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Cisuralian–Guadalupian brachiopod assemblages from the northern Tengchong Block in western Yunnan, China and their paleogeographical implications—a revisit

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Non-technical Summary.—Paleontological data from the late Paleozoic strata of western Yunnan, southwestern China, have played significant roles in understanding the history of the Cimmerian continental blocks and the Paleotethys Ocean. In this paper, we describe and illustrate brachiopod fossils from the early to middle Permian strata of western Yunnan, China. These brachiopods were collected from three beds of the Shanmutang section, and composed of three assemblages, which in ascending order include the *Elivina-Etherilosia* Assemblage from the top of the Kongshuhe Formation, the *Spiriferella-Spiriferellina* Assemblage from the base of the Dadongchang Formation, and the *Waagenites-Costiferina* Assemblage from the lower part of the Dadongchang Formation. The first assemblage is considered to be most likely late Sakmarian to early Artinskian, the second assemblage probably late Artinskian, and the third assemblage late Roadian to early Wordian in age. It is noticed that there is a transition from cool-water brachiopod faunas with Gondwanan affinities to mixed warm-temperate (transitional) faunas with Cathaysian elements during the Artinskian and through the Guadalupian. We consider that this phenomenon probably resulted from the Gondwana deglaciation and the northward drift of the peri-Gondwanan blocks (including the Tengchong Block) during the Cisuralian and Guadalupian.

Abstract.—The early to middle Permian brachiopods from the Tengchong Block in western Yunnan, southwestern China, play important roles in biostratigraphic correlation and paleogeographic inferences of tectonic units on eastern peri-Gondwana. However, detailed taxonomic studies of these brachiopods have been limited. In this paper, we provide the systematic description of three Permian brachiopod assemblages from the Shanmutang section in the northern Tengchong Block, which in ascending order include the *Elivina-Etherilosia* Assemblage from the top of the Kongshuhe Formation, and the *Spiriferella-Spiriferellina* Assemblage and the *Waagenites-Costiferina* Assemblage from the base and lower part, respectively, of the overlying Dadongchang Formation. Based on the biostratigraphic assessment of the brachiopod taxa as well as the age constraints from the associated fusulinid assemblages, the age of the *Elivina-Etherilosia* Assemblage is considered to be most likely late Sakmarian to early Artinskian, the *Spiriferella-Spiriferellina* Assemblage probably late Artinskian, and the *Waagenites-Costiferina* Assemblage late Roadian to early Wordian. A transition from cool-water faunas with Gondwanan affinities to mixed warm-temperate (transitional) faunas with Cathaysian elements is evident for the Artinskian and through the Guadalupian. The climatic transition inferred from the faunal evidence is interpreted to have resulted from the combined effect of Gondwana deglaciation and the northward drift of the peri-Gondwanan blocks (including the Tengchong Block) during the Cisuralian and Guadalupian.

Introduction

Paleontological data from the late Paleozoic strata of western Yunnan, southwestern China, have played significant roles in understanding the history of the Cimmerian continental blocks and the Paleotethys Ocean (Shi et al., 1996; Shen et al., 2000, 2002; Shi and Shen, 2001; Shi et al., 2008, 2011, 2017; Huang et al., 2009, 2015, 2020). The area west of the Lancangjiang (Mekong) River in Yunnan has been divided into three tectonic units (e.g., Jin, 1994, 1996), namely, from west to east, the Tengchong Block, the Baoshan Block, and the Changning-Menglian Belt (Fig. 1). The Tengchong and Baoshan blocks are thought to have been derived from Gondwana as components of the eastern segment of the Cimmerian continental blocks (e.g., Sengör, 1984; Ueno, 2003; Huang et al., 2020), whereas the Changning-Menglian Belt is considered to be remnants of the Paleotethys (e.g., Liu et al., 1991; Fang et al., 1996; Metcalfe, 2013; Wang et al., 2018; Zheng et al., 2021). Permian marine sequences are well exposed in

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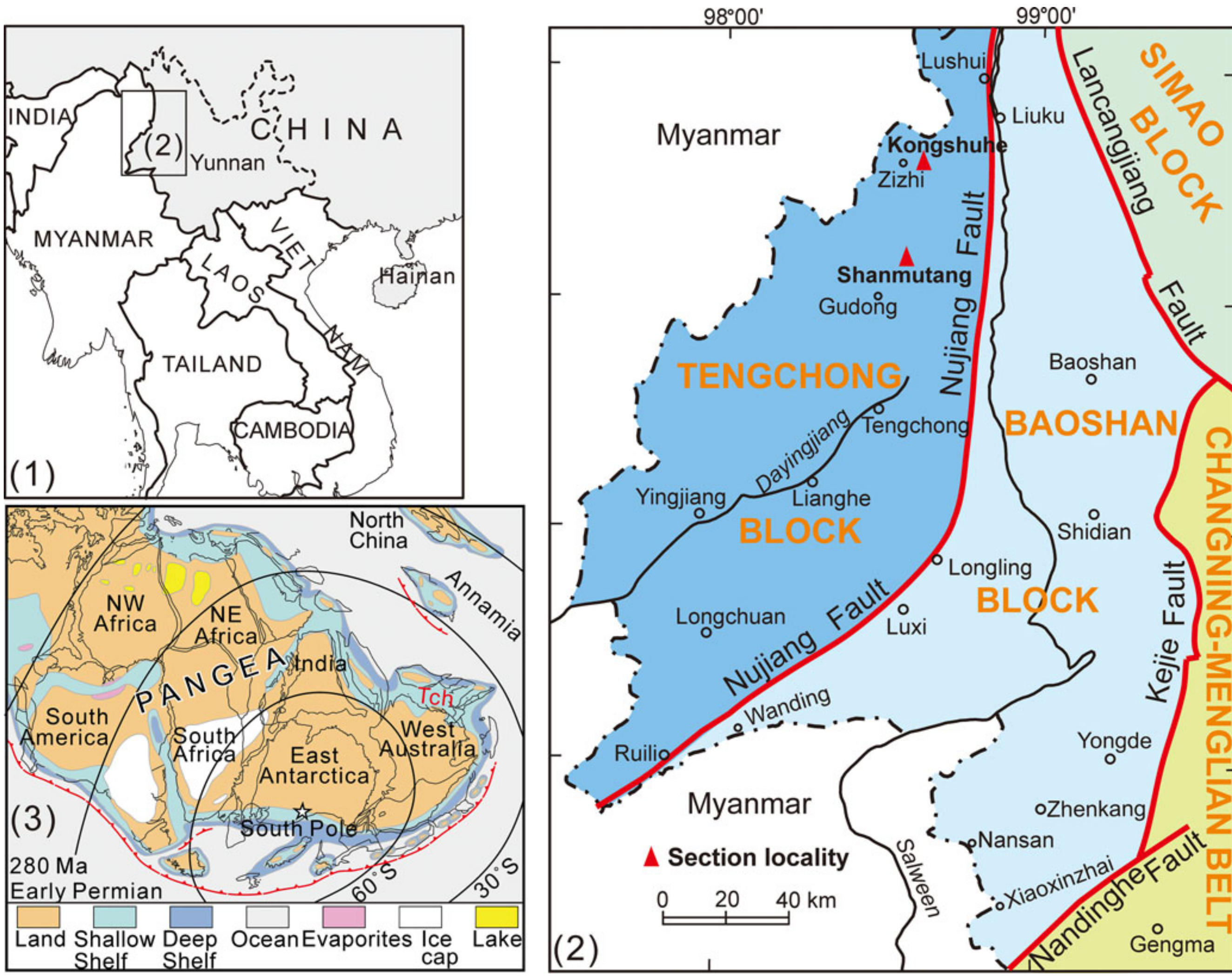

Figure 1. (**1**) Geographic location of the study area in western Yunnan, China, with rectangle indicating (**2**). (**2**) Tectonic subdivision of western Yunnan, with section localities indicated. (**3**) Probable location of the Tengchong Block (Tch in red) in the early Permian (280 Ma); paleogeographic map slightly simplified from Torsvik and Cocks (2013).

the Baoshan and Tengchong blocks. Permian brachiopod fossils from the Baoshan Block and their paleobiogeographic aspects have been relatively well studied (Fang, 1983, 1994; Fang and Fan, 1994; Shi et al., 1996; Shen et al., 2000, 2002; Shi and Shen, 2001), whereas those of the Tengchong Block have so far only received limited attention.

In an article describing the Permian lithostratigraphic succession of Gondwanan affinities in southwest China, Jin et al. (2011) reported three brachiopod assemblages from the Shanmutang section located in the northern part of the Tengchong Block (Fig. 1.2), and they were named as, in ascending order, the *Notospirifer transversa-Elivina yunnanensis* Assemblage from the top of the Kongshuhe Formation, the *Spiriferella qubuensis-Spiriferellina yunnanensis* Assemblage from the base of the Dadongchang Formation, and the *Derbyia grandis-Waagenites mediplicata* Assemblage from a higher level of the Dadongchang Formation. The ages of these three assemblages were inferred to be the Sakmarian–Artinskian, early Kungurian–early Roadian, and Wordian, respectively. However, no detailed taxonomic description of the brachiopods has been provided.

In this paper, we present the systematic descriptions and illustrations of these brachiopod assemblages. We also refine the ages of the assemblages, based on correlations with coeval brachiopod assemblages from other Cimmerian blocks, as well as ages indicated by associated fusulinids. In addition, the paleogeographic implications of these brachiopod assemblages are addressed for a better understanding of the tectonic evolution of the Tengchong Block (and other Cimmerian blocks) during the Permian.

Stratigraphy

The Carboniferous–Permian successions in the northern Tengchong Block include, in ascending order, the Zizhi, Kongshuhe, and Dadongchang formations (Jin, 1994; Fig. 2). The Zizhi Formation consists of >700 m thick monotonous quartz sandstones. The overlying Kongshuhe Formation, 700–900 m thick, consists mainly of diamictites and pebbly mudstones, with relatively minor amounts of dark shales, siltstones, and lenticular limestone beds. The latter lithology (limestone) becomes more

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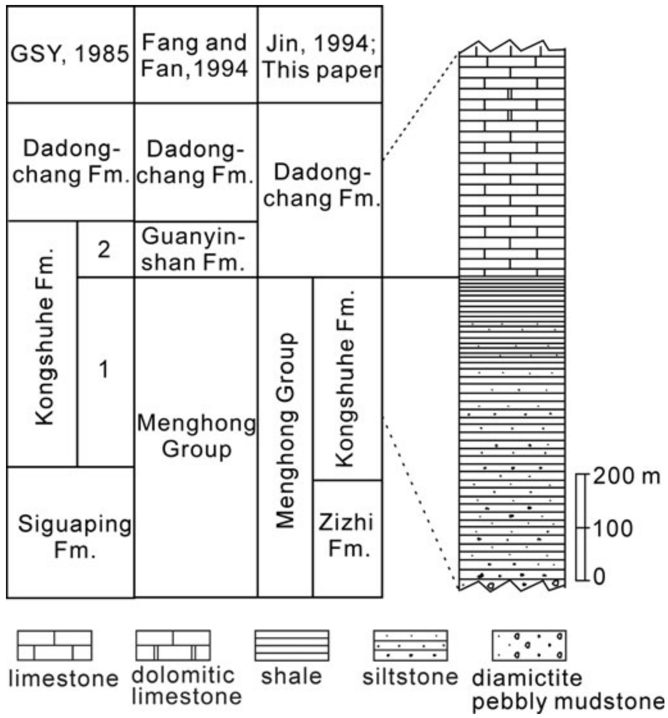

Figure 2. History of the subdivision of Carboniferous-Permian successions in the northern part of the Tengchong Block. A lithological column is presented to help clarify the confusion caused by Geological Survey of Yunnan (1985), who handled the fossiliferous lower part of the carbonate succession as the second member of the Kongshuhe Formation that is otherwise a fining-up clastic succession, for the purpose of giving the Kongshuhe Formation a relatively reliable age. Fang and Fan (1994) named the carbonate second member of the former Kongshuhe Formation as the Guanyinshan Formation, but its upper boundary with the overlying Dadongchang Formation remained a problem, being hardly determinable in the field. Jin (1994) restored the basic meaning of a formation, i.e., a mappable lithological unit, and thus placed the carbonate succession in the Dadongchang Formation. His plan is followed in this paper. Fm. = Formation.

evident and common toward the upper part of the formation, especially in its top 100 m where it contains abundant brachiopods, bryozoans, and crinoids (Shi et al., 2008; Jin et al., 2011; Figs. 2, 3). The Dadongchang Formation is 600 m thick and mostly composed of limestones and dolomitic limestones. The lower part of this formation (~150 m thick) is composed of limestones and bioclastic limestones, containing fusulinids and brachiopods; the middle part (~50 m thick) is characterized by thin-bedded micritic limestones, yielding brachiopods. Upward, it is overlain by thick-bedded, fusulinid-bearing limestones (~100 m thick). The upper part of the formation (~300 m thick) is dominated by dolomitic limestones (Shi et al., 2008; Jin et al., 2011; Fig. 3).

Brachiopod specimens of this study were collected from three levels of the Shanmutang section: the top of the Kongshuhe Formation, base of the Dadongchang Formation (~5–7 m above the base of this formation), and lower part of the Dadongchang Formation (~120 m above the base of the formation) (Fig. 3). The brachiopod specimens from the Kongshuhe Formation are preserved mainly as molds in mudstones, commonly co-occurring with bryozoans and crinoids. On the other hand, the specimens from the Dadongchang Formation mostly retain their calcareous shells with better preservation conditions than those from the Kongshuhe Formation.

Previous studies on Permian brachiopods from the Tengchong Block

Permian brachiopods have been known from the Kongshuhe and Dadongchang formations (or in their equivalent beds) in the Tengchong Block since the 1980s. Wang (1983) first reported nine genera from the upper part of the Menghong Group (= the upper part of the Kongshuhe Formation). In a subsequent regional geological survey report, the Geological Survey of Yunnan (1985) listed 90 brachiopod species in 47 genera from the Kongshuhe Formation (approximately the Kongshuhe Formation and the lower part of the Dadongchang Formation of this study) (Fig. 2). Then, Nie et al. (1993) also listed some brachiopods from the Tengchong Block. However, all of these reports lacked systematic descriptions and illustrations, and no specimens from the studies are available for reinvestigation.

The first systematic paleontological study with illustrations of Permian brachiopods from the Tengchong Block was given by Fang and Fan (1994). The taxa described include three indeterminate species (*Chonetinella* sp. indet., *Echinaria* sp. indet., and '*Martinia*' sp. indet.) from the Menghong Group near Lianghe in the southern Tengchong Block (Fang and Fan, 1994), and a much more diverse brachiopod assemblage consisting of 25 species in 16 genera from the Guanyinshan Formation (= the lower part of the Dadongchang Formation) (Fig. 2) in the Dadongchang in the northern Tengchong Block (Fang and Fan, 1994; see also Fang, 1995). Fang (1995) noted particular similarities between the Guanyinshan brachiopod assemblage, and the *Waagenites-Costiferina* Assemblage reported from the Xiaoxinzhai Formation (corresponding to the Yongde Formation) in Gengma of the Baoshan Block by Fang (1983).

Materials and methods

Approximately 120 brachiopod specimens collected from three levels of the Shanmutang section were first mechanically prepared using steel needles, scalpels, chisels, and brushes to get better exposure of the samples, and then examined with a hand lens and microscope. The photographed samples were first coated with smoked ammonium chloride, and then photographed using a Nikon SMZ18 stereo microscope equipped with a Nikon D800 digital SLR camera.

The systematic study adopted here follows classifications proposed by Brunton et al. (2000a, b) for Productida, Williams et al. (2000) for Orthotetida, Savage et al. (2002) for Rhynchonellida, Alvarez and Rong (2002) for Athyridida, Carter et al. (2006) for Spiriferida, Carter and Johnson (2006) for Spiriferinida, and Lee et al. (2006) for Terebratulida.

Repositories and institutional abbreviations.—All of the described specimens in this study are deposited at the Institute of Geology, Chinese Academy of Geological Sciences, Beijing, China (IGCAGS). Other cited repositories are: NIGP, Nanjing Institute of Geology and Palaeontology, Nanjing, China; USNM, National Museum of Natural History, Washington, D.C.

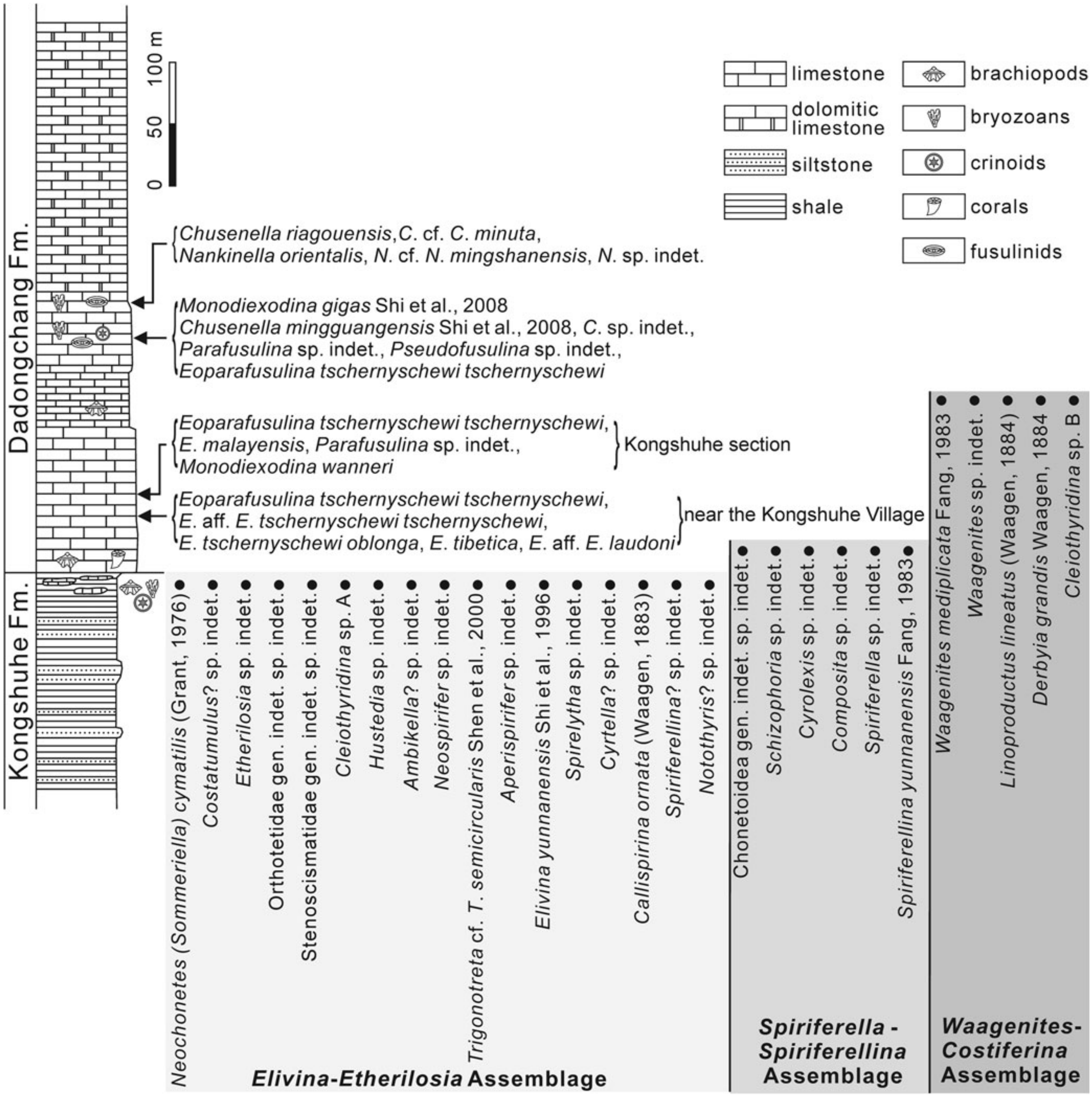

Figure 3. Stratigraphic column of the upper part of the Kongshuhe Formation and the lower part of the Dadongchang Formation in the northern Tengchong Block (modified from Jin et al., 2011). Data are from the Shanmutang section, except as indicated. Taxonomic lists of fusulinids are based on Shi et al. (2008, 2017) and Huang et al. (2020). Species not otherwise mentioned in the text are: *Chusenella* cf. *Chusenella minuta* Skinner, 1969; *Chusenella riagouensis* Chen in Zhang, Chen, and Yu, 1985; *Eoparafusulina* aff. *Eoparafusulina laudoni* (Skinner and Wilde, 1966); *Eoparafusulina malayensis* Igo, Rajah, and Kobayashi, 1979; *Eoparafusulina tibetica* Nie and Song, 1983; *Eoparafusulina tschernyschewi oblonga* (Grozdilova and Lebedeva, 1961); *Eoparafusulina tschernyschewi tschernyschewi* (Grozdilova and Lebedeva, 1961); *Monodiexodina wanneri* Schubert, 1915; *Nankinella* cf. *Nankinella mingshanensis* Sheng and Rui, 1984; *Nankinella orientalis* Miklukho-Maklay, 1954. Fm. = Formation.

