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Lower Permian (Late Kungurian) conodonts from the Sibumasu Terrane, Malaysia: paleoecological, paleobiogeographical and tectonic implications

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Abstract

Late Kungurian (Lower Permian) conodonts are described from the Kanthan Limestone, Perak, Peninsular Malaysia and for the first time from the Sibumasu Terrane of the Malay Peninsula. The co-occurrence of *Gullodus duani*, *Gullodus hemicircularis, Gullodus sicilianus, Mesogondolella lamberti* and *Mesogondolella siciliensis* represent the *Mesogondolella lamberti* International Conodont Zone and the broadly equivalent *Mesogondolella siciliensis* Regional Conodont Zone. A small fault-bounded basal Pennsylvanian (basal Bashkirian) conodont fauna including *Gnathodus girtyi simplex* and *Declinognathodus inaequalis* is also reported. The late Kungurian conodonts from the Kanthan Limestone were deposited in a relatively deep-water environment on the northern passive margin of the Sibumasu Terrane of the eastern Cimmerian Continent located at c. 35ºS latitude. Biogeographically, the fauna represents the southern peri-Gondwana Cool Water Province which is consistent with its palaeogeographic location. A new scheme, utilizing characteristics of P1 elements, including position of the 1st denticle, location of 2nd and 3rd denticles, platform shape, platform cross-section, denticle shape in cross-section, and lateral denticle development is proposed for distinguishing between species of the hindeodid genera *Gullodus*, *Hindeodus* and *Isarcicella.* The late Kungurian fauna from the Kanthan Limestone represents the southern peri-Gondwana Cool Water Province supporting palaeogeographic reconstructions placing the Sibumasu Terrane in moderate southern palaeolatitudes in the Kungurian.

1. Introduction

Carbonate complexes are extensively developed on the Sibumasu Terrane (Metcalfe, 1984, 2017a) in the western part of the Malay Peninsula (west of the Palaeo-Tethyan Bentong-Raub Suture Zone) ranging in age from Ordovician to Triassic. Extensive Palaeozoic limestones and dolostones in the Kinta Valley region of Perak in the Malay Peninsula form part of these carbonate complexes, and these have been subject to karstification and are now exposed in mogote limestone hills and in the valley floor beneath alluvial deposits and have been historically exposed in alluvial tin mines. These limestones have been subjected to regional tectonic metamorphism and to thermal metamorphism by Triassic granites. Limestones in the Kinta Valley, Perak, have been variably referred to in the historical literature as the 'Kinta Limestone' or the 'Chemor/Kanthan Limestone' and 'Kampar Limestone' in the Chemor and Kampar areas, respectively, and range in age from Silurian to Early Permian (Metcalfe, 2017b). Limestone, dolostones and marbles exposed in the Chemor area of the Kinta Valley were referred to as the Kanthan Limestone (after Gunong Kanthan) by Metcalfe (2002), and this term is used in this paper for the carbonate sequences in the Kanthan area. Other Kinta Valley limestones form part of the Palaeozoic sequences to the west of Kampar which were formerly exposed in open cast tin mines (Suntharalingam, 1968; Metcalfe, 2017a). Devonian, Carboniferous and Permian conodonts have been recovered from surface outcrops of the Kanthan Limestone (Alexander & Müller, 1963; Lane *et al.* 1979; Metcalfe, 1979, 1981a, 1983, 2002, 2017b) and more recently from limestones in boreholes near Sungai Siput north of Kanthan and at Malim Nawar a few kilometres north-west of Kampar (Tsegab *et al.* 2017). The first Permian conodonts in Malaysia were reported from a single sample from the Kanthan Limestone at Gunong Kanthan by Metcalfe (1981a). This poorly preserved fauna included '*Neogondolella*' *bisselli* (Clark and Behnken) and '*Anchignathodus*' (*Hindeodus) minutus* (Ellison) and was interpreted as late Wolfcampian (= Artinskian) in age. Extensive sampling of limestones and dolostones in the Palaeozoic sequence west of Kampar (Suntharalingam, 1968) did not yield any conodonts (Metcalfe, 2017b). Based on the small Permian conodont fauna recovered from Gunong Kanthan by Metcalfe (1981a), additional sampling was undertaken in 2002 at

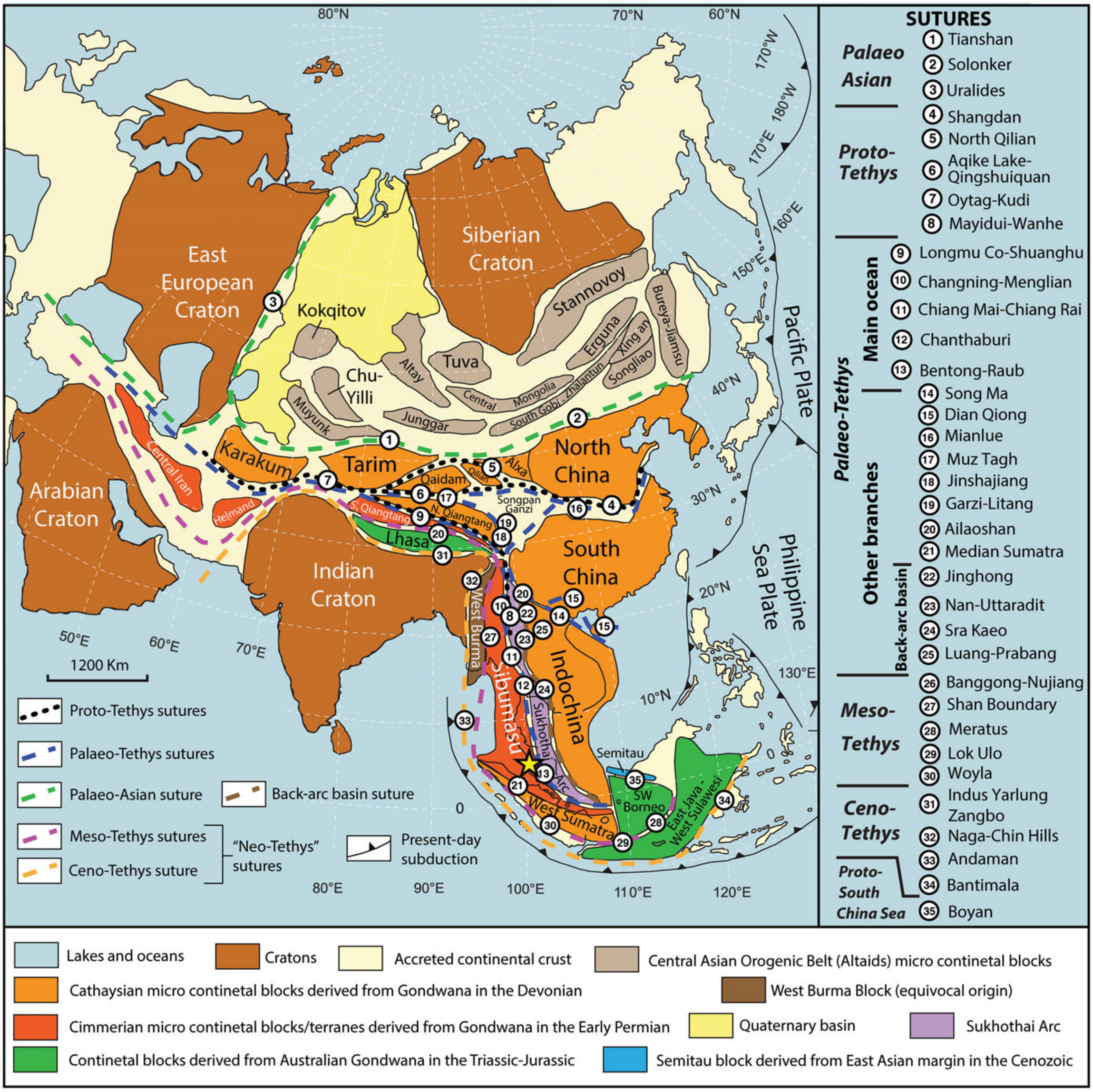

Fig. 1. (Colour online) Continental blocks and principal Tethyan suture zones of Asia. After Metcalfe (2013a, 2021) and Zhao *et al.* (2018). Gunong Kanthan locality is represented by the yellow star.

Gunong Kanthan aimed at obtaining additional Permian conodont material, and this paper reports the results of that subsequent study.

2. Geological, tectonic and stratigraphic setting

2.a. Geological, tectonic and palaeogeographical setting

East Asia comprises a huge collage of allochthonous continental blocks and volcanic arcs bounded by suture zones that represent the remnants of closed ocean basins (Metcalfe, 2021; Fig. 1). The Sibumasu Terrane (Metcalfe, 1984) forms the eastern part of the Cimmerian ribbon continental strip that separated from Australian Gondwana in the Cisuralian (Early Permian), subsequently migrated northwards and collided with proto-Asia in the Middle-Late Triassic (Sengor, 1979, 1984; Metcalfe, 1988, 2000, 2013a, 2017a, 2021; Morley, 2018). The studied Kanthan Limestone at Gunong Kanthan yielding the Late Kungurian conodonts is located on the Sibumasu Terrane in Perak State, Malay Peninsula (Fig. 2).

