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The Global Stratotype Section and Point (GSSP) of the Permian-Triassic Boundary

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The Global Stratotype Section and Point (GSSP) of the Permian-Triassic boundary has been ratified by IUGS. The boundary is defined at the base of Hindeodus parvus *horizon, i.e. the base of Bed 27c of Meishan section D, Changxing County, Zhejiang Province, South China.*

Historic preamble

The Permian-Triassic Boundary Working Group (PTBWG) was established in 1981 by the International Commission on Stratigraphy (ICS) under the leadership of T. Tozer. Until 1984, the ammonoid *Otoceras* was considered as the index fossil of the Permian-Triassic boundary (PTB). In 1986, *Hindeodus parvus* was proposed to substitute *Otoceras* as the boundary marker (Yin et al., 1986), which later obtained the majority approval of PTBWG. The Chinese Working Group on PTB suggested the base of *Hindeodus parvus* horizon, Bed 27c of Meishan section, Changxing County in Zhejiang Province of South China as the GSSP of PTB. During a workshop at Calgary meeting (1993), the PTBWG proposed four candidates for the stratotype of this boundary, i.e., Meishan of Zhejiang, Guryul Ravine of Kashmir, Shangsi of Sichuan, and Selong of Tibet. In the later years search for adequate index fossils at the Shangsi section has not led to valuable discovery. Fruitful teamwork in Selong (Jin et al., 1996; Orchard et al, 1994) revealed, however, the conspicuous hiatus right below the boundary and the uncertainty of the existence of Changhsingian Stage of this section. Work at Guryul Ravine was blocked by the unstable political condition in Kashmir. Although important achievements have been made in other sections of the world, at Gartnerkofel of the Alps, in Arctic Canada and Spiti region of the Himalayas, generally they are still below the standard required by the ICS Guidelines, and no substitute proposal for GSSP of PTB have been made. Meanwhile, works on the Meishan section have been vigorously carried out to satisfy the GSSP requirements. Naturally Meishan became the sole candidate for the GSSP of PTB.

In 1996 nine members of PTBWG published a formal recommendation to set the Permian-Triassic boundary at the first appearance of *Hindeodus parvus*, Bed 27c of Meishan (Yin et al., 1996). This paper later served as the draft for a formal submission of the PTBWG for ballot. On September 18, 1999, the official Chinese Xinhua Daily Dispatch declared a list of localities, including Changxing County, that were ratified to be opened to foreigners by the State Council of China, and quoted: "The spokesman of the Ministry of Public Security announced that according to the 'Foreigner entry and exit law of the People's Republic of China', no travel permits are required for foreigners with valid visas or residential identifications to travel in the above areas." Thus the Meishan section meets the ICS requirement of authorized accessibility for a GSSP. From 1999 to 2000, the proposal for Meishan as the GSSP of PTB passed three runs of ballot. The results are as follows: (1) Vote by PTBWG (October 1999 to January 2000): voting members, 26; votes received, 23 (88%); yes, 20 (87%); no, 3; (2) Vote by the Subcommission on Triassic Stratigraphy (April to June, 2000): voting members, 31; votes received, 27 (87%); yes, 22 (81%); no, 2; abstention, 2; yes for Meishan as GSS, but at different Point, 1; (3) Vote by ICS (September to November, 2000): voting members, 18; votes received, 17 (94.4%); yes, 17 (100%). The proposal was finally ratified by the IUGS Executive Committee in March, 2001. Thus, the GSSP of the Permian-Triassic Boundary is defined at the base of Bed 27c, Meishan Section D, Changxing County, Zhejiang

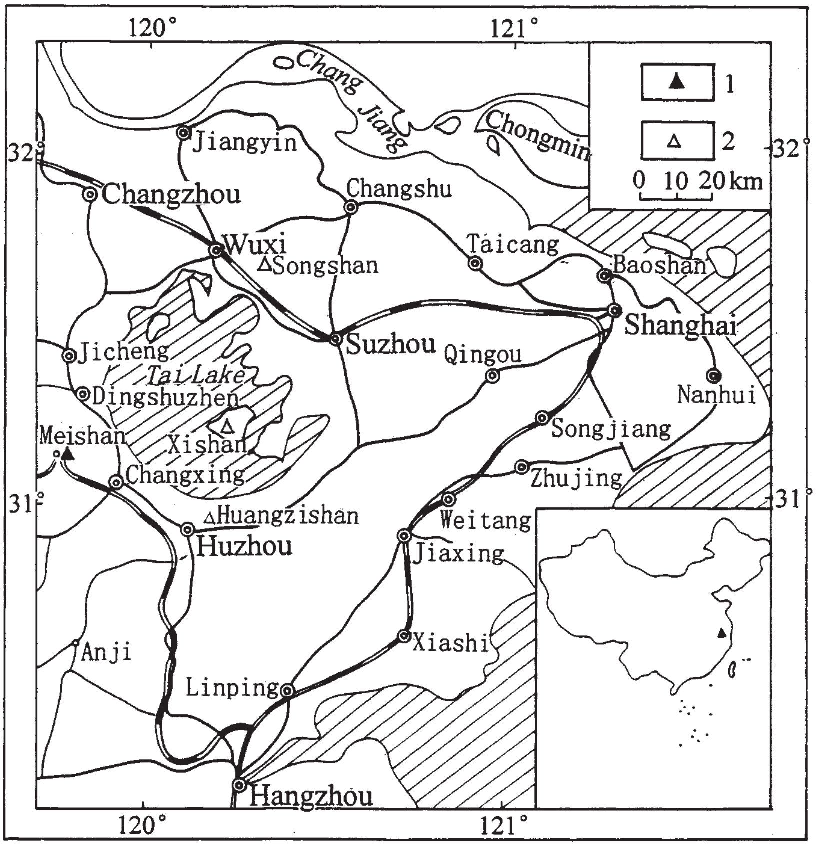


Figure 1 Regional map of Lower Yangtze. 1. Meishan section, the GSSP of the Permian-Triassic boundary; 2. Accessory section of the Permian-Triassic boundary.

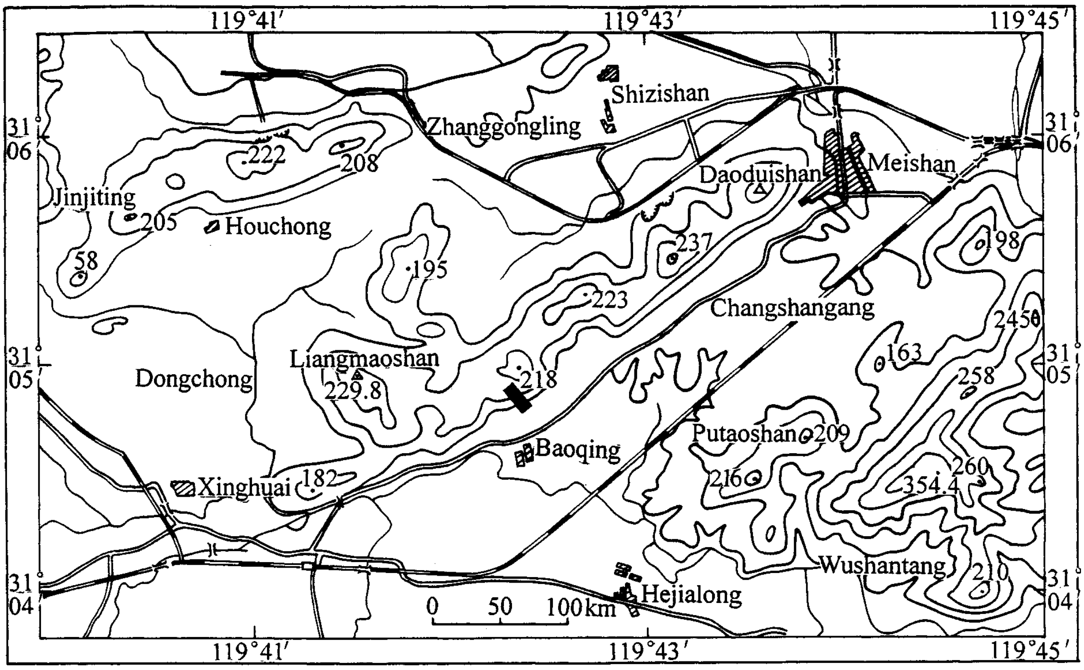


Figure 2 Locality map of Meishan area. Section D is represented by a coarse black segment.

