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Palaeoenvironmental changes at Col des Tribes (Montagne Noire, France), a reference section for the Famennian of north Gondwana-related areas

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Abstract – We present detailed biostratigraphy based on conodonts and palaeoenvironmental trends deduced from microfacies and conodont abundance through the Famennian (Late Devonian) at Col des Tribes (Montagne Noire, France). The succession is characterized by micritic limestones deposited in settings oscillating between mid to outer ramp. Facies contain poor fauna, widely dominated by nektonic organisms. This section is complete and one of the most conodont-rich for the Famennian of the north Gondwana-related area. The Upper Kellwasser event (Frasnian–Famennian boundary) and the Hangenberg (Devonian–Carboniferous boundary) have been lithologically identified. They are characterized by decimetre-thick black dysoxic to anoxic argillaceous sediments. The Condroz and *annulata* events, although not materialized by lithological changes, have been positioned due to the precise stratigraphy. The first event occurred during the deposition of condensed ferruginous facies (griotte limestones) and the second event during the deposition of micrites barren of benthic fauna. The combination of information from both facies and conodont biofacies changes allows a general sea-level curve through the entire Famennian for north Gondwana to be proposed for the first time. At Col des Tribes, the general trend is a slight deepening upwards from *triangularis* to *trachytera* zones, then a pronounced shallowing-upwards trend from upper *trachytera* to *praesulcata* zones. This curve correlates with the well-known reference curve from Euramerica concerning the late Famennian (*trachytera* to *praesulcata* Zones). There are some discrepancies in minor cycles which can be explained by tectonical phenomena at the onset of the edification of the Variscan belt in Europe.

Keywords: conodonts, microfacies, Devonian, Montagne Noire, sea level.

1. Introduction

The Famennian (Late Devonian epoch) is a stage marked by important changes in the biosphere and a period of recurrent environmental perturbations. Seven global events occurred over an interval of *c.* 15 Ma. At its base, the Frasnian–Famennian (F/F) boundary is known as one of the five most drastic episodes of biological extinction of the Phanerozoic and has recently also been considered as a biodiversity crisis due to speciation rate drop (Racki, 2005; Stigall, 2012). This episode is called the Kellwasser event. At the top of the Famennian, the Devonian–Carboniferous boundary is also characterized by a worldwide extinction event called the Hangenberg event (Walliser, 1984). Other global events occurred during the Famennian such as Nehden (House *et al.* 1985; Schülke, 2003; Schülke & Popp, 2005), Enkeberg (House, 1985; Becker, 1993), Condroz (Schülke & Popp, 2005), *annulata* (Becker, 1993; Schülke & Popp, 2005) and Dasberg (Becker, 1993; Hartenfels, 2010; Marynowski, Filipiak & Zaton, 2010). They are generally marked by palaeontological and/or environmental changes (Walliser, 1996; House, 2002).

Among these events, the Kellwasser, *annulata*, Dasberg and Hangenberg are related to worldwide anoxic events. In most of the cases these anoxic events have been studied when easily identified based on facies deposits, i.e. when black shales are present (Becker, 1993; Racka *et al.* 2010). The Condroz event is not paired with anoxia spread, but with termination of black *Cheiloceras* shale due to regression (Walliser, 1996). Independently of any lithological signature, following the Late Devonian conodont zonation established by Ziegler & Sandberg (1990) all these events can be dated and globally correlated. Assumed to be synchronous at the global scale, these events are sometimes related to a glacioeustatic mechanism (Sandberg, Morrow & Ziegler, 2002; Racka *et al.* 2010) and generally to sea-level fluctuations (Walliser, 1996).

Sea-level fluctuations through the Devonian are well known on the east European platform (Alekseev,

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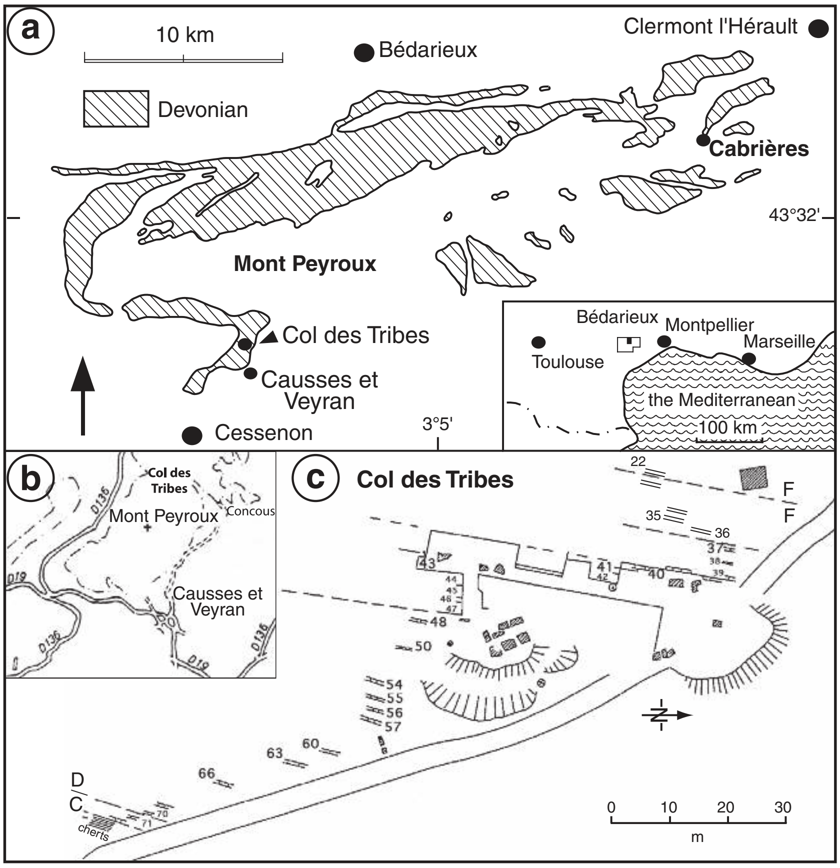

Figure 1. Location of the Col des Tribes section (Montagne Noire, south France). Maps showing: (a) the position of the Montagne Noire in southeastern France; (b) the Col des Tribes section near Causses and Veyran; and (c) the position of the sampled levels (modified from House, 1985; Becker, 1993). F/F --- Frasnian/Famennian boundary; D/C --- Devonian/Carboniferous boundary.

Kononova & Nikishin, 1996) and at the scale of the Euramerica supercontinent (Johnson, Klapper & Sandberg, 1985; Johnson & Sandberg, 1989; Sandberg, Morrow & Ziegler, 2002; Haq & Schutter; 2008; Racka *et al.* 2010). Because of the absence of continuous sections through the Famennian on the north Gondwana-related area (Galatian superterrane, Stampfli *et al.* 2013), sea-level fluctuations are poorly constrained.

The present study focuses on the tracing of Famennian sea-level fluctuations and related events in the Montagne Noire (France). Previous biostratigraphic works at Col des Tribes (CT) were principally based on goniatites (J.D. Price, unpubl. thesis, University of Hull, UK, 1982; Becker, 1993; Becker & Weyer, 2004). The presence of variously abundant conodonts in a series of reconnaissance samples was discovered by G. Klapper in the early 1980s (unpublished results) but detailed conodont biostratigraphy of the entire Famennian sequence remained largely incomplete (Boyer *et al.* 1968). These works however suggested that there were no major biostratigraphical gaps or discontinuities allowing for both microfacies investigations and evaluation of conodont faunal changes to be made throughout the entire Famennian interval.

In this regard we aim to: (1) establish a detailed stratigraphy based on conodont biozonation; (2) establish a model of depositional environments using the evolution of microfacies; and (3) use conodont assemblages to obtain an insight into particular sea-level changes.

2. Geological setting

The Col des Tribes section is located in the Montagne Noire, France (Fig. 1). The Montagne Noire is part of the external tectonic zone of the Variscan belt in southern France (Matte, 1991; Ballèvre *et al.* 2009; Faure, Lardeaux & Ledru, 2009; Fig. 1a), composed of a south-facing pile of low-grade to non-metamorphic rocks (Arthaud, 1970). Even if the palaeolocation of the Montagne Noire during Late Devonian time is still under debate, most authors consider it was on the northern-most margin of Gondwana or on an intermediate block rifted off Gondwana during Early Palaeozoic time and located between Laurussia and Gondwana (Tait, Bachtadse & Dinarès-Turell, 2000; Golonka, 2002; Nysaether *et al.* 2002). During Famennian time, the Montagne Noire should have been part of the Galatian superterrane which was bouded to the SE by the Palaeotethys Ocean and bounded to the NW by the Rheic Ocean (Stampfli *et al.* 2013). The studied section belongs to the inverse limb of the Montpeyroux nappe which suffered very low-grade metamorphism (anchizonal to non-metamorphic, Wiederer *et al.* 2002). It is composed of oxidized sediments assumed to have been deposited on an outershelf submarine rise (Engel, Feist & Franke, 1982).

In contrast to Palaeozoic rocks of the Pyrenees and southern Alps, those of the Montagne Noire did not suffer any alpine deformation which explains the comparatively good preservation of fossils and sedimentary fabrics. The investigated section near Col des Tribes is situated on the eastern slope of the Mont Peyroux summit (Fig. 1), IGN sheet 1:25 000 St Chinian 2544 E, between 43° 29′ 26.65″ N, 3° 5′ 26.28″ E and 43° 29′ 23.94″ N, 3° 5′ 27.50″ E.