The Kanthan Limestone forms part of the western belt of the Malay Peninsula (Fig. 2) and was deposited in a relatively deep continental slope environment (Metcalfe, 2017b; Tsegab *et al.* 2017; Tsegab & Sum 2019) on the northern (present eastern)

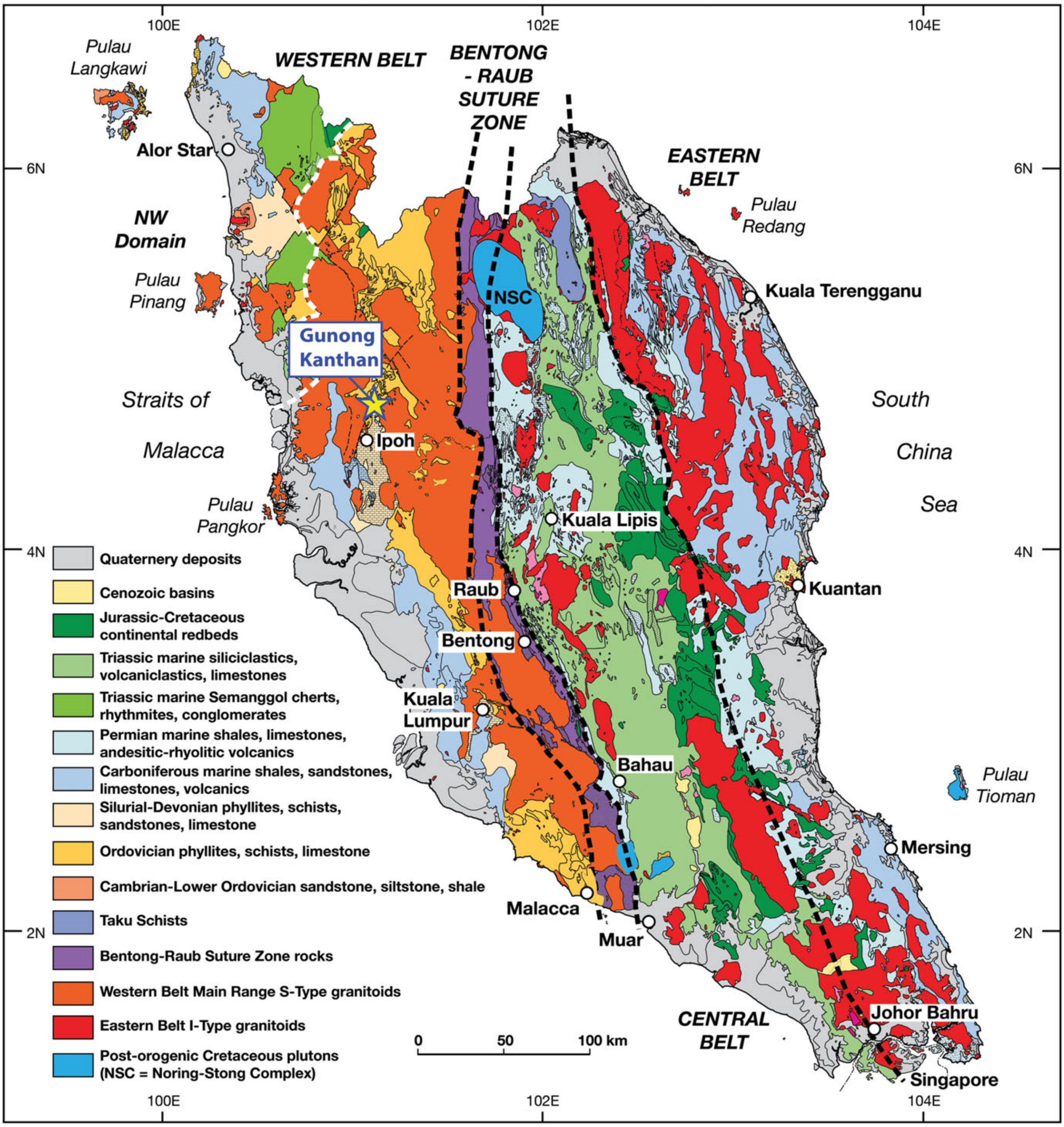

Fig. 2. (Colour online) Geological map of the Malay Peninsula showing location of Gunong Kanthan. After Tate *et al.* (2009) and Metcalfe (2013b).

margin of the Sibumasu Terrane that formed part of the Gondwana margin up to the Early Permian and separated from Gondwana in the Artinskian (Figs. 2, 3, and Supplementary Figure 1).

During the Sakmarian, the Sibumasu Terrane formed part of the western Australian Gondwana margin but by early Artinskian times the terrane had begun to separate and migrate northwards from Gondwana with the opening of the Meso-Tethys Ocean. The Malay Peninsula part of Sibumasu was located at moderately high (35–40 degrees south) palaeo-latitudes in the Sakmarian to Kungurian time interval (Supplementary Figure 1).

2.b. Geographical location, stratigraphical setting and sample locations

2.b.1. Geographical location

The Kanthan Limestone forms part of the Palaeozoic sequences of the Sibumasu Terrane in the Kinta Valley region of western Malay Peninsula (Figs. 2, 4) and has on overall age range from Silurian to Early Permian (Ingham & Bradford, 1960; Suntharalingam, 1968; Lane *et al.* 1979; Metcalfe, 1979, 1981a, 1983, 1984, 2002, 2017b; Lee *et al.* 2004; Fontaine & Ibrahim, 1994; Lee, 2009). Conodont material presented in this paper was recovered from a section

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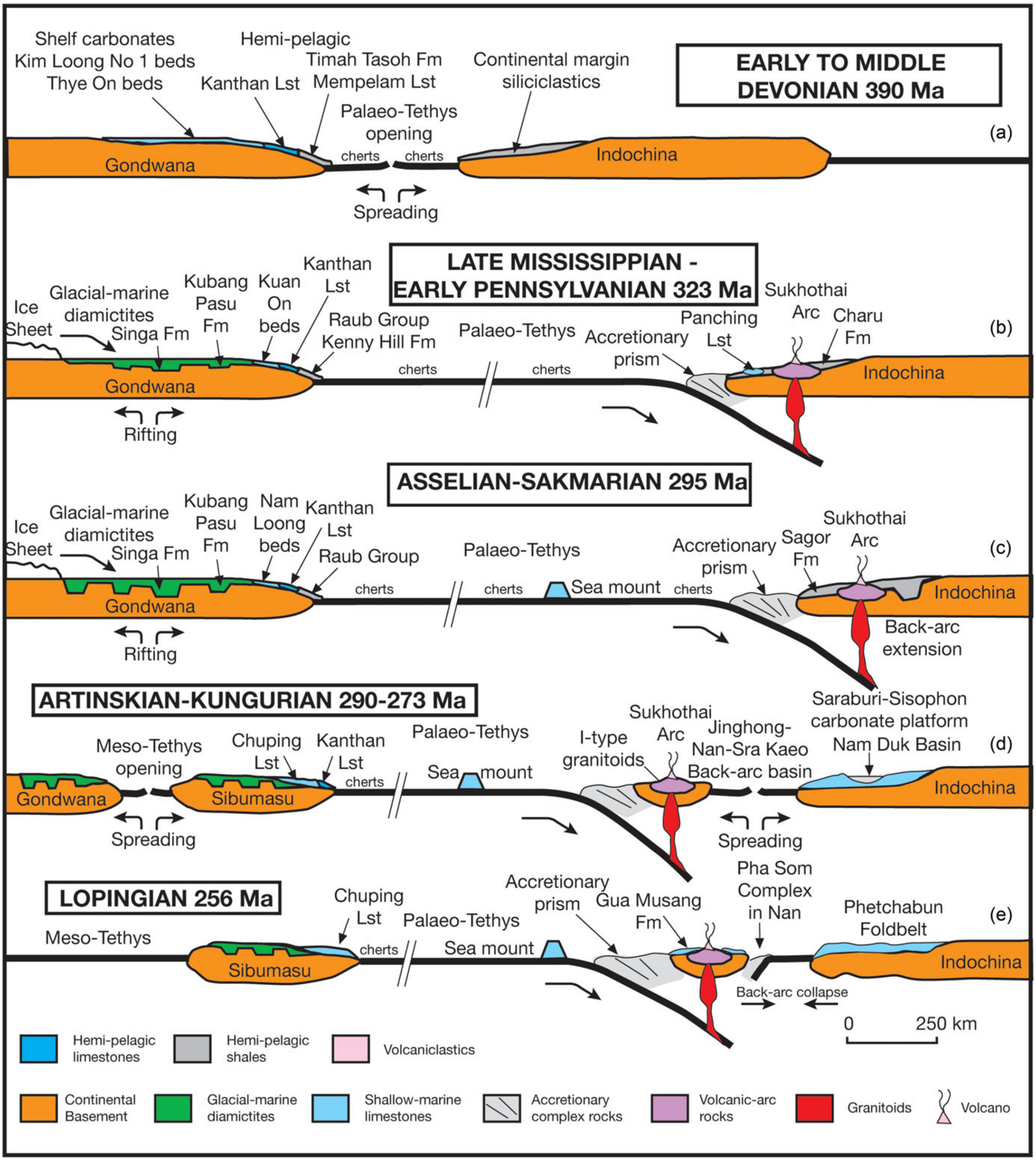

Fig. 3. (Colour online) Cartoon showing the tectonic setting of the Malay Peninsula during Early–Middle Devonian, Carboniferous and Permian times (after Ueno & Hisada 1999; Metcalfe 2000; Sone & Metcalfe 2008; Metcalfe, 2011a, 2011b; Searle *et al.* 2012; Metcalfe, 2013a; Ng *et al.* 2015a, 2015b; Metcalfe, 2017b).

measured at Gunong Kanthan in 2002 east of a section previously measured in 1978 (Fig. 4).

2.b.2. Stratigraphical setting

The studied Kanthan Limestone crops out in the Kinta Valley, Perak, Peninsular Malaysia, and was deposited on the continental margin/slope of the Gondwana-derived Sibumasu Terrane which is separated from the Sukhothai Arc (East Malaya Block) by the Palaeo-Tethys Bentong-Raub Suture Zone (Fig. 5).

The Kanthan Limestone overlies the Ordovician-Silurian siliciclastic Grik and Baling formations (which include the Lawin tuff). The presence of re-worked conodonts in the middle (Devonian-Carboniferous) part of the limestone indicates the presence of non-sequences (Metcalfe, 2002). The Kanthan Limestone is

