Geochemical Stratigraphy and Microvertebrate Assemblage Sequences across the Silurian/Devonian Transition in South China

ZHAO Wenjin[1,*], WANG Nianzhong[1], ZHU Min[1], Ulrich MANN[2], Ulrich HERTEN[2] and Andreas LÜCKE[2]

1 *Key Laboratory of Evolutionary Systematics of Vertebrates, Institute of Vertebrate Paleontology and Paleoanthropology, Chinese Academy of Sciences, Beijing 100044, China*
2 *Institute of Chemistry and Dynamics of the Geosphere ICG-4, Research Center Juelich GmbH, D-52425 Juelich, Germany*

Abstract: Carbon isotope ($\delta^{13}C_{org}$) analyses of non-marine clastic rocks and neritic carbonates and black shales spanning the Silurian/Devonian transition are compared from two richly fossiliferous sequences in Qujing of East Yunnan and Zoige of Sichuan, South China. The two sections, Xishancun and Putonggou sections in South China, reveal positive $\delta^{13}C_{org}$ shifts happening in the Upper Pridoli and Lower Devonian and reaching peak values as heavy as −25.2‰ (Xishancun) and −19.9‰ (Putonggou) in the lowermost Lochkovian following the first occurrence of the thelodont *Parathelodus* and the conodont *Icriodus woschmidti woschmidti* (only in Putonggou Section and together with *Protathyris-Lanceomyonia* brachiopod fauna). These results replicate a globally known positive shift in $\delta^{13}C_{org}$ from the uppermost Silurian to the lowermost Devonian. The $\delta^{13}C_{org}$ variations across the Silurian/Devonian Boundary (SDB) at the two sections in South China exhibit a shift in carbon isotopic composition similar to the detailed SDB curves from the borehole Klonk-1 drilled at top of the Klonk Global Standard Stratotype-Section and Point (GSSP) in the Prague Basin, Czech Republic. In addition, four microvertebrate assemblages, including the Liaojiaoshan, Xishancun, Yanglugou and Xiaputonggou assemblages, are recognized from the Silurian/Devonian transition exposed in the Xishancun and Putonggou sections, respectively. The results from both carbon isotope stratigraphy and microvertebrate assemblage sequences suggest that the SDB in South China is located at the base of the Xishancun Formation (between sample QX-20 and sample QX-21) in the Xishancun Section and the lower part of the Xiaputonggou Formation (between sample ZP-09 and sample ZP-10) in the Putonggou Section. The isotopic trend for organic carbon together with the changes of microvertebrate remains across the SDB can offer an approach to a potential correlation of the SDB from different sedimentary facies, which help to correlate the marine with non-marine deposits.

Key words: Carbon isotope stratigraphy, microvertebrate assemblages, Silurian-Devonian Boundary, marine and non-marine stratigraphic correlation, South China

1 Introduction

East Yunnan and West Qinling are two important areas for the study of the Silurian-Devonian Boundary (SDB) in South China. Many biostratigraphic attempts have been made to locate the SDB in both areas (Luo et al., 1985; Rong et al., 1987, 1990; XIGMR and NIGPAS, 1987a, b; Cai et al., 1994; Fang et al., 1994; Wang, 1995a, 1997, 2000; Shan et al., 1997; Rong and Chen, 2000), and raised the debates on the SDB because the indicator fossils (graptolite *Monograptus uniformis uniformis*, conodont *Icriodus woschmidti woschmidti* and trilobite *Warburgella rugulosa rugosa*) are not coexistent in South China.

Carbon isotope has been intensely used to study secular isotopic variations of ancient ocean water, and some variations in carbon isotopic composition of marine carbonate rocks and components (fossils, marine cements) or lake sediments have been used for chemostratigraphic correlations and paleoenvironmental interpretations (Veizer and Hoefs, 1976; Fischer and Arthur, 1977; Scholle and Arthur, 1980; Dean et al., 1986; Knoll et al.,

* Corresponding author. E-mail: zhaowenjin@ivpp.ac.cn

1986; Popp et al., 1986, 1997; Arthur et al., 1988; Hayes et al., 1989; Kaufman et al., 1991; Geldern et al., 2006; Mischke et al., 2009), in particular some reliable $\delta^{13}C$ curves of both inorganic carbon and organic samples were available for the SDB during the past 13 years (Hladíková et al.,1997; Veizer et al., 1999; Mann et al., 2001; Saltzman, 2002; Herten et al. 2004a, b, c; Buggisch and Mann, 2004; Buggisch and Joachimski, 2006; Gill et al., 2007; Małkowski and Racki, 2009). Since Mann et al. (2001) reported the first isotope curve based on organic carbon for the SDB from a fully cored borehole at the GSSP, some similar change curves of $\delta^{13}C_{org}$ across the SDB were provided at several locations including the sections from Ukraine, Turkey, USA, Morocco, Poland and China (Buggisch and Mann, 2004; Herten et al. 2004a, b, c; Zhao et al., 2010). Previous studies suggested a distinct positive excursion of $\delta^{13}C_{org}$ from the uppermost Silurian to the lowermost Devonian was related to the high bioproductivity, mass burial of organic carbon and transgression-regression of the 3rd order, and represented a global bioproductivity event (Mann et al., 2001). The distinct $\delta^{13}C_{org}$ trend across the SDB seems to provide a consistent chemostratigraphic tool for a worldwide correlation of the SDB (Zhao et al., 2010).

During the past three decades, the macrovertebrate and microvertebrate (scales, teeth, denticles and spines) fossils from the mid-Paleozoic have attracted much attention on account of their anatomical features, the diversity and the evolutionary significance, and proved useful for regional, paleocontinental or intercontinental geological correlations (Blieck and Turner, 2000; Zhao and Zhu, 2007). Various higher taxa such as thelodonts, chondrichthyans, acanthodians, placoderms, actinopterygians, and sarcopterygians have yielded a great variety of microvertebrate assemblages or even zonations in nearly all lithofacies (marine and non-marine deposits) since the performing of UNESCO-IUGS IGCP328 (1991–1996). The microvertebrate remains, such as thelodont scales, have a particularly great significance for the establishment of the SDB (Talimaa, 2000; Märss et al., 2007). Thus, the study on the microvertebrate assemblages across SDB will help to divide subtly the Siluro-Devonian sequences, reliably correlate marine and non-marine deposits in the mid-Paleozoic, and accurately locate the SDB worldwide.

The detailed geochemical analyses, and the research of microvertebrate assemblages from the uppermost Silurian to the lowermost Devonian in East Yunnan and West Qinling areas, may throw new light on the study of the SDB in South China. The purpose of this paper is to provide additional data for a better definition of the SDB in the Xishancun and Putonggou sections of South China by means of chemostratigraphy (including the content of carbonate and total organic carbon, stable isotopic ratios of organic carbon versus depth) and biostratigraphy (including microvertebrate assemblage sequences), thus helping to solve the long-standing debates over the SDB in South China.

