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Stratigraphy and facies development of the marine Late Devonian near the Boulongour Reservoir, northwest Xinjiang, China

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Abstract: Late Devonian to Early Carboniferous stratigraphic units within the 'Zhulumute' Formation, Honggule-leng Formation (stratotype), 'Hebukehe' Formation and the Heishantou Formation near the Boulongour Reservoir in northwestern Xinjiang are fossil-rich. The Hongguleleng and 'Hebukehe' formations are bio-stratigraphically well constrained by microfossils from the latest Frasnian linguiformis to mid-Famennian trachytera conodont biozones. The Hongguleleng Formation (96.8 m) is characterized by bioclastic argil-laceous limestones and marls (the dominant facies) intercalated with green spiculitic calcareous shales. It yields abundant and highly diverse faunas of bryozoans, brachiopods and crinoids with subordinate solitary rugose corals, ostracods, trilobites, conodonts and other fish teeth. The succeeding 'Hebukehe' Formation (95.7 m) consists of siltstones, mudstones, arenites and intervals of bioclastic limestone (e.g. 'Blastoid Hill') and cherts with radiolarians. A diverse ichnofauna, phacopid trilobites, echinoderms (crinoids and blastoids) together with brachiopods, ostracods, bryozoans and rare cephalopods have been collected from this interval. Analysis of geochemical data, microfacies and especially the distribution of marine organisms, which are not described in detail here, but used for facies analysis, indicate a deepen-ing of the depositional environment at the Boulongour Reservoir section. Results presented here concern mainly the sedimentological and stratigraphical context of the investigated section. Additionally, one Late Devonian palaeo-oceanic and biotic event, the Upper Kellwasser Event is recognized near the section base.

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Stratigraphy and facies development of the marine Late Devonian near the Boulongour Reservoir, northwest Xinjiang, China

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1. Introduction

The Late Devonian sequence near the Boulongour Reservoir (Junggar area, Northwest Xinjiang) is characterized by an abundant and diversified fossil flora and fauna consisting of acritarchs, spores, radiolarians, sponges, corals, trilobites, ostracods, gastropods, cephalopods, brachiopods, bryozoans, echinoderms (blastoids and crinoids), conodonts and fish teeth. Most of the fossil groups listed above were collected from the Hongguleleng Formation. The Hongguleleng Formation was introduced in 1973 for the Famennian deposits of the West Junggar area during an expedition organized by the Chinese Academy of Geological Sciences and the Research Group on Stratigraphy of Regional Geological Reconnaissance Brigade of Xinjiang. Fossils from the Hongguleleng Formation were first published in the Atlas of Paleontology of Northwest China (1983).

Major overviews of the stratigraphy of northern Xinjiang have been given by the Compiling Group for Regional Stratigraphic Scheme of Xinjiang Uygur Autonomous Region (1981), Zeng and Xiao (1991) for Devonian and Wu (1982) for Carboniferous units, but much information has been presented in smaller papers since these syntheses of 20 and 30 years ago. We draw attention to contributions on sedimentology by Gong and Liu (1993) and Wei et al. (2009), on microfauna (bryozoans, ostracods and microvertebrate remains) by Xia (1997a), and important papers on conodonts by Zhao (1986). Taxonomic papers on Devonian and presumed Early Carboniferous (Mississippian) faunas and floras have been contributed by nearly 70 palaeontologists. Their contributions can be summarized (in approximate chronologic sequence for each major group) as follows: macroflora (Sze, 1960; Dou, 1983; Cai and Qin, 1986; Cai, 1989; Cai and Wang, 1995; Cai and Chen, 1996; Wang et al., 2004; Wang and Xu, 2005; Fu, 2006; Xu, 2006; Wang, 2008; Xu and Wang, 2008; Xu et al., 2008, 2011; Fu et al., 2011), microflora (Lu and Wicander, 1988), corals (Wang and Zhao, 1987; Liao and Cai, 1987; Liao, 1987; Cai, 1988, 1996; Soto and Lin, 1997, 2000; Liao, 2001; Soto and Liao, 2002; Wang et al., 2004), bryozoans (Xia, 1997a), brachiopods (Zhang and Zhang, 1983; Zhang et al., 1983; Zhang, 1985, 1987; Sartenaer and Xu, 1989; Xu et al., 1990; Xu, 1999; Zhao et al., 2000; Chen et al., 2002; Chen and Liao, 2006; Chen and Yang, 2011; Zong and Ma, 2012; Zong et al., 2012); cephalopods (Wang, 1983; Liang and Wang, 1991; Ruan, 1995), trilobites (Zhang, 1983), echinoderms (Waters et al., 1991, 1995, 2003, 2008; Hou et al., 1993; Lane et al., 1995, 1997; Waters and Webster, 2009; Webster and Waters, 2009), conodonts (Zhao, 1986; Xia, 1996, 1997a, 1997b; Zhao et al., 2000), and microvertebrates (Xia, 1997a).

Observations relating the Hongguleleng Formation with strata above and below as well as its lateral extent and correlation have produced differing interpretations. A high-resolution stratigraphy and biostratigraphy remains lacking. During the fieldwork from 2000 on, our research group measured several bed-by-bed stratigraphic sections of the Hongguleleng Formation, especially the type section near the Boulongour Reservoir; other sections at Yidimaodaongbo, Genaren, Qiligoa, Emuha and Aoroa have been bed-by-bed sampled for conodonts.

Here we present the results of our study on bio- and chemostratigraphy and facies of the sequence near the Boulongour Reservoir ranging from the base of the Hongguleleng Formation to the base of the Heishantou Formation.

2. Regional geology

2.1. Tectonic setting of the West Junggar area

The West Junggar area of northwest Xinjiang-Uygur Autonomous Region belongs to the Central Asian Orogenic Belt (CAOB), bordered on the north by the Siberian Craton and on the south by the North China–Tarim Craton (Jahn et al., 2000; Chen and Arakawa, 2005; Cocks and Torsvik, 2007; Windley et al., 2007). Buckman and Aitchison (2004) hypothesize a complex amalgamation-history of intra-oceanic island arcs and continental fragments to become part of the CAOB prior to the end of the latest Carboniferous. The tectonics and ophiolite belts of northern Xinjiang and especially the Hoxtolgay area and how these may relate to the Central Asian Orogenic Belt have not been foci of our research. Such matters can be approached through contributions made by Li et al. (1991), Huang et al. (1995), Buckman and Aitchison (2001, 2004), Xiao et al. (2008) and de Jong et al. (2009). Reconstructions hypothesized for the Central Asian Orogenic Belt (Windley et al., 2007; Xiao et al., 2010) would locate the Hongguleleng Formation at approximately 25 to 30 degrees north, a more tropical setting than the previous palaeogeographic reconstructions reported by Waters et al. (2003). The diversity of the marine faunas of the Hongguleleng Formation is consistent with a tropical setting.

2.2. Previous investigations

The stratotype of the Hongguleleng Formation, first studied by the Chinese expedition in 1973, is located north of Hoxtolgay, about 1.5 km northwest of the Boulongour Reservoir (Fig. 1). The oldest beds of the sequence consist of tuffaceous sandstones and conglomerates succeeded by limestones, including bioclastic limestones, variegated siliceous, tuffaceous siltstones and fine-grained sandstones. Hou and Wang (1988) re-defined the lithological units. Non-calcareous clastic rocks, for example, tuffaceous sandstones and conglomerates forming part of what was interpreted as the basal sequence of the Hongguleleng Formation, were excluded from the Hongguleleng Formation and assigned to the Zhulumute Formation. The name Zhulumute Formation has been used in lithostratigraphic schemes since then, although Xiao et al. (1992, p. 32), Xu (1999), and Cai (2000) indicated that this, being based on facies, fossil content and suggested correlation of the sequences, could be assigned to the underlying Hujiersite Formation. This idea is supported by Wang Yi and Xu Honghe (pers. comm. 2012), based on fieldwork and study of plants including megaspores from this interval. They have suggested (pers. comm. 2012) that the Hujiersite Formation includes an interval of Frasnian age previously referred to as Zhulumute Formation in some publications (compare Fig. 2). Because the latter has priority and may be best construed as including this interval, we refer to it provisionally and informally as the ‘Zhulumute’ Formation, deferring a definite conclusion as to appropriate nomenclature until more information comes available.

The ‘Zhulumute’ Formation is widespread in western Junggar and yields abundant plant fossils such as *Leptophloeum rhombicum* and *Sublepidodendron*, consistent with a Frasnian age (Hou et al., 1993; Cai, 2000; Ma et al., 2009). Ma et al. (2011) suggested a parallel unconformity at its boundary with the Hongguleleng Formation (Fig. 2), a conclusion that does not find support from our excavation of the boundary interval (see below). Hou et al. (1993, p. 2), Xia (1996, p. 101) and Wang Yi and Xu Honghe (pers. comm. 2012) considered the ‘Zhulumute’ Formation to be conformably overlain by the Hongguleleng Formation.

Xiao et al. (1992, cf. our Fig. 2) divided the Hongguleleng Formation into two parts. Xu et al. (1990) and Hou et al. (1993) suggested recognition of three members (Lower, Middle and Upper). Subsequent authors suggested the lithologic character of the ‘Unnamed Formation’ of Hou et al. (1993) equates with the basal part of the Heishantou Formation *sensu* Xiao et al. (1992). The previously suggested Carboniferous age of the ‘Unnamed Formation’ (or ‘Heishantou Formation’) is based on the occurrence of the brachiopod genus *Syringothyris* and rugose corals by Hou et al. (1993). Division of the Hongguleleng Formation into seven or eight lithostratigraphic units was suggested by Hou et al. (1993; cf. Ma et al., 2011). Another subdivision into five lithostratigraphic units was proposed by Xia (1996). Xu’s profile of the Hongguleleng Formation (Xu et al., 1990) implies more than 800 m (cf. Fig. 2), far more than observed by others. Xia (1997a,b) suggested the upper part of the Hongguleleng Formation may correspond to the lower part of the Hebukehe Formation, a unit which, according to conodonts was thought to range from the *crepida* to Early *expansa* Biozone at its type locality near the Hebukehe River (c. 8 km NW of Hoxtolgay). It seems that ever since the Second Team of the Regional Geological Reconnaissance Brigade of Xinjiang proposed the Hebukehe Formation in 1979, most subsequent authors have suggested modifications of the time-interval it represents, mostly without firm grounds for so doing (cf. Wu, 1982; Wu and Wang, 1983; Zhang, 1985; Zhao, 1986; Wang and Zhao, 1987; Zhang, 1987; Cai, 1988; Xiao et al., 1992; Zhao et al., 2000; Zhao, 2009). Because its lithology is rather distinctive we have been inclined to follow Xia (1997a,b) though indicating our uncertainty by single inverted commas, i.e. ‘Hebukehe’ Formation.

