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Frasnian (Late Devonian) conodonts and environment at the northern margin of the Algerian Sahara platform: the Ben Zireg section

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Abstract – The Ben Zireg anticline NW of Bechar yields the currently most-important Frasnian succession on the northern margin of the Algerian Sahara. It represents 26.5 m of calcilutites which are attributed to the middle–late Frasnian. As the early Frasnian is not represented, the succession rests conformably on undifferentiated, probably late Givetian, substrate. Fine-scaled conodont biostratigraphy reveals a continuous sequence of Montagne Noire Zones 5–13, superseded by the earliest Famennian Lower *triangularis* Zone. The deposits are organized into 15 sedimentary cycles that are initially condensed and become dilated upwards. Conodont biofacies indicate an overall deepening towards the top of the section with an episode of slight shallowing at the MN11/12 transition marked by an increase of ancyrodellids, which is also seen in the Marhouma section of the Ougarta region (SW Algeria). Homogeneous calcareous microfacies with only a few shaly intercalations determine a predominantly oxygenated depositional environment on an outer platform, submarine rise or ramp setting. This is also indicated by relatively low sedimentation rates which are similar in selected sections from the Tafilalt platform, and contrast with those from the Marhouma trough and the Maider basin. Unlike other Frasnian successions south of the Atlas Fault, but similar to the Moroccan Meseta, the Upper Kellwasser horizon is clearly discriminated at Ben Zireg by an outstanding occurrence of black shales on top of the oxygenated latest Frasnian deposits.

Keywords: Frasnian, conodont biostratigraphy, biofacies, depositional environment, NW Algerian Sahara.

1. Introduction

The Ben Zireg area at 50 km NE of Bechar township constitutes the north-easternmost exposure of Saharan Palaeozoic deposits adjacent to the Main Atlas Fault. They differ from all neighbouring outcrops of the Bechar basin, such as Soltane el Betoum and Maider el Mhadjib to the north and west of Djebel Antar (Weyant, 1988) (Fig. 1a), in comprising a well-exposed, almost complete, succession of Cambro-Ordovician – early Carboniferous marine sediments. As such, the Ben Zireg section is a reference for the northern margin of epi-continental Sahara in SW Algeria, at 200 km from the Palaeozoic sediments of the Ougarta region further to the south (Fig. 1a). A major description of the structure and stratigraphy by Pareyn (1961) was mainly devoted to Carboniferous sediments; apart from a few other scattered Devonian (Frasnian in particular) stratigraphic data, this area has remained largely unstudied in terms of biostratigraphical subdivision and sedimentary development.

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After the first recognition of Devonian fossils at Ben Zireg by G.B.M. Flamand (unpub. thesis, University of Lyon, 1911), Menchikoff (1936) established the existence of Late Devonian series based on cephalopods. Among them, *Pharciceras* was considered at that time representative of the early Frasnian period. However, this taxon is now restricted to the latest Givetian period since the definition of Frasnian stage boundaries by SDS/IUGS (Klapper, Feist & House, 1987; Klapper *et al*. 1993). The presence of Frasnian strata was definitely established when Massa, Combaz & Manderschied (1965) recovered the first conodonts, notably *Ancyrognathus asymmetricus* and *Ancyrodella curvata*.

Since then, and in contrast to numerous conodont-based biostratigraphical investigations in the neighbouring Tafilalt area (e.g. Belka *et al.* 1999), no more work has been carried out to evaluate the extent and completeness of the lower Upper Devonian sediments in the Algerian part of northern Sahara.

