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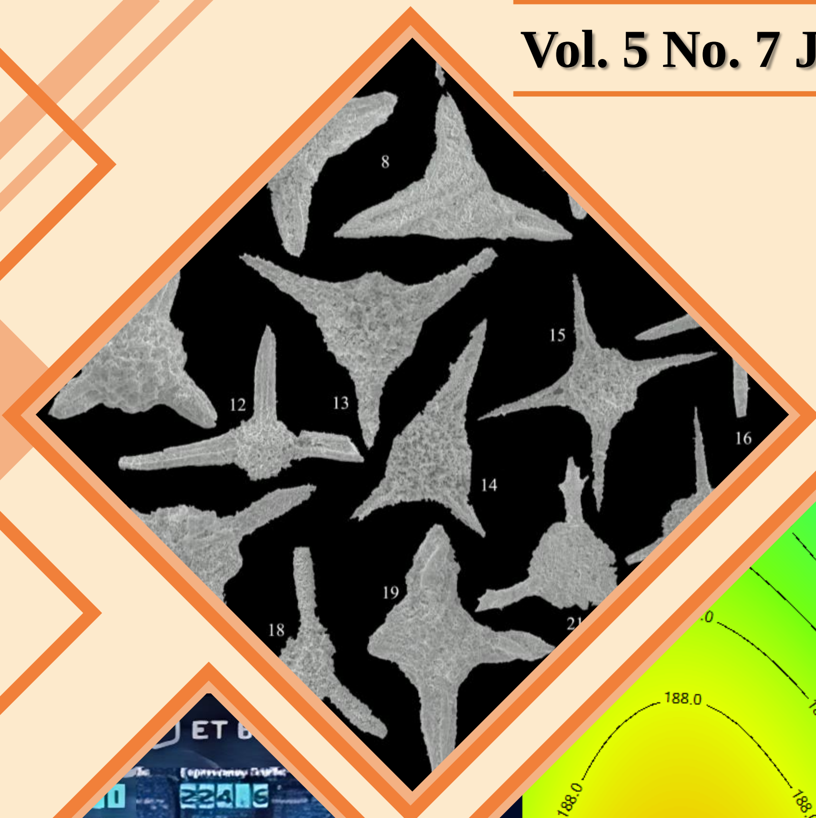

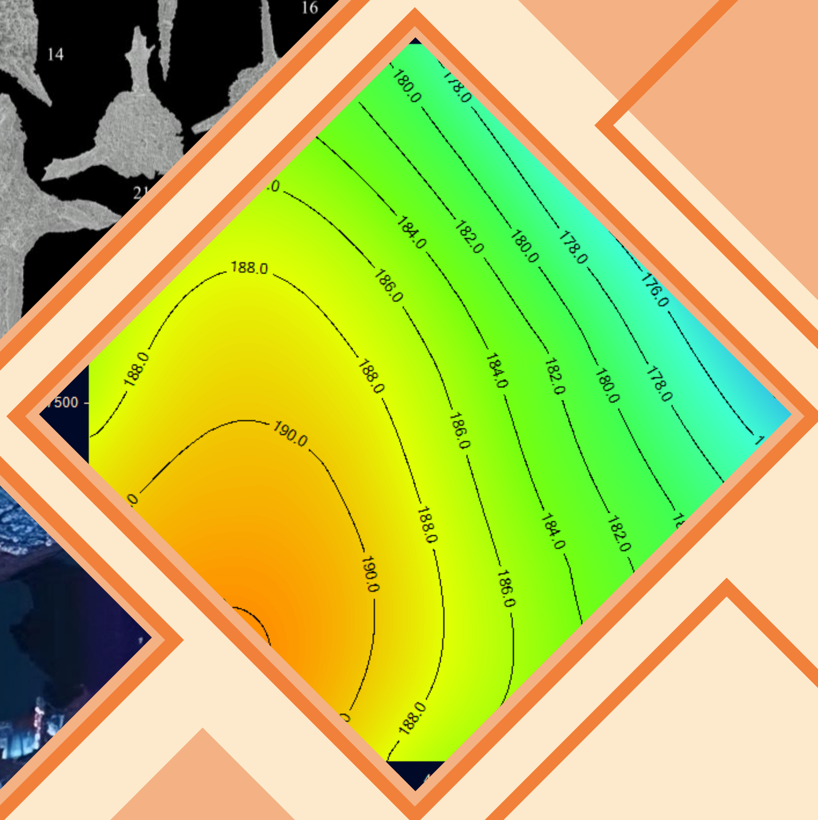

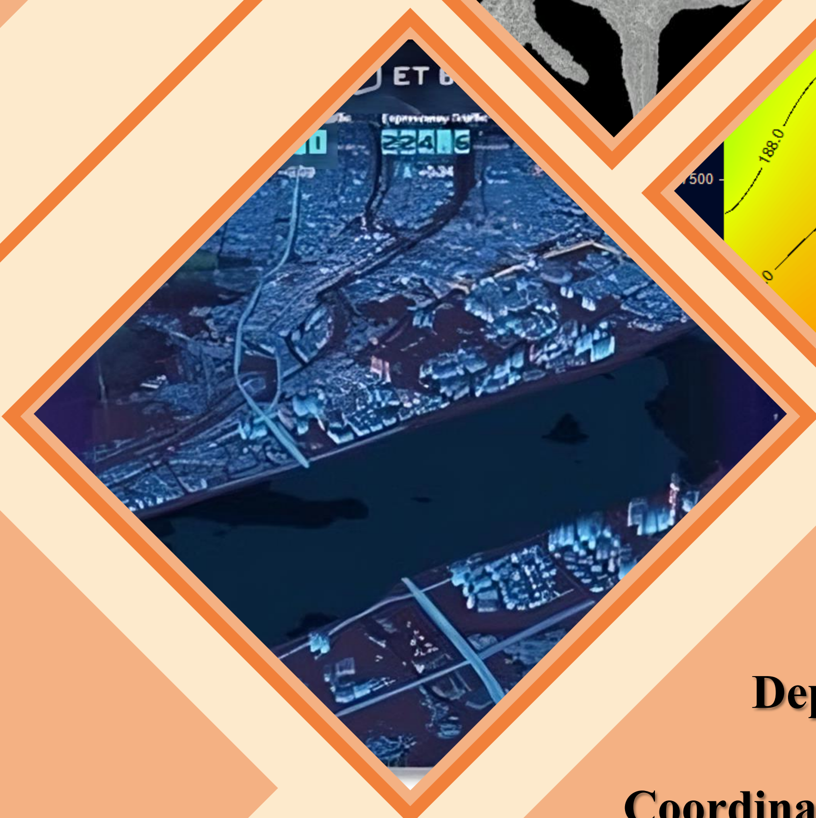

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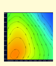
On the cover

1) Triassic radiolarians from the Kanchanaburi area, western Thailand. *(Doungrutai Saesangseeroong et al., p.26, fig. 8)*

2) Hangzhou Intelligent Urban Management Database (*Liu Jia et al., p.37, fig. 5)*



3) Head distribution map (*Jirapat Phetheet et al., p.47, fig. 5)*

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Triassic radiolarian assemblages from the chert-clastic rock sequences in the Kanchanaburi area, western Thailand

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Abstract

Early to early Late Triassic radiolarian assemblages have been identified in the chert-clastic rock sequences in the Kanchanaburi area, western Thailand. These rock sequences consist of well-bedded chert a few centimeters thick alternating with thin-films of shale and interbedded with siliceous shale and sometimes quartz-rich sandstone. The radiolarian assemblages are; the *Parentactinia nakatsugawaensis*, *Eptingium nakasekoi*, *Triassocampe deweveri*, Spine A2 and *Muelleritirtis cocholeata* assemblages of Early-to-early Late Triassic, which are known from Japan, USA, Russian Far East, European Tethys, northwestern Peninsular Malaysia, Philippines, and several areas in Thailand. The occurrence of the Early to early Late Triassic radiolarians from bedded chert sequences in this area suggests that the Palaeo-Tethys Ocean and Panthalassa Ocean were probably connected by seaways at this time and might have shared the same oceanic circulation system. Forty-five species belonging to 23 genera and five unidentified radiolarians with type A to E of radiolarian spines are investigated. These radiolarian-bearing rocks seem to have been deposited in a hemipelagic environment at the continental slope of the eastern margin of the Sibumasu Terrane. The occurrence of early Late Triassic radiolarians from bedded chert sequences in the Kanchanaburi area indicates that the closure of the Palaeo-Tethys Ocean occurred at least after early Late Triassic time.

Keywords: Kanchanburi, Palaeo-Tethys, Radiolarian, Sibumasu, Thailand, Triassic

1. Introduction

It is now accepted that the tectonic subdivision of mainland Thailand consists of four principal continental blocks, from west to east, Sibumasu Terrane, Inthanon Zone, Sukhothai Terrane, and Indochina Terrane (e.g., Sone & Metcalfe, 2008; Metcalfe, 2011, 2017). The origin of the two continental blocks, Sibumasu and Indochina Terrane are believed to be the northern margin of Gondwanaland. Two continental blocks drifted away from Gondwanaland at different times. The development process of the Tethyan Ocean was divided into several stages created by the rift of continental blocks, and finally, these continental blocks amalgamated to form the mainland South East Asia (e.g. Metcalfe, 1999, 2013).

Detailed age determinations based on radiolarian biostratigraphy of pelagic, hemi-pelagic and continental margin sediments distributed in Thailand are very important to elucidate the tectonic development of the Palaeozoic and Mesozoic orogenic belts and the continental collision and or closing of the Palaeo-Tethys Ocean. In Thailand, Triassic radiolarians have been reported from several areas such as the Mae Sariang area (Kamata et al., 2002), the Mae Hong Son-Mae Sariang area (Feng et al., 2005) and the Mae Sot and Umphang areas (Ishida et al., 2006) in western Thailand, the Chiang Dao area (Sashida et al., 2000a) and the Nan area (Saesaengseerung et al., 2008) in northern Thailand, the Trat area (Sashida et al., 1997) in eastern Thailand, and the Saba Yoi (Sashida et al., 2000b) and Hat Yai (Kamata et al., 2014) areas in southern peninsular Thailand (Fig 1A). These studies suggest that the radiolarian bearing-rocks are thought to have been deposited in the Palaeo-Tethys Ocean, back-arc basin or hemipelagic marginal seas. This study aims to clarify the age and infer the depositional environment of the radiolarian-bearing fine-grained siliceous rocks distributed in the Kanchanaburi area, from where we do not have sufficient radiolarian data except for the provisional reports by Sashida et al. (1998, 2019). The study area is located within the eastern part of the Sibumasu Terrane (Fig.1 A). The geological investigations were carried out in the Nong Prue district, north of Kanchanaburi City, during 2006-2008 to collect radiolarian-bearing rocks (Fig. 1B and 1C). Well to moderately preserved radiolarian faunas of the Early to early Late Triassic age and some foraminifers and sponge spicules are discovered in siliceous-rock samples. Forty-five radiolarian species belong-ing to 24 genera with 6 unidentified radiolarians and A to E types of radiolarian spines are identified.

Radiolarian specimens discussed herein were extracted from siliceous sedimentary rock by following the method described by Passagno & Newport (1972). The rock samples such as chert and siliceous shale were prepared for hydrofluoric acid treatment. The radiolarian extraction method is divided into acid treatment, sieving, drying, picking, coating, and photo-graphy. Dried residues were observed for radiolarians under the binocular microscope. Radiolarians were picked up by fine blush and took photographs with a Scanning Electron Microscope (SEM) and coated with gold.

2. Tectonic framework of Thailand

The mainland of Thailand is traditionally regarded as consisting of two principal continental blocks, the western Sibumasu (Shan-Thai Terrane in part) and eastern Indochina blocks which were thought to have been positioned along the outer margin of northern Gondwanaland in the Early Palaeozoic around the palaeoequator (Bunopas, 1981, 1992; Metcalfe, 2005). The Sibumasu and Indochina terranes are separated by the remnants of the Palaeo-Tethys Ocean such as the northern Nan-Uttaradit (Nan) and southern Sra (Sa) Kaeo-Chanthaburi suture zones (Bunopas, 1981, 1992; Metcalfe, 1999; Hada et al., 1999; Mantajit, 1999, Agematsu et al., 2006; Wonganan & Caridroit, 2005; Ishida et al., 2006). Recently, several investigators have contributed to the study of the tectonic evolution in northern and western Thailand and various opinions regarding the boundary as a remnant of the Palaeo-Tethys Ocean have been proposed. They are the Mae Hong Son-Mae Sariang region (also called Mae Yuam Fault Zone) (Helmcke, 1985; Ueno & Igo, 1997; Ferrari et al., 2008), and the Chiang Mai Suture Zone (Metcalfe, 2002, 2011) or the Inthanon Suture Zone (Sone & Metcalfe, 2008). Furthermore, the Nan-Uttaradit suture in northern Thailand has been regarded as representing a segment of the back-arc basin which opened in Carboniferous time between the Sukhothai Terrane and Indochina Terrane (Ueno & Hisada, 1999; Wang et al., 2000; Metcalfe, 2011). They are interpreted as an extensive accretionary complex of the closed Palaeo-Tethys Ocean and consist of various types of rocks such as basaltic volcanics, limestones, radiolarian chert, S-type granitoids and mylonitic/gneisses (Sone & Metcalfe, 2008). The Indochina Block possibly drifted away from Gondwanaland in the Devonian. The Sibumasu Block lifted from Gond-wanaland after the Early Permian and collided with the Indochina Block in the Late Triassic, after the closing the Palaeo-Tethys Ocean (e.g., Bunopas, 1981; Metcalfe, 1999, 2011, 2017).

Concerning the previous works of Triassic radiolarian fauna and their palaeogeography in northwestern Thailand, Kamata et al., (2002) discovered Triassic radiolarian faunas from the Mae Sariang area and suggested that the chert of the Mae Sariang Group seems to have been deposited on an eastern continental margin of the Sibumasu Block. The occurrence of Late Triassic (early Carnian) radiolarians from the Mae Sariang area indicates that the closure of the Palaeo-Tethys Ocean occurred after the early Carnian. Feng et al. (2005) reported Permian and Triassic radiolarians from north-western Thailand along the highway from Mae Hong Son to Mae Sariang. They suggested that radiolarian-

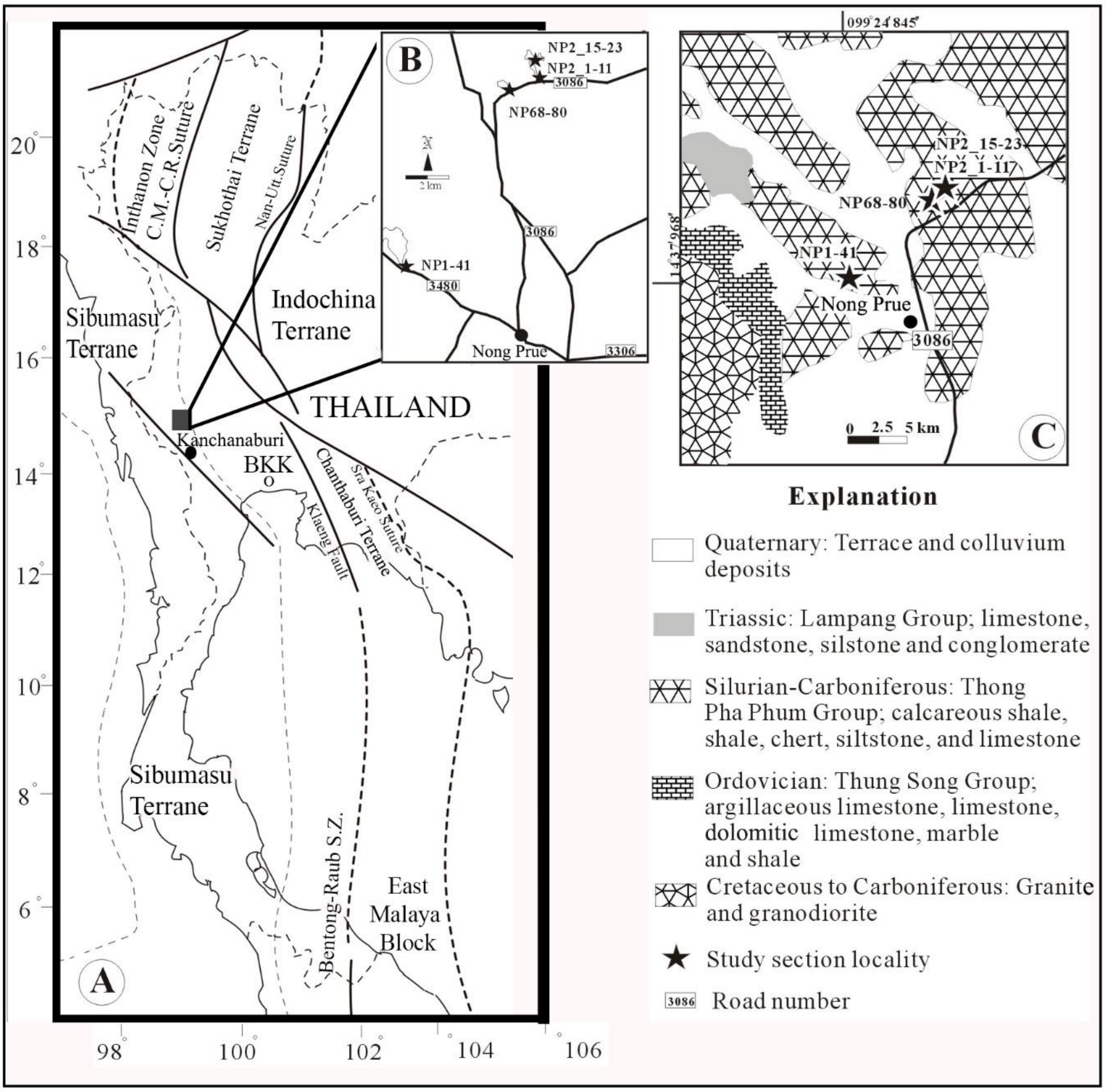

Fig. 1: (A) Index map showing the study area, faults, and sutures in Thailand. Basic Map is from Metcalfe (2017). (B) The locality map of the study sections in the Nong Prue area. (C) Simplified geological map of the Nong Prue district, Kanchanaburi Province, western Thailand. (After the Geological Map of Thailand by Department of Mineral Resources, Thailand, 1999).

-bearing rocks were accumulated at a pelagic basin during the Late Palaeozoic and Triassic and the Sibumasu Block was not a single block during this age span, but compose of the Palaeotethyan Ocean and two continental terranes that were affiliated with the Gondwana (Tengchong-Phuket terrane) and Cathaysian (Simao-Lampang terrane) domains. Furthermore, Ishida et al. (2006) studied the Middle to Late Triassic (Ladinian to Rhaetian) radiolarians in the Mae Sot and Umphang areas, the westernmost part of Thailand and showed new micropalaeontological evidence for a Late Triassic orogeny (late Indosisian).

3. Lithology and lithostratigraphy

Seven study sections of chert-clastic rock sequences were investigated for the litho-logical analysis (Fig. 1B). Sections NP 1-14, NP 15-21, and NP 22-41 (099°24′845″E, 14°37′968″N) are roadcut outcrops and small quarry along road no. 3480 about 5 km northwest of Nong Prue city. Section NP 57-67, NP 68-80, NP 2-1-11, and NP 2-15-23 are in quarry outcrops of a small hill, northern side of the road no. 3086 about 10 km north of the Nong Prue city. Based on the geological map of Thailand (1999), the localities of the study sections belong to the

Thong Pha Phum Group (Silurian-Carbo--niferous) which consists of calcareous shale, shale, chert, siltstone, and limestone (Fig. 1C). Folding and faulting are observed at all of the study sections. Well bedded chert (gray to black or green color), normally has a thickness of few centimeters alternated with thin-films of shale and interbedded with shale, siliceous shale, and sometimes quartz-rich sandstone layers. Section NP 1-14 is at a quarry about 20 m thick and consists of greenish bedded chert (bed about 2-20 cm thick) alternated with thin-films of shale and siliceous shale. Based on the radiolarian analysis, the sequence of chert in this outcrop is overturned completely. Section NP 15-21 is at a small quarry is about 7 m thick and is consisting of gray chert (bed about 3-20 cm thick) alternated with thin-films of shale and siliceous shale. Sandstone layers are presenting irregularly by fault cutting in the lower part of this section. Section NP 22-41 (about 18 m thick) is a roadside outcrop and consists of greenish bedded chert alternated with thin-films of shale and siliceous shale and interbedded with quartz-rich sandstone beds (Fig. 4A). Section NP 57-67 is at a quarry about 10 m thick, and is consisting of black siliceous shale in the lower part and is overlain by the gray-greenish bedded chert (bed about 2-20 cm thick) alternated with thin-films of shale and siliceous shale. Section NP 68-80 is also at a small quarry, about 12 m thick, and is consisting of gray to greenish bedded chert (bed about 3-20 cm thick) alternated with thin-films of shale and siliceous shale. Section NP 2-1-11 is a quarry outcrop in the Wat Wangwanaram (temple) (099º27′672″E, 14º41′822″N) and has about 20 m thickness consisting of sandstone bed in the top and is unconformably covered by gray to black shale (about 5 m thick). Greenish gray chert (bed about 5 cm thick) is alternated with thin-films of shale and siliceous shale. Section NP 2-15-23 is in the big quarry outcrop, about 0.5 km north of Sections NP 2-1-11. This section is about 6 m thick consisting of gray-black shale (about 1 m thick) in the lowermost and is overline by green-black bedded chert (bed about 2-20 cm thick) which is alternated with thin-films of shale and siliceous shale in the upper part. The lithologic column and stratigraphic distribution of radiolarian species of the study sections are showing in Figs 2 and 3. Under the microscope, the quartz-rich sandstone is coarse, poorly sorted and consists of subangular to subrounded quartz grains with a few feldspar and rock fragments (Figs 4B-4D). The chert has a matrix consisting of microcrystalline quartz that includes radiolarian tests, sponge spicules, and calcareous organisms such as foraminifers. This chert contains terrigenous quartz grains larger than silt-sized particles (Figs. 4E-4G).