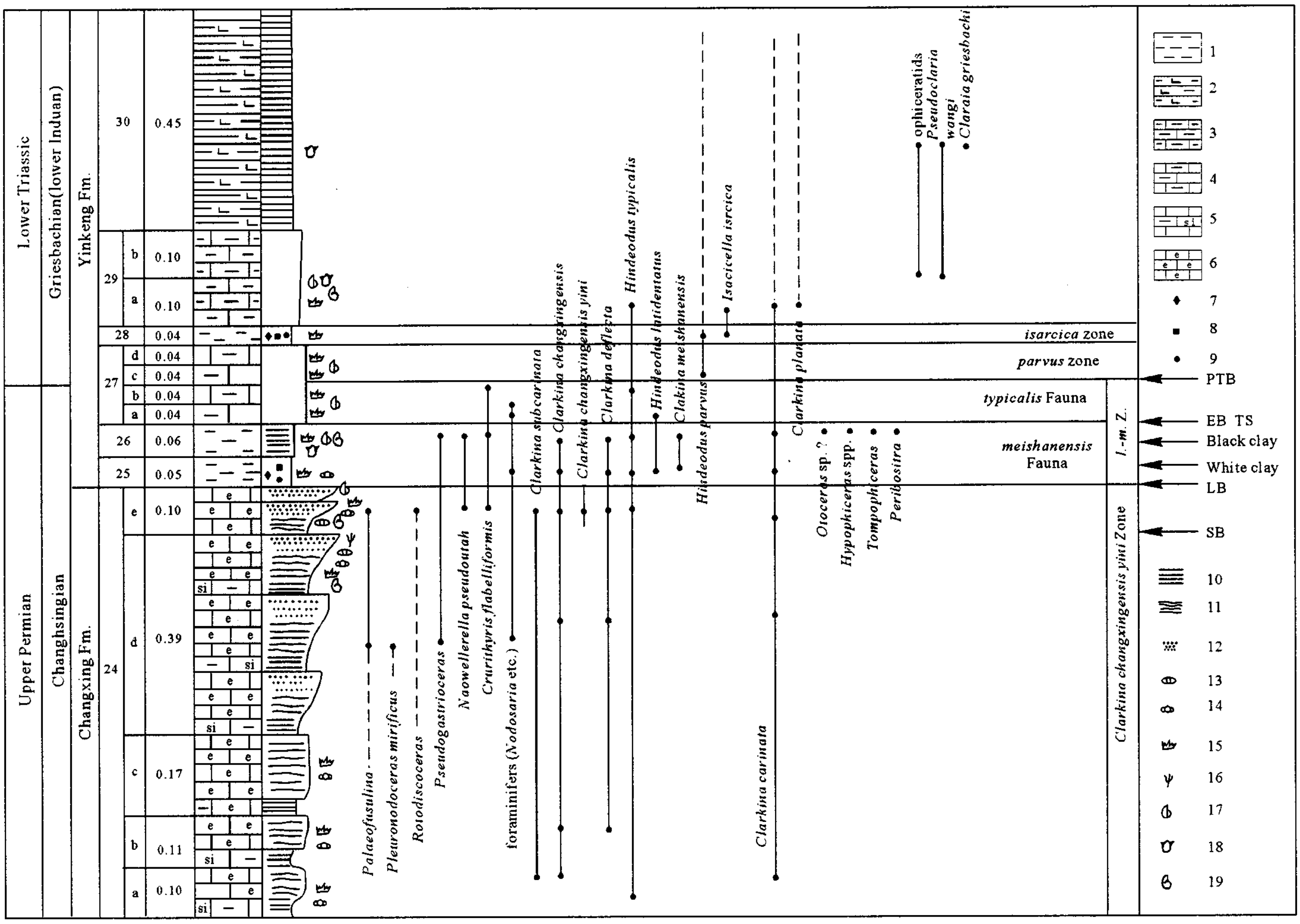


Figure 3 Litho- and biostratigraphic column of PTB strata of Meishan section D. l.-m. Z. Hindeodus latidentatus-Clarkina meishanensis Zone, SB sequence surface, LB lithostratigraphic boundary, EB eventostratigraphic boundary, TS transgressive surface, PTB Permian-Triassic boundary. 1. clay, 2. calcareous mudrock, 3. marl, 4. argillaceous micrite, 5. siliceous micrite, 6. bioclastic micrite, 7. highquartz, 8. zircon, 9. microsphaerules, 10. horizontal bedding, 11. wavy bedding, 12. convolute bedding, 13. fusulinids, 14. foraminifers, 15. conodonts, 16. calcareous algae, 17. brachiopods, 18. bivalves, 19. ammonoids.

Province, China, at the horizon where the conodont *Hindeodus parvus* first appeared.

The section and point

Changxing can be reached either by railway from Hangzhou or by express highway from Shanghai, Nanjing and Hangzhou within 2–3 hours' drive. A branch railway and highway connect Changxing with Meishan and Xinghuai, the nearest village to Section D (Figures 1, 2). The Meishan quarries are being excavated to use the limestone of Changxing (or Changhsing) Formation for construction, thus providing several PTB sections named from A to F and Z from west to east, and Section D is in the middle of the quarried outcrops (Plate 1, Figs.1, 2). Walking distance from Xinghuai or from highway directly to Section D is about 1 km. A small stele was erected in front of the section to indicate the conservation of the Changxing Limestone, in accordance with regulations of the provincial administration. A 6-meter high monument will soon be established nearby to symbolize this GSSP.

The regional strata include marine Silurian to Lower Triassic, terrestrial Jurassic and Quaternary. Regional framework comprises a series of NE trending folds initially formed during the Indosinian (Triassic) Orogeny but superimposed by the Yanshanian (Jurassic and Cretaceous) structures, constituting the Shizishan Synclinoria, on the southeastern wing of which the type section is located (Plate 1, Fig.6, refined to replace Figure 2 of Yin et al., 1996).

Because description of the section and other basic data have been given in Yin et al. (1996) and Yin (ed., 1996), the following text will emphasize new data since 1996.

Correlation potential

Hindeodus parvus is now recognized as the index fossil, and the worldwide correlation of PTB strata based on conodonts and ammonoids has been proposed by Yin et al. (1996). For North America please see Paull and Paull (1994) and Henderson and Baud (1996). The negative excursion of $\delta^{13}C$ has been suggested as an auxiliary marker of PTB. Although *Hindeodus* is generally considered to be shallow water, *H. parvus* is exceptional. It is not facies related or latitude-restricted, and can be discovered both in shallow water and pelagic deposits (Kozur, 1996; Lai, 1998), as can also be judged by its worldwide occurrences (see Table 1).

The PTB strata are stable throughout whole Yangtze Platform. Their lithology and thickness change insignificantly and can be readily traced regardless of various geologic settings (Peng and Tong, 1999).

Biostratigraphy

A range chart of important fossils discovered at Meishan Section is drawn on Figure 3. For detailed conodont and ammonoid occurrences please refer to Yin (ed., 1996). It is to be noted that the *Clarkina changxingensis-C. deflecta* Zone, previously established to represent Subdivisions 2, 3 and 4, has been refined recently (see Table 1). Its main part, or Subdivision 2, which corresponds to the ammonoid *Pseudotirolites-Pleuronodoceras* Zone, is subdivided into two conodont zones, namely, in ascending order, *C. changxingensis* and *C. changxingensis yini* zones. Its upper part, Subdivisions 3 and 4 (Beds 25, 26 and 27a-b), is renamed *Hindeodus latidentatus-Clarkina meishanensis* Zone (Pl.1, Fig.3). The following is a brief complement to the description of the conodont zones at PTB of Meishan section:

***Clarkina changxingensis yini* Zone:** This zone was proposed by Mei et al. (1998) in Bed 24 of Meishan section, beginning at the FAD of *Clarkina changxingensis yini* Mei, Zheng et Wardlaw and ending at the FAD of *C. meishanensis* Zhang, Lai et Ding (Plate 1, Fig.5). The fossils in this zone are highly diverse and include 12 conodont species (Figure 3). At the Meishan section it associated with ammonoid *Rotodiscoceras* sp. and fusulinid *Palaeofusulina* sp.