2 Regional Setting and Stratigraphical Characteristics

The Silurian/Devonian transition is well preserved in Qujing of East Yunnan (non-marine facies) and Zoige of West Qinling (neritic facies) (Cai et al., 1994; Fang et al., 1994; Wang et al., 1998; Wang, 2000) (Fig. 1). Tectonically, the Qujing region is located in the southwest margin of the South China Block (SCB) during the mid-Paleozoic (Zhao and Zhu, 2007). However, there are many debates on the tectonic evolution of West Qinling (Zhang, 1987; Du, 1995; Yin and Huang, 1995; Yin et al., 1999; Cao and Hu, 2000; Feng et al., 2003). Here, we follow Cao and Hu (2000), who suggested that West Qinling as a part of the SCB was located at the northwest margin of the SCB during the mid-Paleozoic. The Siluro-Devonian biota of West Qinling shows the proximity to that from the Xiangzhou type of South China (XIGMR and NIGPAS, 1987a, b; Wang et al., 1998). The Silurian/Devonian transition in the two above mentioned areas should characterize two different kinds of Siluro-Devonian deposits in the SCB, the main body of Pan-Cathaysian Landmass Group (Xu et al., 1996; Zhao and Zhu, 2010) (Fig. 1).

In Qujing, the continuous strata from the Upper Pridoli to the lower Lochkovian are best exposed in the Xishancun Section close to the Xishancun Village (Fig. 2a), and the Paleozoic sedimentary basin (Qujing Basin) is referred to as the intercontinental marginal fault basin (Zheng and Zhang, 1989; Dong 1992; Zeng et al. 1992; Shan and Wang, 2000). The main sedimentary environments can be recognized as the gulf type and the tidal flat type (Fan and Liu, 1995). The change of transgression to regression and the basement fault activity controlled the formation and evolution of the basin (Zeng et al. 1992; Mei et al. 2004). The Guangxi Movement during the Caledonian Tectonic Cycle at the turn of the Silurian and Devonian had a strong effect on the evolution of the Qujing Basin (Wu, 2000), in particular the sedimentation during the period. The continuous SDB sequence in the Xishancun Section, including the upper part of the Yulungssu Formation and the lower part of the Xishancun Formation, is well-developed and exposed with abundant fossils (Fig. 2b). The upper part of the Yulungssu Formation is characterized by black shales, considered upper black fissile shale because the rock can

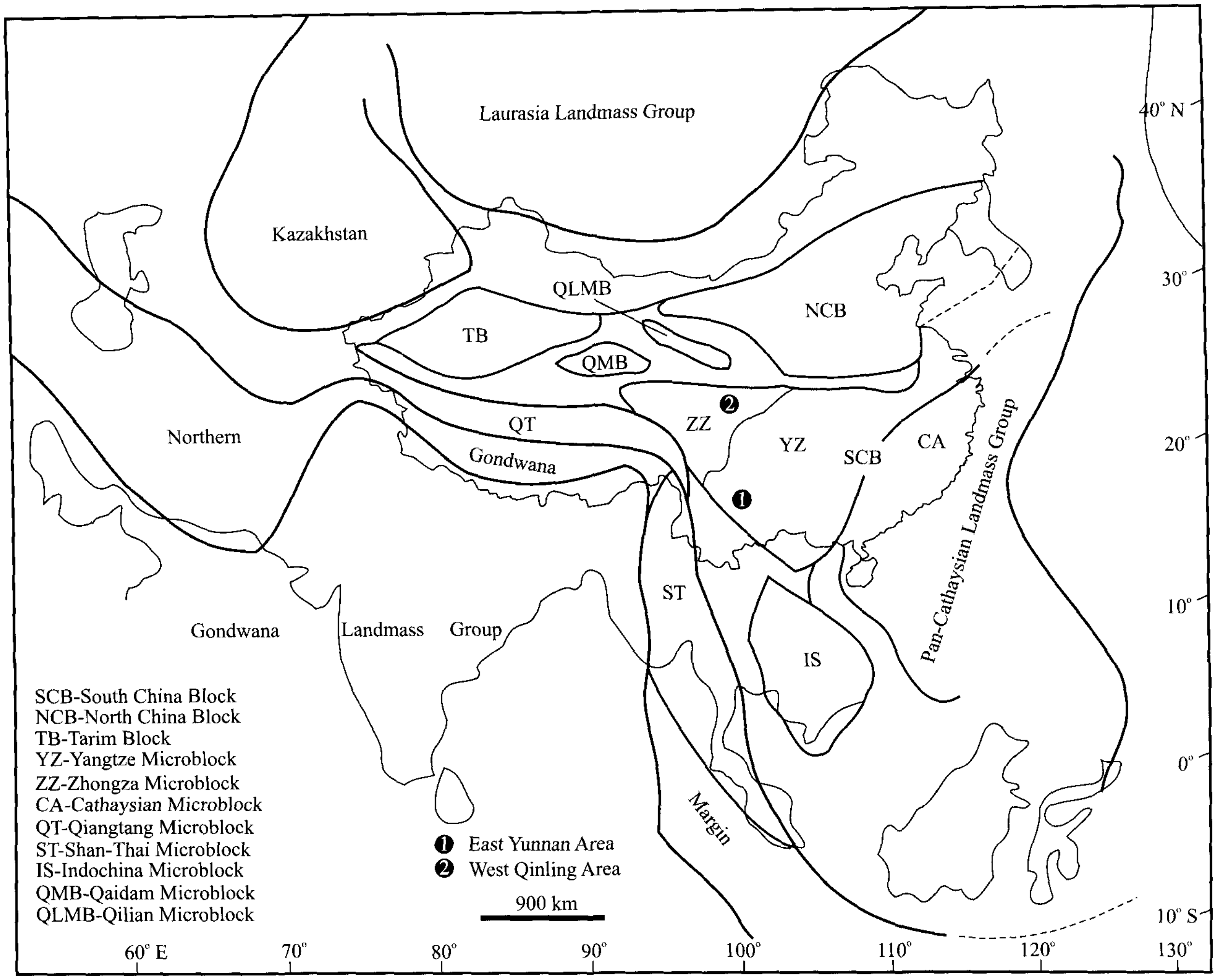

Fig. 1. Outline map showing the location of the South China Block in Silurian and Devonian (revised from Xu et al., 1996).

be readily broken into thin layers on weathering (Fang et al., 1985). The lower part of the Xishancun Formation is represented by the grey–yellow sandstone and siltstone intercalated with the silty shale (Fang et al., 1985). The fossils spanning the SDB in the section were mainly composed of invertebrates (Wang et al., 1992; Cai et al., 1994; Fang et al., 1994), spores and plant fossils (Li and Cai, 1978; Gao, 1981; Fang et al., 1994; Hao et al., 2007; Xue, 2009), and fossil fishes, including the endemic galeaspids, placoderms and sarcopterygians, and microvertebrate remains (Liu, 1965, 1975; P'an and Wang, 1978; Wang and Dong, 1989; Wang, 1995a, b, 2000; Zhu and Schultze, 1997; Gai and Zhu, 2007) (Fig. 2b).