The sedimentary structures of these rocks are shown in Fig. 5. The contact between the chert and sandstone beds is not strongly deformed (Figs 5A and 5B). Some cherts are shown the lateral change of the clay layer to the siliceous part (Fig. 5C). In the base of bedded chert, we can see load-casted structures (Figs 5F and 5G). Moreover, this chert has a small sandstone lens in which angular chert fragments are present (Fig. 5I). Convolute bedding structure (Fig. 5E) and plane lamination (Fig. 5D) were also present in shale, chert, and siliceous shale. Some mudrock-chert shows characteristics of soft-sediment which are folded and partially fluidized (Fig. 5H). Based on these lithological characteristics, these rocks seem to have been deposited at the rather high angle slope in a hemipelagic basin rather than at a flat plane of the continental shelf or deep ocean basin. Furthermore, the study sections are quite different from those of a sandstone-chert mélange which is a chaotic mixture derived mainly from the dismembered upper part of the Ocean Plate Stratigraphy (Wakita & Metcalfe, 2005).

4. Radiolarian fauna and age assignment

Radiolarians obtained from chert and siliceous shale successions in the study area are shown in Figs. 2 and 3 and the selected species are shown in Figs. 6-8. We establish the following five radiolarian assemblages in chert sections from Kanchanaburi, in ascending order; the *Parentactinia nakatsugawaensis*, *Eptingium nakasekoi*, *Triassocampe deweveri*, Spine A2, and *Muelleritortis cocholeata* assemblages.

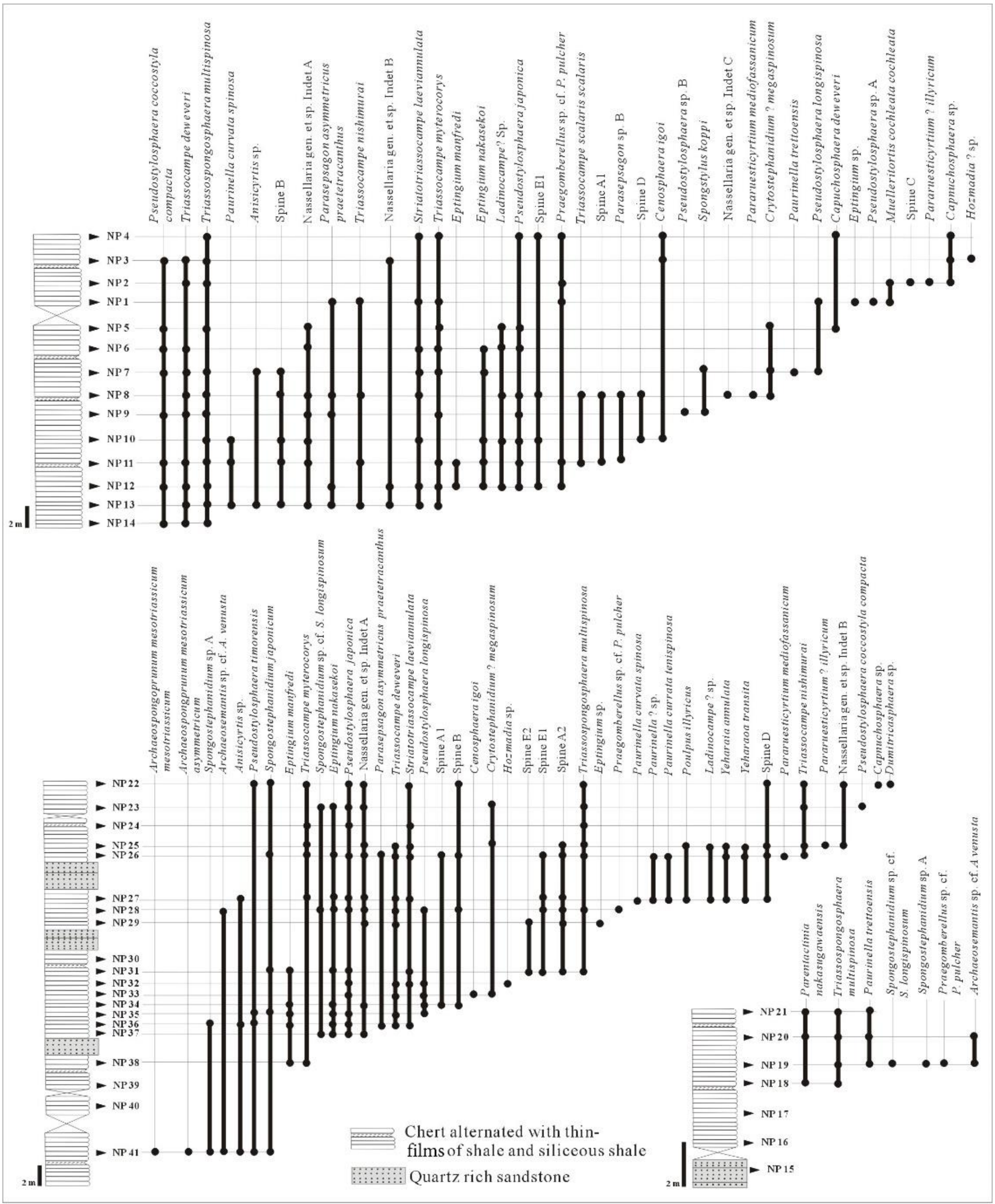

Fig. 2: Lithostratigraphic column and stratigraphic distribution of radiolarians in Section NP1-14, NP 15-21 and NP 22-41

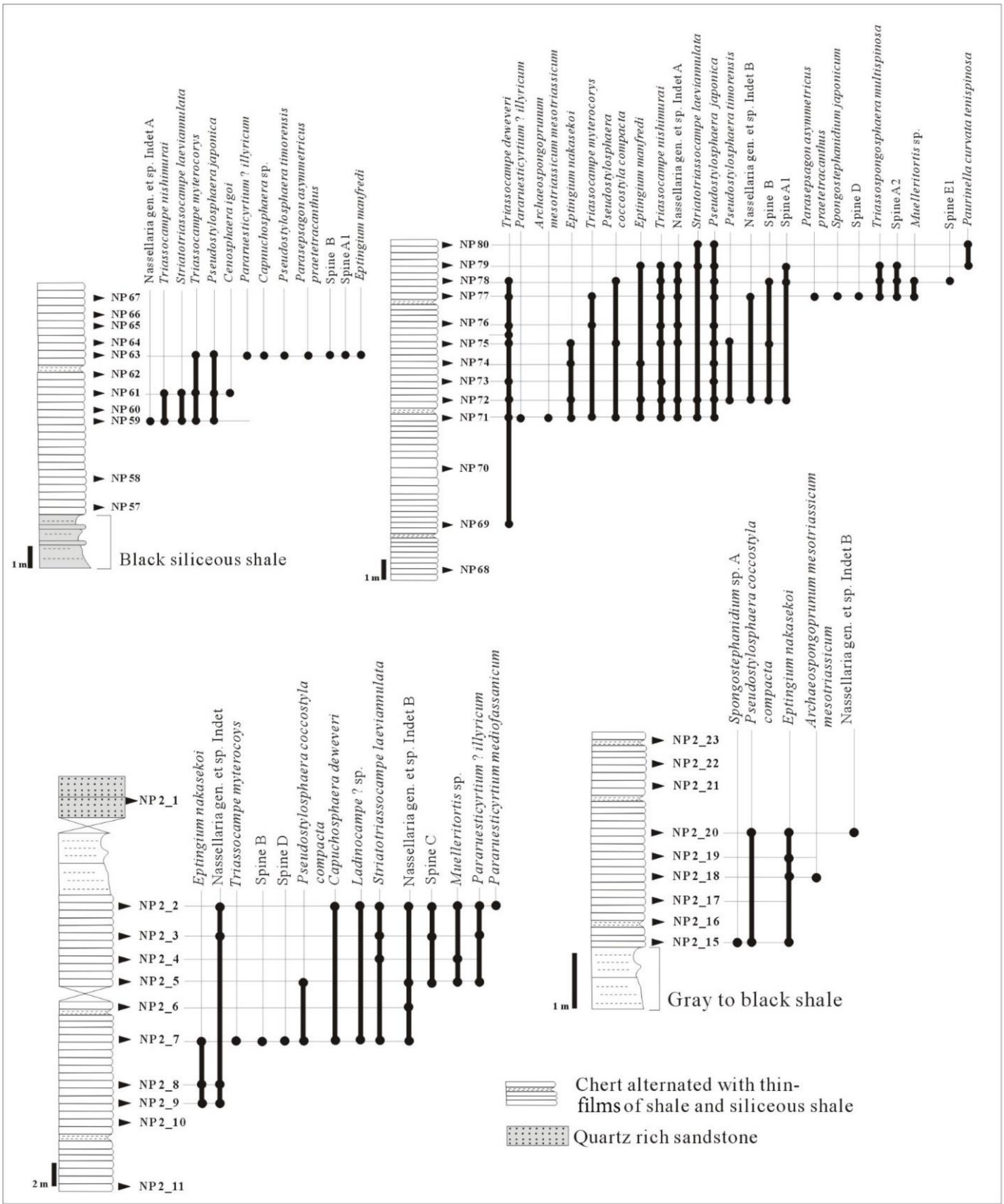

Fig. 3: Lithostratigraphic column and stratigraphic distribution of radiolarians in Section NP 57-67, NP 68-80, NP2_1-11 and NP2_15-23.

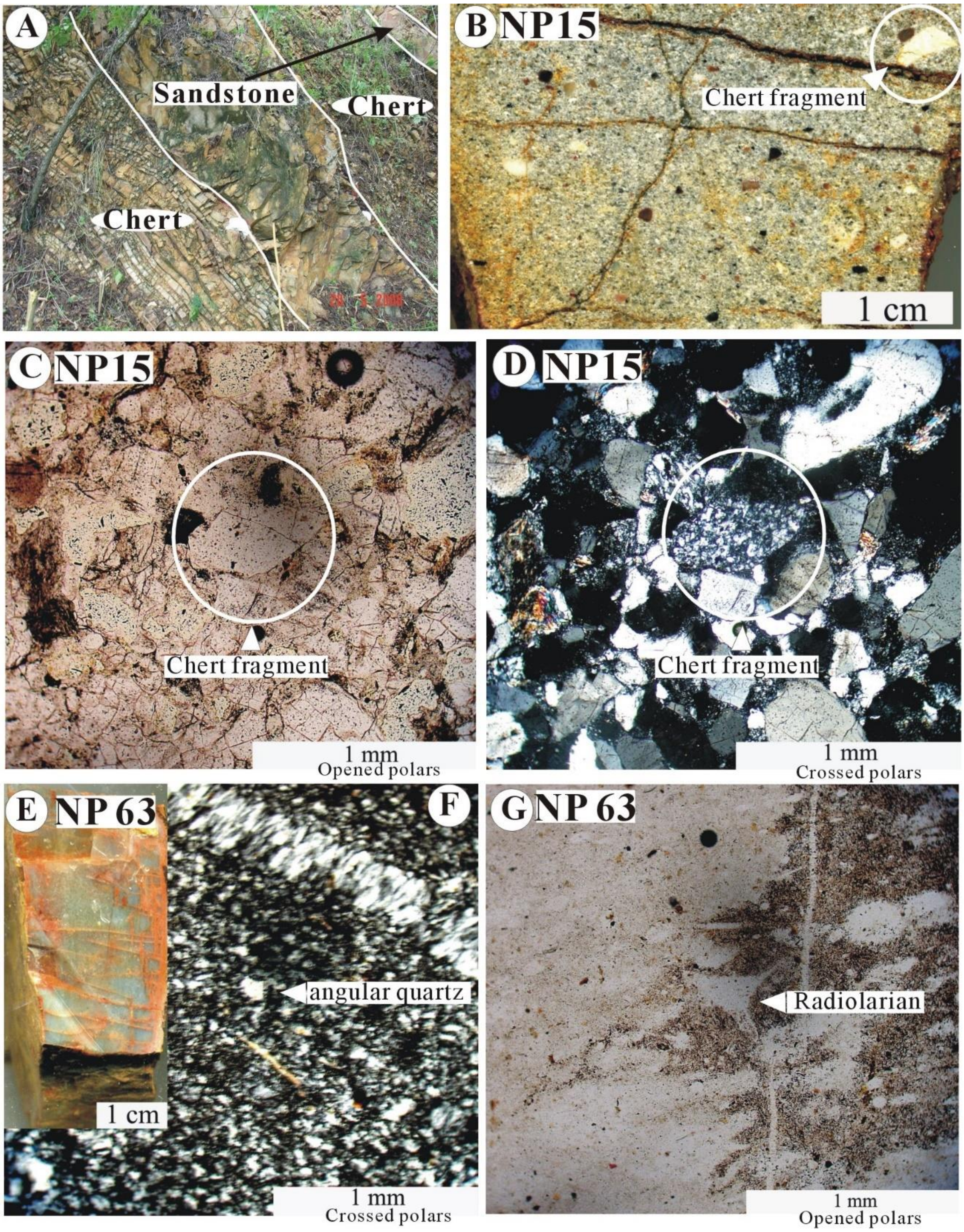

Fig. 4: (A) Photo of the chert-clastic rock sequence showing bedded chert intercalated with sandstone bed. (B) The polished surface of quartz-rich sandstone (sample number NP 15) (C and D) Microphotographs of the sample number NP 15 (E) Polished surface of chert (sample number NP 63) (F and G) Microphotographs of sample number NP 63

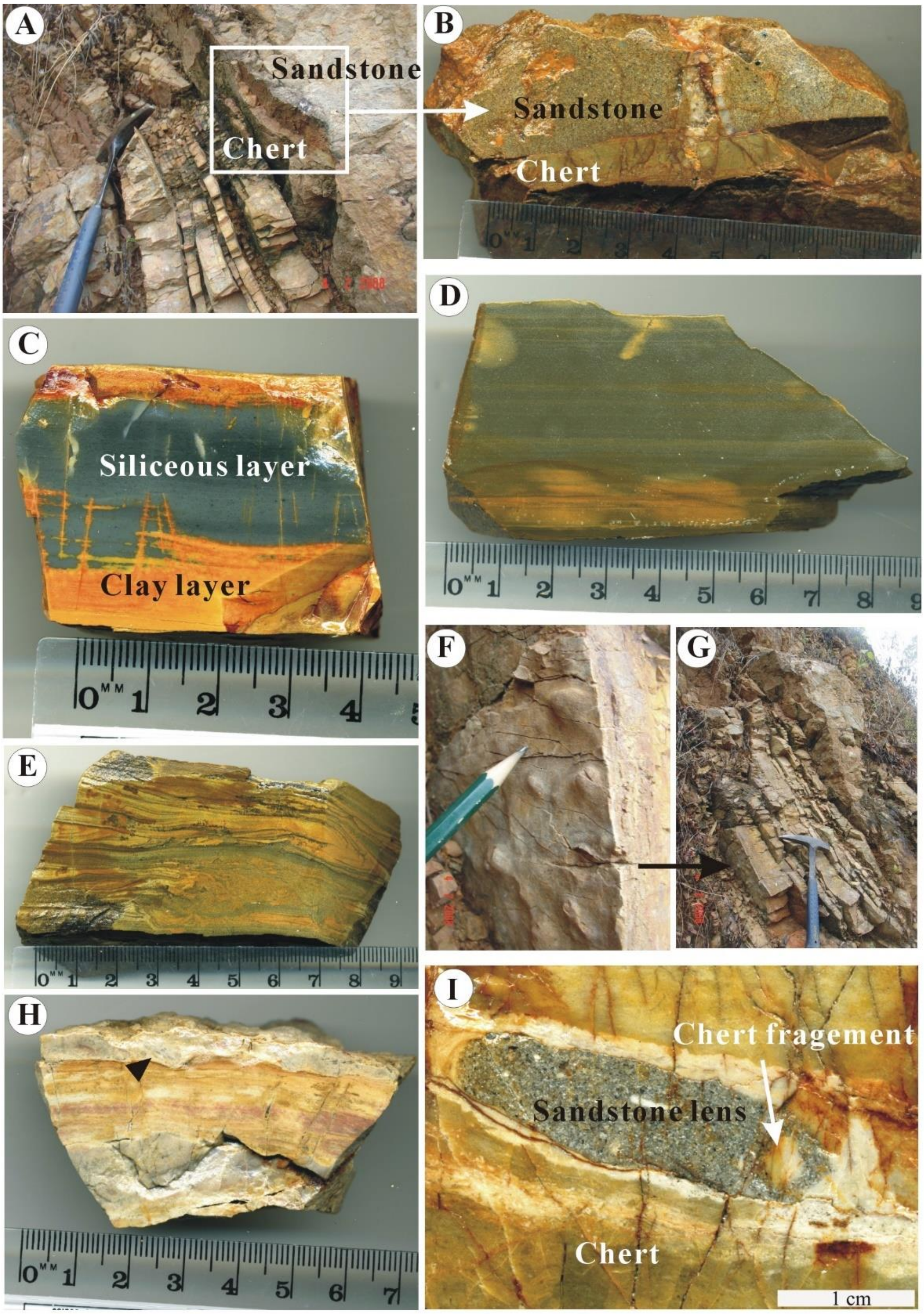

Fig. 5: (A) Photo of outcrop showing bedded chert associated with sandstone bed. (B) Polished surface photo showing the contract boundary of chert and sandstone samples. (C) Lateral change of clay layer and siliceous part (D) Plane lamination in black shale (E) Convolute bedding structure in shale (F and G) Load-casted structure in bedded chert (H) Soft- sediment folded and partially fluidized sets (I) Sandstone lens in chert sample

The *P. nakatsugawaensis* assemblage is identified only in the section NP 15-21. The following radiolarian species characterize this assemblage; *Praegomberellus* sp. cf. *P. pulcher* Kozur and Mostler, *Triassospongosphaera multispinosa* (Kozur and Mostler), *Spongostephanidium* sp. cf. *S. longispinosum* Sashida, *Spongostephanidium* sp. A and *Archaeosemantis* sp. cf. *A. venusta* Sashida. A similar radiolarian fauna has been reported from Ban Huai Tin Tang, north of Chiang Dao, northern Thailand (Sashida et. al, 2000a), the Mae Sariang area (Kamata et. al, 2002) and the Hat Yai area of southern Peninsular Thailand (Kamata et al., 2014). Although we do have "*Follicucullus*" which is a representative genus of the Middle to Late Permian and known from late Olenekian, this assemblage is roughly correlated to the late Olenekian TR0 or TR1 of Sugiyama (1997).

The *E. nakasekoi* assemblage was recognized in the Sections NP-2-1-11, and NP-2-15-23. This assemblage is characterized by the occurrence of *Pseudostylospahera coccostyla compacta*, *Spongostylus* sp. A and Nassellaria gen. et sp. indet. The first occurrence of *E. nakaekoi* defines the base of TR2A (Sugiyama, 1997), and this assemblage lacks the multisegmented Nasselarinas such as *Triassicampe*, this assemblage is correlated to TR2A by Sugiyama (1997). The age of this assemblage may be early Anisian. A similar radiolarian fauna has been described from the Hat Yai area of southern Peninsular Thailand (Kamata et al, 2014).

The *Triassocampe deweveri* assemblage was identified in the sections NP-4-14, NP-22-41, and NP-68-80. This assemblage is characterized by the occurrence of *Spongostephanidium japonicum* (Nakaseko and Nishimura), *Pseudostylosphaera coccostyla compacta* (Nakaseko and Nishimura), *P. japonica* (Nakase ko and Nishimura), *Cenosphaera igoi* Sashida, *T. nishimurai* Kozur and Mostler, *T. myterocorys* Sugiyama, *Yeharaia annulata* Nakaseko and Nishimura, *Y. transita* Kozur and Moslter, *Pararuesticyrtium mediofassanicum* Kozur and Mostler, *Eptingium manfredi* Dumitrica, and others. This fauna resembles TR2C (Sugiyama, 1997), of which the base is defined by the first occurrence of *T. deweveri*. The age of this assemblage is assigned to be Middle Triassic (middle to upper Anisian) based on the age of associated conodonts (Sugiyama, 1997). A similar radiolarian fauna is known from the Trat area of Eastern Thailand (Sashida et al., 1997) and the Hat Yai area of southern Peninsular Thailand (Kamata et al., 2014).