Conodonts from Hongguleleng Formation near the Boulongour Reservoir were said (Zhao and Wang, 1990) to range from *crepida* to *marginifera* biozones. Hou et al. (1993), following them, suggested the Hongguleleng Formation was early to middle Famennian (Fig. 2). Later, Xia (1997a), on the basis of conodont collections from the stratotype section, suggested a span of late Frasnian to early Famennian (Late *rhenana* Biozone through the

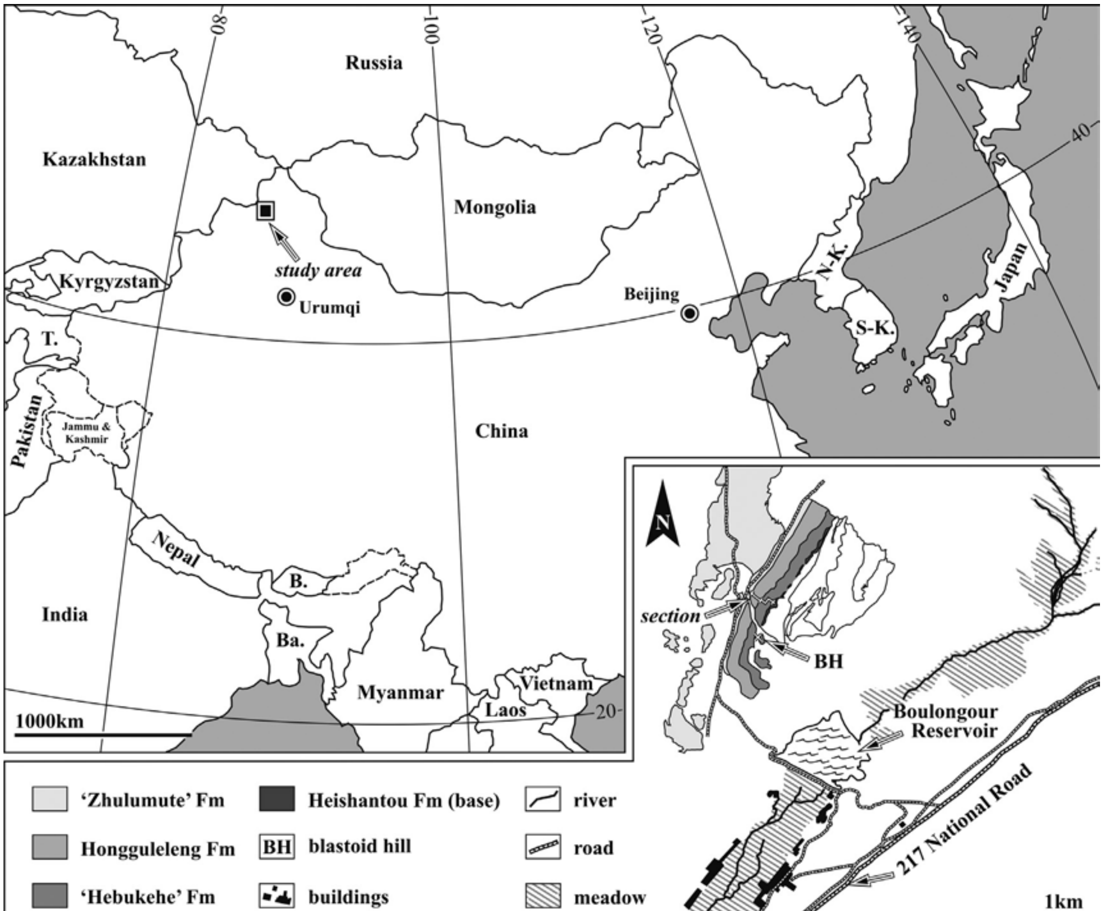

Fig. 1. Location of the investigated area near the Boulongour Reservoir, northwest Xinjiang, China.

Middle, possibly into Late *crepida* Biozone) (Fig. 2), a surprisingly brief interval not consistent with our conodont data which indicate middle and late Famennian as well. No documentation of conodont faunas has been forthcoming since Xia's (1997a) work.

3. Material and methods

More than 150 rock samples for microfacies, biostratigraphic and geochemical analyses were collected by our working group in 2000, 2005, 2007 and 2011 from the Late Devonian sequence in the vicinity of the Boulongour Reservoir (formation-base: N 46°45^{0}11^{00} ; E 86°08^{0}20^{00}). The collection of rock samples for microfacies analysis was carried out bed by bed with regard to lithological changes observed in field. All sample numbers with sample distance (measured in centimetres above the base of formation), as well as measurement results of geochemical analyses are provided in Table 1. A total of 86 five x five cm thin sections were prepared in the laboratory of Graz University. In order to describe the carbonate microfacies, the classifications of Dunham (1962) and Folk (1965) were used in this paper. The entire collection of thin sections and reference hand-specimens is stored at the Nanjing Institute of Geology and Palaeontology, Chinese Academy of Sciences (NIGP- ASMM65–NIGPASMM151). Codes for bed numbers are: HO/1/ 1 = Hongguleleng Formation/Unit 1/bed 1. Abbreviations in Table 1 are: ZH = 'Zhulumute' Formation, HO = Hongguleleng Formation, HE = 'Hebukehe' Formation, HEI = Heishantou Formation.

For biostratigraphy, several hundred limestone samples of 3–5 kg were dissolved following the standard procedure for conodont extraction (Anderson et al., 1995; Jeppsson and Anehus, 1995). For heavy liquid separation sodium polytungstate was used following the methods of Anderson et al. (1995). The color alteration index (CAI) of conodonts is 2–3. The voluminous conodont collections obtained during our study and identified by Ruth Mawson will be stored in the collections of the Institute of Geology and Palaeontology of Academia Sinica in Nanjing.

In order to gain additional data-sets for chemostratigraphy and palaeoenvironmental interpretation, stable isotopes of bulk sedimentary carbonate ($d^{13}C_{carb}$), total organic carbon (TOC) and sulfur content were analyzed (Table 1). For $d^{13}C_{carb}$ analysis, rock powders were produced from fresh surfaces or from polished slabs of 72 specimens by drilling the micritic matrix under a binocular microscope. Isotope analyses were performed on a Finnigan MAT 251 mass spectrometre at the Czech Geological Survey, Prague (Table 1, samples where sample distance equates to sample number) and a Finnigan MAT 252 mass spectrometre at the University of Erlangen (Table 1, sample number equates to bed number). A few additional samples (HO/01/299, HO/01/330b-3 and SA/29) were analyzed at the University of Graz using a Finnigan Delta Plus isotope-ratio mass spectrometre. All stable isotope ratios are expressed in the standard delta (d) notation as per mil (‰) against Vienna Pee Dee Belemnite (Vienna-PDB) standard.

In this study, TOC and sulfur content were measured in 63 samples on a LECO CS-300 (version 1.0, Year 1992) at University of Graz. They are expressed in Figs. 3 and 4 as C_{org} and S_{tot}, respectively. For organic C and total S, approximately 1 gram of fine powder of each sample was treated 3 times with 2 N HCl for 24 h to remove the carbonate component. Following acid treatment,

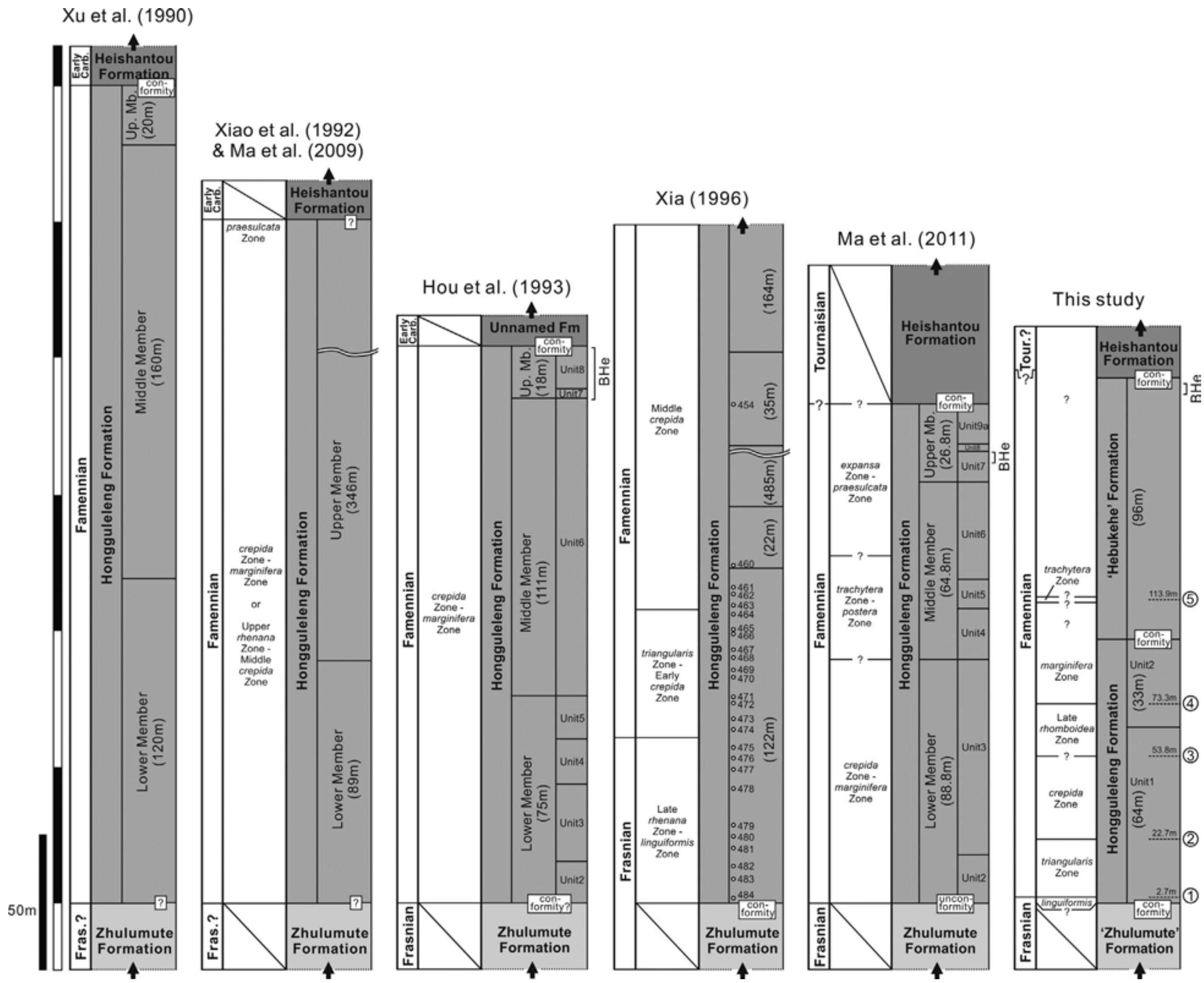

Fig. 2. Stratigraphic nomenclature involving conodont data used by various workers for the Late Devonian cropping out near the Boulongour Reservoir, based on Xu et al. (1990), Xiao et al. (1992) and Ma et al. (2009), Hou et al. (1993), Xia (1996), Ma et al. (2011) and the present study. BHe indicates 'Blastoids Hill equivalent'. Numbers 1 to 4 on the right side of the column mark the beginning of conodont biozones: 1. *triangularis* Biozone, 2. *crepida* Biozone, 3. Late *rhomboidea* Biozone, 4. *marginifera* Biozone, 5 is within the *trachytera* Biozone. Nos. 454 and 460–484 with circles in the third column indicate sample numbers (AEJ) for bryozoans provided by Xia (1997a, p. 93). Numbers in brackets show the thickness of stratigraphic units.

the samples were rinsed to neutrality (3 times with distilled water). The resulting dried powder was then analyzed. Calcium carbonate content of rock samples was calculated by using the standard formula TIC × 8.33 = $CaCO_3$.

4. Results

4.1. Lithology and facies development

In the type-section near the Boulongour Reservoir four formations are discriminated: 'Zhulumute', Hongguleleng, 'Hebukehe' and Heishantou formations (Figs. 2–4, and panoramic view in Fig. 7). A bed-by-bed profile (Figs. 5 and 6) documents lithology and fossil content (Fig. 8). Several temporary trenches were dug to obtain exposures of *in-situ* beds across intervals, especially where covered by soil and scree. The boundary of the 'Zhulumute' Formation with the Hongguleleng Formation is at N46°45^{0}11.20^{00} ; E86°08^{0}20.10^{00} . The top of the Hongguleleng Formation (= base of the 'Hebukehe' Formation) lies at N46°45^{0}09.50^{00} ; E86°08^{0}26.00^{00} . The top of the 'Hebukehe' Formation (= base of Heishantou Formation) is documented at N46°45^{0}08.80^{00}; E86°08^{0}31.20^{00}.

4.1.1. 'Zhulumute' Formation (uppermost part)

The uppermost 17 m of the 'Zhulumute' Formation consists mainly of olive gray to light olive gray volcaniclastic sandstone (bed-thickness 1–5 m). Sediment particles are fine to medium-sized and moderate- to well-sorted. Apart from rare plant remains no fossils are preserved. Two volcaniclastic conglomerate levels occur at ca. 17 m and ca. 7 m below the top of the unit; both are poorly sorted, medium to very coarse grained with fine- to medium-sized pebbles (Fig. 5A). Above these horizons are 3.8 m of olive gray volcaniclastic arenites. The youngest bed of this unit is a fining-upward sequence from a moderate to well-sorted, fine to medium size sand to a tuffaceous mudstone with thin layers of very well sorted and very fine grained sand to silt near the top.