In West Qinling, the Silurian/Devonian transition, including the Yanglugou and Xiaputonggou formations with abundant fossils, are well developed in Zoige (Sichuan Province) and Tewo (Gansu Province) areas (XIGMR and NIGPAS, 1987a, b; Wang et al., 1998) (Fig. 3a). The SDB sequence in the Putonggou Section is mainly composed of grey phyllite-like calcareous shale intercalated with several beds of limestones (with metamorphosed) (Fig. 3b). Rich fossils in the SDB sequence of the Putonggou Section include conodonts, brachiopods, corals, spores and vertebrate remains, indicating a shallow sea shelf facies (Wang, 1981a; XIGMR and NIGPAS, 1987a, b; Wang et al., 1998).

3 Samples and Methods

Based on previous biostratigraphic studies (Wang, 1980, 1981a, b, 1995a, b; Fang et al., 1985, 1994; XIGMR and NIGPAS, 1987a, b; Cai et al., 1994; Wang et al., 1998), we collected 21 samples at about 0.6 m intervals from a 12 m section (Xishancun Section – QX Section) in East Yunnan, and 28 samples at about 1.5 m intervals from a 48 m section (Putonggou Section – ZP Section) in West Qinling (Figs. 4 and 5). Every sample here, in fact, includes two kinds of sample, one (3 kg in weight) is of microvertebrate fossil sample and another (200 g in

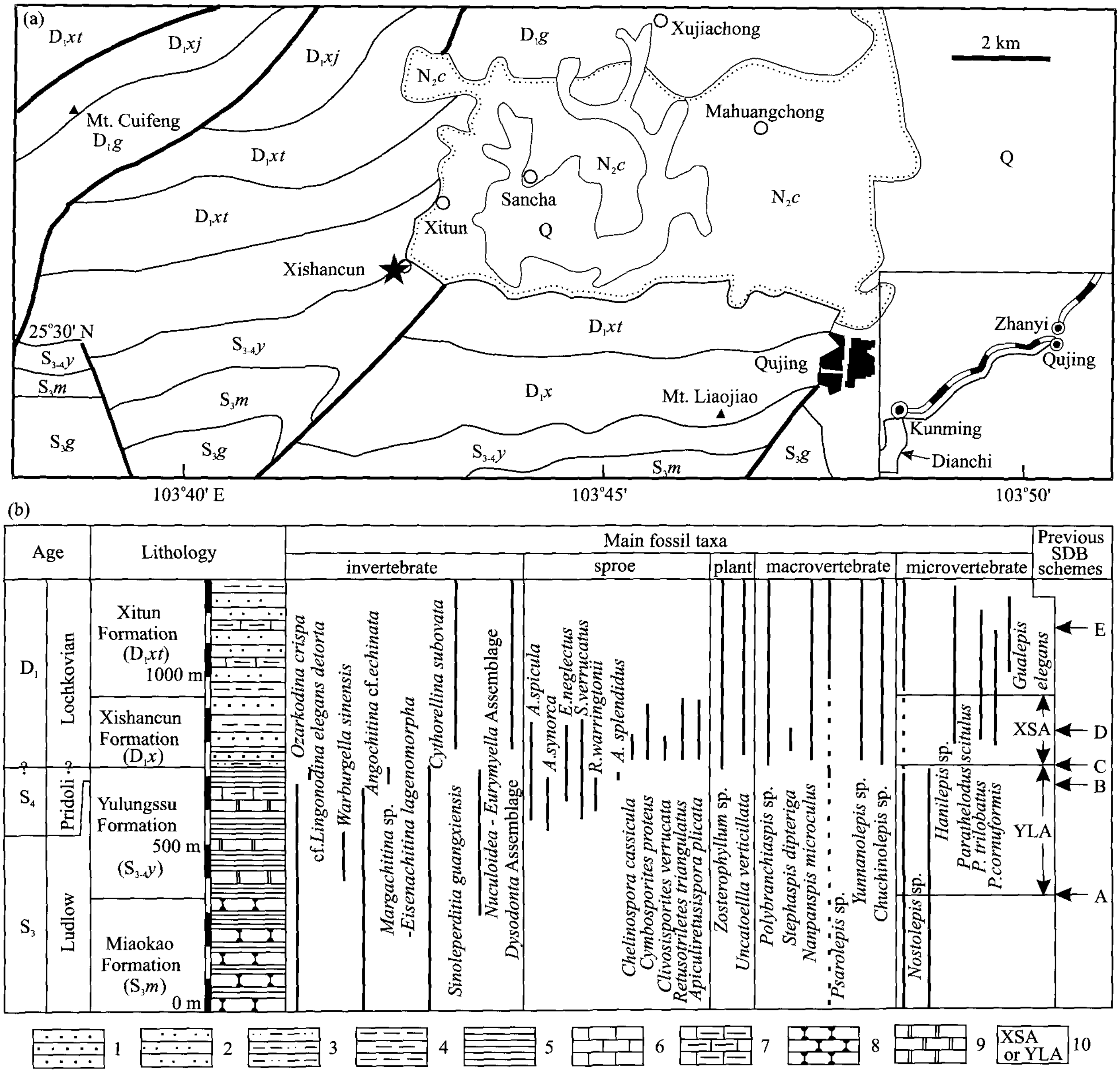

Fig. 2. (a) Generalized map showing geologic aspects of the Qujing region and location of the Xishancun Section (revised from Fang et al., 1985); (b) The geologic columnar section of Silurian and Devonian sequence and biostratigraphy in Qujing, East Yunnan, South China (revised from Fang et al., 1985; Wang, 2000).

1, Sandstone; 2, siltstone; 3, silty mudstone; 4, mudstone; 5, shale; 6, limstone; 7, muddy limestone; 8, strumous limestone; 9, dolomite; 10, Xishancun assemblage or Yulungssu assemblage.

weight) is of geochemical sample. All sampling positions were placed near to the potential SDB location in the two sections (Figs. 2b, 3b and 5). We studied the microvertebrate remains picked from the samples, and analyzed the contents of organic carbon, carbonate carbon and total sulfur, in order to check the availability of organic carbon for isotopic analyses.

The samples for the study of microvertebrate remains were treated with dilute acetic acid in the laboratory of the Institute of Vertebrate Paleontology and Paleoanthropology (IVPP), Chinese Academy of Sciences (CAS). The samples for the geochemical analysis were measured and analyzed in the laboratory of the Institute of Chemistry and Dynamics of the Geosphere ICG-4, Research Center Juelich GmbH, Germany. The detailed measurement process about the contents of total organic carbon (TOC), carbonate carbon, total sulfur (TS) and the $\delta^{13}C_{org}$ values was introduced in one of our recent papers (Zhao et al., 2010). Organic carbon and sulfur contents of individual rock powders were determined by use of a Leco carbon-sulfur analyzer, and the whole rock samples for isotopic analyses of organic carbon were analyzed online