The Spine A2 assemblage is recognized in the sections NP-22-38 and NP-68-80. The species of this assemblage is almost the same as the *T. deweveri* assemblage but is distinguished by the occurrence of Spine A2. According to Sugiyama (1997), the first occurrence of Spine A2 defines the base of TR3A (Sugiyama, 1997). Based on the faunal similarity and the occurrence of Spine A2, this assemblage can be correlated with the latest Anisian TR3A of Sugiyama (1997). A similar radiolarian fauna has been reported from the Hat Yai area of southern peninsular Thailand by Kamata et al. (2014).

The *Muelleritortis cochleata* assemblage is recognized in the Sections NP-4-14 and NP-2-1-2.11. This assemblage is characterized by the occurrence of *Capnuchosphaera* sp., *Dumitricasphaera* sp., *Y. annulata*, *Y. transita*, *P. mediofassanicum*, Spine A to E, and others. The faunal composition of this assemblage except for the occurrence of *Capnuchoshaera* is similar to that of TR4A (Sugiyama, 1997). This assemblage may be correlated to the late Ladinian TR4A of Sugiyama. However, in the presence of the genus *Capnchospahera*, the age of this assemblage can range up into Late Triassic (early Carnian; TR5A by Sugiyama, 1997). A similar radiolarian fauna has been reported from the Mae Sariang area (Kamata et al., 2002).

In summary, five radiolarian assemblages from the bedded chert sequences in the Kan chanaburi area correspond to TR or TR1, TR2A, TR2B, TR3A, and TR4A or (TR5A) of Sugiyama (1997), respectively, which indicate Early to Middle Triassic (or early Late Triassic), late Olenekian (Late Spathian) to Ladinian (or early Carnian).

5. Systematic Palaeontology

The taxonomical framework is followed by De Wever et al. (2001) and O'Dogherty et al. (2009a, b). The palaeontological investigation was undertaken by D. Saesaengseerung. Synonym lists are limited only for selected ones that have descriptive works. Radiolarian species discussed in this paper are stored in the collection of the DMR and shown in Figs 6-8.

Class Actinopoda

Subclass Radiolaria Müller, 1858

Superorder Polycrystina Ehrenberg, 1838, emend. Riedel, 1967

Order Spumellaria Ehrenberg 1875, emend De Wever et al., 2001

Family Actinommidae Haeckel, 1862, emend. Reidel, 1967

Genus *Cenosphaera* Ehrenberg, 1854

Type species *Cenosphaera plutonis* Ehrenberg, 1854

***Cenosphaera igoi* Sashida, 2000a**

Figure 8.27

Cenosphaera igoi Sashida. Sashida et al., 2000a, p. 804, figs. 10.7, 10.8; Saesaengseerung et al., 2008, p. 403, fig. 8.26; Munasri & Putea, 2019, p. 6, 7, figs. 6a-6f.

Remarks: Our specimens resemble the holotype and paratypes of the species *Cenosphaera igoi*, having a rather thick-walled spherical shell with about 100 circular pores on a hemisphere. Pores are usually hexagonally framed and bear small spines at vertices. This species differs from *C. andoi* Sugiyama, 1992 described from Mino Terrane, central Japan by having circular pores.

Occurrence: Triassic from the Kanchanaburi area, western Thailand, northern Thailand, and Sumatra Island, Indonesia.

Superfamily Sponguracea Haeckel, 1862

Family Archaeospongoprunidae Pessagno, 1973

Type genus: *Archaeospongoprunum* Pessagno, 1973

Genus *Archaeospongoprunum* Pessagno, 1973

Type species: *Archaeospongoprunum venadoensis* Pessagno, 1973

***Archaeospongoprunum mesotriassicum mesotriassicum* Kozur & Mostler, 1981**

Figure 7.29

Archaeospongoprunum mesotriassicum mesotriassicum Kozur & Mostler, 1981, p. 41, pl. 42, fig. 4; Kozur & Mostler, 1994, p. 53, pl. 7, fig. 3.

Remarks: Several examined specimens are consisting of shell asymmetrically spindle-shaped with several layers of a fine-spongy meshwork. This species differs from *A. bispinosum* Kozur & Mostler (1981) by having two polar spines.

Occurrence: Middle Triassic from the Kanchanaburi area, western Thailand, and European Tethys.

***Archaeospongoprunum mesotriassicum asymmetricum* Kozur & Mostler, 1981**

Figures 7.26 and 7.30

Archaeospongoprunum mesotriassicum asymmetricum Kozur & Mostler, 1981, p. 41, pl. 42, fig. 3; Kozur & Mostler, 1994, p. 53, pl. 7, fig. 4

Remarks: Examined specimens differ from *A. mesotriassicum mesotriassicum* Kozur & Mostler by having asymmetrical spongy shell.

Occurrence: Middle Triassic from the Kanchanaburi areas, western Thailand, and Europea Tethys.

Family Gomberellidae Kozur & Mostler, 1981

Type genus: *Gomberellus* Dumitrica, Kozur & Mostler, 1981

Genus *Praegomberellus* Kozur & Mostler, 1994

***Praegomberellus* sp. cf. *P. pulcher* Kozur & Mostler, 1994**

Figure 8.25

Praegomberellus pulcher Kozur & Mostler, 1994, p. 58, pl. 9, figs. 6, 8

Remark: Poorly-preserved specimens were recovered, which slightly resemble *Praegomberellus pulcher* Kozur & Mostler by having diagnostic features. They are a sub-globular spongy shell with numerous spines. The spines have three-ridges and equal length of which three are closely spaced around one pole and other spines are irregularly distributed. However, spine poles of the examined speci-men are unclear.

Occurrence: Triassic from Kanchanaburi area, western Thailand, and European Tethys.

Family Pyramispongiidae Kozur & Mostler, 1978, emend. De Wever et al., 2001

Type genus: *Pyramispongia* Pessagno, 1973

Genus *Triassospongosphaera* (Kozur & Mostler, 1979)

Type species: *Triassospongosphaera triassicus* Kozur & Mostler, 1979

***Triassospongosphaera multispinosa* (Kozur & Mostler, 1979)**

Figure 8.26

Acanthospongosphara multispinosa Kozur & Mostler, 1979, p. 50. pl. 20, fig. 3

Triassospongosphaera multispinosa Kozur & Mostler, 1979. Kozur & Mostler, 1981, p. 67, pl. 58, fig. 3; Lahm, 1984, p. 66, 67, pl. 11 fig. 10; Sashida et al. 1999a, p. 772, figs 8.14, 8.15; Feng et al., 2009, p. 591, figs. 5.20-5.22.

Remarks: Examined specimens have a spongy shell with several straight and rod-like spines. Each specimen has equal spines. Although internal shell structure cannot be determined, outer shell features resemble those of the above-listed specimens of this species.

Occurrence: Triassic from the Kanchanaburi area, western Thailand, European Tethys, Timor Island, Indonesia, and northern Tibet.

Genus *Paurinella* Kozur & Mostler, 1981

Type species: *Paurinella curvata* Kozur & Moslter, 1981

***Paurinella trettoensis* Kozur & Mostler, 1994**

Figure 8.22

Paurinella trettoensis Kozur & Mostler, 1994, p. 74, pl. 15, fig. 15

Remarks: Shell is sub-spherical, spongy, with three needle-like spines, one of which is very long, the other 2 are short. Although one of the spines and internal layer cannot be determined, other features are identical to those of *P. trettoensis* Kozur & Mostler.

Occurrence: Middle Triassic from the Kanchanaburi area, western Thailand, and European Tethys.

***Paurinella curvata spinosa* Kozur & Mostler, 1994**

Figure 7.33

Paurinella curvata tenispinosa Kozur & Mostler, 1994, p. 71, pl. 15, figs. 1, 8

Remarks: Shell is characterized by having numerous layers of a spongy network around a microsphere with three main spines and no by-spines. The three main slender spines have round cross-sections and each are curved in a different direction from the plane. Two of the main spines are always curved against each other. Our poorly preserved specimens do not display the needle-like by-spines.

Occurrence: Middle Triassic from the Kanchanaburi area, western Thailand, and European Tethys.

***Paurinella curvata tenispinosa* Kozur & Mostler, 1994**

Figures 7.31 and 7.32

Paurinella curvata tenispinosa Kozur & Mostler, 1994, p. 71, pl. 15, figs. 2, 3

Remarks: This species differs from *P. curvata spinosa* Kozur & Mostler by having two main spines curved against each other and the absence of by-spines.

Occurrence: Middle Triassic from the Kanchanaburi area of western Thailand and European Tethys.

Paurinella? sp.
Figure 8.16

Remarks: Shell is characterized by having numerous layers of spongy network with four main spines and no by-spines. This form is questionably included in the genus *Paurinella* because of the presence of four main spines.

Occurrence: Middle to Late Triassic from the Kanchanaburi area of western Thailand.

Family Oertlispongidae Dumitrica, Kozur & Mostler, 1980

Type genus *Oertlispongus* Dumitrica, Kozur & Mostler, 1980

Genus _Paroertlispongus_ Kozur & Mostler, 1981

Type species: *Paroetlispongus multispinosus* Kozur & Mostler, 1981

Spine A1

Paroertlispongus multispinosus Kozur & Mostler, 1981

Figure 7.6

Paroertlispongus multispinosus Kozur & Mostler 1981, p. 48, pl. 1, fig. 3; Lahm, 1984, p. 45, pl. 7, figs. 5, 6; Kozur & Mostler, 1994, p. 69, pl. 12, fig. 10, pl. 13, fig. 4, 11; Kozur, 1996, p. 291, pl. 1, fig.1; Feng et al., 2001, p. 192, pl. 6, figs. 12, 14—18; Feng et al., 2009, p. 587, figs. 4-2, 4-3.

Remark: Spines are rod-like and straight consisting of a conical root and a long stem gradually tapering to an ended. Possible derivation of these spines is *Paroertlispongus multispinosus* Kozur & Mostler (1981) by having straight and thick spines. This spine is similar to that of *Oertlispongus diacanthus* Sugiyama, 1992, but the later spine is longer than the present spines.

Occurrence: Middle to Late Triassic from the Kanchanaburi area, western Thailand, northern Thailand, European Tethys, southern Turkey (Tekin et al., 2016), northern Tibet, southwest Yunnan, China.

Genus _Oertlispongus_ Dumitrica, Kozur & Mostler, 1980

Type species: *Oertlispongus inaequispinosus* Dumtrica, Kozur & Mostler, 1980

Spine A2

Oertlispongus inaequispinosus Dumitrica, Kozur & Mostler, 1980

Figures 7.8 and 7.9

Oertlispongus inaequispinosus Dumitrica, Kozur & Mostler, 1980, p. 5, pl.10, fig. 7; Kozur & Mostler, 1996, p. 108, 109, pl. 14, figs. 10, 11; Feng et al., 2009, p. 589, figs. 4. 18-4.22.

Oertlispongus inaequispinosus inaequispinosus Dumitrica, Kozur & Mostler, 1994, p. 61, pl. 10, figs. 1, 3.

Spine A2, Sugiyama, 1997, p. 137, 138, fig. 35.3

Remark: Spines are rod-like and curved. The curvature varies from a form with a slightly curved distal end to another strongly curved, sickle-like spine. The derivation of Spine A2 is *Oertlispongus inaequispinosus* Dumitrica, Kozur & Mostler, 1980.

Occurrence: Middle to Late Triassic from the Kanchanaburi area, western Thailand, southern Peninsular Thailand (Kamata et al., 2014), northern Tibet, southern Turkey (Tekin et al., 2016), and European Tethys.

Genus _Pseudoertlispongus_ Lahm, 1984

Type species: *Pseudoertispongus weddigi* Laham, 1984

Spine B

Pseudoertlispongus angulatus Kozur, 1996
Figure 7.7
Pseudoertlingus angulatus Kozur, 1996, p. 291, 292, pl. 1, figs. 4, 5.

Remark: Spines are rod-like and curved in the end. The possible derivation of Spine A2 is *Pseudoertlispongus angulatus* Kozur.

Occurrence: Middle to Late Triassic from the Kanchanaburi area, western Thailand, and southern Turkey (Tekin et al., 2016).

Genus *Dumitricasphaera* Kozur & Mostler, 1979 emend Lahm 1984

Type species: *Dumitricasphaera goestlingensis* Kozur & Mostler, 1979

***Dumitricasphaera* sp.**

Figure 7.13

Remarks: The illustrated specimen has a spherical spongy shell and two polar spines. Polar spines are three-bladed and very stout. The spinule on the top of polar spines curved downwards following the outline of the spongy shell. This feature is similar to that of genus *Dumitricasphaera* Kozur and Mostler.

Occurrence: Triassic from Kanchanaburi area, western Thailand.

Spine C

***Dumitricasphaera planustyla* Lahm, 1984**

Figure 7.12

Dumitricasphaera planustyla Lahm, 1984, p. 71, pl. 12, fig. 9

Remark: Examined specimens are similar to the polar spines of *Dumitricasphaera planustyla* Lahm. However, they have the polar spines which have shorter branches and the branch of the slightly curved polar spine.

Occurrence: Middle to Late Triassic from the Kanchanaburi area, western Thailand, and European Tethys.

Genus *Falcispongus* Dumitrica, 1982

Type species: *Falcispongus falciformis* Dumitrica, 1982

Spine D

***Falcispongus falciformis* Dumitrica, 1982**

Figures 7.1-7.5

Falcispongus faciliforma Dumitrica, 1982, p. 66, pl.1, fig. 5, pl. 2, figs. 1, 3, 7, pl. 3, figs. 2, 3, 5, 6.; Feng et al., 2009, p. 589, fig. 4.13-4.16, 4.27-31.

Remark: Examined spines have the outer wing which widens proximally and gradually tapers distally. The wing portion of the main spine is quite similar to the spine shape of *Falcispongus falciformis* Dumitrica.

Occurrence: Middle to Late Triassic from the Kanchanaburi area, western Thailand, northern Tibet, and European Tethys.

Genus *Baumgartneria* Dumitrica, 1982

Type species: *Baumgartneria retrospina* Dumitrica, 1982

Spine E1

***Baumgartneria retrospina* Dumitrica, 1982**

Figure 7.10

Baumgartneria retrospina Dumitrica, 1982, p.70, pl. 9, figs. 2-8, pl. 10, figs. 1,2, pl. 12, fig. 3.

Remark: Several poorly-preserved specimens are examined. These spines have triangular and broad axial forms. The wing portion of the main spine is quite similar to the spine shape of *Baumgartneria retrospina* Dumitrica.

Occurrence: Middle to Late Triassic from the Kanchanaburi area, western Thailand, southern Turkey (Tekin et al., 2016), and European Tethys.

Spine E2

***Baumgartneria bifurcata* Dumitrica, 1982**

Figure 7.11

Baumgartneria bifurcate Dumitrica, 1982, p.71, pl. 10, figs. 3, 4; Kozur & Mostler, 1994, p. 64, pl. 13, figs. 3, 5, 6, 10.

Remark: Several poorly-preserved specimens are spines without a spongy shell. These spines have straight branches spine and perpendicular to the stem. The wing portion of the main spine is quite similar to the spine shape of morphotype II, *Baumgartneria bifurcata* Dumitrica.

Occurrence: Middle Triassic from the Kanchanaburi area, western Thailand, Japan (Sugiyama, 1997), southern Turkey (Tekin et al, 2016), and European Tethys.

Family Stylosphaeridae Haeckel, 1882

Genus *Spongostylus* Haeckel, 1882

Type species: *Spongostylus hastatus* Haeckel, 1882

Spongstylus koppi (Lahm, 1984)

Figure 7.25

Cromyostylus? *kopi* Lahm, 1984, p. 68, pl. 12, figs. 1, 2.

Spongopallium? *koppi* (Lahm). Gorican & Buser, 1990, p. 157, pl. 4, fig. 1

Spongstylus koppi (Lahm). Sashida et al., 1999a, p. 771, fig. 8.12

Remarks: This species has a spongy shell with two thin and slightly twisted polar spines which distinguish this species from other species in genus *Spongostylus* Haeckel. This form is identified to *Spongstylus kopi* (Lahm) by having diagnostic shell features.

Occurrence: Middle Triassic from the Kanchanaburi area, western Thailand. This species has been reported from the Middle Triassic (Anisian to Ladinian) in European Tethys, southern Turkey (Tekin et al., 2016), and Timor Island.

Order Entactinaria Kozur and Mostler, 1982

Family Palaeoscenidiidae Riedel, 1967, emend. De Wever et al., 2001

Type genus: *Palaeoscenidium* Deflandre, 1953

Genus _Parentactinia_ Dumitrica, 1978b

Type species: *Parentactinia pugnax* Dumitrica, 1978b

Parentactinia nakatsugawaensis Sashida, 1983

Figure 8.3

Parentactinia nakatsugawaensis Sashida, 1983, p. 172-173, pl. 37, fig. 1-9; Sashida, 1991, p. 687-689, figs. 5-15, 16, 6.1, 6.3-6.6; Sugiyama, 1992, p. 1212-1213, figs. 14.7a-14.10; Blome & Reed, 1992, p. 376, figs. 13.7, 13.12; Sashida et al. 2000a, p. 801, fig. 8. 24; Sashida, et al., 2000b, p. 86, figs.7.1-7.7 Kamata et al. (2002), p. 491-506, figs. 5A; Takahashi & Miyake, 2014, p.286, figs. 204.1-204.3

Remarks: Most of the specimens have a loose latticed shell, which is a diagnostic character of this species. The specimen is incomplete but has the skeletal characters of *P. nakatsugawaensis* Sashida, 1983 such as a short median bar, short apical spines, and long basal spines.

Occurrence: Early to Middle Triassic from the Kanchanaburi area, western Thailand. This species has been reported from the Early to Middle Triassic (Olenekian to Anisian) in Japan, Vietnam, southern and northern Thailand, and North America.

Family Eptingiidae Dumitrica, 1978a

Type genus: *Eptingium* Dumitrica, 1978a

Range: Middle Triassic (Anisian) to Late Jurassic (Tithonian)

Genus _Eptingium_ Dumitrica, 1978a

Type species: *Eptingium manfredi* Dumitrica, 1978a

Eptingium nakasekoi Kozur & Mostler, 1994

Figure 8.8

Eptingium nakasekoi Kozur and Mostler, 1994, p. 43, pl. 1, fig. 5; Sugiyama, 1997, p. 176, figs. 27-4, -5; Spiller, 2002, p. 38, pl. 4, fig. q; Feng et al., 2009, p. 596, fig. 6.8.

Remarks: Three main spines of this species are characterized by the grooves and ridges, pointed in ends that are almost the same length.

Occurrence: Middle Triassic from the Kanchanaburi area, western Thailand, southern Peninsular Thailand (Kamata et al., 2014), Japan, European Tethys, northwestern Malaysia, northern Tibet, and southern Turkey (Tekin et al., 2016).

Eptingium manfredi Dumitrica, 1978a

Figure 8.7

Eptingium manfredi Dumitrica, 1978a, p. 7, 8, pl. 3, figs. 3, 4, pl. 4, figs. 1, 2, 5-7; Gorican & Buser, 1990, p. 144, pl. 8, figs. 7, 8; Yeh, 1990, p. 23, pl. 6, figs. 4, 5, 8, 9; Bragin, 1991, p. 109, pl. 2, figs. 12, 13; Sashida et al., 1993b, p. 82, 83, fig. 6.1, 6.2; Kellic & De Wever, 1995, p. 144, 145, pl. 1, figs. 11, 12; Kozur et al., 1996, p. 204, 205, pl. 10, figs. 1-4, 6, 10; Sashida et al.,1997, p. 13, figs. 6-12, 13; Sashida et al., 2000a, p. 806, figs. 9.13-9.16; Feng et al., 2009, p. 598, fig. 6.6.

Eptingium manfredi manfredi Dumitrica. Sashida et al., 1999a, p. 773, fig. 6.16, 6.17; Spiller, 2002, p. 37, pl.4, figs. n, o.

Remarks: As discussed by the previous authors, this species has a variable shape and torsion of the spine. Examined specimens have a shell with three equal, broad-bladed spines and do not have any spine torsion. The end of the spines is rounded.

Occurrence: Middle Triassic from the Kanchanaburi area, western and northern Thailand, southern Peninsular Thailand (Kama-ta et al., 2014), Russian Far East, European Tethys, Japan, northern Tibet, southern Turkey (Tekin et al., 2016) and northwestern Peninsular Malaysia (Basir, 1997).

Eptingium sp.

Figure 8.9

Remarks: Our examined specimens have a shell with grooves and ridges of three main spines. This form differs from other species of *Eptingium* by having a smaller shell.