***Hindeodus latidentatus-Clarkina meishanensis* Zone:** This zone includes the 'boundary clay beds' (Beds 25 and 26) and Beds 27a and 27b, starting at the FADs of *Hindeodus latidentatus* (Kozur, Mostler et Rahimi-Yard) and *C. meishanensis*, and terminating at the FAD of *Hindeodus parvus* (Kozur et Pjatakova). The diversity of this zone decreases to include only nine conodont species but the abundance is relatively high, and *C. changxingensis* and *C. deflecta* are still the predominant forms. The horizon of this zone corresponds with the *Otoceras* Bed of Zhao et al. (1981), the Mixed Bed 1 and lower Mixed Bed 2 of Sheng et al. (1984, 1987), the Lower Transitional Bed and lower Upper Transitional Bed of Yin (1985, 1994), and the Boundary Bed 1 and lower Boundary Bed 2 of Wang (1994). Two faunas are distinct in this zone: the *C. meishanensis* Fauna in Beds 25 and 26 and the *H. typicalis* Fauna in Beds 27a and 27b. *C. meishanensis* is characteristic in the lower fauna, associated by ammonoids *Otoceras?* sp. and *Hypophiceras* spp., while *H. typicalis* is distinctive in the upper one. At the boundary between these faunas disappeared most of the Permian *Clarkina*-group conodonts such as *C. deflecta, C. changxingensis, C. orientalis* and *C. meishanensis*. At the continuous PTB sections in South China, and even across the world, there is usually an interval right below the FAD of *H. parvus* containing mostly the 6-element conodonts *H. typicalis, H. minutus* and few *Ellisonia* sp., but rarely other conodonts.

***Hindeodus parvus* Zone:** This zone occupies Beds 27c and 27d. Its base is defined by the FAD of *H. parvus* and the top by the FAD of *Isarcicella isarcica* (Huckriede) (Plate 1, Fig.4). The major fossils of this zone are *H. parvus* and *Ellisonia* sp. in very low diversity. It corresponds with the upper Mixed Bed 2 (Sheng et al., 1984, 1987), the upper Transitional Bed of Yin (1985, 1994) and the upper Boundary Bed 2 of Wang (1994). This zone has been observed at 27 localities of 11 provinces in South China, as well as at the Selong of Tibet, China, Guryul Ravine of Kashmir, Spiti of India, Abadeh and Kuh-e-Ali Bashi of Iran, Narmal Nala of Pakistan, Gartner Kofel of Austria, Tesero of Italy, western America and other localities (Table 1). Recently it has been discovered in the Arctic areas of Canada, Australia and Timor as well.

***Isarcicella isarcica* Zone:** This is a range zone defined by the extension of *I. isarcica*. It is located in Beds 28 and 29 of Meishan section. The fossils of this zone have low diversity but high abundance and the various species of *Isarcicella* developed well. It corresponds with the Mixed Bed 3 of Sheng et al. (1984, 1987), the top of the Upper Transitional Bed of Yin (1985, 1994) and the base of the Boundary Bed 3 of Wang (1994). This zone is found at many sections of South China, Tibet, Pakistan, Kashmir, India, Iran, Italy, west America, Australia, Austria and Canada (Table 1). It should be indicated here that Dai and Zhang (in Li et al., 1989) named a new species, *Isarcicella staeschi*, based upon an element of single process only at the oral side, which is here included in *I. isarcica* (Huckriedge). Therefore the *Isarcicella staeschi* Zone of Wang (1996, 1998) is not used in this paper.

Above the *Isarcicella isarcica* zone (Beds 28, 29) have been found upper Griesbachian *Clarkina carinata-C. planata* (Bed 30 upward), lower Dienerian *Neospathodus kummeli* (135.84 m from PTB), upper Dienerian *N. cristagalli* (234.53 m) and lower Smithian *N. waageni* (279.33 m) at Meishan Section D (Tong and Yang, 1998). So far concerning the PTB interval, the conodont sequence of Meishan is the most complete one in the world. Therefore, although its PTB strata are thin there is no reason to suspect a hiatus within the strata.

As to the lineage of *H. parvus*, there is a consensus about the 4 stages in the evolution of *parvus*: Stage 1 (latest Permian)—*H. latidentatus* (Zhang et al., 1995; Ding et al., 1996; Wang, 1996) or *H. latidentatus preparvus* (Kozur, 1996; Wang, 1998; Orchard and Krystyn, 1998). Stage 2 (earliest Triassic)—*H. parvus* (many authors) or *H. parvus erectus* (Kozur, 1996; Wang, 1998). Stage 3—*Isarcicella turgida* (Zhang et al., 1995; Ding et al., 1996), *I.*

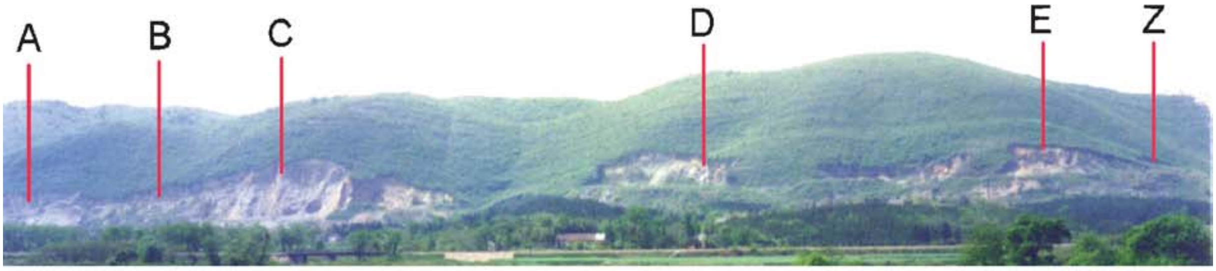
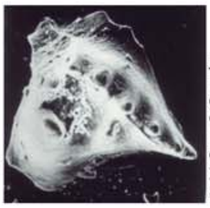


Fig.1

Fig.2

Hindeodus parvus (Kozur et Pjatakova) lateral view, x60; Coll.No.D-27d Bed 27d of Section D



Isarcicella isarcica (Huckriede) Oral surface view, x50; Coll. No.CBV-28; Bed 28 of Section A

Fig.4

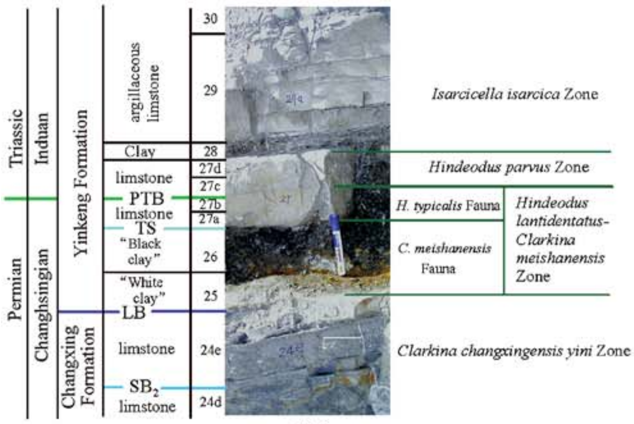


Fig3

Hindeodus lantidentatus (Kozur, Mostler et Rahimi-Yazd), lateral view, x50; Coll. No.CBIV-25; Bed 25 of Section C

Hindeodus typicalis (Sweet) lateral view, x40; Coll. No.D-27a; Bed 27a of Section D

Clarkina meishanensis (Zhang,Lai et Ding), oral surface view, x40; Coll.No.CBII-26; Bed 26 of Section D

Clarkina changxingensis yini Mei, Zhang et Wardlaw, oral surface view, x40; Coll. No.CBIII-24e; Bed 24e of Section C

