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Sun, YD, Liu, XT, Yan, JX et al. (7 more authors) (2017) Permian (Artinskian to Wuchapingian) conodont biostratigraphy in the Tieqiao section, Laibin area, South China. Palaeogeography, Palaeoclimatology, Palaeoecology, 465 (A). pp. 42-63. ISSN 0031-0182

https://doi.org/10.1016/j.palaeo.2016.10.013

Early-Middle Permian conodont biostratigraphy in the Tieqiao section, Laibin area, South China

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Abstract

Permian strata from the Tieqiao section (Jiangnan Basin, South China) contain several distinctive conodont assemblages. Early Permian (Cisuralian) assemblages are dominated by the genera *Sweetognathus, Pseudosweetognathus* and *Hindeodus* with rare *Neostreptognathodus* and *Gullodus.* Gondolellids are absent until the end of the Kungurian stage—in contrast to many parts of the world where gondolellids and *Neostreptognathodus* are the dominant Kungurian conodonts. A conodont changeover is seen at Tieqiao and coincided with a rise of sea level in the latest Kungurian: the previously dominant sweetognathids were replaced by mesogondolellids. The Middle and Late Permian (Guadalupian and Lopingian Series) witnessed a dominance of gondolellids (*Jinogondolella* and *Clarkina*), the common presence of *Hindeodus* and decimation of *Sweetognathus*.

Twenty one main and six subordinate conodont zones are recognized at Tieqiao, spanning the lower Artinskian to lowermost Wuchiapingian Stage. The main (first occurrence) zones are, in ascending order by stage: the *Sweetognathus (Sw.) whitei*, *Neostreptognathodus (N.) pequopensis-Sw. toriyamai*, and *Sw. asymmetrica* n. sp. Zones for the Artinskian; the *N. prayi*, *Sw. guizhouensis*, *Sw. iranicus*, *Sw. adjunctus*, *Sw. subsymmeticus*, *Sw. hanzhongensis*, *Mesogondolella (M.) idahoensis* and *M. lamberti* Zones for the Kungurian; the *Jinogondolella (J.) nankingensis* Zone for the Roadian; the *J. aserrata* Zone for the Wordian; the *J. postserrata*, *J. shannoni*, *J. altudaensis*, *J. prexuanhanensis*, *J. xuanhanensis*, *J. granti* and *Clarkina (C.) hongshuiensis* Zones for the Capitanian and the *C. postbitteri*

Zone for the base of the Wuchiapingian. The subordinate (interval) zones are the *Pseudosweetognathus costatus*, *Pseduosweetognathus monocornus*, *Hindeodus (H.) gulloides*, *Pseudohindeodus ramovsi*, *Gullodus sicilianus*, *Gullodus duani* and *H. excavates* Zones.

In addition, three new species, *Gullodus tieqiaoensis* n. sp., *Pseudohindeodus ellipticae* n. sp. and *Sweetognathus asymmetrica* n. sp. are described. Age assignments for less common species e.g., *Pseudosweetognathus monocornus* are reassessed based on a rich conodont collection.

Key words: conodont, Permian, biostratigraphy, Cisuralian, Guadalupian, Kungurian, South China

1. Introduction

Conodonts are important index fossils in the Palaeozoic and Triassic, due to their high speciation rates, geographically widespread distribution and in part high abundance in marine sediments. Conodont biostratigraphy provides the best method for high-resolution, supra-regional correlations of Permian strata, because other key taxa such as ammonoids are often scarce in many locations, whilst foraminifers and brachiopods are generally long ranging and facies controlled and thus less useful for age diagnosis. As a consequence, Permian conodont taxonomy and biostratigraphy have been the topics of extensive study since the 1950s (e.g., Youngquist et al., 1951; Clark and Behnken, 1971; Ritter, 1986; Wardlaw and Grant, 1990; Mei et al., 1994a; Wardlaw, 2000; Nestell et al., 2006; Lambert et al., 2010; Shen et al., 2012). The importance of conodonts in stratigraphy is exemplified by their use at Global Boundary Stratotype Section and Points: as of 2016, conodonts define of the bases of all but one of the 29 stages between the Pragian (Lower Devonian) and Rhaetian (Upper Triassic), 17 of which have been ratified by the International Commission on Stratigraphy.

The diversity of Permian conodonts is generally low in comparison to that observed for other time periods, with typically less than five genera and two dozens of species occurring in any given Permian stage. Conodont zones are also relatively long for some intervals. For instance, though substantial investigations have been carried out in West Texas (e.g., Wardlaw, 2000; Nestell et al., 2006; Nestell and Wardlaw, 2010a; Wardlaw and Nestell, 2010), only one standard conodont zone has been established for the Roadian and Wordian stages (Henderson et al., 2012). This reflects a true low point in the diversity of conodonts during their long evolutionary history. A further complication is that minor changes in Permian conodont morphology require a careful taxonomic examination of different species. New species are rarely reported from regions other than West Texas and South China, perhaps owing to a decrease in research effort and a substantial loss of expertise in recent years.

Establishing a robust biostratigraphic scheme in different areas is essential for supra-regional correlation. Permian conodonts have been best studied in the Urals of Russia (Early Permian), West Texas (Middle Permian) and South China (Late Permian and the Permo-Triassic boundary) (e.g., Chuvashov et al., 1990; Mei et al., 1994b; Zhang et al., 1995; Wardlaw, 2000; Lambert et al., 2002; Jiang et al., 2007; Nestell and Wardlaw, 2010b). The Early to Middle Permian of South China has attracted comparatively little research attention and is less systematically studied.

This study presents a high-resolution conodont record for the Tieqiao section, Guangxi, South China. New data, spanning the Artinskian (Early Permian) to the early Wuchiapingian (Late Permian), substantially improve existing records of the section, first described two decades age in the context of the Capitanian-Wuchiapingian (Guadalupian-Lopingian) transition (Mei et al., 1994c; Wang, 2002).

2. Geological Setting

The Yangtze region was a large isolated platform situated within the Permian equatorial Tethys (Fig. 1) with extensive carbonate deposition and diverse sedimentary facies. It is an ideal location for conodont studies. The Laibin area is located in the Jiangnan Basin towards the southwestern margin of the Yangtze Platform (Wang and Jin, 2000). A series of superb sections are exposed along the banks of Hongshui River (Shen et al., 2007) and these have been comprehensively studied for the Capitanian-Wuchiapingian transition (e.g., Mei et al., 1994c; Wang et al., 2004; Jin et al., 2006; Wignall et al., 2009b; Chen et al., 2011).

The Permian strata of the region consist of thick Early Permian platform carbonates, subordinate Middle Permian slope as well as basinal carbonates and cherts. Late Permian rocks are geographically more variable, including coal seams, reef build-ups and radiolarian cherts (Sha et al., 1990; Shen et al., 2007; Qiu et al., 2013).