Occurrence: Middle Triassic from the Kanchanaburi area, western Thailand.

Genus _Cryptostephanidium_ Dumitrica, 1978a

Type species: *Cryptostephanidium cornigerum* Dumitrica, 1978a

Cryptostephanidium? _megaspinosum_ Sashida & Kamata, 1999

Figure 8.11

Cryptostephanidium? *megaspinosum* Sashida & Kamata in Sashida et al, 1999a, p. 773, figs. 6.11-6.13.

Remarks: Shell has a sub-spherical to spherical outline with small pores. The pore frames are very high and small nodes are present. Three main spines are very broad and gradually pointed distally. The furrows between the blades are wide and deep. The internal spicular system cannot be observed. Although examined specimens have equal length of spines, they are safely identified to *Cryptostephanidium*? *Megaspinosum* Sashida & Kamata,1999.

Occurrence: Middle Triassic from the Kanchanaburi area, western Thailand, and Timor Island.

Genus _Spongostephanidium_ Dumitrica, 1978a

Type species: *Spongostephadium spongiosum* Dumitrica, 1978a

Spongostephanidium japonicum (Nakaseko and Nishimura, 1979)

Figure 8.10

Trilonche japonica Nakaseko and Nishimura, 1979, p. 72, pl. 4, figs. 8, 10.

Cryptostephanidium sp. E, Cheng, 1989, p. 148, pl. 7, fig.6.

Spumellaria gen. et sp., indet. A, Cheng, 1989, p. 147, pl. 6, fig. 8, pl. 7, figs. 1, 2.

Cryptostephanidium sp., Sashida et al., 1993b, p. 84, figs. 6- 6-9.

Cryptostephanidium japonicum (Nakaseko & Nishimura). Gorican & Buser, 1990, p. 142, pl. 8, fig.3; Yeh, 1990, p. 22, pl. 4, fig. 10, pl. 5, figs. 1, 2, 7, pl. 10, fig. 11, pl. 11, fig. 18; Ramovs & Gorican, 1995, p. 184, pl. 5, fig. 1; Kozur et al., 1996, p. 207-208, pl. 6, figs. 1-3

Spongostephanidium japonicum (Nakaseko & Nishimura, 1979), Sashida et al., 1999a, p. 775, figs. 6.1, 6.2, 6.6-6.8, 6.10

Remarks: Examined specimens are characterized by having a shell with rather thick three spines and strong and high nodes on the vertices of pore frames. This species is quite similar to *S. japonicum* (Nakaseko and Nishimura, 1979) by having diagnostic features.

Occurrence: Triassic from the Kanchanaburi area, western Thailand, Japan, Philippines, European Tethys, and Timor Island.

Spongostephanidium sp. cf. _S. longispinosum_ Sashida, 1991

Figure 8.13

Spongostephanidium longispinosum Sashida, 1991, p. 694, figure 7-1-3

Remarks: Examined specimens are slightly similar to *S. longispinosum* Sashida in having a spongy shell with rod-like three spines with pointed ends.

Occurrence: Triassic from the Kanchanaburi area, western Thailand.

***Spongostephanidium* sp. A**

Figure 8.14

Remarks: Examined specimens have high nodes on the pore frames of the shell with rather thick three rod-like spines. Three main spines are short and strong with pointed ends and three grooves in the base. We included this species in genus *Spongostephanidium* Dumitrica by having diagnostic shell features.

Occurrence: Triassic from the Kanchanaburi area, western Thailand.

Family Hindeosphaeridae, Kozur & Mostler, 1981

Type genus: *Hindeosphaera* Kozur & Mostler, 1979

Genus *Parasepsagon* Dumitrica, Kozur & Mostler, 1980

Type species: *Parasepsagon tetracanthus* Dumitrica, Kozur & Mostler, 1980

***Parasepsagon robustus* Kozur & Mostler, 1981**

Figure 8.23

Parasepsagon robustus Kozur & Mostler, 1981, p. 35, 36, pl. 5, fig. 1.

Remarks: Cortical shell globular. All four robust spines have the same size and are situated in one plane. Their axes show perpendicular. The spines become continuously narrower from their relatively broad basis toward the tips. They are tricarinate with broad ridges and deep furrows. Their terminal part is round and needle-like.

Occurrence: Middle Triassic from the Kanchanaburi area, western Thailand, and European Tethys.

***Parasepsagon asymmetricus praetetracanthus* Kozur & Mostler, 1994**

Figure 8.15

Parasepsagon asymmetricus praetetracanthus Kozur & Mostler, 1994, p. 49, 50, pl. 5, figs. 3

Remarks: Our examined specimens have a cortical shell of globular with maybe four spines. The spines have the same size and are situated in one plane. The spines became continuously narrower from their relatively broad basis toward the tips. They are three broad ridges and deep furrows. Their terminal part is round and needle-like. We included examined specimens in *P. asymmetricus praetetracanthus* Kozur and Mostler, although, inner structure and layer cannot be observed.

Occurrence: Middle Triassic in the Kanchanaburi area, western Thailand, and European Tethys.

***Parasepsagon* sp. A**

Figure 8.24

Remarks: This species differs from *P. robustus* Kozur and Mostler by having slender four main spines.

Occurrence: Middle Triassic from the Kanchanaburi area, western Thailand.

***Parasepsagon* sp. B**

Figure 8.12

Remarks: This species differs from other species of genus *Parasepsagon* by having longer main spines

Occurrence: Middle Triassic from the Kanchanaburi area, western Thailand.

Family Muellertortiidae Kozur, 1988

Genus Muelleritortis Kozur, 1988

Type species: *Emiluvia* (?) *cochleata* Nakaseko & Nishimura, 1979

***Muelleritortis cochleata cochleata* (Nakaseko & Nishimura, 1979)**

Figure 8.19

Emiluvia? *cochleate* Nakaseko & Nishimra, 1979, p. 70, pl.3, figs. 2, 4, 6.

Muelleritortis cochleata cochleata (Nakaseko & Nishimura), Kozur, 1988, p. 53, pl. 1, figs. 1-8, pl. 2, figs. 1, 2, pl. 3, fig. 1; Kozur & Mostler, 1996, p. 86, pl. 2, figs. 1, 4, 8, 13, pl. 3, figs. 1, 3; Kamata et al., 2002, p. 501, fig. 6D.

Remarks: Examined specimens have a spherical to the subspherical shell and four main spines. Three main spines are twisted tightly and have grooves and ridges. An untwisted spine is slightly longer than the other spines. These characters are those of *M. cochleata cochleata* (Nakaseko & Nishimura).

Occurrence: Middle to Late Triassic from the Kanchanaburi area, western Thailand, northern Thailand, European Tethys, and Japan.

***Muelleritortis* sp.**

Figure 8.20

Remarks: Examined specimen has a spherical to the subspherical shell with grooves and ridges on four main spines. Three main spines are untwisted. One spine is slightly longer than the other spines.

Occurrence: Middle to Late Triassic from the Kanchanaburi area, western Thailand.

Genus *Pseudostylosphaera* Kozur & Mostler, 1981

Type species: *Pseudostylosphaera gracilis* Kozur & Mostler, 1981

***Pseudostylosphaera coccostyla compacta* (Nakaseko & Nishimura, 1979)**

Figures 7.19, 7.20, 7.22, 7.23.

Archaeospongoprunum compactum Nakaseko & Nishimura, 1979, pl. 1, figs. 3, 7; Spiller, 2002, p. 44, pl. 6, fig. k, l.

Pseudostylosphaera coccostyla compacta (Nakaseko & Nishimura, 1979), Kozur & Mostler, 1994, p. 44, pl. 1, fig. 8.

Stylosphaera compacta (Nakaseko & Nishimura, 1979), Bragin, 1991, p. 89, pl. 10, figs. 1, 2.

Pseudostylosphaera compacta (Nakaeko & Nishimura, 1979), Yeh, 1990, p. 15, pl. 4, figs. 3, 4, 20; Feng et al., 2009, p.593, figs. 5.5-5.7.

Remarks: Cortical shell is ellipsoidal with two equal polar spines. The broad ridges of the very big polar spine are subdivided by a central furrow. Examined specimens are quite similar to *P. compacta* (Nakaseko & Nishimura).

Occurrence: Middle Triassic from the Kanchanaburi area, western Thailand. This species has been reported from the Middle Triassic from Russian Far Eastin, Philippines, European Tethys, northwestern Peninsular Malaysia (Basir, 1997), and Japan.

***Pseudostylosphaera timorensis* Sashida & Kamata, 1999**

Figure 7.24

Pseudostylosphaera timorensis Sashida et.al., 1999a, p. 770, figs. 8.3-8.6.

Remarks: The globular shell is large for the genus and has many circular pores on its surface with two stout polar spines. The polar spines have three-bladed and needlelike distal ends. One polar spine is long, which is approximately the same length as that of the shell diameter, the other is half as long.

Occurrence: Middle Triassic from the Kanchanaburi area, western Thailand, southern Turkey (Tekin, 2016), and Timor Island.

***Pseudostylosphaera japonica* (Nakaseko & Nishimura, 1979)**

Figures 7.16-7.18

Archeospongoreunum japonica Nakaseko & Nishimura, 1979, p. 67, pl. 1, figs. 2, 4, 9

Pseudostylosphaera japonica (Nakaseko & Nishimura), Yeh, 1989, p. 63, pl. 1, fig. 4; Cheng, 1989, p. 143, pl. 6, fig. 1, pl. 7, fig. 7; Yeh, 1992, p. 61, pl. 7, figs. 8-10; Kozur et al., 1996, p. 212-213, pl. 6, fig. 15; Sugiyama, 1997, p. 186, fig. 48.15; Gorican & Buser, 1990, p. 155, 156, pl. 5, fig. 2; Kamata et al., 2002, p. 500, fig. 5F; Spiller, 2002, p. 44, 45, pl. 6, figs. m, n, o; Saesaengseerung et al., 2008, p. 405, figs. 8.24, 8. 25.

Stylosphaeara japonica (Nakaseko & Nishimura, 1979), Bragin, 1991, p. 91, pl.1, figs.11, 13, pl. 9, figs. 13, 14.

Remarks: An illustrated specimen is poorly preserved and has two straight and three-bladed polar spines which are equal in length of the main axis of the shell. These characters are the diagnosis of *P. Japonica*.

Occurrence: Middle Triassic from the Kanchanaburi area, western Thailand, northern Thailand, southern Peninsular Thailand (Kamata et al., 2014), European Tethys, northwestern Peninsular Malaysia (Basir, 1997), Rusian Eart East, southern Turkey (Tekin et al., 2016) and Japan.

Pseudostylosphaera longispinosa Kozur & Mostler, 1981

Figures 7.14 and 7.15

Pseudostylosphaera longispinosa Kozur & Mostler, 1981, pl. 1, fig. 6; Gorican & Buser, 1990, p. 155, pl. 5, figs.3-5.

Pseudostylosphaera longispinosa Kozur & Mostler, 1981, Sugiyama, 1997, p. 186, fig. 48.16; p. 15, pl. 4, fig. 2.

Remarks: Several examined specimens are characterized by having a spongy shell with two polar spines. The polar spines are long and three broad ridges. This species is identified to *P. longispinosa* Kozur & Mostler, 1981 by having its diagnostic shell features.

Occurrence: Middle Triassic from the Kanchanaburi area, western Thailand, Japan, and European Tethys.

Pseudostylosphaera sp. A

Figure 7.21

Remarks: This species is characterized by having a globular shell that is large for the genus and has many circular pores on its surface with two polar spines. These polar spines are stout, three-bladed, and have torsion. Examined specimen differs from *Pseudostylosphaera timorensis* Sashida & Kamata by having torsion spines.

Occurrence: Middle Triassic from the Kanchanaburi area, western Thailand.

Pseudostylosphaera sp. B

Figure 7.27 and 7.28

Remarks: Our examined specimens differ from *Pseudostylosphaera* sp. A by having two main spines without torsion and they are always curved against each other.

Occurrence: Middle Triassic from the Kanchanaburi area, western Thailand.

Family Capnuchosphaeridae De Wever, 1979, emend. Pessagno, 1979

Type genus: *Capnuchosphaera* De Wever, 1979

Genus *Capnuchosphaera* De Wever, 1979

Type species: *Capnuchosphaera triassica* De Wever *in* De Wever *et al.*, 1979

Capnuchosphaera deweveri Kozur & Mostler, 1979

Figure 8.21

Capnuchosphaera deweveri Kozur & Mostler, 1979, p. 75, pl. 10, figs. 4-7; pl. 12, fig. 1; De Wever, 1982, p. 153-154, pl. 3. figs. 10, 11; pl. 4, figs. 1, 2; Blome, 1984, p. 16, pl. 1, figs. 3, 8, 9, 16, 18; pl. 11, figs. 1, 2, 16; Lahm, 1984, p. 81, pl..14, fig.7; Yeh, 1990, p. 8, pl. 2, fig. 5, pl. 10, fig. 8; Sashida et al., 1996a, p. 229, 230, figs. 7-8, 11, 12.

Remarks: Although our examined specimens are poorly preserved, the size of the shell and outer shell shape are identical with those of the original specimens described by Kozur & Mostler (1979). This species is easily distinguished from other species of *Capnuchosphaera* by having slender arms, and longer twisted and terminal parts.

Occurrence: Late Triassic (early Carnian) from the Kanchanaburi area, western Thailand, European Tethys, Japan, Philippines, North America, and Timor Island.

Capnuchosphaera sp.

Figures 8.17 and 8.18

Remarks: Poorly-preserved specimens are characterized by a rather thin tube-like arm without any flared or distinctly twisted part. We assigned this species in genus *Capnuchosphaera* De Wever.

Occurrence: Late Triassic (early Carnian) from the Kanchanaburi area, western Thailand.

Order Nassellaria Ehrenberg, 1875

Family Achaeosementidae Kozur & Mostler, 1981, emend. De Wever et al., 2001
Type genus: *Archaeosemantis* Dumitrica, 1978b

Genus *Archaeosemantis* Dumitrica, 1978b
Type species: *Archaeosemantis pterostephanus* Dumitrica, 1978b

***Archaeosemantis* sp. cf. *A. venusta* Sashida, 1983**

Figures 8.1 and 8.2

Archaeosemantis venusta Sashida, 1983, p. 171, pl.36, figs. 1, 2, 4-9; Sashida, 1991, p. 681-696, figs. 5-4-8

Remarks: Examined specimens have spicules commonly with five to six spines arising from a very short median bar. Two basal spines are long and distal half of them are curved inward, which gradually tapered toward the end. The apical spines are three, long and straight. Examined specimens are similar to *A. venusta* Sashida, 1983.

Occurrence: Early to Middle Triassic from the Kanchanaburi area, western Thailand.

Family Poulpidae De Wever, 1981

Type genus: *Poulpus* De Wever, 1979

Genus *Poulpus* De Wever 1979

Type species: *Poulpus piabyx* De Wever *in* De Wever et al., 1979

***Poulpus illyricus* Kozur & Mostler, 1994**

Figures 8.4 and 8.5

Poulpus illyricus Kozur & Mostler, 1994, p. 117, pl. 29, figs. 8-10, pl. 32, figs. 1, 2, 4
Remarks: Examined specimens are characterrized by having a monocytid shell. Cephalic is large and hemiglobular with a large spicular system. Three tricarinate feet are stout, large, in the basal part cylindrical with low continuation if the inner ridge.

Occurrence: Middle Triassic from the Kanchanaburi area, western Thailand, and European Tethys.

Genus *Hozmadia* Dumitrica, Kouzur & Mostler, 1980

Type species: *Hozmadia retriculata* Dumitrica, Kozur & Mostler, 1980

***Hozmadia* sp.**

Figure 8.6

Hozmadia sp. A, Sashida et al., 1999a, p. 779, figs. 10.15-10.18

Remarks: Shell consists of a sub-spherical to rather elongate cephalis with a stout horn and three feet. We included examined specimens in genus *Hozmadia* Dumitrica, Kozur & Mostler, although the internal spicular system and pores cannot be observed at all.

Occurrence: Triassic from the Kanchanaburi area, western Thailand. Species probably identified to the present species has been reported from the Middle Triassic in Timor Island.

Family Planispinocyrtiidae Kozur & Mostler, 1981

Type genus: *Planispinocyrtis* Kozur & Mostler, 1981

Genus *Ladinocampe* Kozur, 1984

Type species: *Ladinocampe multiperforata* Kozur, 1984

***Ladinocampe*? sp.**

Figures 6.14-6.16

Remarks: Examined specimens have elongated conical shell, smooth poreless cephalic, with large and tricarinate apical horn. Thorax and abdomen display distinctly broader, hoop-like segments until the end of the columella that contains numerous small pores. We tentatively included this species in genus *Ladinocampe* Kozur by having diagnostic shell features.

Occurrence: Triassic from the Kanchanaburi area, western Thailand.

Family Ruesticyrtiidae Kozur & Mostler, 1979

Type genus: *Ruesticyrtium* Kozur & Mostler, 1979

Genus *Striatotriassocampe* Kozur & Mostler, 1994

Type species: S*triatotriassocampe nodosoannulata* Kozur & Mostler, 1994

***Striatotriassocampe laeviannulata* Kozur & Mostler, 1994**

Figures 6.8 and 6.9

Striatotriassocampe laeviannulata Kozur & Mostler, 1994, pl. 43, figs. 3, 7, 8

Remarks: Examined specimens resemble *Striatotriassocampe laeviannulata* Kozur & Mostler by having the slender subcylindrical and very long test. Cephalic is rounded conical and smooth or with few pores at the junction. Posthoracic segments are ring-like and become distal wards slightly higher. In the following segments, the pores are more numerous and more restricted to the lower part of the segment.

Occurrence: Middle Triassic from the Kanchanaburi area, western Thailand, southern Turkey (Tekin et al., 2016), and European Tethys.

Genus *Triassocampe* Dumitrica, Kozur & Mostler, 1980, emend. Blome, 1984

Type species: *Triassocampe scalaris* Dumitrica, Kozur & Mostler, 1980

***Triassocampe deweveri* (Nakaseko & Nishimura, 1979)**

Figures 6.22-6.24

Dictyomitrella deweveri Nakaseko & Nishimura, 1979, p. 77, pl. 10, figs. 8? 9.

Triassocampe deweveri (Nakaseko & Nishimura, 1979), Kozur & Reti, 1986, p. 288, fig. 5-E; Cheng, 1989, p. 148, pl. 6, figs. 13-14, pl. 7, figs. 10-11; Yeh, 1990, p. 28, pl. 7, figs. 7, 18, 20, pl. 11, figs. 2-3, 7-8, 13-14; Feng & Liu, 1993, p. 547, pl. 3, figs. 1-4; Kozur & Mostler, 1994, p. 140, pl. 42, fig. 1, pl. 44, fig. 14, pl. 45, fig 6; Ramovs & Gorican, 1995, p. 192, pl. 7, figs. 13-14; Sashida et al, 2000b, p. 91, 93, figs. 8- 1-5, 7, 8, 11-13, 22-25, 27, 28; Xia & Zhang, 2000, p.78, pl. 2, figs. 1-5; Feng, et al., 2001, p. 182, pl. 3, figs. 1-6; Spiller, 2002, p. 39, pl.5, figs. , d, e, f, g, h; Saesaengseerung et al., 2008, p. 406, 407, figs. 8.1-8.3; Feng et al., 2009, p. 597, fig. 7.1-7.4.

Remarks: Examined specimens have a long conical test of which upper part of the cephalic conical, lower part cylindrical with the small and hoop-like thorax. Although all the following segments are inversely trapezoidal of the chamber, this feature is not very distinct. The proximal ring of nodes is in all post-thoracic segments distinctly separated from the segments. These shell features are quite similar to those of *Triassocampe deweveri* (Nakaseko & Nishimura, 1979).

Occurrence: Middle Triassic from the Kanchanaburi area, western Thailand, northern Thailand, southwestern China, Philippines, European Tethys, northern Tibet, southern Turkey (Tekin et al, 2016), and Japan.

***Triassocampe nishimurai* Kozur & Mostler, 1994**

Figure 6.1

Triassocampe nishimurai Kozur & Mostler, 1994, p. 144, pl. 44, fig. 7, pl. 45, figs. 4, 9-11; Saesaengseerung et al., 2008, p. 407, fig. 8. 11.

Remarks: Poorly-preserved specimen has a slender and sub-cylindrical test with long, cylindrical, apically broadly rounded, and large cephalothorax. The cephalic part is poreless and smooth. The thorax displays one ring of tiny, mostly closed pores. Abdomen and postabdominal segment display two rings of tiny pores that are mostly closed. This specimen is compared to *T. nishimurai* Kozur & Mostler, although the distal segments cannot be observed.

Occurrence: Middle Triassic from the Kanchanaburi area, western Thailand, and European Tethys.

***Triassocampe myterocorys* Sugiyama, 1992**

Figures 6.19-6.21

Triassocampe myterocorys Sugiyama, 1992, p. 1198, figs. 11.1-11.3b; Sashida et al., 2000a, p. 807, figs. 9.2-9.5.; Feng et al., 2001, p. 180, pl. 2, figs. 16, 17.

