

The outer lamella covers the carapace's surface and curves inward at the ventral margin to form the inner lamella, which is only the calcified part in that area. The dorsal side is where the two sides of the outer lamella join (interlock) to form a hinge, welded by a thin strip of soft tissue called the ligament. The right and left valves are usually difference in size and have an overlap but in some groups like Myodocopid the valves usually have the same size or very similar in size. The hinges are composed

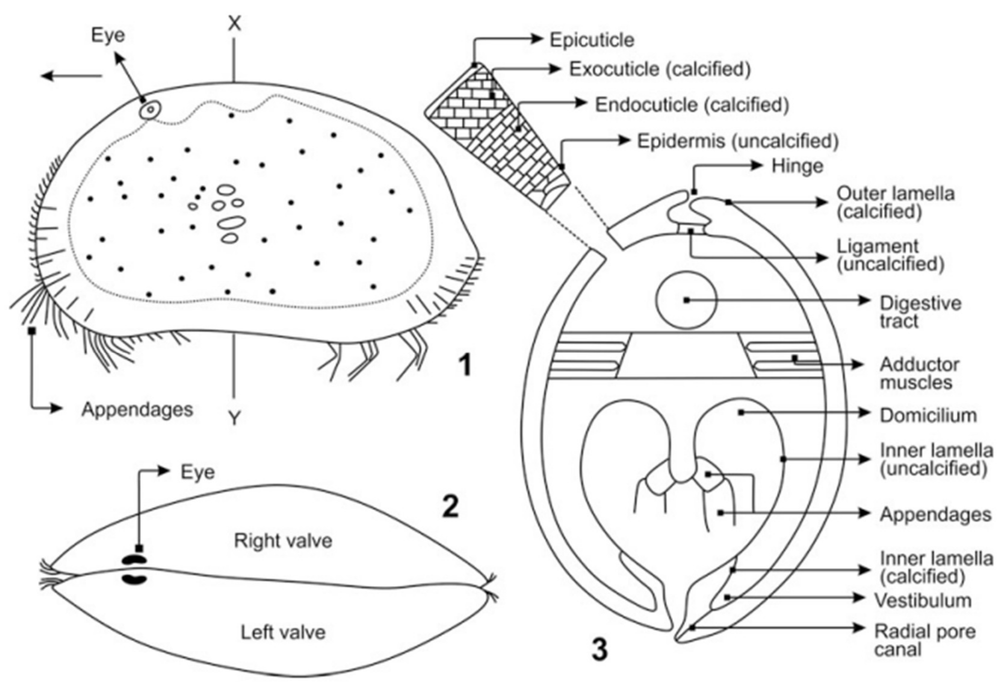


Figure 2.4 Morphology of ostracod carapace (Jain, 2020).

of sockets, bars, grooves, and teeth, whose shapes (Figure 2.5) and arrangements vary and serve as useful tools for identifying ostracods.

The ostracod body is short and laterally compressed, showing no trace of segmentation, with only a slight constriction to distinguish the boundary between the head and thorax. Ostracods have four pairs of appendages: antennae, mandibles, and maxillae, along with one to three pairs of thorax legs and a furca (Figure 2.5).

Antennules function as a locomotor organ (swimming, digging, climbing) or sensory organ or balancing organs.

Antennae also serve as a locomotor organ.

Mandibles function as a tool for feeding (digging, holding, cutting).

Maxillae functions as a support organ for the mandibles to move food into their mouths.

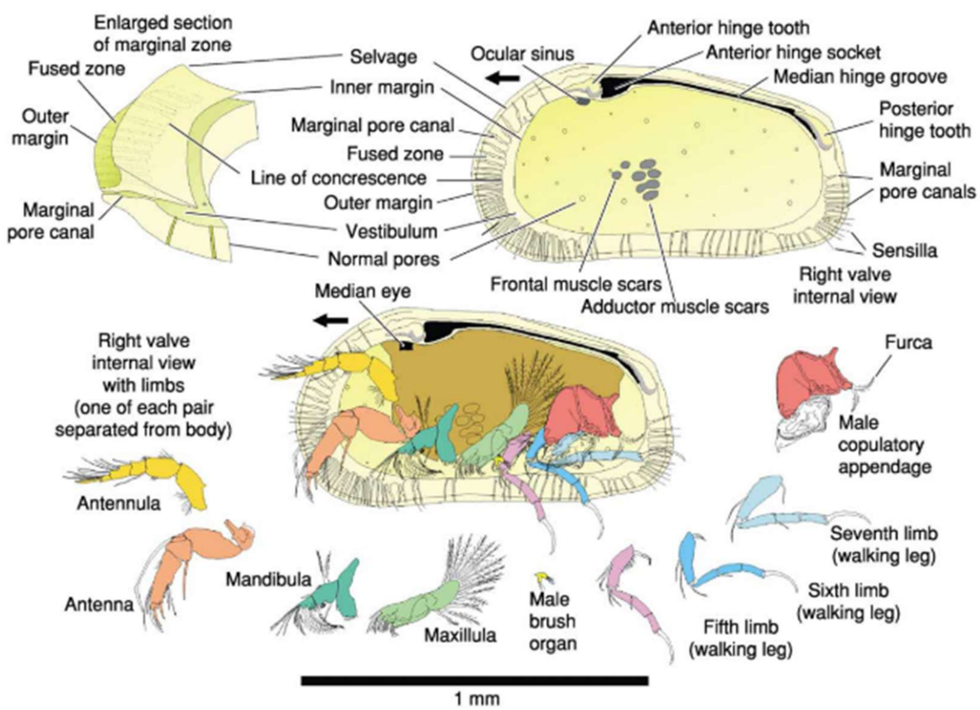


Figure 2.5 Internal valve morphology and limps of a cytheroidean podocopids (Horne, 2005).