The studied section at Tieqiao (23° 42.733' N, 109° 13.533' E) is exposed on the northern bank of the Hongshui River, southeast of the town of Laibin (Figs. 1, 2). The Permian strata measure 1307 m thick and comprise the Maping, Chihsia, Maokou, Heshan, Wuchiaping and Talung Formations, spanning the earliest Permian (Asselian) to the Permian-Triassic boundary (Sha et al., 1990). The section is very fossiliferous with foraminifers, calcareous algae, crinoids, sponges and corals being prolifically abundant (e.g., Wang and Sugiyama, 2000; Bucur et al., 2009; Zhang et al., 2015), whilst bivalves and ammoinods occur less frequently. Well-preserved *Zoophycos* trace fossils are also abundant (Gong et al., 2010).

Sha and colleagues (1990) pioneered the study of the Tieqiao section and subdivided the section into 15 Members and 139 Beds. Our study follows these subdivisions (Figs. 3-5) for consistency and focuses on the stratigraphy and conodont zonation of the Chihsia and Maokou formations (Bed 1 to Bed 109). The Chihsa Fm. generally records deposition in a carbonate ramp setting, whilst the Maokou Fm. comprises slope to basin transition facies. The two formations are overall 710 m thick and range from the Sakmarian (?) to the Capitanian-Wuchiapingian boundary (Figs. 3-5).

3. Materials and Methods

The section was sampled over four field campaigns between 2005-2010. During the spring of 2010, the water of the Hongshuihe River fell to its lowest level of the past ten years due to a severe drought, which allowed us to describe and sample several normally submerged parts of the section (e.g., Bed 17 and Bed 112). A total of 374 rock samples were collected with a sampling resolution of ~1-2 m for most parts of the section. Cherts and grainstones bearing abundant corals and fusulinid foraminifers were avoided during sampling due to complications in conodont extraction and low conodont yields. Each sample weighed between 2.5 and 8 kg.

Three hundred and eleven samples were processed in the micropaleontology laboratory at China University of Geosciences (Wuhan) and 63 samples were processed at the GeoZentrum Nordbayern, Universität Erlangen-Nürnberg. All samples were dissolved using 7-10% diluted acetic acid, wet sieved and air-dried. The insoluble residues were separated by using heavy liquid fractionation (Jiang et al., 2007). Conodont specimens were hand picked using a binocular. Conodonts from Tieqiao are generally well preserved with colour alternation index ranging from 1.5 to 2.5. A total of 8 733 specimens were obtained from sample process at Wuhan lab and about ~3 000 specimens was recovered at Erlangen. Results from both laboratories were cross checked.

4. Stratigraphy and Conodont Zonation

4.1 Sakmarian (?)

The lowermost part of the studied section (Beds 1 to 16, Chihsia Fm.) consists mainly of thin-to-medium bedded dark-grey bioclastic micrites, marls and black shales (Fig. 2). Brachiopods, gastropods, crinoids, bryozoans and sponges are the most abundant fossils. Age assignment for this part of the section is controversial. Sha et al. (1990) suggested an Asselian age for the underlying Maping Fm. and reported the occurrence of the fusulinacean *Eoparafusulina* sp., *Nankinella* sp., *Pamirina* sp., *Staffella* sp. and *Pseudofusulina* sp. from Bed 1 to Bed 16, implying a possible Sakmarian age for the unit. Mei et al. (1998) inferred this unit to be of “Longlinian” age—a Chinese equivalent of the Artinskian by original definition (Sheng and Jin, 1994; Jin et al., 1997), now re-defined as Sakmarian (Fig. 24.1 in Henderson et al., 2012). Based on consideration of all published fossil materials, Shen et al. (2007) tentatively assign this part of the section to the Artinskian.

Few conodonts were recovered from this part of the section, despite great efforts. Many ramiform elements were recovered from Bed 8, but none is age-diagnostic. The precise age of this unit therefore remains unresolved.

4.2 Artinskian

Beds 17 to 26 consist mainly of dark-grey to grey bioclastic pack- and grainstones. The conodont assemblage is dominated by *Sweetognathus whitei* and affinitive species and thus indicates an Artinskian age. *Neostreptognathodus* and *Hindeodus* are rare whilst gondolellids are absent. The base of the Artinskian stage cannot be precisely defined because the first appearance datum (FAD) of *Sweetognathus whitei* cannot be ascertained due to the inaccessibility of the submerged lower part of Bed 17 and the absence of diagnostic conodonts from beds below this level. In ascending order, three conodont zones were established for the Artinskian.

1). *Sweetognathus whitei* Zone

The lower limit of this zone is not defined. The upper limit is defined by the FAD of *Sweetognathus* (*Sw.*) *toriyamai* and *Neostreptognathodus ex gr.*

pequopensis.

Sw. whitei was one of the most cosmopolitan conodonts during the Early Permian (Mei et al., 2002). It is known e.g. from North and South China, Japan, U.S.A., Canada and Colombia. (Rhodes, 1963; Igo, 1981; Orchard, 1984; Ritter, 1986; Ding and Wan, 1990; Ji et al., 2004) and is considered a good marker for the base of Artinskian.

2). *Neostreptognathodus ex gr. pequopensis* - *Sweetognathus toriyamai* Zone

Lower limit: FAD of *Sw. toriyamai* and *Neostreptognathodus (N.) ex gr. pequopensis* with both taxa first occurring at the same level. Upper limit: FAD of *Sw. asymmetrica* n. sp. The FAD of *Sw. bogoslovskajae* occurs in this zone. *Sw. bogoslovskajae* is known to co-exist with *N. pequopensis* in Nevada and has a range restricted to the upper "Baigendzhinian" (equivalent to uppermost Artinskian to lower Kungurian) (Ritter, 1986). Wang (2002) reported the occurrence of *Sw. variabilis* in this zone (in Bed 18 of Tieqiao). We have found morphotypes which are similar to *Sw. variabilis* but the specimens are not sufficiently well-preserved to make an identification.

3). *Sw. asymmetrica* n. sp. Zone

Lower limit: FAD of *Sw. asymmetrica* n. sp. Upper limit: FAD of *Neostreptognathodus prayi*. *Hindeodus catalanoi* and *Sw.*cf. *windi* co-occur in this zone. This zone probably straddles the Artinskian-Kungurian boundary due to the absence of the *N. pnevi* zone at Tieqiao.

4.3 Kungurian

Kungurian rocks, spanning from Bed 27 to the lower part of Bed 109, consist mainly of medium-to-thick bedded fossiliferous pack- and grainstones with common chert nodules in the lower part. Medium to thin bedded lime mudstones and wackestones were gradually developed higher in the Kungurian strata, with a notable shift in fossil assemblages from a bryozoan- and calcareous algae-dominated shallow water facies (Beds 89-99) to a sponge spicule and radiolarian rich deeper water facies (Beds 100-111).