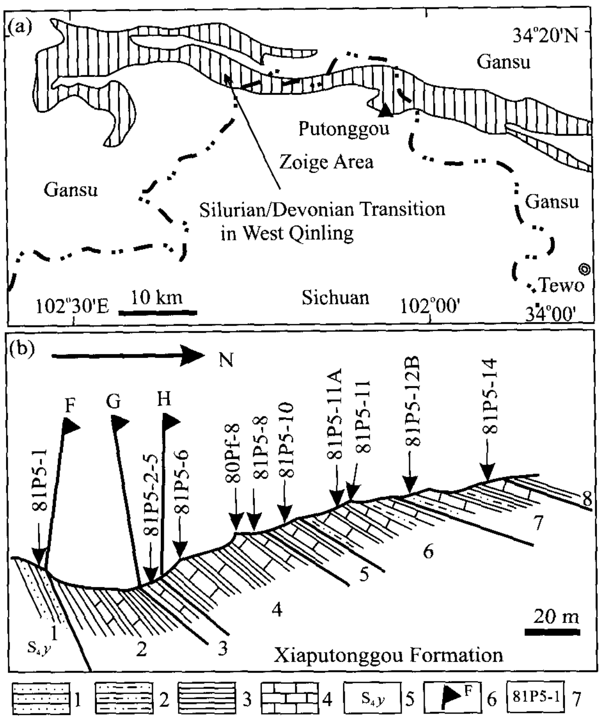

Fig. 3. (a) The distribution of Silurian/Devonian transition in the West Qinling area (revised from XIGMR and NIGPAS, 1987a); (b) The cross-section of the Silurian/Devonian transition and the previous sample localities at the Putonggou Section (revised from XIGMR and NIGPAS, 1987a).

1, Fine sandstone; 2, silty mudstone; 3, shale; 4, limestone; 5, Yanglugou Formation; 6, previous Silurian/Devonian boundary (SDB) scheme; 7, previous sample number.

by an Optima (Micromass Ltd.) isotope ratio mass spectrometer. Determinations were carried out by comparison with internal reference samples, which are calibrated against the Vienna PeeDee Belemnite standard (VPDB). Accuracy and precision was controlled by replicate measurements of laboratory standards and was better than ± 0.1‰ (1σ) for carbon isotopes.

4 Geochemical Results and Chemostratigraphy

4. 1 Geochemical results

In the Xishancun Section, the values of TOC and TS contents are not high, ranging from 0.03% to 0.19% and from 0% to 0.04%, respectively. The $CaCO_3$ contents in the section show a distinct change trend. The values from sample QX-06 to sample QX-16 fluctuate within 5%. Then a distinct increasing trend is observed from sample QX-16 to sample QX-24, the values vary from 5% to 30%. Subsequently the values also undulate within 5%. The $\delta^{13}C_{org}$ values mainly vary between from −28.6‰ to −25.2‰, and exhibit two individual peak values (positive shift) in samples QX-21 (−25.5‰) and QX-13 (−25.2‰), and two individual nadirs (negative shift) in samples QX-25 (−28.6‰) and QX-07 (−27.5‰) (Fig. 4).

The geochemical results from the Putonggou Section in West Qinling are very similar to those in the Xishancun Section. The values of TOC and TS contents are ranging from 0.03% to 0.17% and from 0% to 0.07%, respectively. The $CaCO_3$ contents are apparently related to the lithological change. The values in shales or sandstones are very low, and those in limestones are very high. The $\delta^{13}C_{org}$ values vary between −26‰ and −23‰, and mainly exhibit five reliable peak values and seven reliable nadirs in the Putonggou Section, West Qinling (Zhao et al., 2010) (Fig. 5).

4.2 Chemostratigraphy in East Yunnan and West Qinling

The lower values of TOC and TS contents from three sections in the SCB are mainly related to the type and amount of organic matter, preservation potential and sedimentary rate. Here we try to fix the SDB in two sections from SCB, mainly based on the carbon isotopic variation pattern encountered in the Prague Basin, Turkey and Morocco. We refer to the overall trend line at the individual sections in order to avoid short-time local influences such as short blooms by primary producers.

Based on the correlation of $\delta^{13}C_{org}$ variations among the Xishancun, Esenyali (Turkey) and Klonk-1 (close to GSSP) sections, it is likely to place the SDB in the Xishancun Section in between sample QX-21 and sample QX-20, the base of Xishancun Formation or the top of Yulungssu Formation (Fig. 6). This result is based on the correlation with the Klonk-1 and Esenyali sections (Mann et al., 2001; Herten et al., 2004c) with some distinct peak levels of $\delta^{13}C_{org}$. The peaks at the locations of samples QX-21 and QX-13 in the Xishancun Section correspond to the peaks occurring at depth levels of 24.78 m and 25.84 m in the Klonk-1 Section and the peaks at depth levels of 36.60 m and 43.66 m in the Esenyali Section, respectively.

Recently, we have discussed the correlation of $\delta^{13}C_{org}$ variations among the Putonggou, Morocco, and Klonk-1 (close to GSSP) sections (Zhao et al., 2010). It is likely to place the SDB in the Putonggou Section in between sample ZP-10 and sample ZP-09, the lower part of the Xiaputonggou Formation (Fig. 7).

5 Microvertebrate Assemblages

In Qujing, East Yunnan, rich microvertebrate remains were recorded from Ludlow to Lower Devonian (Wang, 1984, 1992, 1995a, b, 1997; Wang and Dong, 1989), together with abundant macrovertebrate remains including galeaspids, placoderms and sarcopterygians (Liu, 1965,