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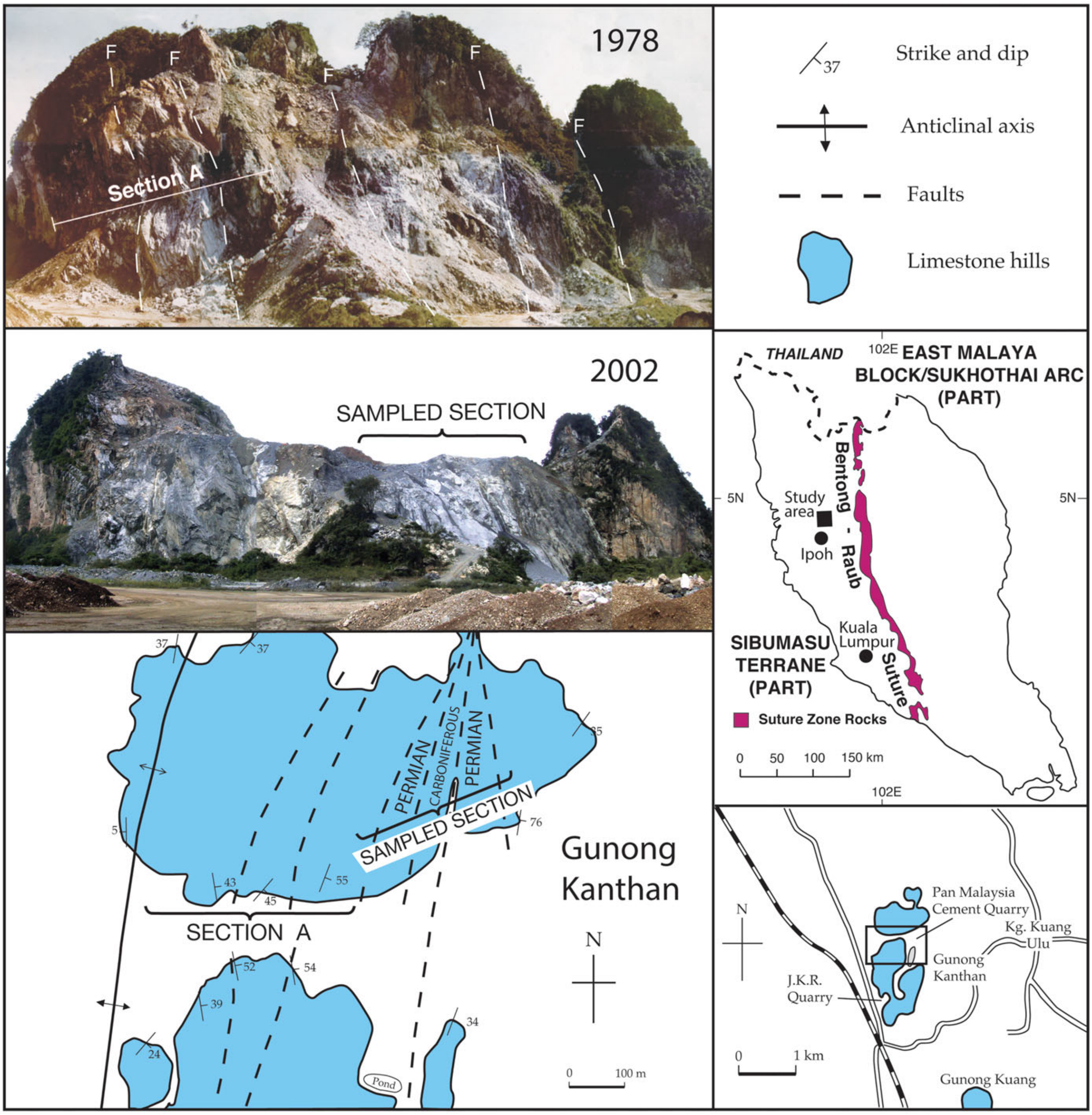

Fig. 4. (Colour online) Location of Gunong Kanthan, Perak, Peninsular Malaysia and location of sections sampled for conodonts in 1978 (see Metcalfe, 1979, 1981a, 2002, 2017b) and 2002 (results presented in this paper). After Metcalfe (2002).

unconformably overlain by continental redbeds, the Saiong Beds, of late Jurassic-Cretaceous age.

2.b.3. Structural geology

The sampled sequence forms part of the eastern limb of a large N-S trending anticline (Fig. 4). The core of the anticline is formed by Devonian limestones, and the eastern flank includes faulted packages of Carboniferous and Permian strata. Deformation includes syn-sedimentary faults and slump folds on which have been superimposed Indosinian tectonic folding and faulting and ductile high-temperature folding and shearing related to Late Triassic-Early Jurassic granite emplacement (Choong *et al.* 2016); see Fig. 6 for some examples. Major faults are represented by thick breccia zones (Fig. 6).

2.b.4. Sample locations

Twenty samples were collected from a sequence of limestones and breccias measured in 2002 located on the eastern flank of the anticline at Gunong Kanthan (Fig. 4). The sampled sequence comprises 160 m of strata which generally dips steeply (70–75 degrees east but in places vertical). There are two major fault zones represented by thick breccia horizons that separate an out of

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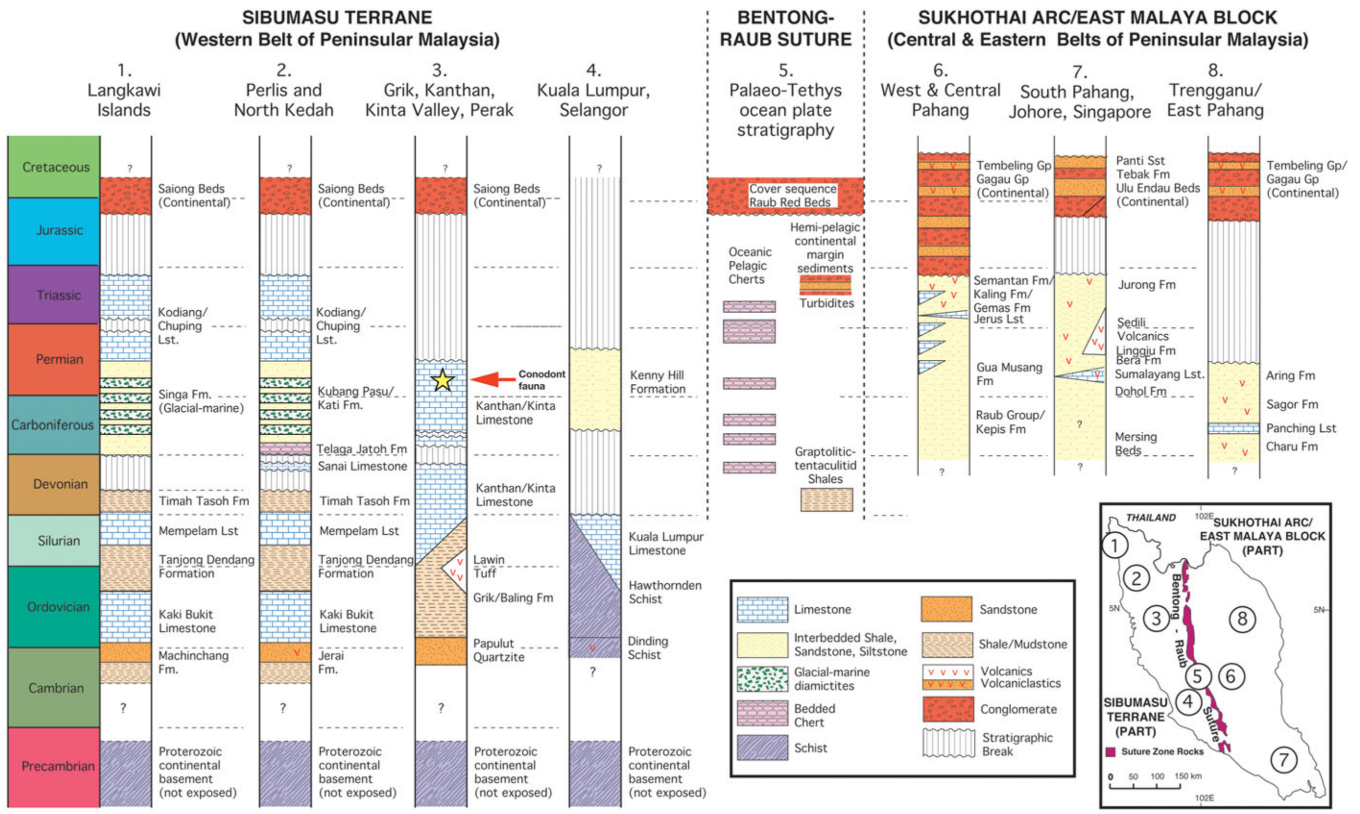

Fig. 5. (Colour online) Representative stratigraphic columns for the Sibumasu Terrane and East Malaya Block (Sukhothai Arc). Modified after Metcalfe (2000, 2013b) and Meor *et al.* (2014). Red arrow and yellow star indicate the sampled horizon.

sequence sliver of Carboniferous limestones from the otherwise Lower Permian limestones (Fig. 6). The sampled limestones also exhibit some minor folds and faults, some of which may represent slumps and soft-sediment deformation (Fig. 6).

The sampled limestones include dark-grey thin-bedded shaley limestones, dark grey to black bedded laminated limestones, paler grey bedded and more massive limestones. The limestones are dolomitized to variable degrees and exhibit multiple phases of dolomitization from early diagenetic through various stages of replacement dolostones related to fracture systems and hydrothermal fluids (Hui *et al.* 2022). Limestone breccias recorded in the sampled section are highly sheared and contain angular clasts and some discontinuous limestone beds and are interpreted here as major fault zones. The discontinuous limestone beds in the breccia zones only yielded a few fragmentary conodont elements and could not be specifically dated.

3. Conodont faunas, ages, colour, textural alteration and taxonomic notes

3.a. Faunas and ages

Fourteen of the 20 samples collected yielded conodonts. Preservation is variable with all conodonts showing both metamorphic colour and textural alteration due to both regional tectonism and thermal heating as previously reported at Gunong Kanthan by Metcalfe (2002, 2003). Recovered faunas are mainly of P1 elements and of low diversity. Conodont abundances are variable but generally low from less than 1 element per kilogram up to 26 per kilogram (Table 1).

3.a.1. Carboniferous conodonts

Samples GK11 and GK12 (Fig. 6 and Table 1) yielded just a few conodont elements, but these include *Gnathodus girtyi simplex*, *Gnathodus girtyi*? and *Declinognathodus inaequalis* (Fig. 7). The co-occurrence of these taxa indicates a basal Pennsylvanian (early Bashkirian) age (Fig. 8). Similar Carboniferous faunas with such co-occurrences were reported from Gunong Kanthan by Metcalfe (1979, 2002, 2017b).

3.a.2. Permian conodonts

Permian conodonts have been recovered from limestones to the west (0–60 m) and east (98–160 m) of the out of sequence Carboniferous block bounded by major fault breccia zones (Figs. 4, 6). Limestones within the 0–60 m limestone package yielded moderately abundant conodonts, whereas the limestones from 98 to 160 m yielded very few conodonts (Table 1).