Thorax legs develop differently in each group, some groups have developed the legs to function as additional maxillae or to aid the respiration and some groups can develop multiple pairs of thorax legs.

Furcae is probably used as locomotor organs.

Other than internal organs like the heart, digestive organs or genital organs, ostracods have adductor muscles attached to both valves functions to close or open the carapace which leave a scar at both valves (Figure 2.5) that are preserved in a fossil.

### 2.3.3 Classification criteria of ostracod fossil

The classification of living ostracods is based on carapace morphology, soft part morphology, and DNA analyses. However, since fossilized ostracods rarely preserve soft tissues, their identification relies solely on carapace morphology. Key diagnostic features include carapace shape (e.g., ovate, elongate, spherical, rectangular), valve symmetry, and hinge characteristics, which help distinguish major ostracod groups. Surface ornamentation, such as smooth, pitted, ridged, or spined textures (Figure 2.6), can further refine identification down to the genus or species level.

Dimorphism is common in ostracods, with differences in size, shape, and sculpture observed between males and females or juveniles and adults of the same species. Sexual dimorphism is often linked to reproductive adaptations, where females may have a swollen posterior region to accommodate eggs or a brood pouch, while males are typically smaller. Ontogenetic differences (juvenile vs. adult) are generally limited to size in smooth-shelled species, but many groups exhibit distinct changes in sculpture due to incomplete development in juvenile stages compared to adults.

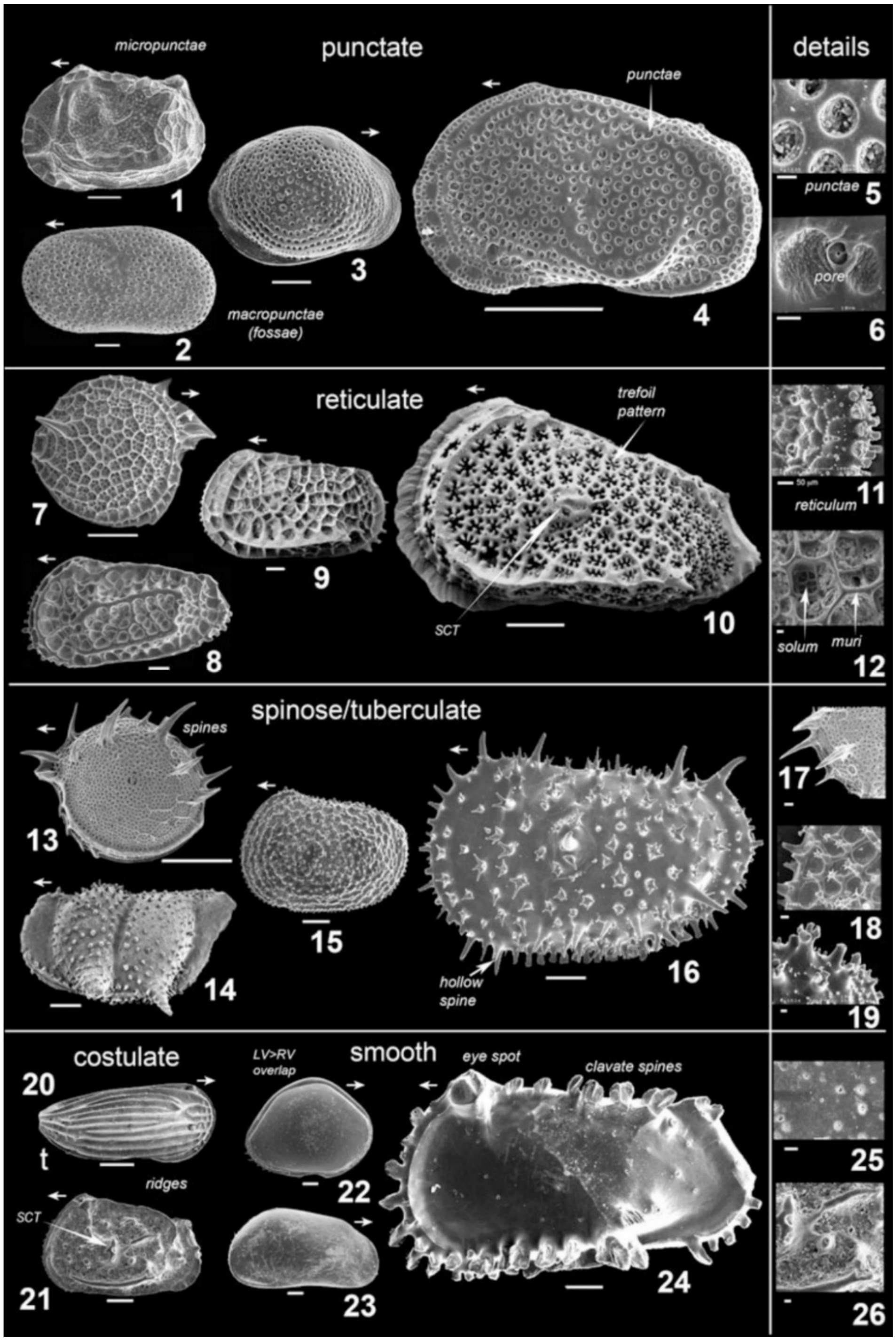


Figure 2.6 Example of ostracod sculptures (Rodriguez-Lazaro and Ruiz-Munoz, 2012).

### 2.3.4 Study of Silurian-Devonian ostracod in Thailand

Studies on Silurian–Devonian ostracods in Thailand are limited, with only the recent work on the Kuan Tung Formation providing new data (Promduang and Chitnarin, 2025). Most previous research has focused on Upper Paleozoic ostracods, particularly in central Thailand (e.g., Chitnarin and Ketwetsuriya, 2021; Chitnarin et al., 2008, 2017), while Dill et al. (2004) reported late Paleozoic ostracods from Surat Thani Province.