Fig.5

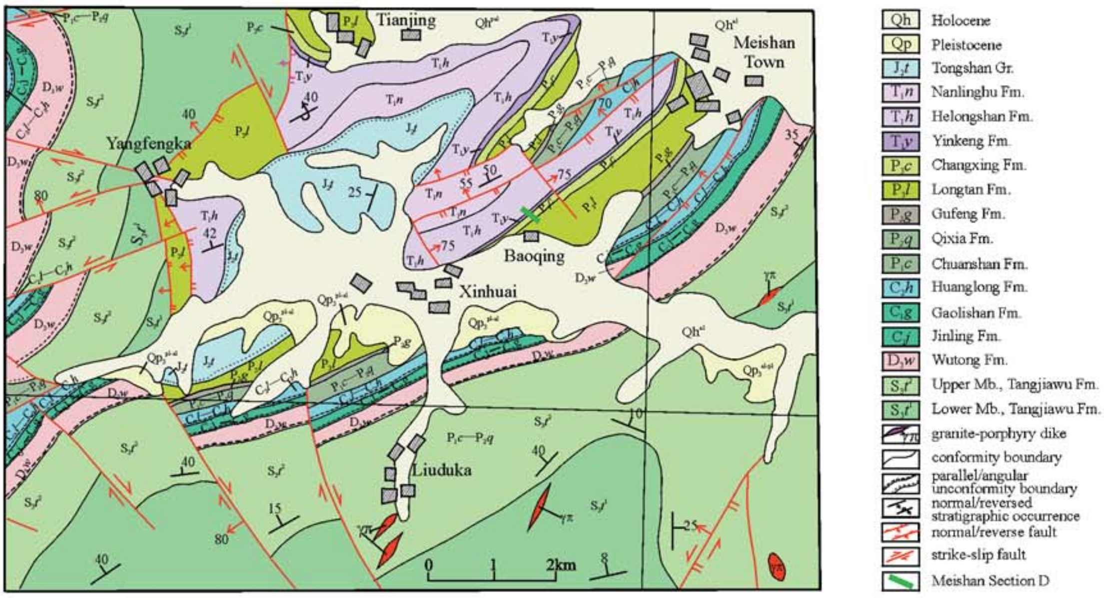


Fig.6

Plate 1 explanations: Fig. 1 Panorama of the Meishan sections taken from south of the Meishan hills. From west to east are the quarries: A, B, C, D (GSSP), E, Z. Fig. 2 View of Meishan Section D, showing the lithostratigraphic units. Fig. 3 The PTB strata of Meishan section. SB2: type 2 sequence stratigraphic boundary; LB: lithostratigraphic boundary between the Yinkeng and Changxing Formations; TS: transgressive surface; PTB: Permian-Triassic Boundary (chronostratigraphic boundary). Fig. 4 Lower Induan conodonts from Meishan section. Fig. 5 Upper Changhsingian conodonts from Meishan section. Fig. 6 Geological map of Meishan area.

Table 1 Correlation of the Permian-Triassic boundary strata of the world.

Stage	Subdivision	Conodonts	Ammonoid	MEISHAN Sheng et al., 1984, 1987; Yang et al., 1987; Yin ed., 1996	SHANGSI Li et al., 1989; Yang et al., 1987; Chinese PTBWG, 1993	GURYUL RAVINE Nakazawa et al., 1975; Matsuda, 1981; Kapoor, 1992	NARMAL NALA Kummel et Teichert, 1970; Pak.-Jap. Res. Gr., 1985	SELONG Rao et Zhang, 1985; Yao et Li, 1987; Wang et al., 1989; Orchard et al., 1994
Triassic	6	*Isarcicella isarcica* Zone	*Ophiceras* Zone	Mixed bed 3 (Beds 28 up) *I. isarcica* *H. parvus* *Ophiceras* *Pseudoclaria wangi* *Claraia griesbachi*	Bed 9 15 *I. isarcica* *I. turgida* *H. parvus* *C. griesbachi* *Ps. wangi*	Kuhnamuh E3 (Beds 60 up) *I. isarcica* *Ophiceras* *C. griesbachi* *C. carinata*	Kathwai Upper Unit *I. isarcica* *Ophiceras connectens* *C. carinata*	Bed 22 *H. parvus* *Ophiceras* *C. carinata*
	5	*Hindeodus parvus* Zone	Upper *Otoceras* Zone	Bed 27 c, d *H. parvus* *H. typicalis* *H. julfensis* *H. latidentatus* *C. changxingensis*	Beds 7 8 *Claraia* *I. turgida*	E2 Beds 56 59 *O. woodwardi* *H. parvus* *H. typicalis*	Midlle Unit *H. parvus* *H. typicalis* *Ophiceras connectens*	*2 Bed 20u 21 *I. isarcica* *O. woodwardi* *H. parvus* *H. typicalis* *C.* aff. *changxingensis* '*Peribositra*'
Permian	4	*Hindeodus typicalis* Fauna (*H. latidentatus-C. meishanensis* Zone)	Lower *Otoceras* Zone	Bed 27 a, b *H. typicalis* *X. elongatus*		E2 Bed 55 *H. typicalis* *C. carinata* *Kyanites*	*H. typicalis*	
	3	*Clarkina changxingensis* Fauna (*H. latidentatus-C. meishanensis* Zone)		Mixed Bed 1 (Beds 25, 26) *Otoceras*? *Hypophiceras* *H. typicalis* *H. latidentatus* *C. changxingensis* *C. deflecta* '*Peribositra*' Perm. brachi.	Bed 6 *Hypophiceras* *C. changxingensis* Bed 5 (Black clay)*3 *Metophiceras* *Tompophiceras* *Pseudotirolites*?	E2 Beds 52 54 *O. woodwardi* *Glyptophiceras*' '*Peribositra*' *H. typicalis* Perm. brachi	Lower Unit Perm. brachi. & forams unstable clay	--------
	2	*C. changxingensis yini* Zone *C. changxingensis* Zone	*Pseudotirolites - Pleuronodoceras* Zone	Beds 24 down *Palaeofusulina* *Pleuronodoceras* *Rotodiscoceras* *C. changxingensis* *C. deflecta*	*Pseudotirolites* *Pleuronodoceras* *C. changxingensis* *C. deflecta*	? Kuhnamuh E1 Perm. brachi. & forams '*Perbositra*'	--------	
	1	*Clarkina subcarinata* Zone	*Paratirolites* Zone *Shevyrevites* Zone	L. Changxing Fm. *Tapshanites* *C. subcarinata*	L. Dalong Fm. *Tapshanites* *C. subcarinata*	Zewan D?	--------	--------
		Underlying strata				Zewan D		Selong Gr.

Note 1: Mixed Bed 1 (Sheng et al., 1984) or lower Transitional Beds (Yin, 1985) corresponds to Subdivisions 3+4; Mixed Bed 2 or upper Transitional Beds corresponds to *parvus* Zone plus *typicalis* interval; Mixed Bed 3 corresponds to Subdivision 6 IO Zone.

Note 2: Rao and Zhang (1985), Yao and Li (1987) and Wang et al. (1989) reported Clarkina changxingensis and C. deflecta in Beds 20-21, which was refuted by Orchard et al. (1994). Rao and Zhang (1985) reported I. isarcica at this level, while Orchard et al. (1994) confirmed its occurrence only in upper Bed 20 which underlies Otoceras woodwardi (Bed 21).

Table 1 Correlation of the Permian-Triassic boundary strata of the world (Continued).