The co-occurrence of *Gullodus duani*, *Gullodus hemicircularis, Gullodus sicilianus, Mesogondolella lamberti* and *Mesogondolella siciliensis* in samples GK01 to GK07 indicate a late Kungurian age for the package of limestones represented by these samples (Fig. 6) and represent the *Mesogondolella lamberti* International Conodont Zone and the broadly equivalent *Mesogondolella siciliensis* Regional Conodont Zone (Henderson, 2018; Lambert *et al.* 2007; Yuan *et al.* 2022); see Fig. 9. Similar Late Kungurian

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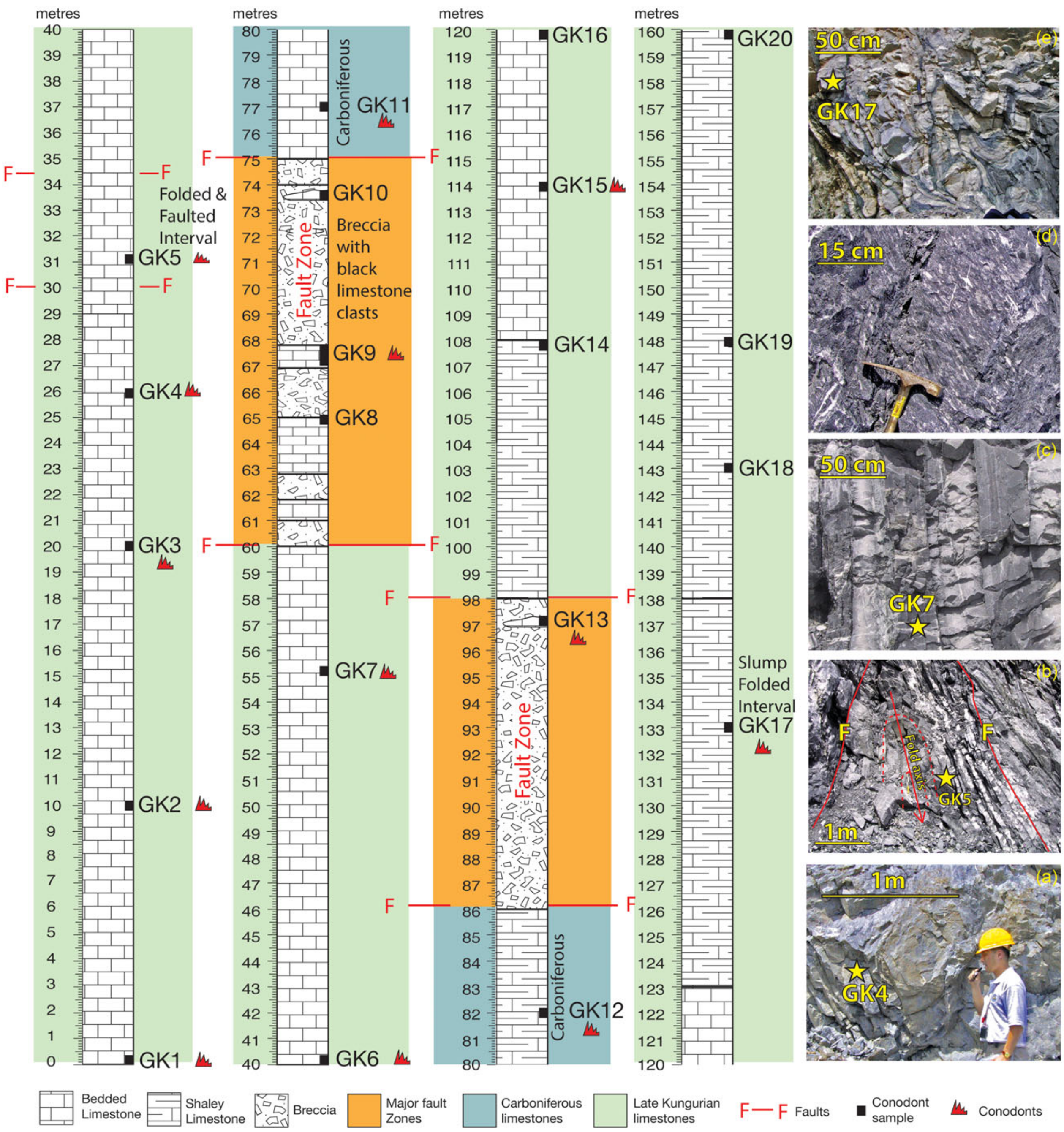

Fig. 6. (Colour online) Sequence of limestones and breccias measured at Gunong Kanthan in 2002 showing sample locations and field photos. Note that two major breccia horizons represent fault zones that separate two Lower Permian limestone sections (0–60 m and 98–160 m) from an out of sequence block of Carboniferous limestones (75–86 m) from the otherwise Lower Permian strata. (a) Thick bedded limestones and location of sample GK4; (b) faults and folds at 30–34 m and location of sample GK5; (c) bedded laminated limestones and location of sample GK7; (d) sheared fault breccia at 60–61 m; and (e) slump folded interval between 132 and 135 m and location of sample GK17.

faunas have been reported from the E-Lert Formation of Thailand (Burrett *et al.* 2015), from Laibin, South China (Sun *et al.* 2017), from the Sibumasu Terrane in eastern Myanmar (Yuan *et al.* 2020) and from the South Qiangtang Block in Tibet (Yuan *et al.* 2022).

Limestones from 98 to 160 m yielded only three conodont elements. The occurrence of *Mesogondolella siciliensis* together with *Hindeodus* sp. indicates a probable Late Kungurian age representative of the *Mesogondolella siciliensis* Regional Conodont Zone.

3.b. Conodont colour and textural alteration

Conodont elements exhibit colours ranging from dark grey to white representing Colour Alteration Indices (CAIs) from 6 to 8 (Epstein *et al.* 1977; Rejebian *et al.* 1987) consistent with those

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Table 1. Conodont elements and other microfossils recovered from the studied sequence.

Sample number	*Declinognathodus inaequalis*	*Gnathodus girtyi ?*	*Gnathodus girtyi simplex*	*Gullodus duani*	*Gullodus hemicircularis*	*Gullodus sicilianus*	*Gullodus* sp.	*Mesogondolella lamberti*	*Mesogondolella siciliensis*	*Mesogondolella* sp.	*Hindeodus* sp.	*Streptognathodus* sp.?	M Elements	S Elements	Unidentifiable element fragments	TOTAL	Sample weight (kg)	Conodont Colour Alteration Index (CAI)	Fish teeth	Shark scales
GK01								2	7	2					1	12	3	6 to 8		
GK02									6	6	1				8	21	7.5	6 to 8	2	1
GK03									2	3					8	13	4	6	2	
GK04						1	1	16	43	57				2	25	145	5.5	6 to 8	2	
GK05				5	2	6		2	15	14		1			15	60	5	6 to 8	2	
GK06				2		4		5	23	18					14	66	2	6 to 8		
GK07				1		1		31	25	14			2		6	80	1	6 to 8		
GK08																0	5			
GK09															2	2	4	6		
GK10																0	4			
GK11		1														1	5	8		
GK12	1		1												3	5	4.5	8		
GK13															1	1	5.5	6		
GK14																0	5		1	
GK15												1				1	5	6		
GK16																0	4.5			
GK17									1		1					2	5	6		
GK18																0	5			
GK19																0	6.5		1	
GK20																0	6			

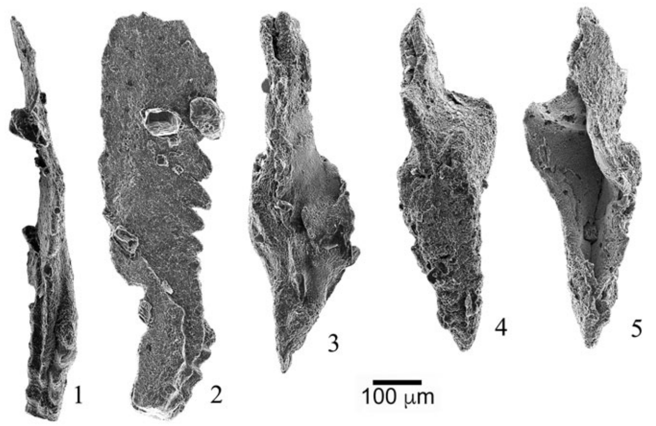

Fig. 7. Basal Pennsylvanian (basal Bashkirian) P1 element conodonts from the out of sequence Carboniferous limestones (see Fig. 6). 1, 2, *Declinognathodus inaequalis* (Higgins), oral and inner lateral views of specimen GK12/1, sample GK12. 3, *Gnathodus girtyi simplex* Dunn, oral view of specimen GK12/2, sample GK12. 4, 5, Gnathodus girtyi?, oral and basal views of specimen GK11/1, sample GK11.

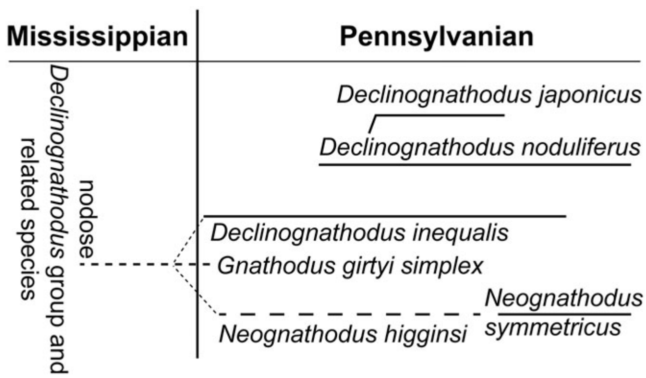

Fig. 8. Evolution of the nodose *Declinognathodus* group and related species at the Mississippian-Pennsylvanian boundary. After Hu *et al.* (2019a, 2019b).