This study aims to provide fine-scaled conodont biostratigraphy and biofacies. The sedimentary dynamics of the Ben Zireg section emphasizes the importance of its pivotal position between Frasnian sections on

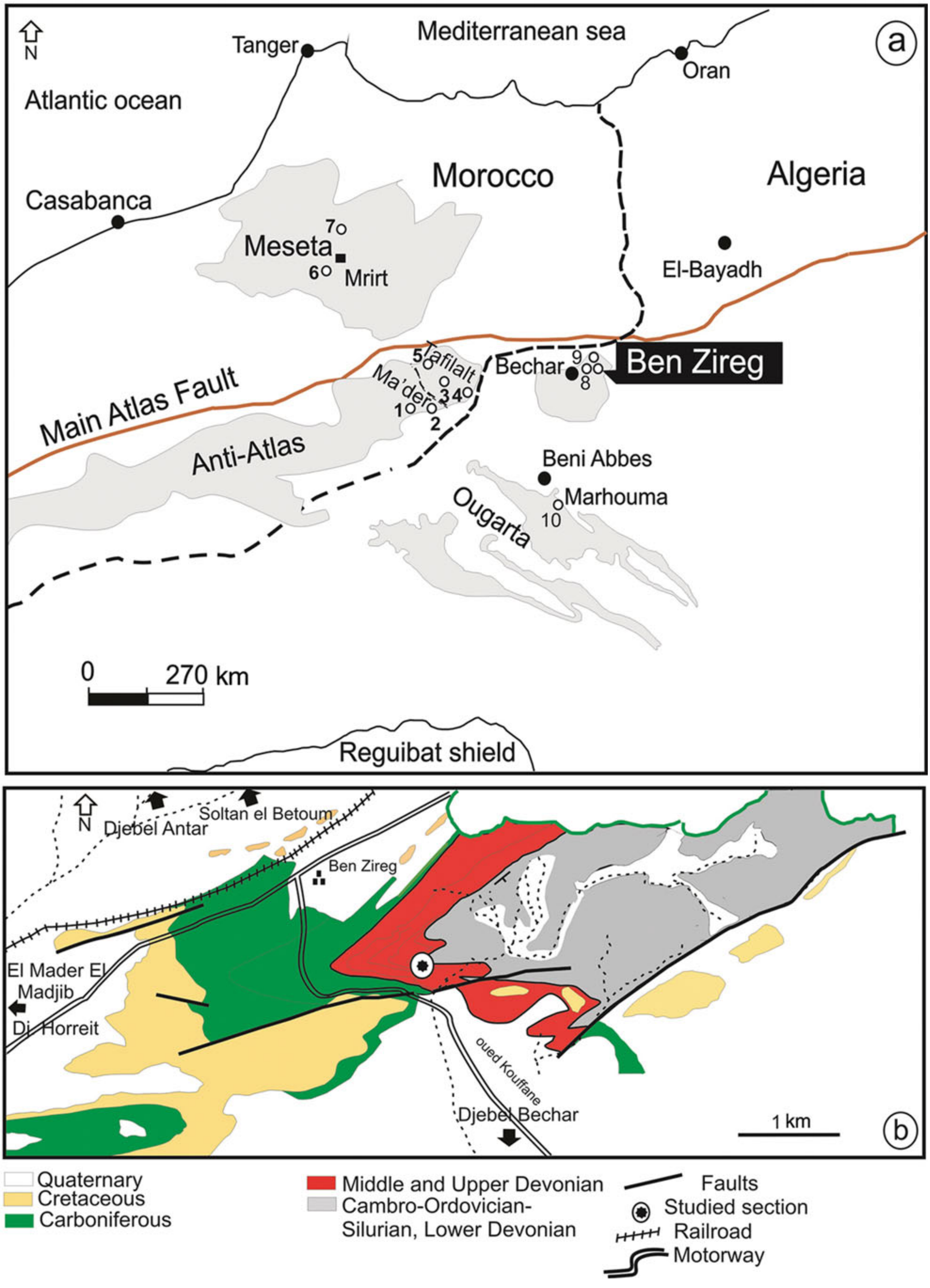

Figure 1. (Colour online) Main Palaeozoic outcrops in NW Africa. (a) location of selected Frasnian sites: 1, Bou Terga; 2, Jebel Atrous II; 3, Bou Thrafine; 4, Ouidane Chebbi; 5, Oued Rheris; 6, Anajdam; 7, Bou Alzaz nord; 8, El Mader el Madjib; 9, Soltane el Boutoum; 10, South Mahrouma; and (b) investigated section in the Ben Zireg anticline (after Pareyn, 1961).