The conodont biostratigraphy of the basal Kungurian stage has been a matter of debate (Wang et al., 2011). Kozur et al. (1995) suggested the cline *Neostreptognathodus pequopensis*-*N. pnevi* to be suitable for a definition for the Artinskian-Kungurian boundary. Mei et al. (2002) proposed the FAD of *N. pequopensis* or *Sw. guizhouensis* to define the base of the Kungurian whereas Chuvashov et al. (2002) formally proposed the FAD of *N. pnevi* as diagnostic of the base of the Kungurian, a definition that has been generally accepted (Henderson et al., 2012). However, due to the absence of *N. pnevi* at Tieqiao, we alternatively suggest the base of the Kungurian be defined by the FAD of *N. prayi*. Eight conodont zones were established for the Kungurian, described in ascending order below:

4). *Neostreptognathodus prayi* Zone

Lower limit: FAD of *Neostreptognathodus prayi*. Upper limit: FAD of *Sw.*

guizhouensis. The *N. prayi* Zone is the second oldest zone of the Kungurian in the standard Permian conodont zonation (Henderson et al., 2012) and so the *N. prayi* zone at Tieqiao does not indicate the "true" earliest Kungurian (Fig. 6). *Sw. clarki,* a species most commonly seen in the late Artinskian (Beauchamp and Henderson, 1994), also occurs in this zone. The first occurrence (FO) of *Sw. clarki* at Tieqiao is only slightly lower than that of *Sw. guizhouensis*.

5) *Sw. guizhouensis* Zone

Lower limit: FAD of *Sw. guizhouensis.* Upper limit: FAD of *Sw. iranicus*. Except for in the lower part of this ~180 m thick conodont zone, conodonts are relatively rare. The long-ranging species *Pseduosw. costatus* is the only species that was sparsely recovered in the upper part of this zone.

6) *Sw. iranicus* Zone

Lower limit: FAD of *Sw. iranicus.* Upper limit: FAD of *Sw. subsymmetricus*. As with the *Sw. guizhouensis* Zone, both conodont diversity and abundance are very low. A major stratigraphic complication at this level of the section is that Beds 76-88 are a tectonic repetition of older beds (also see Sha et al., 1990).

7) *Sw. adjunctus* Zone

Lower limit: FAD of *Sw. adjunctus*. Upper limit: FAD of *Sw. subsymmetrics*. *Sw.* cf. *paraguizhouensis* appears in this zone. Sha et al. (1990) reported the occurrence of *"Neogondolella" bisselli* in this zone (Bed 91). However, "*N*". *bisselli* is an older species which often co-occurred with the Artinskian *Sw. whitei* group (e.g., Behnken, 1975; Clark et al., 1979; Orchard, 1984; Wang, 1994; Mei et al., 2002). The occurrence of *bisselli* obviously contradicts a Kungurian age of the host strata and also is not confirmed by our dataset.

Sw. adjunctus is also known from the uppermost Victorio Peak Formation from Texas and the upper Pequop Formation from Nevada, USA (Behnken, 1975) as well as from south-central British Columbia, Canada (Orchard and Forster, 1988): All of these occurrences are dated to be of late Leonardian age in the Permian regional stratigraphy (=middle to late Kungurian). Because of the wide distribution of *Sw. adjunctus*, this zone therefore has high potential for super-regional correlation.

8) *Sw. subsymmetricus* Zone

Lower limit: FAD of *Sw. subsymmetricus.* Upper limit: FAD of *Sw. hanzhongensis.* This zone correlates to the Kungurian "*M. siciliensis-Sw. subsymmetricus*" zone in southern Guizhou (Mei et al., 2002).

Sw. subsymmetricus is well known from the Kungurian of Guizhou and Guangxi in South China, as well as from Thailand and Oman (Mei et al., 2002 and this study; Henderson and Mei, 2003; Metcalfe and Sone, 2008; Burrett et al., 2015). The assertion that *Sw. subsymmetricus* is restricted to the Roadian (Kozur, 1993) is incorrect.

9) *Sw. hanzhongensis* Zone

Lower limit: FAD of *Sw. hanzhongensis.* Upper limit: FAD of *M. idahoensis.* The

FAD of *Pseudohindeodus augustus* and *Pseudohindeodus ramovsi* occurs in the middle part of this zone. A turnover in the dominant conodont fauna initiated during this zone. *Hindeodus* becomes abundant whilst the abundance and the diversity of *Sweetognathus* decreases. *Hindeodus permicus*, *H. gulloides* and *H. aff. wordensis* all occur in this zone.

10) *Mesogondolella idahoensis* Zone

Lower limit: FAD of *M. idahoensis.* Upper limit: FAD of *M. lamberti.* Conodont faunas change from *Hindeodus-Pseduohindeodus-Sweetognathus-* dominated and gondolellid-free assemblages to gondolellid-dominated assemblages in this zone (Bed 109). This shift in conodont assemblage coincides with a lithological change from thick- and medium- bedded wackestones to more cherty, medium- to thin-bedded wacke- and carbonate mudstones.

11) *M. lamberti* Zone

Lower limit: FAD of *M. lamberti.* Upper limit: FAD of *J. nankingensis.* Carbonate of the M. lamberti Zone (Beds 110-111) are more thinly bedded with an increasing abundance of sponge spicules and radiolarian tests, indicating deepening and a relative sea level rise in the latest Kungurian.

4.4 Roadian

The Roadian strata consist of less than 5 m thick finely laminated and thinly bedded carbonate mudstones starting at the top of Bed 111 (Fig. 2B). A major sea-level rise is known from the Early-Middle Permian transition and is manifest at Tieqiao by a transition to thinly bedded radiolarian cherts by Bed 112 (Wordian age). By this time, deep, basinal sedimentation was established in the region. The minor thickness of the Roadian strata may be attributed either to condensation during this sea level rise or to hiatus resulting in a loss of strata (due to sudden loss of carbonate production below the carbonate compensation depth). Only one conodont zone is recognized.

12) *Jinogondolella nankingensis* Zone

Lower limit: FAD of *J. nankingensis.* Upper limit: FAD of *J. aserrata. Pseudohindeodus ramovsi* are abundant. Fine lamination in the upper (Roadian) part of Bed 111 indicates minor bioturbation.

4.5 Wordian

Wordian strata are presented by Bed 112 to lowermost part of Bed 116. The sediments consist of thinly bedded radiolarian cherts in the lower part (Beds 112-113), thickly bedded bioclastic wacke- and packstones in the middle (Bed 114, also known as "the Great White Bed") and alternation of cherts and lime mudstones in the upper part (Bed 115-116). One conodont zone is recognized.

13) *J. aserrata* Zone

Lower limit: FAD of *J. aserrata*. Upper limit: FAD of *J. postserrata*. The FAD of *J. palmata* occurs at the same level as the FAD of *J. aserrata*. This is generally consistent with the record in west Texas where the FAD of *J. palmata* was reported very close to the FAD of *J. aserrata* (Nestell and Wardlaw, 2010a).

Several species, such as *J. errata, Gullodus duani* and the long ranging species *Sw. hanzhongensis* and *Pseudohin. ramovsi* appear in the middle-upper part of this zone.

4.6 Capitanian

The Capitanian (Beds 116-119) is the most intensively studied interval in the Laibin area (Mei et al., 1994c; Jin et al., 2006; Chen et al., 2009; Wignall et al., 2009b). Strata of this age consist of medium bedded alternating cherts and lime mudstones in the lower part (Beds 116-118) overlain by pack- to grainstones (Laibin Limestone Member, Bed 119). Here we only give a brief description of the conodont zones of this stage since they have been well studied.