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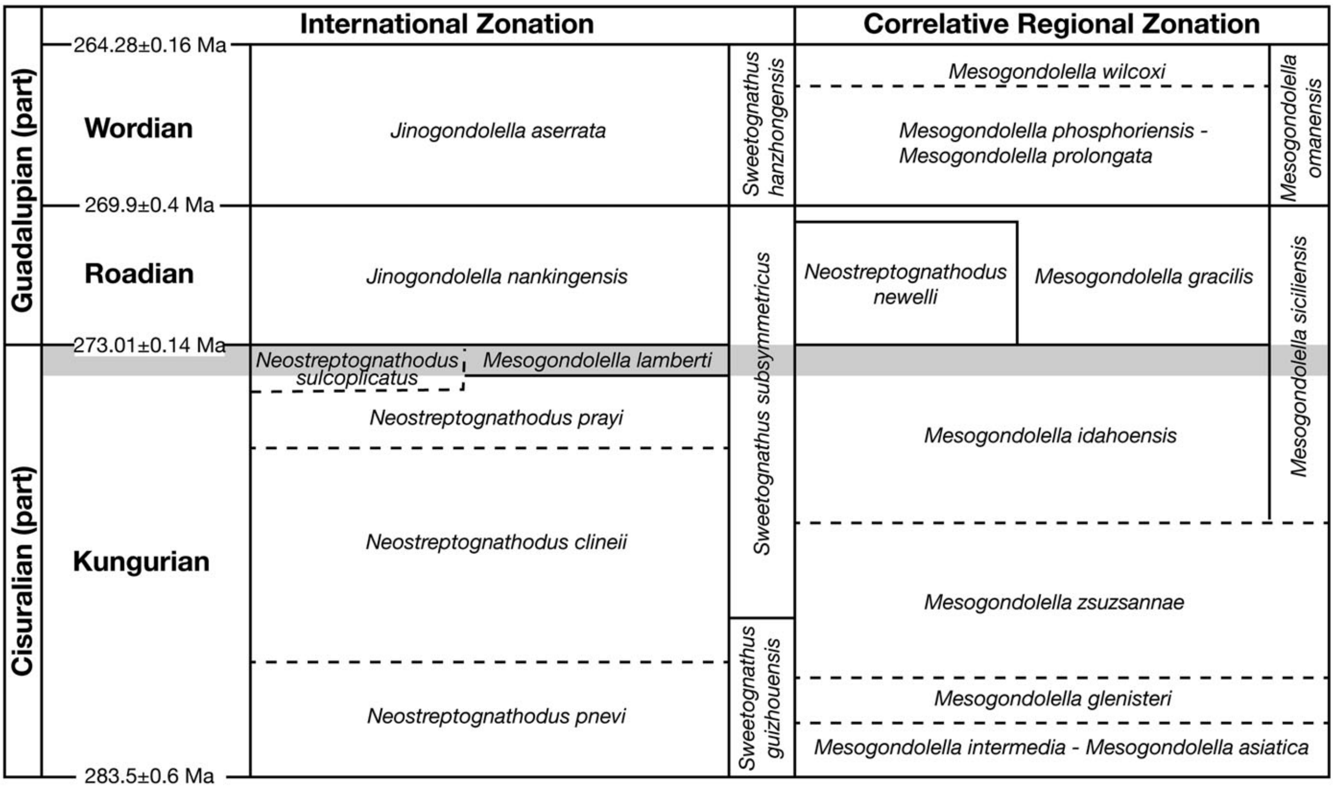

Fig. 9. Late Cisuralian and early Guadalupian international and correlative regional conodont zonations. Grey band indicates the biostratigraphic horizon of the Kanthan Limestone late Kungurian conodont fauna presented in this paper. After Henderson (2018). Stage boundary high-precision U-Pb isotopic ages are from Shen *et al.* (2022).

reported previously from the Kanthan Limestone (Metcalfe, 2002, 2003). Textural alteration of the conodonts includes cracking and pitting (e.g. Fig. 12; 1–5), partial dissolution (e.g. Fig. 12; 5), folding (e.g. Fig. 13; 12, 13, 17, 19) and boudinage (e.g. Fig. 13; 18) consistent with both thermal and regional metamorphism. See Metcalfe (2003) for further details.

3.c. Taxonomic notes

Declinognathodus inaequalis (Higgins, 1975)

Synonomy, diagnosis and description: See Higgins (1975), Nemyrovska (1999) and Hu *et al.* (2019a)

Material: 1 P1 element (GK12/1) from sample GK12.

Remarks: *Declinognathodus inaequalis* was first established as a sub-species of *Idiognathoides noduliferus* by Higgins (1975) and then subsequently re-classified as a species of *Declinognathodus* (e.g. Riley *et al.* 1987; Sanz-Lopez *et al.* 2006, 2013; Hu *et al.* 2019a, 2019b). It is the oldest nodose morphotype of the *Idiognathoides noduliferus* s.l. group, the first appearance of which is used to recognize the base of the Pennsylvanian (base Bashkirian) at the mid-Carboniferous GSSP at Arrow Canyon, Nevada, USA (Lane *et al.* 1999). Recent studies have proposed that *Declinognathodus inaequalis* should be specifically used to globally recognize and correlate the mid-Carboniferous boundary (Hu *et al.* 2019a, 2019b).

Gnathodus girtyi simplex Dunn (1965)

Synonomy, diagnosis, description and discussion: See Dunn (1965) and Higgins (1975).

Material: 1 P1 element (GK12/2) from sample GK12.

Remarks: This is a well-established sub-species that straddles the Mississippian-Pennsylvanian (mid-Carboniferous) Boundary (Higgins, 1975; Metcalfe, 1980, 1981b; Lane *et al.* 1999; Hu *et al.* 2019b).

Genus *Gullodus* Kozur (1993)

Original Diagnosis (Kozur, 1993): Spathognathodiform element with short to moderately long anterior blade that bears 3–6 broad denticles. In the anterior part of the anterior blade, one to two small denticles are present. The following two denticles are large, and the third or fourth denticle is the largest one. After the largest denticle two smaller, but also broad denticles may be present.

The posterior blade is somewhat to very much longer than the anterior one. It consists mostly of numerous (more than 10, mostly 13–15) small triangular denticles of nearly equal size. Only in the stratigraphically oldest form the posterior blade has 7, rather long subtriangular denticles. Under the entire posterior blade, a large cup is present. Basal cavity strongly expanded. Under the posterior blade, a broad basal furrow is present that becomes narrower against the anterior end of the blade.

Emended Diagnosis (Sun *et al.* 2017): Spathognathodiform elements with a medium to long anterior blade and a posteriorly positioned, strongly expanded basal cavity. Denticles occur on the blade and above the basal cavity and are in most cases without ornamentations. Denticles are generally 10–18 in number, and those above the basal cavity can be expanded and form a carina-like structure or narrow transverse ridges. Small coalesced denticles are sometimes developed on the anterior edge forming an 'anterior blade'. Length/height ratio is between 1.5 and 3. Basal

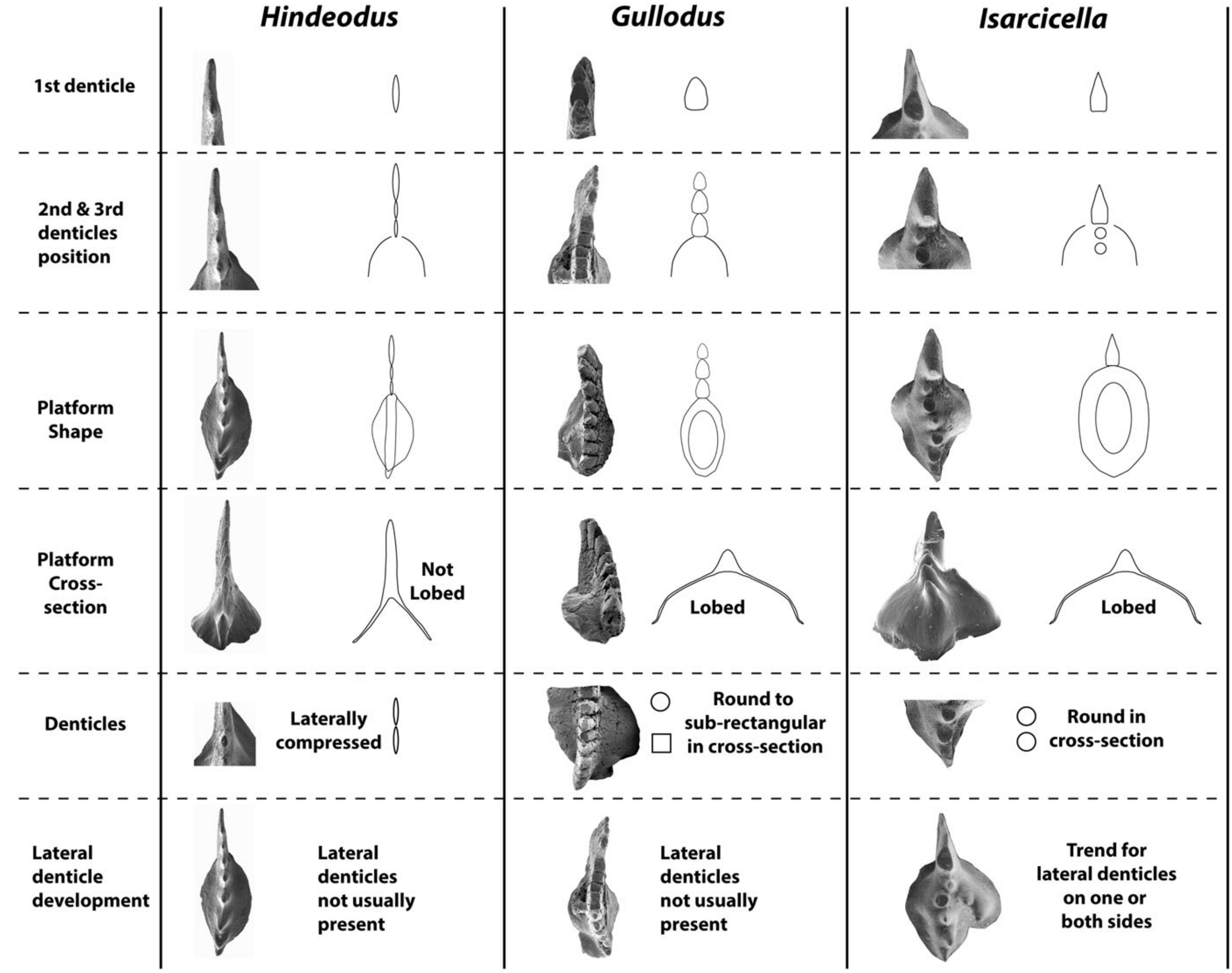

Fig. 10. Proposed criteria to distinguish between the genera *Hindeodus*, *Gullodus* and *Isarcicella* (Partly after Metcalfe & Crowley, 2020). Note: 1st denticles of some P1 elements may have one or more small anterior accessory denticles and are not necessarily the cusp of the element.

cavities are expanded and non-ornamented and occupy 1/3 to 2/3 of the full body.

Emended Diagnosis (This paper): Spathognathodiform elements with a medium to long anterior blade and a posteriorly positioned, strongly expanded basal cavity. Denticles occur on the blade and above the basal cavity and are in most cases without ornamentation. Denticles are generally 10–18 in number, and those above the basal cavity can be expanded and form a carina-like structure or narrow transverse ridges. The cusp and subsequent few denticles have a pear-shaped cross-section. Other denticles are round to sub-rectangular in cross-section and not laterally compressed. Small coalesced denticles are sometimes developed on the anterior edge forming an 'anterior blade'. Length/height ratio is between 1.5 and 3. Basal cavities are expanded and lobed, non-ornamented and occupy 1/3 to 2/3 of the full body.