3. Methods

3.a. Palaeoenvironments

A total of 71 samples were collected (Figs 1b, 2a), marked in the field by pink numbers. Bed numbers mostly coincide with those formerly marked by House & Price (in Becker, 1993, pp. 91–92). Many covered intervals were made accessible by hand digging. A total of 71 thin-sections were cut for microfacies analysis from the same samples used for conodont studies. Based on field and microscopic observations (semi-quantitative estimate of the relative abundance of bioclasts) and palaeontological qualitative results, four facies types are distinguished (Flügel, 2004). As facies are poorly diversified at Col des Tribes where the carbonates generally yield few bioclastic debris (only one sample provided up to 15 % of bioclasts), we chose the following ratios of bioclast abundance to illustrate vertical changes along the section: very rare: <1 %; rare: 1–2 %; frequent: 2–6 %; and abundant: 6–15 %. In order to characterize the depositional environment, we introduced the ratio $N/(N+B)$ where N is the abundance of debris of nektonik organisms, B is the abundance of benthic organisms and $N+B$ represents the total abundance of bioclasts (nektonik + benthic) (see Flügel, 2004 for palaeoenvironmental setting of organisms). Even if such a ratio is dependent upon very different palaeoenvironmetal parametres (dysoxia, nature of bottom, currents, etc.), we consider it useful for discrimating large-scale proximal to distal trend changes. The most frequent pieces of benthic organisms are issued from thin-shelled and less than 500-μm-long ostracods, echinoids (crinoids), trilobites, brachiopods and, to a lesser extent, gastropods, bivalves, silicified foraminifers, sponges and possibly microbes. Nektonic organisms are represented by cephalopods (ammonoids), thin-shelled pelagic molluscs (‘filaments’ in thin-section), pelagic ostracods (entomozoans) and calcified radiolarians (<200 μm). Most foraminifers, conodont elements and fish teeth were also found from residues of washed samples. The lithological description is based on Dunham’s (1962) carbonate rock classification refined by Embry & Klovan (1971). Each facies is related to a depositional environment according to the zonations proposed by Wright & Burchette (1996) and Flügel (2004). The pelagic carbonate systems of Devonian time are known to be large-extent platforms (Peterhänsel & Pratt, 2001; Morrow & Sandberg, 2008). The vertical change of facies during Famennian time suggests a low-angle ramp depositional system. Inner-ramp deposits correspond to marine sediments which were deposited above the base of the fair-weather wave action. Mid-ramp deposits were deposited between the lower limit of fair-weather wave action and the base of storm-wave action. Outer-ramp – basinal deposits were deposited under the lower limit of storm-wave action (Fig. 2b).

3.b. Faunas

A total of 71 samples were sampled for conodont studies. The weight of the samples analysed varied within the range 50–730 g depending on the abundance of conodonts (Table 1). The samples were taken at intervals of 0.1–1.0 m over the entire section in order to capture the changes in lithology. The samples were dissolved in dilute formic acid (10 %). The insolute residues were separated through two sieves (100 μm and 1 mm). The two fractions were dried and picked up under a binocular microscope in order to collect the microfossils. All conodonts (Table 1) occurring in the residues were picked up. Some conodont elements were identified at the specific level for biostratigraphy (Fig. 3). For biodiversity analyses, the absolute and relative abundances of the different genera present in the samples have been investigated. When present, trilobites provided additional information about palaeoenvironment.

3.b.1. Conodont absolute and relative abundances

Absolute abundance was estimated as the number of platform elements (P1) per kilogram of rock. Since the differences in absolute abundances reach several orders of magnitude, these data have been log-transformed. Very different weight of rocks have been analysed in order to obtain a total close to 100 platform elements for each level, allowing for a reliable estimation of relative abundances. When the number of platform elements was <100, values were excluded from the analyses (see Table 1). Among these platform elements, several genera can be identified that have been related to different environmental preferences (Seddon & Sweet, 1971; Sandberg, 1976). The variations of the relative proportion of the different genera are assumed to provide an indirect water depth proxy.

Such an approach is called biofacies analysis (Seddon & Sweet, 1971; Sandberg, 1976). In this study the procedure established by Sandberg (1976) has been followed. Each biofacies was named after the one or two most abundant genera among the conodont platform elements, usually constituting at least 75–80 % of the total platform elements. During the investigated period, *Icriodus* and *Protognathodus* are considered as characteristic of shallow marine environments (Sandberg & Dreesen, 1984), whereas *Palmatolepis* and *Siphonodella* have been interpreted as associated with

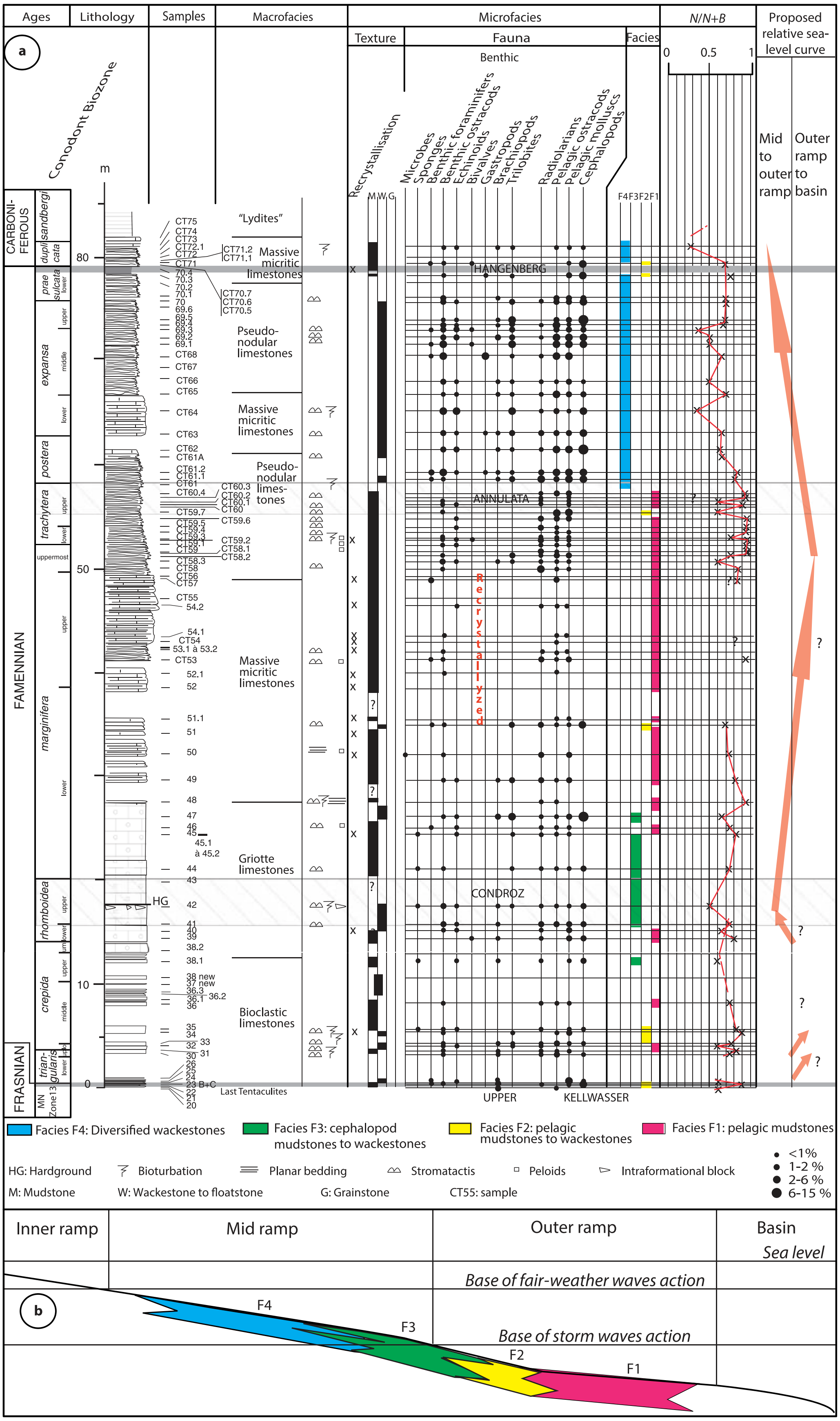

Figure 2. (Colour online) Col des Tribes section with microfacies interpretations and proposed relative sea-level changes. Conodont zones after Ziegler & Sandberg (1990). Estimated sea-level variations based on *N*/(*N*+*B*) ratio, where *N* represents nektonic faunas and *B* benthic faunas. Blackish argillaceous sediments are depicted in grey, shadings represent the tentative position of some Famennian events. lo – lower; up – upper; um – uppermost.