In Southeast Asia, Silurian–Devonian ostracod study is similarly scarce, with notable studies from Vietnam documenting Late Silurian ostracods from the estuarine deposits of the Si Ka Formation, suggesting early estuarine colonization by ostracods (McGairy et al., 2021; Williams et al., 2023).

## 2.4 Ecology of Silurian-Devonian marine ostracod

### 2.4.1 Overview of ostracod ecology

Ostracods are predominantly having benthic mode of life with only known pelagic ostracods belonging to Myodocopida (Horne, 2005). The earliest known ostracod dates back to the Early Ordovician period (e.g., Salas et al., 2007; William et al., 2008), probably have benthic lifestyle, dominated by Palaeocopida which included some Podocopida, Platycopida and Leperditicopida having restricted to shelf area and show sign of the assemblage that related to depth (Horne, 2003), also Leperditicopida and leperditelloidean palaeocopids dominated marginal marine tidal flat environment in Ordovician (Williams and Siveter, 1996). In Silurian, most ostracods have benthic lifestyle living mostly on relatively shallow shelves and shelf slopes as a crawler, swimmer or burrower (Perrier and Siveter, 2013). But in Middle Silurian, Myodocopida which may originated in Late Ordovician and been benthic at that time ventured into pelagic niche (Siveter et al., 1991), and by the Late Silurian, ostracods (Palaeocopida and Leperditicopida) began colonizing brackish waters (Horne, 2003; McGairy et al., 2021). During the Carboniferous period, otracods extended their range to include terrestrial aquatic systems (Bennett et al., 2012; Iglikowska, 2014). Today, ostracods are a highly diverse group, occupying a wide variety of aquatic habitats, from deep-sea bathyal-abyssal regions (Yasuhara et al., 2008; Brandão et al., 2019) to temporary ponds (Ottonello and Romano, 2011).

### 2.4.2 Ecology of Devonian ostracod

In the Devonian period, three ecotypes of marine ostracods were recognized (Bandel and Becker, 1975). The ecotypes were later revised and reclassified under the term "Mega-Assemblages" (Casier et al., 1995; Casier, 2004, 2017). The Three Mega-Assemblages include Eifelian, Thuringian, and Myodocopid Mega-Assemblages (Figure 2.7).

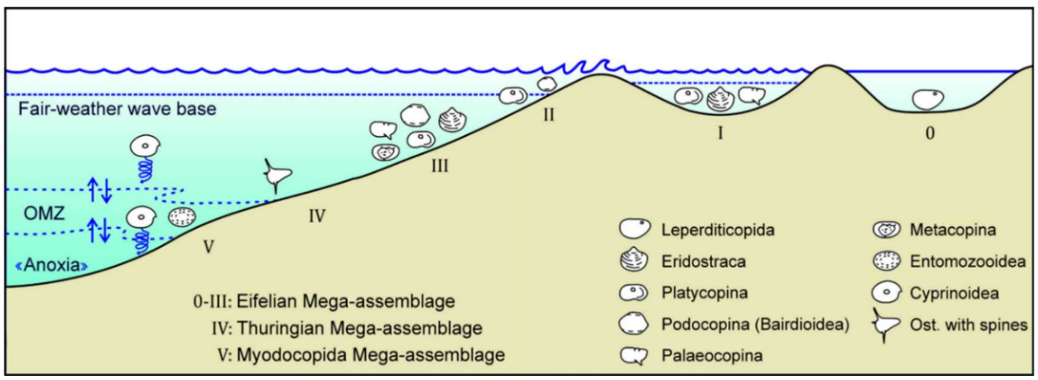


Figure 2.7 Three ostracod mega-assemblages (Crasquin and Horne, 2018).

#### 2.4.2.1 The Eifelian Mega-Assemblages

Comprised 4 assemblages 0-IV

The Assemblage 0: This assemblage, composed solely of large Leperditicopida ostracods, is an indicator of lagoonal environments.

The Assemblage I: This assemblage is characterized by low species diversity, often with a high abundance of specimens, and interprets as a semi-restricted water environment. The species within this assemblage primarily include euryhaline Platycopida, along with Metacopida, Palaeocopida, and Eridostracina. In conditions where salinity nears normal marine levels, some Podocopida may also be present. Additionally, this assemblage may display stacked ostracod valves or a cup-in-cup structure (Figure 2.8), formed by wavelet induced processes, a phenomenon typically occurs in very shallow, but continuously agitated waters (Boomer et al., 2001).

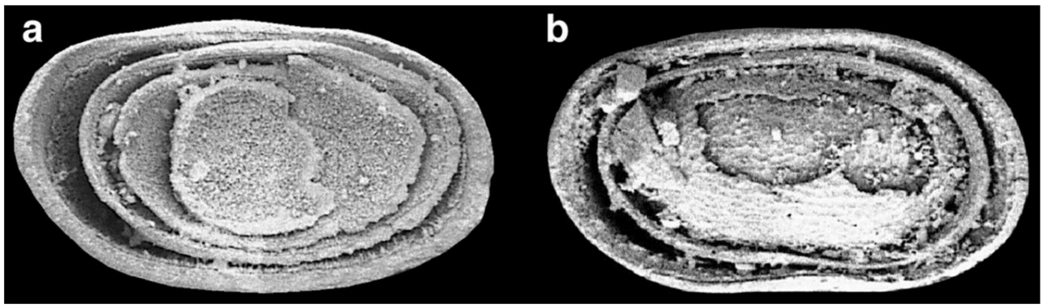


Figure 2.8 Stacked valves or cup in cup structure of ostracods (Casier, 2007).