14) *J. postserrata* Zone

Lower limit: FAD of *J. postserrata*. Upper limit: FAD of *J. shannoni*.

15) *J. shannoni* Zone

Lower limit: FAD of *J. shannoni*. Upper limit: FAD of *J. altudaensis*.

16) *J. altudaensis* Zone

Lower limit: FAD of *J. altudaensis*. Upper limit: FAD of *J. prexuanhanensis*. This interval is characterized by higher extinction rates as well as the onset of Emeishan volcanism (Wignall et al., 2009a; Sun et al., 2010). Losses include many foraminifers, calcareous algae in the equatorial realm and many brachiopods in the boreal realm (Bond et al., 2010; Bond et al., 2015). Though there are no obvious lithological changes in the *J. altudaensis* Zone at Tieqiao, the last appearances of several long-ranging conodonts, such as *Gullodus duani*, *Sw. hanzhongensis* and *Pseudohind. ramovsi*, are all recorded in this zone.

17) *J. prexuanhanensis* Zone

Lower limit: FAD of *J. prexuanhanensis*. Upper limit: the FAD of *J. xuanhanensis*. This zone has not been recognized in western Texas (Lambert et al., 2002). However, it is also distinguishable in the Tieqiao (Guangxi, this study) and at Dukou (Sichuan, Mei et al., 1994a) sections. In condensed sections in Guizhou, the *J. prexuanhanensis* zone is often combined with the younger J*. xuanhanensis* zone as the *J. prexuanhanensis-J. xuanhanensis* assemblage zone (Sun et al., 2010).

Sw. fengshanensis occurs in this zone. *Sw. fengshanensis* was established in the late Capitanian strata at Fengshan, northwestern Guangxi (Mei et al., 1998). At the Penglaitan section, *Sw. fengshanensis* spans from the upper *J. postserrata* zone to the lower *J. xuanhanensis* zone, representing the last in the evolutionary lineage of sweetognathids in South China (Mei et al., 2002).

18) *J. xuanhanensis* Zone

Lower limit: FAD of *J. xuanhanensis*. Upper limit: FAD of *J. granti*. Many mature morphotypes of *J. shannoni* occur in the lowermost part of this zone and are very similar to their counterparts from West Texas (Lambert et al., 2002; Wardlaw and Nestell, 2010). Volcaniclastic material starts to be deposited during this zone and becomes more common in the overlying *J. granti* Zone, presumably corresponding to the large scale of explosive eruptions of the Emeishan Traps (e.g., Sun et al., 2010).

19) *J. granti* Zone

Lower limit: FAD of *J. granti*. Upper limit: FAD of *Clarkina hongshuiensis*. Conodonts are prolifically abundant in this zone with a typical yield rate of ~100 specimens per kg rock.

20) *Clarkina hongshuiensis* Zone

Lower limit: FAD of *C. hongshuiensis*. Upper limit: FAD of *C. postbitteri*.

4.7 Wuchiapingian

The early Wuchiapingian (Bed 120) is characterized by deposition of extensive bedded cherts with intercalated pinkish limestone lenses. Evidence for a relative sea level fall towards the end of Wuchiapingian is indicated by a reduction of chert thickness up-section with carbonate sedimentation increasing. Eventually, this basinal setting evolved into a sponge reef facies (Beds 124-132) in the middle-late Wuchiapingian lacking conodonts. *Clarkina transcaucasica* was found in Bed 134. One conodont zone is established for the earliest Wuchiapingian at Tieqiao:

21) *Clarkina postibitteri* Zone

Lower limit: FAD of *C. postbitteri*. Upper limit: not determined.

5. Subordinate zones and reassessment for age assignments of rare species

Seven subordinate zones are established at Tieqiao, representing interval zones based on occurrences of long ranging species. The subordinate zones are less effective for stratigraphic correlation but can provide a valuable reference for cases when a single conodont assemblage is obtained from an age-ambiguous lithologic unit (e.g., Burrett et al., 2015). In the following section, we first describe the ranges of these subordinate zones in the Tieqiao section, followed by comments on the range of the zonal species. A correlation with the main conodont zones is shown in figure. 6. Note that the range of the species can be much longer than the respective zone.

1) *Pseudosweetognathus* (*Pseudosw.*) *costatus* Interval Zone

Lower limit: FAD of *Pseudosw. costatus.* Upper limit: FAD of *Pseudosw. monocornus*. The *Pseudosw. costatus* Zone spans the early Artinskian to middle Kungurian (Bed 19 to Bed 94). Elements of long-ranging species *H. minutus* are abundant in the lower part of this zone and there is a single occurrence of *H.* aff. *catalanoi* in the lowermost.

Pseudosweetognathus costatus was established in Artinskian strata of South China (Wang et al., 1987) and also reported from Thailand, co-existing with a typical Kungurian taxon *Sw. subsymmetricus* (Metcalfe and Sone, 2008). Our data confirm former observations and indicate that the range of *Pseudosw. costatus* extends from the Artinskian *Sw. asymmetrica* n. sp. Zone to the Kungurian *Sw. adjunctus* Zone. In the middle Kungurian, *Pseudosw. costatus* was replaced by

Pseudosw. monocornus.

2) *Pseudosweetognathus monocornus* Interval Zone

Lower limit: FAD of *Pseudosw. monocornus.* Upper limit: FAD of *H. gulloides*. This zone comprises Bed 94 to Bed 102 at Tieqiao, and is of late Kungurian age.

Li et al. (1989) established the species *Pseudosweetognathus monocornus* (under the genus "*Sichuanognathodus*") from the upper part of Maokou Fm. at Shangsi. A later and detailed study of the same section reported a *Jinogondolella* and *Hindeodus* dominated fauna which indicates an early Capitanian age for the upper Maokou Fm. (Sun et al., 2008).

Pseudosweetognathus monocornus is found in the upper part of Chihsia Fm. and lower part of Maokou Fm. at Tieqiao and here is reassigned a middle-Kungurian to early-Roadian age. This species only occurred with shallow water, high energy assemblage composed of calcareous algae, corals and foraminifers found in thickly bedded bioclastic pack- and grainstones. We thus speculate that the occurrence of *Pseudosw. monocornus* might be facies-related, and its presence in Wordian to lower Capitanian strata elsewhere (Li et al., 1989) cannot be excluded.

3) *Hindeodus gulloides* Interval Zone

Lower limit: FAD of *H. gulloides*. Upper limit: FAD of *Pseudohindeodus ramovsi*. This zone occupies Bed 102 and correlates to the middle part of *Sw. hanzhongensis* zone, representing a Late Kungurian age.

The species *H. gulloides* Kozur and Mostler, 1995, ranges from upper Kungurian to Roadian. In northeast Thailand, *H. gulloides* occurs at an age-equivalent level as in South China and co-existed with a typical late Kungurian assemblage which consists of species *Mesogondolella siciliensis, Pseudohindeodus oertlii* (= *angustus*) and *Sw. subsymmetricus* (Burrett et al., 2015). In west Texas, the species was recovered from the upper part of Road Canyon Fm., representing a late Roadian age (Kozur and Mostler, 1995).