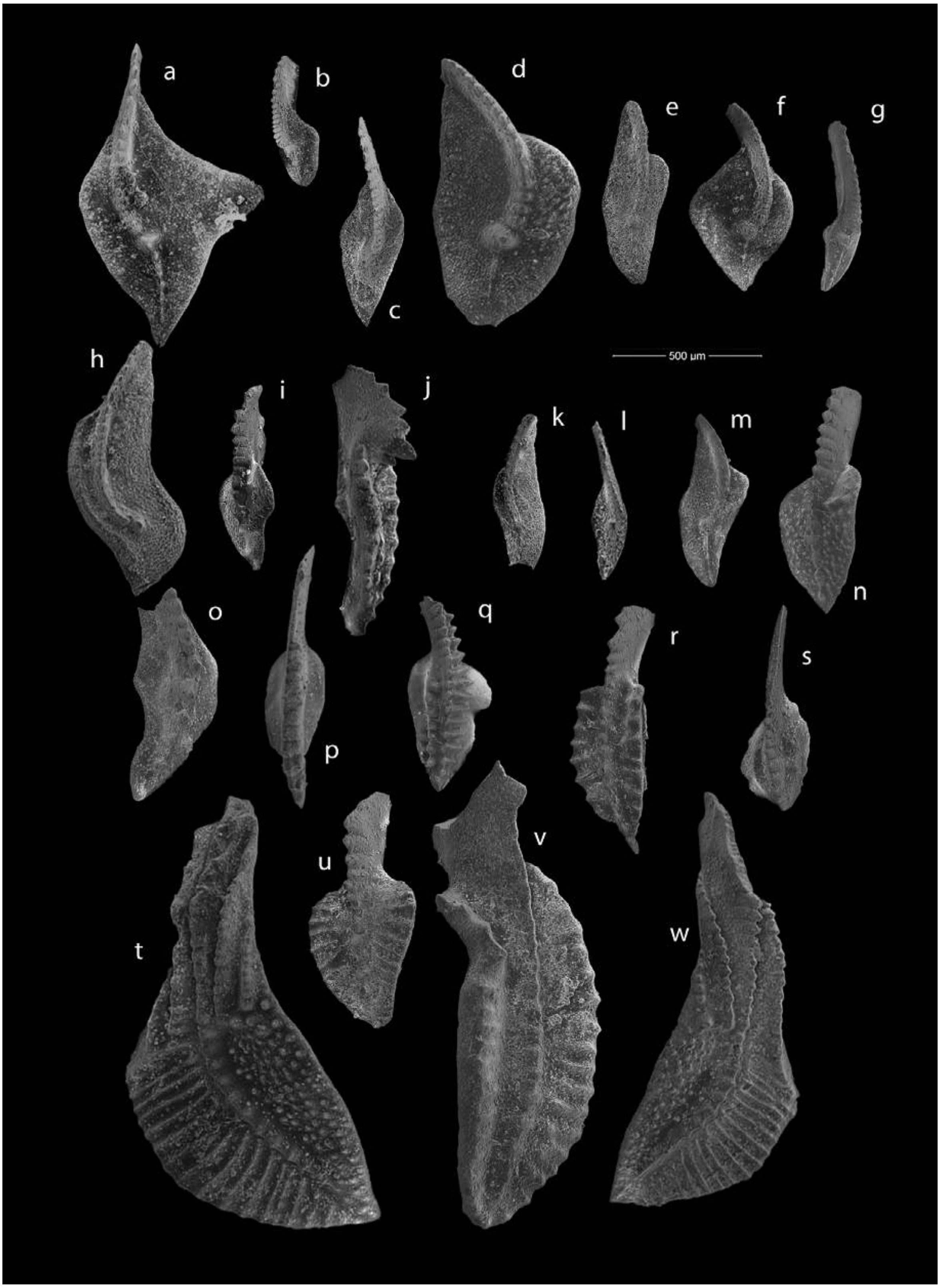

Figure 3. Famennian biostratigraphic species. (a) *Palmatolepis triangularis* Sannemann, 1955; (b) *Palmatolepis minuta minuta* Branson & Mehl, 1934; (c) *Palmatolepis termini* Sannemann, 1955; (d) *Palmatolepis crepida* Sannemann, 1955; (e) *Palmatolepis glabra prima* Ziegler & Huddle, 1969; (f) *Palmatolepis rhomboidea* Sannemann, 1955; (g) *Palmatolepis gracilis gracilis* Branson & Mehl, 1934; (h) *Palmatolepis marginifera marginifera* Helms, 1959; (i) *Polygnathus glaber bilobatus* Ziegler, 1962; (j) *Scaphignathus velifer velifer* Helms, 1959; (k) *Palmatolepis perlobata helmsi* Ziegler, 1962; (l) *Palmatolepis gracilis sigmoidalis* Ziegler, 1962; (m). *Palmatolepis perlobata postera* Ziegler, 1960; (n) *Polygnathus styriacus* Ziegler, 1957; (o) *Palmatolepis gracilis expansa* Sandberg & Ziegler, 1979; (p) *Bispathodus costatus* Ziegler, Sandberg & Austin, 1974; (q) *Bispathodus ultimus* Bischoff & Ziegler, 1957; (r) *Siphonodella sulcata* Huddle, 1934; (s) *Protognathodus meischneri* Ziegler, 1962; (t) *Siphonodella quadruplicata* Branson & Mehl, 1934; (u). *Pseudopolygnathus triangulus triangulus* Voges, 1959; (v) *Siphonodella duplicata* Branson & Mehl, 1934; (w) *Siphonodella cooperi* Hass, 1959.

Table 1. Numbers of platform conodont genera per level. The samples in bold are not included in the analyses due to the very low abundance of conodonts. Pa – *Palmatolepis*; Po – *Polygnathus*; Ps – *Pseudopolygnathus*; Bi – *Bispathodus*; Br – *Branmehla*; Me – *Mehlina*; An – *Ancyrodella*; Ic – *Icriodus*; Sc – *Scaphignathus*; Pr – *Protognathodus*; Si – *Siphonodella*.

Samples	Depth (m)	Weight (kg)	Pa	Po/Ps	Bi/Br/Me	Ic	Sc	Pr	Si	Total
CT72	81.5	70		60					115	175
CT72-1	**81.25**	**50**		**21**	**1**			**2**	**2**	**26**
CT73	81	410		43				31		74
CT72	80	250		143	12				5	160
CT71	79.5	170		73				5	3	81
CT70-7	79.4	180		50	20					70
CT70-5	79.2	200		10				22		32
CT70-2	77.5	420	32	42	150				1	225
CT70-1	76.3	110	19	26	49					94
CT70	75.8	140		30	67				2	99
CT69-5	74	150		21	75					96
CT69-4	73.5	340	1	22	69					92
CT69-3	73	280	5	26	97					128
CT69-1	71.7	240	19	84	113					216
CT68	70.5	180	19	20	63					102
CT67	69.5	220	31	5	250					286
CT66	68.5	210	36	5	113					154
CT65	67	100	13		57					70
CT64	65.2	130	40	1	44					85
CT63	63	350	92	69	81					242
CT62	61.5	210	45	5	150					200
CT61	58	450	27	3	20		5			55
CT60-2-4	57.2	490	22	7	10		16			55
CT60-1	56.2	480	62	5	36		17			120
CT60	56	340	39	15	26		20			100
CT59-4-5	54	660	47	4	27		8			86
CT59-2-3	52.9	730	60	4	36		2			102
CT59-1	52.5	350	97	8	8	1				114
CT59	51.7	470	102	11	17	6				136
CT58-1-2	51	330	102	6	6					114
CT58-0-3	50	380	59	3	8		1			71
CT57	49.5	130	38	2	3					43
CT56	49	150	96	15	7					118
CT55	47.2	270	47	17	24	1				89
CT54-2	**46.5**	**90**	**14**	**4**	**4**					**22**
CT54	43	560	36	15	9					60
CT53	41.2	210	377	25	51	4				457
CT52	38.5	120	33	12	8					53
CT51-1	35.5	120	70	11	2					83
CT51	34.2	140	109	9	18					136
CT50	32.2	240	184	13	1	1				199
CT49	29.5	140	170	10	3					183
CT48	27.5	160	116	2	1					119
CT47	26	140	209	29	11					249
CT46	25	540	79	43	1					123
CT45-1-2-3	22.5	730	67	4	4					75
CT44	21	110	62	8	6					76
CT43	19.5	240	48	2	3					53
CT42	17.2	170	242	43	7	20				312
CT41	15.6	110	149	8	5	5				167
CT39-40	14.75	680	62	21	3	3				89
CT38	**10.8**	**160**	**15**	**3**		**9**				**27**
CT37	10	160	119			2				121
CT36	8	140	31	5		8				44
CT35	6	500	143	3		1				147
CT32-34	4.75	450	64	3						67
CT31	3.5	300	105	7		10				122
CT30	3.3	250	97	15	1	9				122
CT24	0.6	160	132	18		46				196
CT23bc	0.35	200	117	20	15 An	1				153
CT22	0.2	290	107	49	4 An	10				170
CT20	0	180	230	6	22 An	2				260

deeper conditions (Sandberg, 1976). *Bispathodus* and morphologically related genera such as *Branmehla* and *Mehlina* are grouped under the term bispathodids (Ziegler & Sandberg, 1984). Together with *Polygnathus* they are considered as ubiquitous, but bispathodids are considered as characteristic of the euphotic zone of deep environments (Sandberg, 1979; Ziegler & Sandberg, 1984). *Scaphignathus* and *Alternognathus* are characteristic of very shallow water, principally found in inner platforms, and are poorly represented on outer platforms (Sandberg, 1976). These biofacies models are consistent with those developed by Savoy &

Harris (1993) for a Famennian ramp deposited in North America.

4. Results and interpretations

4.a. Lithology and macrofauna

The Famennian deposits at Col des Tribes comprise a 84-m-thick carbonate succession (Fig. 2a). Above a 0.05-m-thick dark clayey level at the base, the lowest 17 m of the section are composed of poorly cropping out, yellowish mudstones to wackestones organized into decimetre-thick beds. Scarce fragments of blind trilobites were found (*Nephranops*, bed CT25). Beds can display a nodular aspect because of important post-depositional pressure-dissolution processes (stylolithes, pseudonodular texture). Between 17 and 31 m, typical griotte limestones ('vrai griottes', Boyer *et al.* 1968) are exposed (Fig. 4a, b). These are composed of massive, red mudstones to wackestones/floatstones organized into decimetre-thick beds. They display numerous centimetre-sized ammonoids concentrated in the uppermost part of the beds and a nodular texture. Carbonate nodules are composed of cephalopods or micrite coated by millimetre-thick ferruginous argilites (Fig. 4b). Ammonoids often display geopetal infillings without preferential orientation. Micritic nodules are millimetre- to centimetre-sized and are arranged parallel to bedding. Laterally they change into fragmented to intact micritic beds. At 20.5 m a bed with intraformational breccias is intercalated, characterized by angular, decimetre- to metre-wide tilted griotte blocks (Figs 2, 3a; Wendt & Aigner, 1985; Becker, 1993).

Above the breccias is an irregular centimetre-thick ferruginous hardground with abundant ammonoids which were eroded in the upper part and contains patches of iron incrustations. The following beds (CT43, 44) yield blind phacopid trilobites (*Tripholiops*) and, in argillaceous interstices, reduced eyed *Calybole* proetids among mass occurrences of *Guerichia* bivalves. Between 31 and 52 m above the base of the section are massive, greyish mudstones (Fig. 4c) organized into decimetre-thick beds with locally planar laminations and sparse ammonoids. Between 52 and 63 m pseudonodular mudstones are exposed (Fig. 4d), composed of centimetre-thick beds which have experienced pressure-dissolution processes with irregular stylolites leading to their nodular aspect. Some ammonoids are present. Above are 7-m-thick pink massive wackestones with rare blind trilobites (*Dianops*, *Chaunoproetus*), followed by 12-m-thick pseudonodular wackestones with numerous ammonoids and trilobites (*Haasia*, *Helioproetus*). At 82 m above the base of the section is a 0.6-m-thick dark argillaceous interval. The uppermost part of the section, between 83 and 85 m above its base, comprises massive mudstones with discrete, plane laminations. Trilobites (*Liobolina*) of early Tournaisian age are abundant. Above the limestones, black radiolarian cherts ('lydites') of middle Tournaisian age occur.

4.b. Conodont biostratigraphy

In this paper, the Montagne Noire zonation by Klapper (1989) is followed for the Frasnian, the Ziegler & Sandberg (1990) zonation for the Famennian and the Sandberg *et al.* (1978) zonation for the Tournaisian. Some variations on the Famennian scheme proposed by Corradini (2008) and Kaiser *et al.* (2009) have also been taken into account.

The youngest Frasnian, almost all the Famennian and two Tournaisian zones have been discriminated in the Col des Tribes section. The distribution of the determined species present all along the section is depicted in Figure 5.

The lowest part of the section (CT20–23) delivered the species *Palmatolepis bogartensis*, *Ancyrodella curvata* late form and *Ancyrognathus asymmetricus*, indicating the Biozone 'Montagne Noire Zone 13' of latest Frasnian age (Klapper, 1989).

Levels CT24, 25 can be dated to the first zone of the Famennian, the Lower *triangularis* Zone due to the occurrence of *Palmatolepis praetriangularis*, *Pa. triangularis* and *Pa. delicatula delicatula*.

The entry of the marker *Pa. minuta minuta* in sample CT30 allows the discrimination of the Upper *triangularis* Zone. The conodont association is dominated here by *Palmatolepis triangularis*, *Pa. subperlobata* and *Pa. tenuipunctata*, indicating the upper *triangularis* Zone.