Stage	Subdivision	HAMBAST C (Abadeh) Iran.-Jap. Rea. Gr., 1981	KUH-e-ALI BASHI Teichert et al., 1973; Altiner et al., 1980; Golshani et al., 1986	DORASHAM II 3 Kotlyar et al., 1983, 1991; Zakharov, 1985, 1992	TESERO Broglio Loriga et al., 1988; Broglio Loriga et Cassinis, 1992	GART-NER-KOFEL Holser et al., 1991	OTTO FIORD, GRIESBACH CREEK Tozer, 1961, 1967; Henderson, 1993; Baud et Henderson, 1996	WENGENER HALVO, SE KAP STOSCH (Greenland) Teichert et Kummel, 1972; Teichert et al., 1976	SETO-RAIM, VERK-HOYAN Days et al., 1979
Triassic	6	Elikah Unit a, Bed 3 up *H. parvus* *I. turgida* *I. isarcica* *Claraia* *Xenodiscus*	*Claraia* limestone (22 M, U & up) *Claraia* spp. *Ophiceras* *I. isarcica*	*Claraia* Beds 23-24 (Zakharov, 1992) *I. isarcica* *H. parvus* *I. turgida* *Ophiceras* *Claraia*	Mazzin, Beds 40 up *Claraia* (Bed 40) *I. isarcica* (Bed 46A)	Mazzin *I. isarcica* *I. turgida* *H. parvus*	*Ophiceras commune* *Claraia*	*Ophiceras commune* *Claraia stachei*	*Glyptophiceras nielsoni*
	5	Unit a, Beds 1 2 *I. isarcica* *H. parvus*	Bed 22L *H. parvus* *H. typicalis*	Beds 13b 22 (Zakharov,1992) *H. parvus* *Claraia* (rare) *H. latidentatus* (Kozur, 1980) *I. turgida* (Kotlyar et al., 1991)	L. Mazzin *Unionites-Lingula* *H. parvus* *Ellisonia* sp. No Perm. brachi. & forams	L. Mazzin *H. parvus*	*Otoceras boreale* *Claraia* *Hindeodus parvus* *Clarkina carinata* *C. meishanensis*	*Metophiceras subdemissum*	*Otoceras boreale*
Permian	4		Bed 21 *H. typicalis*?	Red clays and marls *C. changxingensis* *C. deflecta* *H. typicalis* *H. latidentatus* (Kotlyar et al., 1991)	U. Tesero-lowest Mazzin *Towapteria scythica* (Bed 12) Perm. brachi.				
	3	Unit a, Bed 0 (Shale)	Ali Bashi Fm. *C. changxingensis* ?*Pleuronodoceras* ?*Pseudotirolites*			U. Tesero + basal Mazzin *H. typicalis* *H. latidentatus* L. Tesero	*Otoceras concavum* *O. boreale* (?) *Clarkina deflecta* *C.* cf. *subcarinata*	*Hypophiceras martini* *H. triviale*	*Otoceras concavum*?
	2			*Pleuronodoceras occidentale* with same conodonts as the overlying bed	L. Tesero 'Mixed fauna' Perm. brachi. & forams	Bellerophon Fm.	- - - - - - - - -	- - - - - - - - -	- - - - - - -
	1	Hambast Fm. U 7 *Paratirolites,* *Iranites* *Julfotoceras* *C. subcarinata* *Shevyrevites*	Ali Bashi Fm. *Paratirolites* Zone *C. subcarinata* *Shevyrevites*	*Paratirolites kittli* *C. subcarinata* *H. typicalis* Permian forams	Bellrophon Fm. Beds 17b Perm. brachi. & forams	*Hemigordius* *Globivalvulina*	- - - - - - - - - - - - - - - - - -	- - - - - - - - - - - - - - - - - -	- - - - - - - - - - - - - -
							Degerbols Fm.	Foldvik Creek Fm.	Imtachan Fm.

` The attribution of Beds 21 (upper) and 21 is thus a dilemma: they may belong either to upper Otoceras subdivision according to the existence of O. woodwardi, or to subdivision 6 according to the existence of I. isarcica. Taking into consideration the possible existence of Clarkina changxingensis, C. deflecta and the uneven surface immediately below, a kind of condensation of reworking could be assumed.

Note 3: Lithologically and faunistically Bed 5 corresponds to Mixed Bed 1 of Meishan and thus to Subdivision 4. Bed 6 is also enclosed in Subdivision 4 due to faunal similarity.

staechei (Wang, 1998; Orchard and Krystyn, 1998) or none (Kozur, 1996). Stage 4—*I. isarcica* (generally agreed). Opinions on Stage 3 are controversial but this stage, being post-*parvus*, is of less significance in boundary demarcation and is characterized by transitional morphology on lateral elevation, and so can be neglected in a broad sense of lineage. We try to avoid the usage of subspecies of *parvus* for the marker of PTB because it is still disputed and there is as yet no thorough discussion of their distribution in the world. Such a situation will cause correlation problems if the subspecies are used as PTB index fossils. Trying to reach a consensus, we propose a more concise lineage consisting of *H. latidentatus* (and *H. latidentatus preparvus*) *H. parvus*—*I. isarcica* (Figure 4).

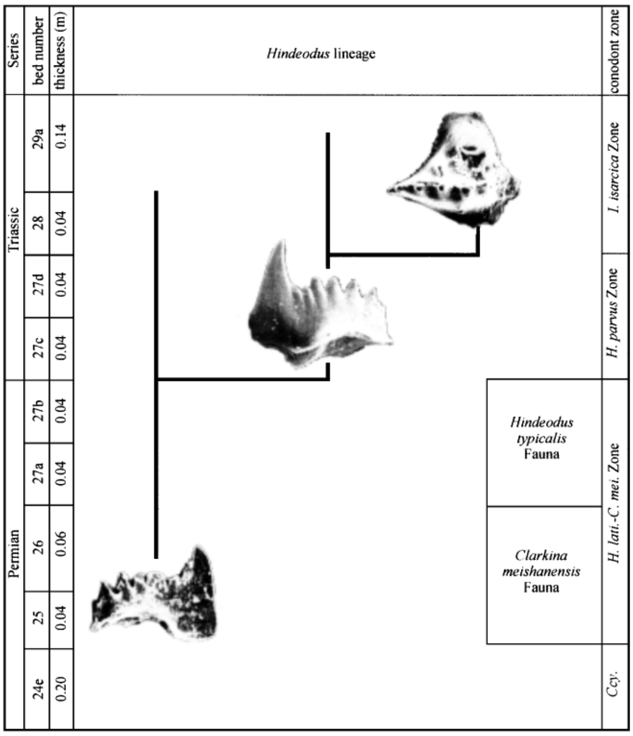


Figure 4 Hindeodus evolutionary lineage at the Permian-Triassic boundary Ccy.—Clarkina changxingensis yini Zone; H. lati.- C. mei.—Hindeodus latidentatus - Clarkina meishanensis.

With *parvus* approved as PTB marker, the age of *Otoceras* should be reconsidered. In the Wengener Halvo section, Greenland, above the disconformity surface lie the *Hypohiceras triviale* and *martini* zones, 15 m and 20 m thick respectively, representing the lower *Otoceras* Zone. The horizon 37 m above the disconformity surface is signalized by *O. boreale* and *M. demissum*. *Ophiceras commune* together with *Claraia stachei*, representing the *isarcica* Zone, lies at about 75 m. It was once reported that *H. latidentatus* occurs in the *subdemissum-boreale* Zone (Kozur, 1993), but the occurrence has not been confirmed by illustration, so we still set the PTB below the *subdemissum* Zone. In the Griesbach Creek and Otto Fiord sections, Arctic Canada (Tozer, 1967; Henderson and Baud, 1996), above the disconformity surface are local clastics with Permian fossil fragments. From the overlying basal shale begins the Otoceras bed. It is subdivided into a lower *Otoceras* (*O. concavum*) bed and an upper *Otoceras* (*O. boreal*) bed. The lower *Otoceras* bed contains Changhsingian conodonts. The upper *Otoceras* bed lies above a thin fissile black shale, where *O. boreale* appears, but at Griesbach Creek *O. concavum* also co-occurs at this level. At Otto Fiord *H. parvus* occurs about 31.5 m above the disconformity surface, a few meters below the last occurrence of *O. boreale*, so here *parvus* Zone largely overlaps *boreale* Zone. It is evident now that the Arctic lower *Otoceras* Bed and part of upper *Otoceras* Bed is Permian, not Triassic. Orchard and Krystyn (1998) subdivided the Himalayan *Otoceras* Beds into a lower *latilobatum* and a higher *woodwardi* Zone. Their demarcation line is oblique to time horizon and thus heterochronic, and both are correlated to *H. parvus* and lower *Isarcicella* Zones. There is as yet no *Otoceras* occurrence below *parvus* Zone. At Meishan and Shangsi (Sichuan Province) sections, the *Hypophiceras* fauna and *Otoceras?* occur in the clay beds (Beds 25–26 at Meishan) below PTB. At Guryul Ravine of Salt Range, the FAD of *Otoceras woodwardi* also precedes *parvus*. Graphic correlation has been discussed in Sweet (1992) and briefly introduced in Yin et al. (1996). The conclusion is that the FAD of *parvus* predates that of *Otoceras* but all occur in one Standard Time Unit and can not be subdivided.