Remarks: As suggested by Sugiyama (1992), this species has quite a wide variety in shell morphology. Illustrated specimens show the variation in the shape of the cephalic.

Occurrence: Middle Triassic from the Kanchanaburi area, western Thailand, southwestern China, and Japan.

Triassocampe scalaris scalaris Dumitrica, Kozur & Mostler, 1980

Figure 6.25

Triassocampe scalaris scalaris Dumitrica, Kozur & Mostler, 1980, p. 26, pl. 9, figs. 5, 6, 11, pl. 14, figs. 2; Kozur & Mostler, 1994, p. 145, pl. 44, figs. 1-6, 10-12; pl. 45, figs. 1, 2, pl. 1, 2, pl. 47, figs. 2, 3.

Triassocampe scalaria Dumitrica, Kozur & Mostler, 1980, Feng et al., 2001, p. 182, pl. 3, figs. 14-16; Feng et al., 2009, p. 597, figs. 7.5-7.7.

Remarks: Examined specimen displays at least in the first 3 post thoracic segments 2 distinct rings of nodes separated by a slight incision. The segments are therefore short cylindrical with the slight median incision. These shell features are quite similar to those of *T. scalaris scalaris* Dumitrica, Kozur & Mostler.

Occurrence: Middle Triassic from the Kanchanaburi area, western Thailand, southwestern China, European Tethys, and northern Tibet.

Genus *Yeharaia* Nakaseko & Nishimura, 1979

Type species: *Yeharaia elegans* Nakaseko & Nishimura, 1979

Yeharaia annulata Nakaseko & Nishimura, 1979

Figures 6.17 and 6.18

Yeharaia annulata Nakaseko & Nishimura, 1979, p. 10, figs. 1, 7, pl. 2, fig. 5; Kozur & Mostler, 1994, p. 147, pl. 46, figs. 6-11, pl. 47, figs. 4, 5.

Remarks: Several poorly-preserved specimens are characterized by having a conical shell with a long apical horn. Abdomen and post--abdominal chambers are hoop-like segments that display single rings of tiny pores. Features of examined specimens are quite similar to those of *Yeharaia annulata* Nakaseko & Nishimura.

Occurrence: Middle Triassic from the Kanchanaburi area, western Thailand, Japan, and European Tethys.

Yeharaia transita Kozur & Mostler, 1994

Figures 6.10-6.12

Yeharaia transita Kozur & Mostler, 1994, p. 148, pl. 46, figs. 1-4, 12.

Remarks: *Y. transita* is distinguished from the other *Yeharaia* species by its very small apical horn.

Occurrence: Middle Triassic from the Kanchanaburi area, western Thailand, and European Tethys.

Genus *Pararuesticyrtium* Kozur & Mostler, 1981

Type species: *Pararuesticyrtium densiporatum* Kozur & Mostler, 1981

Pararuesticyrtium? *illyricum* (Kozur & Mostler, 1981)

Figure 6.7

Triassocampe illyrica Kozur & Mostler, 1981, pl. 15, fig. 2; Yeh, 1989, p. 75, pl. 2, figs. 14, 23.

Pararuesticyrtium? *illyricum* (Kozur & Mostler), Kozur & Mostler, 1994, pl. 43, figs. 11, 12, 15, 16; Saesaengseerung et al., 2008, p. 406, figs. 8. 12, 8. 13.

Remarks: Our examined specimen is poorly preserved and has the most complete segment display only two rings of pores and hooplike segments. Therefore, we questionably assigned this species to *P. illyricum.*

Occurrence: Middle Triassic from the Kanchanaburi area, western Thailand, Philippines, and European Tethys.

Pararuesticyrtium mediofassanicum Kozur & Mostler, 1994

Figure 6.13

Pararuesticyrtium mediofassanicum Kozur & Mostler, 1994, p. 109-101, pl. 28, figs. 1-4, 9,11.

Remarks: The test is conical and has a narrow distal skirt. The cephalothorax is dome-shape, smooth, and poreless. The cephalic part is rounded conical to subhemiglobular. The examined specimens are identical to *P. mediofassanicum* Kozur & Mostler by having a diagnostic shell outline.

Occurrence: Middle Triassic from Kanchanaburi area, western Thailand, and European Tethys.

Family Anisicyrtiidae Kozur & Mostler, 1981

Genus *Anisicyrtis* Kozur & Mostler, 1981

Type species: *Anisicyrica hungarica* Kozur & Mostler, 1981

***Anisicyrtis* sp.**

Figures 6.26-6.28

Remarks: Examined specimens have a subconical test and moderately large cephalic with tricarinate apical horn. Abdomen and postabdominal segment are low, separated by a very narrow and shallow constriction. Thorax, abdomen, and postabdominal segment are always covered by thick outer pore frames. We included this species in genus *Anisicyrtis* Kozur & Mostler by having diagnostic shell features.

Occurrence: Middle Triassic from the Kanchanaburi area, western Thailand.

Nassellaria gen. et sp. indet. A

Figures 6.2 and 6.3

Remarks: Test has a dome-shaped cephalic which lacks a horn. Obscure segments have numerous pores. This unidentified species differs from *Triassocampe deweveri* (Nakaseko & Nishimura) by lacking hoop-like thorax and abdomen.

Occurrence: Triassic from the Kanchanaburi area, western Thailand.

Nassellaria gen. et sp. indet. B

Figure 6.4

Remarks: Examined specimens have a conical test without horn and cephalic. Shell cover is smooth with horizontally arranged of several small pores. This unidentified species differs from Nassellaria gen. et sp. indet. A by having a smooth shell.

Occurrence: Triassic in the Kanchanaburi area, western Thailand.

Nassellaria gen. et sp. indet. C

Figures 6.5 and 6.6

Remarks: Several poorly preserved specimens were examined. The test has a conical shape with unclear segments which disarranged small pores. The caphalic is dome-shaped without horns.

Occurrence: Triassic in the Kanchanaburi area, western Thailand.

6. Correlation and palaeogeographic significance

In northern Thailand, the occurrence of long-duration radiolarian bearing-rocks (Devonian to Middle Triassic bedded chert) have been reported from the Fang area, north of Chiang Mai (e.g. Caridroit et al., 1990; Sashida et al., 1993a, 1998, 2000a; Wonganan & Caridroit, 2005). The Fang chert is well bedded, with beds of several centimeters intercalated with shale a few millimeters in thickness. Under microscopic observation, it is composed of abundant radiolarian tests and sponge spicules with clay minerals. This chert completely excludes coarse-grained terrigenous materials and thought to have been deposited in a pelagic environment far from land areas (Matsuda & Isozaki, 1991). These pelagic cherts are probably continuous toward northwestern Thailand e.g., along the highway from Mae Hong Son to Mae Sariang (Feng et al., 2005) and the Mae Sot and Umphang areas (Ishida et al., 2006) where radiolarian-bearing rocks are thought to have been deposited in the deep basin of Palaeo-Tethys Ocean. In contrast, the Triassic cherts in the Mae Sariang area of the Mae Sariang Group along the Thai--Myanmar border seem to differ from the pelagic bedded chert in its lithological charactersand intercalations of calcareous formations (Kamata et al., 2002). Kamata et al. (2002) suggested that chert successions distributed in the Mae Sariang area have been accumulated at the eastern continental margin of the Sibumasu Block within the western part of Palaeo-Tethys Ocean.

Based on the lithostratigraphy and radiolarian ages, the chert and clastic rock sequences in the Kanchanaburi area are correlated to the rock units distributed in the Mae Sariang area. The occurrence of early Late Triassic (early Carnian) radiolarians from the Mae Sariang (Kamata et al., 2002) and Kanchanaburi areas indicates that the depositional basins were present until the early Late Triassic time in the western part of the Palaeo-Tethys Ocean.
Kamata et al. (2014) described the litho- and biostratigraphy of fine-grained siliceous rock successions in the Hat Yai area of southern Peninsular Thailand. According to their study, fine-grained siliceous sedimentary rocks distributed in this area, are divided into two units of the lower shale unit and the upper chert unit. The lower shale unit yielded Late Middle to early Late Permian and the upper unit Early to Middle Triassic radiolarians, respectively. They suggested that the clastic-chert successsions in the Hat Yai area are correlated with the Permo-Triassic Semanggol Formation (e.g., Teoh, 1992; Basir et al., 1995) of northwestern Peninsular Malaysia and Triassic chert in the Hat Yai area is not typical pelagic deep-water sediment deposited on an abyssal plain and instead, it is better to interpret as continental slope sediments overlying Permian fine--grained clastic rocks. The depositional environment of the chert in this area was likely restricted to the vicinity of a continental slope and rise, based on the lithological and biostrtigraphical analyses. They also inferred that the continental margin of the Sibumasu Block along the of Palaeo-Tethys Ocean was represented by a stable passive margin without much tectonic activity and the closure of Palaeo-Tethys Ocean between the Sibumasu and Indochina terranes occurred at least after the Middle Triassic in southern Peninsular Thailand. In our provisional study in the Kanchanaburi area, Upper Permian chert and overlying siliceous shales that include uppermost Permian conodont-bearing limestone lens have been identified (Sashida et al., 2019). Jenjitpaiboon and Chonglakmani (2014) summarized the stratigraphy and fossils of the area about 10 km northwest of Nong Prue, western Kanchanaburi. They discriminated four stratigraphic units, Units A to D in ascending order in this area. Unit A consists of shale, calcareous shale, and limestone and Roadian–Wordian (Guadalupian, Middle Permian) ammonites were identified from the shale part of this unit. Unit B unconformably covers unit A and consists of limestone conglomerate, limestone, shale, and siliceous shale. The limestone conglomerate yielded Permian fusulinids, but they inferred the age of this unit to be Triassic. Unit C conformably overlies unit B and is composed of shale and siliceous shale. Unit D conformably covers unit C and consists of sandstone and shale. From the shale part of units C and D, Carnian–Norian (Late Triassic) bivalves, *Halobia* and others, have been identified. In the Nong Prue area, thick Permian–Triassic carbonate rocks correlated to the Chuping and Kodiang Limestone (e.g., Koike, 1982, Basir et al., 1995) in peninsular Malaysia and the Khlong Kon Limestone (e.g., Sashida et al, 1999b) and Chaiburi Formation (Ampornmaha, 1995) in southern peninsular Thailand are not found. In the Nong Prue area, western Kanchanaburi, there are two types of sedimentary rock sequence, one is that deposited in rather deep-sea continental slope to abyssal plain represented by the present Triassic radiolarian-bearing chert and the other is the continental shelf where clastic sediments were deposited yielding Upper Triassic *Daonella-Halobia* faunas. Based on these lithological and chronological features, our studied area correlated to the Semanggol Formation of northwestern peninsular Malaysia and Late Permian and Early–Middle Triassic siliceous rock sequence in the Hat Yai area, southern peninsular Thailand.

Based on the above mentioned several lines of evidence we can conclude that the closure of the Palaeo-Tethys Ocean probably occurred at least after the early Late Triassic (early Carnian) (Fig. 9B). In addition, Triassic radiolarian faunas from our studied area are similar to those of northwestern Peninsular Malaysia (e.g., Basir, 1997 Spiller, 2002), Philippines (e.g., Yeh, 1990), Japan (e.g., Sugiyama, 1997),

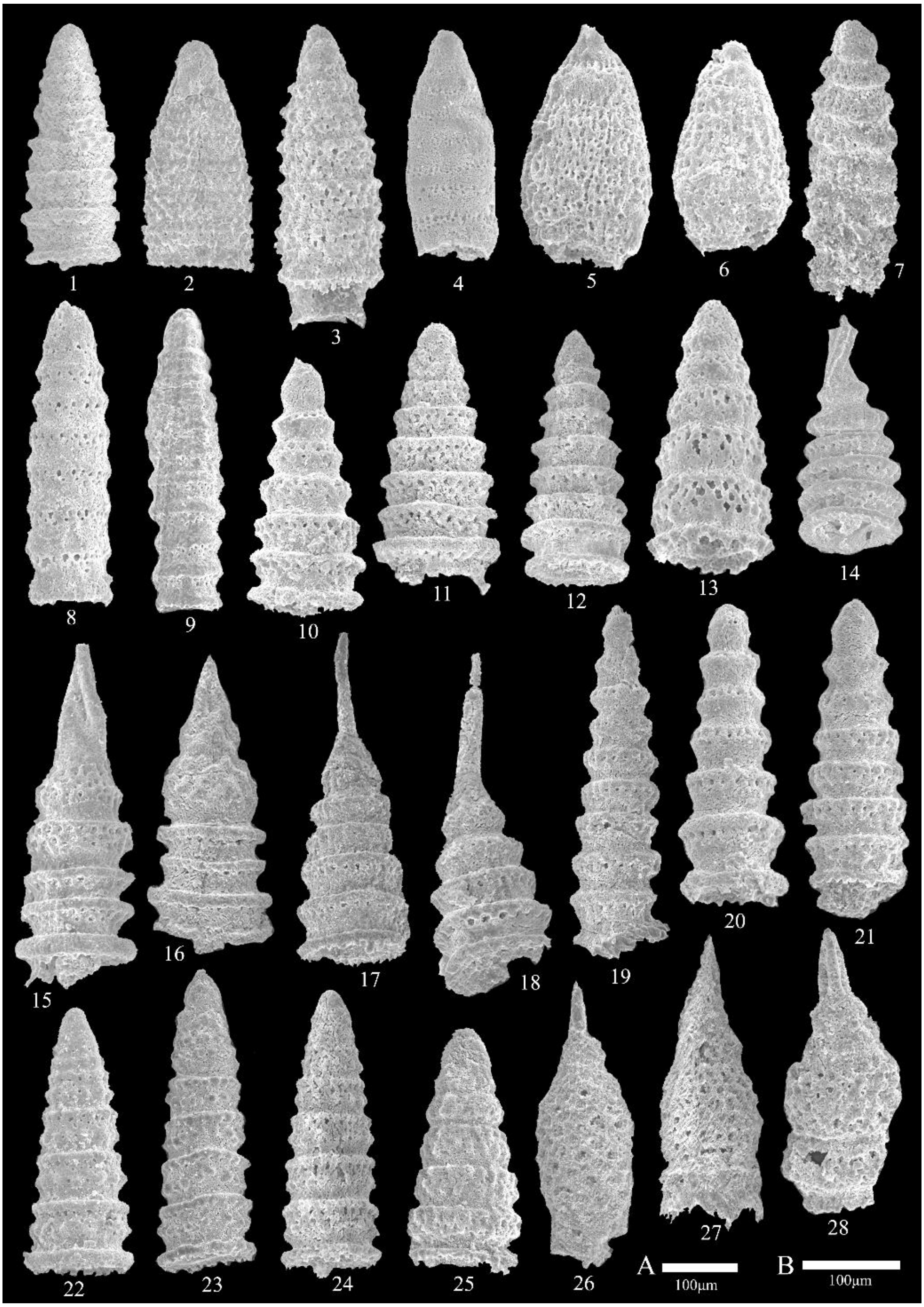

Fig. 6: Triassic radiolarians from the Kanchanaburi area, western Thailand. All figures are scanning electronic micrographs. 1. *Triassocampe nishimurai* Kozur & Mostler, 2, 3. Nassellaria gen. et sp. Indet. A, 4. Nassellaria gen. et sp. Indet. B, 5, 6. Nassellaria gen. et sp. Indet C, 7. *Pararuesticyrtium*? *illyricum* Kozur & Mostler, 8, 9. *Striatotriassocampe laeviannulata* Kozur & Mostler, 10-12. *Yeharaia transita* Kozur & Moslter, 13. *Pararuesticyrtium mediofassanicum* Kozur & Mostler, 14-16. *Ladinocampe*? sp., 17, 18. *Yeharaia annulata* Nakaseko & Nishimura, 19-21. *Triassocampe myterocorys* Sugiyama, 22-24. *Triassocampe deweveri* (Nakaseko & Nishimura), 25. *Triassocampe scalaris scalaris* Dumitrica, Kozur & Mostler, 26-28. *Anisicyrtis* sp. Scale bar A: figs. 8, 9, 19-21; Scale bar B: figs. 1-7, 10-18, 22-28.

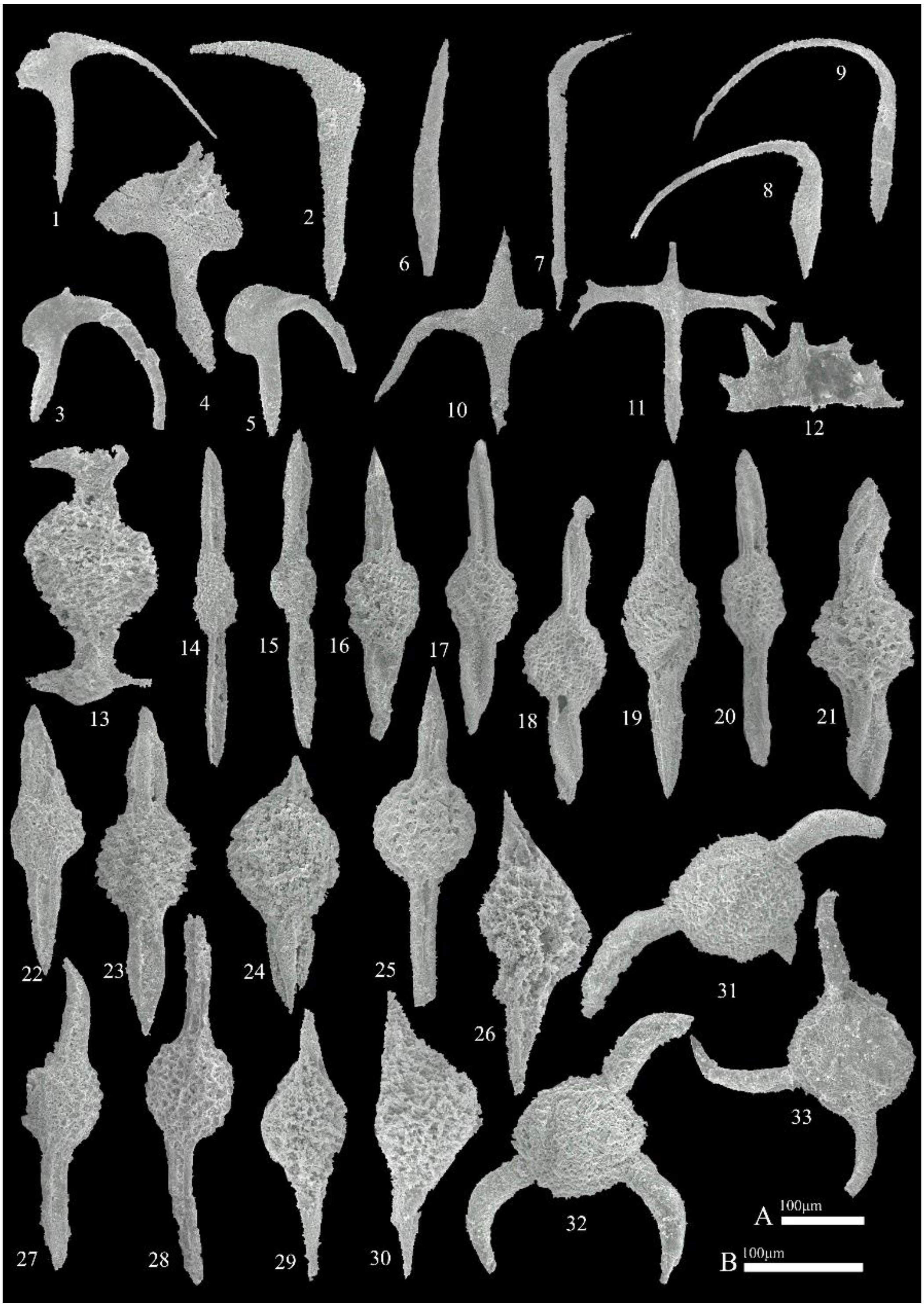

Fig. 7: Triassic radiolarians from the Kanchanaburi area, western Thailand. All figures are scanning electronic micrographs. 1-5. Spine D, *Falcispongus falciformis* Dumitrica, 6. Spine A1, *Paroertlispongus multispinosus* Kozur & Mostler, 7. Spine B, *Pseudoertlispongus angulatus* Kozur, 8, 9. Spine A2, *Oertlispongus inaequispinosus* Dumitica, Kozur & Mostler, 10. Spine E1, *Baumgartneria retrospina* Dumitrica, 11. Spine E2, *Baumgartneria bifurcate* Dumitrica, 12. Spine C, *Dumitricasphaera planustyla* Lahm, 13. *Dumitricasphaera* sp., 14, 15. *Pseudostylosphaera longispinosa* Kozur & Mostler, 16-18. *Pseudostylosphaera japonica* (Nakaseko & Nishimura), 19, 20, 22, 23. *Pseudostylosphaera coccostyla compacta* (Nakaseko & Nishimura), 21. *Pseudostylosphaera* sp. A, 24. *Pseudostylosphaera timorensis* Sashida & Kamata, 25. *Spongstylus koppi* (Lahm), 26, 30. *Archaeospongoprunum mesotriassicum asymmetricum* Kozur & Mostler, 27, 28, *Pseudostylosphaera* sp. B, 29. *Archaeospongoprunum mesotriassicum mesotriassicum* Kozur & Mostler, 31, 32. *Paurinella curvata tenispinosa* Kozur & Mostler, 33. *Paurinella curvata spinosa* Kozur & Mostler. Scale bar A: figs. 13-25, 27, 28, 31-33; Scale bar B: figs. 1-12, 26, 29, 30.