4) *Pseudohindeodus ramovsi* Interval Zone

Lower limit: the FAD of *Pseudohindeodus ramovsi*. Upper limit: the occurrence of *Gullodus sicilianus*. This zone spans from Bed 103 to Bed 115, representing a latest Kungurian to Wordian age.

The species *Pseudohindeodus ramovsi* Gullo and Kozur, 1992 has a much longer range than the Interval Zone. Wardlaw (2000) reported sporadic occurrences of this species from the Kungurian to Capitanian. Our data are consistent with Wardlaw (2000), suggesting that *Pseudohindeodus ramovsi* spanned from the late Kungurian *Sw. hanzhongensis* to the middle Capitanian *J. altudaensis* Zone.

Another associate species in this zone is *Pseudosw. augustus* (Igo, 1981). This species has been reported from coeval Kungurian strata in Japan (Igo, 1981; Shen et al., 2012), but can also occur in much older strata such as in the Artinskian (Orchard and Forster, 1988).

5) *Gullodus sicilianus* Interval Zone

Lower limit: FO of *G. sicilianus.* Upper limit: FAD of *Gullodus duani*. This zone covers the middle part of Bed 115, representing a middle-late Wordian age.

Gullodus sicilianus (Bender and Stoppel, 1965) ranges from the Roadian to Wordian (Kozur, 1993). It is a rare taxon that is known mostly from the Tethys realm during the Wordian (Kozur, 1995).

6) *Gullodus duani* Interval Zone

Lower limit: FAD of *Gullodus duani*. Upper limit: prolific occurrence of *H. excavatus.* This zone comprises Bed 115 to Bed 118, covering much of the Capitanian. An associated taxon *Hindeodus catalanoi* ranges through the upper part of this zone. Though Gullo and Kozur (1992) assigned a Wordian age for *H. catalanoi*, this form is found in the Capitanian at Tieqiao, suggesting a longer range of the species than its original definition.

Gullodus duani Mei et al. 2002 is a rather rare species in the Guadalupian. This species was originally recovered from the Maokou Fm. from Guangxi and is only known from South China. At Tieqiao, this species is known from uppermost Wordian to middle Capitanian strata.

7) *H. excavatus* Interval Zone

Lower limit: the prolific occurrence of *H. excavatus.* Upper limit: FAD of *C. postbitteri* (the Capitanian-Wuchiapingian boundary). At Tieqiao, this zone is represented by the Laibin Limestone Member (Bed 119) of a late Capitanian age.

Hindeodus excavatus is another long-ranging species in the Permian, but its use as a zonal fossil derives from its prolific abundance in the late Capitanian.

6. Systematic palaeontology

Genus *Gullodus* Kozur, 1993

Emended diagnosis: 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 10-15 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 cavities are greatly expanded, non-ornamented and occupy 1/3 to 2/3 of the full body.

Remarks: the diagnosis of this genus (Kozur, 1993) should be emended because it is often hard to differentiate between *Gullodus* and *Hindeodus*. The emended diagnosis also includes wider variability of *Gullodus* species. Key differences between *Gullodus* and *Hindeodus* are the shape and position of the basal cavity and the length/height ratio: *Hindeodus* has a more centrally positioned basal cavity and lower length/height ratio. A key difference between *Gullodus* and *Sweetognathus* is that denticles of *Gullodus* are not ornamented while those of

Sweetognathus develop nodes. *Gullodus* can be differentiated from *Pseudohindeodus* because the basal cavity of the latter is more (horizontally) expanded and ornamented with a surface apron and occupies ≥2/3 of the full element length.

Based on the revised diagnosis, *Gnathodus sicilianus* Bender and Stoppel, 1965 should remain as *Gullodus sicilianus* as suggested by Kozur (1993). However, *Pseudohindeodus catalanoi* Gullo and Kozur (1992) and *Gullodus hemicircularis* Kozur, 1993 should belong to *Hindeodus*, rather than *Pseudohindeodus* or *Gullodus*.

Occurrence: Kungurian to Capitanian

***Gullodus tieqiaoensis* n. sp. Sun and Lai**

Plate 4, figs. 6, 7.

No reported specimens are similar to this species.

Etymology: From the name of the section from where the species is described.

Holotype: Specimen S1_060 (Pl. 4, fig.6) from sample 41-1 of Bed 41, Chihsia Fm., Tieqiao Section, South China.

Paratype: Specimen S1_062 (Pl. 4, fig.7) from sample 41-2 of Bed 41, Chihsia Fm., Tieqiao Section, South China.

Diagnosis: A *Gullodus* species with a high length/height ratio and a robust cusp.

Description: Body slim and elongated. Length/height ratio is ~2. The cusp is tall, wide and robust, normally twice as high as the denticles and three times wider than the denticles. 13-17 densely arrayed denticles decease in height posteriorly. Posterior denticles on the basal cavity are more expanded and thus wider than the rest. They can be lower and more fused. The basal cavity is expanded, leaf or irregular shaped and occupies the posterior 2/3 of the element. The widest point is in the posterior 1/4 to 1/3.

Remarks: This species has a very high length/height ratio and a posteriorly positioned, expanded but non-ornamented basal cavity that extends to the posterior end. It thus belongs to *Gullodus* rather than *Hindeodus* or *Pseudohindeodus*.

Occurrence: lower Chihsia Fm. (early Kungurian), Tieqiao, South China

Genus *Hindeodus* Rexroad & Furnish, 1964

Hindeodus catalanoi Gullo and Kozur, 1992

Plate 7, Figs. 6-8.

Pseudohindeodus catalanoi Gullo and Kozur, 1992 p. 225, pl. 5, fig. A.

Hindeodus gulloides Burrett et al. 2015, p. 111-113, Fig. 6, figs. J-I.

Diagnosis: A *Hindeodus* species that is triangular shaped with 2 to 3 anterior coalesced denticles and 12-15 densely arrayed denticles.

Remarks: The species resembles its Artinskian-Kungurian and “Roadian” predecessors *H. hemicircularis* Kozur 1993 and *H. gulloides* Kozur and Mostler, 1995. They all have two to three anterior denticles. However, *H. hemicircularis* is sub-semicircular shaped and has fewer but wider denticles while *H. gulloides* is more elongated and has a much broader cusp than the current species.

Occurrence: upper Maokou Fm. (middle-late Capitanian), Tieqiao, South China; Wordian of Sicily.

***Hindeodus* sp. A Sun and Lai**

Plate 4, Figs. 23, 26.

Diagnosis: A *Hindeodus* species whose outline is close to that of an isosceles triangle.

Description: Body triangular shaped with a long anterior edge. Anterior angle is around 45°-60°. Two or three small coalesced denticles may develop on the anterior edge. Medium sized cusp followed by three low denticles. Posterior denticles are taller and wider and decrease in height towards the posterior end. The basal cavity is medially expanded and central positioned.

Remarks: The species resembles *H. permicus* but differs by its outline and shapes of denticles.

Occurrence: upper Kungurian, basal Maokou Fm. of South China

Genus *Pseudohindeodus* Gullo and Kozur, 1992

***Pseudohindeodus ellipticae* n. sp. Sun and Lai**

Plate 4, fig. 13; Plate 7. fig. 14.