Brachiopod assemblages: composition, age, and paleobiogeographical implications

The brachiopod specimens described in the present study were originally referred by Jin et al. (2011, fig. 3), but without description or illustration. Detailed systematic study of these specimens herein undertaken (see Systematic paleontology section below) has allowed us to revise and update their taxonomic identifications and species composition list (Table 1). Consequently, based on this study, as well as taking into account the previously reported taxa from the Tengchong Block (e.g., Fang and Fan, 1994; Fang, 1995), we recognize three brachiopod assemblages from the Permian strata in the northern Tengchong Block, in ascending order: the *Elivina-Etherilosia* Assemblage, the *Spiriferella-Spiriferellina* Assemblage, and the *Waagenites-Costiferina* Assemblage.

Table 1. Taxonomic composition of three Permian brachiopod assemblages in northern Tengchong Block, showing the original species listed by Jin et al. (2011) and the corresponding emendation in this paper. -= not present; * = new addition; § = we consider that the specimens of Jin et al. (2011) from the lower part of the Dadongchang Formation can be assigned to the *Waagenites-Costiferina* Assemblage previously recognized by Fang (1995), and thus we adopt Fang's assemblage name here; R = taxonomic treatment revised. Note that the assemblages are now named after representative genera.

Assemblage	Jin et al. (2011: fig. 3)	This study
Waagenites-Costiferina §	*Waagenites mediplicata* Fang, 1983	*Waagenites mediplicata* Fang, 1983
	Waagenites sp. indet.	*Waagenites* sp. indet.
	Ogbinia? sp. indet.	-
	Stereochia yunnanensis (Fang, 1983)	-
	Linoproductus lineatus (Waagen, 1884)	*Linoproductus lineatus* (Waagen, 1884)
	Orthotetes sp. indet.	*Derbyia grandis* Waagen, 1884[R]
	Derbyia grandis Waagen, 1884	*Derbyia grandis* Waagen, 1884
	Cleiothyridina cf. *Cleiothyridina aculeata* Fang, 1983	-
	-	*Cleiothyridina* sp. B*
Spiriferella-Spiriferellina	-	Chonetoidea gen. indet. sp. indet.*
	Schizophoria sp. indet.	*Schizophoria* sp. indet.
	Tornquistia? sp. indet.	-
	Stenoscisma cf. *Stenoscisma purdoni* (Davidson, 1862)	*Cyrolexis* sp. indet.[R]
	Stenoscisma sp. indet.	-
	Spirigerella sp. indet.	*Composita* sp. indet.[R]
	Composita sp. indet.	*Composita* sp. indet.
	Spiriferella qubuensis Zhang in Zhang and Jin, 1976	*Spiriferella* sp. indet.[R]
	Spiriferella sp. indet.	-
	Spiriferellina yunnanensis Fang, 1983	*Spiriferellina yunnanensis* Fang, 1983
	Spiriferellina sp. indet.	-
Elivina-Etherilosia	*Neochonetes* (*Sommeriella*)? sp. indet.	-
	Chonetinella sp. indet.	*Neochonetes* (*Sommeriella*) *cymatilis* (Grant, 1976)[R]
	Comuquia tengchongensis sp. nov.	*Etherilosia* sp. indet.[R]
	Retimarginifera cf. *Retimarginifera alata* Waterhouse, 1981	*Neochonetes* (*Sommeriella*) *cymatilis* (Grant, 1976)[R]
	Anidanthus? sp. indet.	-
	Cancrinella sp. indet.	*Costatumulus*? sp. indet.[R]
	-	Orthotetidae gen. indet. sp. indet.*
	Stenoscisma cf. *Stenoscisma quasimutabilis* Waterhouse, 1981	Stenoscismatidae gen. indet. sp. indet.[R]
	Cleiothyridina sp. indet.	*Cleiothyridina* sp. A
	Hustedia sp. indet.	*Hustedia* sp. indet.
	Crurithyris sp. indet.	*Notothyris*? sp. indet.[R]
	Tomiopsis sp. indet.	*Ambikella*? sp. indet.[R]
	Notospirifer extensa sp. nov.	*Cyrtella*? sp. indet.[R]
	Notospirifer yunnanensis sp. nov.	*Spiriferellina*? sp. indet.[R]
	-	*Aperispirifer* sp. indet.*
	Neospirifer hardmani (Foord, 1890)	*Neospirifer* sp. indet.[R]
	Trigonotreta semicircularis Shen, Shi, and Zhu, 2000	*Trigonotreta* cf. *Trigonotreta semicircularis* Shen, Shi, and Zhu, 2000[R]
	Sulciplica shanmutangensis sp. nov.	*Aperispirifer* sp. indet.[R]
	Elivina yunnanensis Shi, Fang, and Archbold, 1996	*Elivina yunnanensis* Shi, Fang, and Archbold, 1996
	Spirelytha sp. indet.	*Spirelytha* sp. indet.
	Punctospirifer afghanus Termier et al., 1974	*Spiriferellina*? sp. indet.[R]
	Spiriferellina sp. indet.	*Callispirina ornata* (Waagen, 1883)[R]

The Elivina-Etherilosia *Assemblage.*—This assemblage occurs in the top of the Kongshuhe Formation at the Shanmutang section (Fig. 3), composed of: three productides—*Neochonetes* (*Sommeriella*) *cymatilis* (Grant, 1976), *Costatumulus*? sp. indet., and *Etherilosia* sp. indet.; an orthotetide—Orthotetidae gen. indet. sp. indet.; a rhynchonellide—Stenoscismatidae gen. indet. sp. indet.; two athyridides—*Cleiothyridina* sp. A and *Hustedia* sp.; six spiriferides—*Ambikella*? sp. indet., *Neospirifer* sp. indet., *Trigonotreta* cf. *Trigonotreta semicircularis* Shen, Shi, and Zhu, 2000, *Aperispirifer* sp. indet., *Elivina yunnanensis* Shi, Fang, and Archbold, 1996, and *Spirelytha* sp. indet.; three spiriferinides (*Cyrtella*? sp. indet., *Callispirina ornata* (Waagen, 1883), and *Spiriferellina*? sp. indet.; and a terebratulide—*Notothyris*? sp. indet. In the assemblage, the spiriferides show the highest generic diversity with six genera, followed by productides and spiriferinides with three genera each (Fig. 4.1). The athyridides are minor, represented by two genera. Both orthotetide and rhynchonellide brachiopods are uncommon, each represented by only a single indeterminate genus. Terebratulides are represented by one genus (Fig. 4.1). Regarding species abundance, spiriferides are the most abundant, followed in turn by productides and spiriferinides (Fig. 4.2).

Jin et al. (2011, p. 379) suggested that the *Elivina-Etherilosia* Assemblage (equivalent to their *Notospirifer transversa-Elivina yunnanensis* Assemblage) is late Sakmarian to early Artinskian in age, based on the supposed temporal ranges of the genera *Trigonotreta* Koenig, 1825, *Spirelytha* Fredericks, 1924, and the species *Elivina yunnanensis*. Although these taxa have been partially revised in this study, this age assignment remains valid and is followed here. It is also supported by the occurrence of *Neochonetes* (*Sommeriella*) *cymatilis*, which was reported from the Ko Yao Noi Formation, southern Thailand of late Sakmarian age (Waterhouse, 1981).

The *Elivina-Etherilosia* Assemblage appears most correlative with the *Callytharrella dongshanpoensis* Assemblage from the Dingjiazhai Formation of the Baoshan Block (Nie et al., 1993; Shen et al., 2002), evidenced by a number of shared genera in both assemblages including *Trigonotreta* and *Elivina* Fredericks, 1924 (Fig. 5). The *Elivina-Etherilosia* Assemblage also shows strong affinities with the brachiopod fauna from the

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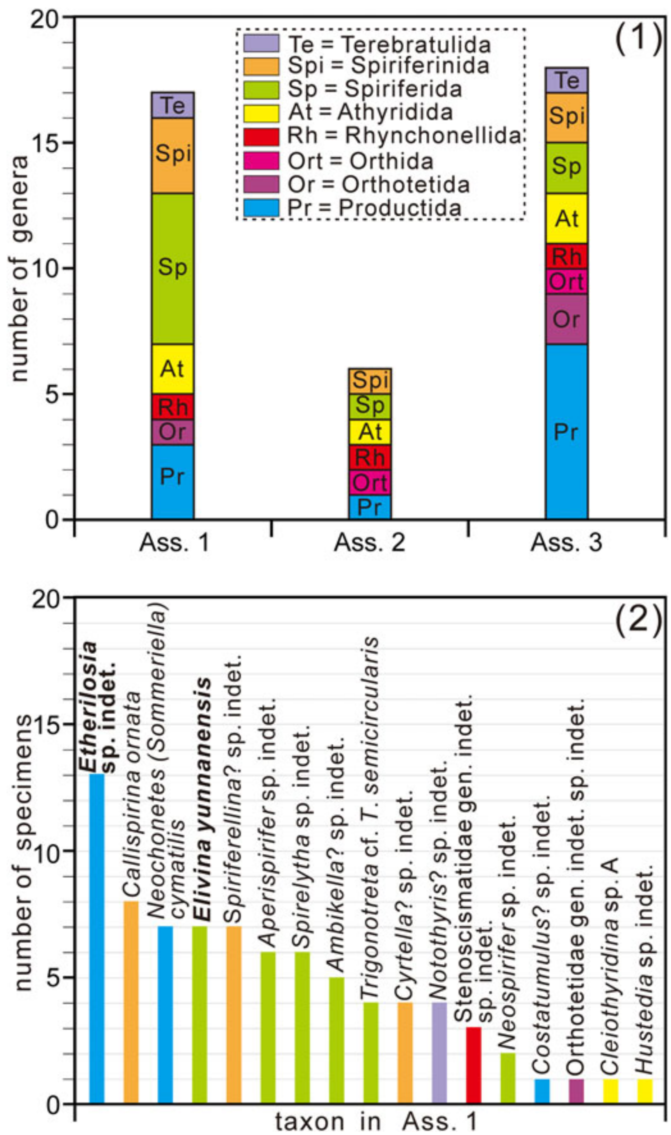

Figure 4. (**1**) Faunal compositions of three brachiopod assemblages in the northern Tengchong Block. (**2**) Diagram showing the number of specimens of each taxon in Ass.1. Naming genera of the assemblage are in bold. A similar diagram is neither drawn for Ass. 2 nor for Ass. 3, because Ass. 2 is represented only by 17 specimens in total, and Ass. 3 comprises our data from the Shanmutang section (22 specimens) and previous data from the Dadongchang section (Fang, 1995), and the latter did not provide numbers of specimens. Ass.1 = *Elivina-Etherilosia* Assemblage; Ass. 2 = *Spiriferella-Spiriferellina* Assemblage; Ass. 3 = *Waagenites-Costiferina* Assemblage.

Callytharra Formation (late Sakmarian), Western Australia (Archbold, 1993b, p. 315), with which it shares such genera as *Trigonotreta*, *Elivina*, and *Spirelytha*. The *Spinomartinia prolifica* Assemblage from the Ko Yao Noi Formation, southern Thailand (Waterhouse, 1981) seems to resemble the *Elivina-Etherilosia* Assemblage: for instance, *Neochonetes* (*Sommeriella*) Archbold, 1982 is in common in these assemblages; *Costatumulus*? sp. indet. in the latter is close to *Costatumulus cancriniformis* (Chernyshev, 1889) in the former; Stenoscismatidae gen. indet. sp. indet. is similar to *Stenoscisma quasimutabilis* Waterhouse, 1981; and *Notothyris*? sp. indet. resembles the juvenile of *Notothyris hexeris* Waterhouse, 1981. In addition, the *Elivina-Etherilosia* Assemblage is comparable to the *Bandoproductus monticulus-Spirelytha petaliformis* Assemblage (named by Xu et al., 2021) of the Sibumasu Block (of Sakmarian–early Artinskian) in the age, including brachiopod faunas from the Nam Loong No. 1 Mine beds of western Malaysia (Shi and Waterhouse, 1991) and from the Khao Phra Formation, southern Thailand (Shi et al., 2002). The brachiopod assemblage from the Maubisse Formation near the Bisnain village, western Timor (Archbold and Barkham, 1989), also shows some similarity with the *Elivina-Etherilosia* Assemblage, particularly in that both share the genus *Elivina*.

The Spiriferella-Spiriferellina *Assemblage*.—This assemblage occurs in the base of the Dadongchang Formation in the Shanmutang section (Fig. 3), possessing Chonetoidea gen. indet. sp. indet., *Schizophoria* sp. indet., *Cyrolexis* sp. indet., *Composita* sp. indet., *Spiriferella* sp. indet., and *Spiriferellina yunnanensis* Fang, 1983. In this assemblage, each order contains one genus (Fig. 4.1). Notably, spiriferinides and rhynchonellides are the most abundant in terms of specimens recovered. The *Spiriferella-Spiriferellina* Assemblage is found to share one genus (*Spiriferella* Chernyshev, 1902) with the *Costiferina-Stenoscisma gigantea* Assemblage from the Ri'a Formation, Xainza, Tibet (Zhan and Wu, 1982).

Jin et al. (2011) inferred a probable early Kungurian–early Roadian age for the *Spiriferella-Spiriferellina* Assemblage, based on the supposed age of *Spiriferella qubuensis* Zhang in Zhang and Jin, 1976 (synonymized as *Spiriferella nepalensis* Legrand-Blain, 1976 by Shen and Jin, 1999, p. 557) and *Spiriferella salteri* (Chernyshev, 1902). However, the present study cannot confirm the occurrences of these two species in the assemblage (see Systematic paleontology section), necessitating a reconsideration of its age. The lower part of the Dadongchang Formation has been known to yield a fusulinid assemblage dominated by *Eoparafusulina* Coogan, 1960 (Fig. 3), indicative of a late Sakmarian–Artinskian age (Shi et al., 2008; Jin et al., 2011; see also Fig. 5), as documented in the Kongshuhe section (~50 km north of the Shanmutang section; see Fig. 1.2). In another section (~4 km east of the Kongshuhe Village), *Eoparafusulina* also occurs in the lower part of the Dadongchang Formation (Huang et al., 2020). Judging from their positions in the basal carbonate bed of the formation, these fusulinid-bearing horizons might be stratigraphically somewhat higher than the bed of the *Spiriferella-Spiriferellina* Assemblage in the Shanmutang section (Fig. 3). Recently, Xu et al. (2022) thought that the *Eoparafusulina* fauna might come from the upper Kongshuhe Formation, because they guessed that the rock samples containing the *Eoparafusulina* fauna might represent fallen loose stones from the Kongshuhe Formation. However, this assumption is not supported by our field observations, because not only is the Kongshuhe Formation in a lower position, but also the stratigraphic level of the samples bearing well-preserved *Eoparafusulina* is characterized by oolitic limestones, purplish bioclastic limestones, and grayish bioclastic limestones, and these lithologies representatively occur only in the lower part of the lower Dadongchang Formation (Huang et al., 2020, p. 3). Some notable differences in biofacies between the Shanmutang and the Kongshuhe sections, e.g., the underdevelopment of the above-mentioned oolitic limestones in the

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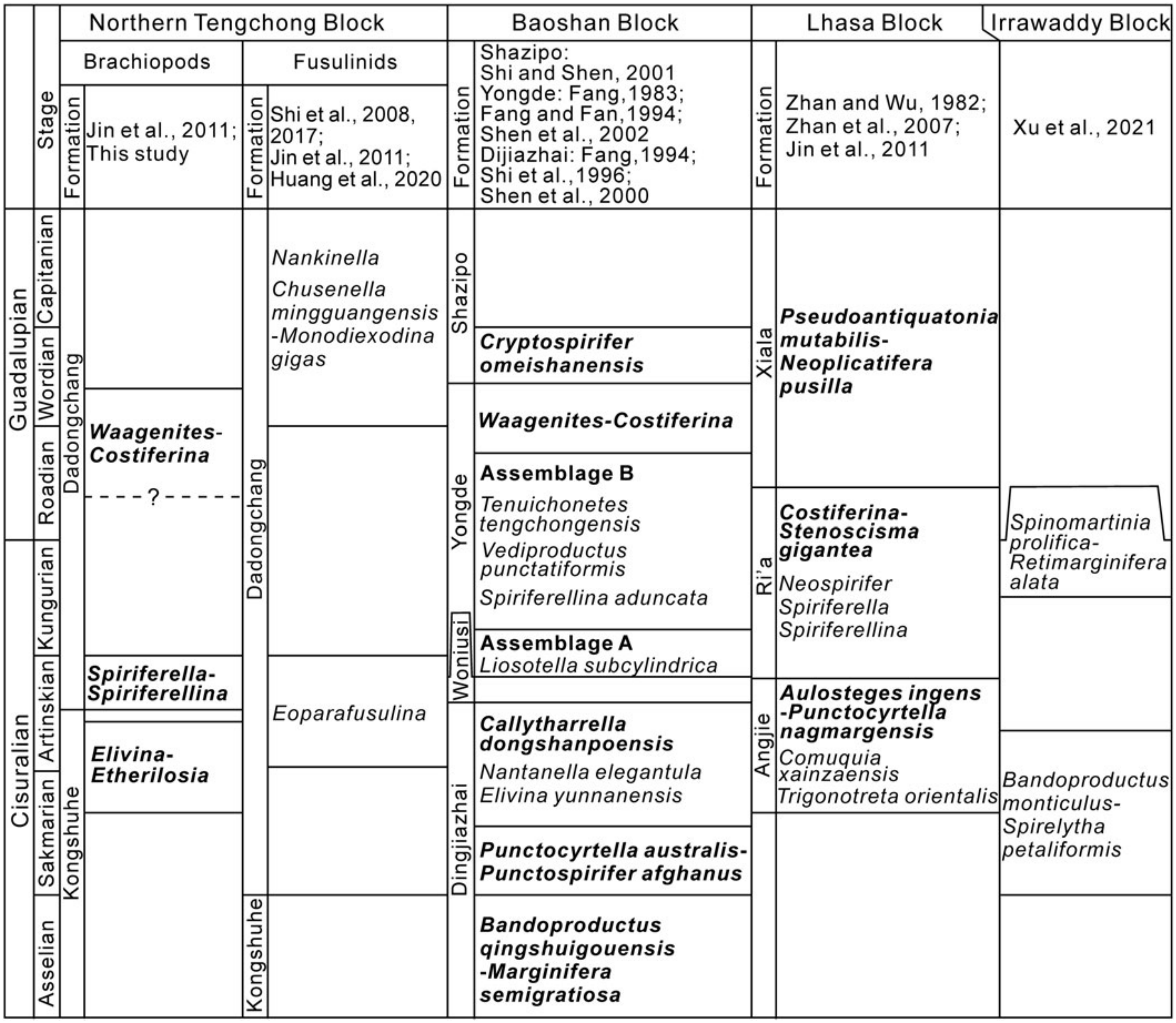

Figure 5. Brachiopod assemblages in the northern Tengchong Block and their correlation with other faunas in the Baoshan, Lhasa, and Irrawaddy blocks. Species not otherwise mentioned in the text are: *Aulosteges ingens* (Hosking, 1931); *Bandoproductus monticulus* Waterhouse, 1982; *Bandoproductus qingshuigouensis* Shen, Shi, and Zhu, 2000; *Callytharrella dongshanpoensis* Shen, Shi, and Zhu, 2000; *Comuquia xainzaensis* Zhan et al., 2007; *Cryptospirifer omeishanensis* Huang, 1933; *Liosotella subcylindrica* Jin and Fang, 1985; *Marginifera semigratiosa* (Reed, 1927); *Nantanella elegantula* Grabau, 1936; *Neoplicatifera pusilla* Zhan and Wu, 1982; *Pseudoantiquatonia mutabilis* Zhan and Wu, 1982; *Punctospirifer afghanus* Termier et al., 1974; *Punctocyrtella australis* (Thomas, 1971); *Punctocyrtella nagmargensis* (Bion, 1928); *Retimarginifera alata* Waterhouse, 1981; *Spinomartinia prolifica* Waterhouse, 1981; *Stenoscisma gigantea* (Diener, 1897); *Tenuichonetes tengchongensis* (Fang, 1994); *Vediproductus punctatiformis* (Chao, 1927).