In view of the above statement, the *Otoceras*-bearing strata should be subdivided into two beds. The Lower *Otoceras* Bed, containing only *O. concavum* and its equivalents *Hypophiceras* (*triviale*, *martini* and *changxingense*), is latest Permian in age. The Upper *Otoceras* Bed contains *latilobatum*, *woodwardi* and *boreale*, which mainly corresponds to the *parvus* Zone, with the exception that *woodwardi* may extend onto the lower *isarcica* Zone. Because the base of the Griesbachian Substage was initially defined by the FAD of *Otoceras concavum*, it spans the uppermost Permian and the lowest Triassic. In this text, 'Griesbachian' is used to represent the Lower Induan, excluding the *concavum* bed. The Induan Stage, formally recognized by STS as the basal stage of Triassic, should be accordingly defined as by the FAD of *parvus* rather than *Otoceras*.

Sequence stratigraphy and cyclostratigraphy

During the PTB interval the Lower Yangtze, where the Meishan section is located, was a rifted block in the NE part of the archipelagic Tethys (Yin et al., 1999; Yan and Yin, 1999). This block inclined northwestward from Songjiang to Hushan (Figure 5). The facies changed from carbonate platform to offshore. The inclination was interrupted by a SW-NE uplift (Niutoushan in Figure 5). Meishan was located in an intra-platform depression between the uplift and platform, thus showing transitional aspects in facies, platform to slope, with small-scale turbidites in middle Changhsingian. The palaeo-latitude was ca 20˚N (Liu et al., 1999).

Three third-order sequences are established for the Changhsingian -"Griesbachian" (lower Induan) strata at Meishan Section D and can be correlated within the isochronous stratigraphic framework across various facies of Lower Yangtze (Zhang et al., 1997). They are named SQ1, SQ2 and SQ3 in ascending order, corresponding roughly to the lower and the upper part of Changhsingian Stage and the 'Griesbachian' Substage.

The Changhsingian-'Griesbachian' strata of Meishan are mainly carbonates and shales, making semi-quantitative determination of the water depth difficult. We have developed the ecostratigraphic approach of this geological interval (Yin et al., 1995), specially designed to incorporate habitat types of fossil biota to palaeobathymetry, and subsequently to relative sea level changes in Yangtze Platform.

The base of SQ1 is a first-type sequence boundary (SB1). A marked fall of sea level took place at the end of Wuchiapingian. Meishan of Changxing was Habitat Type III (abbreviated as HT III) in the middle-late Wuchiapingian and shallowed up to HT II at the end of Wuchiapingian. The top of SQ1 and both bases and tops of SQ2 and SQ3 are second-type sequence boundary surfaces (SB2). The base of SQ2 is placed between Beds 15 and 16 and the base and top of SQ3 are respectively between Beds 24d and 24e and between Beds 39 and 40. The bases of SQ2 and SQ3 are wavy, with fillings of thin calcareous limonitic mudrocks and abraded bio-clastics in interwave depressions. The microfacies across these boundary surfaces are discontinuous. The rocks below the surfaces are of reverse grading beddings. Across the boundary, HT III$_1$ replaced HT III$_2$ and shallow habitat types moved basinward to produce progradational

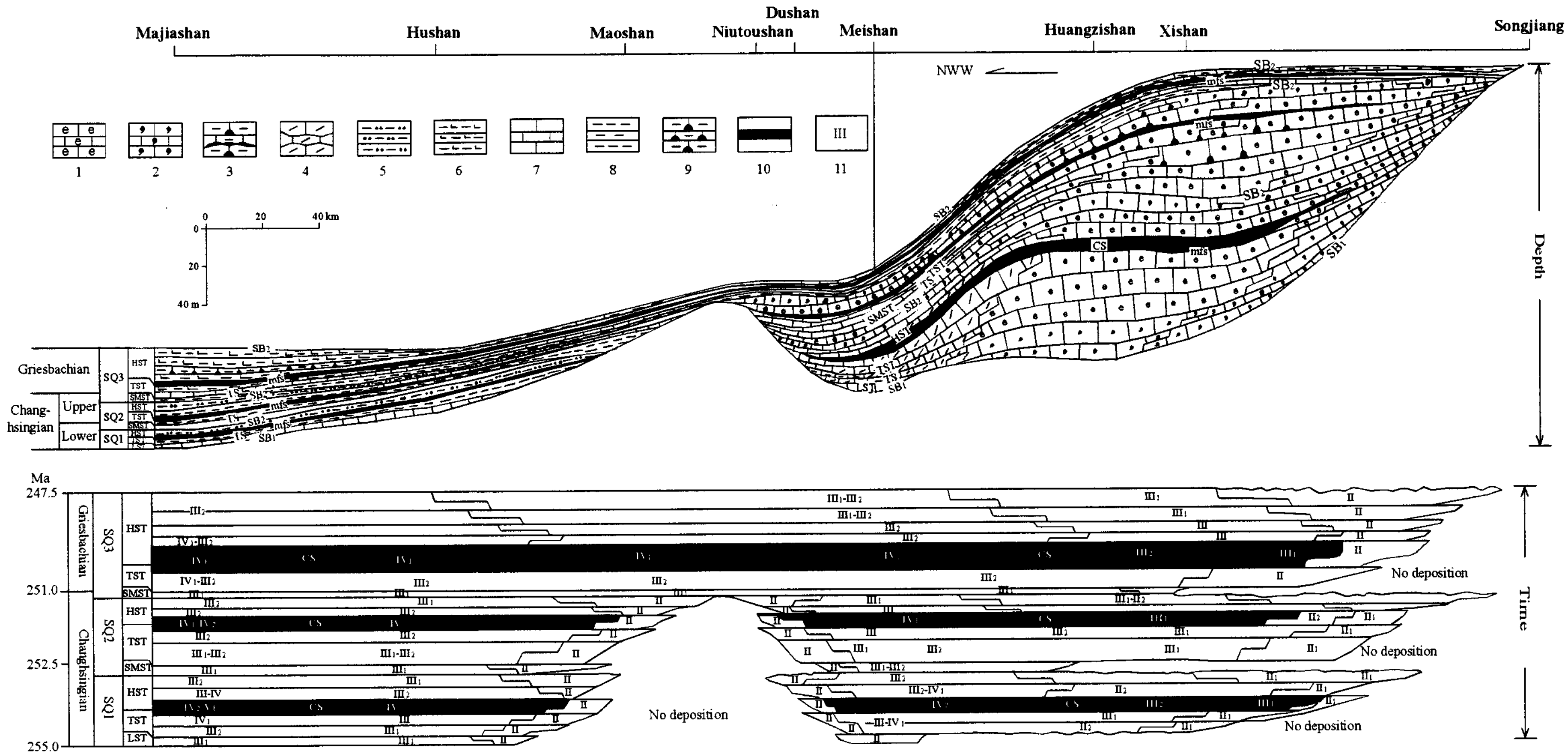


Figure 5 Schematic diagram of the Changhsingian-Griesbachian sequence stratigraphy of the Lower Yangtze region, showing the paleogeographic setting of Meishan SB1: type 1 sequence boundary; SB2: type 2 sequence boundary; TS: transgressive surface; mfs: maximum flooding surface; LST: lowstand systems tract; TST: transgression systems tract; HST: highstand systems tract; SMST: shelf margin systems tract; I, II, III, ...: habitat types. 1. open carbonate platform system; 2. restricted or semi-restricted carbonate platform system; 3. warps in carbonate platform; 4. front slope of platform margin system; 5. silty mudstone facies of offshore system; 6. calcareous mudstone facies of offshore system; 7. micrite facies of offshore system; 8. siliceous mudstone facies of offshore system; 9. nodular limestone facies of offshore system; 10. condensed section of maximum transgression; 11. habitat type. Following is the explanation of the Habitat Types (HT, Yin et al., 1995) used in this paper. HT II: intertidal, foreshore and shoreface habitat type; HT III: upper neritic habitat type (roughly corresponding to upper offshore, or inner shelf, or water depth between normal and storm wave bases); HT III_1: upper upper neritic (ca. 10-30 m) habitat type; HT III_2: lower upper neritic (ca. 30-50 or 60 m) habitat type; HT IV_1: upper lower neritic (ca. 50 or 60-100 m) habitat type; HT IV_2: lower lower neritic (ca. 100-200 m) habitat type.

parasequences set. Therefore, short-term exposures on land or small hiatuses existed at the sequence boundaries. Although there is no evident mark of exposure or absence of strata at the top of SQ3, the parasequence stacking patterns change abruptly. They are progradational below the boundary but retrogradational above it.