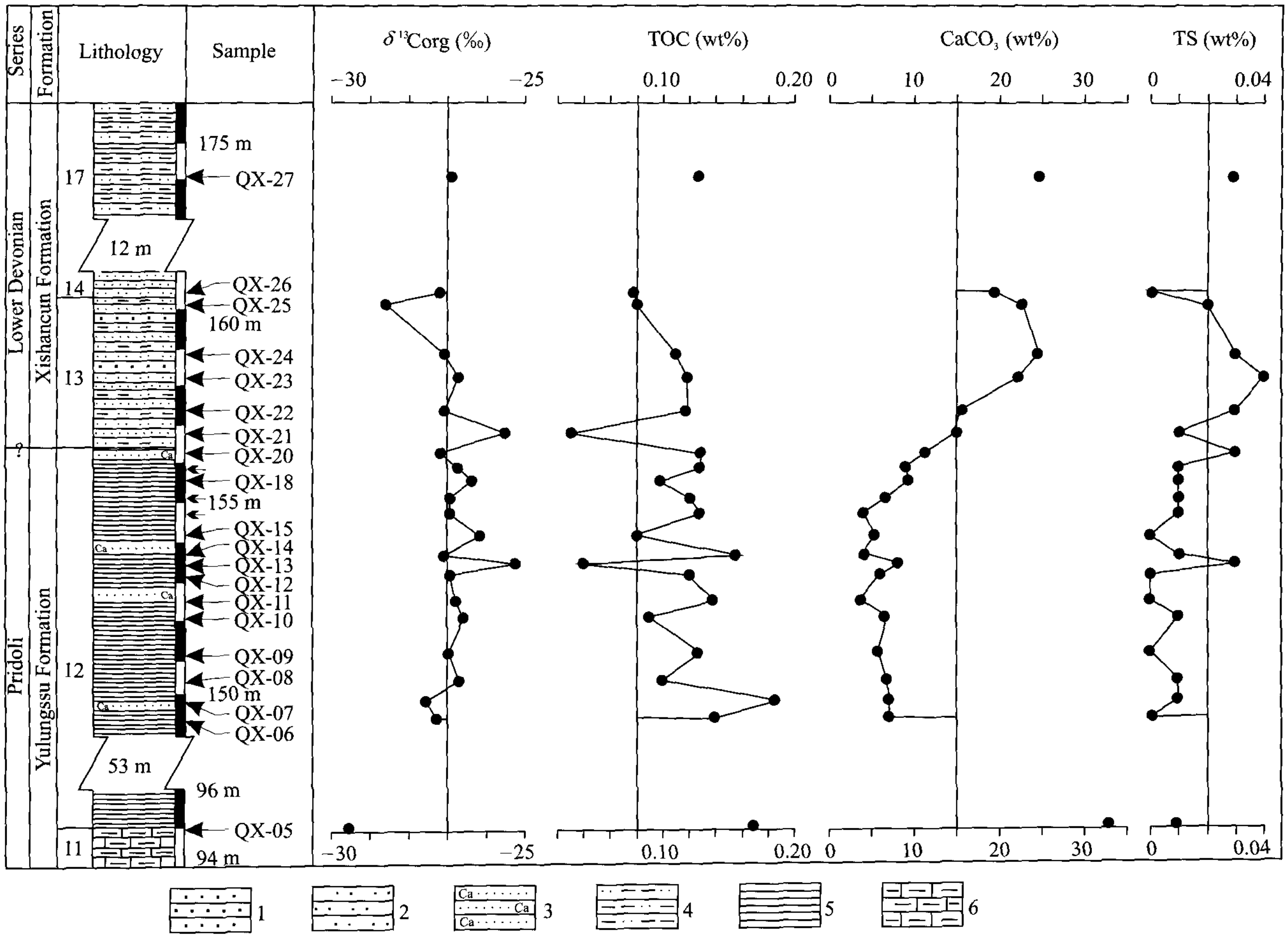

Fig. 4. The stratigraphic succession, carbonate and total organic carbon content as well as the stable isotopic ratio of organic carbon versus depth in the Xishancun Section, East Yunnan of China.

1, Sandstone; 2, siltstone; 3, calcareous siltstone; 4, silty mudstone; 5, shale; 6, muddy limestone.

1975; P'an and Wang, 1978; Wang, 1995b, 1997, 2000; Zhu and Schultze, 1997; Gai and Zhu, 2007; Zhu et al., 2009). Since recently we failed to extract more microvertebrate remains from the Xishancun Section, the discussions on microvertebrate assemblages of Qujing are mainly based on the published data. In West Qinling, rich microvertebrate remains, collected and studied by Wang et al. (1998), showed a continuous microvertebrate assemblage sequence from Late Silurian to Early Devonian. To address the SDB issue, we extracted additional microvertebrate remains from the beds close to the traditional SDB in the Putonggou Section of West Qinling.

The microvertebrate remains across the Silurian/Devonian transition in Qujing include the acanthodians *Nostolepis sinica*, *N. striata*, *N.* sp. and *Hanilepis wangi* from the Yulungssu Formation (Gagnier et al., 1989; Wang and Dong, 1989), and the thelodonts *Parathelodus scitulus*, *P. trilobatus* and *P. cornuformis* from the Xishancun Formation (Wang, 1995a, 1997) (Fig. 2b). Zhao and Zhu (2010) recently summarized two vertebrate assemblages from the Yulungssu and Xishancun formations– the Liaojiaoshan and Xishancun assemblages, respectively. The Liaojiaoshan Assemblage should be equivalent to the *Nostolepis sinica* Assemblage of Zhu and Wang (2000) or the upper part of the *Hanilepis-Naxilepis* Assemblage of Wang (1995a, 1997), and the Xishancun Assemblage to the *Poracanthodes zoigenensis-P.* cf. *porosus* Assemblage or *Polybranchiaspis liaojiaoshanensis-Laxaspis qujingensis* Assemblage of Zhu et al. (2000), or to the lower part of the *Parathelodus-Polybranchiaspis* Assemblage of Wang (1995a, 1997). The microvertebrate remains in the Liaojiaoshan Assemblage are characterized by the acanthodians, and most of them are extensions of the elements from the underlying middle–lower part of the *Hanilepis-Naxilepis* Assemblage (Fig. 2b). The microvertebrate remains in the Xishancun Assemblage are represented by *Parathelodus*, which combines the features of *Thelodus* and *Turinia* (Wang, 1995a, 1997). Generally, *Thelodus* ranges from Wenlock to Pridoli, and *Turinia* is confined to Early–Middle Devonian (Gross, 1967; Turner, 1973; Karatajūtė-