The Assemblage II: This assemblage is characterized by a moderately diverse ostracod, predominantly consisting of large, thick-shelled Podocopida and Platycopida. Notably, juvenile ostracods are usually absent, and carapaces are often found fragmented. Assemblage II indicates a very shallow, open-marine environment with constant agitation, situated above the fair-weather wave base. Occasionally, oolites are found accreting around ostracods.

The Assemblage III: This assemblage is characterized by a diverse range of ostracods, including most orders such as Podocopida, Metacopida, Palaeocopida, Platycopida, and Eridostracina. It typically represents environments found below the fair-weather wave base, and sometimes even below the storm-wave base. In Assemblage III, the ratio between Metacopida and Podocopida shifts with increasing water depth: Podocopida shows a decline in both diversity and abundance, while Metacopida become more dominant. As a result, the ratio of Metacopida to Podocopida may be used as an indicator of water depth.

**2.4.2.2 The Thuringian Mega-Assemblage**

The Assemblage IV: This assemblage consists mainly of thin-shelled, spiny ostracods, mostly from the Podocopid group, with some representation from Metacopids and Palaeocopids. These ostracods are typically found in very calm, possibly colder marine settings, below the storm-wave base. Their fragile shells likely evolved as an adaptation to such stable conditions. Notably, these ostracods are cosmopolitan and, unlike those in other groups, appear to have experienced slower evolutionary changes during the Palaeozoic. In particularly deep, tranquil waters, some Metacopida species also develop spines on their carapaces.

**2.4.2.3 The Myodocopid Mega-Assemblage**

The Assemblage V: This assemblage is defined by the presence of Entomozoidea or Cyprinoidea of Myodocopida, which represents the low-oxygen marine environments. Cypridinids were active swimmers, as shown by their large anterior rostrum that allowed swimming limbs to extend. They are typically preserved in oxygen-poor settings, often found with their valves separated but still close together, resembling a butterfly shape (Figure 2.9). Entomozoidea, known for their fingerprint-like shell patterns, hold significant biostratigraphic importance, though their exact lifestyle remains uncertain and debated.

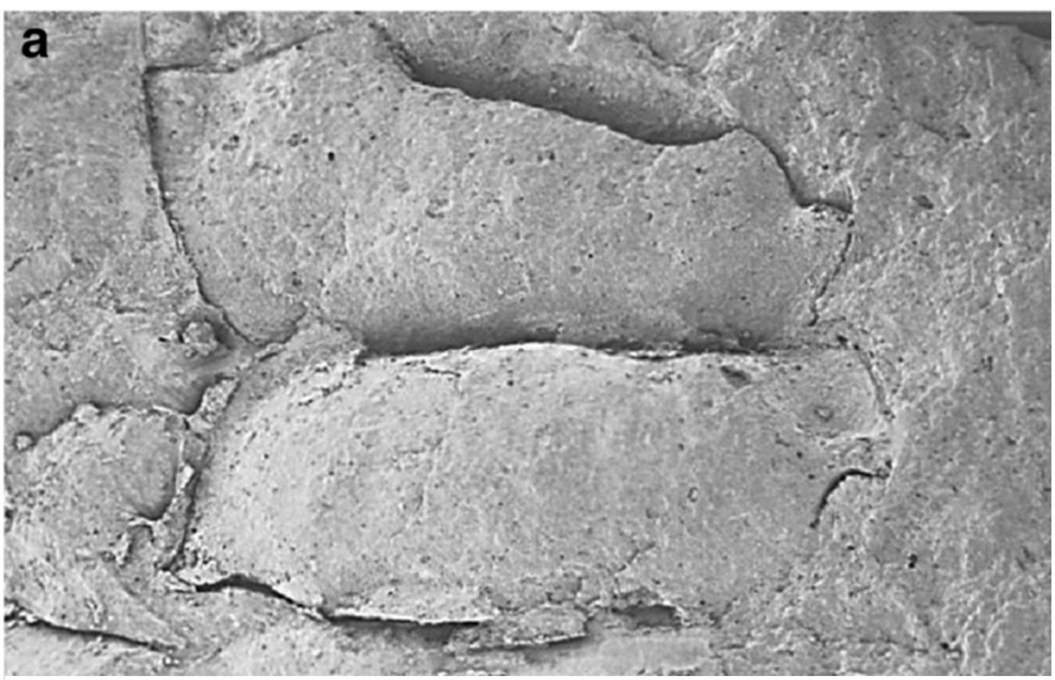


Figure 2.9 Butterfly position of *Palaeophilomedes neuvillensis* Casier, 1988 in Casier (2017).

## 2.5 Conodont

### 2.5.1 Overview

Conodonts were jawless, eel-like marine vertebrates (Briggs, 1992; Sansom et al., 1992; Donoghue et al., 2000; Rasmussen and Stouge, 2018). Based on the presence of a tail fin and well-developed eyes, conodonts are thought to have had a pelagic or nektobenthic lifestyle, likely residing in the photic zone (Sweet, 1988; Rigo and Joachimski, 2010; Rasmussen and Stouge, 2018). The fossil record dates back to the Cambrian period, with extinction occurring in the Late Triassic.

Conodonts are commonly discovered as mineralized, tooth-like elements that function as a feeding apparatus within the oral cavity. These conodont elements are composed of phosphatic bioapatite, a material highly resistant to diagenesis, preserving chemical signatures that reflect their original biological composition. Consequently, chemical analyses of these elements provide valuable insights into ocean geodynamics and past climates.

Conodonts have been extensively used in the biostratigraphy of Paleozoic marine carbonates and have played a vital role in paleoecological and biogeographical studies (Sweet and Donoghue, 2001). Despite uncertainties about their ecology and feeding habits, conodont elements are invaluable for biostratigraphy, as their first appearance datum (FAD) and last appearance datum (LAD) help define specific chronological ranges. Their broad geographic distribution, rapid evolutionary changes, and morphological diversity make them essential tools for precisely correlating rock layers across different regions.