The Lower *crepida* Zone is documented, and corresponds to sample CT31 which contains the first *Palmatolepis crepida.*

The occurrence of *Pa. termini* in sample CT32 allows the attribution of that level to the Middle *crepida* Zone. The Upper *crepida* Zone begins in level CT37 and the lower boundary is identified by the first occurrence of the marker *Pa. glabra prima*.

The presence of the Uppermost *crepida* Zone is attested in the level CT38-2 with the first appearance of the species *Pa. glabra pectinata*.

After this interval, level CT39 belongs to the Lower *rhomboidea* Zone due to the occurrence of the index species *Pa. rhomboidea*. The Upper *rhomboidea* Zone is identified here from the entry of *Pa. gracilis gracilis* in level CT41.

The Lower *marginifera* Zone starts 23 m above the base of the section and is recognized by the presence of the marker *Pa. marginifera marginifera* in sample CT44. The Upper *marginifera* Zone is discriminated in level CT52 by the first occurrence of *Polygnathus glaber bilobatus*. The entry of *Scaphignathus velifer* within the level CT58 allows the identification of the Uppermost *marginifera* Zone (equivalent to the *velifer* Zone of Corradini, 2008).

The base of the Lower *trachytera* Zone is identified in level CT59-1 due to the occurrence of *Pa. perlobata helmsi*. The appearance of *Pa. gracilis sigmoidalis* in

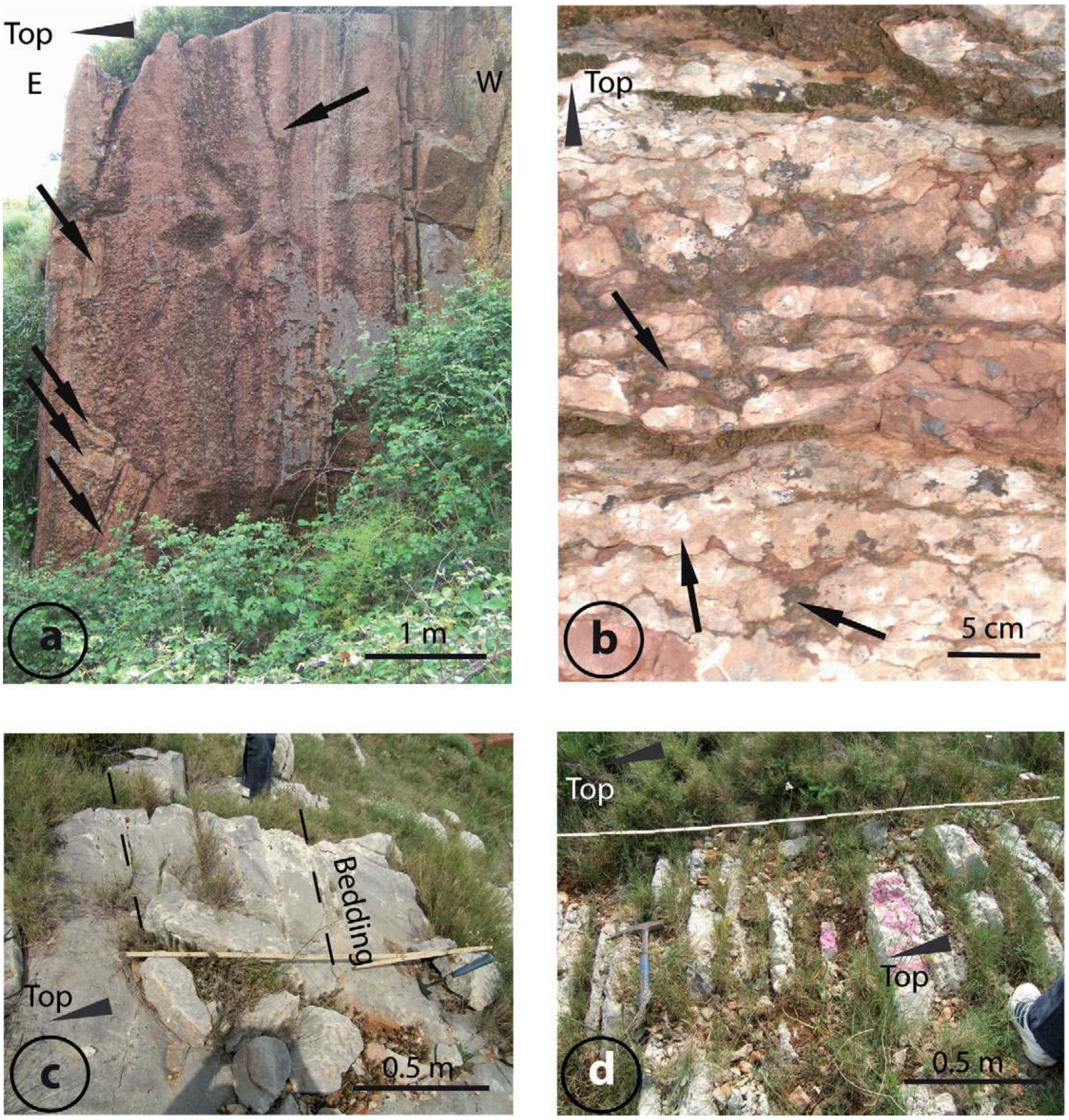

Figure 4. (Colour online) Famennian beds at Col des Tribes section. (a) General view of the Griotte limestones. On the left, arrows point to intraformational breccia; on the right, arrow points to intraformational sliding. Between are nodular limestones. (b) Detail of the nodular limestones. Arrows point to micritic nodules and streching of non-totally lithified micritic beds. (c) View of the massive micritic limestones. (d) View of the thin-bedded, pseudonodular limestones. Top – top of the beds.

sample CT59-5 allows the discrimination of the base of the Upper *trachytera* Zone.

An undifferentiated *postera* Zone is discriminated at 51–56 m from the base of the section. The base is recognized by the occurrence of the index, *Pa. perlobata postera*, in sample CT61.

The occurrence of *Pa. gracilis expansa* in sample CT63 marks the base of the Lower *expansa* Zone, whereas the entry of *Bispathodus spinulicostatus* in sample CT65 allows this level to be referred to the Middle *expansa* Zone. The Upper *expansa* Zone is discriminated by the presence of the marker *Bispathodus ultimus* in level CT66.

The base of the Lower *praesulcata* Zone is identified by the presence of the first representatives of *Siphonodella* in sample CT70, where both straight and curved forms occur. Following the suggestion of Corradini (2008), the Middle *praesulcata* Zone is not considered here and has been included in the Lower *praesulcata* Zone due to the difficulty of discriminating this zone and its poor definition. The Lower *praesulcata* Zone extends up to level CT70-4, corresponding to the Hangenberg shales equivalent.

The first level above the Hangenberg shale equivalent belongs to the Lower *duplicata* Zone, due to the occurrence of the marker S. *duplicata* morphotype 1; the Upper *praesulcata* and the *sulcata* Zone are therefore not present. The Lower *duplicata* Zone extends up to level CT71. Above, the Upper *duplicata* Zone has not been discriminated and the top of the section (CT72-1) belongs to the upper part of the *sandbergi* Zone (equiavalent to the *quadruplicata* Zone of Kaiser *et al.* 2009) because of the occurrence of *S. quadruplicata* and *Ps. triangulus triangulus*.

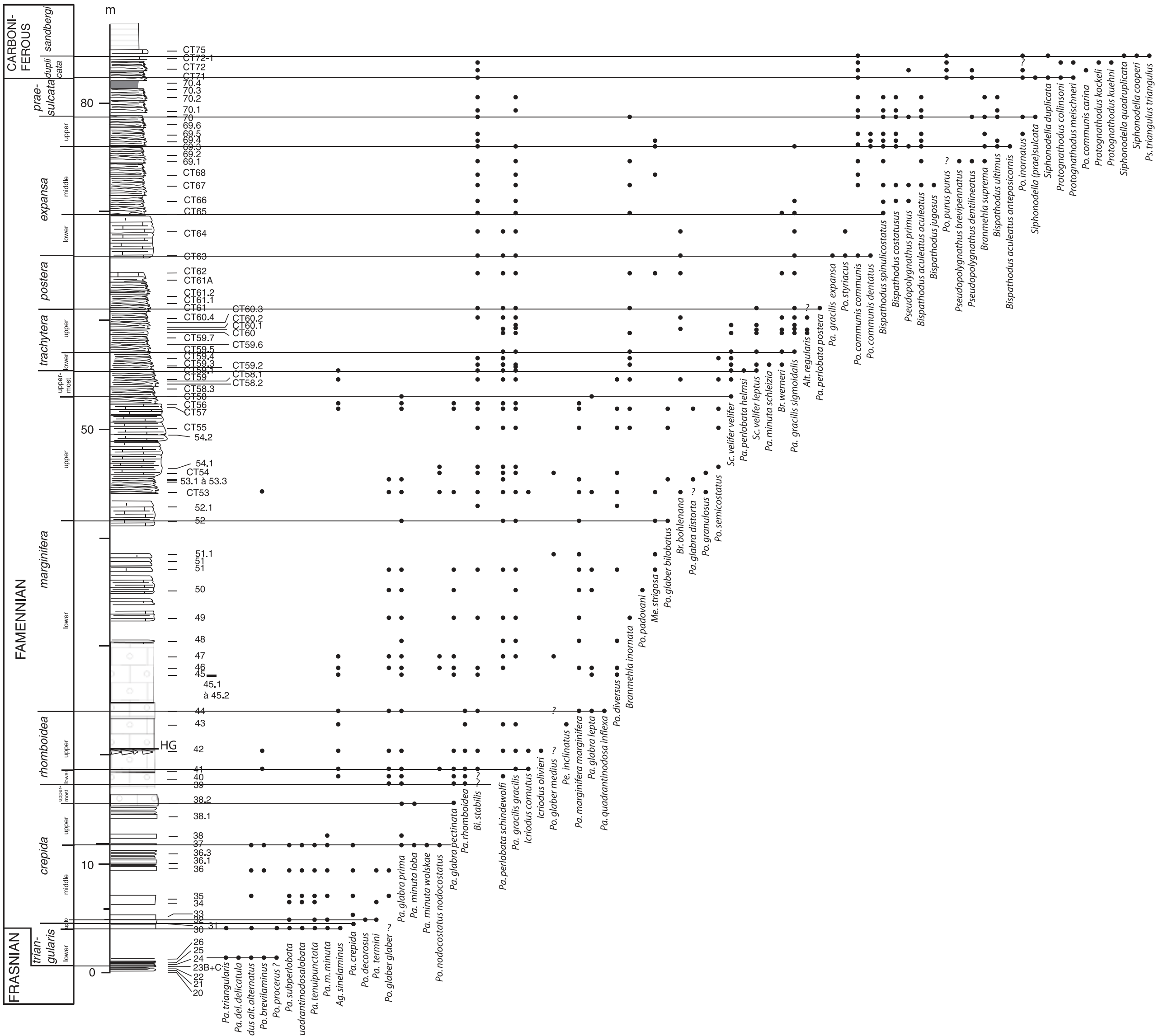

Figure 5. Distribution of major conodont species in the Famennian beds at the Col des Tribes section, Montagne Noire, France. Pa – *Palmatolepis*; Po – *Polygnathus*; Ps – *Pseudopolygnathus*; Bi – *Bispathodus*; Br – *Branmehla*; Me – *Mehlina*; An – *Ancyrodella*; Ic – *Icriodus*; Sc – *Scaphignathus*; Pr – *Protognathodus*; Si – *Siphonodella*.