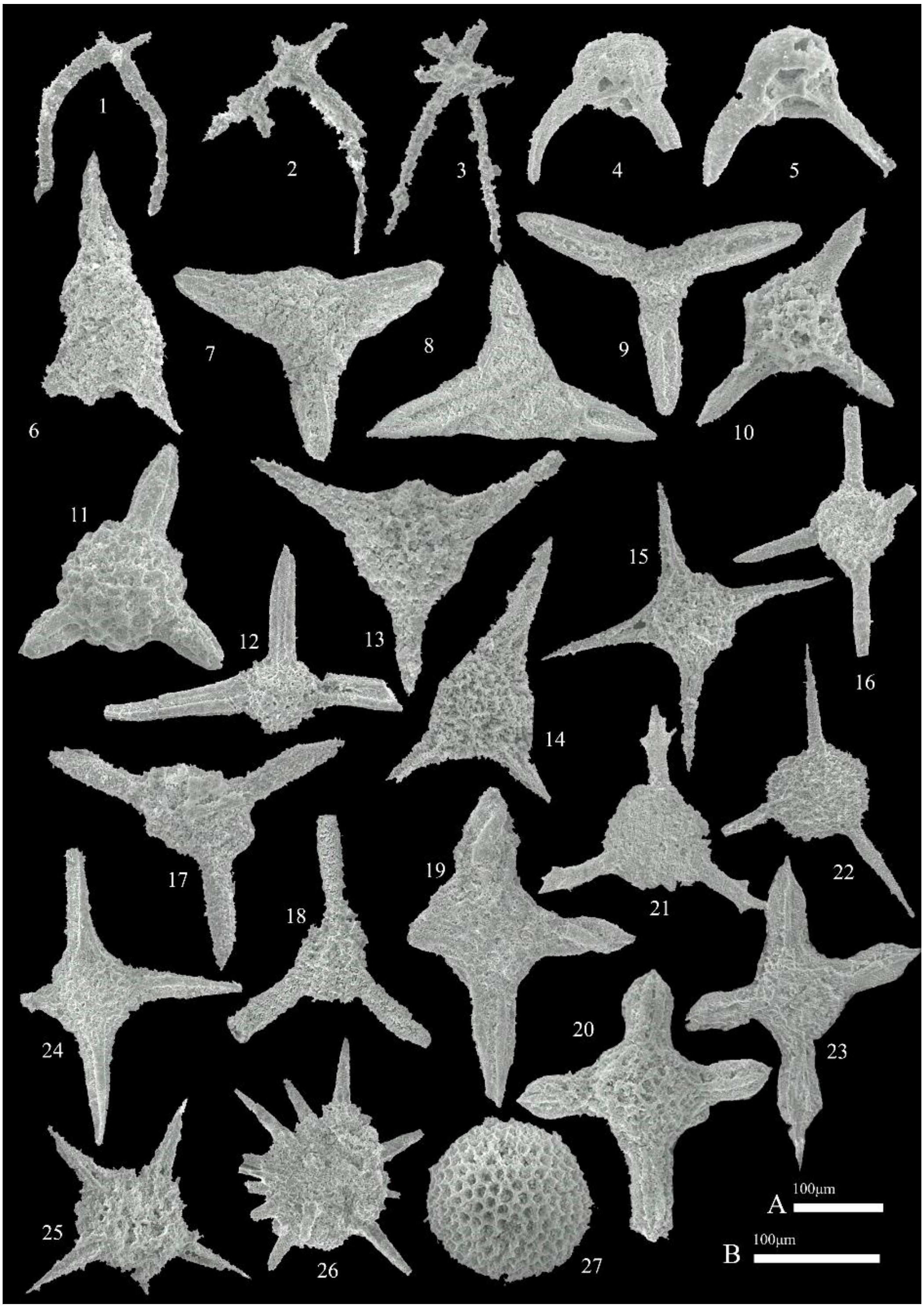

Fig. 8:. Triassic radiolarians from the Kanchanaburi area, western Thailand. All figures are scanning electronic micrographs. 1, 2. *Archaeosemantis* sp. cf. *A. venusta* Sashida, 3. *Parentactinia nakatsugawaensis* Sashida, 4, 5. *Poulpus illyricus* Kozur & Mostler, 6. *Hozmadia* sp., 7. *Eptingium manfredi* Dumitrica, 8. *Eptingium nakasekoi* Kozur & Moster, 9. *Eptingium* sp., 10. *Spongostephanidium japonicum* (Nakaeko & Nishimura), 11. *Cryptostephanidium* ? *megaspinosum* Sashida & Kamata, 12. *Parasepsagon* sp. B, 13. *Spongostephanidium* sp. cf. *S. longispinosum* Sashida, 14. *Spongostephanidium* sp. A, 15. *Parasepsagon asymmetricus praetetracanthus* Kozur & Mostler, 16. *Paurinella*? sp., 17-18. *Capnuchosphaera* sp., 19. *Muelleritortis cochleata cochleata* (Nakaseko & Nishimura), 20. *Muelleritortis* sp., 21. *Capuchosphaera deweveri* Kozur & Mostler, 22. *Paurinella trettoensis* Kozur & Mostler, 23. *Parasepsagon robustus* Kozur & Mostler, 24. *Parasepsagon* sp. A, 25. *Praegomberellus* sp. cf. *P. pulche* Kozur & Mostler, 26. *Triassospongosphaera multispinosa* (Kozur & Mostler), 27. *Cenosphaera igoi* Sashida. Scale bar A: figs. 7-24, 26, 27; B: figs. 1-6, 25.

Oregon, USA (Blome & Reed, 1992), Rusian Far East (Bragin, 1991), European Tethys (e.g., Kozur & Mostler, 1994), of which radiolarian-bearing rocks are thought to have been deposited in the Panthalassa and western Palaeo-Tethys oceans. Although, the positions of Japan, Russian Far East, and western North USA are located in the middle to rather a high latitude in the northern hemisphere at present. Their radiolarian-bearing cherts are thought to have been deposited at low latitudes in the Panthalassa Ocean (Isozaki, 1997). This may indicate that the Palaeo-Tethys and Panthalassa oceans were connected by seaways at this time and shared the same oceanic circulation system.

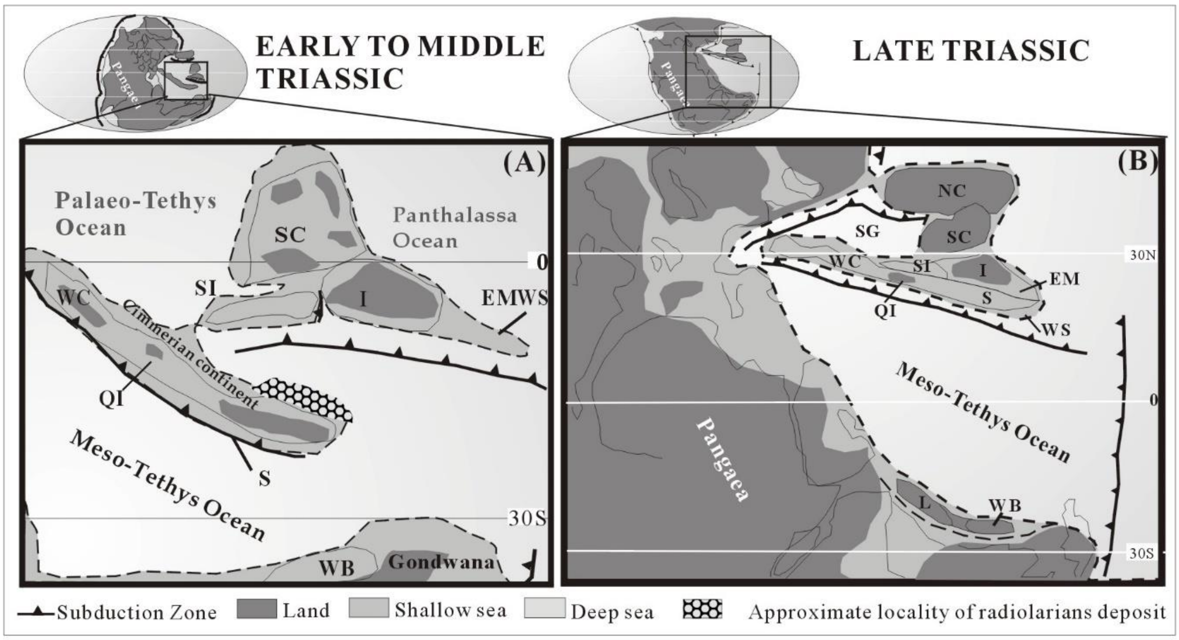

Fig. 9: (A) Palaeogeographic Reconstruction of the Tethyan region for Triassic showing the postulated positions of East and South-East Asian terranes, and the distribution of land; the plot approximates the locality of radiolarian-bearing rocks of the Kanchanaburi area, western Thailand. NC, North China; SC, South China; I, Indochina; EM, East Malaya; WS, West Sumatra; QI, Qiangtang; WC, Western Cimmerian Continent. The basic map is after Metcalfe (2011)

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Development and Application of Geological Survey Information Technology in CGS

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Abstract

Geological informatization has undergone three development periods, namely digitization period, networking period, and intelligence (big data) period. The paper reviewed the role China Geological Survey (CGS) has played in the course and summarized major contributions over the past two decades. For fully utilizing the massive geodata for better supporting social and economic development, CGS conducted research and development of geo-information technologies, such as various software tools by adopting the current popular GIS, database and computer technologies, the upgraded Digital Geological Survey System (DGSS) based on cloud computing, big data and AI application, the national geodatabase system, the model and standard system, and the national geological database --GeoCloud 3.0. CGS also participated in several international cooperative programs, e.g. the Deep-time Digital Earth (DDE) and International Geoscience Program (IGCP), which promoted the progress of geoinformation technology in the world at large. In the new era, CGS has to conquer a series of obstacles to ensure secured data management, high level of data integration, guaranteed data quality and intelligent services.

Keywords: Achievements, Application, Big Data, GeoCloud, Geological Informatization

1. Introduction

The rapid development of information technology has given birth to the contemporary technological revolution, transforming and overturning our existing work and life patterns. Geological survey is fundamental and pioneering for social and economic development, which lays solid foundation for energy and resources management and development, natural disaster prevention, environmental protection, infrastructure construction, etc. The integration of geological survey with information technology made by China Geological Survey has undergone some important periods. It gained great momentum since beginning of the 21st century, with fruitful and remarkable achievements (Yongjie, 2007). The article, based on the authors' understanding of and practical experience in geological information construction research, systematically overviews and summarizes the major achievements, and proposes the development direction in the future.

2. Three development periods of geological informatization

The geological informatization process is generally in line with the national informatization process. After the digitization and networking periods, it's entering into the big data era (Hequan, 2013).

2.1 Digitization period. The period, started from the 1960s and ended in 2002 with the invention of field digital collector, features with digital recording and single machine computing. The geological survey applying IT technology in terms of computerization at the early stage, i.e., replacing human with calculator or computer, followed by the set up of various retrospective databases, as well as computer facilitated calculation and statistical analysis. At the late stage it came computer aided drafting (CAD), which gradually developed into compilation of vector maps by using GIS technology, and compilation of geological reports by using computer. In 2002, China Geological Survey successfully developed the field digital collector (Chaoling, 2016), a cornerstone marking the realization of digitization in geological survey. As a result, the related working methods of geological survey have basically achieved the transformation from analog to digital mode.

2.2 Networking period. The period, started from 2002 and ended in 2016 with the implementation of China's geological big data project (Yongjie, 2016; Yongjie, 2018), features with interconnection and sharing based on digitization. It covers data file sharing, email transmission, network office work, network computing and information services. The China Geological Survey, built up in 1999, launched the Digital Land Programme in this period, and proposed the overall framework of geological survey informatization in 2002 based upon advanced computer, network, wireless communication and database technologies.

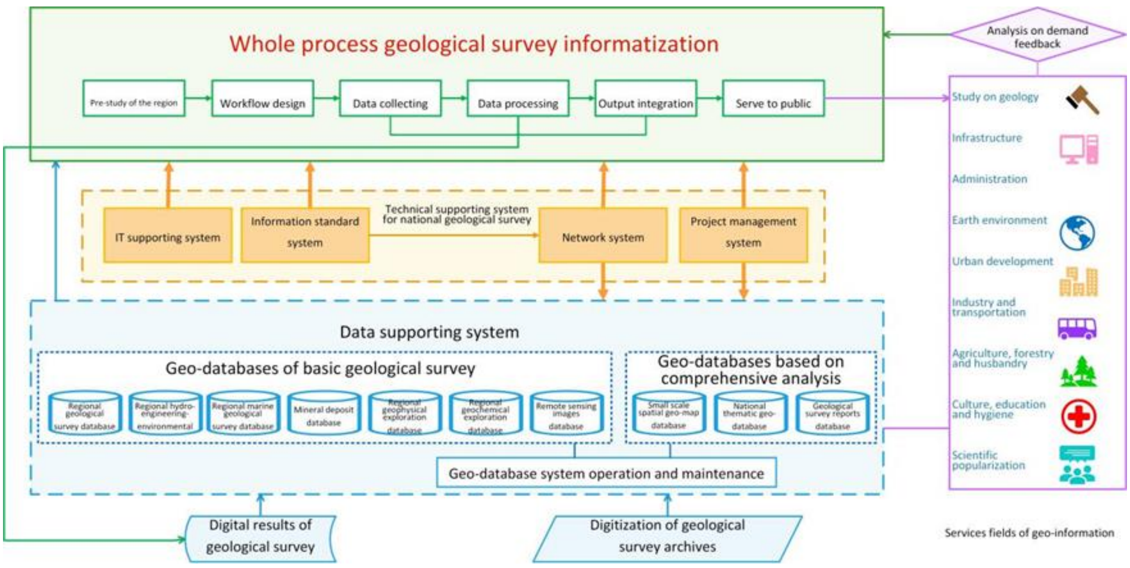

Fig. 1: Architecture of geological survey informatization construction (Jiahuan, 2005)

2.3 Intelligence (big data) period. The period started from 2016, featuring with rapid data clustering, virtual management of information infrastructure, data mining and fusion analysis. With the fast advancing of big data, cloud computing and intelligence, the projects "Geological Big Data Technology Development and Pilot Application" and "Geological Big Data and Information Services" were implemented, resulting in the put forward of systematic geological big data infrastructure (Fig.2) as well as construction ideas, such as to improve the geodata collecting and processing system in a more normative way, to set up the geodata clustering system to be a real time updating system, to form and enrich the geodata and information service system, to promote collaborative services, to build up the "GeoCloud" big data supporting platform, etc.

3. Major achievements

Over the past two decades, CGS has accumulated huge amount of information and geological data. In order to fully utilize these data for better supporting social economic development, CGS conducted around 1,500 projects for informatization with considerable outputs.

3.1 Research and development of various software tools

Geo-database management software: used for management of multi-source heterogeneous data of different scales, in terms of geology, mineral, energy, geophysics, geochemistry, remote sensing, marine, etc. Geological survey data collecting software: used for field data collection in geological mapping, mineral

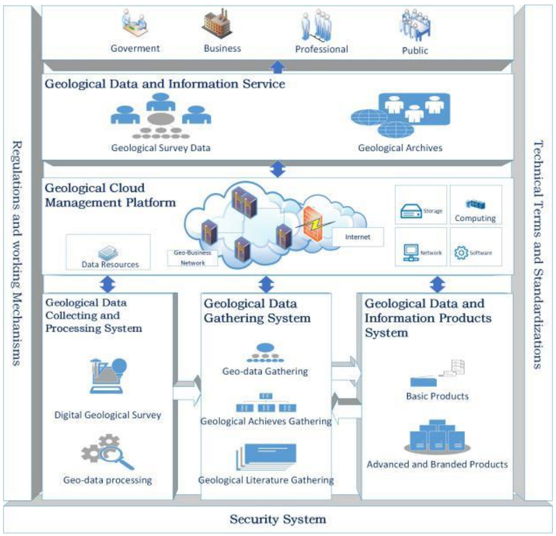

Fig. 2: Architecture of the construction of geological big data system (Yongjie, 2023)

resources exploration, energy resource investigation, ground water inspection and environmental geological survey, etc. Geological 3D modeling software: used for 3D modelling and simulation in geological structure study, mineral exploration, oil and gas basin analysis, marine geology, etc. with gravity, magnetic, electricity and seismic data of geophysical survey (Minghua, 2011), and deep-Earth exploration data and drone data. Simulation and prediction software: used for data processing, data analysis, data mining, data simulation and prediction in the studies related with geophysics, geochemistry, petroleum, natural gas, geological disaster, remote sensing, geothermal, ground stress, etc.

3.2 Development and upgrading of Digital Geological Survey System (DGSS)

The research and pilot test of field data collector can be dated back to late 1990s, and was completed in 2002 with the establishment of point-routing-boundary (PRB) geological mapping data description model. The technology, widely deployed to regional geological survey projects in field data collection, data sorting, data processing, and presentation of result information, basically realized the informatization of geological survey (Chaoling, 2016).

With the improvement of information technology, CGS integrated the existing regional geological survey data collection system, mineral resources investigation and assessment system, digital compass, mineral exploration data collection and reserve calculation functions to develop the Digital Geological Survey System (DGSS).

Nowadays, the big data, cloud computing and wireless communication technologies need to be combined. Through efforts, a push service system for location based geological data and archive was proposed, as well as remote virtual computing, mineral and rock identification system, etc. All these has upgraded the DGSS to be a more intelligent system.

In terms of intelligent geological mapping (Yangchun, 2021), the purpose is to improve the ability of geological object identification, such as tectonics, lithology, lithological combinations, to improve the efficiency and accuracy of field survey, to deepen the level of pre-study and comprehensive study, to enhance the ability to solve key geological issues, and to diversify result presentation to provide optimized services, through combination of vast data, massive knowledge and AI algorithm. As a result, the technical framework driven by “data+knowledge+intelligent algorithm” was set up, which greatly improved the ability of intelligent data collection and the accuracy of geological object recognition.