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both sides of the Main Atlas Fault, that is, the allochthonous Hercynian Meseta of Central Morocco and its eastern prolongation into the Algerian Hercynian Tifrit Horst, and cratonic Gondwana sections in both SW Algeria (Marhouma) and Tafilalt/Maider in SE Morocco (Fig. 1a).

2. Geological setting

In contrast to Palaeozoic rocks north of the alpine Main Atlas Fault, which were affected by complex tangential tectonics and deformation during the Variscan Irogeny (e.g. Allary, Lavenu & Ribeyrolles, 1976), the Palaeozoic deposits of the western Sahara platform north of the Precambrian Reguibat shield (Fig. 1a) were generally only weakly deformed to create wide synclinal and narrower anticlinal structures. Devonian sedimentation rates reflect basin- and ridge-dependent depositional environments (Elmi & Ameur, 1984; Conrad, Massa & Weyant, 1986; Wendt *et al.* 2006). Exposures of the NE Bechar basin close to the Atlas Fault are more intensely folded to form narrow E–W-trending anticlinal structures, often over-thrusted to the north. These features, along with the occurrence of synorogenic wildflysch sediments with olistolites of various ages characterizing the Dinantian of Ben Zireg (Pareyn, 1961), might indicate dynamic relations to the Maghrebian Variscan belt in the north.

In this context, the Ben Zireg Palaeozoic rocks form an acute, narrow anticlinal structure with subvertical axial plane, opening to the ENE under 50°, before being unconformably covered by continental Permo-Triassic sediments and marine Liassic and Cenomanian–Turonian deposits (Fig. 1b). The structure is crossed by numerous vertical faults that run subparallel to the Main Atlas Fault, also affecting the Cretaceous cover, and may belong to the alpine transform system. The eastern end of the structure is framed by a prominent ridge of some 200 m of Middle–Late Devonian carbonates, easily accessible from the south where the road from Ben Zireg station to Taghit runs along the Oued Ben Zireg shortly before it bends to the south (Fig. 1b). The investigated Frasnian section is situated on the steep southern flank of the Devonian ridge along a southerly directed, deeply incised gorge (coordinates 31° 54′ 39.4″ N, 001° 47′ 58.8″ W, Fig. 1b).

3. Material and methods

One single section was logged in detail and 37 oriented samples were taken both for sedimentological investigations and conodont research. Thin slices from all samples were cut to investigate the corresponding microfacies. Microfacies were determined by using optical observations with a photonic microscope. Depositional settings result in zonations proposed by Wright & Burchette (1996) and Flügel (2004). Noticeable is a general recrystallization of micrite into microsparite in all samples, and the presence of pressure-dissolution surfaces indicative of a discrete cleavage. These features are related to the Variscan deformation and do not allow observations of the primary matrix of the rocks.

For conodont extraction, the calcareous samples were dissolved in 10 % acetic acid. Sulphuric acid (10 %) was used to dissolve iron-hydroxide and pyrite-rich samples (beds BZ1A, 1C and BZ2). The insoluble residue was then rinsed through two sieves (1 mm and 100 μm). Residues smaller than 1 mm were dried and handpicked using a stereomicroscope. Specimens were photographed with SEM (JEOL 5600). All platform (P1) elements were picked (2660 elements; Table 1). The limestone samples yielded relatively abundant conodont elements (mean of 115 kg^{-1}). Some of these elements were identified at the specific level for biostratigraphy. In this paper the biostratigraphic zonations are those of Klapper (1989, 2007*a*, *b*) and lowermost Famennian biostratigraphic zonation is that of Schülke (1999). Figured conodont specimens are housed in the collections of the University of Montpellier and are labelled UM-BZA-01 to 23.

Among the platform P1 elements, different genera can be recognized that are assumed to have different ecological preferences (e.g. Seddon & Sweet, 1971; Sandberg, 1976). The changing distribution patterns of conodont abundance (called biofacies) in space and time can therefore provide some information about the depositional environment. The biofacies is named after the one or two most-abundant genera, and trends in the variations of the relative proportion of the different genera are assumed to provide indirect water depth proxy through time.