4.c. Tentative location of the events

Except for the two major Upper Devonian events – the Kellwasser at the Frasnian–Famennian boundary and the Hangenberg event just before the Devonian–Carboniferous boundary – the other Famennian events are not represented by blackish argillaceous deposits or other particular deposits. Based on the detailed biostratigraphy, we propose a position of the events as follows from bottom to top (Fig. 2): the Condroz event occurs in the upper *rhomboidea* Zone (levels CT41–43); and the *annulata* event occurs in the upper *trachytera* Zone (Walliser, 1996) and can be located in successive CT59-5 to CT60-3 samples (Fig. 2).

4.d. Facies description and interpretation

At Col des Tribes a limitation to microfacies analysis is sometimes recrystallization of the fine-grained carbonates, probably due to late diagenesis during nappe setting up. In some cases, small-sized fragments cannot be easily identified and the original micritic cement is changed into microsparite. The most deformed samples show microshear zones and stylolites underlined by ferruginous surfaces, and the adjacent rock suffered intensive recrystallization into mosaic calcite. Nevertheless, it is possible to distinguish from macroscopic observations and microscopic investigations four main facies, namely F1–F4 (Fig. 2a). These facies are organized into a ramp depositional system (Fig. 2b).

4.d.1. *Facies F1: pelagic mudstones*

The limestones of F1 (Fig. 6) are greyish and display some parallel-bedding laminations. They are mudstones with widely dominant pelagic fauna composed of calcitized radiolarians (Fig. 6a), entomozoan

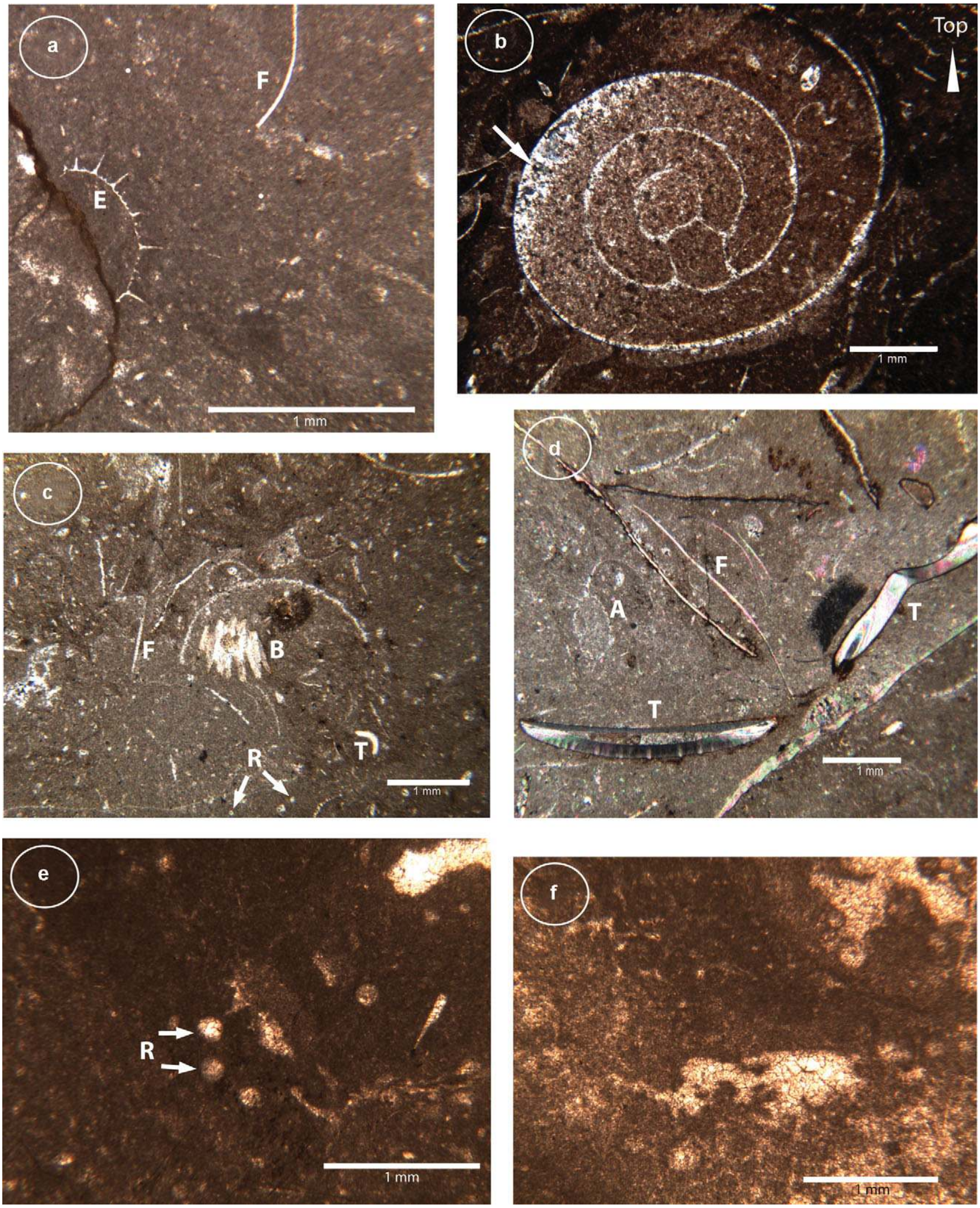

Figure 6. (Colour online) Characteristic microfacies types from thin-sections, Col des Tribes (France). A – ammonoid; B – brachiopod; E – entomozoan; F – filament (pelagic bivalve); T – trilobite; R – radiolarian. (a) Microfacies F1: pelagic mudstone with entomozoans, filaments and radiolarians (CT59). (b) Microfacies F2: pelagic mudstones to wackestones (CT32). (c) Microfacies F3: cephalopod mudstone to wackestone. Note geopetal infilling (arrow) oblique on bedding, indicating post-depositional rotation (CT41). (d) Microfacies F4: diversified fossiliferous wackestone (CT66). (e) Calcitized radiolarians (CT61-1). (f) Fenestral fabric: amalgamated peloids (dark) leave space for spar-filled cavities (light) (CT69-2).

ostracodes and filaments (bivalves). The benthic fauna is poor (very rare to <3 %), mostly represented by ostracods, some echinoid fragments and rare benthic foraminifers and trilobites sclerites. Noticeable is the scarcity of cephalopods. Geopetal infillings of early cavities (some hundreds of micrometres long, microstromatactis or dessication figures) are frequent. The micritic matrix sometimes displays a peloidal texture (Fig. 6b), suggesting local microbial activity in some levels (Kazmierczak, Kremer & Racki, 2012). Burrowing is scarce and only plane lamination structures were observed. Plane lamination is defined by discrete changes in concentration of pelagic molluscs, entomozoans and radiolarians. No current structures have been evidenced in facies F1. It has been identified in the lower part of the section (samples CT30–32, 39, 40 and 46). It is widely developed in the central part of the section from samples CT48 to 60-4. The $N/(N+B)$ ratio ranges from 0.7 to 1.0. Note that the most elevated values are grouped from samples CT 58-1 to 60-4, correlative with very scarce benthic foraminifers, trilobites and brachiopods (Fig. 2a). These features indicate that facies F1 was deposited in low-energy conditions under the storm-wave base, in an outer-ramp – basin setting (Fig. 2b). The scarce burrowings suggest some oxygenated bottoms (Droser & Bottjer, 1986), at least during levels CT48, CT59-3 and CT61-1.

4.d.2. F2: Pelagic mudstone to wackestone

Facies F2 (Fig. 6) is poorly represented in the section (samples CT34, 35, 59-7). It is composed of decimetre-thick greyish to yellowish limestones. Pelagic organisms are dominated by radiolarians, entomozoan ostracodes, pelagic molluscs (‘filaments’) and cephalopods. Benthic organisms (3–5 %) are often preserved as small-sized well-sorted fragments of echinoids, ostracods and trilobites. They are more abundant and more diversified than compared to facies F1. Geotrope infillings of early cavities or fossils are present. No current structure has been evidenced. The $N/(N+B)$ ratio falls within the range 0.6–0.8.

Facies F2 is interpreted as deposited under the storm-wave base in an outer-ramp setting (Fig. 2b). A part of the bioclasts probably originated in the innermost parts of the ramp.

4.d.3. F3: Cephalopod mudstone to wackestone (typical griotte limestones)

Facies F3 is composed of reddish, massive nodular or wavey laminated mudstones to wackestones (Fig. 4a, b). Pelagic organisms are dominant with abundant centimetre-sized goniatites (Fig. 6) and entomozoan ostracodes, pelagic bivalves and some radiolarians. Benthic organisms are present (1–5 %) and diversified with trilobites, brachiopods, echinoids, benthic ostracods and foraminifers. The $N/(N+B)$ ratio has values 0.5–0.8. The micritic matrix suffered early diagenetic processes (D. Michel, unpubl. thesis, University of Paris, Paris Sud, 1981) leading to cracks and micritic nodules embedded by iron-clay coatings or sedimentary deposits. Micritic geopetal infillings are frequent in ammonoid shells.

The goniatites are well sorted, suggesting current activity prior to their deposition. Iron- and manganese-oxide-encrusted hardgrounds and numerous crypto-hardgrounds indicate condensation episodes during times of low sedimentation rates and bacterial activity (Préat *et al.* 1999). Intraformational breccias with tilted consolidated slabs of rock (centimetres to a metre wide), and micritic nodules with cephalopods exhibiting variously inclined geopetal structures pointing to different degrees of rotation, indicate unstable conditions with repeated slidings of not completely lithified sediments. These features suggest the griotte limestones were deposited on a slope under current activity, probably under the fair-weather wave action (middle–outer ramp, as also suggested by Préat *et al.* 1999 at Coumiac; Fig. 2b).