Shanmutang area and the better development of a dark gray, thin-bedded limestone member in the Shanmutang area, might indicate that the depositional environments of the two areas are somewhat different. Nevertheless, considering the ages of the underlying *Elivina-Etherilosia* Assemblage, which was assigned an age of late Sakmarian–early Artinskian, and the overlying *Eoparafusulina* fusulinid fauna, which has an age of a late Sakmarian–Artinskian, the age of the *Spiriferella-Spiriferellina* Assemblage is more likely to be late Artinskian.

The Waagenites-Costiferina *Assemblage.*—The *Waagenites-Costiferina* Fauna was proposed as a representative brachiopod fauna from the Guanyinshan Formation in the Dadongchang by Fang (1995), comprising 25 species in 16 genera. In the present study, we recovered a brachiopod assemblage from the lower part of the Dadongchang Formation in the Shanmutang section, which includes: three productides—*Waagenites mediplicata* Fang, 1983, *Waagenites* sp. indet., and *Linoproductus lineatus* (Waagen, 1884); an orthotetide—*Derbyia grandis* Waagen, 1884; and a rare athyridide—*Cleiothyridina* sp. B. Except for *Linoproductus lineatus*, other two named species were also found in the *Waagenites-Costiferina* fauna previously reported from the Dadongchang section by Fang (1995). Despite the diversity difference between the two sections, all of these brachiopods are regarded as members of the same assemblage, due to the

Table 2. Taxonomic composition of the *Waagenites-Costiferina* Assemblage in northern Tengchong Block. Two species of the Dadongchang section need to be revised concerning their taxonomy (indicated in bold). * = genus absent in the Dadongchang section; S = species shared in the Shanmutang and Dadongchang sections.

Dadongchang section (based on Fang, 1995)	Shanmutang section (this study)
Chonetinella tengchongensis Fang, 1995; *Waagenites yunnanensis* Fang, 1983; *Waagenites mediplicata* Fang, 1983; *Waagenites simplex* Fang, 1983; *Waagenites guanyinshanensis* Fang, 1995; *Lissochonetes ambiensis* (Waagen, 1884); *Costiferina indica* (Waagen, 1884); *Wyndhamia* sp. indet.; *Leptodus nobilis* (Waagen, 1883); *Leptodus tenus* (Waagen, 1883); *Leptodus ovatus* Fang, 1995; *Orthotetes picta* Fang, 1983; *Derbyia grandis* Waagen, 1884; *Orthotichia indica* (Waagen, 1884); *Orthotichia incisiva* (Waagen, 1884); *Stenoscisma purdoni* (Davidson, 1862); *Cleiothyridina aculeata* Fang, 1983; *Spirigerella minuta* Waagen, 1883; *Spirigerella media* Waagen, 1883; ***Neospirifer kubeiensis* Ting, 1962 (emend. Zhang in Zhang & Jin, 1976) = *Neospirifer* (*Quadrospira*) *tibetensis* Ting, 1962 based on Shen et al. (2001, p. 162);** *Squamularia indica* (Waagen, 1883); ***Spiriferellina ornata* (Waagen, 1883) = *Callispirina ornata* (Waagen, 1883), based on Shen et al. (2016, p. 533);** *Spiriferellina yunnanensis* Fang, 1983; *Dielasma itaitubense* (Derby, 1874); *Dielasma nummulus* (Waagen, 1882)	*Waagenites mediplicata* Fang, 1983[S]; *Waagenites* sp. indet.; *Linoproductus** *lineatus* (Waagen, 1884); *Derbyia grandis* Waagen, 1884[S]; *Cleiothyridina* sp. B

lithologic similarity in the fossil-bearing beds as well as their taxonomic resemblance.

In the *Waagenites-Costiferina* Assemblage (combining the data of both the Dadongchang and Shanmutang sections; Table 2), productides show the highest generic diversity, followed by orthotetides, athyridides, spiriferides, and spiriferinides, whereas orthides, rhynchonellides, and terebratulides each include only one genus (Fig. 4.1). The *Waagenites-Costiferina* Assemblage has also been recognized in the Baoshan Block (Fang, 1983), sharing 15 species in 10 genera with the Tengchong Block. In Tibet, the *Pseudoantiquatonia mutabilis-Neoplicatifera pusilla* Assemblage from the Xiala Formation of the Lhasa Block (Zhan and Wu, 1982) is also comparable with the *Waagenites-Costiferina* Assemblage, as evidenced by their common genera *Chonetinella* Ramsbottom, 1952, *Waagenites* Paeckelmann, 1930, *Leptodus* Kayser, 1883, *Spirigerella* Waagen, 1883, and *Neospirifer* (*Quadrospira* Archbold, 1997).

Shi and Archbold (1995) suggested a Kazanian–Midian age (Roadian–Capitanian) for the *Waagenites-Costiferina* Assemblage from the Yongde Formation in the Baoshan Block. Later, Shi and Archbold (1998) reassigned a Kubergandian age (late Kungurian–early Roadian) for the brachiopod assemblage, according to fusulinids occurring in the Dadongchang Formation in the Tengchong Block. Studies on fusulinids associated with the *Waagenites-Costiferina* Assemblage in the Shanmutang section also provided its age information; *Chusenella mingguangensis* Shi et al., 2008 and *Monodiexodina gigas* Shi et al., 2008, which occurred on the horizon above the *Waagenites-Costiferina* Assemblage bed (Fig. 3), indicate a Wordian–Capitanian age (Shi et al., 2008). Further upward, another fusulinid-bearing bed dominated by *Chusenella* Hsu, 1942 and *Nankinella* Lee, 1934 (Fig. 3) was also reported in the same section (Shi et al., 2017). These two fusulinid faunas have been considered either Roadian–Capitanian or Wordian–Capitanian in age (Shi et al., 2008, 2017; Fig. 5). The age of the *Waagenites-Costiferina* Assemblage can also be confined by the *Eopolydiexodina*-bearing strata of Wordian age (Huang et al., 2009), which overlies the assemblage bed in the Baoshan Block (see also Shi and Shen, 2001). Therefore, the *Waagenites-Costiferina* Assemblage is most probably late Roadian–early Wordian in age, but its lower boundary in the Kungurian cannot be excluded.

Paleobiogeographical implications.—The *Elivina-Etherilosia* Assemblage is represented by several typical Gondwanan elements, e.g., *Trigonotreta*, *Aperispirifer* Waterhouse, 1968, and *Elivina* (Waterhouse, 1964, 1968; Shi et al., 1995; Shi and Archbold, 1998; Li et al., 2012; Xu et al., 2021). *Etherilosia* Archbold, 1993a was previously reported from the Cundlego and Callytharra formations, Carnarvon Basin, Western Australia (Prendergast, 1943; Coleman, 1957; Archbold, 1993a), and can be regarded as a Gondwanan genus. *Neochonetes* (*Sommeriella*) occurs in Western Australia and southern Thailand (Grant, 1976; Archbold, 1981). *Spirelytha* and *Neospirifer* Fredericks, 1924 are known to be antitropical genera (Shi et al., 1995; Shi and Grunt, 2000; see also Xu et al., 2021). *Callispirina* Cooper and Muir-Wood, 1951 occurs mainly in the peri-Gondwanan blocks, including: the middle–late Permian of the Salt Range in Pakistan (Waagen, 1883; Reed, 1944), the Ko Noi Formation, southern Thailand (Waterhouse, 1981), and the Pija Member of the Senja Formation, Nepal (Waterhouse, 1983). No typical Tethyan (warm-water) elements have been detected in the assemblage (Table 3). Thus, the *Elivina-Etherilosia* Assemblage represents a cool-water fauna with a relatively strong Gondwanan affinity.

The *Spiriferella-Spiriferellina* Assemblage appears to be dominated by genera with wider distributions. *Spiriferella* is a genus showing an antitropical distribution (Shi et al., 1995; Shi and Grunt, 2000). *Spiriferellina* Fredericks, 1924 is known to be cosmopolitan (Carter and Johnson, 2006). *Cyrolexis* Grant, 1965 was reported from the lower *Productus* Limestone of Pakistan, lower Permian of Russia (Grant, 1965), and upper Permian of southern China (Xu and Grant, 1994; Shen et al., 1992). Thus, the *Spiriferella-Callispirina* Assemblage overall represents a biogeographically mixed fauna.

Shi and Archbold (1998) considered that the *Waagenites-Costiferina* Assemblage from the Tengchong and Baoshan blocks, as reported by Fang (1983, 1995) and Fang and Fan (1994), represents a mixed fauna, containing Gondwanan, Cathaysian, and cosmopolitan genera. Among the 18 genera in this

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Table 3. The biogeographically significant genera in the three Permian brachiopod assemblages in northern Tengchong Block, combining the data of both the Shanmutang and Dadongchang (Fang, 1995) sections.

Assemblage	Genus	Distribution
Waagenites-Costiferina	*Chonetinella* Ramsbottom, 1952	Antitropical
	Waagenites Paeckelmann, 1930	Antitropical
	Lissochonetes Dunbar and Condra, 1932	Cosmopolitan
	Costiferina Muir-Wood and Cooper, 1960	Gondwanan
	Linoproductus Chao, 1927	Cosmopolitan
	Wyndhamia Booker, 1929	Antitropical
	Leptodus Kayser, 1883	Cathaysian
	Orthotetes Fischer de Waldheim, 1829	Cosmopolitan
	Derbyia Waagen, 1884	Cosmopolitan
	Orthotichia Hall and Clarke, 1892	Cosmopolitan
	Stenoscisma Conrad, 1839	Cosmopolitan
	Cleiothyridina Buckman, 1906	Cosmopolitan
	Spirigerella Waagen, 1883	Cathaysian
	Neospirifer (*Quadrospira*) Archbold, 1997	peri-Gondwanan
	Squamularia Gemmellaro, 1899	Cathaysian
	Callispirina Cooper and Muir-Wood, 1951	peri-Gondwanan, southwestern US
	Spiriferellina Fredericks, 1924	Cosmopolitan
	Dielasma King, 1859	Cosmopolitan
Spiriferella-Spiriferellina	*Schizophoria* King, 1850	Cosmopolitan
	Cyrolexis Grant, 1965	Pakistan, Russia, South China
	Composita Brown, 1845	Cosmopolitan
	Spiriferella Chernyshev, 1902	Antitropical
	Spiriferellina Fredericks, 1924	Cosmopolitan
Elivina-Etherilosia	*Neochonetes* (*Sommeriella*) Archbold, 1982	Western Australia, southern Thailand
	Etherilosia Archbold, 1993a	Gondwanan
	Cleiothyridina Buckman, 1906	Cosmopolitan
	Hustedia Hall and Clarke, 1893	Cosmopolitan
	Neospirifer Fredericks, 1924	Antitropical
	Trigonotreta Koenig, 1825	Gondwanan
	Aperispirifer Waterhouse, 1968	Gondwanan
	Elivina Fredericks, 1924	Gondwanan
	Spirelytha Fredericks, 1924	Antitropical
	Callispirina Cooper and Muir-Wood, 1951	peri-Gondwanan, southwestern US

assemblage in the Tengchong Block (see Table 3), *Costiferina* Muir-Wood and Cooper, 1960 is a typical Gondwanan genus (Shi et al., 1995; Shi and Archbold, 1998), whose occurrence in the assemblage indicates the Gondwanan affinity of the tectonic block (although the genus has not been detected in our collection). *Neospirifer* (*Quadrospira*) occurs in Western Australia and in the early–late Permian of the Cimmerian blocks (Archbold, 1997). The existence of three antitropical genera, i.e., *Chonetinella*, *Waagenites*, and *Wyndhamia* Booker, 1929 (Shi et al., 1995; Shi and Grunt, 2000), also supports that there were cool-water components, probably linked to the high-latitude Gondwana Realm. On the other hand, the occurrence of three genera with Cathaysian affinities, i.e., *Leptodus*, *Spirigerella*, and *Squamularia* Gemmellaro, 1899 (Change into (Shi and Archbold, 1995, 1998; Shi et al., 1995), explains that the Tengchong Block was also strongly influenced by warm-water currents from the Paleotethys Ocean. Nine genera—*Lissochonetes* Dunbar and Condra, 1932, *Linoproductus* Chao, 1927, *Orthotetes* Fischer de Waldheim, 1829, *Derbyia* Waagen, 1884, *Orthotichia* Hall and Clarke, 1892, *Stenoscisma* Conrad, 1839, *Cleiothyridina* Buckman, 1906, *Spiriferellina*, and *Dielasma* King, 1859—are known to be cosmopolitan.

To sum up, during the late Sakmarian–early Artinskian, the northern Tengchong Block was dominated by a cool-water fauna represented by the *Elivina-Etherilosia* Assemblage, carrying strong similarities to coeval brachiopod faunas from other Cimmerian continental blocks, including the Baoshan Block (Shi and Archbold, 1998), the Lhasa Block (Zhan et al., 2007), and the Sibumasu Block (Xu et al., 2021). The brachiopods of the late Artinskian age in northern Tengchong are represented by the *Spiriferella-Spiriferellina* Assemblage, indicative of a biogeographically mixed fauna. The overlying *Waagenites-Costiferina* Assemblage of late Roadian–early Wordian age contains more warm-water Cathaysian elements. Thus, it is evident that the brachiopod fauna of the northern Tengchong Block evolved from a cool-water Gondwana-type fauna in the early early Permian to a mixed fauna with warm-water Cathaysia-type species through the late early Permian–middle Permian. Such an unambiguous paleobiogeographic evolutionary pattern of the Tengchong Block through the early–middle Permian is in accord with a similar temporal biogeographic succession of the Irrawaddy Block in eastern Myanmar (Xu et al., 2021).

The transition of Permian brachiopod assemblages in the northern Tengchong Block, like in the Irrawaddy and Sibuma blocks, has been interpreted as a result of the combined effect of deglaciation and the northward drift of the peri-Gondwanan blocks (Shi and Archbold, 1998; Shi, 2001; Xu et al., 2021). The deglaciation of Gondwana commenced in the middle Sakmarian (Montañez and Paulsen, 2013), as evidenced by facies changes from glaciogenic diamictites to fine-grained siliciclastics across all peri-Gondwana blocks (Wopfner and Jin, 2009). Up sequence, as demonstrated by the Shanmutang section (Fig. 3), siltstones and shales of the Kongshuhe Formation are replaced by limestones bearing increasingly more diverse faunas including brachiopods, corals characterized by mixed Gondwanan and Cathaysian elements, bryzoans dominated by wide-ranging genera and a proportion of Gondwanan or peri-Gondwanan elements (Fang and Fan, 1994; Shi and Archbold, 1998), crinoids, and fusulinids, and also some oolites (Huang et al., 2020), suggesting continued and enhanced warming in the northern Tengchong Block.

Systematic paleontology

The specimens with certain identification are described and discussed below. Other specimens are only figured here, under the names that were tentatively suggested by Jin et al. (2011, fig. 3), because it is not possible to reveal additional characters for a more accurate identification based on insufficient or not well-preserved materials.

Order Productida Sarytcheva and Sokolskaya, 1959
Family Rugosochonetidae Muir-Wood, 1962
Genus *Neochonetes* Muir-Wood, 1962
Subgenus *Neochonetes* (*Sommeriella*) Archbold, 1982

Type species.—*Chonetes prattii* Davidson, 1859, probably from the Sakmarian–early Aktinskian of Western Australia.

Remarks.—*Neochonetes* (*Sommeriella*) was first proposed by Archbold (1981) under the name *Neochonetes* (*Sommeria*) to define the *Neochonetes* Muir-Wood, 1962 with a conspicuously developed ventral sulcus, gentle dorsal fold, and hinge spines at ∼40–45°. *Neochonetes* (*Sommeriella*) differs from *Chonetinella* mainly in developing distinct growth lines (Archbold, 1981).

Neochonetes (*Sommeriella*) *cymatilis* (Grant, 1976)
Figure 6.1–6.9

1976 *Chonetinella cymatilis* Grant, p. 77, pl. 16, figs. 1–58.
1981 *Chonetinella andamanensis*, Waterhouse, p. 65, pl. 2, figs. 18, 19, pl. 3, figs. 1–18.
1983a *Neochonetes (Sommeriella)? cymatilis*, Archbold, p. 70.
2016 *Neochonetes (Sommeriella) cymatilis*, Wu et al., p. 510.
2021 *Chonetinella cymatilis*, Xu et al., p. 1169, fig. 6.5–6.9.

Holotype.—USNM 211993 from the Rat Buri Limestone, Ko Muk, southern Thailand (Grant, 1976, pl. 16, figs. 26–30).

Occurrence.—Top of the Kongshuhe Formation; Ko Yao Noi Formation, Ko Yao Noi, southern Thailand; Rat Buri Group, Ko Muk, southern Thailand; Taungnyo Group, Zwekabin Range, Myanmar.

Description.—Shell small, ∼7–9 mm long in most specimens, and 15 mm wide in largest specimen; outline transversely subquadrate; lateral profile concavoconvex; cardinal extremities rounded; ears small and flat.

Ventral valve moderately convex; sulcus prominent, relatively narrow in general, starting from beak and becoming deeper and wider anteriorly (Fig. 6.3), but sometimes much widely developed near beak with swollen umbo (Fig. 6.1). Dorsal valve slightly concave; fold distinctly developed, originating from beak and gradually widening anteriorly (Fig. 6.5). Surface of both valves fully covered by fine costellae; growth lines mostly occurring on anterior part.

Ventral interior with elongate muscle scars bisected by 3.6 mm long median ridge (Fig. 6.7). Dorsal interior strongly endospinose, with cardinal process pit; inner socket ridges long, parallel to hinge; median septum anteriorly elevated; accessory septa lacking (Fig. 6.9).

Materials.—Seven specimens including three ventral internal molds (IGCAGS 20001, 20003, 20006); one ventral external mold (IGCAGS 20004); one broken ventral valve (IGCAGS 20002); one dorsal external mold (IGCAGS 20005); one dorsal internal mold (IGCAGS 20007).