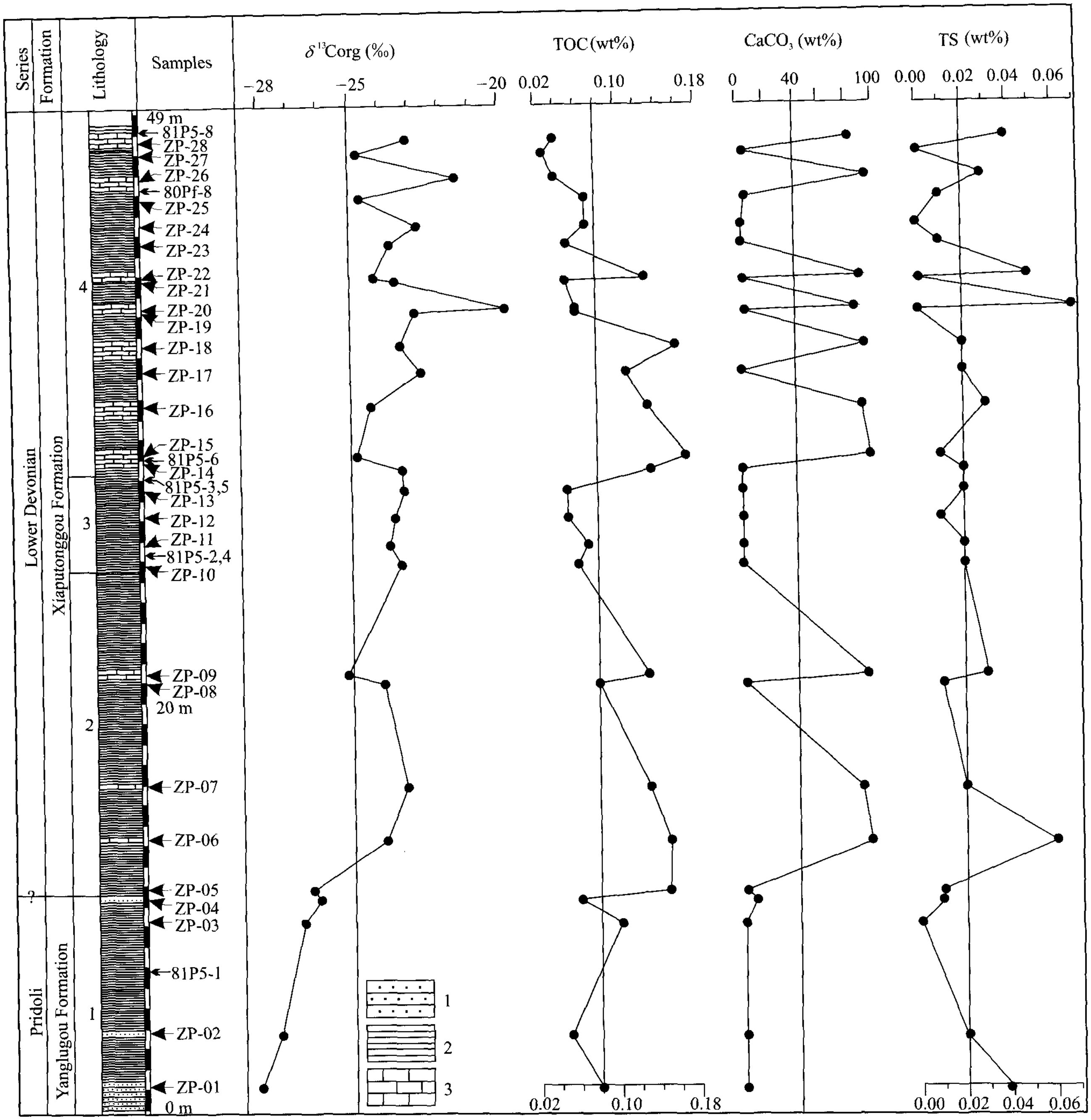

Fig. 5. The stratigraphic succession, carbonate and total organic carbon content as well as the stable isotopic ratio of organic carbon versus depth in the Putonggou Section (revised from Zhao et al., 2010).
1, Fine sandstone; 2, shale; 3, limestone.

Talimaa, 1978; Märss, 1986; Wang, 1995a, 1997; Märss and Miller, 2004). Considering its transitional features, *Parathelodus* probably ranges from the Pridoli to the Lochkovian of Early Devonian. Recently, we found some *Parathelodus* material from the Xiaputonggou Formation in the Putonggou Section, in conjunction with conodont *Icriodus woschmidti woschmidti* (Wang, 1981a; Li, 1987) (Fig. 8). Thus, *Parathelodus* is probably of the early Lochovian age, and the *Parathelodus*-bearing strata in Qujing should be referred to as the lower Lochkovian. We further suggest to place the level of the SDB in the Xishancun Section at the top of Yulungssu Formation or the base of the Xishancun Formation (Figs. 2b and 6), and corroborate the previous scheme based on the study of the spores, plants, ostracods, chitinozoans, conodonts and vertebrates (Ge et al., 1979; Wang, 1980, 1981b, 2000; Lin et al., 1984; Walliser and Wang, 1989; Wang et al., 1992; Cai et al., 1994; Fang et al., 1994; Hao et al., 2007) (Fig. 2b).

The microvertebrate remains across the Silurian/

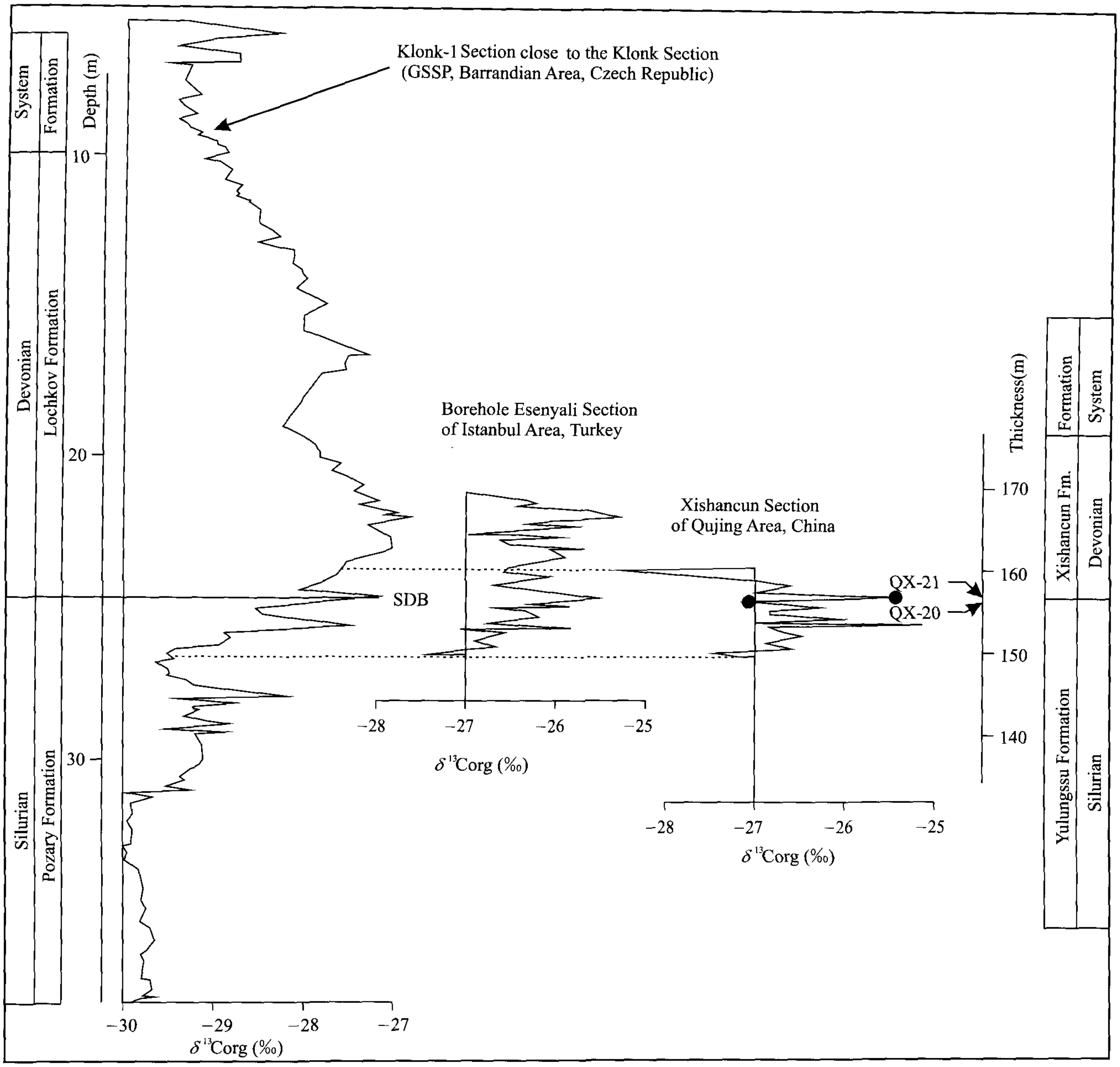

Fig. 6. Chemostratigraphic correlation of the isotopic variation of organic carbon among the borehole Klonk-1 drilled through the sedimentary rock sequence at the Global Standard Stratotype-Section and Point (GSSP) location (Klonk, Suchomasty, Czech Republic), the Esenyali Section (Turkey), and the Xishancun Section in East Yunnan, China (in ‰–Vienna PeeDee Belemnite).