The deposition of ’griottes limestones’ often occurred through Devonian time. It has been a matter of much debate, but most authors suggest that these limestones were deposited in a low-energy environment on platforms or ramps, but under tectonically instable conditions (e.g. Bourrouilh, 1981; Coudray & Michel, 1981; D. Michel, unpubl. thesis, University of Paris, Paris Sud, 1981; Franke & Walliser, 1983; Dreesen, 1989) as for the Rosso Ammonitico deposits of the Tethys Ocean during Mesozoic time.

4.d.4. F4: Diversified fossiliferous wackestones

Facies F4 (Fig. 6) is composed of greyish massive to pseudonodular, centimetre- to decimetre-thick beds. Pelagic organisms comprise undetermined rare radiolarians, entomozoan crustaceans, pelagic bivalves and abundant goniatites. The benthic fauna is well represented (5–15 %) and diversified with trilobites and benthic ostracods, sparse echinoids, brachiopods, gastropods, bivalves and foraminifers. The proportions of pelagic organisms and benthic organisms are rather similar with a slight domination of pelagic organisms, the $N/(N+B)$ ratio falling within the range 0.4–0.6. Geopetal infillings of cavities and burrows are present. Only local plane laminations have been found, but the intensive post-depositional pressure/dissolution responsible for the pseudonodular texture probably hides most of the sedimentary structures.

The presence of diversified benthic fauna and of pelagic fauna, associated with poorly sorted goniatites, indicates a depositional environment shallower than the previous environments. Some organisms are well preserved, such as trilobites, while others are broken. Noticeable is the absence of current structures, and between bioclasts the matrix is micritic. All these features indicate a middle–uppermost outer-ramp depositional system (Fig. 2b).

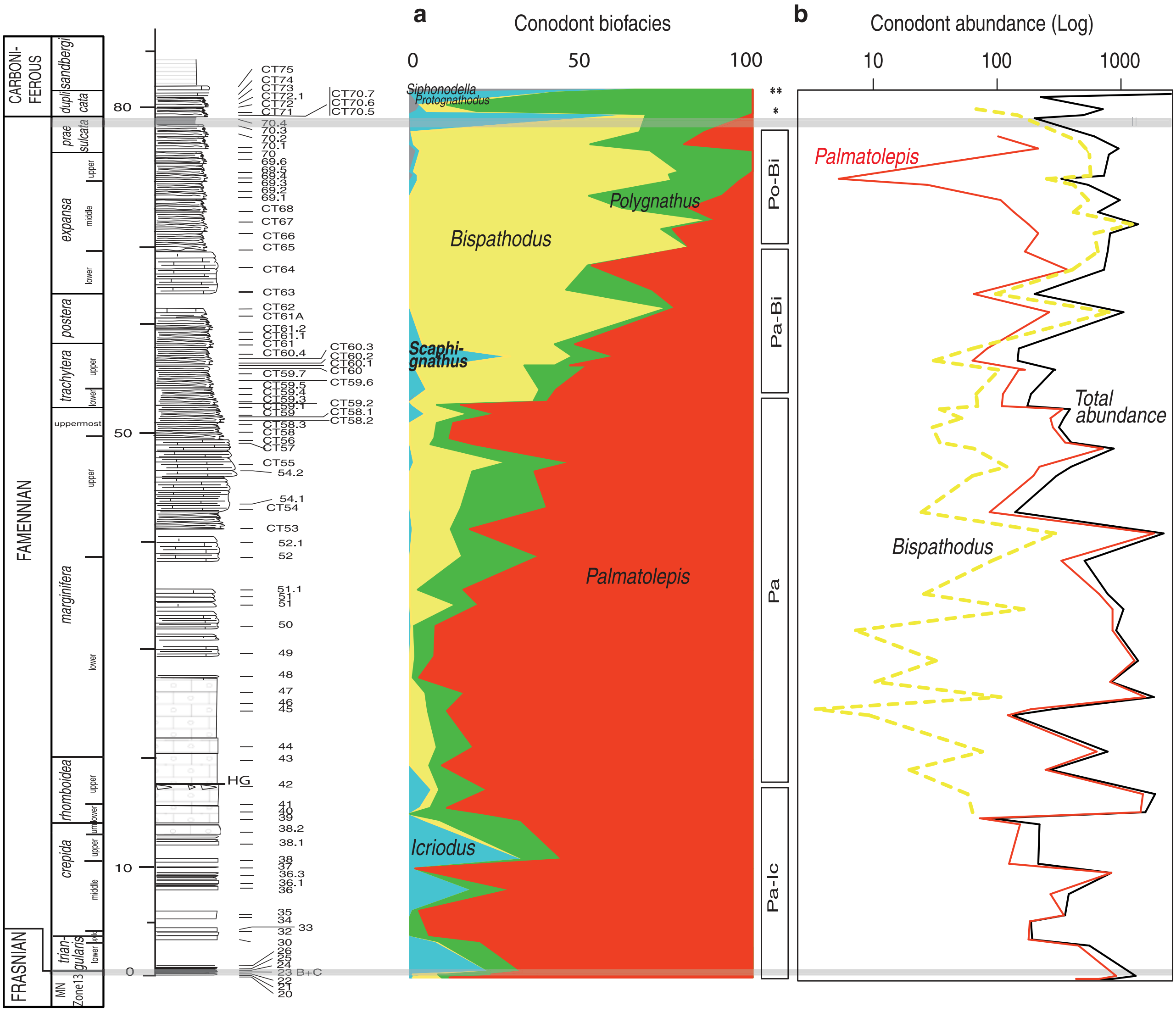

Figure 7. (Colour online) Relative and absolute abundances of conodonts at the Col des Tribes (France) during Famennian time. (a) Percentage of conodont genera. (b) Abundance of platform genera conodonts per kilogram (in log). Black line: total number of platform conodont specimens; red line: total number of *Palmatolepis* specimens; and yellow dotted line: *Bispathodus* specimens. Grey: identified Famennian events; shading: tentative position of some Famennian events. Pa-Ic – *Palmatolepis–Icriodus* biofacies; Pa – *Palmatolepis* biofacies; Pa-Bi – *Palmatolepis–Bispathodus* biofacies; Po-Bi – *Polygnathus–Bispathodus* biofacies; Pr-Po – *Protognathodus–Polygnathus* biofacies; Si-Po – *Siphonodella–Polygnathus* biofacies.

4.e. Conodont genera and abundances

4.e.1. Abundance

After complete processing of the sampled limestones, almost 7200 platform conodont elements were obtained for abundance evaluation (Table 1). The abundances are very variable through the section with an estimated mean of more than 600 platform elements per kilogram (Fig. 7). Some levels are very poor however and have been excluded from the analyses (Table 1). Autochtony of conodont assemblages is indicated by the rather high percentage of juveniles as well as ramiform elements among the conodont assemblages; additionally, conodonts are well preserved. These support the exclusion of sorting processes such as current activity or downslope gravity flow, as recorded in other slope settings (e.g. Bàbek & Kalvoda, 2001; Vierek & Racki, 2011). Among the genera occurring during the Famennian, *Palmatolepis* is always present and is the major representative of the conodont fauna in the first 50 m (Fig. 7). After the *annulata* event, the *Bispathodus* specimens replace *Palmatolepis*. The abundances of *Icriodus* and *Protognathodus* are noticable in a few levels: at the base of the section for the former (samples CT30–42) and at the top for the latter (H71–72).

Although always present, *Polygnathus* is never dominant except at the top of the section just after the Hangenberg event (Fig. 7).

The last sampled level dated as Carboniferous (CT72-1) is dominated by the genus *Siphonodella* (Table 1). When present, other genera (including *Pseudopolygnathus*, *Scaphignathus* and *Alternognathus*) are always rare.

4.e.2. Conodont biofacies (Fig. 7)

Six biofacies can be distinguished, from bottom to top of the sampled section: (1) palmatolepid-icriodid; (2) palmatolepid; (3) palmatolepid-bispathodid; (4) polygnathid-bispathodid; (5) polygnathid-protognathodid; and (6) polygnathid-siphonodellid.

4.e.2.a. Biofacies 1

At the base of the section (Lower *triangularis* through *rhomboidea* zones), the faunas are dominated by palmatolepids but the percentage of icriodids can reach 25 %. The co-occurrence of the deep-water *Palmatolepis* with a significant contribution of *Icriodus*, considered a shallow-water indicator, coincides with the pseudo-nodular limestone deposits, facies F2. This high proportion of *Icriodus* can reflect the telescoping of normally shallower-water faunas related to eustatic sea-level fall and increased downslope sediment transport, often associated with the aftermath of the F/F crisis (Sandberg *et al.* 1988). The largest *Icriodus* peak (level CT38) is often regarded as coinciding with the Nehden event, which is interpreted to be triggered by a short sea-level fall (Schülke, 2003). This increase has also been interpreted to be due to oceanic factors such as the overturn of oxygen-poor water masses that may have selectively reduced 'offshore pelagic' conodont taxa (Sandberg *et al.* 1988; Schindler, 1990; Buggisch, 1991). This could also be the result of biological factors such as the opportunistic occupation of niche space vacated by other conodont groups, as suggested by Corradini (1998, 2003), in typical pelagic sections where the large amount of new Famennian species of icriodids led to the introduction of a palmatolepid-icriodid biofacies regarded as pelagic.

4.e.2.b. Biofacies 2

This biofacies starts with the Condroz event. The percentages of the conodont genera *Polygnathus*, *Icriodus* and *Bispathodus* are rather low (<15 %) in the sampling interval CT42–50 (Fig. 2), allowing a palmatolepid biofacies to be defined in that interval (Lower *marginifera* Zone). This genus is known to be confined to deep-water zones, and is clearly dominant in facies deposited below the storm-wave action (Facies F1). The proportion of bispathodids slightly increases afterwards but remains low (<10 %) from level CT51 to CT58 (uppermost *marginifera*).