Above the transgressive surface (TS) of SQ1 in Meishan is packstone about one meter thick with scour channel fillings, which resulted from regional pass-by washing action as the scouring generally occurs above wave base at the beginning of transgression. TS of SQ2 coincides with the explosive event surface of *Clarkina changxingensis* population. This surface is also the transformation horizon from the underlying progradation to the overlying retrogradation parasequences pattern. The base of Bed 27a is TS of SQ3, which is the boundary from the stagnant anoxic shale of Bed 26 to the open-platform limestone of Bed 27. This transgression led to the occurrence and radiation of the Triassic new comers represented by *H. parvus*. Though there was a lag, it is thus an important biological change-over surface as well as facies transformation.

The maximum-flooding surface (mfs) of SQ1 is marked by the replacement from the dark gray medium-bedded bio-clastic packstone and wackestone with wavy beddings to the gray-black medium- to thin-bedded carbonaceous and siliceous micrite with horizontal lamination. Above mfs of SQ2 is medium-bedded carbonaceous bio-clastic micrite with slightly wavy beddings, containing a few radiolarians. The base of Bed 36 in Meishan section is mfs of SQ3, marked by the predominance of black shale with horizontal beddings. These mfs are the boundaries between lower transgression systems tract (TST) and upper high-stand systems tract (HST), indicating the transformation from retrogradation to aggradation.

SQ3 is worthy of further investigation. Its basal part (Beds 25-29) constitutes the Boundary Beds (Plate 1, fig.3, Peng and Tong, 1999) which can be traced throughout the Yangtze Platform. The Boundary Beds consist of the following elements. 1. Overlying strata: grayish green or yellowish thin calcareous mudstone, intercalated by marl, yielding *Claraia* and *Ophiceras*; 2. Top Clay (corresponding to Bed 28 of Meishan section): gray thin illite-montmorillonite (or illite), occasionally containing kaolinite, usually of volcanic origin, several centimeters to ten centimeters thick; 3. Boundary Limestone (Bed 27): gray medium-thick bedded siliceous or argillaceous-bearing or dolomitic micritic limestone, ca 20 cm thick; 4. Bottom Clay (Beds 25 and 26): gray thin illite and montmorillonite of volcanic origin, containing a little kaolinite, several centimeters to tens centimeters thick. The bottom clay is also found in Abadeh section of Iran, Nammal section of Pakistan, and the sections of Southern Alps (Table 1); 5. Underlying strata: gray thick siliceous micrite in carbonate facies such as at Meishan, or grayish brown thin chert or siliceous argillite in chert facies. The Boundary Beds are characterized by mixed fauna of the Permian relicts and Triassic newcomers. The former includes dwarfed brachiopods (*Crurithyris*) and conodonts (*Clarkina changxingensis*); the latter includes conodonts (*Hindeodus parvus*) and bivalves (*Claraia*).

The upper part of SQ3 is characterized by many cycles of mudrock-limestone couplets or bundles, traceable and correlatable in the whole Lower Yangtze region (Tong, 1997). The cyclic beds involve three conodont zones: *parvus* Zone, *isarcica* Zone and *carinata-planata* Zone. Five Yangtze sections including Meishan were studied with measurement and lithologic identification at centimeter level, and treated with time series analysis in thickness, lithology and proportion of argillaceous and calcareous components. Figure 6 shows five spectral density peaks correlatable in the Yangtze. Frequencies of Peaks 1 and 4 correspond to the ratio of eccentricity (100 ka) and precession (21.7 ka), suggesting that the cyclicity is probably related to the Milankovitch climate cycles. The time span of 'Griesbachian' Substage (SQ3) calculated by such postulation is 1.7

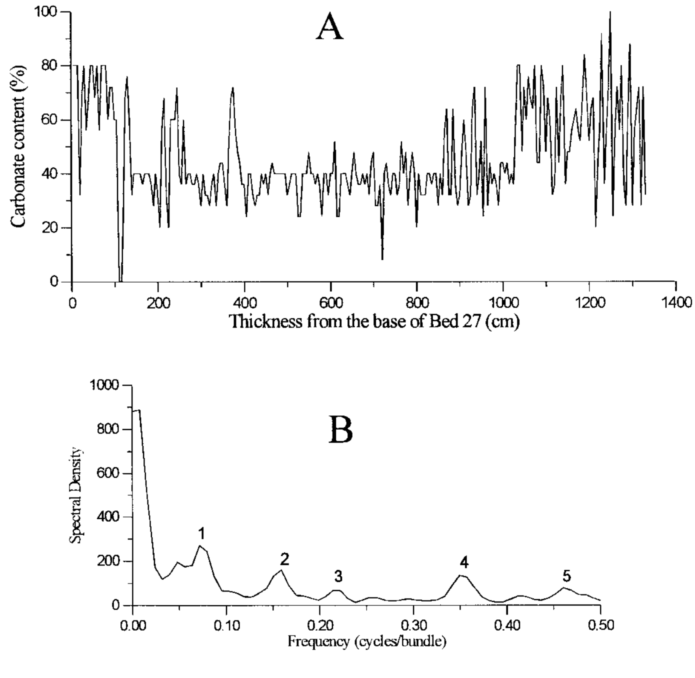


Figure 6 Distribution of the 'Griesbachian' carbonate content at Meishan section D in 5-cm interval (A) and the diagram of the spectral analysis based on the lithologic bundles (B).

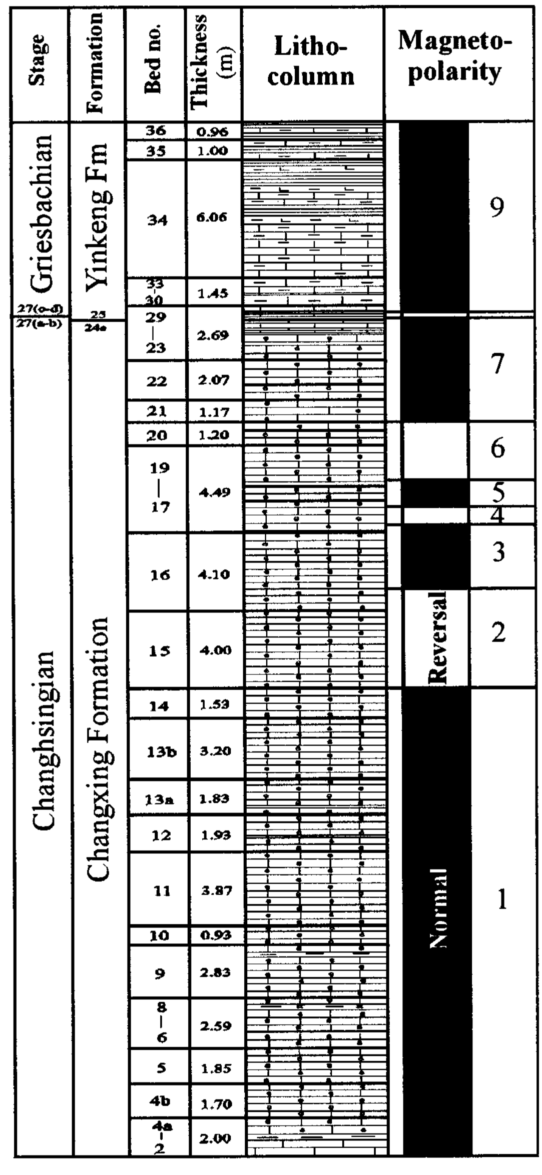


Figure 7 Magnetostratigraphy of Meishan Section D.