Devonian transition in the Putonggou Section are composed of the acanthodians *Gomphonchus sandelensis* and Ischnacanthidae gen. indet from the upper part of the Yanglugou Formation (Wang et al., 1998), and the thelodonts (*Parathelodus scitulus*, *P. asiaticus* and *P. cornuformis*), the acanthodians (*Nostolepis gracilis*, *N. striata*, *N. tewonensis*, *Gansuichthys liui*, *Poracanthodes zoigenensis*, *Ischnacanthys* sp.) (Wang et al., 1998), the chondrichthyan (cf. *Arauzia*) and a small plate of pectoral fin of cf. *Chuchinolepis* (placoderm) from the lower part of the Xiaputonggou Formation (Fig. 8). The thelodont, placoderm and chondrichthyan materials are firstly discovered in West Qinling. In contrast to the rich and diverse microvertebrate remains from the Xiaputonggou Formation, the microvertebrate fossils from the Yanglugou Formation are poor and less diversified. In the Putonggou Section, we can recognize two microvertebrate assemblages: the Yanglugou Assemblage from the upper part of the Yanglugou Formation, and the Xiaputonggou Assemblage from the lower part of the Xiaputonggou Formation in association with the conodont *Icriodus woschmidti woschmidti* (Wang, 1981a; Li, 1987) (Fig. 8). Three species of *Parathelodus* in the Xiaputonggou Assemblage are also discovered in the Xishancun and

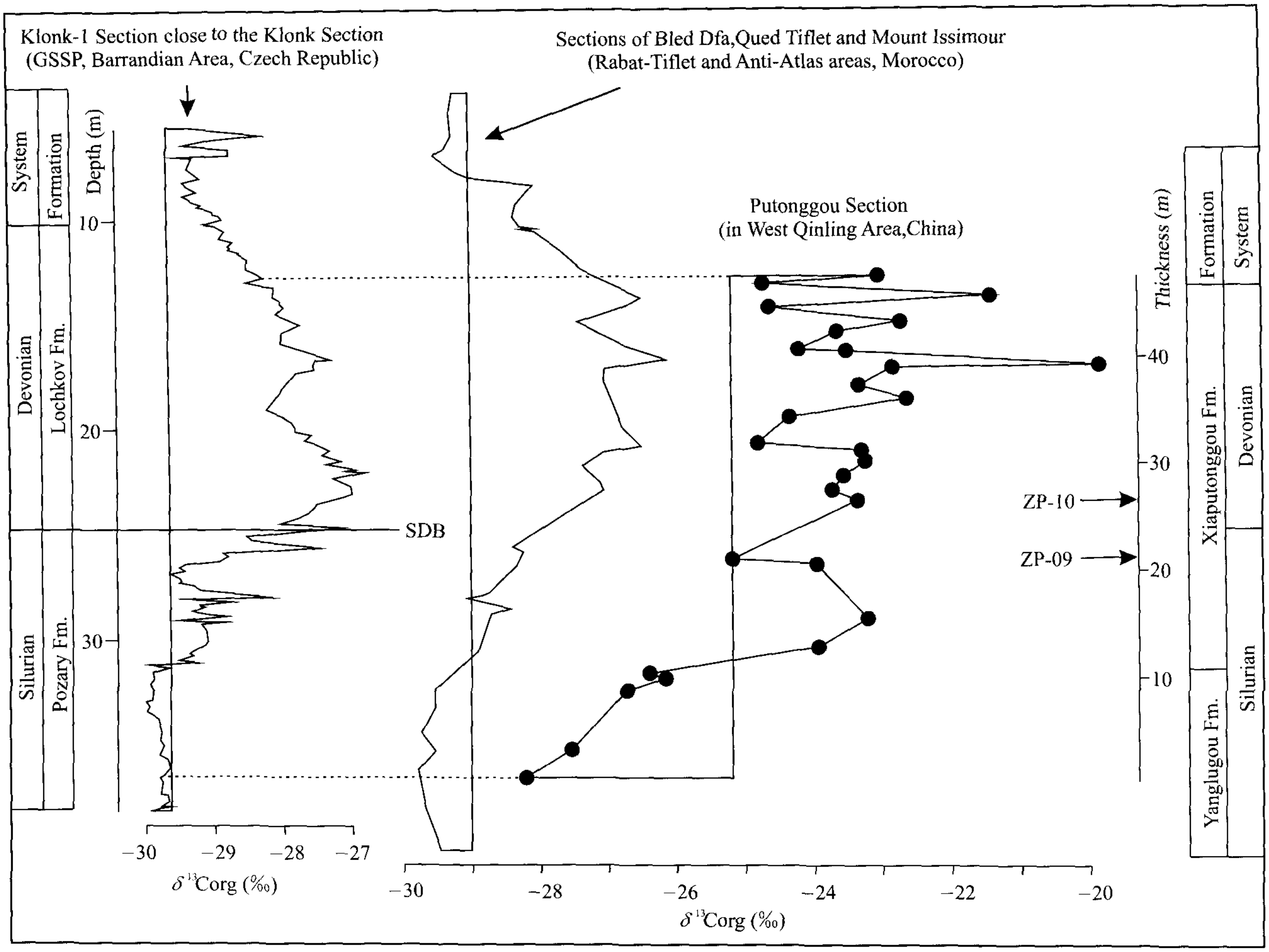

Fig. 7. Chemostratigraphic correlation of the isotopic variation of organic carbon among the borehole Klonk-1 drilled through the sedimentary rock sequence at the Global Standard Stratotype-Section and Point (GSSP) location (Klonk, Suchomasty, Czech Republic), the Morocco sections, and the Putonggou Section in West Qinling, China (in ‰–Vienna PeeDee Belemnite) (revised from Zhao et al., 2010).

Xitun (lower part) formations in East Yunnan (Wang, 1995a, 1997), indicating the related strata (such as the lower part of the Xiaputonggou Formation and Xishancun Formation) can be well correlated with the early Lochkovian age. Although the ischnacanthid *Gomphonchus sandelensis* has a long duration from the upper part of the Yanglugou Formation to the lower part of the Xiaputonggou Formation, an indeterminate form of Ischnacanthidae is confined within the Yanglugou Formation in the Putonggou Section (Wang et al., 1998) (Fig. 8). Thus, Wang et al. (1998) suggested that the Yanglugou Assemblage should be of the Late Pridoli age. A gap exists between these two microvertebrate assemblages (Fig. 8), and we cannot provide a relatively precise SDB in the Putonggou Section based on the study of microvertebrate assemblage. However, it is out of the question that the level of SDB in the section will be strictly restricted between sample ZP-02 (or 81P_5-1) and sample ZP-15 (or 81P_5-6) (Fig. 8).

6 Discussions and Conclusions

Although the conodont *Icriodus woschmidti woschmidti* has been collected from the Xiaputonggou Formation in West Qinling, the SDB in the area remains contentious because one cannot decide whether the lowest bed of *I. woschmidti woschmidti* in the area represents its first appearance (Rong et al., 1987). As for the level of SDB in East Yunnan, it is a more puzzling question because of the lack of any indicator fossils. The present research on the carbon isotope stratigraphy together with microvertebrate assemblages has considerably increased our knowledge of SDB, and may help to clarify the debates on the study of SDB in these two areas.