4.1.2. Hongguleleng Formation

The Hongguleleng Formation is herein restricted to the interval of limestone bearing beds and measures 96.8 m (Figs. 2 and 3). Two units are distinguished: Unit 1 (64.3 m) and Unit 2 (32.5 m). Unit 1 begins with the lowest limestone bed above the volcaniclastic deposits of the 'Zhulumute' Formation. These basal limestone beds consist of densely packed brachiopod shells in an olive gray matrix (Fig. 5B): primarily chonetids at the very base of the sequence with

Table 1
Geochemical data from the Late Devonian sequence of the Hongguleleng strato-type near the Boulongour Reservoir. Abbreviations: ZH = 'Zhulumute' Formation, HO = Hongguleleng Formation, HE = 'Hebukehe' Formation, HEI = Heishantou Formation.

Fm/unit/bed	Sample distance	Sample no.	$d^{13}C$ (‰ PDB)		$d_{18}O$ (‰ PDB)		S_{tot} (wt.%)		TC (wt.%)		TOC (wt.%)		TIC	$CaCO_3$	
	Above Fm-base (cm)		Mean	St. dev.	Mean	St. dev.	Mean	St. dev.	Mean	St. dev.	Mean	St. dev.	Mean	Factor	%
ZH/-1/9	-790	ZH/-1/9					0.04	0.01	0.17	0.01	0.18	0.00	-0.01	8.33	-0.12
ZH/-1/14	-95	ZH/-1/14					0.03	0.01	0.12	0.00	0.12	0.00	-0.01	8.33	-0.07
ZH/-1/14top	-10	ZH/-1/14top					0.03	0.01	0.13	0.00	0.14	0.01	-0.01	8.33	-0.11
HO/1/1	5	HO/1/1	-5.72	0.01	-15.72	0.03	0.03	0.00	9.40	0.04	0.10	0.01	9.30	8.33	11 Al
HO/1/3	65	HO/1/3	-3.23	0.02	-15.17	0.01	0.03	0.00	8.11	0.17	0.14	0.01	7.97	8.33	66.40
HO/1/4	70	70	-3.30		-15.10										
HO/1/11-7	380	380	0.08		-8.04										
HO/1/13	580	580	0.22		-7.92										
HO/1/17	620	620	0.52		-9.38										
HO/1/18	792	HO/1/18	0.59	0.01	-10.52	0.04	0.02	0.00	11.13	0.11	0.11	0.00	11.02	8.33	91.81
HO/1/29	915	HO/1/29	0.25	0.02	-10.75	0.02	0.02	0.00	9.48	0.09	0.12	0.01	9.36	8.33	78.00
HO/1/39	1042	HO/1/39	0.54	0.01	-10.60	0.02	0.03	0.00	8.71	1.27	0.13	0.01	8.59	8.33	71.55
HO/1/41	1048	HO/1/41	0.50	0.01	-10.14	0.03	0.02	0.00	9.19	0.07	0.12	0.00	9.07	8.33	75.54
HO/1/53	1093	HO/1/53	-0.28	0.02	-12.19	0.04	0.02	0.00	9.81	0.06	0.12	0.01	9.68	8.33	80.64
HO/1/58	1128	HO/1/58	0.08	0.01	-10.39	0.01	0.02	0.00	10.50	0.04	0.10	0.01	10.40	8.33	86.64
HO/1/61	1150	1150	0.62		-10.87										
HO/1/64	1178	HO/1/64	-0.20	0.01	-13.50	0.03	0.02	0.00	8.50	0.03	0.11	0.00	8.39	8.33	69.85
HO/1/102	1352	HO/1/102	0.27	0.02	-9.32	0.01	0.02	0.00	8.99	0.10	0.10	0.00	8.89	8.33	74.06
HO/1/105	1361	HO/1/105	0.33	0.01	-9.95	0.02	0.02	0.00	10.28	0.04	0.12	0.02	10.16	8.33	84.67
HO/1/121	1457	1450	0.39		-8.03										
HO/1/127	1482	HO/1/127	-0.26	0.02	-8.48	0.03	0.04	0.00	10.85	0.06	0.14	0.01	10.71	8.33	89.22
HO/1/142	1575	HO/1/142					0.02	0.00	8.86	0.16	0.09	0.01	8.77	8.33	73.07
HO/1/157	1662	HO/1/157	-0.06	0.01	-10.27	0.01	0.04	0.01	10.44	0.05	0.10	0.01	10.34	8.33	86.14
HO/1/158	1665	1660	0.23		-8.17										
HO/1/186	1760	HO/1/186	-0.28	0.01	-10.49	0.03	0.02	0.00	9.30	0.02	0.13	0.01	9.16	8.33	76.32
HO/1/203	1805	1800	0.06		-8.11										
HO/1/207	1812	1810	0.19		-7.16										
HO/1/251	1930	1930	-0.47		-11.21										
HO/1/255	1940	HO/1/255					0.02	0.00	9.80	0.09	0.10	0.01	9.70	8.33	80.78
HO/1/282a	2085	2050	-0.41		-8.01										
HO/1/291 c	2800	2800	0.06		-8.45										
HO/1/295	3100	3100	0.02		-8.10		0.03	0.01	9.05	0.06	0.09	0.00	8.97	8.33	74.69
HO/1/295a	3380	3380	-0.57		-8.43										
HO/1/299	3800	HO/1/299	-0.30	0.01	-9.41	0.01									
HO/1/322	4140	4140	-0.49		-8.05										
HO/1/323	4580	4620	-0.22		-8.11		0.01	0.00	10.10	0.12	0.08	0.01	10.02	8.33	83.45
HO/1/328a	5060	5060	0.18		-7.07										
HO/1/329	5165	5240	-0.15		-8.49										
HO/1/330a-1	5380	5380	-0.18		-9.43										
HO/1/330a-3	5770	5770	-0.19		-8.12										
HO/1/330b-3	5959	HO/1/330b-3	0.10	0.01	-8.83	0.02	0.02	0.00	9.34	0.07	0.09	0.00	9.25	8.33	77.07
HO/2/1	6440	HO/2/1					0.04	0.00	10.27	0.10	0.09	0.00	10.18	8.33	84.76
HO/2/5	6447	HO/2/5					0.02	0.00	9.09	0.07	0.08	0.01	9.01	8.33	75.04
HO/2/6	6490	6490	0.19		-6.56										
HO/2/24	6780	6780	-0.09		-8.12		0.01	0.00	10.12	0.05	0.06	0.00	10.05	8.33	83.74
HO/2/27	6850	6850	-0.16		-7.02										
HO/2/33	6940	6940	-0.20		-6.69										
HO/2/35	6960	HO/2/35					0.02	0.00	10.15	0.15	0.06	0.00	10.09	8.33	84.04
HO/2/45	7072	HO/2/45					0.03	0.00	9.47	0.04	0.06	0.02	9.41	8.33	78.42
HO/2/72	7400	7400	-0.12		-8.51										
HO/2/83	7517	HO/2/83					0.03	0.00	10.17	0.08	0.08	0.01	10.10	8.33	84.11
HO/2/107	7708	HO/2/107					0.04	0.00	10.66	0.04	0.07	0.01	10.60	8.33	88.27

(*continued on next page*)

Table 1 (*continued*)

Fm/unit/bed	Sample distance	Sample no.	d^{13}C (‰ PDB)		d$_{18}$O (‰ PDB)		S_{tot} (wt.%)		TC (wt.%)		TOC (wt.%)		TIC	$CaCO_3$	
	Above Fm-base (cm)		Mean	St. dev.	Mean	St. dev.	Mean	St. dev.	Mean	St. dev.	Mean	St. dev.	Mean	Factor	%
HO/2/108	7715	7590	0.07		-6.15										
HO/2/156a-5	8060	8060	0.07		-7.41										
HO/2/156a-9	8150	8150	0.24		-7.76										
HO/2/186	8395	HO/2/186					0.01	0.00	6.40	0.08	0.10	0.01	6.30	8.33	52.48
HO/2/194c	8570	8570	0.15		-7.38										
HO/2/213	8750	8750	0.41		-7.52										
HO/2/234	8842	HO/2/234					0.02	0.00	9.17	0.01	0.09	0.01	9.08	8.33	75.62
HO/2/263	8946	9130	0.53		-8.08										
HO/2/273	9045	9240	1.36		-10.20										
HO/2/275b	9081	HO/2/275b	1.43	0.02	-9.07	0.02	0.07	0.08	10.66	0.50	0.08	0.01	10.58	8.33	88.09
HO/2/291	9328	HO/2/291					0.02	0.00	6.96	0.09	0.08	0.00	6.88	8.33	57.32
HO/2/295	9465	HO/2/295	0.32	0.01	-14.00	0.02	0.04	0.01	2.38	0.02	0.16	0.00	2.22	8.33	18.49
HO/2/297a	9528	HO/2/297a	1.54	0.02	-9.23	0.03	0.02	0.00	5.31	0.08	0.10	0.00	5.22	8.33	43.48
HO/2/297c	9536	HO/2/297c	1.48	0.02	-10.25	0.02	0.02	0.00	8.12	0.15	0.09	0.02	8.02	8.33	66.83
HO/2/303	9557	HO/2/303	1.33	0.01	-9.21	0.02	0.02	0.00	7.13	0.21	0.07	0.01	7.06	8.33	58.77
HO/2/304	9560	HO/2/304	1.57	0.01	-9.41	0.02	0.03	0.01	8.31	0.05	0.13	0.02	8.18	8.33	68.14
HO/2/305	9562	HO/2/305	1.54	0.01	-8.34	0.02	0.02	0.00	9.62	0.27	0.10	0.01	9.52	8.33	79.32
HO/2/306	9575	HO/2/306	1.75	0.02	-9.72	0.03	0.02	0.00	3.45	0.02	0.09	0.01	3.35	8.33	27.94
HO/2/306a	9615	HO/2/306a	1.75	0.01	-9.96	0.03	0.03	0.00	6.11	0.06	0.12	0.00	5.99	8.33	49.92
HO/2/306b	9635	HO/2/306b	1.62	0.01	-10.62	0.02	0.02	0.01	4.83	0.06	0.21	0.03	4.62	8.33	38.48
HO/2/306c	9665	HO/2/306c	1.56	0.02	-11.56	0.03	0.02	0.00	5.20	0.10	0.22	0.01	4.99	8.33	41.53
HE/1 a	1150	Sa/1					0.04	0.02	0.09	0.01	0.12	0.01	-0.02	8.33	-0.19
HE/1b	1400	Sa/2					0.04	0.01	0.12	0.00	0.11	0.00	0.01	8.33	0.06
HE/2b	1540	Sa/4					0.02	0.00	0.20	0.00	0.27	0.02	-0.07	8.33	-0.57
HE/3	1545	Sa/5	0.48	0.03	-14.35	0.02	0.06	0.01	0.23	1.32	0.16	0.01	0.07	8.33	0.57
HE/5	1570	Sa/6	0.91	0.02	-15.00	0.03	0.03	0.00	3.66	0.03	0.13	0.01	3.53	8.33	29.40
HE/9	1840	Sa/7	-0.17	0.01	-13.58	0.02	0.04	0.00	1.62	0.02	0.16	0.01	1.46	8.33	12.19
HE/11	2120	Sa/8					0.02	0.00	0.54	0.00	0.13	0.01	0.42	8.33	3.47
HE/17	2300	Sa/9	0.85	0.01	-14.51	0.03	0.03	0.01	1.68	0.01	0.11	0.00	1.57	8.33	13.10
HE/30	2598	Sa/11					0.02	0.00	0.46	0.00	0.13	0.01	0.33	8.33	2.75
HE/32	2560	Sa/12					0.03	0.01	0.41	0.00	0.16	0.01	0.25	8.33	2.08
HE/36a	3212	Sa/15					0.06	0.02	0.07	0.00	0.12	0.00	-0.05	8.33	-0.40
HE/37	5880	Sa/19	0.40	0.01	-13.68	0.03	0.02	0.00	0.82	0.01	0.13	0.01	0.69	8.33	5.77
HE/60	7035	Sa/24					0.03	0.01	0.20	0.00	0.14	0.02	0.06	8.33	0.51
HE/95	8140	Sa/28	1.34	0.01	-12.12	0.03	0.06	0.01	7.28	0.06	0.16	0.03	7.12	8.33	59.29
HE/109	9020	Sa/29	0.70	0.23	-11.54	0.38									
HE/126	9360	Sa/29a	0.85	0.02	-13.27	0.02	0.03	0.00	3.19	0.11	0.25	0.01	2.94	8.33	24.46
HE/130	9530	Sa/30b	1.01	0.01	-12.68	0.02	0.05	0.00	2.16	0.03	0.20	0.01	1.96	8.33	16.33
HEI/4	650	Sa/33	-1.09	0.01	-15.63	0.03	0.04	0.01	2.26	0.04	0.26	0.03	1.99	8.33	16.59
HEI/14c	1468	Sa/34	0.71	0.02	-11.80	0.03	0.02	0.00	2.58	0.06	0.32	0.02	2.25	8.33	18.77
HEI/18	1655	Sa/35	-1.48	0.01	-17.06	0.03	0.02	0.00	7.49	0.07	0.30	0.03	7.19	8.33	59.93
HEI/21b	1710	Sa/37	0.06	0.03	-12.76	0.02	0.07	0.00	1.01	0.01	0.42	0.18	0.59	8.33	4.94