4.e.2.c. Biofacies 3

Bispathodids and polygnathids increase simultaneously (*trachytera* Zone) with the *annulata* event deposits. The contribution of *Palmatolepis* drops from 80 % (*triangularis* Zone to uppermost *marginifera* Zone) to 30–40 % (*postera* and *expansa* zones) concomitantly to the deposition of the shallowest facies (Facies 4 dominant). In this bispathodid-palmatolepid biofacies there is still a high percentage of *Bispathodus* which presumably lived in the euphotic zone of pelagic seas (Sandberg, 1976; Ziegler & Sandberg, 1984). *Palmatolepis* is considered as a genus living in deep water (Sandberg, 1976). A co-occurrence of these two genera has been observed in association with the *annulata* black shale deposits in Poland (Kowala section), and was interpreted as a position of the section close to pelagic ridge (Racka *et al.* 2010). The change from a palmatolepid biofacies to a palmatolepid-bispathodid biofacies was already observed for two sections in Sardinia (Corradini, 2003) after the *trachytera* zone, and may emphasize sea-level fall.

The short occurrence of *Scaphignathus* (CT59-3–60-4) during this palmatolepid-bispathodid biofacies seems to contradict a shallow-water preference for this genus (Sandberg, 1976), but may indicate that the genus was transported during fluctuating water depth changes allowing the presence of organisms into the waters above submarine rises (Sandberg & Ziegler, 1979). Another explanation could be better water oxygenation, permitting the introduction and mixing of this shallow-water genus into the pelagic palmatolepid-bispathodid biofacies.

4.e.2.d. Biofacies 4

Bispathodids become increasingly abundant during the *expansa* Zone and lower *praesulcata* Zone, reaching 60–80 % of the total number of specimens. During the 2 m preceeding the Hangenberg event, biofacies 4 is characterized by the relative increase of *Polygnathus* at the expense of *Palmatolepis*, suggesting a slight shallowing. This unusual biofacies has been related to a shallow environment in an extensive flat sea bottom in Spain by García-Alcalde & Menéndez-Alvarez (1988).

4.e.2.e. Biofacies 5

The onset of biofacies 5, composed of *Polygnathus*-*Protognathodus* at the top of the section below the Devonian–Carboniferous boundary and above the Hangenberg event, confirms a shallowing-upwards trend which is observed at numerous geographic locations (Ziegler, Ji & Wang, 1988; Girard, 1994).

4.e.2.f. Biofacies 6

At the end of the sampled interval, biofacies 6 is composed of a high proportion of siphonodellids which are assumed to be pelagic–hemipelagic genus (Lane, Sandberg & Ziegler, 1980). They increase in abundance towards deeper water, thus indicating a deepening-upwards trend as proposed in other places (Girard, 1994; Sanz Lopez, García López & Montesinos, 1999).

4.e.3. Correlation between microfacies and conodont data

Synchronous and similar trends emerge from the comparison of sea-level proxies (Fig. 8). Here only the percentage of *Palmatolepis* is considered as the more relevant index to estimate sea-level changes, as this genus is assumed to live in deeper environments than the other genera. It is compared to the $N/(N+B)$ ratio through Famennian time. The results of both these sea-level estimators are concordant.

Linear regression analysis of microfacies estimated by the $N/(N+B)$ ratios and biofacies estimated with the percentage of *Palmatolepis* reveals a significant

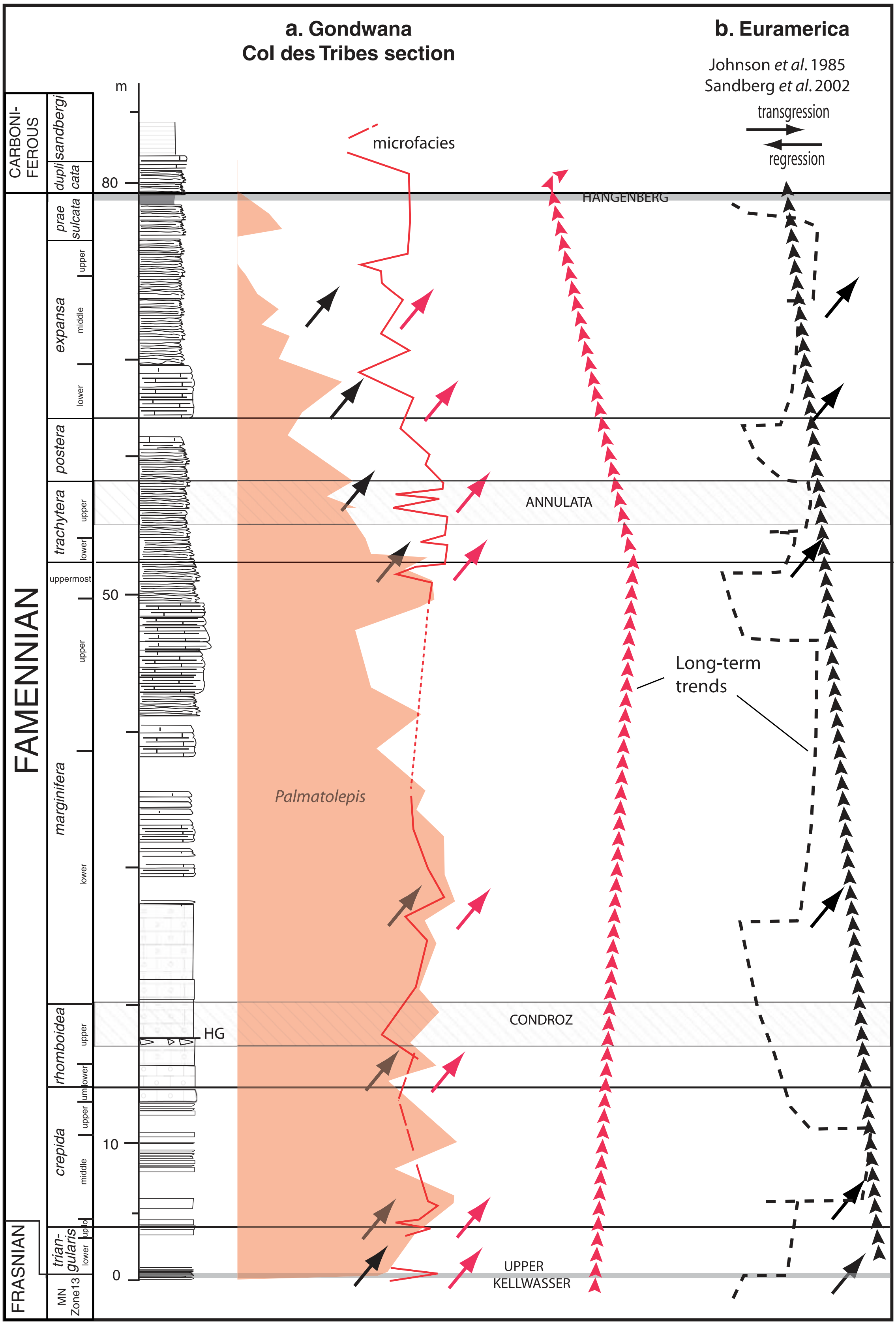

Figure 8. (Colour online) Comparison between different Late Devonian sea-level indicators. (a) From left to right: sea-level curve proposed in this paper based on the $N/(N+B)$ ratio and percentage of the *Palmatolepis* genus through the Col des Tribes (MN, France). Long-term sea-level curve at Col des Tribes by combining microfacies and conodont informations. (b) Sea-level curve according to Johnson, Klapper & Sandberg (1985) and Sandberg *et al.* (2002) with the five transgressive starts recognized through the Famennian. Conodont zones are figured according to the depth of the Col des Tribes. Grey: identified Famennian events; shading: tentative position of some Famennian events.

correlation ($N = 43$; $R = 0.50$; $P = 0.000$). The correlation is confirmed ($P<0.002$) using the non-parametric Kendall test, used to measure the congruent relation between two measured proxies. Eight remarkable periods of sea-level rise are evident, highlighted by an increase in *Palmatolepis* percentage (black arrows in Fig. 8) and an increase in the $N/(N+B)$ ratio (red arrows in Fig. 8; see online colour version).

5. Discussion

The Col des Tribes section contains relatively abundant and diversified conodont assemblages. This section is one of the most fossiliferous Famennian sections for conodonts worldwide. Consequently, different proxies indicative of environmental changes (sea level) and hypotheses influencing the onset of anoxic sediments can be discussed.

5.a. Relative sea-level changes

The agreement between the proxies used in this study allows to the proposal of a complete curve for sea-level changes through Famennian time for the Col des Tribes section (Fig. 8a).

The long-term trend indicates a progressive sea-level rise from the Upper *triangularis* Zone to the uppermost *marginifera* Zone, followed by a gradual sea-level fall from the Lower *trachytera* Zone to the uppermost *praesulcata* Zone.

These results are in accordance with the results of Johnson, Klapper & Sandberg (1985), Haq & Schutter (2008) and Sandberg, Morrow & Ziegler (2002) for the *trachytera-praesulcata* interval (Fig. 8b). This regressive trend has also been observed in other areas from north Gondwana, such as in Algeria (Wendt *et al.* 2006). This long-term trend is punctuated by cycles of minor changes in sea level. Johnson, Klapper & Sandberg (1985) and Sandberg, Morrow & Ziegler (2002) reported six transgressive cycles. The detailed study of the Col des Tribes section allows the proposal of a curve for the Galatian superterrane. From the Upper *triangularis* Zone to the Lower *marginifera* Zone three cycles are identified based on simultaneous and similar trends in both proxies. Two transgressive events are in accordance with the previous results (Lower–Middle *crepida* and Lower *marginifera* zones), and a new event has been identified (Lower *rhomboidea* zones). In the Col des Tribes section as in Euramerica, minor cycles have not been found in the Upper *marginifera* Zone. Later, the three transgressive events of Johnson, Klapper & Sandberg (1985) and Sandberg, Morrow & Ziegler (2002) are identified (Lower *trachytera* and Lower and Middle *expansa* zones), and a third event is now depicted for the north Gondwana-related area in the Upper *trachytera* Zone.

As a whole, the main discrepancies between our curve and the previous curves are: (1) the absence of a transgressive trend at the Frasnian–Famennian boundary as well as a regressive trend between the Upper *crepida* and the Lower *marginifera* zones; and (2) the presence of a transgressive trend during the *marginifera* Zone. The differences between our curve and that of Johnson, Klapper & Sandberg (1985) or Wendt *et al.* (2006) could be a result of the following factors: (1) our outcrop data provide lower resolution because some parts of the section are not exposed, especially during the lower Famennian (*triangularis* and *crepida* zones), or because parts of the section suffered recrystallization and the results of microfacies analysis are not accurate enough (*marginifera* Zone); (2) transgressive trends proposed by Johnson, Klapper & Sandberg (1985) are based on data from facies shifts in basinal deposits whereas our samples were collected on a ramp, an environment which is more sensitive to sea-level changes; or (3) local or regional tectonic events, even if moderate, can hide low-amplitude sea-level changes. Such tectonic events can be expected in a flexural basin on continental crust which characterizes the Devonian of the Montagne Noire (Raymond, 1987); this concerns the Famennian deposits at the transition between the Devonian ramp and the Early Carboniferous flysch basin in particular (Engel, Feist & Franke, 1982).