Pseudohindeodus sp. Wang, 1995, pl. 1, figs. 1a, 1b.

Etymology: From the oval shape of the basal cavity of the species.

Holotype: Specimen S7_001 (Pl. 7, fig. 14) from sample 104-2 of Bed 104, Maokou Fm., Tieqiao Section, South China.

Paratype: Specimen S2_075 (Pl. 4, fig. 13) from sample 104-2 of Bed 104, Maokou Fm., Tieqiao Section, South China.

Diagnosis: A *Gullodus* species with an asymmetrical basal cavity that is near oval in shape.

Description: Element is small and rounded. Cusp is large, robust and higher and broader than any following denticles. The 5-8 denticles immediately behind the cusp are thin and more fused with each other and thus can appear as a ridge. The last 4-6 denticles are the largest amongst all denticles. They are lower, more rounded in shape and relatively evenly spaced with each other with a small gap in between. The basal cavity is decorated with an apron, horizontally expanded, asymmetrical and very rounded. The outline of the basal cavity is close to an oval.

Remarks: the species resembles *Pseudohindeodus ramovsi*. However, *ramovsi* has a near triangular basal cavity whilst *Pseudohindeodus ellipticae* n. sp. has a more rounded basal cavity.

Occurrence: upper Kungurian to lowermost Roadian, basal Kufeng Fm. and lower Maokou Fm. of South China.

Genus *Sweetognathus* Clark, 1972

***Sweetognathus asymmetrica* n. sp. Sun and Lai**

Plate 1, Figs. 1, 7, 14, 17.

Etymology: The species name refers to its asymmetric anterior transverse ridges.

Holotype: Specimen S1_018 (Pl. 1, Fig.1) from sample 18-1 of Bed 18, Chihsia Fm., Tieqiao Section, South China.

Paratypes: Specimen S1_037 (Pl. 1, Fig.7) from sample 22-2 of Bed 22, Chihsia Fm., Tieqiao Section, South China.

Diagnosis: A Type III sweetognathid (definition follows Ritter, 1986) with short blade and asymmetric anterior transverse ridges.

Description: Short blade, often bearing 4-6 denticles; the cusp is moderately big, the first denticle is the biggest and very often fused with the cusp and forms a high robust cusp; the other denticles are much smaller, lower and more fused toward to the carina. The first two denticles are occasionally both very high, robust and triangular in shape. Transverse ridges are clearly incised. There are commonly 6 to 8 transverse ridges. The first one or two ridges are always asymmetrically developed—in most cases the left nodes are missing. The widest part of the carina is in the middle. The basal cavity is leaf- to heart-shaped and moderately expanded, occupying the posterior half of the full element length.

Remarks: This species is similar to *Sw. subsymmetricus.* Both species developed asymmetric anterior transverse ridges. However, the current species differs from *Sw. subsymmetricus* by: 1) the length ratio of free blade/carina < 1 (most commonly 1/3), whereas that of *Sw. subsymmetricus* is generally≥1; 2) the cusp is large tall and robust, whereas that of *Sw. subsymmetricus* is moderately large, compared with other denticles on the blade; 3) an apparent gap between blade and carina; *Sw. subsymmetricus* has low small denticles connecting blade and carina; 4) *Sw. subsymmetricus* has a less expanded basal cavity and a narrower carina, therefore appears more "slim"; 5) gaps between transverse ridges that become lager toward the posterior end.

Though *Sw. subsymmetricus* and *Sweetognathus asymmetrica* n. sp. may have close affinities, *Sw. asymmetrica* n. sp. is restricted to the Artinskian to earliest Kungurian whereas *Sw. subsymmetricus* is found in younger rocks of late Kungurian to Roadian age (Kozur, 1995). Many reported occurrences of *Sw. subsymmetricus* in pre-middle-Kungurian strata (that have not been illustrated) should be reassessed.

The paratype shares a few common features with *Sw. variabilis*. They both have two big triangular-shaped denticles. The key difference is the position of the basal cavity. *Sw. variabilis* has a basal cavity near the posterior end. In addition, *Sw. variabilis* has a long blade (blade/carina ratio ≥1) and five transverse ridges with the widest being near the posterior end. *Sw. asymmetrica* n. sp. has a blade/carina ratio always <1, and usually seven or more transverse ridges while the widest occurs near the middle of the body. In addition, neither of *Sw. subsymmetricus* and *Sw. variabilis* should be considered as synonyms of *Sw. paraguizhouensis* and *Sw. guizhouensis* (Shen et al., 2012).

Occurrence: Artinskian-basal Kungurian, basal Chihsia Fm. of South China

Note: The specimen shown in fig. 3 in Pl. 4 seemly has a gap between blade and carina. This is only because in the lateral view the SEM took the part with missing nodes in the asymmetric anterior transverse ridges.

***Sweetognathus sp.* A**

Pl. 1 fig. 9

Diagnosis: A Type III sweetognathid with tall and slim denticles and narrow ridges.

Description: Body elongated with a height/length ratio ≈ 1/2. Cusp tall and slim, at least twice as high as any following denticles. The cusp is immediately followed by five to six very slim denticles. The first and third denticles are the lowest. A gap is developed between the fourth and fifth denticles. Nodes are short, forming 5-7 low and generally evenly spaced ridges.

***Sweetognathus toriyamai* (Igo, 1981)**

Pl.1, fig. 12, 15.

Neostreptognathodus toriyamai Igo, 1981, p. 42-43, pl. 6, figs. 1-16

Sweetognathus whitei Igo, 1981, Pl. 7, fig.7?

Remarks: The denticles of this species point forwards. The carina is lens-shaped—thus the widest is near the middle. There is a short and narrow ridge connecting the blade and carina. The ridge is relatively high anteriorly and decreases in height towards the carina, thus giving a triangular shape if laterally viewed.

Comparisons: The short narrow ridge between the free blade and carina is one of the most distinguishable features of this species. This species has a broad, lens-like carina, which is similar to *Sw. behnkeni*. However, the latter species has "ledge-like" decorations on the carina, whereas *Sw. toriyamai* is decorated by lower transverse ridges.

Occurrence: Artinskian, basal Chihsia Fm. of South China and Kuchibora Fm. of Japan.

7. Conclusions:

A detailed conodont biostratigraphic and taxonomic study of the Early and Middle Permian strata at Tieqiao, South China has enabled recognition of 21 main and 7 subordinate conodont zones. Three new species are established. The following conclusions can be drawn:

1) The Tieqiao strata record a change in conodont faunas from Early Permian *Sweetognathus* dominated assemblages to Middle Permian gondolellids dominated assemblages from the latest Kungurian onwards. This shift coincided with a relative sea-level rise and change to deeper water facies.

2) The Early Permian *Sweetognathus* fauna represents an important evolution lineage and a shallower (surface?) water group, which evolved in parallel to the contemporary but possibly deeper-dwelling *Mesogondolella* fauna.

3) The Chihsia Fm., which had been in many cases erroneously regarded as a Middle Permian unit, is of Early Permian age. It spans the Artinskian to the late Kungurian whilst the overlying Maokou Fm. straddles the Early and Middle Permian from the late Kungurian to latest Capitanian. The Chihsia/Maokou lithological boundary is thus locally not suitable for defining the Early-Middle Permian boundary (Kungurian-Roadian stage boundary).