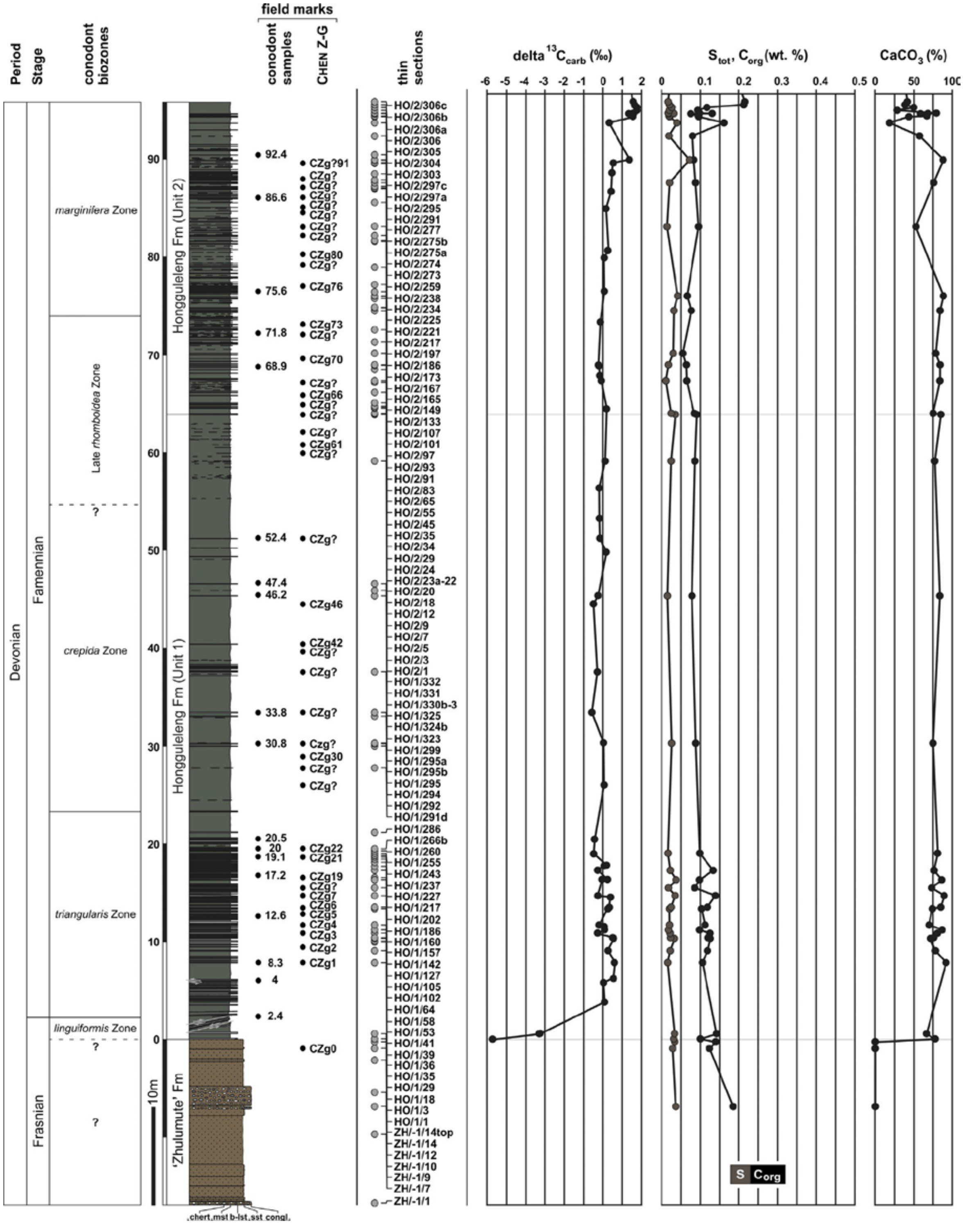

Fig. 3. Lithological column of the 'Zhulumute' Formation (uppermost part) and the Hongguleleng Formation at Boulongour Reservoir showing geochemical trends of stable isotopes of bulk sediment carbonate ($d^{13}C_{carb}$), total organic carbon (TOC), sulfur content and $CaCO_3$. Samples used for geochemical analyses are listed in Table 1. Rock colors and sample numbers still visible on single beds (by Chen, Z.-G. and from our working group) are indicated here and in Fig. 4 for better orientation in field. Abbreviations: mst = mudstone; b-lst = bioclastic limestone; sst = silt- to sandstone; congl = conglomerate.

diversity increasing upwards (Fig. 8). Limestone beds are typically olive gray to light brownish gray. They have a thickness of a few centimetres, but can reach up to one decimetre. Limestone beds in Unit 1 are regarded as slightly argillaceous to argillaceous based on microfacies and total inorganic carbon (TIC) values between 8.39% and 11.02%. Some beds have TIC values below 8% connected with marly composition (cf. Table 1). Some beds show additional features including graded bedding (mainly fining-upward sequences), low angle cross-bedding, or limonitic crusts. Reworked clasts of green siliceous mudstone were noted in tempestitic

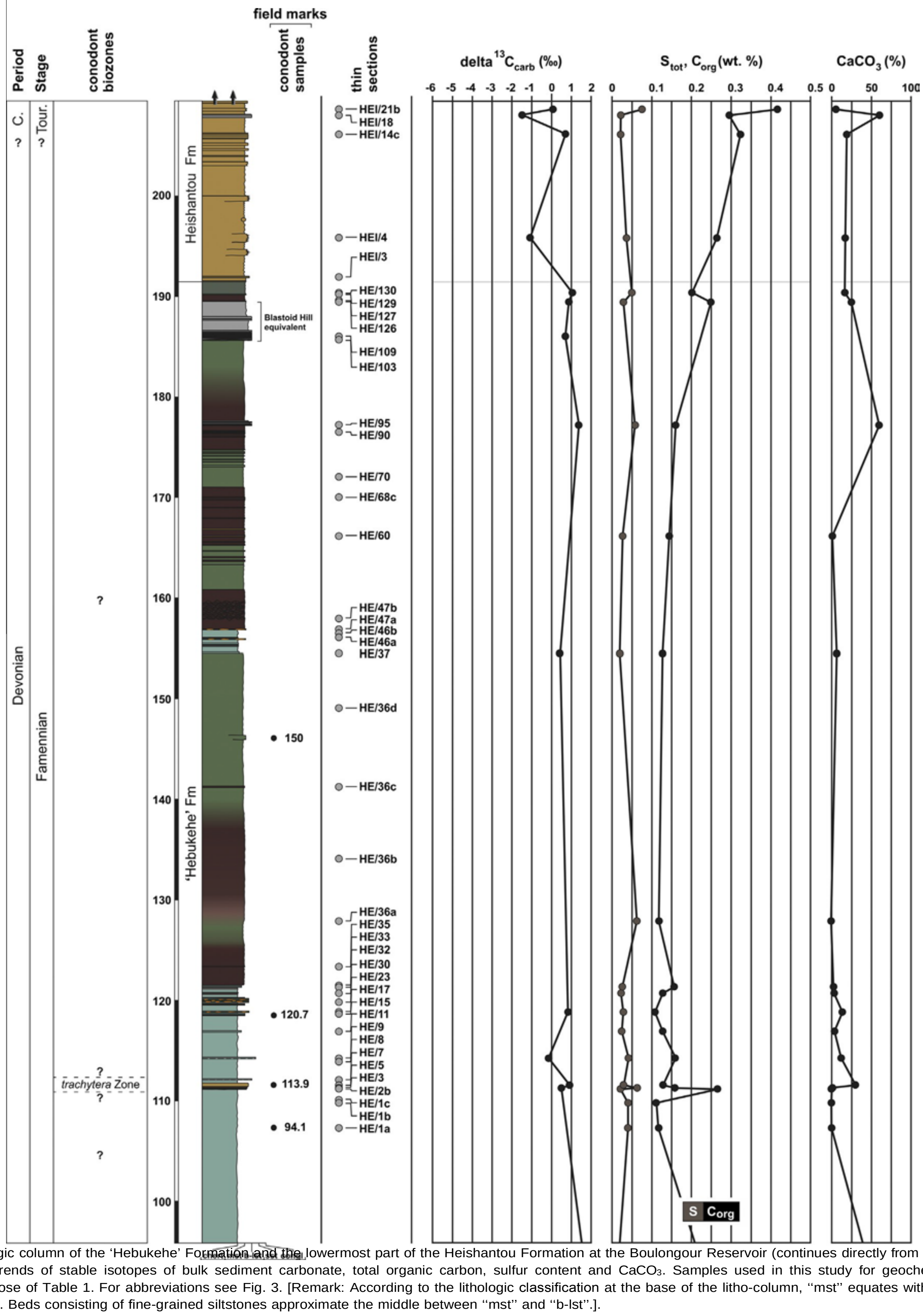

Fig. 4. Lithologic column of the 'Hebukehe' Formation and the lowermost part of the Heishantou Formation at the Boulongour Reservoir (continues directly from Fig. 3), showing geochemical trends of stable isotopes of bulk sediment carbonate, total organic carbon, sulfur content and $CaCO_3$. Samples used in this study for geochemical analyses accord with those of Table 1. For abbreviations see Fig. 3. [Remark: According to the lithologic classification at the base of the litho-column, ''mst'' equates with mudstone and silty mudstone. Beds consisting of fine-grained siltstones approximate the middle between ''mst'' and ''b-lst''.].

deposits associated with shell accumulations or in specific levels near the top of a bed. Skeletal components are mainly brachiopod shells, bryozoans, crinoid ossicles, ostracod valves and conodonts. Subordinate solitary rugose corals, gastropods and fish teeth occur at some levels (Fig. 8). Some limestones show significant infaunal activity (Fig. 5C). In general beds are intercalated by 1–20 cm (near the base also more than 60 cm) thick intervals of olive gray shale (unfossiliferous, or spiculitic mudstone).