Remarks: The genus *Gullodus* was first established by Kozur (1993) who designated *Gnathodus sicilianus* Bender and Stoppel (1965) as the type species. Kozur (1993) also described a new species, *Gullodus hemicircularis* and designated the specimen figured as *Hindeodus*? sp. by Van Den Boogaard (1987, p. 25, Fig. 10e) as the holotype specimen. The hindeodid genera *Gullodus, Hindeodus*, *Pseudohindeodus* and *Isarcicella* are all similar, and some species have been assigned to different hindeodid genera by different authors using different criteria. Sun *et al.* (2017) proposed a new amended diagnosis for the genus *Gullodus* as they regarded the original Kozur diagnosis as inadequate in recognizing the difference between *Hindeodus* and *Gullodus*. In the amended diagnosis, the main features considered diagnostic of *Gullodus* are a medium to long anterior blade, a posteriorly positioned, strongly expanded basal cavity, a length/height ratio of between 1.5 and 3 and expanded non-ornamented basal cavities that occupy 1/3 to 2/3 of the full P1 element. The cross-sectional shape of denticles, used by Metcalfe and Crowley (2020) to distinguish between *Hindeodus* (laterally compressed denticles) and *Isarcicella* (round peg-like denticles), was not considered as a criteria by Sun *et al.* (2017) in distinguishing hindeodid genera. The denticles of *Gullodus* are round to sub-rectangular in cross-section and not laterally compressed (Fig. 10), and this characteristic is here considered important following Metcalfe and Crowley (2020). This has been taken into account in the amended diagnosis presented in this paper to help distinguish the genus from *Hindeodus*. It is here

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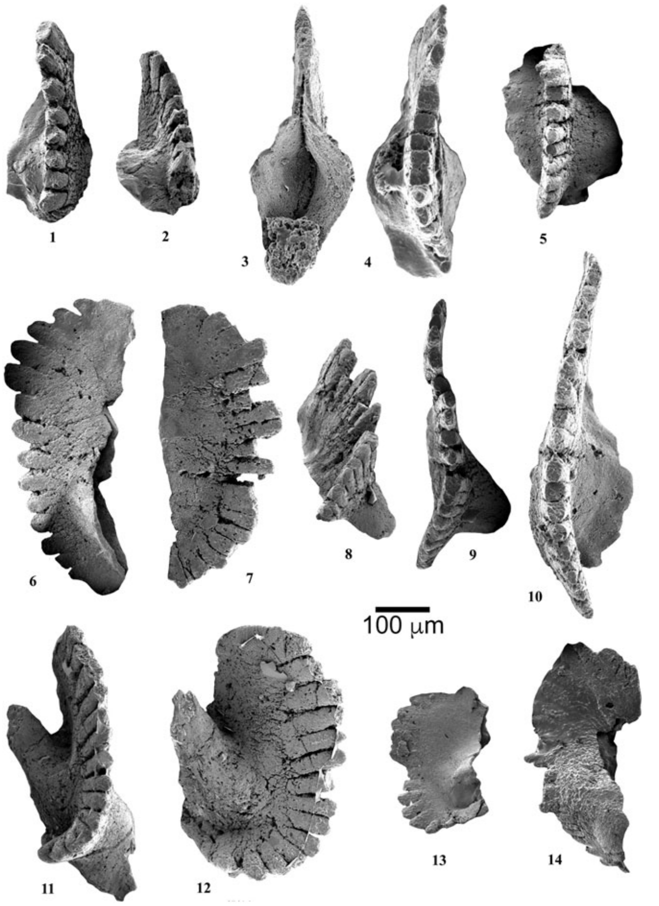

Fig. 11. Late Kungurian *Gullodus* P1 element conodonts from the western (lower 0–60 m) part of the sampled sequence (see Fig. 6). 1–5, *Gullodus duani* Mei *et al.* (2002); 1, 2, oral and posterior views of specimen GK5/1, sample GK5; 3, 4, basal and oral views of specimen GK5/2, sample GK5; 5, oral view of specimen GK5/19, sample GK5. 6–10, *Gullodus sicilianus* (Bender & Stoppel, 1965); 6, lateral view of specimen GK5/13, sample GK5; 7, 8, lateral and posterior views of specimen GK7/4, sample GK7; 9, oral view of specimen GK5/4, sample GK5; 10, oral view of specimen GK5/6, sample GK5. 11–13, *Gullodus hemicircularis* Kozur (1993); 11, 12, oral and inner lateral views of specimen GK5/14, sample GK5; 13, lateral view of specimen GK5/18, sample GK5; and 14, *Gullodus* sp., lateral view of specimen GK4/20, sample GK4.

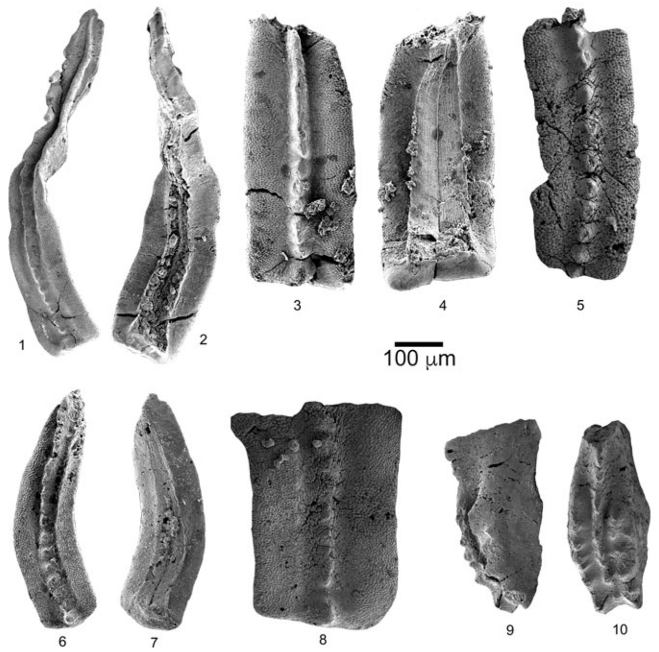

Fig. 12. Late Kungurian *Mesogondolella lamberti* and *Streptognathodus* sp.? P1 element conodonts from the western (lower 0–60 m) part of the sampled sequence (see Fig. 6). 1–8, *Mesogondolella lamberti* Mei and Henderson (2002); 1, 2, oral and basal views of specimen GK4/5, sample GK4; 3, 4, oral and basal views of specimen GK4/6, sample GK4; 5, oral view of specimen GK7/6, sample GK7; 6, 7, oral and basal views of specimen GK4/3, sample GK4; 8, oral view of specimen GK4/19, sample GK4; and 9, 10, *Streptognathodus* sp.? inner lateral and oral views of specimen GK5/2, sample GK5.

proposed that the Permian-Triassic genera *Gullodus*, *Hindeodus* and *Isarcicella* can be distinguished from each other using critical criteria and characteristics of the P1 elements, including position of the 1st denticle, location of 2nd and 3rd denticles, platform shape, platform cross-section, denticle shape in cross-section, and lateral denticle development (Fig. 10).

Occurrence: Sicily, South China, Malay Peninsula, NE Thailand, Timor,

Stratigraphic range: Kungurian to Capitanian

Gullodus duani Mei *et al.* (2002)

(Fig. 11; 1–5)

Synonomy, diagnosis and description: See Mei at al. (2002) and Sun *et al.* (2017).

Material: eight P1 elements (five from sample GK5; two from sample GK6; one from sample GK7).

Remarks: *Gullodus duani* was first established by Mei *et al.* (2002). A diagnosis was provided, but a full description of the new species was not presented. The species was recorded from the Guadalupian Maokou Formation, South China. Sun *et al.* (2017) recorded the species from the uppermost Wordian to middle Capitanian at Tieqiao, South China, and proposed a *Gullodus duani* Interval Zone of Wordian-Capitanian age. Occurrence of this species in the late Kungurian here reported from the Sibumasu Terrane of Malaysia significantly extends the age range of this species.

Occurrence: Sicily, South China, Malay Peninsula.

Stratigraphic range: Kungurian to Capitanian

Gullodus hemicircularis Kozur (1993)

(Fig. 11; 11–13)

Diagnosis: See Kozur (1993).

Material: eight P1 elements (five from sample GK5; two from sample GK6; one from sample GK7).

Occurrence: Sicily, South China, Malay Peninsula, NE Thailand, Timor.

Stratigraphic range: Kungurian to Capitanian

Remarks: This species was re-interpreted to belong to *Hindeodus* by Sun *et al.* (2017) but is here retained in the genus *Gullodus* because it does not have laterally compressed denticles on the P1 element that are diagnostic of species of *Hindeodus* (Fig. 10). Some elements identified as *Hindeodus gulloides* (Kozur & Mostler, 1995) by Burrett *et al.* (2015, Fig. 6, j–m) are here regarded as probable *Gullodus hemicircularis*, but unfortunately no oral views were provided. Burrett *et al.* (2015) commented on the transitional nature of these forms between *Gullodus* and *Hindeodus*.