5.b. Anoxic events

The Col des Tribes section is characterized by a continuous succession of limestones devoid of anoxic (organic-matter-rich) deposits, except for two levels with weathered blackish deposits. The lower level is located at the top of the MN13 zone and corresponds to deposits of the Upper Kellwasser event. The upper deposit is located in the uppermost part of the Lower *praesulcata* Zone and corresponds to deposits of the Hangenberg event. Two other widely known events of the Famennian, Condroz and *annulata*, cannot be identified by facies changes. Contrary to some other Devonian events, which are difficult to place due to the imprecision of the current stratigraphy when they are not lithologically defined (i.e. the Lower Kellwasser event; Girard & Renaud, 2007), the Condroz and the *annulata* events can be easily positioned. The new biostratigraphic frame allows the positioning of the Condroz in the Upper *rhomboidea* and *annulata* in the Upper *trachytera* zones (Fig. 2a). Moreover, the Condroz and *annulata* events are related to major environmental changes at the global scale (Walliser, 1996; Becker, Ashouri & Zyazdi, 2004; Racka *et al.* 2010). Note that no bioturbation was recorded in any of the intervals where anoxic events are assumed to occur (Fig. 2). At Col des Tribes, important changes in the conodont assemblages are recorded at levels assumed to have been deposited during these events. That indicates that their location in the carbonate succession is robust.

The Upper Kellwasser event is lithologically represented by dark grey limestones (sample CT23, Fig. 2a). It occurs just before the first occurrence of Famennian conodont and trilobite faunas (*Nephranops*). This event is associated with a major crisis, recognized at the global scale (McGhee, 1996; Walliser, 1996). The crisis is marked, among other features, by a drastic turnover of conodonts, the disappearance of the genus *Ancyrodella* and a total replacement of *Palmatolepis* species. Accompagnying the reduction in conodont diversity, changes in the generic composition of conodont faunas were observed at a global scale (Sandberg *et al.* 1988; Ji & Ziegler, 1993; Girard & Feist, 1996; Lazreq, 1999; Morrow, 2000). The biotic changes were surimposed to numerous abrupt environmental changes (Gerecke & Schindler, 2012) that are evidenced in the geological record by sea-level fluctuations, intervals of anoxic deposits (Bond & Wignall, 2008) and major worldwide excursions in the stable carbon and oxygen isotopes (Buggisch, 1991; Joachimski & Buggisch, 2002; Joachimski *et al.* 2009).

The Condroz event is represented by the Upper *rhomboidea* Zone (samples CT42–43), and is considered to have been triggered by a regressive phase (Walliser, 1996; Schülke & Popp, 2005). The sea-level curve of Johnson, Klapper & Sandberg (1985) shows a sharp sea-level fall during this time interval. At Col des Tribes, the Condroz event began during the deposition of the lower half of the griotte limestones during a short-term regressive event. A short-term transgressive event (Fig. 8a) began after this. This part of the griotte limestones is characterized by abundant ferruginous clays and at least one hardground, compatible with condensation processes on a slope during sea-level rise. This situation has been described elsewhere in the Montagne Noire (D. Michel, unpubl. thesis, University of Paris, Paris Sud, 1981; Feist, 2002) or in Germany (Schülke & Popp, 2005).

The *annulata* event is not associated with extinction of faunas but rather with originations (House, 1985; Becker, 1993; Hartenfels, 2010). The *annulata* event is generally lithologically marked by dark to black sediments. The woldwide occurrence of black shale sediments supports the hypothesis that this event was caused by short-term flooding on the continent by oxygen-depleted waters due to a rise of the anoxic layers (Wilde & Berry, 1984). These deposits are often coincident with a significant contribution of assumed shallow-water conodonts such as *Scaphignathus*, observed in numerous parts of the world. As a consequence, the definition of the uppermost *marginifera* zone is based on the first occurrence of one species of this genus (*Scaphignathus velifer*) in pelagic sequences (Ziegler, 1962, 1971). To explain the presence of *Scaphignathus* in pelagic sequences, Sandberg & Ziegler (1979) suggested that this genus was transported from shallow-depth submarine rises into the deep-sea environment.

At Col des Tribes, despite the absence of significant lithological changes, the *annulata* event can be biostratigraphically located at the top of the Upper *trachytera* Zone (Walliser, 1996; Racka *et al.* 2010). Facies analyses indicate that *annulata* occurred during the deposition of the deepest sediments of the section during a short-term transgressive context. The same results have been found by Racka *et al.* (2010) in Poland where they observed an episodic sea-level rise interrupting an overall regressive trend, and in Germany where Schülke & Popp (2005) assumed that the anoxic levels represented transgressive conditions. This is in concordance with the sea-level curves established by Johnson, Klapper & Sandberg (1985) at a global scale or by Sandberg, Morrow & Ziegler (2002) for the North American area (Fig. 8b). If organic-matter-rich sediments had not been found at Col des Tribes, the period of the *annulata* event would be characterized by rare to absent benthic fauna limited to some benthic ostracods and pieces of echinoids. The occurrence of peloids and microdessication vugs suggest local microbial activity, as proposed in Poland in the Hangenberg shale (Kazmierczak, Kremer & Racki, 2012). Some pelagic organisms are present, except for ammonoids. The scarcity and poorly diversified fauna suggest that some dysoxic conditions could exist, especially for bottom sea waters, but carbonates could still be deposited in an outer-ramp setting.

This event coincides with a radiation of pelagic faunas, mainly goniatites (House, 1985; Becker, 1993). At Col des Tribes, abundant cephalopods suddenly appear a few metres above the end of the *annulata* (Fig. 2a). This shows that for this event the influence of global environment on the organisms exceeds the influence of local conditions, which determine whether anoxic sediments are deposited. Similar results have already been observed for the Lower Kellwasser event at the end of the Frasnian (Girard & Renaud, 2007).

The Dasberg event coincides with an eustatic rise marked by transgressive pulses at the base of the Lower *expansa* Zone (Hartenfels & Becker, 2009; Hartenfels, 2011). It is known as a worldwide hypoxic event (Hartenfels & Becker, 2009), sometimes marked by two discrete anoxic events interpreted to be the result of the major transgressions (Marynowski, Filipiak & Zaton, 2010). At Col des Tribes no anoxic sediments occur around the Lower *expansa* Zone. A slight deepening is observed which could correspond to this crisis, but the absence of any changes in the conodont faunas or microfacies composition does not allow the confirmation of this hypothesis.

By constrast, the Hangenberg event is typified by a lithological change (shale deposit) and by a ‘turnover’ in the conodont fauna (disappearance of *Palmatolepis* and development of a *Protognathodus* biofacies). Similar changes of the environment (Hangenberg shale deposit) as well as of the conodont assemblages (development of a protognathodid biofacies) are remarkable at the global scale (e.g. Girard, 1994). At Col des Tribes the Hangenberg occurred during a regressive trend on a global scale as proposed by Johnson, Klapper & Sandberg (1985). Opposing results have also been proposed, however. On Baltica, Marynowski *et al.* (2012) found Hangenberg shale deposit beginning in transgression. The same trends were also observed in another section from the Montagne Noire (France), where Girard (1994) and Kaiser, Steuber & Becker (2008) suggested a transgressive trend associated with the beginning of the Hangenberg shales.

Global-scale anoxic events are frequently recorded through Phanerozoic time (e.g. Wilson & Norris, 2001; Caswell & Coe, 2012; McLaughlin, Emsbo & Brett, 2012), with concomitant extinction and faunal turnover. Anoxic deposits require particular conditions for their formation such as high organic productivity (Murphy *et al.* 2000; Riquier *et al.* 2006), poor seawater circulation or installation of oxygen-impoverished bottom water (Murphy *et al.* 2000; Buggisch & Joachimski, 2006). They can be deposited during a fall or rise in sea level, in relation to ocean temperature change (e.g. Joachimski & Buggisch, 2002; Dopieralska, 2003; Arthur & Sageman, 2005). The globally known anoxic events are not lithologically represented by black deposits at Col des Tribes, except for the Upper Kellwasser and the Hangenberg. Depositional environments are located in an open-sea, low-energy, mid- to outer-carbonate muddy ramp setting marked by deepening trends and transgressives pulses.

In this part of the Montagne Noire, despite the deepening trend associated with the period where anoxic deposits could be deposited, the depositional environment was perhaps not deep enough to induce the deposition of typical black shales; micritic limestones could still be deposited, as recorded elsewhere in the world (Playford, 1980; Schülke & Popp, 2005; Königshof *et al.* 2012). Such a scenario has already been proposed for a Moroccan section just before Turonian (Cretaceous) time, when anoxic conditions characteristic of the OAE2 (oceanic anoxic event 2) did not reach the local shallow-water environments (Gertsch *et al.* 2010). The shallow-water fore-reef and shoal limestone successions in the Holy Cross Mountains are also denoted by an obscured Kellwasser record (Casier *et al.* 2000; Bond, Wignall & Racki, 2004).

6. Conclusions

The Col de Tribes section displays an almost uninterrupted fine-grained carbonate succession through the whole Famennian in the Montagne Noire. The study of conodonts allows the proposal of a detailed biostratigraphical frame, with all of the conodont zones represented along the 84-m-thick section. Facies analysis indicates a depositional setting on a middle–outer, carbonate and muddy ramp. The combination of faunal and facies analyses provides insight into the variations of sea level on the northern Gondwana margin during the Famennian. The sea-level rose slightly from the uppermost *triangularis* Zone to the Upper *trachytera* Zone, then dropped from the *trachytera* Zone to the uppermost *praesulcata* Zone. This long-term trend was punctuated by at least seven short-term cycles. The main discrepancies with Laurussia or Gondwana curves may be related to the initiation of a south-facing flexural basin in the Montagne Noire.

At Col des Tribes the Upper Kellwasser and Hangenberg events are recorded by blackish organic-matter-enriched deposits associated with changes in conodont assemblages, which occurred during sea-level falls. In contrast, major intra-Famennian events such as the *Condroz* and *annulata* events are not materialized by specific lithological changes such as the display of black shales for the latter, though their time-equivalents can be positioned in the section. The *Condroz* event is represented by iron-argillaceous deposits and hardgrounds which accumulated during a sea-level rise. The *annulata* is typified by deposits mostly barren of fauna and by a strong decrease in *Palmatolepis* content which were laid down during a major sea-level rise.

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