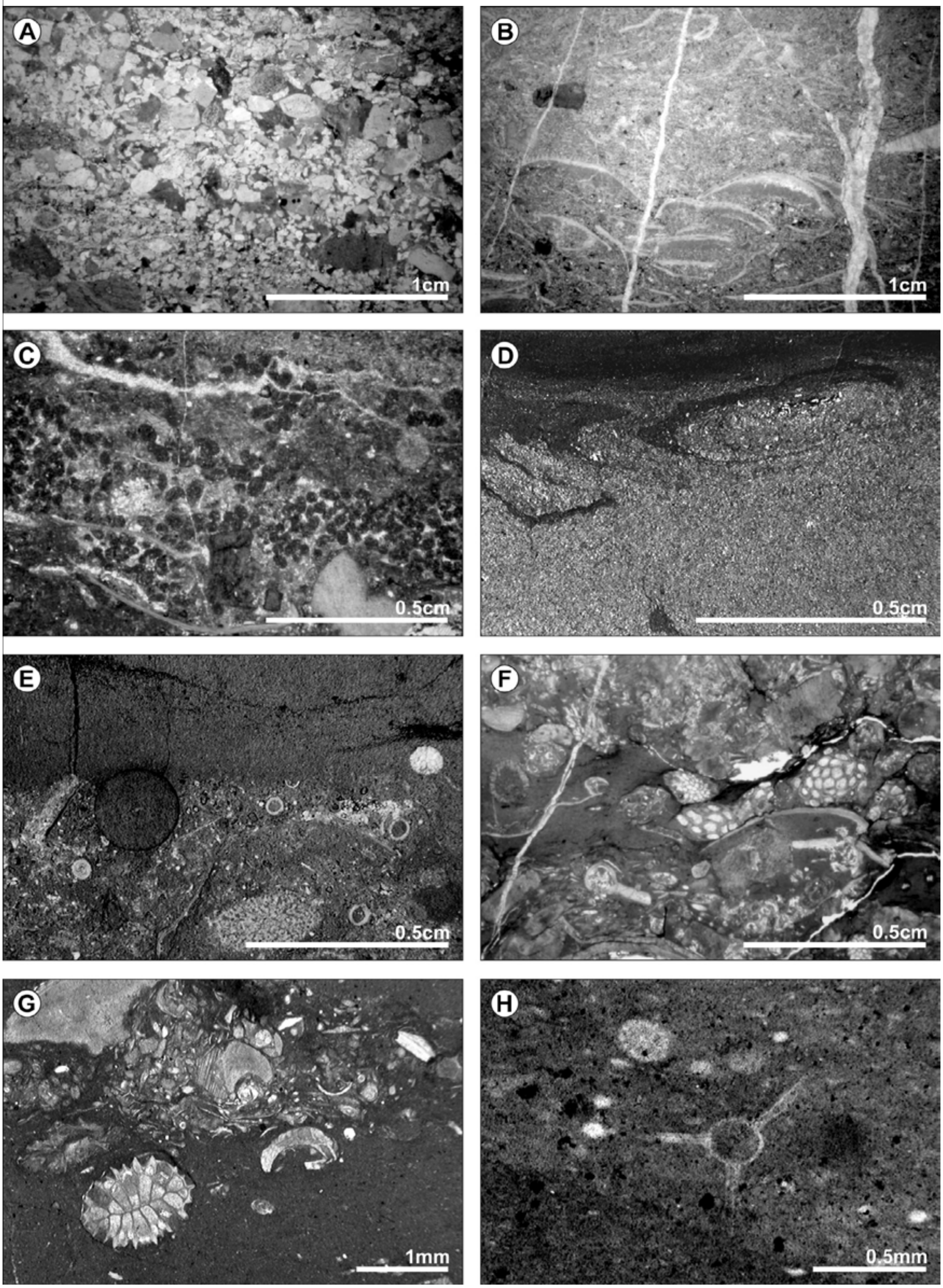

Fig. 5. (A) Volcaniclastic sandstone, ZH/01/-01 (NIGPMM65); (B) Packstone, brachipod shell layers, HO/01/01 (NIGPMM74); (C) Bioclastic limestone with large peloids, HO/ 01/157 (NIGPMM88); (D) Strongly bioturbate fine grained siltstone, HO/01/331 (NIGPMM104); (E) Truncated bioclastic limestone, HO/02/01 (NIGPMM105); (F) Bioclastic pack- to grainstone rich in bryozoans, trilobites, crinoids, rugose corals and brachiopods, HO/02/186 (NIGPMM125); (G) Carbonaceous shale with bioclastic accumulations from the top of the Hongguleleng Formation, HO/02/306c (NIGPMM134); (H) Radiolarian chert from the base of the 'Hebukehe' Formation, HE/1a (NIGPMM135).

From ca. 21 m above the base, shale intervals become thicker and limestone beds are replaced by single horizons of limestone nodules. The predominant lithology in this interval is fine-grained carbonaceous siltstone, sometimes bioturbated (Fig. 5D). Some nodular levels yield abundant fossils. Nodules consist primarily of mudstone with few indeterminant filaments. Some of the thick shale intervals have fenestellid bryozoans, ostracods, single crinoid ossicles, some have a few rugose corals and brachiopods. The fauna

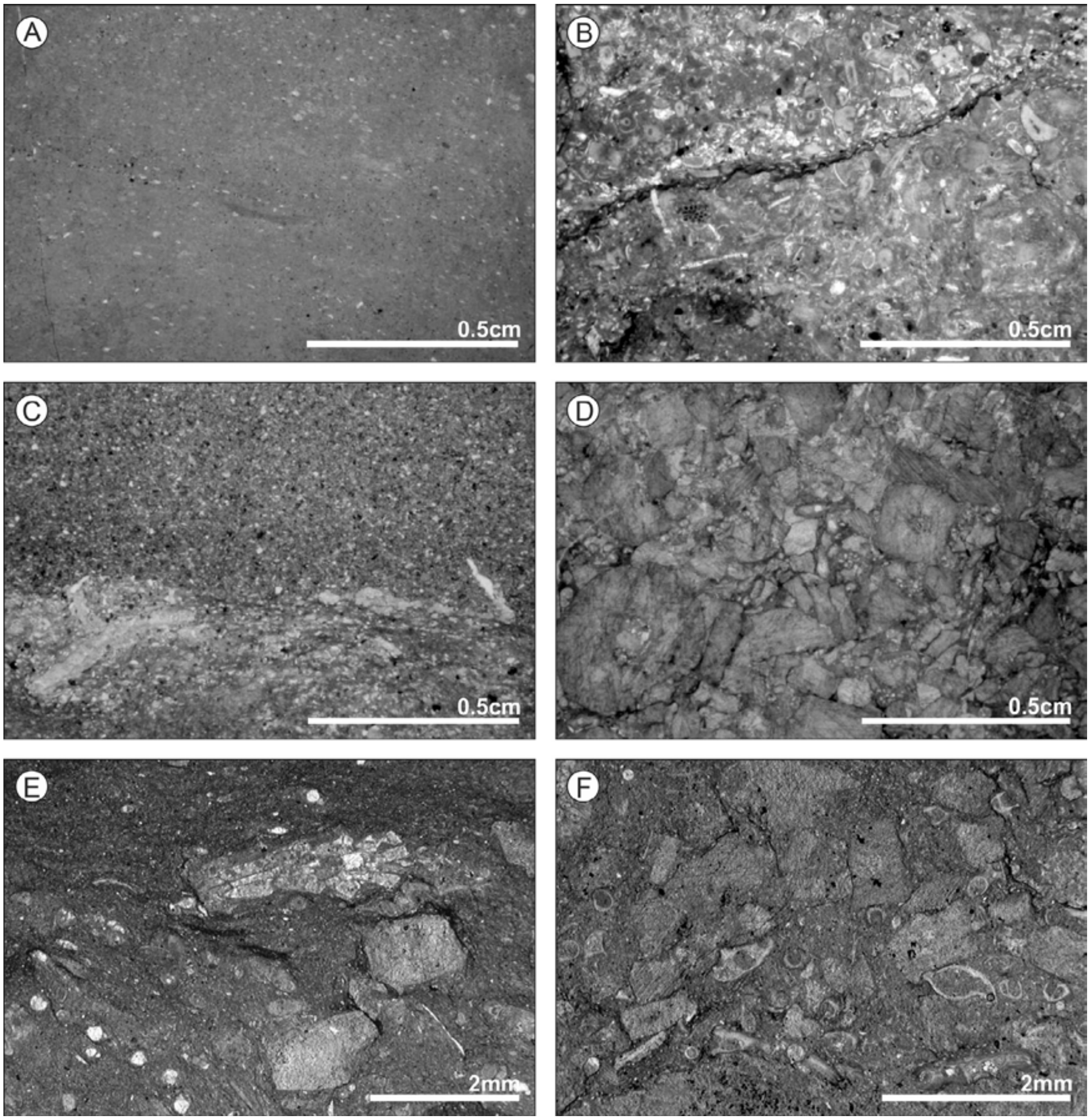

Fig. 6. (A) Radiolarian-bearing slightly silty chert, HE/8 (NIGPMM137); (B) Crinoidal pack- to grainstone, HE/17 (NIGPMM139); (C) Silt- to sandstone, HE/36c (NIGPMM140); (D) Crinoidal grainstone, HE/103 (NIGPMM141); (E) Carbonaceous green shale to siltstone yielding bryozoans, crinoid ossicles and ostracods from the top of the 'Hebukehe' Formation, HE/130 (NIGPMM143); (F) Yellowish gray to light olive brown silty wacke- to packstone (fossil content: crinoids, bryozoans, brachiopods, ostracods and trilobites) from the base of the Heishantou Formation, HEI/3 (NIGPMM144).

differs at this interval, being characterized by productid brachiopods and fenestellid bryozoans presumed more tolerant of muddy, soft bottom conditions.

The base of Unit 2 is indicated by the occurrence of the first continuous bioclastic limestone bed succeeding the interval of shale with levels of limestone nodules. Limestone beds in Unit 2 have a slightly different character compared with beds in Unit 1. Commonly they are light olive green to brownish gray and very thin (average: 2–3 cm, some only half-a-centimetre). In general the TIC ranges between 2.22% and 10.60%, with values below 8% becoming dominant towards the top of the unit. Fossil-rich carbonate beds are sometimes truncated after consolidation and covered by mudstone (Fig. 5E). Bryozoans, brachiopods, crinoid ossicles, rugose corals and trilobites are the dominant skeletal components in bioclastic pack- and grainstones (Fig. 5F). Exuvia of small phacopid trilobites (commonly cephala and pygidia, and few complete specimens) are not found in the Unit 1, but occur abundantly throughout Unit 2. Fossils remain abundant to the top of the Hongguleleng Formation (Fig. 5G) even though the silicate content of the bulk-rock increases up to 60%. At the boundary with the 'Hebukehe' Formation, there is a distinctive change from such calcareous shale to chert (Fig. 5H) accompanied by a change in color from greenish gray to pale green and a change in the fossil community.