Remarks.—These specimens are assignable to *Neochonetes* (*Sommeriella*) *cymatilis* based on the similarities in shell size and profile, having a deep ventral sulcus, fine costellae, and growth lines, as well as the low median septum and socket ridges in the dorsal interior, and a median ridge and muscle areas in the ventral interior.

Chonetinella cymatilis Grant, 1976 was reassigned to *Neochonetes* (*Sommeriella*) in doubt by Archbold (1983a), but without any explanation. Later, this species was revised as *Neochonetes* (*Sommeriella*) *cymatilis* by Wu et al. (2016, p. 510).

Chonetinella andamanensis Waterhouse, 1981, from the Ko Yao Noi Formation, southern Thailand, was originally supposed to be distinguishable from *Neochonetes* (*Sommeriella*) *cymatilis* in having a less transverse shell outline. However, the morphological difference was regarded as intraspecific variation by Xu et al. (2021), which is also followed here.

Chonetinella tengchongensis Fang, 1995, from the Guanyinshan Formation, Tengchong, which is probably more attributable to *Neochonetes* (*Sommeriella*) in the presence of growth lines, develops a very weak ventral sulcus and, therefore, is clearly distinguished from *Neochonetes* (*Sommeriella*) *cymatilis*. The present specimens resemble *Chonetinella unisulcata* Chang (Zhang) in Zhang and Jin, 1976, reported from the Selong Group (Zhang and Jin, 1976) and the Qubuerga Formation (Shen et al., 2003) in the Mt. Qomolangma region, southern Tibet, in having a transversely subquadrate outline. However, the former differs in its smaller shell size.

Genus *Waagenites* Paeckelmann, 1930

Type species.—*Chonetes grandicostus* Waagen, 1884 from upper *Productus* Limestone in Salt Range, Pakistan.

Remarks.—*Waagenites* resembles the genus *Tethyochonetes* Chen et al., 2000 in internal structures, however, the latter has finer costae, a transversely rectangular outline, less strongly concavoconvex shells, and less distinct sulcus and fold. Subsequently, *Tethyochonetes* was treated as a subjective junior synonym of *Fusichonetes* Liao in Zhao et al., 1981 by Wu et al. (2016), who doubted that the differences between the two type specimens represent intraspecific variation.

Waagenites mediplicata Fang, 1983
Figure 7.6, 7.7

1983 *Waagenites mediplicata* Fang, p. 97, pl. 2, figs. 4–6.
1994 *Waagenites mediplicata*, Fang and Fan, p. 76, pl. 19, figs. 1–3, pl. 29, figs. 1–3.
1995 *Waagenites mediplicata*, Fang, p. 137, pl. 3, figs. 1–3.

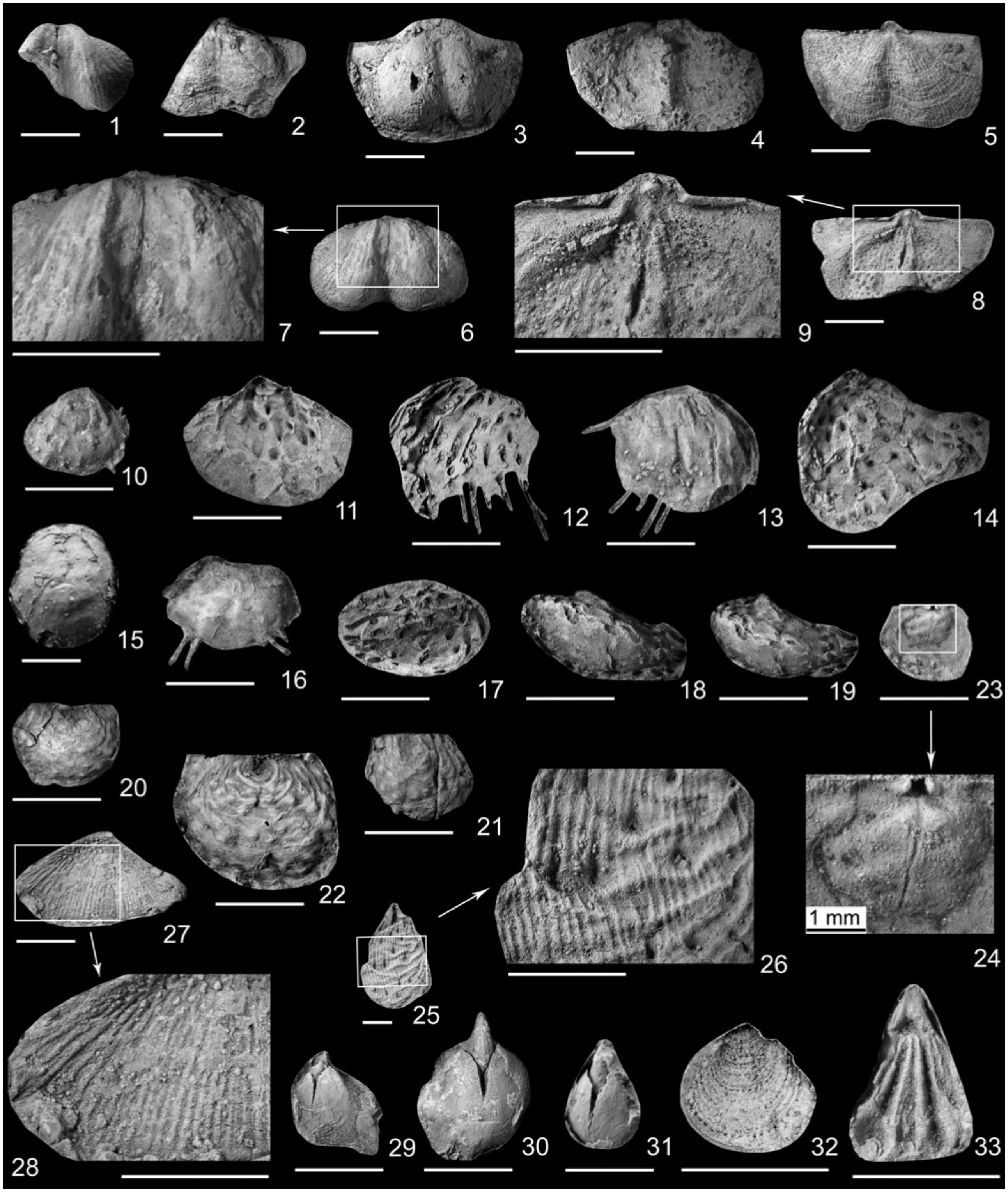

Figure 6. Brachiopods from the top part of the Kongshuhe Formation in the northern Tengchong Block. (**1–9**) *Neochonetes* (*Sommeriella*) *cymatilis* (Grant, 1976): (**1**) 0036, ventral internal mold, IGCAGS 20001; (**2**) 220708-3-a, ventral valve, IGCAGS 20002; (**3**) 0218-5-a, ventral internal mold, IGCAGS 20003; (**4**) 0813-1-a, ventral external mold, IGCAGS 20004; (**5**) 0806-6-a, dorsal external mold, IGCAGS 20005; (**6, 7**) 0813-4-a, ventral internal mold and enlargement showing the median myophragm and muscle scars, IGCAGS 20006; (**8, 9**) 0813-2-a, dorsal internal mold and enlargement showing short median septum and endospines, IGCAGS 20007. (**10–24**) *Etherilosia* sp. indet.: (**10**) 0810-2-a, ventral valve, IGCAGS 20016; (**11**) 0810-1-a, ventral external mold, IGCAGS 20017; (**12**) 0811-1-a, ventral external mold, IGCAGS 20018; (**13**) 0811-10-a, ventral valve, IGCAGS 20019; (**14**) 0810-6-a, ventral external mold, IGCAGS 20020; (**15**) 0079, ventral valve, IGCAGS 20021; (**16**) 0807-3-b, ventral valve, IGCAGS 20022; (**17**) 0807-4-c, ventral external mold, IGCAGS 20023; (**18, 19**) 0807-5, two ventral views of a ventral valve, IGCAGS 20024; (**20**) 0810-3-a, dorsal external mold, IGCAGS 20025; (**21**) 0811-11-a, dorsal external mold, IGCAGS 20026; (**22**) 0807-1-d, dorsal external mold, IGCAGS 20027; (**23, 24**) 0810-4, dorsal internal mold and enlargement showing the bilobed cardinal process, muscle scars, and thin median ridge, IGCAGS 20028. (**25, 26**) *Costatumulus*? sp. indet., 0219-4-b, ventral external mold and enlargement showing the ribs and spines, IGCAGS 20035. (**27, 28**) Orthotetidae gen. et sp. indet., 0210-4-b, dorsal external mold and enlargement showing the costellae, IGCAGS 20114. (**29–31**) Stenoscismatidae gen. indet. sp. indet.: (**29**) 0812-4-a, ventral internal cast, IGCAGS 20043; (**30**) 0811-12-a, ventral internal cast, IGCAGS 20044; (**31**) 0062, ventral internal cast, IGCAGS 20045. (**32**) *Cleiothyridina* sp. A, 0209-3-b, ventral external mold, IGCAGS 20115. (**33**) *Hustedia* sp. indet., 0210-5-a, ventral external mold, IGCAGS 20116. Scale bars = 5 mm, unless otherwise labeled.

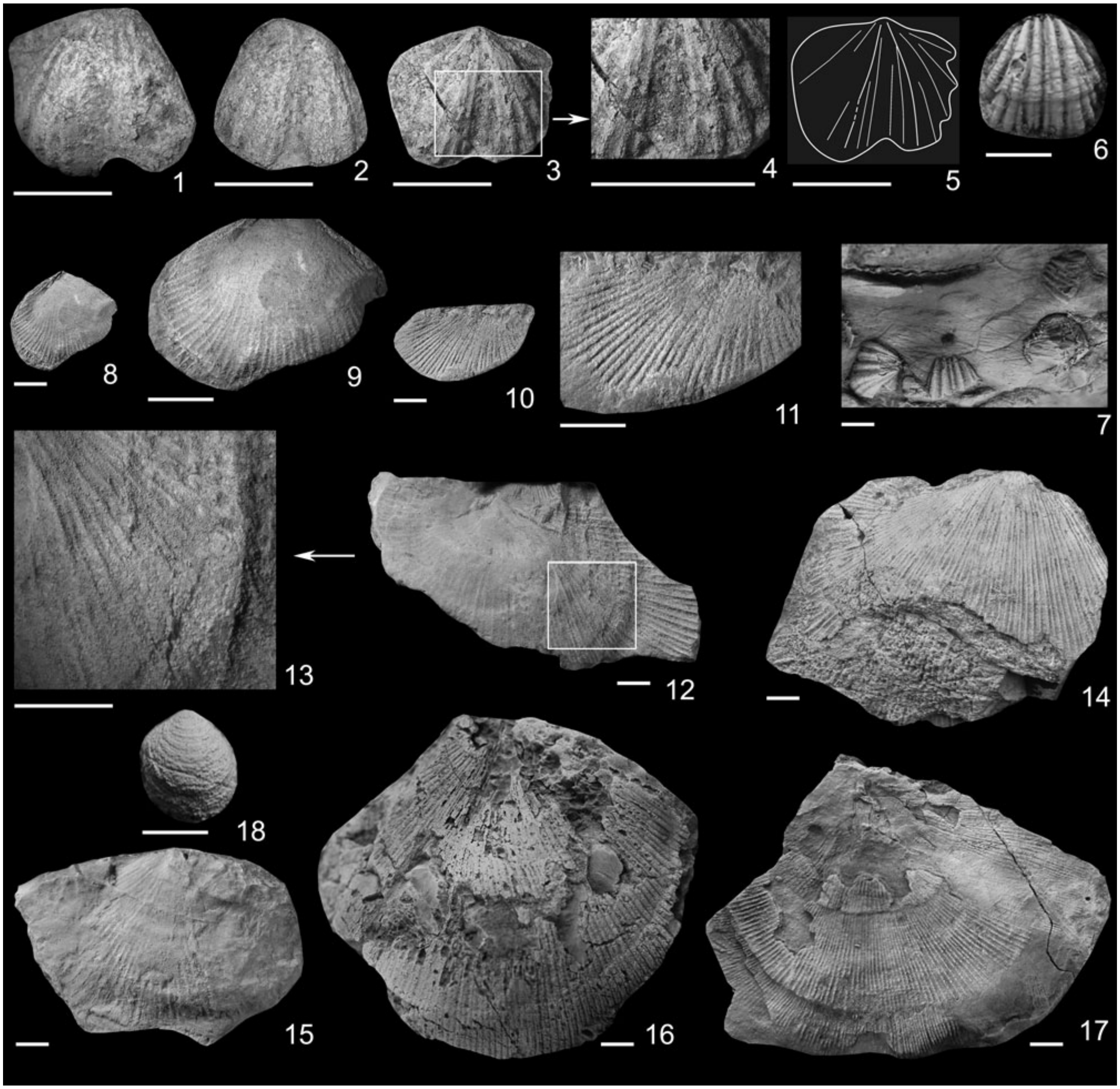

Figure 7. Brachiopods from the lower part of the Dadongchang Formation in the northern Tengchong Block. (**1–5**) *Waagenites* sp. indet.: (**1**) 0819-1-c, ventral vlave, IGCAGS 20013; (**2**) 0819-2-a, ventral valve, IGCAGS 20014; (**3–5**) 0819-3-a, ventral valve and enlargement showing fine capillae, plus costal diagram, IGCAGS 20015. (**6, 7**) *Waagenites mediplicata* Fang, 1983: (**6**) 0368, ventral valve, IGCAGS 20008; (**7**) 0363, slab with *Waagenites mediplicata*, IGCAGS 20009–20012. (**8–17**) *Derbyia grandis* Waagen, 1884: (**8, 9**) 0533, dorsal valve and enlargement of dorsal valve, IGCAGS 20036; (**10, 11**) 0546, ventral external mold and enlargement showing the costae increase pattern, IGCAGS 20037; (**12, 13**) 0554, dorsal valve and enlargement showing the costae increase pattern, IGCAGS 20038; (**14**) 0121, dorsal valve, IGCAGS 20039; (**15**) 0563, ventral valve, IGCAGS 20040; (**16**) 0180, ventral valve, IGCAGS 20041; (**17**) 0197, ventral valve, IGCAGS 20042. (**18**) *Cleiothyridina* sp. B, 0235, ventral valve, IGCAGS 20117. Scale bars = 5 mm.

Holotype.—Specimen 81112 from the Yongde Formation, Xiaoxinzhai section, Gengma, southwestern Yunnan, China (Fang, 1983, pl. 2, fig. 4a–e). The specimen is deposited at Yunnan Institute of Geological Sciences.

Occurrence.—Lower part of the Dadongchang Formation; Yongde Formation, Gengma, China; Guanyinshan Formation, Tengchong, China.

Description.—Shell small, ∼9 mm wide in largest specimen; outline quadrate, with maximum width at hinge line. Ventral sulcus broad, containing thin, low median costa and two lateral costae. Each flank of ventral valve relatively steep, with three primary costae. Costae strong and rounded in general, and those adjacent to sulcus bifurcating two or three times on anterior part (Fig. 7.6); growth lines irregularly spaced.

Materials.—Five ventral valves (IGCAGS 20008–20012).

Remarks.—Six species of *Waagenites* have been reported so far from Yunnan (Fang, 1983, 1995; Fang and Fan, 1994), among

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which, *Waagenites fasciata* Fang, 1983 and *Waagenites gengmaensis* Fang, 1983 are from the Yongde Formation, Gengma of southwestern Yunnan; *Waagenites guanyinshanensis* Fang, 1995 from the Guanyinshan Formation, Tengchong; and *Waagenites yunnanensis* Fang, 1983, *Waagenites mediplicata*, and *Waagenites simplex* Fang, 1983 from the Yongde and Guanyinshan formations. All of these species are small in shell size, with a quadrate outline and coarse costae. They can be further subdivided into two groups: one is with fasciculate costae, especially adjacent to the sulcus, including the species *Waagenites yunnanensis*, *Waagenites mediplicata*, *Waagenites fasciata*, and *Waagenites guanyinshanensis*; and the other is with simple costae, including the species *Waagenites simplex* and *Waagenites gengmaensis*. Later, *Waagenites yunnanensis* from the Xiaoxinzhai Formation, was also illustrated and described by Chen et al. (2000, p. 5, figs. 2D, E, 3).

The present specimens are most similar to *Waagenites mediplicata*, one of the three *Waagenites* species occurring in both the Yongde and Guanyinshan formations, in having a quadrate shell outline, the sulcal plications, and distinct bifurcating costae on and near the ventral sulcus.

Waagenites sp. indet.
Figure 7.1–7.5

Occurrence.—Lower part of the Dadongchang Formation.

Description.—Shell small, ~10 mm wide in largest valve; outline subquadrate, with length/width ratio ~1.12. Ventral valve moderately convex; ventral sulcus deep, originating from beak, generally bearing two pairs of costae (Fig. 7.5); each ventral flank ornamented in general with three coarse costae; micro-ornament composed of fine capillae (Fig. 7.4).

Materials.—Three ventral valves, with abrasion to some degree (IGCAGS 20013–20015).

Remarks.—These specimens are characterized by the quadrate outline, deep sulcus, and coarse costae, which suggests their assignment to the genus *Waagenites*. It is worth noting that the sulcus of the present specimens is not as deep as that in the type species *Waagenites grandicosta* (Waagen, 1884). However, *Waagenites* also includes species with a moderately developed sulcus, e.g., *Waagenites dichotoma* (Waagen, 1884), *Waagenites squamulifera* (Waagen, 1884), *Waagenites deplanata* (Waagen, 1884), and *Waagenites aequicosta* (Waagen, 1884), all from the *Productus* Limestone (Waagen, 1884, pls. 60, 61). Hence, the varieties of development of the sulcus probably represents interspecific variation within *Waagenites,* whereas the quadrate shell outline and coarse costae could be more important to identify the genus.

The present specimens are not matched with the *Waagenites* species previously reported from the Tengchong Block. They differ from *Waagenites mediplicata* co-occurring in the Dadongchang Formation in the lack of a median costa on the ventral sulcus. These specimens are also distinguished from *Waagenites yunnanensis* both from the Yongde and Guanyinshan formations in having a slightly convex valve.

The present specimens are more similar to *Waagenites dichotoma* (see Waagen, 1884, p. 633, pl. 61, fig. 4) from the middle *Productus* Limestone in Salt Range, Pakistan, in a sulcus that is deepest and widest anteriorly, the bundle costae adjacent to the sulcus, and weak convexity of ventral valve, but our specimens differ in fewer costae on the sulcus and lateral flanks.

Waagenites speciosus Waterhouse and Piyasin, 1970 from limestones at Khao Phrik in southern Thailand, later assigned to *Waterhouseiella* Archbold, 1983a by Archbold (1983a), is comparable in the weak convexity of the ventral valve; however, the Thai species is more transverse in outline, having more and finer costae (see also Grant, 1976, p. 81, pl. 17, fig. 21).

Family Linoproductidae Stehli, 1954
Genus *Linoproductus* Chao, 1927

Type species.—*Productus cora* d'Orbigny, 1842 from the lower Permian of Bolivia.

Remarks.—*Linoproductus* is similar to the genera *Coolkilella* Archbold, 1993a and *Kasetia* Waterhouse, 1981 in having fine costae and lacking dorsal spines. However, these genera can be easily differentiated: *Linoprodutus* is medium to large, having a gently concave dorsal corpus and a posteriorly inflated ventral profile. *Coolkilella* has a dorsal valve showing a flat or very gently concave visceral disc and strong geniculation anteriorly. *Kasetia* is small and has concentric narrow rugae.