Gullodus sicilianus (Bender & Stoppel, 1965)

(Fig. 11; 6–10)

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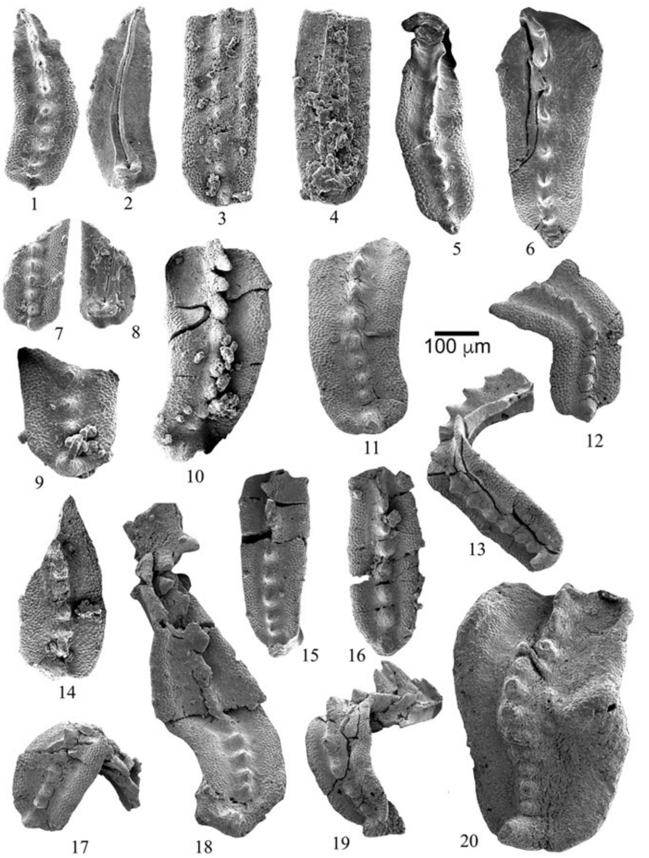

Fig. 13. Late Kungurian *Mesogondolella siciliensis* (Kozur, 1975) P1 element conodonts from the western (lower 0–60 m) part of the sampled sequence (see Fig. 6). 1, 2, oral and basal views of specimen GK2/3, sample GK2; 3, 4, oral and basal views of specimen GK3/3, sample GK3; 5, oral view of specimen GK4/1, sample GK4; 6, oral view of specimen GK4/5, sample GK4; 7, 8, oral and basal views of specimen GK3/4, sample GK4; 9, oral view of specimen GK4/3, sample GK4; 10, oral view of specimen GK4/6, sample GK4; 11, oral view of specimen GK4/18, sample GK4; 12, oral view of specimen GK4/12, sample GK4; 13, oral view of specimen GK4/11, sample GK4; 14, oral view of specimen GK4/2, sample GK4; 15, oral view of specimen GK4/23, sample GK4; 16, oral view of specimen GK4/24, sample GK4; 17, oral view of specimen GK4/22, sample GK4; 18, oral view of specimen GK4/7, sample GK4; 19, oral view of specimen GK4/14, sample GK4; and 20, oral view of specimen GK4/8, sample GK4.

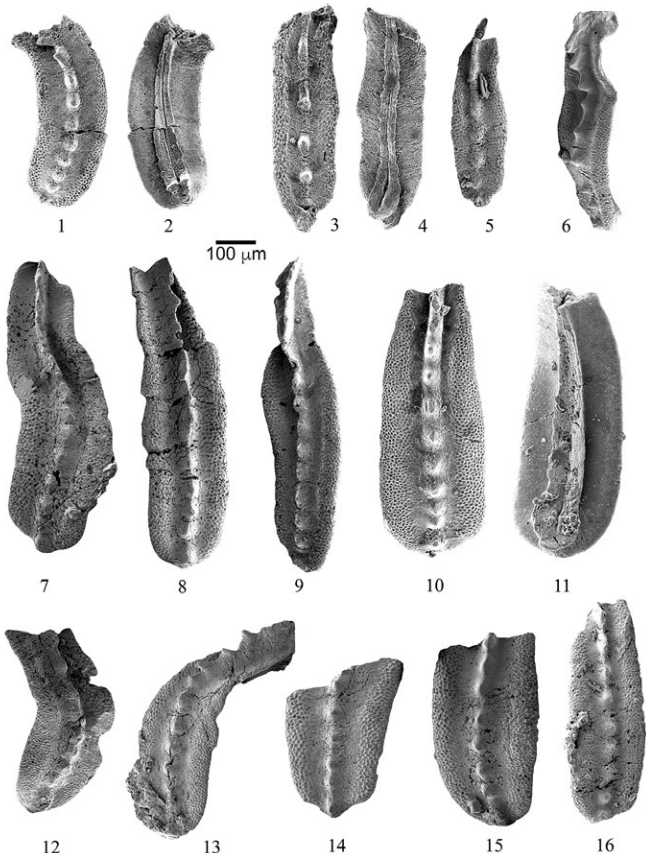

Fig. 14. Late Kungurian *Mesogondolella siciliensis* (Kozur, 1975) P1 element conodonts from the western (lower 0–60 m) part of the sampled sequence (see Fig. 6). 1, 2, oral and basal views of specimen GK4/4, sample GK4; 3, 4, oral and basal views of specimen GK4/2, sample GK4; 5, oral view of specimen GK5/3, sample GK5; 6, oral view of specimen GK5/12, sample GK5; 7, oral view of specimen GK5/22, sample GK5; 8, oral view of specimen GK5/11, sample GK5; 9, oral view of specimen GK5/5, sample GK5; 10, 11, oral and basal views of specimen GK5/3, sample GK5; 12, oral view of specimen GK5/15, sample GK5; 13, oral view of specimen GK5/16, sample GK5; 14, oral view of specimen GK5/17, sample GK5; 15, oral view of specimen GK5/7, sample GK5; and 16, oral view of specimen GK5/10, sample GK5.

Original diagnosis (in German): See Bender and Stoppel (1965).

Material: 12 P1 elements (1 from sample GK4; 6 from sample GK5; 4 from sample GK6 and 1 from sample GK7).

Occurrence: Sicily, South China, Malay Peninsula, Timor.

Stratigraphic range: Kungurian to Wordian.

Remarks: *Gullodus sicilianus* (Bender & Stoppel, 1965) is a rare taxon known mainly from the Wordian (Roadian) of the Tethys realm (Kozur, 1993, 1995). Its occurrence in the Late Kungurian of Malaysia extends the known range of this species. The species differs from *Gullodus duani* in that the carina extends to the end of the cup, and it has a higher blade and larger size (Mei *et al.* 2002)

Mesogondolella lamberti Mei and Henderson (2002)

(Fig. 12; 1–8)

Diagnosis (from Mei & Henderson 2002): Pa element of young and adult specimens has a small cusp that is only slightly bigger than the posterior denticles, an anterior blade with largely fused denticles, and a platform with the middle and posterior parts usually parallel-sided and anterior part tapering evenly towards anterior and thus straight-sided. The apparatus is as the same as that constructed by Orchard and Rieber (1999) for *Neogondolella* and has a bifurcate Sc 1 element in which one of the bifurcate processes consists of only one denticle.

Diagnosis (from Lambert *et al.* 2007): A species of *Mesogondolella* characterized by a P1 element with a moderate cusp of circular to elongate circular cross-section, a moderate-height to low blade, roughly parallel posterior lateral margins, and a thin brim on larger specimens.

Synonomy, description and discussion: See Mei and Henderson (2002) and Lambert *et al.* (2007).

Occurrence: West Texas, South China, Oman, British Columbia, Malay Peninsula.

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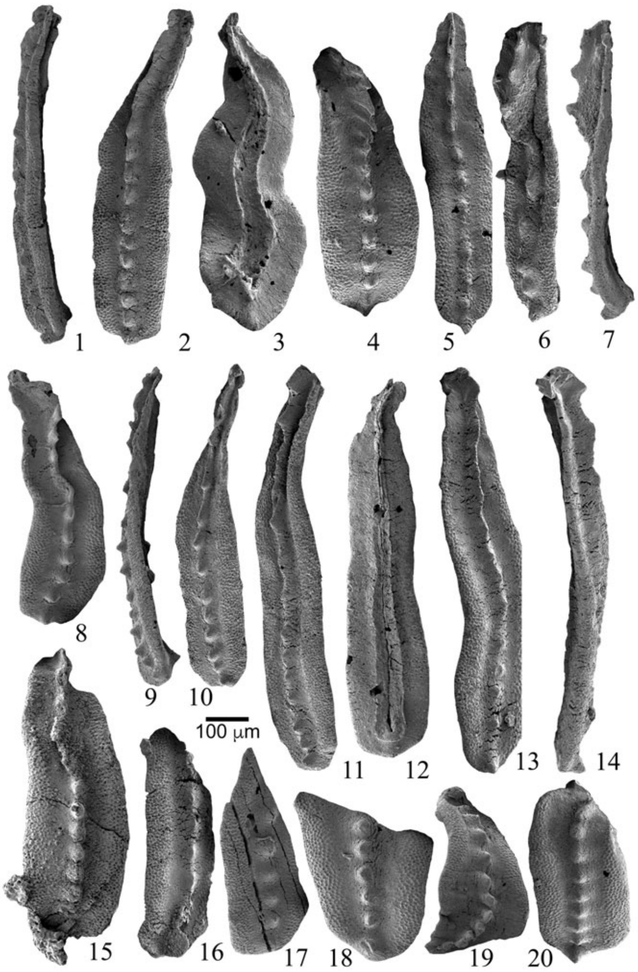

Fig. 15. Late Kungurian *Mesogondolella siciliensis* (Kozur, 1975) P1 element conodonts from the western (lower 0–60 m) part of the sampled sequence (see Fig. 6). 1, 2, oral and basal views of specimen GK7/1, sample GK7; 3, basal view of specimen GK7/3, sample GK7; 4, oral view of specimen GK7/4, sample GK7; 5, oral view of specimen GK7/14, sample GK7; 6, 7, oral and inner lateral views of specimen GK7/15, sample GK7; 8, oral view of specimen GK7/8, sample GK7; 9, 10, inner lateral and oral views of specimen GK7/10, sample GK7; 11, oral view of specimen GK7/12, sample GK7; 12, basal view of specimen GK7/13, sample GK7; 13, 14, oral and inner lateral views of specimen GK7/18, sample GK7; 15, oral view of specimen GK7/9, sample GK7; 16, oblique oral view of specimen GK7/5, sample GK7; 17, oral view of specimen GK7/7, sample GK7; 18, oral view of specimen GK5/20, sample GK5; 19, oral view of specimen GK5/9, sample GK5; and 20, oral view of specimen GK7/16, sample GK7.

Stratigraphic range: Kungurian to Wordian.

Remarks: Designation of this taxon as a species of *Mesogondolella* (Lambert *et al.* 2007) rather than a sub-species of *Mesogondolella idahoensis* (Mei & Henderson 2002) is here supported.

Mesogondolella siciliensis (Kozur, 1975)

(Fig. 13; 1–20; Fig. 14; 1–16; Fig. 15; 1–20)

Synonomy: See Kozur (1975) and Mei and Henderson (2002).

Emended Diagnosis (from Mei & Henderson 2002): A species of *Mesogondolella* in which the Pa element of young and adult specimens has a small cusp that is equal to or only slightly bigger than the posterior denticles, an anterior blade with high and largely fused denticles, and a platform that is usually widest around the middle part. The posterior denticles are more discrete than the anterior ones. The apparatus is the same as that constructed by Orchard and Rieber (1999) for *Neogondolella*, but the Sc1 element does not have a bifurcate anterior process.

Occurrence: Sicily, Oman, South China, West Texas, Baker Terrane in Oregon, USA, Malay Peninsula, NE Thailand.

Stratigraphic range: Late Kungurian.