4.1.3. 'Hebukehe' Formation

The 'Hebukehe' Formation reaches a thickness of 95.7 m near the Boulongour Reservoir. Chert at its base has sparse macrofossils, but yields spicules and radiolarians (Fig. 5H). Radiolarians are green in thin sections from the lowermost 15 m. Chert in this lowest bed is not homogenous; some levels have slightly increased silt content. Succeeding dark yellowish brown siltstones with monospecific concentrations of tiny valved brachiopods that are overlain by a few beds of pale olive, strongly bioturbated silty mudstones. One of these, bed HE/5, is 35 cm thick and can easily be recognized in the field by its prominent beige to orange weathering-color (TIC = 3.53%). Bed HE/7, a bioclastic limestone with a layer of single

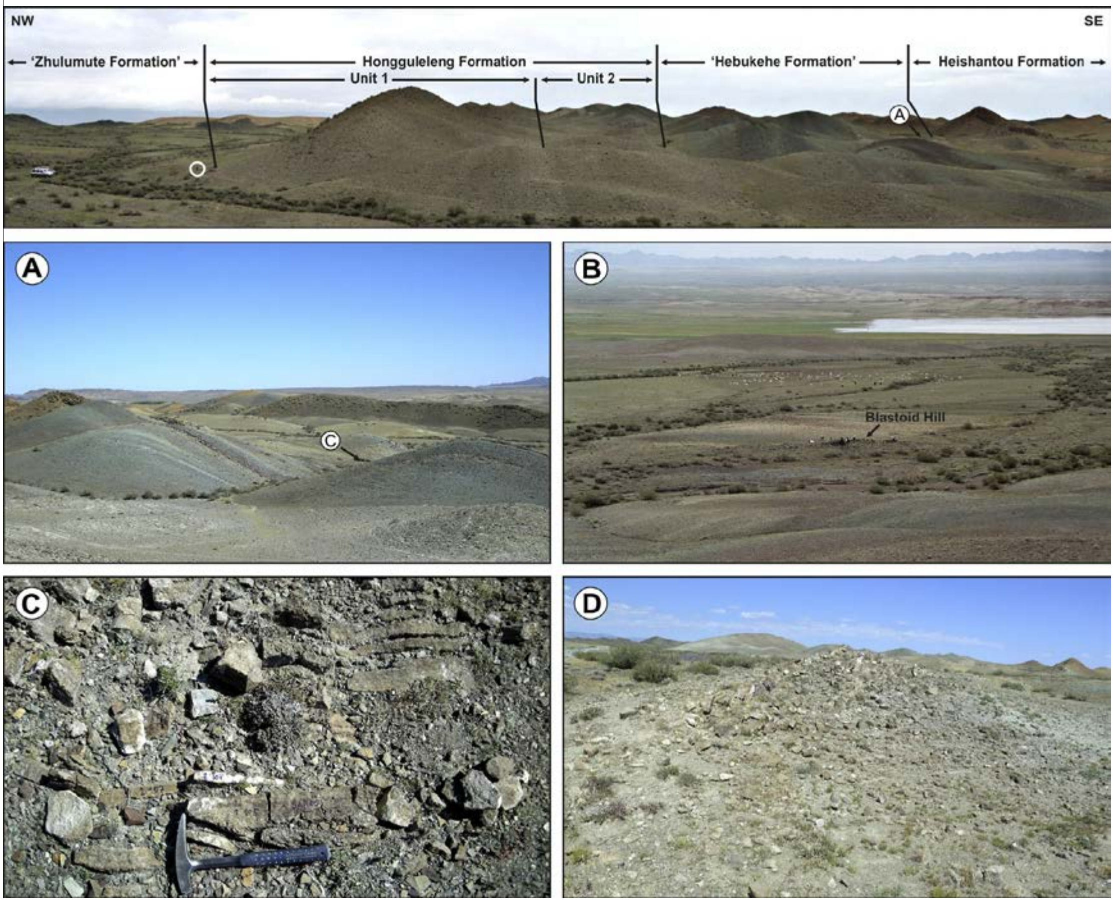

Fig. 7. Panoramic view of the Late Devonian sequence near the Boulongour Reservoir. Circle indicates Ruth Mawson near the base of the Hongguleleng Formation. (A) View towards East on the tectonically slightly displaced hills of the 'Hebukehe' Formation with ''C'' indicating the position of the 'Blastoid Hill equivalent' near the top of the formation; (B) View towards SE at 'Blastoid Hill' with the Boulongour Reservoir in the background; (C) Crinoidal grainstone beds of 'Blastoid Hill equivalent'; (D) View of 'Blastoid Hill' as is indicated in ''B'' (view towards NNE).

reworked radiolarian-bearing mudstone clasts at its base, is succeeded by a tuffaceouse breccia with chert and radiolarian-rich lithoclasts up to 10 mm in diametre. It is followed by radiolarianbearing green silty chert (Fig. 6A), alternating with strongly bioturbated green to brownish or dark dusky brown siltstones. The latter beds can be slightly carbonaceous (TIC with max. values of 1.57%). Some beds of this interval, between approx. 18.3 to 25.8 m above the formation base, have individual horizons with pinkish gray or orange weathering limestone lumps consisting of fine bioclastic pack- to grainstone (Fig. 6B). These are ovate, sometimes elongated and s-shaped, and reach 6–10 cm in size. Skeletal grains are strongly fragmented crinoid ossicles, broken pieces of bryozoan branches (rare), ostracod valves and spicules. Phacopid trilobite cephala and pygidia occur in intercalated green shales. An unidentified cephalopod was found in bed HE/18.

Overlying sediments consist of green shale alternating with red silt and/or fine grained sandstone (Fig. 6C); a few levels of small brachiopods and complete phacopids occur in this interval. Above, slightly silty olive gray chert and green chert was deposited (beds HE/37 to HE/46). In the lowest part of bed HE/47 brownish gray lime-mudstone clasts yield spicules, radiolarians, and rare ostracods; a few trilobites occur in a matrix of green silty chert and siltstone. Higher in this bed the lithology changes into poorly sorted dark reddish brown weathering siltstone with a more nodular character.

From bed HE/48 until HE/88, green and reddish brown shale and siltstone with a variable bed-thickness of 4–250 cm occur. Bed HE/94 consists of olive gray shale overlain by a 7 cm thick bed of dark yellowish brown crinoidal pack to grainstone (TIC = 7.12%). Subsequent beds have increased skeletal grains, primarily crinoidal debris. The next 8 m exposes reddish brown and green shale.

An interval of yellowish gray crinoidal grainstones begins with bed HE/103 (Fig. 6D) and continues to bed HE/121. The composition of the sediment (still fossiliferous) increases in relative proportion of silt. In addition to an abundant and highly diverse echinoderm fauna (crinoids and blastoids) obtained from the aforementioned interval, the number of bryozoan specimens increases from bed HE/126 towards the top of the formation. The uppermost part of the 'Hebukehe' Formation consists of silty bioclastic packstone to wacke- and packstone, reddish brown siltstone (bed HE/128) and finally turns into bioturbated bioclastic calcareous green shale to siltstone (Fig. 6E).

4.1.4. Heishantou Formation (lowermost part)

Yellowish gray to light olive brown silty bioclastic wackestones to bioclastic calcareous siltstones occur in the base of the Heishantou Formation (Fig. 6F). Except for the lowest three beds, the lower 15–20 m have orange-weathering molds of brachiopods and bryozoans. Somewhat better preserved fossils such as leptaenid and lingulid brachiopods occur in a few beds, HEI/8, HEI/18 and HEI/ 21b. Bed HEI/21b yields numerous shells of well-preserved lingulids considered important for the interpretation of the depositional environment. Within this interval, HEI/18 represents the first bed

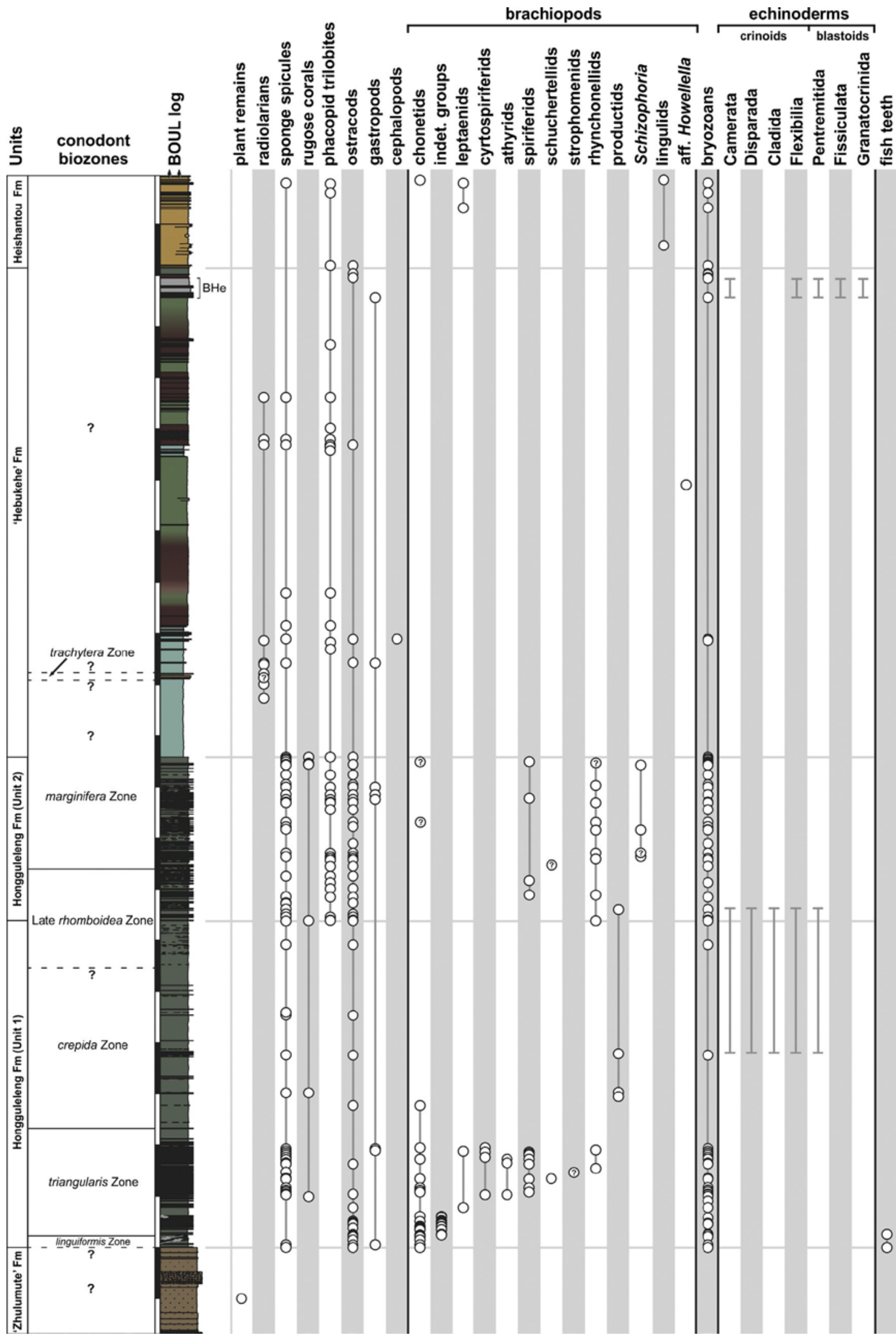

Fig. 8. Occurrences of fossil groups. Range-bars are used for crinoids and blastoids collected from the scree of distinctive intervals such as the 'marly beds' and 'Blastoid Hill' (*sensu* Hou et al., 1993). Abbreviation: BOUL log = lithological column of the Boulongour Reservoir section as shown in Figs. 3 and 4.

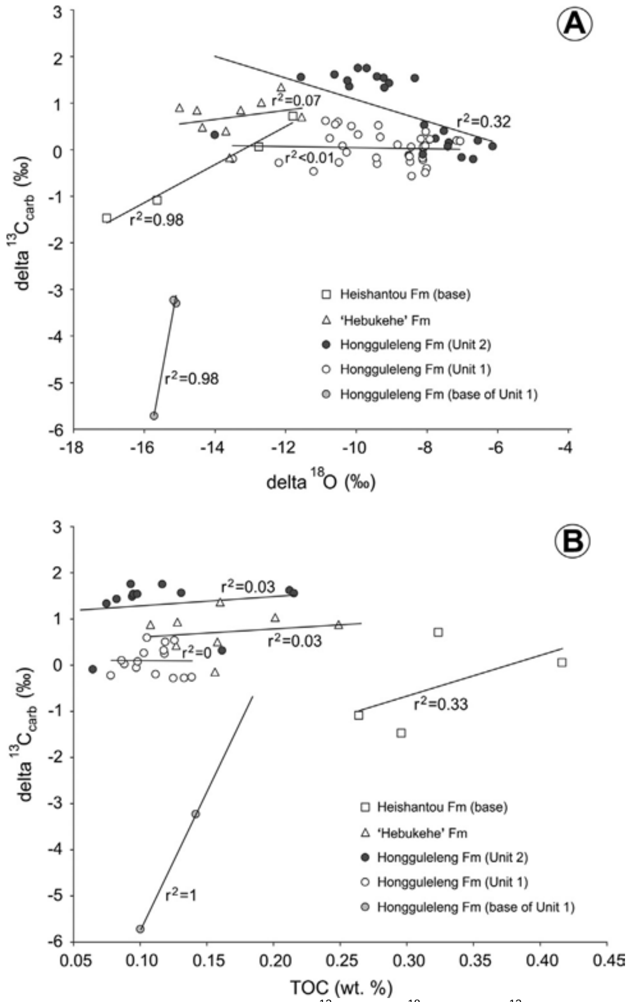

Fig. 9. Scatter plot of bulk-sediment of (A) $d^{13}C_{carb}$ vs. $d^{18}O$ and (B) $d^{13}C_{carb}$ vs. total organic carbon (TOC).

above the formation base with increased total inorganic carbon to values about 7.2%.