Linoproductus lineatus (Waagen, 1884)
Figure 8

1884 *Productus lineatus* Waagen, p. 673, pl. 66, figs. 1, 2, pl. 67, fig. 3.
1897 *Productus lineatus*, Diener, p. 14, pl. 4, figs. 2–5.
1927 *Linoproductus lineatus*, Chao, p. 129, pl. 15, figs. 27, 28.
1964 *Linoproductus lineatus*, Wang et al., p. 323, pl. 52, figs. 18, 19.
1978 *Linoproductus lineatus*, Feng and Jiang, p. 260, pl. 92, fig. 4a–c.
1978 *Linoproductus lineatus*, Tong, p. 231, pl. 81, fig. 7a, b.
1984 *Linoproductus lineatus*, Yang, p. 222, pl. 34, fig. 14.
1996 *Linoproductus lineatus*, Zeng et al., pl. 6, fig. 12a–c.
2000 *Linoproductus lineatus*, Chen and Shi, p. 551, fig. 4.20.
2001 *Linoproductus lineatus*, Shi and Shen, p. 248, pl. 1, figs. 5, 6.

Holotype.—Several specimens (but without formal specimen number) from the *Productus* Limestone, Salt Range, Pakistan (Waagen, 1884, pl. 66, figs. 1, 2, pl. 67, fig. 3).

Occurrence.—Lower part of the Dadongchang Formation; Wargal Formation of the Salt Range, Pakistan, northwestern Himalaya; Maokou Formation or equivalents of South China; Shazipo Formation, Baoshan, China.

Description.—Shell large, with width of 50 mm in the largest valve, elongate subrectangular in outline; cardinal extremities rounded. Ventral valve moderately convex but inflated on

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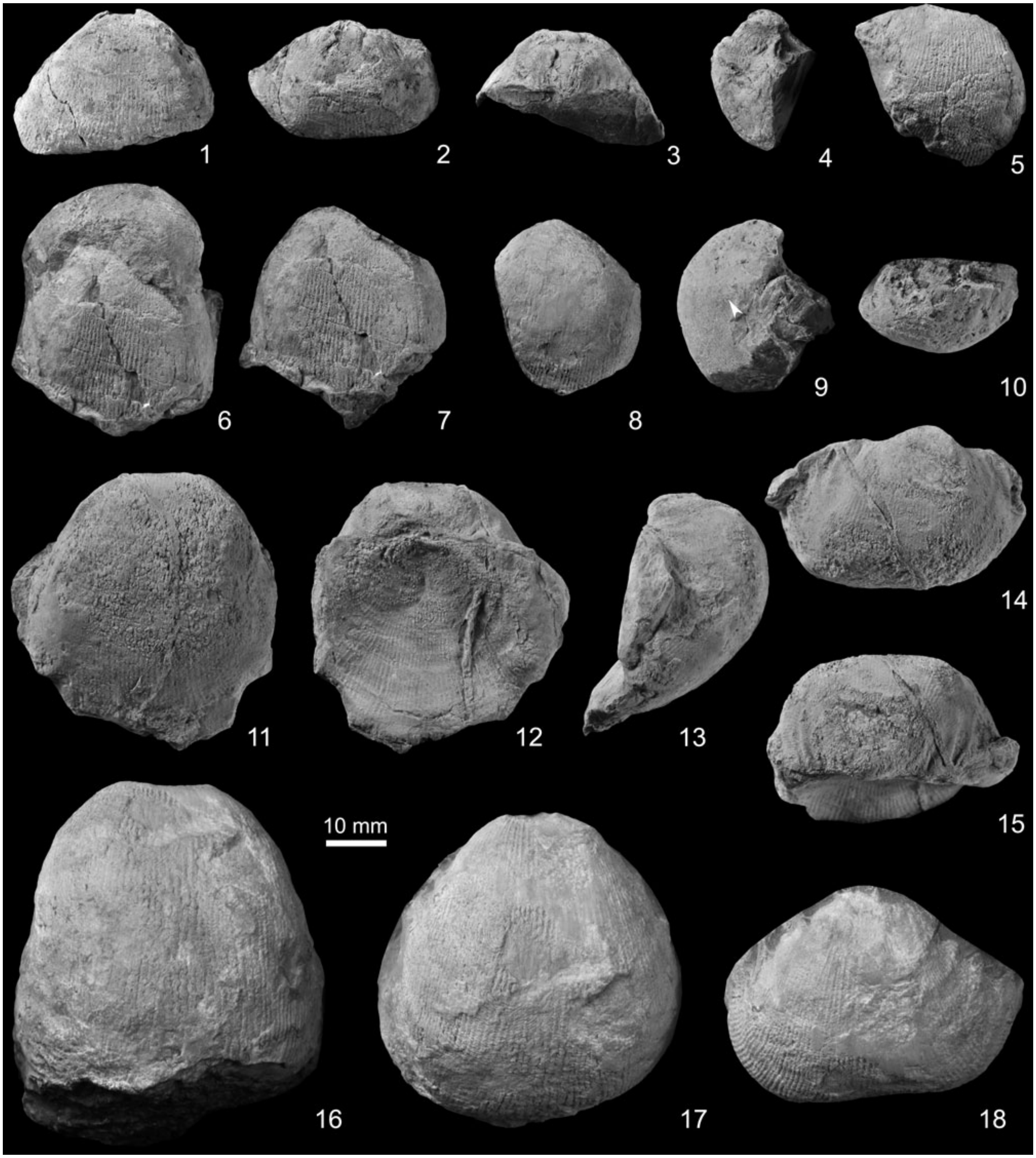

Figure 8. Brachiopods from the lower part of the Dadongchang Formation in the northern Tengchong Block. (**1–18**) *Linoproductus lineatus* (Waagen, 1884): (**1–4**) 0582, ventral, ventral, posterior, and lateral views, respectively, of ventral valve, IGCAGS 20029; (**5**) 0565, ventral valve, IGCAGS 20030; (**6, 7**) 0614, two ventral views of ventral valve, IGCAGS 20031; (**8–10**) 0646, ventral, lateral (white arrow = a spine base), and posterior views, respectively, of ventral valve, IGCAGS 20032; (**11–15**) 0726, ventral, dorsal, lateral, ventral, and posterior views, respectively, of a conjoined shell, IGCAGS 20033; (**16–18**) 0113, three ventral views of ventral valve, IGCAGS 20034.

posterior part; lateral slopes sharply inclined; sulcus absent. Dorsal valve slightly concave, without median fold.

Shell surface covered by numerous costae; costae fine, separated by narrower interspaces, approximately eight costae per 10 mm at anterior part; concentric rugae (or wrinkles) on ventral ears, ventral flanks (Fig. 8.15), and dorsal corpus (Fig. 8.12); spine bases rarely remaining on ventral valve but fully absent on dorsal valve.

Materials.—Six specimens, including five ventral valves (IGCAGS 20029–20032, 20034) and one conjoined shell (IGCAGS 20033).

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Remarks.—The present specimens are similar to *Linoproductus lineatus* from the Wargal Formation of the Salt Range, Pakistan (Waagen, 1884) in the shell outline and sparse ventral spines on the ventral valve.

Several different views have been expressed regarding the differences between *Linoproductus lineatus* and *Linoproductus cora* (d'Orbigny, 1842). First, Waagen (1884) stated that *Linoproductus cora* develops no sulcus on the ventral valve, whereas *Linoproductus lineatus* has a distinct broad impression on the median part of the ventral vale. Then, Diener (1897) reported that the majority of *Linoproductus lineatus* from the Himalayan also develop the ventral median sulcus, which is not distinctly marked. However, Chao (1927) more strongly emphasized the different shell shapes of *Linoproductus lineatus* and *Linoproductus cora*: *Linoproductus lineatus* from the Permian *Productus* Limestone is more rectangular with the sides nearly parallel (Chao, 1927, p.131), whereas *Linoproductus cora* from Bolivia is essentially triangular with the sides of the umbonal region diverging. Later, Wang et al. (1964) followed this opinion, and mentioned that *Linoproductus lineatus* is commonly rectangular in outline, whereas *Linoproductus cora* shows a triangular to oval outline with more ventral spines. In addition, *Linoproductus lineatus* is generally characterized by a relatively small shell and weakly defined rugae across the visceral discs (Shi and Shen, 2001). In summary, the shell shape and spine number on the ventral valve appear to have a high discriminating value to distinguish *Linoproductus lineatus* and *Linoproductus cora*, which is followed here.

The present specimens differ from *Linoproductus tingriensis* Ching (= Jin) in Zhang and Jin, 1976 from the Qubuerga Formation, southern Tibet (Zhang and Jin, 1976, pl. 7, figs. 11–13, pl. 9, figs. 3–5) in being larger with fewer spines on the ventral valve.

Family Monticuliferidae Muir-Wood and Cooper, 1960
Genus *Costatumulus* Waterhouse in Waterhouse and Briggs, 1986

Type species.—*Auriculispina tumidus* Waterhouse in Waterhouse et al., 1983 from the lower Permian Tiverton Formation, Queensland, Australia.

Remarks.—The major differences between *Cancrinella* Fredericks, 1928 and *Costatumulus* lie in that the former develops dorsal spines (Archbold, 1993a), whereas the latter lacks spines but bears dimples or pits on the dorsal valve (He et al., 2005, 2019; Li et al., 2012; Shen et al., 2016). In addition, *Costatumulus* has a gently convex ventral valve, with the corpus cavity becoming moderate until the adult stage, and developed rugae. On the other hand, *Cancrinella* has a deep corpus cavity (Brunton et al., 2000b, p. 533–538).

Costatumulus? sp. indet.
Figure 6.25, 6.26

Occurrence.—Top of the Kongshuhe Formation.

Description.—Ventral external surface covered with costae, spines, and wrinkles; costae fine and dense, numbering seven in 3 mm at the anterior part of valve; spines arranged in quincunx, having elongate swollen bases; wrinkles strongly developed but discontinuous.

Materials.—One incomplete specimen (ventral external mold; IGCAGS 20035).

Remarks.—The present specimen is similar to both *Cancrinella* and *Costatumulus* in the shell ornaments including fine and dense costae, wrinkles, and prominent spines arranged in quincunx. Due to the lack of dorsal valves, it is hard to determinate whether our specimen develops dorsal spines or not, which is regarded as the major differences between *Cancrinella* and *Costatumulus*. Thus, the present specimen is tentatively assigned to *Costatumulus* in doubt, based on the relatively weak convexity of the ventral valve.

The specimens previously assigned to *Cancrinella cancriniformis* (Chernyshev, 1889) from the Ko Yao Noi Formation, southern Thailand (Waterhouse, 1981, pl. 18, fig. 4) were reassigned to *Costatumulus* due to lacking dorsal spines (Li et al., 2012, p. 300). The present specimen is close to these Thailand specimens in its fine and dense costae, ventral spines, and wrinkles. Our specimen resembles *Costatumulus irwensis* (Archbold, 1983b) and *Costatumulus occidentalis* Archbold, 1993a from the late Sakmarian and early Artinskian of Western Australia in having rugae across the ventral valve. However, without the dorsal valve, the differences between the Tengchong specimen and those from Western Australia are not inferred.

Family Strophalosiidae Schuchert, 1913
Genus *Etherilosia* Archbold, 1993

Type species.—*Strophalosia etheridgei* Prendergast, 1943 from the late Sakmarian of Western Australia.

Etherilosia sp. indet.
Figure 6.10–6.24

Occurrence.—Top of the Kongshuhe Formation.

Description.—Shell small, ovate in outline, with both width and length commonly <10 mm. Ventral valve evenly convex, without sulcus. Dorsal valve slightly concave; fold absent.

Ventral spines relatively coarse, hollow, at least on posterior part (Fig. 6.14). Surface of dorsal valve ornamented by concentric rugae and dimples (Fig. 6.21, 6.22); concentric rugae distinctly developed, irregularly spaced, especially on posterior part, sometimes discontinuous; dimples coarse, regularly spaced along concentric rugae; no spines on dorsal valve.

Sockets distinctly developed, deep and divergent; dorsal muscle scars bisected by long, thin median ridge (Fig. 6.24).

Materials.—Thirteen specimens, including five ventral valves (IGCAGS 20016, 20019, 20021, 20022, 20024), four external ventral molds (IGCAGS 20017, 20018, 20020, 20023), three dorsal external molds (IGCAGS 20025–20027), and one dorsal internal mold (IGCAGS 20028).

Remarks.—The present specimens are assignable to *Etherilosia*, based on the small shell size, oval outline, relatively coarse ventral spines, concentric rugae on the dorsal valve, prominent sockets, and a median ridge in the dorsal interior.

The Tengchong specimens are very similar to *Etherilosia etheridgei* (Prendergast, 1943) from the Callytharra Formation, Carnarvon Basin, Western Australia (Coleman, 1957), in shell size and outline, ventral spines, dorsal ornamentation, dorsal deep sockets, and median ridge. However, the poorly preserved ventral valves, from which it is unknown whether the concentric lamellae and interarea are present, prevent further comparison. *Etherilosia prendergastae* (Coleman, 1957), from the Cundlego and Callytharra formations in the Carnarvon Basin, is different from our specimens in its relatively larger shell size and more spines on ventral valve (Archbold, 1993a). However, adequate comparison is difficult in view of the paucity of specimens and the limited preservation.

Order Orthotetida Waagen, 1884
Family Derbyllidae Stehli, 1954
Genus *Derbyia* Waagen, 1884

Type species.—*Derbyia regularis* Waagen, 1884 from the Guadalupian of the Salt Range in Pakistan.

Remarks.—*Magniderbyia* Ting, 1965 was proposed to replace the genus *Licharewiella* Sokolskaya, 1960; Sokolskaya (1960, December) was not aware of that this genus name had been utilized for a productide from the Permian of the western of Kunlun Mountain by Ustritsky (1960, March). Therefore, the genus *Licharewiella* established by Sokolskaya should be abandoned. Later, *Licharewiella* was treated as a junior synonym of *Derbyia* by Cooper and Grant (1974), which was adopted by Williams et al. (2000).

Derbyia grandis Waagen, 1884
Figure 7.8–7.17

1884 *Derbyia grandis* Waagen, p. 597, pl. 51, fig. 1a–d, pl. 52, figs. 1, 3, pl. 53, figs. 3, 5.
1916 *Derbyia grandis*, Broili, p. 7, pl. 115, fig. 9.
1962 *Schellwienella acutangula* (Huang, 1933), Ting, p. 457, pl. 4, fig. 3a.
1973 *Derbyia grandis*, Grunt and Dmitriev, p. 84, pl. 3, figs. 1–4.
1974 *Wardakia grandis* Termier et al., p. 94, pl. 9, figs. 2–5, pl. 10, figs. 1–3.
1976 *Orthotetes* cf. *Orthotetes gyppyi* (Thomas, 1958), Zhang and Jin, p. 160, pl. 1, fig. 3.
1980 *Derbyia grandis*, Li et al., p. 336, pl. 159, fig. 13.
1996 *Derbyia grandis*, Angiolini, p. 9, pl. 1, figs. 7–9.
2003 *Derbyia grandis*, Shen et al., p. 60, text-fig. 4, pl. 1, figs. 1–3.

Holotype.—Several specimens listed (but no formal specimen numbers) from the middle to upper *Productus* Limestone, Salt Range, Pakistan (Waagen, 1884, pl. 51, fig. 1a–d, pl. 52, figs. 1, 3, pl. 53, figs. 3, 5).

Occurrence.—Lower part of the Dadongchang Formation; *Productus* Limestone, Salt Range, Pakistan; Nifokoko River, Mollo Region, Timor; Qubuerga Formation, Mt. Qomolangma region, southern Tibet; Wardak, central Afghanistan; Panishah Formation, central Karakorum.

Description.—Shell large, >75 mm wide in largest specimen. Ventral valve weakly convex and nearly flat at anterior part. Dorsal valve moderately and evenly convex. Shell surface fully covered by costae; costae fine, increased by intercalation and bifurcation, six to eight per 5 mm at anterior margin, intersected by fine growth lines (Fig. 7.9); secondary costae as thick as primary ones at anterior part; interspaces wider than costae. Internal structures unknown.

Materials.—Seven specimens: three incomplete dorsal valves (IGCAGS 20036, 20038, 20039) and four ventral valves (IGCAGS 20037, 20040–20042).

Remarks.—The present specimens resemble *Derbyia grandis* in the large shell, evenly convex dorsal valve, nearly flat anterior part of the ventral valve, and costae increasing both by intercalation and bifurcation. Our specimens are also similar to *Derbyia profunda* Cooper and Grant, 1974 from western Texas, in the large shell and fine costae, but the latter develops more crowded costae, numbering 15 or 16 in 5 mm. *Derbyia nigpi* Chen and Liao, 2007 from the upper Changhsing Formation, South China can be distinguished from *Derbyia grandis* by its smaller size and highly conical umbo of the ventral valve.

Order Rhynchonellida Kuhn, 1949
Family Stenoscismatidae Oehlert, 1887
Stenoscismatidae gen. indet. sp. indet.
Figure 6.29–6.31

Occurrence.—Top of the Kongshuhe Formation.

Materials.—Three ventral internal casts (IGCAGS 20043–20045).

Remarks.—All of these small specimens preserved as ventral internal casts are simply characterized by the development of a spondylium in the ventral interior, which suggests that they might belong to the Stenoscismatidae. The elongate spondylium supported by the relatively low median septum in the Tengchong specimens is comparable with the spondylium of *Stenoscisma quasimutabilis* (see Waterhouse, 1981, pl. 19, fig. 9) from the Ko Yao Noi Formation, southern Thailand, but detailed comparison is difficult in view of the limited preservation of our specimens.

Family Psilocamaridae Grant, 1965
Genus *Cyrolexis* Grant, 1965

Type species.—*Cyrolexis haquei* Grant, 1965 from lower *Productus* Limestone, Salt Range, Pakistan.

Cyrolexis sp. indet.
Figure 9.7–9.13

Occurrence.—Base of the Dadongchang Formation.