4) Species such as *J. palmata* and *J. errata* occur at time-equivalent stratigraphic levels at Tieqiao as in west Texas, suggesting that they can be used for intercontinental correlations.

Acknowledgements

Many colleagues helped with field and lab work, including H.S. Jiang (Wuhan), F. Li (now Guilin), Q. Li (now Qingdao), D. Lutz (Erlangen), F. Nenning (now Münster), W. Pan (now Guangzhou), L.N. Wang (Wuhan), Y.J. Yan (now

Lianyungang) and W.Q. Xue (Wuhan). H. Igo and B. R. Wardlaw are thanked for providing conodont literature. Y.D. Sun acknowledges the Alexander von Humboldt Foundation for a fellowship. This study is supported by the Chinese Fundamental Research Funds for the Central Universities (CUG130615), 973 Program (2011CB808800), the Natural Science Foundation of China (41272044; 41472087; 41572002) and the 111 Project (B08030). DB acknowledges funding from the UK Natural Environment Research Council (grant NE/J01799X/1).

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Figure captions

Fig. 1 Middle Permian palaeogeographic reconstructions of South China and Laibin area (after Wang and Jin, 2000; Wignall et al., 2009b).

Fig. 2 Field photographs of the studied section. A, an overview of the Chihsia Fm. in the lower part of the section. A digger in the far side (blue square) as scale. B, a close review of fine laminated Bed 111-112 transition (Roadian-Wordian). The pen (~15 cm long) as scale.

Fig. 3 Log of the lower part of Tieqiao section (Asselian to Kungurian) with conodont ranges and zonation.

Fig. 4 Log of the middle part of Tieqiao section (Kungurian to Wordian) with conodont ranges and zonation. Keys are the same as in Fig. 3. Note that the reported occurrence of *Mesogondolella bisselli* in Bed 91 (Sha et al., 1990) cannot be confirmed by our dataset (for details see discussion of the *Sw. adjunctus* zone). Keys is the same as in figure 3.

Fig. 5 Log of the upper part of Tieqiao section (Wordian to Wuchiapingian) with conodont ranges and zonation. Keys is the same as in figure 3.

Fig. 6 Correlation chart of the Early-Middle Permian with standard conodont zonation (Henderson et al. 2012) and Tieqiao (this study) and Nashui (Mei et al., 2002) sections. 1., *Pseudosw. monocornus*; 2., *H. gulloides*; 3., *G. sicilianus*; 4., *H. excavates*.

Plate 1. SEM images of Tieqiao conodonts-genus *Sweetognathus*. Bar scale for 100 µm, 'a' for oral view, 'b' for lateral view. Default is oral view. 1, 7, 14, 17. *Sweetognathus asymmetrica* n. sp., 1, holotype, S1_018 (18-1); 7, paratype, S1_037 (22-2); 14, S_001 (18-1); 17, S_006 (24A); 2, 16. *Sweetognathus whitei* (Rhodes, 1963), 2, S1_019 (18-1); 16, S_005 (23A); 3, 8. *Pseudosweetognathus costatus* Wang, Ritter and Clark, 1987, 3, S1_021 (19-2), 8, S1_025 (21-2). 4. *Sweetognathus sp.* 4, S1_023 (19-2); 5. Transitional form from *Sw. inornatus* to *Sw. asymmetrica* n. sp., S1_038 (22-2); 6. *Sweetognathus* sp., S1_031 (22-1). 9. *Sweetognathus* sp. A., S1_026 (21-2); 10. *Sweetognathus inornatus* Ritter, 1986, S1_030 (22-1); 11. *Sweetognathus* cf. *bogoslovskajae* Kozur in Kozur and Mostler,

1976, S1_020 (18-1); 12, 15. *Sweetognathus toriyamai* (Igo, 1981), 12, S_002 (17c), 15, juvenile form, S_003 (17c); 13. *Neostreptognathodus* ex gr. *pequopensis*, S_004 (17c).

Plate 2. SEM images of Tieqiao conodonts—genera *Sweetognathus, Pseudosweetognathus, Neostreptognathodus and Hindeodus.* Scale bar is 100 μm, ‘a’ for oral view, ‘b’ for lateral view. Default is oral view. 1, 2, 4, 9. *Sweetognathus bogoslovskajae* Kozur in Kozur and Mostler, 1976, 1, S1_039 (22-2), 2, S1_043 (24-3), 4, juvenile, S1_057 (39-1), 9, S1_051 (27-1); 3, 12. *Sweetognathus guizhouensis* Bando et al., 1980, 3. S1_048 (26-3), 12. S1_055 (39-1); 5-7. *Pseudosweetognathus costatus* Wang, Ritter and Clark, 1987, 5, S1_047 (26-2), 6. S1_049 (26-4), 7. S1_045 (25-2); 8. *Neostreptognathodus prayi* Behnken, 1975, gerontic form, S1_046 (25-2); 10. *Sweetognathus clarki* Morphotype I, (Kozur, 1976), S1_050 (27-1); 11. *Sweetognathus inornatus* Ritter, 1986, S1_053 (29-1); 13. *Hindeodus* aff. *catalanoi*, S1_022 (19-2); 14, 16, 17. *Hindeodus minutus* (Ellison, 1941), 14, S1_044 (25-1), 16, S1_056 (39-1), 17, S1_052 (28-1); 15. *Hindeodus sp.* S1_042 (23-3).

Plate 3. SEM images of Tieqiao conodonts—genera *Sweetognathus* and *Pseudosweetognathus*. Scale bar is 100 μm, ‘a’ for oral view, ‘b’ for lateral view. Default is oral view. 1-3. *Pseudosweetognathus costatus* Wang, Ritter and Clark,

1987, 1. S1_065 (52-2); 2. S1_066 (58-1), 3. S1_068 (65-2); 4, 5. *Sweetognathus iranicus* Kozur, 1975, 4, S1_069 (66-3), 5, S1_071 (71-1); 6. *Pseudosweetognathus monocornus* (Dai and Zhang, 1989), S2_001 (94-2); 7, 9, 19. *Sweetognathus* sp. 7. S1_072 (90-7), 9. S2_002 (97-2), 19. S2_020 (100-1); 8, 10, 11. *Sweetognathus adjunctus* (Behnken, 1975), 8. S2_004 (97-2), 10. S2_005 (97-2), 11. S1_076 (91-1); 12, *Sweetognathus* cf. *paraguizhouensis* S1_078 (91-3); 13. Transitional form between *Sweetognathus iranicus* and *Sweetognathus hanzhongensis*, S2_007 (99-4); 14. *Sweetognathus subsymmetrics* Wang, Ritter and Clark, 1987, S2_039 (100-3); 15-18. *Sweetognathus hanzhongensis* (Wang, 1978), 15, S2_038 (100-5), 16, S2_018 (100-1), 17, S2_010 (100-1), 18, S2_028 (100-3).