### 2.5.2 Conodont element morphology

Conodont elements are primarily categorized based on their shapes and presumed functions within the conodont feeding apparatus. The main morphological types include:

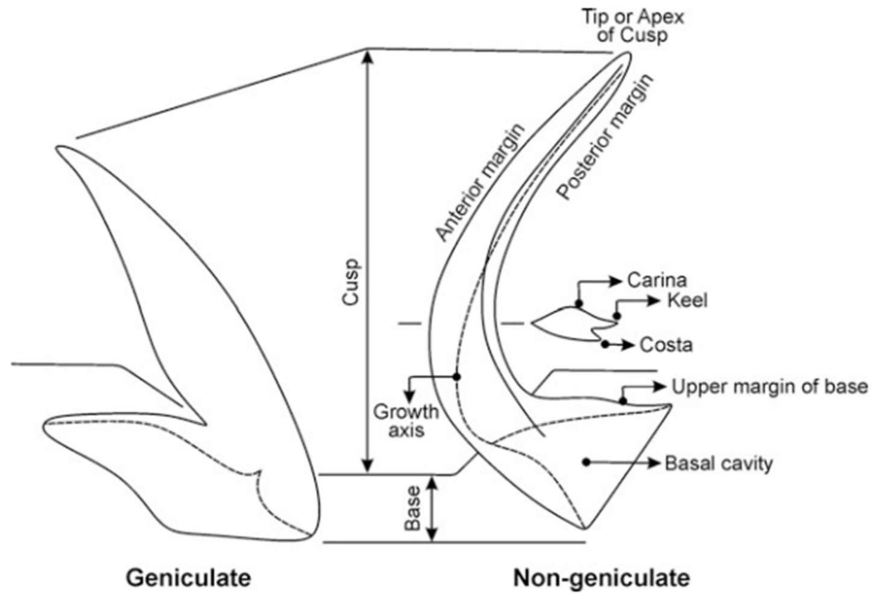


Figure 2.10 Coniform element terminology (Jain, 2020).

Coniform (Cone-shaped): Simple, conical elements resembling single teeth, which can be subdivide into Geniculate and Non-geniculate (Figure 2.10).

Ramiform (Bar-shaped): Elongate, sometimes branched structures that may have multiple cusps or denticles, subdivided into Alate, Digyrate, Quadriramate, Dolabrate, Bipennate Tertiopedate (Figure 2.11).

Pectiniform (Blade, Platform-shaped): Flattened, plate-like elements often bear a series of denticles along one edge, subdivided into Stellate, Pastinate, Angulate, Segminate, Carminate (Figure 2.12).

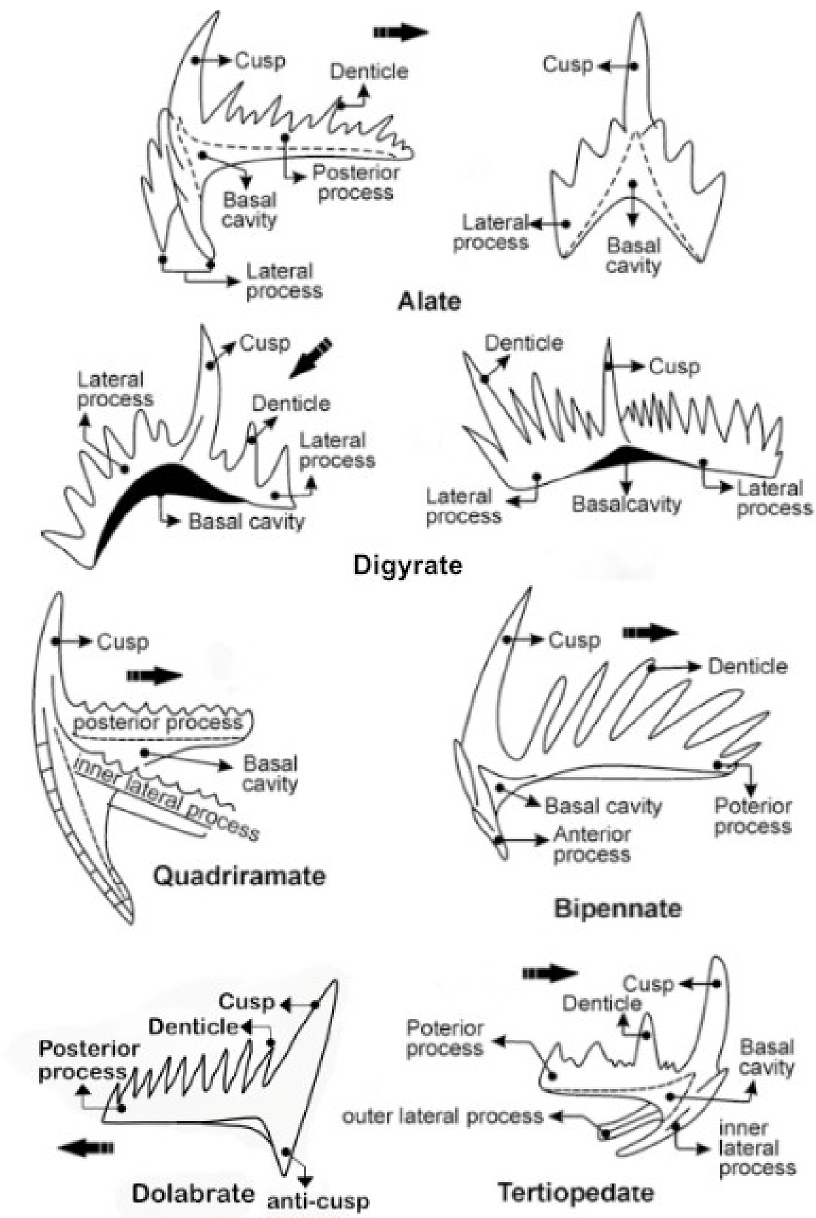


Figure 2.11 Ramiform element: Alate, Digyrate, Quadriramate, Dolabrate, Bipennate, Tertiopedate (Jain, 2020).