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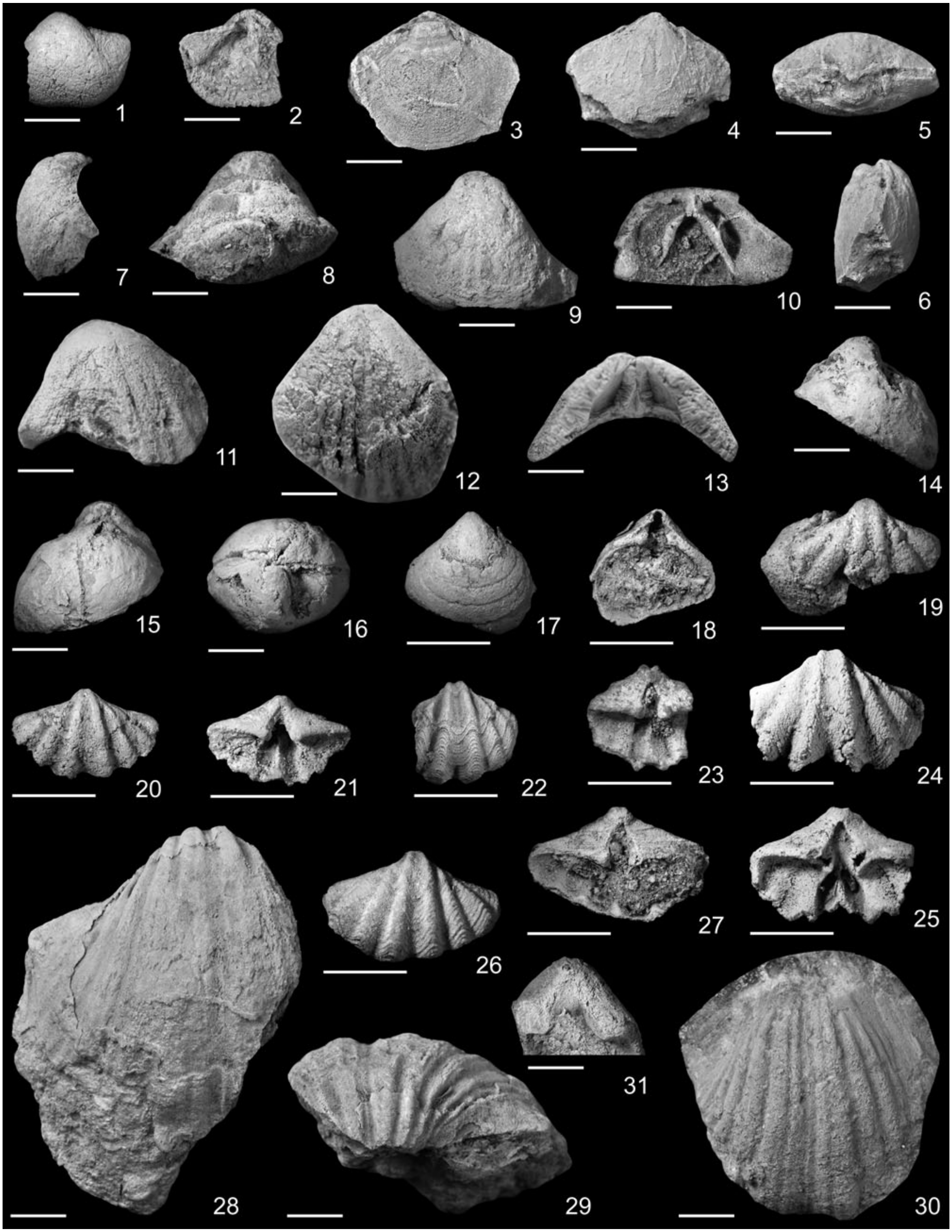
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Figure 9. Brachiopods from the base of the Dadongchang Formation in the northern Tengchong Block. (**1, 2**) Chonetoidea gen. indet. sp. indet., 0819-5, ventral and dorsal views of ventral valve, IGCAGS 20118. (**3–6**) *Schizophoria* sp. indet., 0061, ventral, dorsal, posterior, and lateral views, respectively, of an incomplete shell, IGCAGS 20119. (**7–13**) *Cyrolexis* sp. indet.: (**7–9**) 20220708-1, lateral, ventral, and dorsal views, respectively, of dorsal valve, IGCAGS 20046; (**10**) 0218-8, ventral valve showing the spondylium in the ventral interior, IGCAGS 20047; (**11**) 0200, dorsal valve, IGCAGS 20048; (**12**) 0205, ventral valve, IGCAGS 20049; (**13**) 0209, ventral valve, IGCAGS 20050. (**14–18**) *Composita* sp. indet.: (**14–16**) 0819-6, ventral, dorsal, and posterior views, respectively, of an incomplete shell, IGCAGS 20051; (**17, 18**) 0921-5, ventral and dorsal views of ventral valve, IGCAGS 20052. (**19–27**) *Spiriferellina yunnanensis* Fang, 1983: (**19**) 0921-3, ventral valve, IGCAGS 20098; (**20, 21**) 0917-2, ventral and dorsal views of ventral valve, IGCAGS 20099; (**22, 23**) 0921-2, ventral and dorsal views of ventral valve, IGCAGS 20100; (**24, 25**) 0917-1, ventral and dorsal views of ventral valve, IGCAGS 20101; (**26, 27**) 0917-3, ventral and dorsal views of ventral valve, IGCAGS 20102. (**28–31**) *Spiriferella* sp. indet.: (**28, 29**) 1608, ventral and posterior views of ventral valve, IGCAGS 20070; (**30**) 1631, ventral valve, IGCAGS 20071; (**31**) 0819-4, dorsal view of ventral valve showing ventral apical thickening, IGCAGS 20072. Scale bars = 5 mm.

Description.—Shell elongate globose in outline, with narrow hinge line. Ventral valve evenly convex; umbonal region slightly swollen. Dorsal umbonal region strongly swollen; dorsal beak incurved. Sulcus and fold not prominent. Costae low and simple, occurring only at anterior region of both valves. Ventral interior with spondylium elevated by very low septum anteriorly.

Materials.—Five specimens, including two dorsal valves (IGCAGS 20046, 20048), one ventral valve (IGCAGS 20049), and two ventral valves showing internal structures (IGCAGS 20047, 20050).

Remarks.—The present specimens are assignable to the genus *Cyrolexis* in the elongate globose outline with the narrow hinge line, strongly swollen umbonal area of dorsal valve, and a spondylium in the ventral interior, as well as the simple and rounded costae developed on the anterior part of valve.

They resemble *Cyrolexis haquei* from the lower *Productus* Limestone, Salt Range, Pakistan, in the low costae. However, the Tengchong specimens differ from the latter by a slightly wider outline. *Stenoscisma purdoni* (Davidson, 1862), reported from the Guanyinshan Formation, Dadongchang, Tengchong by Fang and Fan (1994, p. 84, pl. 30, figs. 9, 10; see also Fang, 1995, p. 139, pl. 4, figs. 9, 10), is distinguished from our specimens by its transverse and pentagonal shell outline.

Order Athyridida Boucot, Johnson, and Staton, 1964
Family Athyrididae Davidson, 1881
Genus *Composita* Brown, 1845

Type species.—*Spirifer ambiguus* Sowerby, 1822 in 1821–1822, from the Viséan of England.

Composita sp. indet.
Figure 9.14–9.18

Occurrence.—Base of the Dadongchang Formation.

Description.—Shell moderate in size, subovate in outline, widest near midlength, bioconvex in lateral profile. Fold and sulcus absent on both valves. Ventral beak moderately incurved to suberect; foramen ovate in outline, 1 mm in diameter, with permesothyridid to epithyridid position; delthyrium narrowly triangular. Dorsal valve evenly convex. Three growth lamellae distinctly developed at middle and anterior parts (Fig. 9.17). Internal structures unknown.

Materials.—Two specimens, including one incomplete conjoined shell (IGCAGS 20051) and one ventral valve (IGCAGS 20052).

Remarks.—The present specimens can be assigned to *Composita* in terms of the subovate outline, rounded ventral foramen, the absence of sulcus or fold.

The specimens figured by Fang and Fan (1994, p. 86, pl. 31, figs. 4, 6) as *Spirigerella minuta* Waagen, 1883 from the Guanyinshan Formation, Dadongchang section, Tengchong has an ovate permesothyrid ventral foramen, which is a character of *Composita* (Alvarez and Rong, 2002). Our specimens resemble these in developing a less convex dorsal valve and growth lamellae at middle and anterior parts. *Composita* sp. indet. from the Selong Group in southern Tibet (Shen et al., 2001, p. 178, fig. 14.9) is also similar in its small size, subovate outline, the absence of a sulcus, and the permesothyrid foramen, but further comparison is hampered due to lack of sufficient materials and the limited preservation of internal structures.

Order Spiriferida Waagen, 1883
Family Ingelarellidae Campbell, 1959
Genus *Ambikella* Sahni and Srivastava, 1956

Type species.—*Ambikella fructiformis* Sahni and Srivastava, 1956 from *Eurydesma* beds in Sikkim, eastern Himalaya.

Ambikella? sp. indet.
Figure 10.1–10.9

Occurrence.—Top of the Kongshuhe Formation.

Description.—Shell small, ∼15 mm wide in largest specimen, oval in outline, with rounded cardinal extremities. Ventral valve without sulcus, micro-ornamented by fine, elongated, narrow grooves arranged in quincunx (Fig. 10.3). Ventral interior with slightly divergent to parallel, long dental plates and very shallow, short median ridge (Fig. 10.1); pustules and pits elongated, developed on entire ventral internal floor (Fig. 10.5–10.7).

Materials.—Five specimens, including three ventral internal molds (IGCAGS 20053, 20055, 20056), one ventral external mold (IGCAGS 20057), and one shell fragment (IGCAGS 20054).

Remarks.—The present specimens are provisionally assigned here to *Ambikella*, based on the oval shell outline with obtuse cardinal extremities, micro-ornament composed of elongated grooves, and closely spaced, subparallel dental plates. The development of the elongated pustules and pits on the ventral interiors is similar to the 'ovarian markings' of *Ambikella ovata* (Campbell, 1961) from the Tiverton Formation,

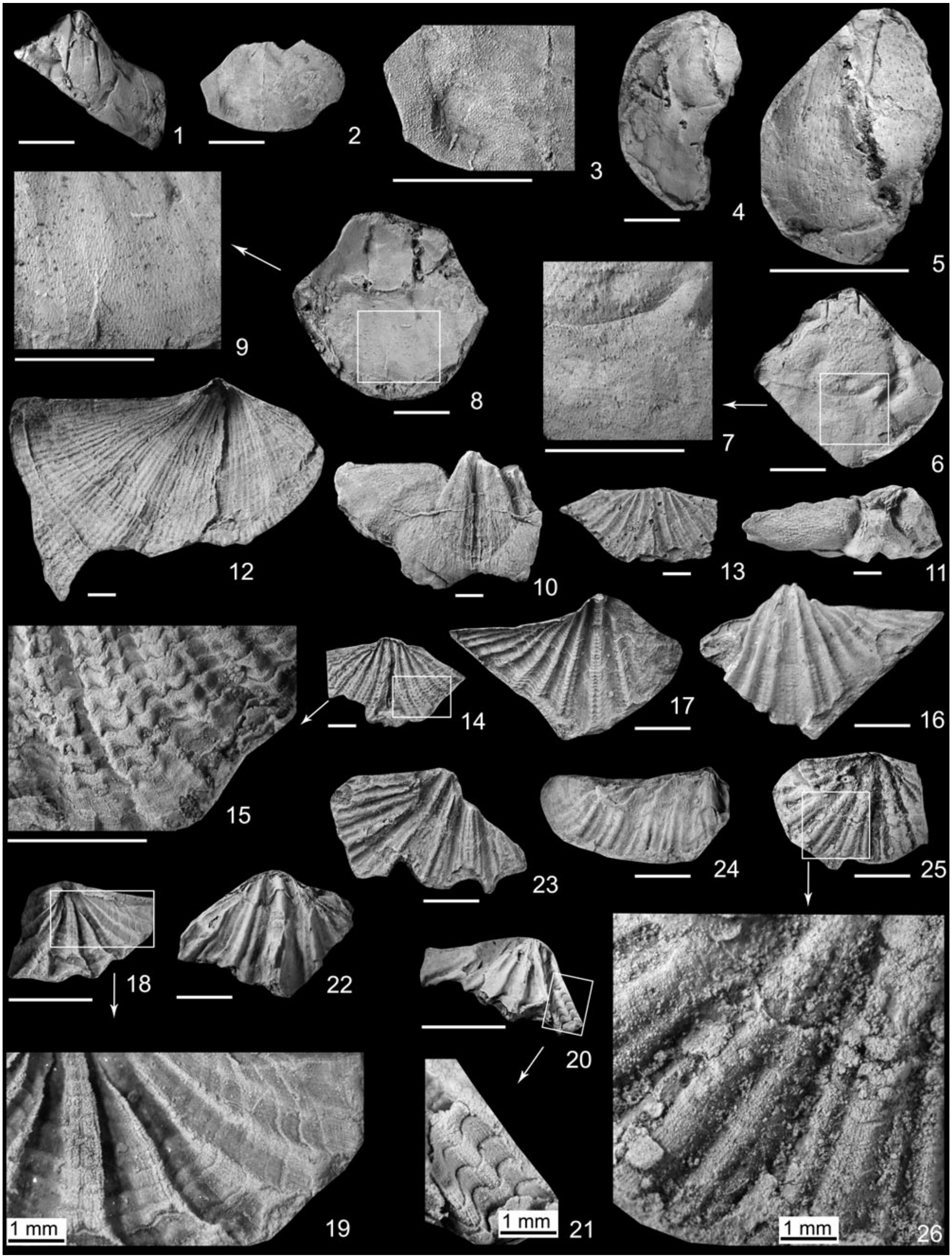

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Figure 10. Brachiopods from the top of the Kongshuhe Formation in the northern Tengchong Block. (**1–9**) *Ambikella*? sp. indet.: (**1**) 0209-5-a, ventral internal mold, IGCAGS 20053; (**2, 3**) 0812-5-a, fragment and enlargement, IGCAGS 20054; (**4, 5**) 0209-4, broken ventral internal mold and enlargement showing the narrow grooves arranged in quincunx, IGCAGS 20055; (**6, 7**) 0492, ventral internal mold and enlargement showing the fine and elongated grooves, IGCAGS 20056; (**8, 9**) 0501, ventral external mold and enlargement showing the micro-ornament, IGCAGS 20057. (**10–12**) *Neospirifer* sp. indet.: (**10, 11**) 0509, ventral and posterior views of ventral internal mold, IGCAGS 20058; (**12**) 0527, dorsal external mold, IGCAGS 20059. (**13–21**) *Aperispirifer* sp. indet.: (**13**) 1567, dorsal internal mold, IGCAGS 20064; (**14, 15**) 1577, dorsal external mold and enlargement showing lamellate valve, IGCAGS 20065; (**16**) 1394, ventral internal mold, IGCAGS 20066; (**17**) 1401, ventral external mold, IGCAGS 20067; (**18, 19**) 0806-4, ventral external mold and enlargement showing the micro-ornaments composed of imbricated growth lamellae and radial capillae, IGCAGS 20068; (**20, 21**) 0811-6, ventral internal mold and enlargement showing the micro-ornaments, IGCAGS 20069. (**22–26**) *Trigonotreta* cf. *Trigonotreta semicircularis* Shen et al., 2000: (**22**) 0218-3-a, dorsal valve, IGCAGS 20060; (**23**) 1547, broken ventral external mold, IGCAGS 20061; (**24**) 0209-6-b, fragment, IGCAGS 20062; (**25, 26**) 0812-3, dorsal external mold and enlargement showing the capillate micro-ornament, IGCAGS 20063. Scale bars = 5 mm, unless otherwise labeled.

Queensland, Australia (see Waterhouse, 2015, p. 150 for more details on the taxonomic assignment of this species). *Ambikella confusa* Waterhouse, 1968 from the Letham Formation, New Zealand is similar to our specimens in the small shell, short grooves, and ventral dental plates, but differs in having a narrow median groove on the sulcus. Our specimens resemble *Ambikella undulosina* Waterhouse and Chen, 2007 from the Galte and Ngawal Members of the Senja Formation, north-central Nepal, in the rounded cardinal extremities and micro-ornaments of fine surface grooves, however, further comparison is hampered due to the limited preservation of external structures.

Family Trigonotretidae Schuchert, 1893
Genus *Neospirifer* Fredericks, 1924

Type species.—*Spirifer fasciger* Keyserling, 1846 from the Cisuralian of Timan Peninsula, Arctic (Russia).

Neospirifer sp. indet.
Figure 10.10–10.12

Occurrence.—Top of the Kongshuhe Formation.

Description.—Shell large, transverse in outline, with largest width at hinge line; cardinal extremities rounded. Shell surface covered by numerous costae; costae fine, nearly equidimensional on anterior part, increased by bifurcation; fascicles prominent at umbonal region (Fig. 10.12); fascicle near fold composed of approximately four costae at umbonal area; growth lamellae distinct on middle and anterior parts of dorsal valve.

Ventral interior with strongly developed and divergent dental plates, delimiting posterior boundary of diductor scars; muscle areas flabellate with longitudinal striates; adductor scars bisected by long median ridge.

Materials.—Two specimens, including one dorsal external mold (IGCAGS 20059) and one ventral internal mold (IGCAGS 20058).

Remarks.—The present specimens are assignable to *Neospirifer* because their shell shape, costal features, and growth lamellae are well matched with the diagnosis of the genus suggested by Archbold and Thomas (1984a, 1986). Our specimens bear a median ridge in the ventral interior, whereas both *Neosprifier hardmani* (Foord, 1890) from Callytharra Formation, Western Australia (Archbold and Thomas, 1986, fig. 3C, G) and *Neospirifer* aff. *Neospirifer hardmani* from southeastern Oman (Angiolini et al., 1997) do not bear any median ridge on their ventral floor.

Neospirifer kubeiensis Ting, 1962 (emend. Zhang in Zhang and Jin, 1976) = *Neospirifer* (*Quadrospira*) *tibetensis* Ting, 1962, based on Shen et al. (2001, p. 162) from the Guanyinshan Formation in the Dadongchang section, Tengchong (Fang and Fan, 1994) resembles our specimens in the large size, prominent dental plates, and muscle scars, but the former has more strongly developed fascicles. Two species of *Neospirifer* were previously reported from the upper part of the Dingjiazhai Formation, Yunnan—*Neospirifer kimsari* (Bion, 1928) and *Neospirifer amphigyus* Cooper and Grant, 1976a, by Fang (1994) and Nie et al. (1993)—but both are morphologically separated from the Tengchong specimens; *Neospirifer kimsari* is distinguished in having acute cardinal extremities, and *Neospirifer amphigys* is different in possessing fine costae forming fascicles from the umbonal region extending to the anterior margin.

Genus *Trigonotreta* Koenig, 1825

Type species.—*Trigonotreta stokesi* Koenig, 1825 from the Permian of Australia.

Trigonotreta cf. *Trigonotreta semicircularis* Shen, Shi, and Zhu, 2000
Figure 10.22–10.26

cf. 2000 *Trigonotreta semicircularis* Shen et al., p. 273, pl. 3, figs. 5–8.

Holotype.—NIGP 130936 from Member B of the Dingjiazhai Formation, at Dingjiazhai, Shidian, western Yunnan, China (Shen et al., 2000, pl. 3, fig. 5).

Occurrence.—Top of the Kongshuhe Formation.

Description.—Shell moderate in size, ∼30 mm wide in dorsal valve (Fig. 10.24). Ventral sulcus moderately developed; dorsal fold prominent; both costate. Lateral flanks on both valves covered by strong plicae; each plica composed of fascicles containing unequal costae, usually with coarse median costa and two or more thin lateral costae (Fig. 10.22, 10.24); capillae present (Fig. 10.26). Shell interiors unknown.

Materials.—Four specimens, including one broken ventral external mold (IGCAGS 20061), one dorsal external mold (IGCAGS 20063), one dorsal valve (IGCAGS 20060), and one fragment (IGCAGS 20062).

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Remarks.—The present specimens are generally well matched with *Trigonotreta semicircularis* from the Baoshan Block, in the prominent sulcus and fold, and fascicles with a coarse median costa and thin lateral costae. However, the latter develops distinct growth lamellae on both valves, which were not observed on our specimens. *Trigonotreta orientalis* Singh and Archbold, 1993 from the Sakamarian of the eastern Himalaya is also similar to *Trigonotreta* cf. *Trigonotreta semicircularis* in the unequal costae in the fascicles with median costae coarser than the lateral costae, but differs from the latter by the prominent concentric lamellae.

Trigonotreta victoriae (Archbold, 1991) from the late Asselian to early Sakmarian of Victoria is similar to our specimens in the poorly developed growth lamellae, but differs in denser fascicles. The Tengchong specimens are similar to *Trigonotreta lightjacki* Archbold and Thomas, 1986 from the Lightjack Formation, Canning Basin, Western Australia in the coarse plicae and distinct dorsal fold, but differ from the latter in the coarser median costae of the fascicles. *Trigonotreta* sp. indet. from the Rat Buri, Thailand (Archbold, 1999) is similar to the Tengchong specimens in the coarse plicae, but differs in the very transverse shell outline.

Genus *Aperispirifer* Waterhouse, 1968

Type species.—*Neospirifer wairakiensis* Waterhouse, 1964 from the Letham Formation, New Zealand.

Aperispirifer sp. indet.
Figure 10.13–10.21

Occurrence.—Top of the Kongshuhe Formation.