Plate 4. SEM images of Tieqiao conodonts—genera *Sweetognathus*, *Gullodus*, *Hindeodus* and *Pseudohindeodus*. Scale bar is 100 μm, 'a' for oral view, 'b' for lateral view. Default is oral view. 1. *Sweetognathus* sp. S2_049 (102-2); 2-4. *Sweetognathus subsymmetrics* Wang, Ritter and Clark, 1987, 2. S2_051 (102-3); 3. S2_056 (102-4); 4. S2_058 (102-4); 5, 15. *Sweetognathus iranicus* Kozur, 1975, 5, S2_082 (105-3), 15, S2_072 (103-2); 6-7. *Gullodus tieqiaoensis* n sp., 6. holotype, S1_060 (41-1), 7. paratype, S1_062 (41-2); 8. *Gullodus sicilianus* (Bender and Stoppel, 1956), S3_020 (115-4); 9, 10, 16, 18. Transitional forms between *Hindeodus* and *Pseudohindeodus*. Note that these elements developed weak apron structures on basal cavities. 9. S1_074 (91-1), 10. S1_075 (91-1), 16. S2_057 (102-4), 18. S2_053 (102-3); 11, 12. *Gullodus duani* Mei et al., 2002, 11. S1_013

(TQ-28), 12. S3_022 (115-7); 13. *Pseudohindeodus ellipticae* n. sp. Sun and Lai, paratype, S2_075 (104-2); 14. *Pseudohindeodus ramovsi* Gullo and Kozur, 1992, S2_073 (103-4); 17. *Hindeodus* cf. *wordensis* Wardlaw, 2000; 17, S2_060 (102-5); 19, 20. *Hindeodus* cf. *julfensis* 19, S2_014 (100-1), 20. S2_011 (100-1); 21. *Hindeodus* cf. *permicus*, S2_050 (102-2); 22, 36. *Hindeodus* sp. 22, S2_061 (102-5), 36, S2_022 (100-3); 23, 26. *Hindeodus* sp. A. 23, S2_068 (103-2); 26, S2_084 (106-1). 24, 25, 27, 30-32, 34, 35. *Hindeodus permicus* (Igo, 1981) 24. S2_081 (105-3), 25. S2_034 (100-4), 27. S2_026 (100-3), 30. S2_083 (105-3), 31. S2_016 (100-1), 32. S2_062 (103-1), 34. S2_071 (103-2); 35, S2_067 (103-2). 28, 29. *Hindeodus minutus* (Ellison, 1941), 28. S2_027 (100-3); 29. S2_021 (100-2); 33. *Hindeodus golloides* Kozur and Mostler, 1995, S2_066 (103-2).

Plate 5. SEM images of Tieqiao conodonts—genera *Mesogondolella* and *Jinogondolella*. Scale bar is 100 μm, 'a' for oral view, 'b' for lateral view. Default is oral view. 1, 7. transitional type between *M. lamberti* to *J. nankingensis*, 1, S3_001 (109-2), 7, S3_012 (113-2); 2. *Mesogondolella lamberti* Mei and Henderson, 2002, S3_002 (109-2); 3, 8. *Mesogondolella* sp., 3, S3_004 (109-3), 8. S3_013 (113-7); 4. *Mesogondolella idahoensis* (Youngquist, Hawley, Miller, 1951), S3_005 (110-2); 5, 6. *Mesogondolella siciliensis* (Kozur, 1975), 5. S3_007 (111-1); 6. S3_006 (111-1); 9. *Jinogondolella nankingensis* (Ching, 1960), S3_011 (111-5); 10-11. *Jinogodolella errata* Wardlaw and Nestell, 2000, 10. S3_019 (115-3), 11. S3_017 (115-2); 12. *Jinogondolella aserrata* (Clark and Behnken, 1979), S3_021 (115-4); 13, 16.

Jinogondolella sp., 13. SP_051 (115-3), 16, S3_037 (116-7); 14, 15. *Jinogondolella postserrata* (Behnken, 1975), S3_028 (116-1); 15. S3_036 (116-7); 17, 18. *Jinogondolella shannoni* (Wardlaw, 1994), 17. S3_040 (116-8); 18, S3_030 (116-2); 19. *Jinogondolella altudaensis* (Kozur, 1992), S3_033 (116-3).

Plate 6. SEM images of Tieqiao conodonts—genera *Jinogondolella* and *Clarkina*. Scale bar is 100 μm, 'a' for oral view, 'b' for lateral view and 'c' for back view. Default is oral view. 1. *Jinogondolella prexuanhanensis* (Mei and Wardlaw, 1994), S4_004 (TQ-11); 2. *Jinogondolella* cf. *prexuanhanensis* SP_010 (118-2); 3-5. *Jinogondolella shannoni* (Wardlaw, 1994), 3. S3_062 (118-2); 4. S4_006 (TQ-17+); 5, SP_014 (118-2); 6, 17. *Jinogondolella* sp., 6, SP_013 (118-2), 17, S_035 (119A); 7. *Jinogondolella xuanhanensis* (Mei and Wardlaw, 1994), 06-70_023 (TQ-6f); 8-11. *Jinogondolella granti* (Mei and Wardlaw, 1994), 8. 06-70_024 (TQ-6f), 9. 06-70_022 (TQ-6f), 10. TQ6f_010 (TQ-6f), 11. 06-70_027b (TQ-6f); 12-13. *Clarkina postbitteri* Mei and Warldlaw, 1994, 12. S6_054 (TQ-1), 13. C6_040a (TQ-1). 14. *Clarkina* sp., S6_055 (TQ-1); 15. *Clarkina transcaucasica* Gullo and Kozur, 1992, S4_003 (134-9); 16. *Clarkina hongshuiensis* Henderson, Mei and Wardlaw, 2002, S_029 (TQ-1).

Plate 7. SEM images of Tieqiao conodonts—genera *Hindeodus, Jinogondolella, Mesogondolella* and *Sweetognathus*. Scale bar is 100 μm, 'a' for oral view, 'b' for

lateral view. Default is oral view. 1, transitional form between *Sweetognathus bogoslovskajae* and *Sweetognathus inornatus*, S_007 (24A); 2. *Sweetognathus inornatus* Ritter, 1986, S_008 (26C); 3. *Sweetognathus fengshanensis* Mei and Wardlaw, 1998, S_016 (117-3); 4. *Mesogondolella idahoensis* (Youngquist, Hawley and Miller, 1951), S_009 (109-2); 5. *Jinogondolella palmata* (Nestell and Wardlaw, 2010), S_025 (111-1-2); 6-8. *Hindeodus catalanoi* (Gullo and Kozur, 1992), 6, S3_052 (117-2), 7, S3_052 (117-2), 8, S3_043 (116-12); 9-10. *Sweetognathus hanzhongensis* (Wang, 1978), 9, S4_012 (TQ-25), 10, S_025 (115-8). 11-12. *Pseudohindeodus augustus* (Igo, 1981), 11, S7_007 (102-4), 12, S7_005 (102-4). 13. *Pseudohindeodus* sp. S7_003 (104-2). 14. *Pseudohindeodus ellipticae* n. sp. Sun and Lai, holotype, S7_001 (104-2).