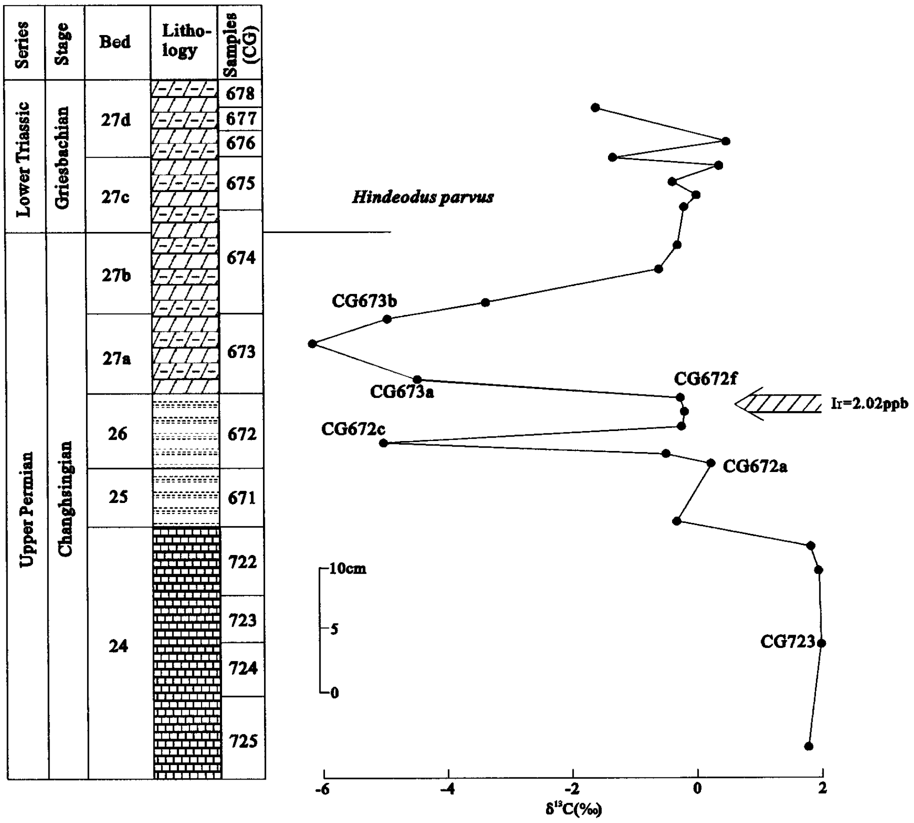


Figure 8 Stable carbon isotope values across the PTB at Meishan section (from Xu and Yan, 1993).

Ma, which is reasonable. However Peaks 2 and 3 do not accord with the period of obliquity (42 ka), so the above statement is a postulation rather than a conclusion.

Magnetostratigraphy

Recent research (Zhu and Liu, 1999) revealed that the Meishan section can be divided into five normal polarity subzones and four reversed polarity subzones (Figure 7). The lower part of the Changhsingian Stage has normal polarity and the upper part has both normal and reversed polarities. Remarkably, Bed 27 has reversed polarity which is inserted between normal polarities spanning PTB strata. The sampling of this research is much denser than previous ones. For Bed 27 the sampling is without interruption, and the tests have been made in the Ultra-conduct Lab of Kobe University. Magnetostratigraphic correlation with other sections is also presented in that paper and Jin et al. (1999).

Eventostratigraphy and chemostratigraphy

These have been discussed in Yin et al. (1996) and Yin (ed., 1996). Recent developments include the following aspects.

Besides the earlier $\delta^{13}C$ curves provided by Xu and Yan (1993) (Figure 8) and other authors, new curves have been presented in Jin et al. (2000, Figure 9), Bowling et al. (1998) and Hansen et al. (1999a). The latter two show a similar profile to previous works. However the former, made from Meishan Section B, only shows a lower depletion of $\delta^{13}C$ in Beds 25 and 26 but not the upper depletion in Bed 27 as displayed in Figure 8. Jin et al. (2000) assume that the upper depletion might reflect strong weathering. This is probable

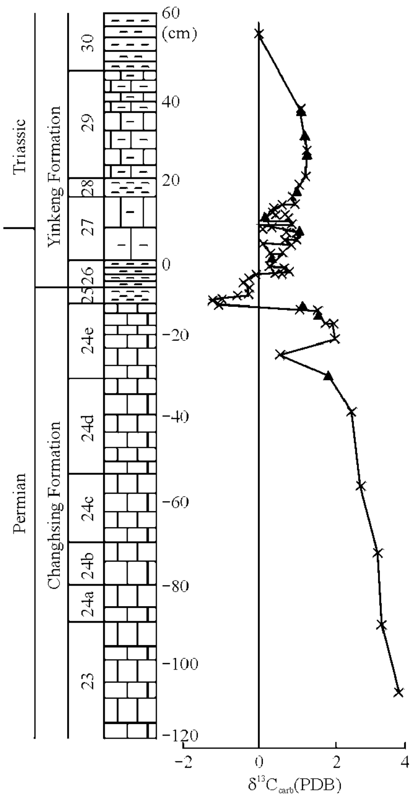


Figure 9 Stable carbon isotope values across the PTB at Meishan section B. Triangles represent replicate results of the same samples, provided by S. D'Hondt (pers. comm.) (from Jin et al., 2000).

Table 2 Radiometric dating of the PTB at Meishan section.

Bed	Claoué-Long et al., 1991	Renne et al., 1995	Bowling et al., 1998	Metcalfe et al., 1999	Mundil et al., 2001
36			250.2 ± 0.2 (U)	252.6 ± 1.2 (S)	
34				253.6 ± 1.3 (S) 249.2—253.5 (U)	
33			250.4 ± 0.5 (U)		
28			250.7 ± 0.3 (U)	251.7 ± 1.4 (S) 251.6 ± 0.3 (U)	
25	251.2 ± 3.4(S)	249.91± 0.15(Ar)	251.4 ± 0.3 (U)	252.4 ± 1.8 (S)	~253 (U)
20			252.3 ± 0.3 (U)		
7			253.4 ± 0.2 (U)		

S: SHRIMP U/Pb, U: conventional U/Pb (zircon), Ar: $^{40}Ar/^{39}Ar$.

since in other sections of the world there is usually only one depletion, and at Nammal section of Salt Range where two depletions occur, the lower one is considered to be due to diagenetic cement (Yin, ed., 1996).

Our suggestion of 3-phases' biotic extinction within the Boundary Beds (Yang et al., 1993; Yin and Tong, 1998) was challenged by Jin et al. (2000). They denied the lower phase within Bed 24, and diminished the significance of the upper phase at Bed 28, leaving only the main or middle phase at Beds 25-26. Their conclusion is that most genera disappeared within a short interval at that horizon, implying a sudden 1-phase extinction around 251.4 Ma. It should be noted that the same viewpoint has been previously demonstrated by our co-authors, Xu and Tong (*in* Yang et al., 1991), who also used a statistic method based on ranges of 362 species. Both 3-phase and sudden (1-phase) viewpoints were published in the same book (Yang et al., 1991), but supported by different phenomena. The 3-phase viewpoint found its provision from fossil range charts of several sections. These two viewpoints need further investigation.

Furthermore, Hansen et al. (1999b) claimed that the magnetic susceptibility curves could be used to correlate the PTB strata of Meishan with other parts of the world.

Radiometric dating

Table 2 shows data obtained from the Meishan section. Bed 25 is a white ash clay 13 cm below PTB, which gives an average age (by four author groups) of 251.23 Ma. Bed 28 is an ash clay 8 cm above PTB, which gives an average age (by two author groups) of 251.2 Ma. It may be relatively safe to set the PTB age briefly at 251 Ma. Mundil et al. (2001) declared a U/Pb single-crystal age of ~253 Ma for the PTB in Meishan. This however is remarkably older than both the above estimation and the 250.0 ± 0.3 Ma age ($^{40}Ar/^{39}Ar$) of the inception of main stage eruption of the Tunguss Traps (Renne et al., 1995), which is regarded as synchronous with the PTB. As there is as yet no notable radiometric dating in other parts of the world, pending further re-investigation we temporarily use 251 Ma for the age of PTB.

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