Description.—Shell moderate in size, ~32 mm wide in most complete dorsal valve (Fig. 10.13), transverse in outline, with angular cardinal extremities. Ventral sulcus narrow, distinctly developed, bearing median costa and two lateral costae (Fig. 10.16). Dorsal fold posteriorly narrow, but gradually widening anteriorly. Each flank covered by seven plicae in the large specimen (Fig. 10.16) and by four plicae in the small specimen (Fig. 10.18); plicae coarse, subangular, separated by deep and wide interspaces; plicae toward lateral margin simple, two or three plicae near sulcus/fold forming fascicles from nearly middle part to anterior (Fig. 10.17), occasionally with fascicles composed of strong median costa and two finer accretional costae (Fig. 10.13). Micro-ornaments composed of imbricated growth lamellae and fine radial capillae, distributed on the plicae and interspaces (Fig. 10.15, 10.19).

Materials.—Six specimens, including one dorsal external mold (IGCAGS 20065), one dorsal internal mold (IGCAGS 20064), two ventral external molds (IGCAGS 20067, 20068), and two ventral internal molds (IGCAGS 20066, 20069).

Remarks.—The present specimens appear to bear the characteristics of typical *Aperispirifer*, e.g., a transverse outline, weakly developed lateral plicae, acute cardinal extremities, unequal costae, and concentric and radial capillae on both valves.

Aperispirifer wairakiensis Waterhouse, 1964 from the Letham Formation, New Zealand and *Aperispirifer lethamensis* Waterhouse, 1968 from the Mangarewa Formation, New Zealand is similar to our specimens in transverse shell shape, narrow sulcus, and narrow fold, but the former two develop four to six pairs of plicae. Due to lack of complete valves in the Tengchong, further comparison including the costal pattern of each plica cannot be carried out.

The present specimens are close to *Neospirifer sterlitamakensis* (Gerassimov, 1929) from the Ko Yao Noi Formation, southern Thailand (Waterhouse, 1981, p. 101, pl. 25, figs. 3–5, pl. 26, figs. 1–5), in a transverse shell with acute cardinal extremities, narrow sulcus, and micro-ornaments consisting of imbricated concentric growth lamellae and fine radial capillae. However, *Neospirifer sterlitamakensis* from Thailand is distinguished in having three to five pairs of plicae composed of strong costae. It is worth noting that Archbold (1999) considered that some materials of *Neospirifer sterlitamakensis* illustrated by Waterhouse (1981) probably represent a group of *Trigonotreta* species, according to the fascicles of three unequal costae and prominent growth lines.

Family Spiriferellidae Waterhouse, 1968
Genus *Spiriferella* Chernyshev, 1902

Type species.—*Spirifer saranae* de Verneuil, 1845 from the Cisuralian, Ural Mountains, Russia.

Spiriferella sp. indet.
Figure 9.28–9.31

Occurrence.—Base of the Dadongchang Formation.

Description.—Shell medium to large, > ~34 mm in width, with longitudinally oval outline. Ventral umbonal region inflated; ventral interarea moderately high. Sulcus shallow, narrow, subplicate, with fine median costa, starting nearly from umbo and extending to anterior margin (Fig. 9.30); lateral flanks covered by four or more pairs of plicae; lateral plicae broad, rounded on crest, separated by narrow interspaces, fasciculate, commonly with three costae (Fig. 9.28). Ventral interior posteriorly filled with callus (Fig. 9.31).

Materials.—Three ventral valves (IGCAGS 20070–20072).

Remarks.—The present specimens are assigned to *Spiriferella* based on the elongate outline, strongly plicate lateral flanks, and thick ventral callus (Waterhouse and Waddington, 1982; Lee et al., 2019). These specimens resemble *Spiriferella sinica* Zhang in Zhang and Jin, 1976 and *Spiriferella qubuensis* from the Selong Group in Himalaya (Zhang and Jin, 1976), in the elongate outline, narrow and shallow sulcus, and the existence of a median costa and two lateral costae on the sulcus. However, the Tengchong specimens differ from the two Himalayan species in the pattern of lateral plication; *Spiriferella sinica* has four pairs of plicae on the lateral flanks, among which, the first and second plicae are trifurcated on anterior part of valve, and *Spiriferella qubuensis* bears six pairs of simple plicae on the lateral slopes. The present

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specimens are also similar to *Spiriferella saranae* (de Verneuil, 1845) from the Jungle Creek Formation, northern Yukon Territory in the elongate shell outline, inflated ventral umbo, and one median costa in the sulcus, but differ in the six to eight weak costae in the sulcus and radial capillae on the ventral valve of the latter (Waterhouse and Waddington, 1982).

Genus *Elivina* Fredericks, 1924

Type species.—*Spirifer tibetanus* Diener, 1897 from the Permian of Chitichun Limestone, Tibet.

Elivina yunnanensis Shi, Fang, and Archbold, 1996
Figure 11.1–11.14

1994 *Spiriferella unicosta* Chang (= Zhang) in Zhang and Jin, 1976, Fang, p. 269, pl. 2, figs. 10–12.
1994 *Spiriferella qubuensis* 'Chang,' Fang, p. 269, pl. 2, figs. 13, 14.
1996 *Elivina yunnanensis* Shi, Fang, and Archbold, p. 98, fig. 5D–M.
2000 *Elivina yunnanensis*, Shen et al., p. 273, pl. 2, figs. 21–25, pl. 3, figs.1–4.

Holotype.—NIGP 124753 from the Dingjiazhai Formation, Dingjiazhai, Shidian, western Yunnan, China (Shi et al., 1996, fig. 5F).

Occurrence.—Top of the Kongshuhe Formation; Dingjiazhai Formation, Baoshan, Shidian, Yongde, China.

Description.—Shell small to medium, circular in outline, with rounded cardinal extremities. Ventral sulcus narrow, distinctly developed; delthyrium triangular (Fig. 11.4); ventral lateral slope possessing approximately five pairs of rounded plicae (Fig. 11.10); plicae bounding sulcus bifurcating.

Ventral interior with short divergent dental plates and median ridge extending to nearly two-thirds of the muscle field (Fig. 11.7); muscle field deeply impressed, longitudinally striated, with variable outline from rounded (Fig. 11.2, 11.4) to elongated oval (Fig. 11.7, 11.8, 11.12).

Materials.—One ventral external mold (IGCAGS 20077), and six ventral internal molds (IGCAGS 20073–20076, 20078, 20079).

Remarks.—The morphology of the present specimens is consistent with that of *Elivina yunnanensis*, particularly in the rounded outline and strongly depressed muscle field that was demonstrated in the specimens from the Dingjiazhai Formation in the Baoshan Block by Shen et al. (2000; see Fig. 5).

Two species of *Spiriferella* were described from the upper part of Dingjiazhai Formation in the Baoshan Block by Fang (1994), which were later renamed *Elivina yunnanensis* by Shi et al. (1996), based on the smaller size, more rounded outline, and simpler costae of the specimens. *Elivina hoskingae* Archbold and Thomas, 1985 from Western Australia is also similar in shell outline, size, the delthyrium partly filled by callus, and deeply impressed muscle scars, but *Elivina yunnanensis* is different in having simple plicae. *Elivina tibetana* (Diener, 1897) from the Permian of Chitchun Limestone, southern Tibet, is larger and elongate in outline compared with the present species (Diener, 1897, pl. 6, figs. 1–7).

Family Elythidae Fredericks, 1924
Genus *Spirelytha* Fredericks, 1924

Type species.—*Spirelytha pavlovae* Archbold and Thomas, 1984b from the Permian of Siberia.

Spirelytha sp. indet.
Figure 11.15–11.24

Occurrence.—Top of the Kongshuhe Formation.

Description.—Shell small, ∼13 mm wide in the largest specimen; outline nearly circular. Dorsal valve slightly convex, without plication on surface. Concentric growth lamellae very prominent, each bearing row of biramous spines (Fig. 11.18). Dorsal interior with short median ridge.

Materials.—Six specimens, including one fragment showing micro-ornament (IGCAGS 20081), one distorted dorsal internal mold (IGCAGS 20080) and external mold (IGCAGS 20082), one dorsal external mold (IGCAGS 20085) and internal mold (IGCAGS 20084), and one distorted dorsal internal mold (IGCAGS 20083).

Remarks.—The present specimens seem compatible with *Spirelytha*, in the ornaments composed of concentric lamellae and biramous spines and the delicate dorsal median ridge (Archbold and Thomas, 1984b).

Our specimens are close to *Spirelytha stepanoviana* Archbold and Thomas, 1984b from the middle Kungurian of the Carnarvon Basin, Western Australia, in the small shell and thin median ridge in the dorsal interior. However, the latter has a broad and low fold (Archbold and Thomas, 1984b, p. 320, fig. 4F–R). Our specimens differ from *Spirelytha petaliforms* (Pavlova, in Grunt and Dmitriev, 1973) from the Nam Loong No. 1 Mine of Perak, West Malaysia by Shi and Waterhouse (1991), from the Gircha Formation, Karakorum by Angiolini (1995), and from the Dingjiazhai Formation in the Baoshan Block by Shen et al. (2000), in having a broad sulcus and fold of the latter.

Order Spiriferinida Ivanova, 1972
Family Syringothyrididae Fredericks, 1926
Genus *Cyrtella* Fredericks, 1924

Type species.—*Cyrtia kulikiana* Fredericks, 1916 from the Permian of Russia.

Cyrtella? sp. indet.
Figure 12.1–12.8

Occurrence.—Top of the Kongshuhe Formation.

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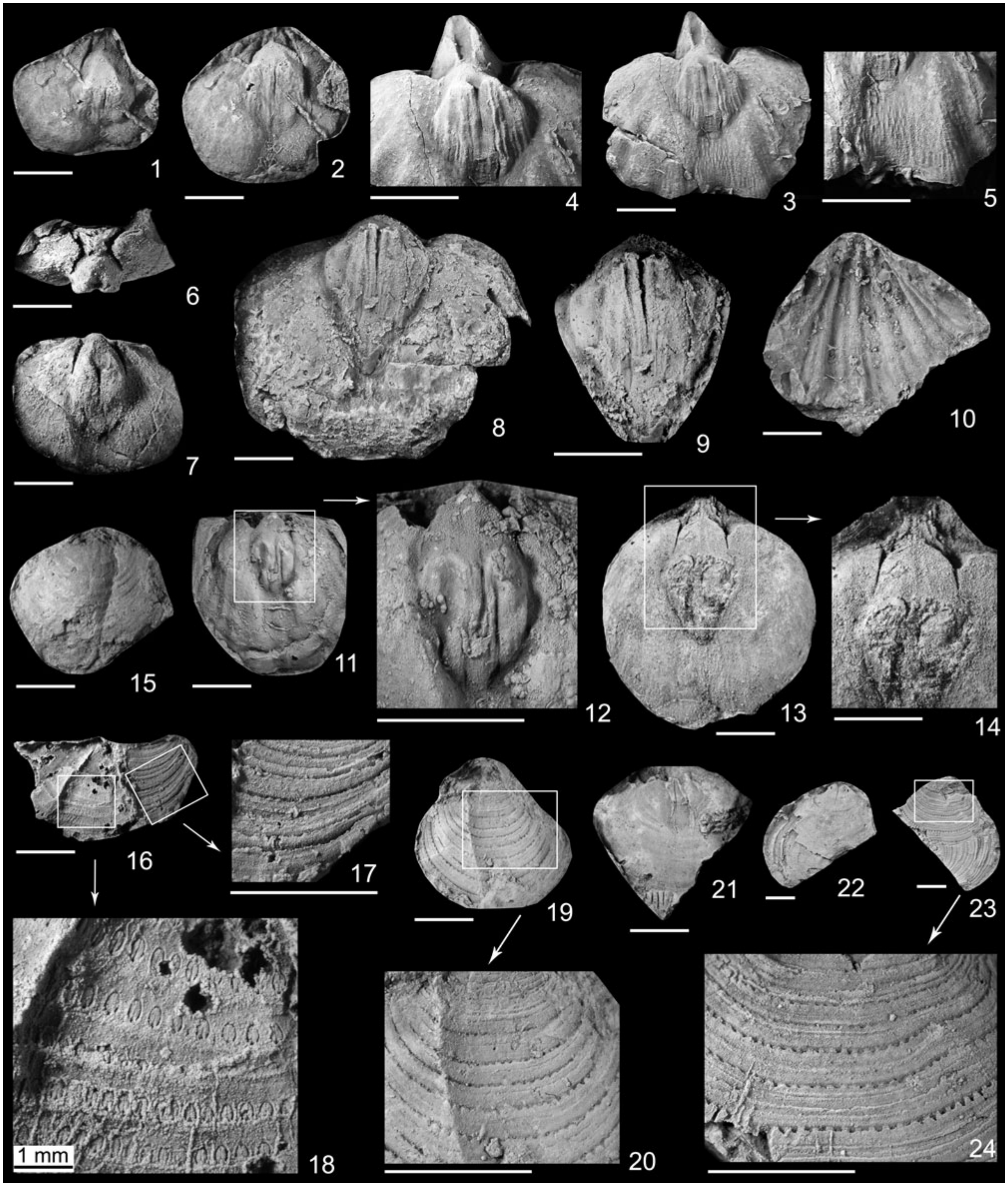

Figure 11. Brachiopods from the top of the Kongshuhe Formation in the northern Tengchong Block. (**1–14**) *Elivina yunnanensis* Shi, Fang, and Archbold, 1996: (**1, 2**) 0817-3, two ventral views of ventral internal mold, IGCAGS 20073; (**3–5**) 1541, ventral internal mold and enlargement showing the muscle fields and median ridge, and enlargement showing the sulcus, IGCAGS 20074; (**6, 7**) 0812-2, posterior and ventral views of ventral internal mold, IGCAGS 20075; (**8, 9**) 1519, ventral internal mold and enlargement showing the muscle fields and a median ridge, IGCAGS 20076; (**10**) 1555, ventral external mold, IGCAGS 20077; (**11, 12**) 0209-7, ventral internal mold and enlargement showing the muscle fields and a median ridge, IGCAGS 20078; (**13, 14**) 0484, ventral internal mold and enlargement, IGCAGS 20079. (**15–24**) *Spirelytha* sp. indet.: (**15**) 0218-6, dorsal internal mold, IGCAGS 20080; (**16–18**) 0812-7, fragment and enlargement showing growth lamellae, and enlargement showing biramous spines, IGCAGS 20081; (**19, 20**) 0218-7, dorsal external mold and enlargement, IGCAGS 20082; (**21**) 0210-1, dorsal internal mold, IGCAGS 20083; (**22**) 1590, dorsal internal mold, IGCAGS 20084; (**23, 24**) 1599, dorsal external mold and enlargement showing spine-bearing growth lamellae, IGCAGS 20085. Scale bars = 5 mm, unless otherwise labeled.

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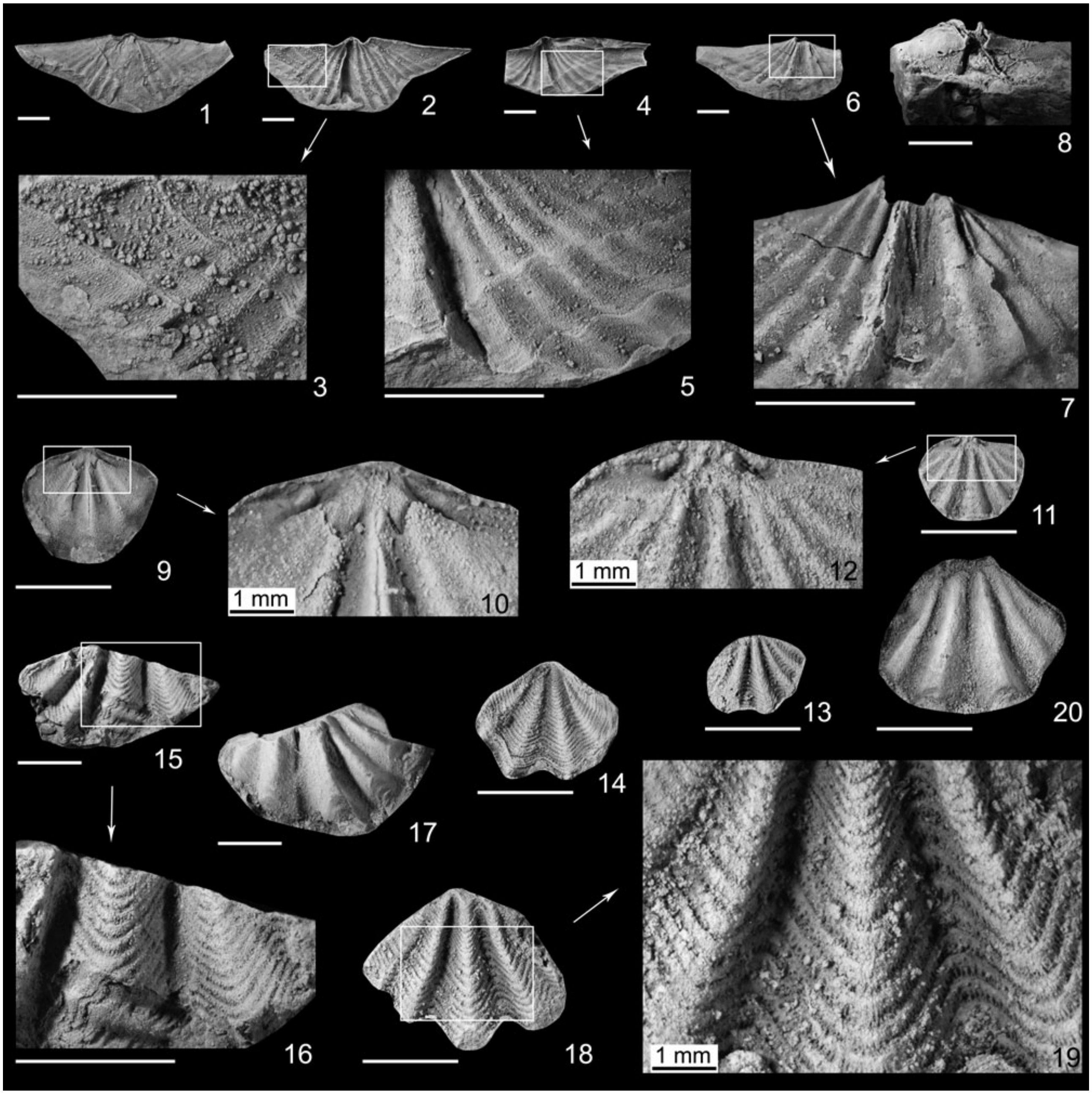

Figure 12. Brachiopods from the top of the Kongshuhe Formation in the northern Tengchong Block. (**1–8**) *Cyrtella*? sp. indet.: (**1**) 1412, dorsal internal mold, IGCAGS 20086; (**2, 3**) 1459, dorsal external mold and enlargement showing the micro-ornaments, IGCAGS 20087; (**4, 5**) 1428, ventral external mold and enlargement, IGCAGS 20088; (**6–8**) 1448, ventral internal mold and enlargement showing the divergent dental plates, and view of ventral interarea with delthyrium, IGCAGS 20089. (**9–20**) *Callispirina ornata* (Waagen, 1883): (**9, 10**) 0811-3, dorsal internal mold and enlargement, IGCAGS 20090; (**11, 12**) 0209-1, dorsal internal mold and enlargement showing the small sockets, IGCAGS 20091; (**13**) 0209-2, dorsal external mold, IGCAGS 20092; (**14**) 0811-5, dorsal external mold, IGCAGS 20093; (**15, 16**) 0218-2, ventral external mold and enlargement showing the micro-ornament, IGCAGS 20094; (**17**) 0218-1, ventral internal mold, IGCAGS 20095; (**18, 19**) 0811-2, ventral external mold and enlargement showing imbricated growth lamellae and dense elongated spinules, IGCAGS 20096; (**20**) 0811-7, ventral internal mold, IGCAGS 20097. Scale bars = 5 mm, unless otherwise labeled.