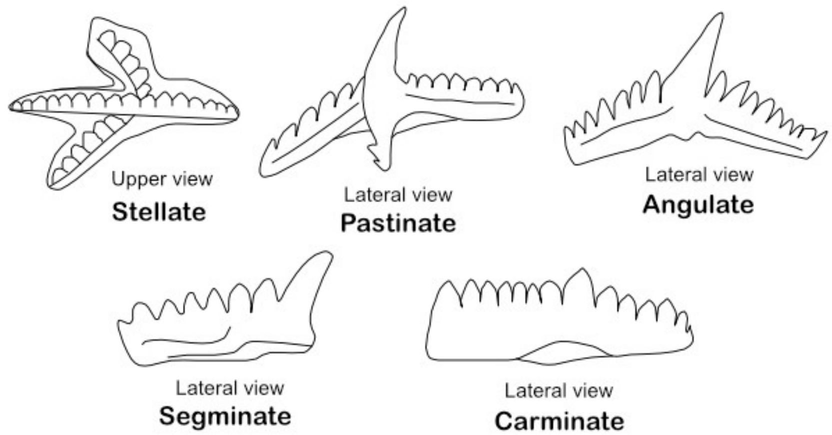


Figure 2.12 Pectiniform element: Stellate, Pastinate, Angulate, Segminate, Carminate (Jain, 2020).

The conodont feeding apparatus is bilaterally symmetrical and consists of distinct elements arranged in the head region. Each species possessed a specific set of elements, divided into an anterior region with M and S elements (Sa, Sb, Sc, and Sd) and a posterior region with P elements (Pa and Pb) (Sweet, 1988; Purnell et al., 2000). Purnell et al. (2000) later refined the classification system, defining element positions based on spatial relationships and body axes, as observed in bedding plane assemblages (Figure 2.13). This led to a standardized nomenclature where elements are labeled with letters and numeric (e.g., P1, P2, S0–S4, M), with S elements numbered outward from S0.

**2.5.3 Silurian-Devonian conodonts in Thailand**

The Silurian-Devonian boundary has long been a subject of detailed stratigraphic investigation, with conodonts playing a crucial role in refining biozonation schemes (Hušková and Slavík, 2020). The FAD of *Caudicriodus hesperius* serves as a key marker for the base of the Devonian, while taxa such as *Ozarkodina confluens* (Branson and Mehl, 1933), *Zieglerodina remscheidensis* (Ziegler, 1960), and *Caudicriodus woschmidti* (Ziegler, 1960) help further constrain the boundary. Recent taxonomic revisions have shown that many late Silurian–Early Devonian conodont genera, previously classified in broad “waste-basket” categories (such as Genus *Ozarkodina* which has been subdivided into *Ozarkodina*, *Zieglerodina*, and *Wurmiella*),

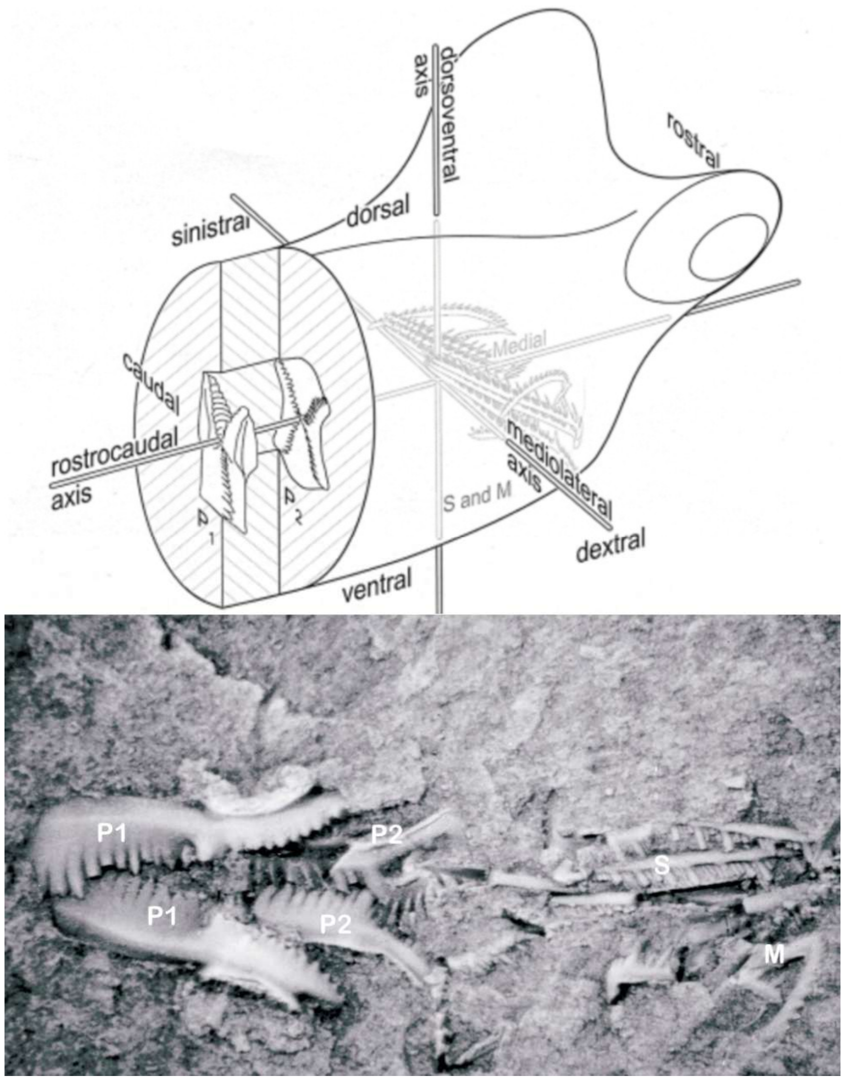


Figure 2.13 The orientation and notation of the Ozarkodinid apparatus drawing (Top) from Purnell et al. (2000) and conodont apparatus in natural assemblage (Bottom) *Idiognathodus* from Sweet and Donoghue (2001).

require re-evaluation to resolve species-level identifications (Ferretti et al., 2022). This refinement is essential for improving the accuracy of conodont-based correlations and biozonation.