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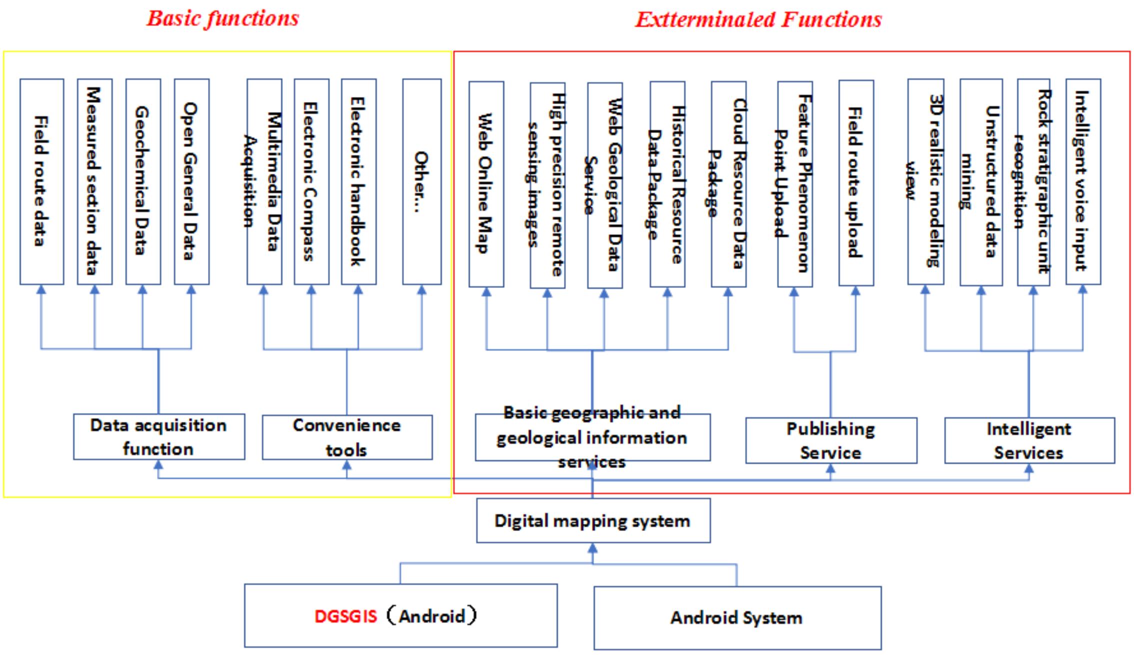

Fig. 3: Digital Geological Survey System for Android

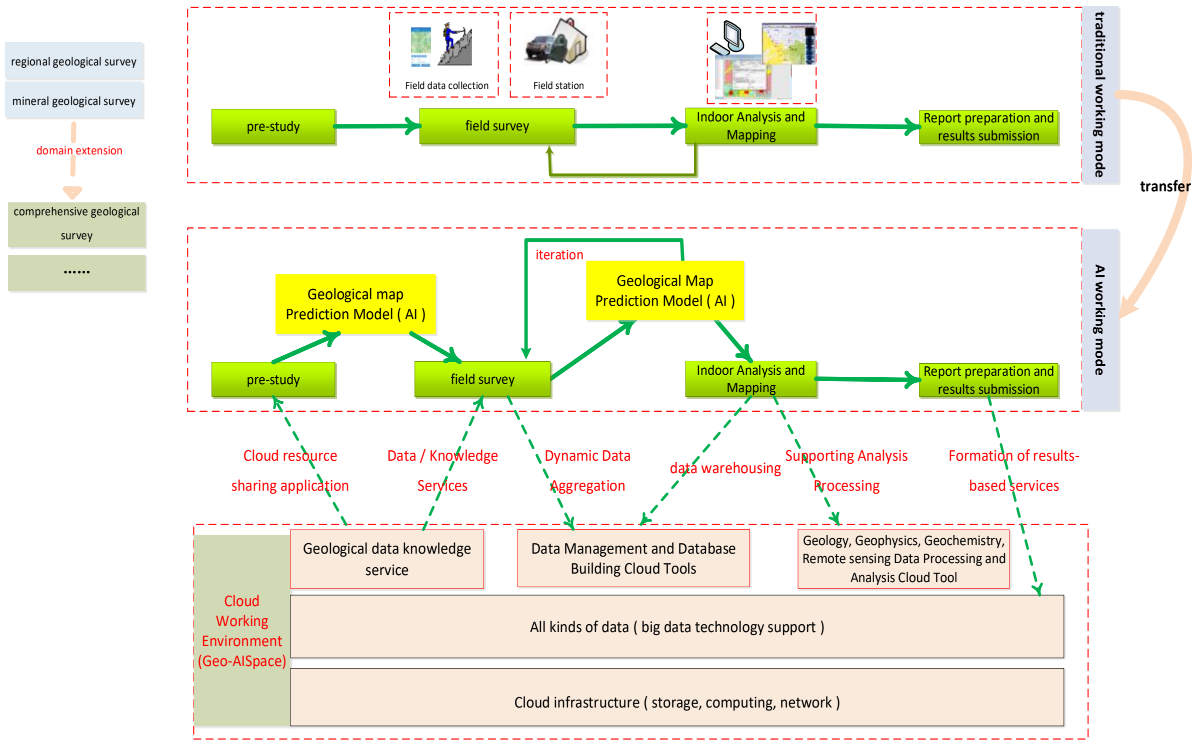

Fig. 4: Technical Framework Driven by Data+Knowledge+Intelligent Algorithm

3.3 Establishment of the national geological database system

CGS has successfully established a system of national geological databases covering various regions at different scales with varied themes, which have been playing fundamental roles in China's geological survey planning, deployment, and mineral resources exploration and utilization, as listed below.

Table 1: Major National Thematic Geological Databases

No.	Name of DB	Description of DB	Function
1	Basic Geology Database	lithology and mineral, structure, paleontology and fossils, isotopic dating data, etc.	support CGS deployment of geological survey and scientific research
2	Marine Ecological Database	marine geological data, structural data, landform data, marine mineral resources data and marine geological hazard data	provide basic data for marine geology and ocean environment studies
3	Geophysical Exploration Database	geophysical surveying data of gravity, aeromagnetic, geomagnetic, electricity and seismic	support to regional geological structure studies, mineral assessment and exploration, and energy resources exploration of petroleum and mining industries
4	Geochemical Survey Database	stream sediment samples' analytical data, heavy minerals data and soil, irrigation water and atmospheric deposition samples data	provide data resource and evidences for mineral exploration, ecological environment assessment, soil quality evaluation and endemic disease studies
5	Remote Sensing Database	satellite images and aerial photographs in the past 10 years	provide efficient use in geohazards mitigation, mining environment monitoring, urban geological survey, etc.
6	Drilling Database	important geological drilled holes data, key physical core images and specimens catalogue data	provide solid support to geological exploration and deep earth studies in China
7	Mineral Resources Database	data of ore distribution, resources and reserves, mineral exploitation and utilization, mining activities and geological settings	support exploration and utilization of mineral resources in China
8	Energy Resources Database	spatial distribution data and reserves of major petroliferous basins, oil fields and natural gas fields	provide support to energy resources exploration in China
9	Geological Disaster Survey Database	data of landslide, collapse, debris flow, land collapse, land subsidence, and surface sinks, along with dynamic monitoring data in major geohazard locations	provide strong support for potential hazard identification and post-disaster reconstruction in China

Table 1: Major National Thematic Geological Databases (continued)

No.	Name of DB	Description of DB	Function
10	Hydrogeological Survey and Water Resources Survey Database	data of groundwater and surface water around China, along with spatial data of over 1,000 national 1:200,000 hydrogeological maps	provide support for efficient utilization of water resources in China
11	Ecological Environmental Survey Database	survey data and real-time monitoring data of urban geology, mining environment, ecological rehabilitation, geological heritage, geoparks, etc.	provide data services for decision making in ecological environment protection and geo-tourism
12	Natural Resources Comprehensive Survey Database	survey data of national and provincial forests, grasslands and wetlands	serve for natural resources management and ecological environment assessment in China

These national thematic databases have been put into application, which well meet the demands of relevant national Ministries and local governments, as well as contributing a great deal to lifting people's living standard in the country (Yongjie, 2011). E.g., the National Geological Disaster Database clearly shows the location, potential affection areas, major causes of the development of geohazards in China's 2,020 counties linked with an technologically unified country-province-city-county 4-level monitoring network. By applying AI technology for geohazards identification and prediction, CGS has acquired 9,675 suspecting hazard locations in China, and thus effectively avoided 4,296 risks by early warning and that saved lives of some 146,000 people and avoid direct economic loss about 5 billion RMB, and the value of the database is obviously reflected in serving the livelihood of the residents.

Another example is the Hangzhou Intelligent Urban Database, which provides basic data to Hangzhou's intelligent management in terms of urban planning, transportation, public security, environment protection, and instant information released to the public for prevision and alleviation of natural disasters. It highly improves the capability of instant response to emergencies and hazards. The database helps the local government on efficient management of modern metropolis to benefit the residents for a better live.

Fig.5: Hangzhou Intelligent Urban Management Data

3.4 Establishment of geological data model and standard system

By referring to international standard systems such as ISO, OGC, W3C, etc., and taking into account both basic standards and thematic standards, CGS has built up a full life cycle standard system, which adopts the four-layer architecture of geological information modeling, enables cross-platform interoperability of data models, and guarantees a strong support of standards to the whole--processdata management of geological survey. These include basic standards, data collection standards, basic geological data model standards, data storage standards, data service standards, data management standards, and software R&D standards, etc. The core basic geological data model standards, consisting of basic geographic, geological, mineral, geophysical and geochemical models provide fundamental support to the formation and management of various geological databases.

3.5 Establishment of national geological database - GeoCloud 3.0

China Geological Survey issued and conducted standards for constructing the national geological database - GeoCloud in 2016. The tasks include integration of information infrastructure, web resource, geodata resource, data processing system, management system, application analysis system, service system, etc., and development of database, platform architecture, portal, etc., with advanced cloud computing, big data and AI technology. The project significantly promoted efficient management of national geoscience data and information. With fast development, today's GeoCloud 3.0 is a clustering service system with 75 large nodes linking national and provincial geological surveys and geoscience research institutions. It provides functions as data resource pool management and coordination, data retrieval and downloading, online data processing and analysis, analysis and application .

Fig. 6: China National Geological Database - GeoCloud 3.0

of thematic data, project management and quality monitoring, automatic data and knowledge pushing, etc

GeoCloud has been used widely to support the planning and deployment of national geological work (Yongjie, 2019). In particular, GeoCloud 3.0 has been supporting the assessment, exploration and utilization of mineral resources. Based on comprehensive integrated analysis of the geological, geophysical, geochemical, remote sensing, heavy minerals and drill holes data form the National Geological Database, different mineralization and exploration models for the optimization of exploration blocks and targeting areas were developed, which guided the delineations and discoveries of more than 30 strategic minerals, such as copper, gold, and polymetallic metallogenic zones, lithium beryllium, niobium and tantalum prospect zones. It also contributed greatly to the decision-making in natural resources management for minerals utilization and mining industry, along with the distribution data of mining rights and current mines and their productions.

3.6 International cooperation in geo--information

Over the past decade, CGS has actively participated in the database construction and data sharing in international big science programs, such as International Geoscience Program (IGCP), Deep-time Digital Earth (DDE), Resource and Environment Effects of Global Karst Dynamic Systems, Mapping the Chemical Earth, etc. Geoinformation cooperation with more than 60 countries including the US, Germany and UK has been conducted and compilation of global digital geological maps and construction of global magmatic rock database, and CGS data and technology sharing to IGCP, DDE, OneGeology, etc. are being actively carried out.

Fig. 7: DDE-China Node

Fig. 8: DDE Standard Task Group Led by CGS

4. Enlightenment for future development

At present, CGS is confronted with lack of data policy for the security management and updating the national geodatabases, lower level of data integration, distributed data center architecture of diverse data formats, etc. Focusing on the new demands of the country's economic and social development, CGS has to further improve the application effect and efficiency with AI and latest technologies to better serve the national geological survey, natural resource management and economic development.

Stresses should be made to deepen the research on improving internationalization, digitization and intelligence of geoscience data models and standards, and on data management software technology for dynamic aggregation and updating of multi-source heterogeneous 2D and 3D spatiotemporal data. Moreover, comprehensive data analysis and simulation should be strengthened to improve the understanding of the earth system. Besides, CGS also needs to push forward the metallogenic belt resource data assessment, the application of cloud computing, big data and AI in intelligent geological survey and mapping, mineral resources prospecting, geohazards identification and early warning, etc.

5. Conclusions

(1) The development of geological informatization led by CGS can be divided into three periods as digitization period, networking period and intelligence (big data) period, each with their own prominent features.

(2) Through consistent efforts for more than two decades, CGS has launched national programs and projects in terms of geological informatization and accumulated rich experience in combining strength from all parts to fulfill her commitment as a non-profit institution.

(3) At present, facing new challenges and opportunities, CGS will attach more importance to advancing the intelligent geological survey course for more extensive application in the national major projects and everyday needs of residents.

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Flood hazard mitigation using managed aquifer recharge: Numerical assessment of a pilot trial in the Nam Kam River Basin, NE Thailand

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Abstract

Flash flooding is one of the most catastrophic natural hazards. These disastrous events may trigger some rainfall-related geohazards, e.g., landslides and slumps. Sakon Nakhon Province, partly located in the Nam Kam River Basin, has been severely damaged by storm-driven floods. Due to the effect of climate change, precipitation has changed in intensity, pattern, and frequency. In 2017, this area was hit by a tropical cyclone causing heavy rainfall and considerable flash flooding. Consequently, residential properties, agricultural areas, and infrastructure facilities were devastated. The storm eventually caused 3-million-dollar worth of damage in the province.

The challenge for policymakers is to develop strategies that can provide long-term solutions to reduce extensive damage caused by the hazards. This study drew on examples of the use of managed aquifer recharge (MAR) as an approach primarily to prevent flood-related issues and store stormwater runoff. The MAR system comprises settling and infiltration ponds constructed in an area of 8,000 m^2. A modeling approach is widely known as a scientific and reliable method for the assessment of MAR systems. Therefore, a groundwater model was developed to simulate MAR and the subsequent movement of groundwater. The MAR model was constructed using a notable 3D groundwater-flow model known as MODFLOW-NWT, in association with a MODPATH particle-tracking model. The model accounted for interactions between artificial lakes (Lak Package) and groundwater. Two model scenarios were developed based on the actual MAR methods applied at the demonstration site: (1) An infiltration pond scenario and (2) an infiltration pond with four recharge wells scenario.

The results revealed that the flow model had an acceptable accuracy with an NRMSE of 8.98%. The annual rate of pond seepage was 90,052 m^3. Additionally, artificially recharged water simulated by virtual particles could travel in the system for at least ten years, with a maximum travel distance of 698.07 meters (0.19 meters/day). In addition to recharge ponds, the runoff was recharged directly into the aquifer via the recharge wells. An annual recharge rate is about 22,600 m^3. The deeper-and-longer flow paths were roughly doubled in the distance compared to the first scenario, being up to 1,683.16 meters away from recharge wells with an average rate of 0.46 meters/day. In conclusion, the MAR system is a practical solution to capture runoff, mitigate downstream flooding, and enhance groundwater storage for sustainable water management. Most importantly, the system may provide indirect solutions for preventing geohazards within the context of river floods, landslides, and slumps.

Keywords: Flood mitigation, Groundwater model, Managed aquifer recharge

1. Introduction

Climate change has always happened on Earth and currently threatens every aspect of human being and other life on the planet. Climate-induced change involves not only increasing average air temperatures but also extreme weather events. Climate-change driven increases in water and food insecurity pose emerging and long-term challenges. Rising temperatures are already shifting precipitation patterns and intensity and may directly affect global food supply quantity and quality going forward (Phetheet et al., 2020). Moreover, under these circumstances, flood risks and water-related damages are projected to increase with every degree of warming (IPCC, 2022).

Thailand is home to almost 70 million people, which are highly dependent on agriculture and water as their primary source of income. Thailand's climate is tropical and humid, with three different seasons through most of the country. The main seasons are a dry and mild season from November to mid-March, the pre-monsoon season from mid-March to mid-May and the rainy monsoon season from mid-May to November. In Thailand, floods are the most common and recurring natural disasters and happen nearly every year during the monsoon season. Due to the effect of climate change, three important sectors of Thailand's economy, including agriculture, tourism, and trade, have been threatened recently (Kisner, 2008).

Several areas in northeast Thailand, especially in the Nam Kam River basin, have frequently suffered from floods (Fig. 1). The Nam Kam River Basin in the provinces of Sakon Nakhon and Nakhon Phanom has an average rainfall of 1,647.8 mm in 2021, which increased by 22% from 1991 (Fig. 2). In 2017, Sakon Nakhon Province was hit by flash floods on Thursday (July 27) night after heavy rains, which were considered the worst flood in 20 years that hit Isan provinces. The flooding was caused by the tropical storm "Sonca", which has caused widespread flooding throughout NE Thailand. Main roads were under nearly one meter of floodwater triggered by flash floods from the Phu Phan Mountains.

Fig. 1: (Left) An office building in Sakon Nakhon city center hit by flood. (Right) The city being submerged by flash flooding on July 28, 2017 (Charuvastra, 2017).

In 2020, the Department of Groundwater Resources (DGR), under the Ministry of Natural Resources and Environment, Government of Thailand, initiated the managed aquifer recharge (MAR) project in Sakon Nakhon and Nakhon Phanom provinces. In this paper, we focus only on a pilot MAR system in Sakon Nakhon Province. This study aims to evaluate the performance of managed artificial recharge, and to access groundwater flow characteristics and define the 3D patterns using forward particle tracking techniques through two recharge structures, including recharge wells and infiltration basins.

2. Methods

2.1 Site description

The MAR site is located in Dong Khwang Village, Dong Mafai Sub-district, Muang Sakon Nakhon District, Sakon Nakhon Province (17°4'21" N, 104°7'4" E). Sakon Nakhon's climate is classified as tropical. The wet season is oppressive and overcast, while the dry season is humid and partly cloudy. The annual average precipitation was 1,563.1 millimeters for the past five years. In July, Dong Khwang's rainfall reached 326.5 millimeters, which is roughly 150% above the

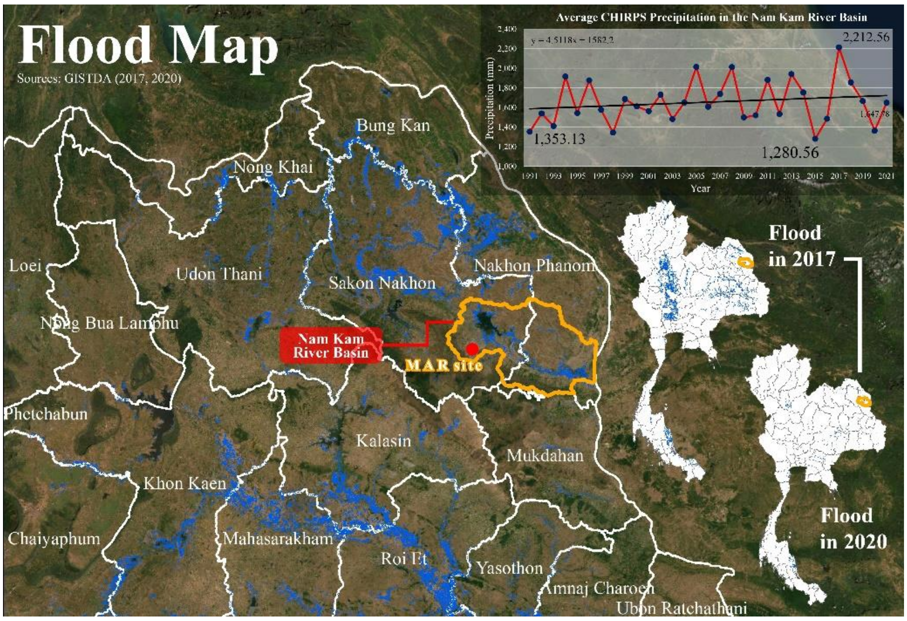


Fig. 2: Map showing flooding areas (scattered blue areas) in NE Thailand in 2017 with average annual precipitation data from 1991 to 2021 in the Nam Kam River Basin (Funk et al., 2015; GISTDA, 2017, 2020).

monthly average (Funk et al., 2015). At the Dong Khwang site, the aquifer is unconfined, and consists mainly of clayey sand, gravelly sand, and siltstone. Local groundwater level ranges from 1.14 (July 2022) to 4.06 (April 2021) meters below the surface. Seasonal groundwater-level fluctuations are approximately 2.92 meters. Hydraulic characteristics of the aquifer are 0.518 m/d, 1.66×10^{-4}, 0.437, and 0.401, for hydraulic conductivity, storativity, total porosity, and effective porosity, respectively (DGR, 2022).

The pilot MAR system at Dong Khwang site was developed in September 2021 (Fig. 3). It includes 5-meter-deep settling and recharge (infiltration) basins. The settling basin was designed to filter fine-grained sediments and minimize clogging of the successive recharge basin. It helps to improve the efficiency of the MAR system. In addition, a weir was constructed between an adjacent stream and the settling basin to control the inflow of surface water to the system. The installation of 15-meter-deep recharge wells allows water from the surface to penetrate to more permeable substrata; therefore, water can percolate directly into the aquifer. Groundwater levels were monitored monthly with six observation wells, five of which were drilled to a depth of 12 meters. The other well was installed to observe the deeper aquifer at 30 meters deep.

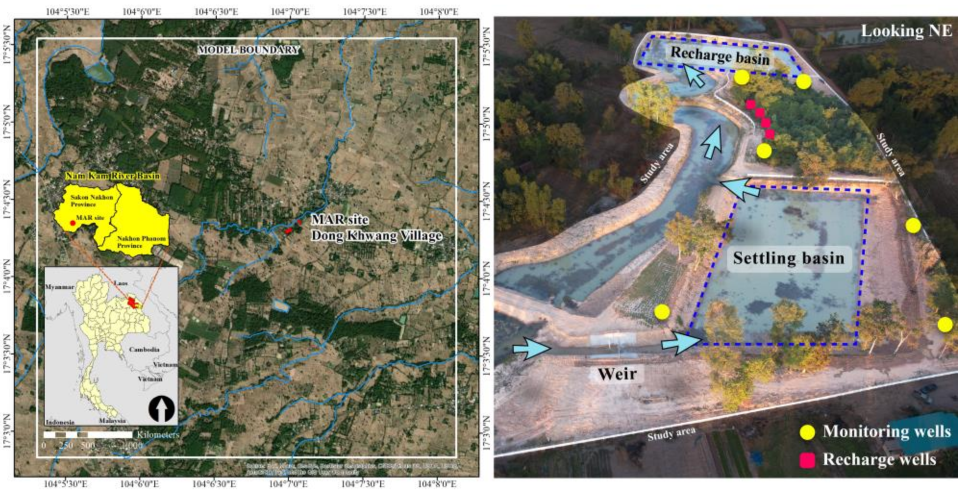


Fig. 3: (Left) A map showing a location of the pilot MAR trial. (Right) An aerial photo of the study area illustrating the system components.