During the Frasnian period, five conodont genera dominated the assemblages. *Icriodus* is considered as characteristic of shallow environments, whereas *Palmatolepis* should prefer deeper conditions. *Ancyrodella* and *Ancyrognathus* are grouped under the term ancyrodellids. Together with *Polygnathus* they are considered as ubiquitous, with a slight preference for deep environments for *Polygnathus* while ancyrodellids would prefer shallow environments (Sandberg *et al.* 1992; Sobstel, Makowska–Haftka & Racki, 2006). The variations of relative abundances of these five different genera were investigated through the Ben Zireg section. The relative abundances of the four groups (*Palmatolepis*, *Icriodus*, *Polygnathus* and ancyrodellids) are provided as a percentage of the total assemblage.

4. Results

4.a. Lithostratigraphy

The Frasnian deposits at Ben Zireg section are 26.5 m thick between sample BZ1 (Givetian) and sample BZ16 (early Famennian) (Fig. 2). Sedimentary rocks display a rhythmic pattern characterized by centimetre- to decimetre-thick alternations (couplets) of hard, fine-grained limestones and softer, argillaceous fine-grained limestones or claystones. In the field, these alternations clearly display a rather constant organization which indicates sedimentary cycles and subcycles (Fig. 3).

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Table 1. Numbers of platform conodont genera at the Ben Zireg section. The low conodont abundances (<20P1) in italic are not included in the biofacies analyses. Pa – *Palmatolepis*; Po – *Polygnathus* and *Linguipolygnathus* (BZ1 only); An – *Ancyrodella* and *Ancyrognathus*; Ic –*Icriodus*.

Sample	Weight (g)	Depth (m)	Pa	Po	An	Ic	Total
BZ16B	200	27.6	52	2		2	56
BZ16A	1138	27.25	193	25		1	219
BZ16	990	26.7	178	31			209
BZ15D	200	26.5	26	5	8		39
BZ15C	827	26	70	18	9	1	98
BZ15A	100	25	21		2	1	24
BZ15	873	24.1	52	5	2	9	68
BZ14D.1	1000	23.5	296	73	9	16	394
BZ14C	*90*	*22.5*	*4*	*8*	*1*		*13*
BZ14	1205	22	80	22			102
BZ13B	210	21	35	13	1	4	53
BZ13A.1	1260	20.1	160	24	19	42	245
BZ13	879	18.5	62	22	1	23	108
BZ12A	751	17.6	5	37	8	4	54
BZ11	230	16	1	14	13	2	30
BZ10B	230	15.5	3	13	4	3	23
BZ10A	200	13.65	7	9	3	3	22
BZ10	671	12.82	15	32	7	9	63
BZ9	456	11.85		44	4	21	69
BZ8A.1	747	11.5	13	54	5	43	115
BZ8A	*140*	*11.25*	*8*	*4*		*5*	*17*
BZ8	875	8.75	12	20	7	43	82
BZ7A	*170*	*9*	*4*	*7*	*1*	*3*	*15*
BZ7	834	8.1	12	41	4	28	85
BZ6B	400	7.25	6	35	1	5	47
BZ6	620	7	4	33		8	45
BZ5B	*150*	*5.25*		*4*	*4*		*8*
BZ5	730	5.75		66		4	70
BZ4B.1	1120	5.25		79	6	40	125
BZ4B	*267*	*5*		*14*		*1*	*15*
BZ3C	*580*	*3.25*		*6*		*1*	*7*
BZ3	610	3	2	12		12	26
BZ2C	*347*	*2.25*		*2*		*3*	*5*
BZ2	1083	1.75	2	13	2	17	34
BZ1C	*1037*	*1*		*3*			*3*
BZ1A	715	0.5	1	48	1	4	54
BZ1	*800*	*0*		*27*		*1* sp.	*28*

Sedimentary cycles are limited at the top and bottom by thick, argillaceous carbonates or dark claystones. Around 20 couplets are generally found between these, organized into four lithological subcycles (each composed of five couplets). Sedimentary subcycles are defined by rhythmic facies and bed-thickness changes. In the present-day, it is not possible to assign a clear significance to these sedimentary cycles. The Frasnian deposits comprise 15 sedimentary cycles. From bottom to top, a general increase in thickness of sedimentary cycles is observed through the Frasnian deposits: cycles 1–9, 11 and 12 are 1 to 2 m thick, while cycles 10 and 13–15 are 2.5–3.5 m thick.