Description.—Shell medium in size, ∼36 mm wide in largest specimen, transversely subtriangular outline with acute cardinal extremities, with width/length ratio of 3.0. Ventral sulcus broad, moderately deep, with rounded bottom; no costae developed in sulcus. Ventral interarea moderately high, weakly concave, with delthyrium of narrow triangular form (Fig. 12.8). Dorsal fold well delimited, narrow but broadening anteriorly, moderately high, with rounded crest. Lateral slopes with seven or more pairs of plicae; plicae distinct, simple, rounded, with wider interspaces. Shell surface ornamented with quincuncially arranged elongate pustules, and discontinuous capillae (Fig. 12.3, 12.5); growth lamellae irregularly spaced.

Ventral interior with short, divergent dental plates, extending anteriorly across outer edges of sulcus-bounding plicae (Fig. 12.7). Adductor muscle scars very narrow; median ridge weakly developed only on posterior part of ventral floor.

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Materials.—Four specimens, including one dorsal external mold (IGCAGS 20087), one dorsal internal mold (IGCAGS 20086), one ventral external mold (IGCAGS 20088), and one ventral internal mold (IGCAGS 20089).

Remarks.—The present specimens resemble *Cyrtella* in the punctate shell, strongly transverse outline, and simple lateral plicae. However, they are assigned to *Cyrtella* in doubt, due to the relatively lower ventral interarea and the presence of a groove in the dorsal fold not established.

It is worth noting that *Punctocyrtella* Plodowski, 1968 was regarded as a synonym of *Cyrtella* by Archbold (1990) and Archbold and Gaetani (1993). However, Angiolini et al. (1997) considered that *Punctocyrtella spinosa* Plodowski, 1968 from Afghanistan should not be synonymized with *Cyrtella*, because *Punctocyrtella spinosa* has a more transverse outline, lower ventral interarea, a higher number of plicae on lateral flanks, spinose micro-ornament, shorter ventral plates, and a smaller delthyrial plate. However, the above differences were more reasonably regarded as the interspecific variations in one genus due to the preservation status and ontogenic stages of specimens (Chen, 2004). The present specimens are similar to *Punctocyrtella spinosa* from the lower Permian of Afghanistan, in having a similar width/length ratio, lower ventral interarea, and deep ventral sulcus, but they differ from the latter by the micro-ornament and fewer plicae on the lateral flanks.

Cyrtella australis Thomas, 1971 from the Callytharra Formation of the Carnarvon Basin, Western Australia has more numerous plicae than our specimens. *Cyrtella noblis* Armstrong, 1970 from the Oxtrack and Flat Top formations of the southwest Bowen Basin, Australia (Waterhouse, 1987) is similar to our specimens in the transverse outline, low ventral interarea, and sharply defined ventral sulcus, but differs in having more pairs of plicae on the lateral flanks and small spines of micro-ornaments.

Family Paraspiriferinidae Cooper and Grant, 1976
Genus *Callispirina* Cooper and Muir-Wood, 1951

Type species.—*Spiriferina ornata* Waagen, 1883 from the upper *Productus* Limestone in the Salt Range, Pakistan.

Callispirina ornata (Waagen, 1883)
Figure 12.9–12.20

1883 *Spiriferina ornata* Waagen, p. 505, pl. 50, figs. 1, 2.
1944 *Spiriferina (Mansuyella) ornata*, Reed, p. 249.
1951 *Callispirina ornata*, Cooper and Muir-Wood, p. 195.
1976 *Callispirina ornata*, Grant, p. 227, pl. 63, figs. 38–46.
1994 *Spiriferina ornata*, Fang and Fan, p. 88, pl. 32, figs. 3–6.
1995 *Spiriferina ornata*, Fang, p. 140, pl. 6, figs. 3–6.

Holotype.—Several specimens listed (but no formal specimen number) from upper *Productus* Limestone in the Salt Range, Pakistan (Waagen, 1883, pl. 50, figs. 1, 2).

Occurrence.—Top of the Kongshuhe Formation; upper *Productus* Limestone, Salt Range, Pakistan; Guanyinshan Formation, Tengchong, China.

Description.—Shell small, subovate in outline, with maximum width near midshell; cardinal extremities rounded. Ventral sulcus smooth, deep, well delineated. Dorsal fold smooth, largely broadening anteriorly. Each lateral flank commonly bearing three simple, strong, angular plicae, separated by angular interspaces.

Growth lamellae imbricate, regularly and closely spaced, three or four per millimeter, almost covering whole shell surface; a single row of elongate spinules densely arranged along edge of each growth lamella (Fig. 12.16, 12.19).

Ventral interior with long median septum extending anteriorly to near midvalve floor. Dorsal interior with cardinal process composed of parallel platelets; sockets widely divergent; inner socket ridges strong; outer hinge plates short and broad; median ridge thin, anteriorly reaching two-thirds of dorsal floor (Fig. 12.9, 12.10).

Materials.—Eight specimens, including two ventral external molds (IGCAGS 20094, 20096), two ventral internal molds (IGCAGS 20095, 20097), two dorsal external molds (IGCAGS 20092, 20093), and two dorsal internal molds (IGCAGS 20090, 20091).

Remarks.—The micro-ornaments of *Callispirina* have been inconsistently observed. Waagen (1883, p. 505) described that *Spiriferina ornata*, as the type species of *Callispirina*, develops closely arranged lamellae. Later, Cooper and Grant (1976b) showed the micro-ornaments of *Callispirina*, including: punctae in concentric rows along growth lines; fine, numerous, regularly or irregularly spaced growth lines; and occasional short, thin, hair-like spinosities. On the other hand, Grant (1976) considered that *Callispirina* develops closely and regularly spaced growth lamellae and concentric rows of punctae but did not mention the occurrence of spines. Waterhouse (1983) re-examined the type material of *Callispirina*, and concluded that the micro-ornaments were composed of closely spaced growth lamellae, a single row of small spines near anterior edge, and two or three rows of punctae, which is followed here. The Tengchong specimens show regularly and closely spaced growth lamellae, and with a single row of small spines near anterior edge, in accord with the characteristic micro-ornament features of *Callispirina*.

The present specimens are most assignable to *Callispirina ornata* (Waagen, 1883) from the upper *Productus* Limestone, Salt Range and from the Guanyinshan Formation, Tengchong (Waagen, 1883; Fang and Fan, 1994, p. 88, pl. 32, figs. 3–6; Fang, 1995, pl. 6, figs. 3–6), based on their shell outline, angular plicae and interspaces, micro-ornament, and ventral internal structures.

Callispirina aff. *Callispirina ornata* from the Nakakubo Formation, west-central Japan, resembles the Tengchong specimens in the small shell, strong fold, and three or four subangular simple plicae on each flank, but differs in the shallow sulcus and being ornamented only by growth lines (Yanagida and Hirata, 1969). *Callispirina ornata* from the Lugu Formation, South Qiangtang Block (Shen et al., 2016) is similar to the Tengchong specimens in the deep sulcus and simple angular plicae, however, the former has five costae on each flank, which is different from that of the Tengchong specimens.

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Callispirina transversa Waterhouse, 1983 from the Ko Yao Noi Formation, southern Thailand is nearly identical to the Tengchong specimens in bearing fine, closely and regularly spaced growth lamellae, with one row of spines along edges, but the Thai species is different in its transverse outline and four pair of plicae on the lateral flanks (Waterhouse, 1981, p. 114, pl. 32, fig. 2, pl. 33, figs. 8, 9, pl. 34, fig. 1). The present specimens are very similar to *Yaonoiella mantajiti* Waterhouse, 1983 from the Ko Yao Noi Formation, southern Thailand in the rounded cardinal extremities and dense growth lamellae, but the latter has a narrower sulcus and micro-ornament composed of growth lamellae with two to four rows of spinules arranged between lamellae (Waterhouse, 1981, p.114, pl. 32, fig. 1, pl. 33, figs. 5–7). *Callispirina austrina* Grant, 1976 from Ko Muk, southern Thailand differs from the present specimens in the more transverse outline, and lower and more plicae (Grant, 1976, p. 230, pl. 63, figs. 1–37).

Family Spiriferellinidae Ivanova, 1972
Genus *Spiriferellina* Fredericks, 1924

Type species.—*Terebratulites cristatus* von Schlotheim, 1816 from the Lopingian of Thuringia, Germany.

Spiriferellina yunnanensis Fang, 1983
Figure 9.19–9.27

1983 *Spiriferellina yunnanensis* Fang, p. 102, pl. 5, figs. 8, 9, pl. 6, figs. 1–4.
1994 *Spiriferellina yunnanensis*, Fang and Fan, p. 88, pl. 24, figs. 3–7, pl. 25, fig. 1.

Occurrence.—Base of the Dadongchang Formation; Yongde Formation, Gengma, Yunnan, China.

Description.—Shell small, 8.7–10.6 mm in width, semielliptical to transverse in outline with rounded cardinal extremities. Ventral sulcus narrow, smooth; ventral interarea moderately high; delthyrium narrowly triangular. Each ventral flank with three strong rounded plicae separated by narrower interspaces. Growth lamellae imbricate, distinct mainly on middle and anterior parts of ventral valve; pustules along the anterior of each growth lamellae (Fig. 9.22). Ventral interior strongly thickened posteriorly; dental plates divergent; diductor scars reniform; ventral median ridge strong.

Materials.—Five ventral valves (IGCAGS 20098–20102).

Remarks.—The present specimens are attributable to *Spiriferellina yunnanensis* from the Yongde Formation, Gengma, based on the small shell, transverse outline with rounded cardinal extremities, few strong plicae on lateral slopes, and micro-ornament including lamellose growth lamellae and pustules (Fang, 1983; Fang and Fan, 1994).

The present specimens are also similar to *Spiriferellina cristata* (von Schlotheim, 1816) from Pössneck, Germany, in the small shell, micro-ornaments including pustules on the surface, and growth lamellae becoming numerous and imbricate toward the anterior margin; however, *Spiriferellina cristata* has five plicae on each side and a deep sulcus that appears to slightly protrude toward the front (Campbell, 1959b). *Spiriferellina yunnanensis* also resembles *Spiriferellina tricosa* Cooper and Grant, 1976b from the Cathedral Mountain Formation, western Texas in the transverse outline, but differs from the latter by more crowded growth lamellae.

Also transverse in outline are *Spiriferellina adunctata* Waterhouse and Piyasin, 1970 from Khao Phrik and *Spiriferellina yanagidai* Grant, 1976 from Ko Muk, the former was considered to be conspecific with *Spiriferellina yunnanensis* by Shen et al. (2002, p. 679). However, *Spiriferellina adunctata* has 8–12 plicae and thorn-like spinules on the shell surface, whereas *Spiriferellina yanagidai* has angular cardinal extremities, fewer growth lamellae, and tube-like spinules, both of which are different from *Spiriferellina yunnanensis* with 6–8 plicae and pustules. *Spiriferellina adunctata* from the Yongde Formation is similar to our specimens in having three coarse, simple plicae on each flank, but further comparison is hampered due to the lack of micro-ornaments in the former (Shen et al., 2002). *Spiriferellina adunctata* reported from the Baliqliq Formation in the Tarim Basin by Chen and Shi (2006) obviously differs from the type specimens from Khao Phrik, Thailand (Waterhouse and Piyasin, 1970) as well as our Tengchong specimens, in having a more rounded outline and prominent ventral umbo.

Spiriferellina? sp. indet.
Figure 13.1–13.15

Occurrence.—Top of the Kongshuhe Formation.

Description.—Shell small, 11.5–20 mm in width; shell outline transverse, with subangular to slightly mucronate cardinal extremities. Dorsal median fold originating from near beak, becoming high and wide on anterior part, with nearly flat folded crest. Each dorsal flank with three to six simple, moderately strong, subangular plicae with rounded crests, separated by wider, rounded interspaces. Growth lamellae sparsely spaced; punctae densely arranged in quincunx (Fig. 13.4, 13.5, 13.13, 13.14).

Dorsal interior with long, fine median ridge, narrow sockets, and divergent inner socket ridges (Fig. 13.11); ctenophoridium small (Fig. 13.9); dorsal adminicula short.

Materials.—Seven specimens: including four dorsal internal molds (IGCAGS 20103, 20106, 20107, 20109) and three external molds (IGCAGS 20104, 20105, 20108).

Remarks.—The present specimens are similar to *Spiriferellina* in the strongly punctate, transverse shell outline, and the lamellose, plicate shell.

Our specimens most resemble *Spiriferellina* sp. indet. from the Taungnyo Group, Myanmar in shell size and outline, a relatively wide anterior fold, six plicae separated by wider interspaces, close and numerous punctae, divergent socket ridges, and cardinal process (Xu et al., 2021). However, adequate comparison is difficult, due to the absence of a ventral valve, and, therefore, they are tentatively assigned to *Spiriferellina* in doubt.

The present specimens are different from *Spiriferellina yunnanensis*, previously reported from the Tengchong Block,

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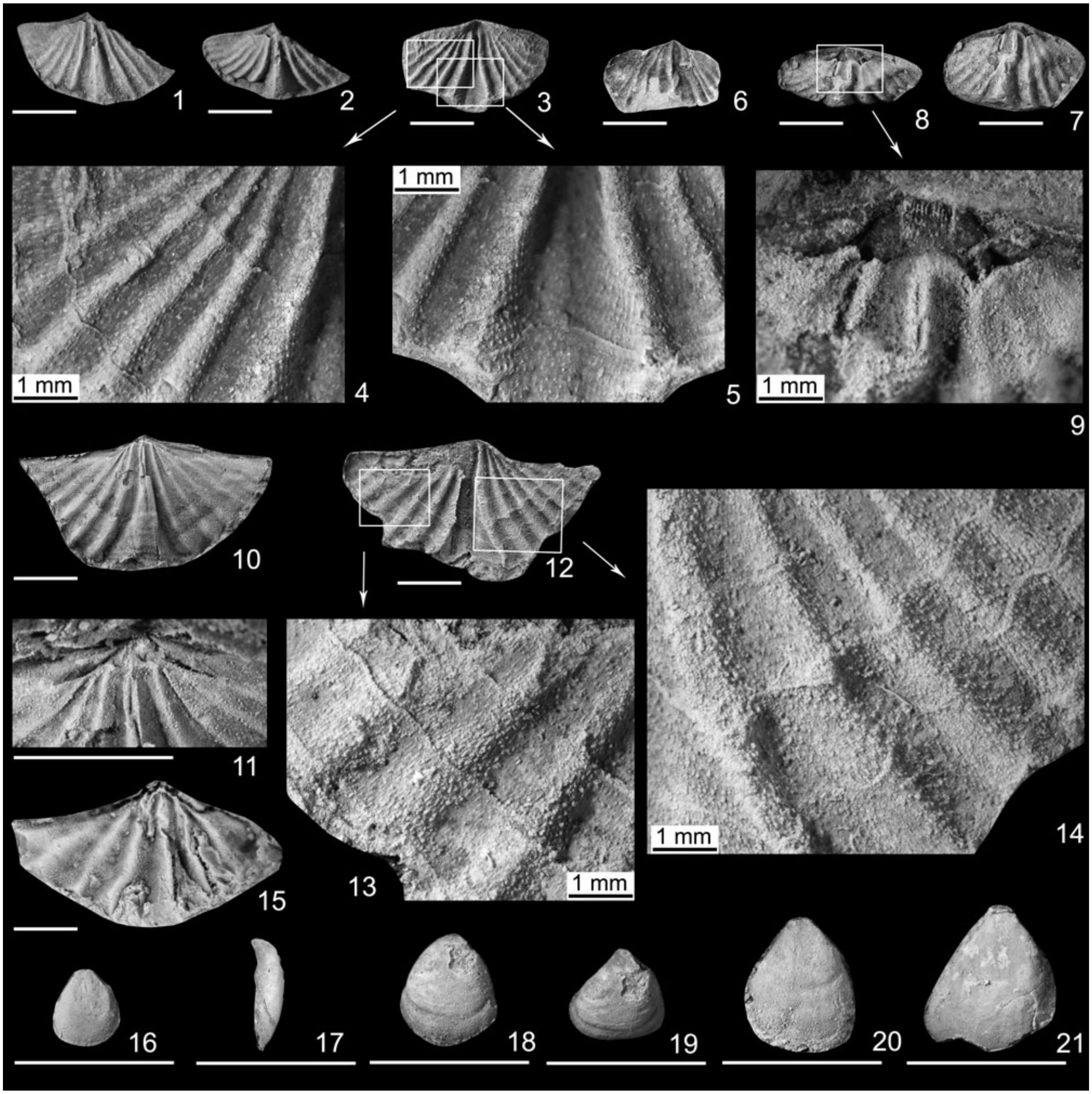

Figure 13. Brachiopods from the top of the Kongshuhe Formation in the northern Tengchong Block. (**1–15**) *Spiriferellina*? sp. indet.: (**1, 2**) 0806-2, two dorsal views of dorsal internal mold, IGCAGS 20103; (**3–5**) 0806-3, dorsal external mold with enlargement, and enlargement showing traces of punctation, IGCAGS 20104; (**6**) 0807-2, dorsal external mold, IGCAGS 20105; (**7–9**) 0806-8, dorsal and posterior views of dorsal internal mold and enlargement showing the ctenophoridium cardinal process and a fine median ridge, IGCAGS 20106; (**10, 11**) 1491, dorsal internal mold and enlargement showing cardinal process and sockets, IGCAGS 20107; (**12–14**) 1474, dorsal external mold and enlargement showing trace of punctation, and enlargement, IGCAGS 20108; (**15**) 0065, dorsal internal mold, IGCAGS 20109. (**16–21**) *Notothyris*? sp. indet.: (**16**) 0210-6b, ventral valve, IGCAGS 20110; (**17–19**) 0812-6, lateral and two ventral views of ventral valve, IGCAGS 20111; (**20**) 0811-8-a, ventral valve, IGCAGS 20112; (**21**) 0811-9-a, ventral valve, IGCAGS 20113. Scale bars = 5 mm, unless otherwise labeled.

in the relatively larger shell and more plicae. The relatively numerous plicae on the flanks of our species (three to six on each flank) allow us to distinguish it from the species *Spiriferellina* from western Texas bearing two to five plicae (Cooper and Grant, 1976b). The Tengchong species appears closer to *Spiriferellina* sp. indet. from the Dingjiazhai Formation (Fang, 1994, pl. 3, fig. 8), owing to the existence of seven to nine plicae on each flank and the development of pustules on the external surface.

Order Terebratulida Waagen, 1883
Family Notothyrididae Licharew in Licharew et al., 1960
Genus *Notothyris* Waagen, 1882

Type species.—Terebratula subvesicularis Davidson, 1862 (p. 378, 379, pl. 28, figs. 3, 4) from the middle *Productus* Limestone in the Salt Range, Pakistan.

Notothyris? sp. indet.
Figure 13.16–13.21

Occurrence.—Top of the Kongshuhe Formation.

Description.—Shell small, ∼3 mm wide and 3.6 mm long in most well-preserved specimen (Fig. 13.18); outline longitudinally elongate. Ventral valve slightly and evenly convex; umbonal region strongly swollen; beak incurved; sulcus absent; ventral flanks nearly smooth but with few growth lamellae on middle and anterior parts. Ventral interiors and dorsal valves unknown.

Materials.—Four ventral valves (IGCAGS 20110–20113).

Remarks.—The present specimens should be assigned to the family Notothyrididae based on the small and smooth shell (Smirnova, 2007). The present specimens are very similar to the juvenile of *Notothyris hexeris* from the Ko Yao Noi Formation, southern Thailand (Waterhouse, 1981, pl. 34, fig. 12). However, it is impossible to make further comparison between our specimens and *Notothyris hexeris*, because there are no adult specimens obtained from Tengchong. Hence, the present specimens are temporarily named *Notothyris* in doubt.

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Declaration of competing interests

The authors declare none.

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