2.2 Hydrogeological and geophysical investigation

According to previous studies, DGR published a suitability map for MAR site selection in the Nam Kam River Basin area. This MAR suitability map was implemented using GIS-based Multi-Criteria Decision Analysis (DGR, 2020). The analysis involved four main criteria, including geology, geomorphology, soil infiltration rate, and slope. As a result, Dong Khwang Village in Sakon Nakhon Province was one of the suitable sites in the Nam Kam River Basin for MAR construction.

Lithological data together with electrical well logging data were collected from the DGR's Groundwater Resources Management Database (Smart Pasutara). Additionally, six boreholes were drilled for permeability test using the falling-head test technique.

A two-dimensional resistivity survey was conducted at the MAR construction site with a spacing of 3 meters electrode (3 lines) and adjacent areas with a spacing of 10 meters electrode (15 lines). The survey aimed to characterize underlying weathering soil and bedrock at the site, and to map the horizontal and vertical variations of subsurface geology for the entire simulated area (DGR, 2022).

All primary data collected in the field and secondary information were integrated and used to construct geological and hydrogeological cross sections. These sections provide in-depth details about geological conditions, illustrate the horizontal and vertical extent of aquifers, and show the groundwater flow direction within the study area.

2.3 Simulation of pilot MAR using groundwater flow model

A groundwater-flow simulation was developed to represent the groundwater system in Dong Khwang Village, Sakon Nakhon Province. The pilot MAR scheme was simulated using the U.S. Geological Survey modular finite-difference flow model to determine the flow of groundwater through aquifers (Harbaugh, 2005). In this study, a Newton-Raphson formulation for MODFLOW-2005 called MODFLOW-NWT (Niswonger et al., 2011) was employed for solving numerical issues of the unconfined groundwater-flow equation. The MODFLOW-NWT provides an alternative solution to deal with drying and rewetting nonlinearities of the system.

The model domain represents a rectangular area of 25 km^2 (2,500 hectares) with grid sizes ranging from 50×50 to 20×20 m^2. A relatively fine-grid discretization (20×20 m^2) is required in the area of interest, such as the MAR site (Mehl et al., 2006). The groundwater model domain was discretized into 124 rows and 124 columns. The model consists of four different layers: (1) the first (uppermost) layer is of relatively low hydraulic conductivity, representing a clayey sand layer, (2) the second layer is highly permeable, being composed of gravelly sand sediments, (3) the third layer is the weathered zone of siltstone, and (4) the fourth layer is a siltstone layer (Fig. 4).

Following the conceptual model, the main input boundaries are located in the southwest from the Phu Phan Mountains, while the main output boundaries are located in northeastern part of the model boundary, where the largest natural lake of northeast Thailand, namely Nong Han, is situated. These boundaries are represented by the General-Head Boundary (GHB) package as the external boundary conditions. The top model layer involves two external surficial stresses simulated using the Recharge (RCH) and Evapotranspiration (EVT) packages. Recharge was estimated from precipitation based on the CHIRPS dataset, which is the rainfall estimates from rain gauge and satellite observations (Funk et al., 2015). The EVT values at the Sakon Nakon weather station were obtained from the Royal Irrigation Department based on reference crop evapotranspiration (ET_o) and crop coefficient (K_c). The main rivers flow from the southwestern side of the model and exit on the northeastern side, which were simulated by the River (RIV) package. Abstraction was simulated by the Well (WEL) package with the negative sign; likewise, recharge wells were calculated by the same package but applied with the opposite sign. Furthermore, the Lake (LAK) package was

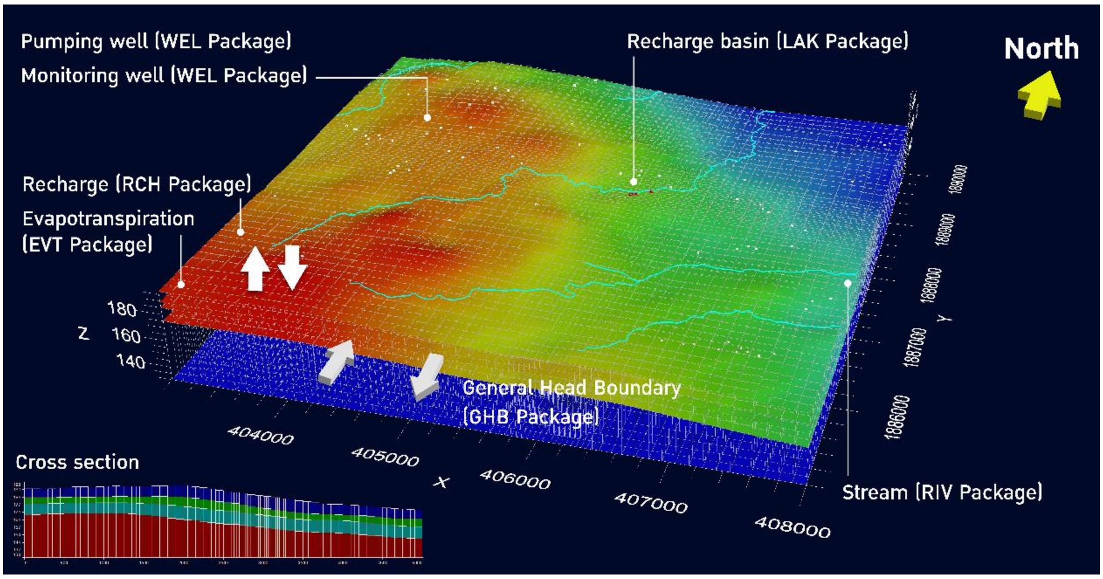


Fig. 4: A schematic diagram representing model layers and MODFLOW packages.

applied to assess the performance of the recharge basin. This package was designed to calculate volumetric water exchange between an artificial lake and an underlying aquifer (El-Zehairy et al., 2018; Merritt & Konikow, 2000). A 10-year simulation begins with monthly data from October 2020 to September 2021. For the remaining nine years (October 2021 to September 2030), input data were defined using annual average values for the projection period.

Groundwater level was monitored from 6 observation wells located around the MAR sites, and the other 71 wells were observed within the model domain. Groundwater levels were measured monthly from October 2020 to April 2022 using an electric tape and an automatic data logger. Data were used to construct head distribution and groundwater-flow direction maps. Afterward, a series of groundwater levels were imported to the model as observed head values for model validation.

After the model performance had been acceptable, MODPATH was employed to compute three-dimensional flow paths for imaginary particles of water moving through the groundwater system (Pollock, 2016). The program is known as a post-processing module that calculates flow paths from MODFLOW's head and flow output files. In addition to particle paths, MODPATH computes the residence time for particles traveling through the system.

3. Results

The results of this study are presented and discussed with the performance of the pilot MAR system. In Thailand, a modeling approach is rarely performed to investigate the dynamics of artificial lake-groundwater interactions. The MAR performance, in terms of groundwater quantity, flow direction, and residence time, will be shown and emphasized hereafter.

3.1 Groundwater flow model

Water balancing of the MAR basin involved many interacting surface, unsaturated zone, and groundwater components. In general, interactions, in terms of quantity, between the MAR system and groundwater can be simply expressed as follows:

$$P + Q_{GWin} + GHB_{in} + Well_{in} + Lake_{in} = ET + Q_{GWout} + GHB_{out} + Well_{out} + Lake_{out} + \Delta S$$

where P is precipitation rate, Q_{GWin} is stream seepage to groundwater, Q_{GWout} is groundwater seepage to stream, GHB_{in} is lateral groundwater inflows, GHB_{out} is lateral groundwater outflows, $Well_{in}$ is inflows from recharge wells, $Well_{out}$ is outflows from pumping wells, $Lake_{in}$ is seepage from the lake into groundwater, $Lake_{out}$ is seepage from groundwater into the lake

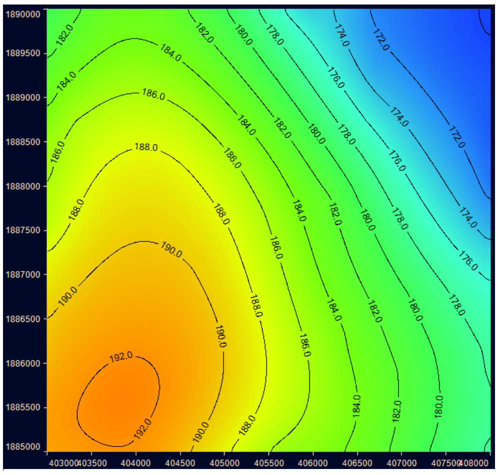
lake, ET is total evapotranspiration, and ΔS is total change in storage.

The water balance of the whole model domain is presented in Table 1. Simulated heads at different periods are shown in Fig. 5: (a) 10 days after simulation, representing the pre-MAR construction phase, (b-d) 6 months, 1 year, and 2 years after simulation, respectively. The effect of artificial recharge is presented as an increase in hydraulic head after year 1 and year 2 (Fig. 5). The calculated results showed a good match between simulated heads and observed heads, which were monitored from 77 observation wells in total, as shown in Fig. 6. The model performance was evaluated using a standard statistical parameter called the normalized root mean square error (NRMSE). The NRMSE of the pilot simulation stands at 8.98%, which was acceptable for this study. A one-year groundwater balance includes six input fluxes: storage (11.17%), wells (0.15%), river leakage (9.06%), head dep bounds (7.11%), recharge (71.90%), and lake seepage (0.61%); and six output fluxes: storage (13.87%), wells (5.54%), river leakage (15.48%), evapotranspiration (7.64%), head dep bounds (57.35%), and lake seepage (0.12%).

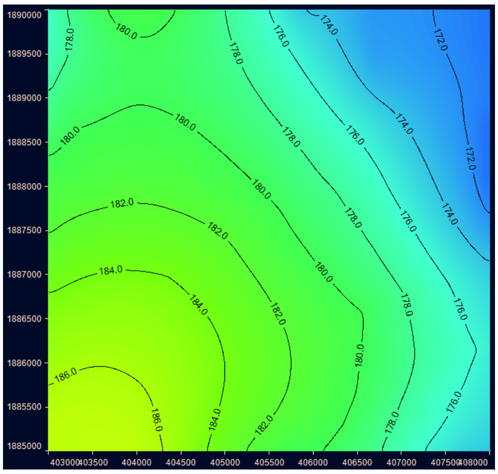
The temporal analysis of artificial lake seepage and groundwater-well recharge fluxes using MODFLOW's Lake and Well packages is the main purpose of this study. Hence, input fluxes of well and lake seepage components were considered in this study. The MAR system has an ability to store stormwater runoff as well as provide direct pathways to convey water underground. Consequently, modeling results revealed that a rate of groundwater recharge (or a seepage rate) via the infiltration basins in Dong Khwang Village was 90,052.3984 m^3 per year, while the recharge wells could supply water of about 22,599.998 m^3 to the subsurface storage in one year. A construction of the 8,000-m^2 (0.8 hectares) MAR system can store surplus water underground roughly 112,652 m^3 annually.

Table 1: Volumetric budget for the entire model at the end of 1-year simulation.

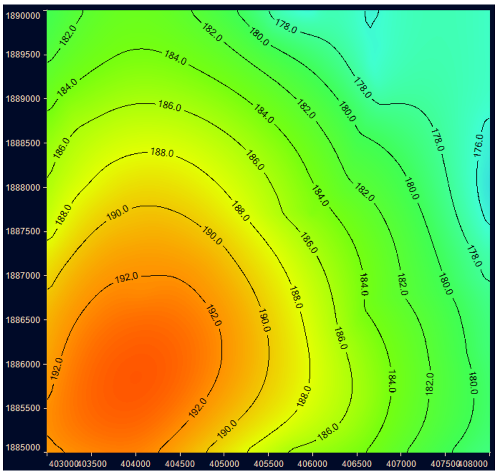
Cumulative volume (m^3)		Rates for this time step (m^3/time step)	
IN:		IN:	
Storage	1,654,455.7500	Storage	3,157.5332
Wells	22,599.9980	Wells	120.0000
River leakage	1,341,774.5000	River leakage	1,782.0767
Head dep bounds	1,052,490.1250	Head dep bounds	119.7833
Recharge	10,649,801.0000	Recharge	50,960.8984
Lake seepage	90,052.3984	Lake seepage	271.5052
Total in	**14,811,174.0000**	**Total in**	**56,411.7969**
OUT:		OUT:	
Storage	2,054,155.2500	Storage	4.2654
Wells	820,049.9375	Wells	2,310.0000
River leakage	2,293,464.5000	River leakage	13,967.9531
ET	1,131,144.1250	ET	6,022.9092
Head dep bounds	8,494,350.0000	Head dep bounds	34,106.7969
Lake seepage	18,032.5684	Lake seepage	0
Total out	**14,811,197.0000**	**Total out**	**56,411.9258**
IN - OUT	-23.0000	**IN - OUT**	-0.1289
Percent discrepancy	-0.00	**Percent discrepancy**	-0.00



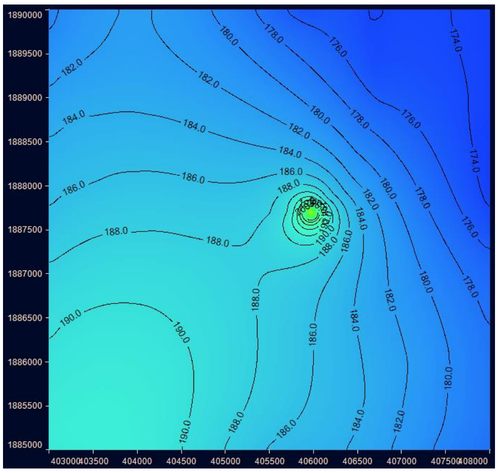
(a) 10 days after simulation
(the pre-MAR construction phase)



(b) 6 months after simulation



(c) 1 years after simulation



(d) 2 years after simulation

Fig. 5: Head distribution map (a) the pre-MAR construction phase, and (b-d) after the MAR operation at different periods.

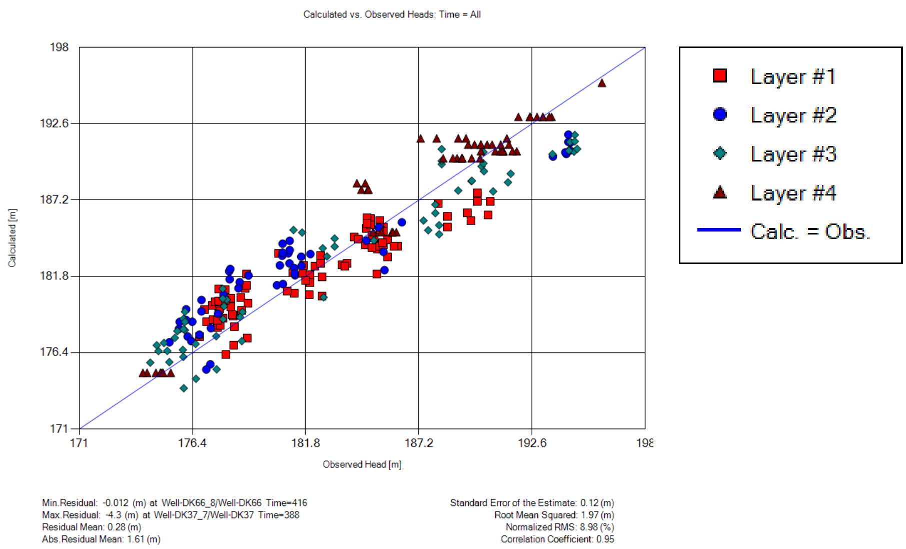


Fig. 6: Comparison between calculated heads and observed heads.

3.2 Particle-tracking model

In this study, a particle-tracking model, MODPATH, was employed to calculate 3D groundwater flow paths from the pilot MAR site (forward-particle tracking), and subsequently track the traveling time and motion of imaginary particles through the groundwater system for ten years. In the beginning, 79 particles were assigned at the bed of artificial lake, and the other 160 particles were created in the center of four 15-meter-deep recharge wells.

After a ten-year simulation, some particles exit from the aquifer after joining surface water bodies and streams. The travel distance of particles (76% of the total particles) from the infiltration ponds are mostly limited to less than 70 meters away from the site in ten years. However, 2.5% of the particles (two particles) can travel much farther, reaching a maximum distance of up to 698.070 meters. The maximum traveling rate of particles is 0.195 meters/day. However, particles simulated at a depth of 15 meters from recharge wells are much longer. Under this scenario, the maximum distance traveled by the particles is 1,683.157 meters, and the minimum distance is 177.617 meters in ten years. Hence, the traveling rate ranges from 0.05 to 0.46 meters/day.

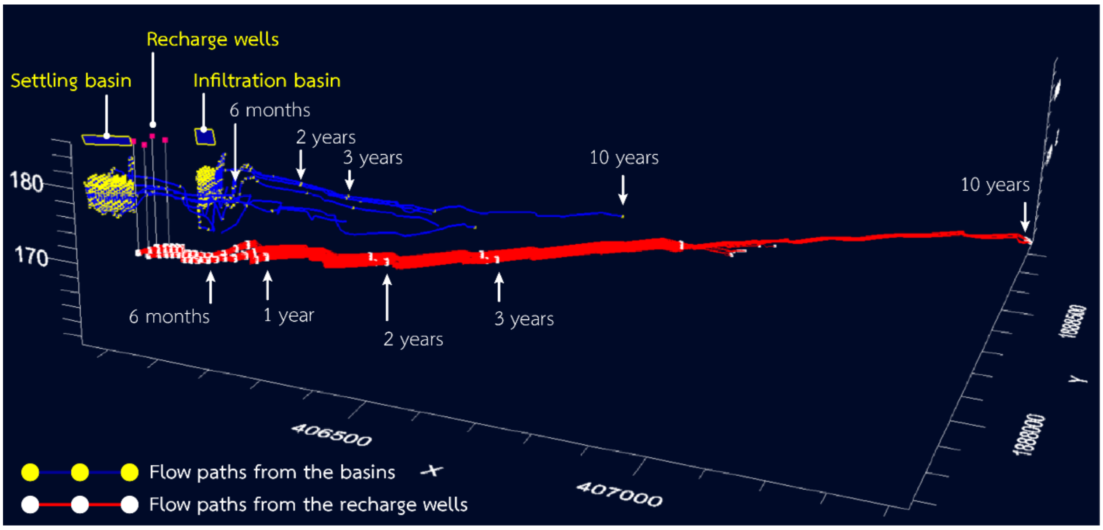


Fig. 7: Three-dimensional flow paths showing flow direction of imaginary particles from the MAR ponds (blue lines) and recharge wells (red lines).

4. Discussion

The numerical model is a simplified representation of the natural groundwater system. The model includes limitations regarding the uncertainty in hydraulic conductivity in areas far from the MAR site, the simulation of lateral groundwater fluxes across the model boundary, and the assumption of uniform storage properties. More importantly, clogging mechanisms were not included in the simulation, causing the model to produce relatively high infiltration rates via the recharge basins. Actual input data were available for one year, while the 10-year projection was assumed to be annual averages of historical data. As presented in Fig. 7, groundwater paths from the MAR basins fluctuated, conforming to seasonal changes in the water table in the first year. Afterward, particles tend to move smoothly because annual average data were applied for model projections.

However, groundwater modeling, presented in this work, is a cost- and time-saving technique to provide an accurate and adequate assessment of the MAR construction. Moreover, this technique can be adopted in any MAR system to select suitable MAR types for construction, design the system, enhance its operation, and propose water management strategies for subsequent uses of groundwater.

These facilities primarily aim to collect surplus water during the wet seasons and drain it down to the groundwater system. However, we can design the MAR system with multiple benefits, such as habitats for wildlife, which could help to make recharge basins more wildlife-friendly, increase vegetative cover, and ultimately create more soil moisture. In addition to being purpose-built recharge structures, the MAR ponds can be used as additional surface-water reservoirs, alternatively providing water for agriculture, livestock, and aquaculture for local people.

5. Conclusions

Recently, extreme precipitation events are expected to intensify with climate change and likely increase the intensity and frequency of flooding (Tabari, 2020). Floods are the deadliest and most common form of natural disaster in Thailand and the world. Floods are unpredictable; therefore, the government must be prepared to always respond.

The Department of Groundwater Resources, Ministry of Natural Resources and Environment, Government of Thailand, is an official agency with the core mission of managing groundwater resources in Thailand. After the Nam Kam River Basin faced the renowned flash flooding in 2017, DGR developed the pilot MAR system and planned to provide guidelines that will effectively mitigate the impact of climate disasters, such as flooding.

This study demonstrates the use of a renowned groundwater-flow model or MODFLOW to assess the performance of the MAR system. The results of flow simulation provide the efficiency of MAR in quantitative aspects and the projection of groundwater flow movement using forward particle tracking techniques. With an area of 0.8 hectares, the pilot MAR system is able to store stormwater runoff underground of about 112,652 m^3 per year. According to the prediction of groundwater movement and its residence time, the maximum travel distance from the MAR pond is 698.070 meters in a decade, with an average of roughly 0.195 meters/day. Particles traveling from the recharge wells, which were drilled to the highly permeable unit, can travel a longer distance. The maximum travel distance is 1,683.157 meters, with an average rate of 0.46 meters/day.

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