4.2. Conodont biostratigraphy

The basal limestone beds of the Hongguleleng Formation have produced conodonts diagnostic of the late Frasnian *linguiformis* Biozone. The Frasnian–Famennian boundary, based on the first occurrence of *Palmatolepis triangularis*, is located 2.7 m above the formation boundary. The base of the biozone is dominated by palmatolepid species but conodont diversity at species-level increases through the interval. The *triangularis* Biozone persists up to 22.7 m where the first occurrence of *Pa*. *crepida* marks the base of the *crepida* Biozone.

The position of the boundary between the *crepida* and *rhomboidea* biozones remains unclear because conodont samples taken between 33.8 and 53.8 m were barren; the sample at 53.8 m produced specimens of *Polygnathus subnormalis*. Because this species ranges from the mid-*rhomboidea* Biozone to the Early *trachytera* Biozone, beds above 53.8 m are considered no older than Late *rhomboidea* Biozone (Fig. 3). A conodont assemblage typical for the *marginifera* Biozone was obtained from beds between 73.3 and 92.9 m. The youngest conodont-bearing sample was a limestone bed approx. 16 m above the base of the 'Hebukehe' Formation; it yields conodonts indicative of the *trachytera* Biozone (conodont sample 113.9; Fig. 4). Other samples taken higher up in the sequence failed to produce biostratigraphically constraining conodonts.

4.3. Geochemical analyses

4.3.1. Carbon and oxygen isotope record

We analyzed stable carbon ($d^{13}C_{carb}$) and oxygen ($d^{18}O$) isotopes of bulk sedimentary carbonate for additional data to help refine our stratigraphic and palaeoenvironmental interpretation. In general, $d^{18}O$ analysis from bulk samples does not produce reliable palaeoenvironmental results compared with data from brachiopod shells or the PO_4-group of conodont apatite. Therefore, values are used for cross plots of $d^{18}O$ vs. $d^{13}C_{carb}$ to test the covariation of carbon and oxygen isotopes of bulk samples, an indication of a diagenetic rather than primary $d^{13}C_{carb}$ signal. $d^{18}O$ values of carbonate bulk-rock samples obtained across the section fall within a range between -17.06‰ and -6.15‰ (Table 1). Fig. 9A shows the covariation between $d^{13}C_{carb}$ and $d^{18}O$ for the lowest beds of Unit 1, including samples from below the F/F boundary, the remainder of the Hongguleleng Formation (Units 1 and 2), the 'Hebukehe' Formation and the base of the Heishantou Formation. Covariance for the base of Unit 1 and the base of the Heishantou Formation is 0.98 (r^2 = 0.98). We recognize that the covariance at the base of the Hongguleleng is based on limited sampling. The interval was more closely sampled in 2011. However, such high covariance indicates that the isotope signal from the base of Hongguleleng Formation and the base of Heishantou Formation may be diagenetic and not a primary signal of marine chemistry. On the other hand, the covariation between $d^{13}C_{carb}$ and $d^{18}O$ for the remaining part of Unit 1 ($r^2 < 0.01$), Unit 2 (r^2 = 0.32) and the 'Hebukehe' Formation (r^2 = 0.07) as well as results from $d^{13}C_{carb}$ vs. TOC cross plots which co-vary up to r^2 = 0.03 gives us confidence that these intervals preserve a primary signal.

A prominent positive excursion in $d^{13}C_{carb}$ is observed at the base of the Hongguleleng Formation across the Frasnian–Famennian boundary, i.e., across the *linguiformis–triangularis* zonal boundary (Fig. 3). Values of $d^{13}C_{carb}$ increase from -5.72‰ in the *linguiformis* Biozone of the Frasnian (HO/1/1; 5 cm) to maximum value +0.62‰ in the *triangularis* Biozone of the early Famennian (HO/1/61; 11.5 m). From the first bed above the Frasnian–Famennian boundary (HO/1/11-7; 3.8 m) to the sample obtained from the top of Unit 1 of the Hongguleleng Formation (HO/1/330b-3; 59.59 m), $d^{13}C_{carb}$ values show less amplitude fluctuation, ranging from -0.49‰ to +0.62‰. In Unit 2 of the Hongguleleng Formation $d^{13}C_{carb}$ values increase slightly towards the upper part of it until HO/2/263 (89.46 m) with a minimum value of -0.2‰ and a maximum value reaching +0.19‰. A positive shift is observed in the upper part of Unit 2 in the *marginifera* Biozone with values from +0.53‰ (HO/2/263) to +1.43‰ (HO/2/275b; 90.81 m). This trend is followed by a decrease to +0.32‰ (HO/2/295; 94.65 m); it increases shortly thereafter to +1.75‰ (HO/2/306; 95.75 m and HO/2/306a; 96.15 m). The high values, which are recorded in the upper part of Unit 2 seem to decrease stepwise across the boundary towards the base of the Hebukeke Formation; low values of -0.17‰ (HE/9; 18.4 m) were obtained. From the base to the upper part of the 'Hebukehe' Formation (HE/130; 95.3 m) $d^{13}C_{carb}$ values fluctuate between a minimum of -0.17‰ (HE/9; 18.4 m) to a maximum of +1.34‰ (HE/95; 81.4 m). The positive $d^{13}C_{carb}$ signal obtained from the topmost part of the 'Hebukehe' Formation (HE/130) decreases to -1.09‰ at the base of the Heishantou Formation (HEI/4; 6.5 m). Values of $d^{13}C_{carb}$ increase again, reaching +0.71‰ (HEI/14c; 14.68 m). This positive shift is followed by another decrease down to -1.48‰ in bed HEI/18 (16.55 m).

4.3.2. TOC and sulfur content

Results for analyses of total organic carbon and sulfur in 63 samples are provided in Figs. 3 and 4; the individual data are listed in Table 1. Significant covariation for samples obtained from the base of Unit 1 ($r^2 = 1$) in the scatter plot of $d^{13}C_{carb}$ vs. TOC (Fig. 9B) appears consistent with diagenetic impact. TOC-values and sulfur content (in wt.%) obtained are quite low; C_{org} ranges from 0.06% to 0.42%, and S_{tot} from 0.01% to 0.07% (Figs. 3 and 4). All beds, sampled through section, are relatively poor in organic carbon and sulfur; this accords with a rather well oxygenated depositional environment (see Section 5).

Total organic carbon remains with ratios below 0.5% across the entire section. Bed ZH/-1/9 from the upper part of the 'Zhulumute' Formation (7.9 m below the base of the Hongguleleng Formation) shows a TOC of 0.18%. This value decreases at the transition between the 'Zhulumute' Formation and Unit 1 of the Hongguleleng Formation, where it reaches a minimum of 0.1% (HO/1/1; 5 cm). Within the alternation of bioclastic argillaceous limestone and green shale (generally poor in fossils) in the lower part of Unit 1, TOC values fluctuate from a minimum of 0.09% (HO/1/142; 15.75 m) to a maximum of 0.14% (HO/1/127; 14.82 m). The curve shows a decrease to slightly lower values (0.08% and 0.09%) from approximately 20 m above the base of Unit 1 to its top. At the base of Unit 2 of the Hongguleleng Formation, the TOC level decreases to 0.06% (HO/2/24; 67.8 m, HO/ 2/35; 69.6 m and HO/2/45; 70.72 m) followed by a positive shift, in the upper part of the Unit 2, reaching 0.22% (HO/2/306c; 96.65 m). TOC values decrease to 0.11% (HE/1b; 14 m) across the cherts at the very base of the 'Hebukehe' Formation. Siltstones above the cherts show a sudden increase in TOC reaching 0.27% (HE/2b; 15.4 m) with a drop off to 0.13% in slightly silty green mudstones (HE/5; 15.7 m). After this shift, values range from 0.11% (HE/17; 23 m) to 0.16% (HE/32; 25.6 m) in the lower part of the 'Hebukehe' Formation. The TOC level gradually increases towards the upper part of the 'Hebukehe' Formation and reaches 0.25% (HE/126; 93.6 m). The uppermost bed of the 'Hebukehe' Formation shows a slight decrease to 0.2% (HE/130; 95.3 m); this is followed by an increase in the lower part of the Heishantou Formation. Bed HEI/21b (17.1 m) from the uppermost part of the section studied shows a highest TOC enrichment reaching up to 0.42%.

The sulfur content consistently has ratios below 0.1% across the entire section and shows a trend similar to TOC. Values gradually decrease across the uppermost part of the 'Zhulumute' Formation and the base of the Hongguleleng Formation to a value of 0.02% (HO/1/18; 7.92 m). Above this bed, values fluctuate from 0.01% to 0.04% until HO/2/234 (88.42 m), followed by an increase to 0.07% at the upper part of Unit 2 (HO/2/275b; 90.81 m). The bed, which shows the positive shift in sulfur content, also records an increased $d^{13}C_{carb}$ value. However, such a significant excursion is not detected in the TOC curve of the same sample (Fig. 3). Similar shifts in trends of $d^{13}C_{carb}$ and S_{tot} are continuously observed across the upper part of Unit 2. The sulfur content decreases to 0.02% above the bed HO/2/275b; it is followed by a slight increase in values to 0.04% (HO/2/295; 94.65 m). Although the lower 20 m of the 'Hebukehe' Formation are characterized by commonly low values between 0.02% and 0.04% two positive peaks have values of 0.06% (HE/3; 15.45 m and HE/36a; 32.12 m). Above HE/36a, there is another negative excursion with values as low as 0.02% before these increase again to 0.06% in bed HE/95 (81.4 m). Above this level, values fluctuate between 0.02% and 0.05% until bed HEI/18 (16.55 m), increasing to 0.07% ca. 17.1 m high in the Heishantou Formation (HEI/21b). A similar prominent positive shift is also recorded for the TOC value of the same sample of bed HEI/21b.

5. Discussion

5.1. Stratigraphy

5.1.1. Lithostratigraphy, boundaries and correlation

In our interpretion, the Hongguleleng Formation is composed of two units with a total thickness of approximately 97 m. The contact between the 'Zhulumute' and the Hongguleleng formations and between the Hongguleleng and the 'Hebukehe' formations seem to be conformable. Minor faults were observed crossing the 'Zhulumute'–Hongguleleng formation boundary with stepwise displacement of the basal-most limestone beds at metre-scale; none of the beds appear sheared off by low angle faults. The lowest limestone beds and intercalated shales deposited above the volcaniclastic siltstones are rich in tuffaceous green mudstone and seem to be deposited without any detectable interruption above the 'Zhulumute' Formation. No hardground or irregular bedding plane marks the upper surface of ZH/-1/14. The Hongguleleng–'Hebukehe' boundary exposes a gradual transition from bioclastic marls and calcareous shale to radiolarian-bearing cherts reflecting continuous sedimentation across the boundary.

In general, the ca. 97 m thick interval of the 'Hebukehe' Formation conforms to the ''Middle and Upper Member of the Hongguleleng Formation'' by Hou et al. (1993). Here we follow Xia's (1997a, pp. 104–106) proposal that the lower part of the Hebukehe Formation can be correlated with the upper part of the Hongguleleng Formation on the basis of lithologic similarities and conodont data from the Lower Member of the Hebukehe Formation in its type-section where ages appear to range through the *crepida* to early *expansa* biozones. The interval of crinoidal grainstones near the top of the 'Hebukehe' Formation ('Blastoid Hill equivalent') is an important horizon (Fig. 7A and C). This interval, originally described by Hou et al. (1993), is a low elevation called, informally, 'Blastoid Hill' (Fig. 7B and D), because of the abundance of blastoids collected there. Blastoid Hill outcrops ca. 400 m south of the type-section (Fig. 1).