In Thailand, studies on the Silurian-Devonian boundary remain limited, partly due to the scarcity of well-preserved boundary strata. Hagen and Kemper (1976) reported Late Silurian conodonts from the Thong Pha Phum area, Kanchanaburi Province, western Thailand, but did not specify the taxa. A study of specimens from a limestone unit by Long and Burrett (1989) marking the boundary between the middle and upper sections of the Kuan Tung Formation of Wongwanich et al. (1990), identified *Pandorinellina steinhornensis steinhornensis*, *Polygnathus lahiosus mawsonae* Long and Burrett, 1989 (later considered synonymous with *Polygnathus bultyncki* Weddige, 1977 by Klapper and Vodrážková, 2013), and *Pseudooneotodus kuangtungensis* Long and Burrett, 1989, indicating an Emsian age. More recently, a conodont assemblage including *Zieglerodina remscheidensis* s.l., *Belodella resima* (Philip, 1965), and *Decoriconus fragilis* (Branson and Mehl, 1933), co-occurring with plate loboliths of scyphocrinitid crinoids, was documented from the Ban Tha Kradan area, Kanchanaburi. This assemblage suggests an age ranging from the late Ludlow (Silurian) to early Lochkovian (Devonian) (Burrett et al., 2024).

## 2.6 Tentaculitoid

### 2.6.1 Overview

These organisms (Figure 2.14) often referred to by many researchers as Tentaculites (which can lead to confusion with the genus *Tentaculites*), are enigmatic

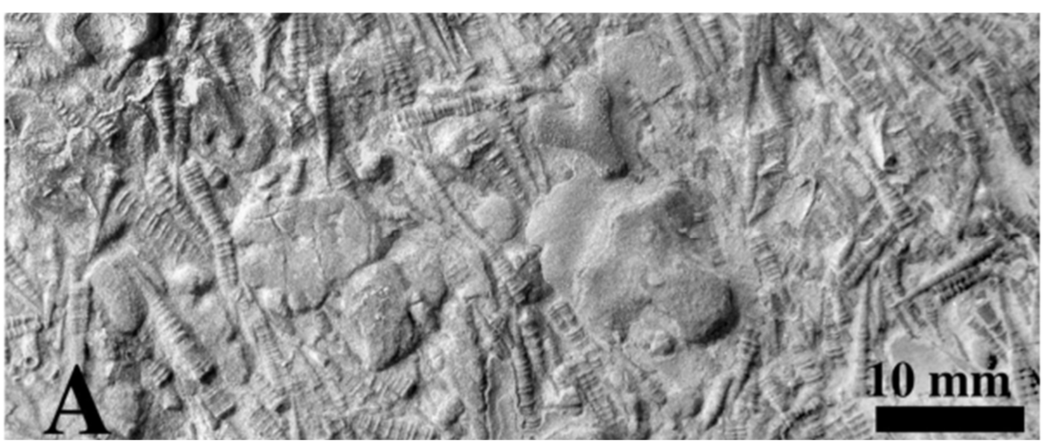


Figure 2.14 *Tentaculites gyracanthus* of Lower Devonian, Manlius Formation, New York State, USA (Cornell et al., 2003).

marine invertebrates with an unresolved taxonomic position. These organisms first appeared in the fossil record during the Ordovician period, underwent significant diversification in the Silurian, and became extinct by the Late Devonian. Despite their widespread fossil records, their biological affinities remain uncertain, and their classification continues to be debated among paleontologists.

Two main theories exist regarding their classification (Wei et al., 2012). The first suggests that tentaculitoids, due to their similarities in shell morphology such as wall structure, septal neck, and siphuncular cord belong to an independent class within Mollusca (e.g., Bouček, 1964; Farsan, 1994). The second theory suggests a closer relationship between tentaculitoids and microconchids, based on shared characteristics like wall microstructure, including microlamellar layers, cross-bladed fabric, and pseudopuncta (Vinn et al., 2008; Vinn, 2010), or an affinity with lophophorates (Larsson, 1979).

The fossil remains of tentaculitoids are small, ringed, conical-shaped shells found in various marine deposits. Their distribution across the seafloor provides valuable insights into paleocurrents (Hladil et al., 1991, 2014; Gügel et al., 2017). Although the origin and affinity of tentaculitoids remain uncertain, their ecological roles are still debated. Overall, thick-walled tentaculitoids are widely thought to have had a benthic lifestyle in shallower waters and are commonly associated with siliciclastic rocks. In contrast, small and thin-walled tentaculitoids were likely planktonic or nektoplanktonic and are more frequently found in deeper sedimentary deposits (Schindler, 2012). Additionally, their broad distribution, short stratigraphic range, and rapid evolutionary rate make tentaculitoids valuable tools in global biostratigraphy (for a comprehensive overview, see Becker et al., 2020).

### 2.6.2 Classification criteria of Tentaculitoid shell

Tentaculitoids are predominantly discovered as shells embedded in rock, making shell morphology the primary criterion for classification. While some researchers have reported organic remains of Tentaculitoids through palynological studies (e.g., Wood et al., 2004; Jarzynka and Filipiak, 2009; Marshall and Telnova, 2012), these specimens are often extracted in a folded or distorted state, making it difficult to accurately discern shell morphology. Consequently, the characteristics of a solid-calcareous shell continue to provide a more reliable basis for classification.