Based on the different groups of fossils found in the Xishancun Section, the SDB was mainly placed at five positions (Fig. 2b) as follows: scheme A, at the base of the Yulungssu Formation according to *Warburgella* (*rugulosa*) *sinensis* (Wu, 1977); scheme B, at the base of

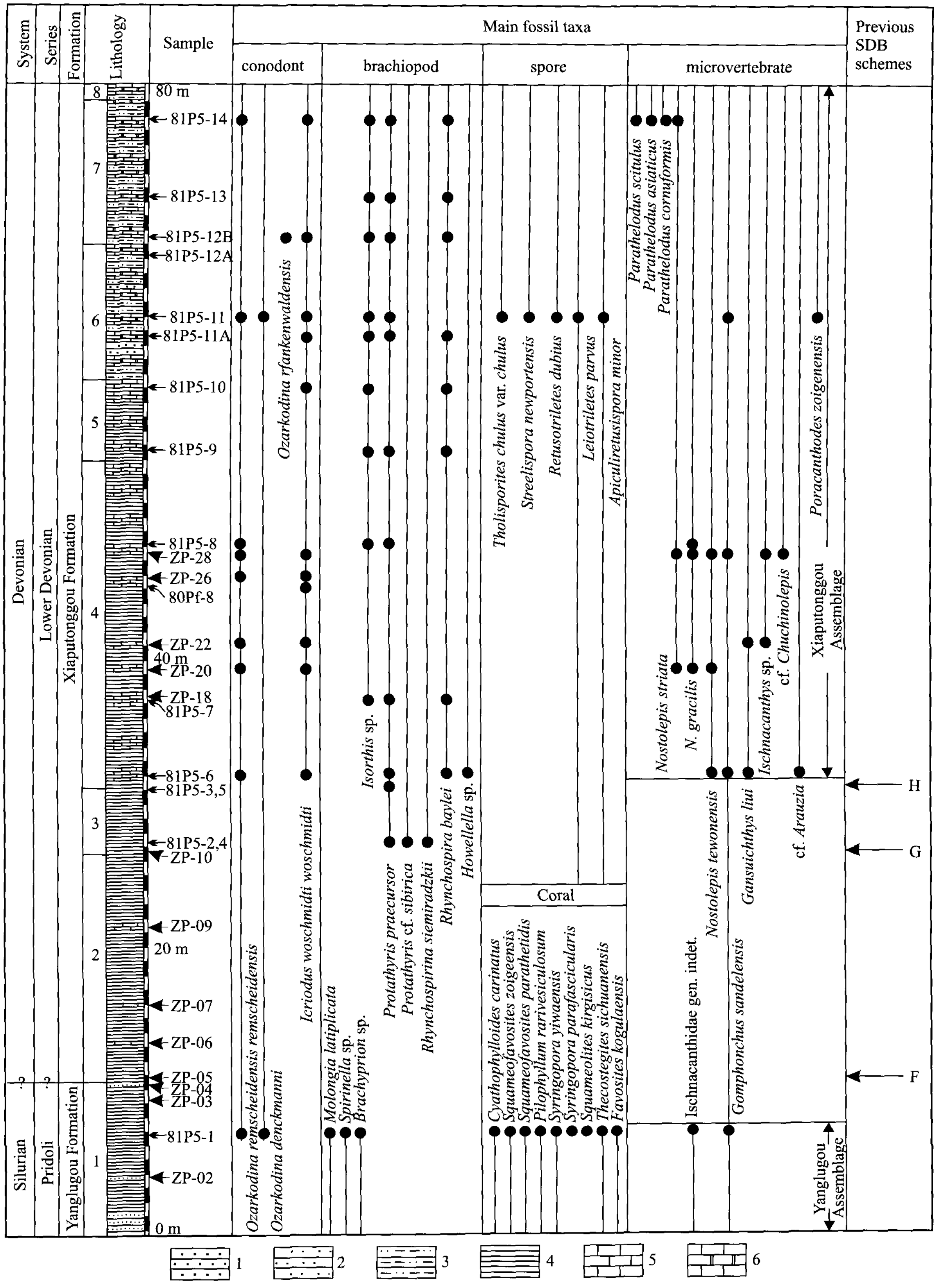

Fig. 8. Biostratigraphy and the Silurian/Devonian Boundary (SDB) schemes in the Putonggou Section in West Qinling, South China (revised from Zhao et al., 2010).

1, Fine sandstone; 2, siltstone; 3, silty mudstone; 4, shale; 5, limstone; 6, dolomitized limestone.

the upper black shale of the Yulungssu Formation based on *Ozarkodina crispa* and sequence stratigraphy (Fang et al., 1985; Shan et al., 1997); scheme C, at the top of the Yulungssu Formation or the base of the Xishancun Formation according to spores, ostracods, chitinozoans, conodonts and vertebrates (Wang, 1981b; Wang et al., 1992; Cai et al., 1994; Fang et al., 1994); scheme D, somewhere within the Xishancun Formation according to the integrated stratigraphy (Rong et al., 1990); and scheme E, somewhere within the Xitun Formation according to microvertebrate remains (Wang, 1995a, 1997). The SDB in the Xishancun Section that we defined by chemostratigraphy and microvertebrate remains here coincides with scheme C, at the base of Xishancun Formation or the top of Yulungssu Formation (Figs. 2b and 6).

Based on the conodont *Icriodus woschmidti woschmidti*, the changes of brachiopod faunas and lithostratigraphical features, the SDB in the Putonggou Section was mainly placed at three positions (Figs. 3b and 8) as follows: scheme F, at the base of the Xiaputonggou Formation mainly based on lithostratigraphical changes (Cao et al., 1987); scheme G, at the base of bed No. 3 of the Xiaputonggou Formation based on the *Protathyris-Lanceomyonia* fauna (Rong et al., 1987); and scheme H, at the base of bed No. 4 of the Xiaputonggou Formation based on the appearance of *I. woschmidti woschmidti* (Wang, 1981a; Li, 1987). Our results suggest that the level of SDB in the Putonggou Section is located in the lower part of the Xiaputonggou Formation, between sample ZP-09 and sample ZP-10, thus supporting scheme G (Figs. 3b, 7 and 8).

Generally, some factors such as thermal maturation can affect the sedimentary $\delta^{13}C_{org}$ (Cramer and Saltzman, 2007; Tao et al., 2009). In order to test the validity of the carbon isotopic data, we looked for and checked the potential parameters indicating the thermal stage of organic matter for East Yunnan and West Qinling. The conodont alteration indices (CAI) of 4–6 in two areas (the conodonts in the Xishancun and Putonggou sections are usually dark grey or black) suggest a burial temperature range of about 190–500°C (Königshof, 2003). Although thermal alteration of kerogen generally increases $\delta^{13}C_{org}$ by about 3 permil within this temperature, the source related carbon isotopic signals should still be in visible range (Des Marais, 2001, and references therein). Furthermore, thermal maturation due to overburden or regional tectonism should have affected the entire section equally (Cramer and Saltzman, 2007). Therefore, it seems that thermal maturation cannot be the cause of any excursion in our data.

At the present stage of the known isotopic data variation and microvertebrate assemblage sequences, the determination of the SDB in two sections of South China by means of chemostratigraphy agrees well with available paleontological data and the biostratigraphic zonation. However, there is still the need for a refined biostratigraphical subdivision in the sedimentary sequences of East Yunnan and West Qinling, South China.

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