The 'Hebukehe' Formation is conformably overlain by the Heishantou Formation. What we regard as the most useful boundary does not correspond with the position drawn by Hou et al. (1993). We draw the boundary at a distinctive lithological change from bioturbated bioclastic calcareous green shale and siltstone to yellowish gray to light olive brown silty bioclastic wackestones and bioclastic calcareous siltstones, easily recognized in the field.

5.1.2. Biostratigraphy

Zhao and Wang (1990) reported the conodonts *Ancyrognathus bifurcatus*, *Polygnathus semicostatus*, *Icriodus cornutus*, *Palmatolepis minuta minuta*, *Pa. perlobata*, *Pa. quadrantinodosa inflexa*, *Pa. glabra prima* and *Pa. glabra pectinata* from limestone beds of the Hongguleleng Formation. None of these are tightly constraining as to age but are consistent with an early to middle Famennian age. Xia (1997a), from more comprehensive sampling, reported three conodont faunas consistent with the Late *rhenana* Biozone (late Frasnian), Middle *crepida* Biozone (early Famennian) and Early *expansa* Biozone (late Famennian). According to Xia, the oldest conodont fauna includes *Icriodus subterminus*, *Polygnathus planarius*, *Po. imparilis*, *Po*. ex gr. *webbi*, and species related to *Ancyrognathus* (see Xia, 1997a, p. 96). The conodont assemblage of the Middle *crepida* Biozone is dominated by *Icriodus* and *Polygnathus*, and includes taxa such as *Icriodus alternatus alternatus*, *Po.* ex gr. *webbi*, *Po. aequalis*, and *Po. brevilamiformis*, none of which are tightly constraining as to age. These two conodont faunas occur in three sections near the Boulongour Reservoir (Xia, 1997a, section A of Fig. 2); an unmeasured section within the same syncline, and at Eregenaren section (Xia, 1997a, section B of Fig. 2). The youngest

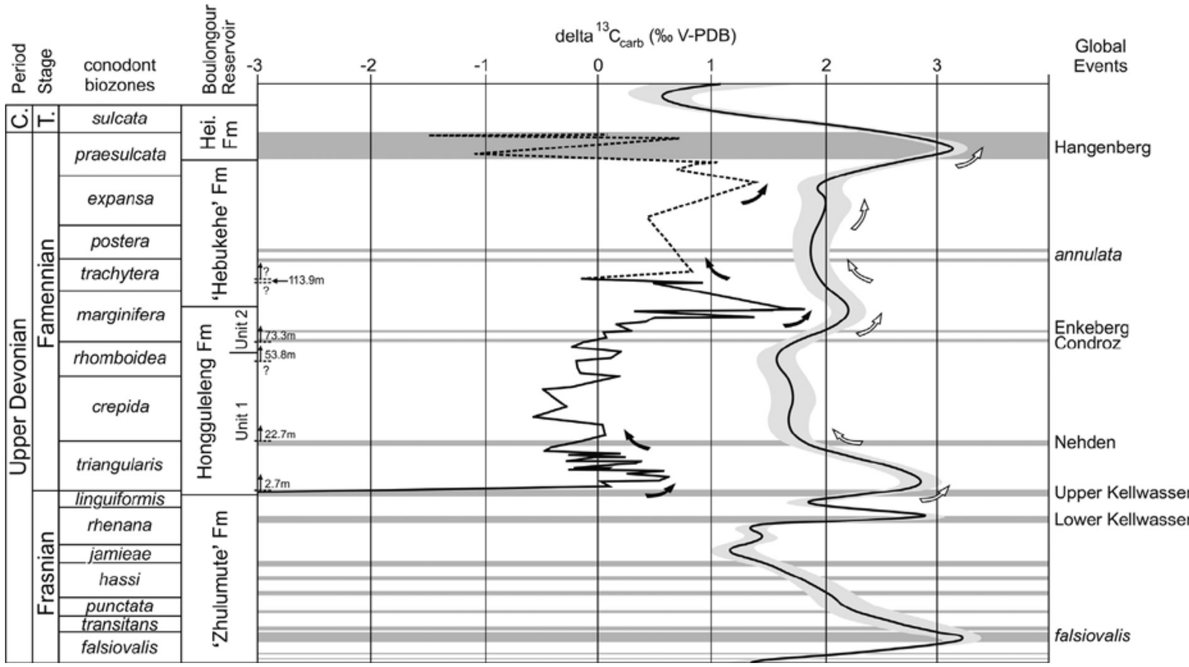

Fig. 10. Comparison of $d^{13}C_{carb}$ values in the samples from the Late Devonian Boulongour Reservoir section (same curve as presented in Figs. 3 and 4) with locfit curve in the Late Devonian presented by Buggisch and Joachimski (2006, p. 81). Global events shown on the right side of locfit curve according to House (2002). Note that the full line of the Boulongour isotope log is biostratigraphically constrained whereas the dotted line from above 113.9 m does not have biostratigraphic calibration.

conodont fauna, obtained from the Hebukehe section, is, according to Xia, indicative of the Early *expansa* Biozone and is characterized by the occurrence of *Polygnathus* ex. gr. *webbi* and *Po. communis communis*.

Study of the conodont faunas from the Hongguleleng Formation indicates five conodont biozones ranging from the latest Frasnian to middle Famennian (cf. Chen et al., 2009): *linguiformis*, *triangularis*, *crepida*, Late *rhomboidea*, and *marginifera* biozones in ascending order. A comprehensive conodont monograph of the entire sequence is presently in preparation by Mawson and others. According to Ma et al. (2011) limestones at the base of Hongguleleng Formation do not extend into the late Frasnian as proposed by Xia (1997a), but begin in the early Famennian as suggested by Zhao and Wang (1990). He asserts, incorrectly, that the brachiopod association is a ''typical post Frasnian–Famennian extinction fauna'' without presenting data on the spectrum of brachiopod species and genera which went into extinction during that event. Conodonts from the lowest limestones of the stratotype of the Hongguleleng Formation are indubitably latest Frasnian *linguiformis* Biozone; the Frasnian–Famennian boundary is discriminated by the entry of *Palmatolepis triangularis* 2.7 m above the base of the formation (Figs. 2 and 3).

Only one conodont biozone, the *trachytera* Biozone, has been identified in the 'Hebukehe' Formation. Other conodont biozones indicative of late Famennian, i.e., *expansa* and *praesulcata* biozones, reported by Xia (1997a), were not encountered in our study. However, it is possible to estimate the age of the upper part of the 'Hebukehe' Formation and the lower part of the Heishantou Formation by comparing the results from the carbon isotopes with the $d^{13}C_{carb}$ composite standard curve of Buggisch and Joachimski (2006) – for further discussion see below.

5.1.3. Chemostratigraphy

A prominent positive $d^{13}C_{carb}$ excursion at the base of Unit 1 of the Hongguleleng Formation across the Frasnian and Famennian boundary (transition between *linguiformis* and *triangularis* biozones) is documented. We have concerns about diagenetic overprinting in the lowermost part of the section and plan more detailed studies to partition the original signal from the diagenetic overprint. Nevertheless, the general trend of the carbon isotope curve from the latest *linguiformis* Biozone to the *trachytera* Biozone (Fig. 10) corresponds well with published results from Central and Southern Europe (Buggisch and Joachimski, 2006; Joachimski et al., 2009) and northwestern Thailand (Königshof et al., 2012, cf. Savage, 2013 for more dates on ages). We also recognize a second positive excursion higher in the section across the *marginifera*–*trachytera* biozones. Though values plotted above the *trachytera* Biozone lack biostratigraphic constraint, the observed trend correlates with the running mean-curve between *trachytera* and *praesulcata* biozones of Buggisch & Joachimski (2006: Fig. 7).

5.2. Depositional environment

Pioneering chonetid faunas settled first on the volcaniclastic sand and siltstones of the underlying 'Zhulumute' Formation. Brachiopod diversity seems to have increased as the marine environment stabilized. Sponge spicules, crinoid ossicles, ostracods, gastropods, conodonts and fish teeth occur in the lowest part of the Hongguleleng Formation (Fig. 8); these are consistent with a relatively shallow depositional environment. A change in the fossil community to one dominated by productid brachiopods, fenestellid bryozoans, ostracods, sponge spicules and solitary rugose corals is observed with the sedimentologic change to predominantly green shale deposition in the upper two-thirds of Unit 1. These soft bottom conditions with its significantly adopted fauna, known also from other places, for example in the Eifel area during the Middle Devonian (Ernst et al., 2011), are later replaced by deposition of thin layers of bioclastic limestones, alternating with mud to silty mudstones of Unit 2. We interpret the changing facies from the Hongguleleng Formation to the 'Hebukehe' Formation to infer a deepening of the depositional environment. The prominent interval known as 'Blastoid Hill' near the top of the 'Hebukehe'

Formation seems to equate with a carbonate lens of approximately 3 m thickness and some few hundred metres in lateral continuity and might be interpreted as a crinoidal shoal. Another distinctive facies change marked by steadily increasing TOC values and the occurrence of lingulid brachiopods occurs within the basal portion of the Heishantou Formation.

5.3. Evidence for the Upper Kellwasser Event

According to Ziegler and Sandberg (1990), the limit between the *linguiformis* and *triangularis* conodont biozones, defined as the Frasnian–Famennian boundary, corresponds to the top of the Upper Kellwasser horizon. House (2002, and references therein) summarized the impact of this global crisis on the diversity of marine faunas, especially emphasizing the extinction among cephalopods. Gereke (2007) and Gereke and Schindler (2012) provide additional details on high-resolution lithostratigraphy and finescale biostratigraphy of classical Kellwasser localities from basinal settings. In the Hongguleleng Formation, the Upper Kellwasser Event is interpreted as occurring at the boundary of the *linguiformis* and *triangularis* biozones. In the lowermost 2.7 m above the formation base, the faunal community is represented by few groups of marine organisms; chonetid brachiopods are dominant. Brachiopods show an increase in diversity soon after in the lower part of the *triangularis* Biozone with the occurrence of eight different groups (see Fig. 8). According to further geochemical analysis, the TOC of carbonate beds does not show values higher than 0.14 %, but this might simply be due to the generally shallow depositional environment. It seems that faunas observed from the very base of the Hongguleleng Formation were affected by the Upper Kellwasser Event, but survived that critical time interval relatively well as documented by a short recovery time and the abundant and diversified faunal assemblages seen higher in the section.

6. Conclusions

1. The Late Devonian sequence near the Boulongour Reservoir is assigned to the 'Zhulumute', Hongguleleng, 'Hebukehe' and Heishantou formations in ascending order. Total thickness from the base of the Hongguleleng Formation to the top of the 'Hebukehe' Formation is approximately 192 m.
2. The contact between the 'Zhulumute' and Hongguleleng Formations is conformable as is the contact between the Honguleleng and 'Hebukehe' Formations. The 'Hebukehe' Formation is conformably overlain by the Heishantou Formation.
3. Five conodont biozones have been discriminated within the Hongguleleng Formation: the late Frasnian *linguiformis* Biozone; the early Famennian *triangularis*, *crepida*, and Late *rhomboidea* biozones; and the mid-Famennian *marginifera* Biozone. One conodont biozone, the middle Famennian *trachytera* Biozone, was discriminated within the 'Hebukehe' Formation.
4. A late Frasnian age for the basal Hongguleleng transgression is indicated by occurrences of an interval with *linguiformis* Biozone conodonts at the base of the formation.
5. At the Boulongour Reservoir, the Frasnian–Famennian boundary is located 2.7 m above the base of the Hongguleleng Formation.
6. The geological age of the 'Hebukehe' Formation near the Boulongour Reservoir is mid-Famennian based on conodont data obtained to date.
7. The Upper Kellwasser Event is inferred from conodont data from the Boulongour Reservoir stratotype section for the Hongguleleng Formation.

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