The facies are rather homogenous with rare macrofossil remains, but slight differences can be depicted as follows (from bottom to top).

1) Above sample BZ1 is a centimetre-thick crust of iron-hydroxide. Between 0.6 and 4 m above the base of the section, centimetre- to decimetre-thick massive, greyish to brownish, micritic limestones and centimetre- to decimetre-thick argillaceous limestones alternate. The first beds above the hard-ground are cherty and ferruginous (BZ1B). The massive limestones are tentaculite-rich wackestones. The top of some beds may be coated with iron-hydroxides. Limestones display a discrete nodular structure and some pyrite crystals.

2) Between 4 and 10.7 m above the base of the section, ferruginous limestones and argillaceous limestones (Fig. 4a) alternate. Ferruginous limestones display a pronounced pseudo-nodular structure underlined by iron-hydroxide films around micritic nodules due to the pressure-dissolution process of tectonic origin or/and bioturbation (also referred to as bioerosion; Elmi & Ameur, 1984). Limestones are mudstones to wackestones with tentaculites (Fig. 4d), some entomozoan crustaceans and pelagic molluscs (‘filaments’). Pyrite crystals are present and sparse phosphate grains occur. Most of the beds are covered with thin iron-hydroxide coatings. Argillaceous limestones also display nodular structure and iron-hydroxide films.

3) Between 10.7 and 15.5 m above the base of the section, massive and argillaceous limestones are found. These are bioturbated mudstones with rare pelagic organisms (tentaculites, entomozoan crustaceans and pelagic molluscs). They also yield foraminifers in residues obtained for conodont extraction. Some centimetre-thick blackish shales are also interbedded.

4) Between 15.5 and 19.5 m above the base of the section are massive, greyish pseudo-nodular

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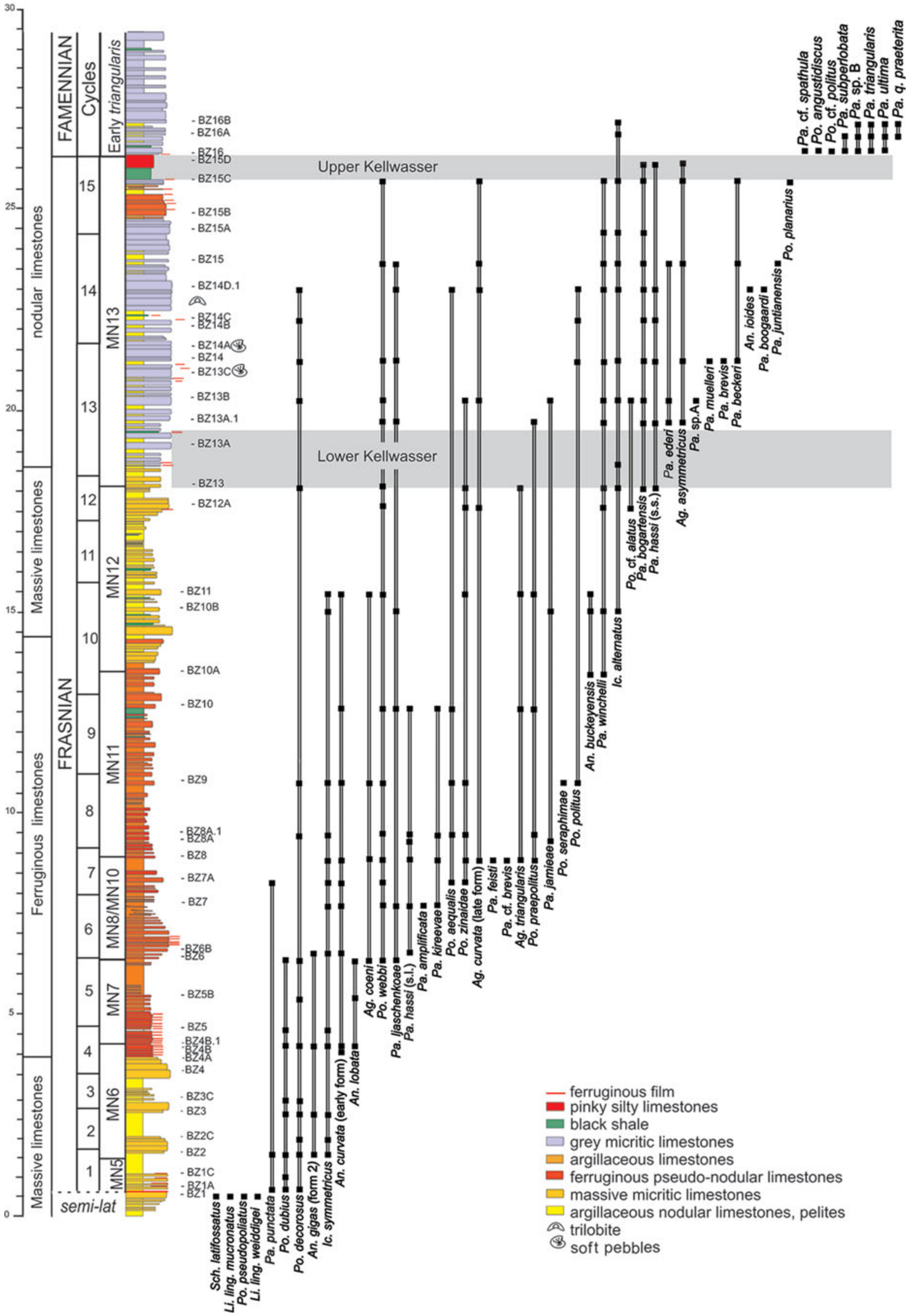