The shell, or conch, of Tentaculitoids is generally straight, ringed, and conical in shape, with an initial chamber that is often used to determine their order. The overall shell shape (e.g. length, width, growth angle), along with the pattern and shape of transverse rings and/or longitudinal ribs (e.g. number of rings, interspace between rings), serves as key features for identifying specimens at the genus and species levels (Figure 2.15). Order Tentaculitida generally has large, thick-walled, ringed, layered shell with narrow apex and mostly represent by genus *Tentaculites.* Order Dacryoconarida has a small, ringed or without ringed, thin shell, bulbous or tear-shaped initial chamber have commonly known group Nowakiidae. Order Homoctenida has

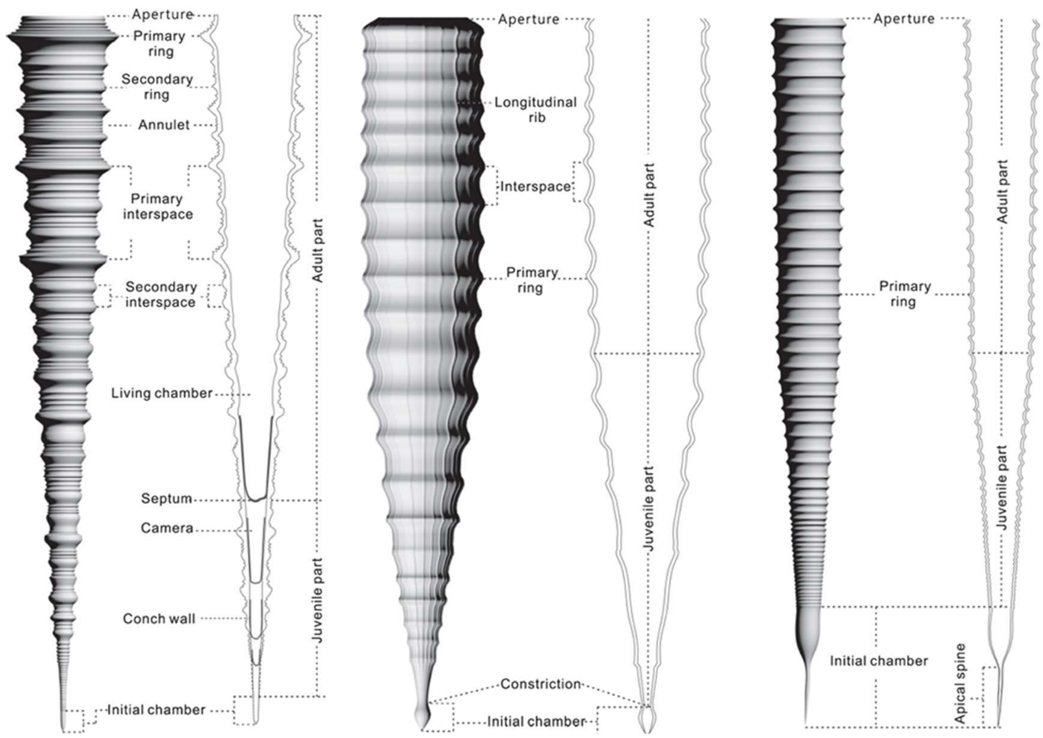


Figure 2.15 Morphology of Tentaculitoids shell, represents left: Tentaculitida (*Tentaculites*); middle: Dacryoconarida (*Nowakia*); right: Homoctenida (*Homoctenus*) from Wei (2019).

small, ringed, thin-shelled, and apical spine in initial chamber and represent by genus *Homoctenus*.

### 2.6.3 Tentaculitoids in Thailand

One of the earliest reports on tentaculitoids in Thailand was by Pitakpaivan et al. (1969), who identified *Tentaculites elegans* (Barrande, 1852) and *Styliolina clavula* in Silurian sandy shale underlying Permian limestone in Si Sawat District, Kanchanaburi Province. Later, Hahn and Siebenhüner (1982) documented fossil assemblages included dacryoconarids, *Nowakia holynensis* Bouček, 1964, *N. sulcata* (Roemer, 1843), *Styliolina* sp., and *Homoctenus hanusi* (Bouček, 1964), from Thong Pha Phum area, with an age range extending from the Ordovician to the Carboniferous. In the 1990s, Dr. Ruan Yi-Ping examined dacryoconarid samples from the Pa Samed Formation (Wongwanich et al., 1990), identifying *Nowakia acuaria*, *N.* cf. *matlockiensis* (Chapman, 1904), *N.* cf. *hercyniana* Alberti, *N.* sp. 1, *Styliolina* sp., *Striatostyliolina* sp., and *Viriatellina* sp., dating from the late Pragian to earliest Emsian (Boucot et al., 1999). Agematsu et al. (2006a) also reported *Nowakia acuaria* from the Pa Samed Formation and documented its presence in Lower Devonian (Emsian) black shale in Satun Province. More recently, Maneerat (2021) identified a diverse tentaculitoid assemblage from the Silurian-Devonian sedimentary rocks of the Thong Pha Phum Group in Ban Tha Kradan, Si Sawat District. The recorded species include *Nowakia acuaria*, *N.* (*Cepanowakia*) *pumilio* Alberti, *Styliolina fissurella* (Hall, 1843), *S. clavulus* Fisher, 1962, *S.* sp. A, *Homoctenus tikhyi* Ljashenko, 1959, and *H. arctus* Li, 1995, suggesting Early Devonian to Late Devonian. Additionally, associated graptolites bearing bed (*Monograptus* sp. and *Diplograptus* sp.) suggesting Silurian? to the Early Devonian.