Remarks: Carinal denticles of *M. siciliensis* are discrete unlike those in *Mesogondolella lamberti* and *M. idahoensis* which are fused at their bases.

Streptognathodus sp. ?

(Fig. 12, Figs 9, 10)

Remarks: Two poorly preserved P1 elements tentatively assignable to *Streptognathodus* were recovered, one from sample GK5 and one from sample GK15. The element from sample GK15 is too poorly preserved to warrant illustration or discussion. The specimen from sample GK5 (specimen GK5/2), is a poorly preserved, broken P1 element and poor preservation precludes unequivocal specific assignment. The presence of *Streptognathodus* in sample GK5 together with late Kungurian conodonts is anomalous. The genus *Streptognathodus* does not extend above the Sakmarian (Henderson, 2018), and this specimen must therefore be re-worked from older upper Carboniferous or Asselian/Sakmarian sediments. Re-worked conodonts are already well documented in the slope-deposited Carboniferous limestones of the Kanthan Limestone (Metcalfe, 2002, 2017b), so re-working of older conodonts in the Permian is plausible and not unexpected.

4. Conodont biofacies and biogeography

4.a. Carboniferous conodonts

The small Carboniferous fauna reported here includes *Gnathodus girtyi simplex*, *Gnathodus girtyi*? and *Declinognathodus inaequalis* which are regarded as representing a deep-water (basinal) biofacies and are cosmopolitan species (Hu *et al.* 2019a, 2019b). The occurrence of these conodonts in the Kanthan Limestone interpreted to have formed on the continental margin/slope of the Sibumasu Terrane located along the Australian Gondwana margin is consistent with the inferred depositional setting (Fig. 3).

4.b. Permian conodonts

4.b.1. Biofacies

Gullodus was interpreted as a shallow-water conodont genus and restricted to the upper part of reef slopes but absent on Permian carbonate platforms or in intraplatform shallow basins by Kozur (1993, 1995). It is interesting to note that species of *Gullodus* occur in the Kanthan Limestone with *Mesogondolella siciliensis,* regarded as a pelagic, open-sea conodont by Kozur (1993) who also noted its co-occurrence with shallow-water conodonts in the platform-slope-derived Socio Limestone blocks of Sicily (Di Stefano & Gullo, 1997). *Mesogondolella lamberti,* also common in the Kanthan Limestone fauna, is also regarded as a pelagic, open-sea conodont.

4.b.2. Palaeobiogeography

Early Permian conodonts show distinct latitudinal (largely temperature-controlled) provinciality (Fig. 16) with North Cool

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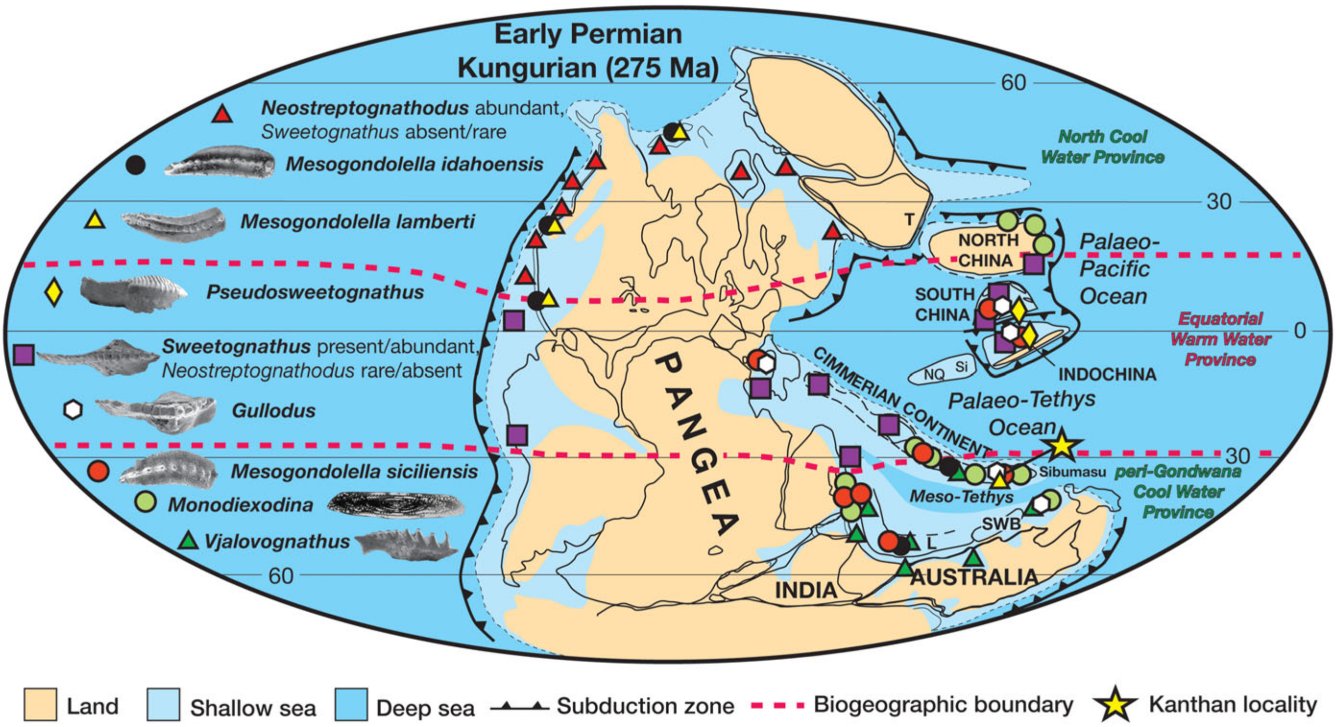

Fig. 16. (Colour online) Early Permian conodont biogeographic provinces plotted on a Kungurian palaeogeographic reconstruction showing the palaeobiogeographic distribution of key conodont genera and species. Partly after Mei and Henderson (2001, 2002), Mei *et al.* (2002), Metcalfe and Sone (2008), Metcalfe (2013a, 2021) and Yuan *et al.* (2015, 2020, 2022). SWB = South West Borneo; NQ = North Qiangtang; Si = Simao; L = Lhasa; T = Tarim.

Water, Equatorial Warm Water and southern peri-Gondwana Cool Water provinces recognized (Mei & Henderson, 2001). The North Cool Water Province is characterized by abundant *Neostreptognathodus* and a general absence or rare occurrence of *Sweetognathus*. The Equatorial Warm Water Province is characterized by abundant *Sweetognathus* and a general absence or rare occurrence of *Neostreptognathodus*. *Pseudosweetognathus* appears to be restricted to the eastern Palaeo-Tethys of this province. The southern peri-Gondwana Cool Water Province is characterized by the distinctive cold-water genus *Vjalovognathus* (Metcalfe & Nicoll, 1995; Nicoll & Metcalfe, 1998) which is restricted to this southern hemisphere province. *Mesogondolella idahoensis* exhibits an antitropical distribution, occurring in both the North Cool Water and peri-Gondwana Cool Water provinces but not in the Tethyan Equatorial Warm Water Province. Occurrences in West Texas are in a location that appears, based on palaeogeograhic reconstructions, to be in a low-latitude warm climate location which seem anomalous (Fig. 16). Further taxonomic studies on the West Texas faunas or the tectonic setting of that location might resolve this issue. The antitropical distribution of *Mesogondolella idahoensis* is mirrored by the cool-water foraminifera genus *Monodiexodina*. *Mesogondolella lamberti* also shows an antitropical distribution. *Mesogondolella siciliensis* is commonly found in the southern peri-Gondwana Cool Water Province and in the Equatorial Warm Water Province but has not been recorded in the North Cool Water Province, suggesting that other factors in addition to temperature may be controlling its distribution. The occurrence of *Mesogondolella siciliensis* cannot be used as an unequivocal indication of warm or tropical ecological conditions. The co-occurrence of 'warm-water' and 'cool-water' conodont faunas in the same samples from deep-water carbonates in Guangxi, South China (Zhang *et al.* 2010) demonstrates this. The genus *Gullodus* occurs in both the Equatorial Warm Water and southern peri-Gondwana Cool Water provinces (Fig. 16) but has so far not been reported from the North Cool Water Province. The late Kungurian conodont fauna reported here from the Kanthan Limestone of the Sibumasu Terrane does not contain any *Sweetognathus* nor any associated fusulinids and represents the southern peri-Gondwana Cool Water Province which is consistent with the palaeogeographic position of the fauna on the Sibumasu Terrane located at about 35 degrees South latitude based on multidisciplinary data. The occurrence of *Mesogondolella lamberti* in the fauna demonstrates the antitropical distribution of this biostratigraphically important species (Fig. 16). The late Kungurian fauna with *M. siciliensis* and co-occurring *Sweetognathus subsymmetricus* and *Sweetognathus guizhouensis* together with fusulinids on the South Qiangtang Block (Yuan *et al.* 2022) indicates a warmer water setting within the Equatorial Warm Water Province reflecting a lower latitudinal position for South Qiangtang. The eastern Cimmerian continental strip therefore straddles the boundary between the Equatorial Warm Water and peri-Gondwana Cool Water provinces (Fig. 16).

5. Conclusions

(1) Late Kungurian (Lower Permian) conodonts are described for the first time from the Sibumasu Terrane of Malaysia.
(2) The late Kungurian fauna includes *Gullodus duani*, *Gullodus hemicircularis*, *Gullodus sicilianus*, *Mesogondolella lamberti* and *Mesogondolella siciliensis*, and the co-occurrence of these represent the *Mesogondolella lamberti* International Conodont Zone and the broadly equivalent

middle part of the *Mesogondolella siciliensis* Regional Conodont Zone.
(3) A fault bounded package of limestones also yielded a small basal Pennsylvanian (basal Bashkirian) fauna that includes *Gnathodus girtyi* simplex, *Gnathodus girtyi*? and *Declinognathodus inaequalis*.
(4) A new proposal for distinguishing species of the hindeodid genera *Gullodus*, *Hindeodus* and *Isarcicella* utilizing characteristics of the P1 elements, including position of the 1st denticle, location of 2nd and 3rd denticles, platform shape, platform cross-section, denticle shape in cross-section, and lateral denticle development, is here presented.
(5) The Kanthan Limestone late Kungurian fauna represents the southern peri-Gondwana Cool Water Province and supports palaeogeographic reconstructions placing the Sibumasu Terrane in moderate southern palaeolatitudes in the Kungurian.

Supplementary material. To view supplementary material for this article, please visit https://doi.org/10.1017/S0016756823000328

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Conflicts of interest. The author declares none.

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