Figure 2. (Colour online) Stratigraphic log with sedimentary cycles, Kellwasser events and distribution of conodont species in the Givetian, Frasnian and lowermost Famennian deposits at Ben Zireg section, Bechar basin. *An – Ancyrodella*; *Ag – Ancyrognathus*; *Pa – Palmatolepis*; *Li – Linguipolygnathus*; *Po – Polygnathus*; *Ic – Icriodus*; *ling – linguiformis linguiformis* (gamma morphotype); *q – quadrantinodosalobata*; s.l. – *sensu lato*; s.t. – *sensu stricto*; LKW – Lower Kellwasser; UKW – Upper Kellwasser; MN – Montagne Noire Zone.

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Figure 3. (Colour online) Exposure of the Ben Zireg Givetian–Famennian succession, showing 15 sedimentary cycles. The Frasnian–Famennian boundary is located above the Upper Kellwasser horizon, and coincides with the top of cycle 15. The scale is given by B. Meyer-Berthaud, 1.55 m tall, upper right.

limestones. These are mudstones with some pelagic organisms (tentaculites, entomozoan crustaceans and pelagic molluscs) and some benthic ostracods (Fig. 4e).

5) Between 19.5 and 26.5 m above the base of the section deposits are dominantly pinkish to greyish pseudo-nodular limestones and interbedded argillaceous micrites (Fig. 4b). Limestones are tentaculite mudstones with some entomozoan crustaceans, pelagic molluscs and goniatites. They also yielded rare benthic ostracods, foraminifers and rare fragments of brachiopods and trilobites; the latter exclusively occur in dish-like flattened mud pebbles occurring on the surface of a single bed (Bed 14D with *Acuticryphops acuticeps*; Fig. 4f). The uppermost part of the Frasnian deposits consists of a 30-cm-thick black shale level overlain by a 35 cm bed of plane-laminated, grain-sorted, pinky calcisiltite between samples BZ15C and BZ16 (Fig. 4c). The significance of this reddish calcisiltite remains unknown. It could have resulted from turbidite current activity, carrying detrital carbonates and iron oxides of possibly continental origin into the offshore domain.

4.b. Biostratigraphy

The first level (BZ1) yields *Linguipolygnathus linguiformis linguiformis* (gamma morphotype), *Li. linguiformis mucronatus*, *Li. linguiformis weddigei*, *Po. pseudofoliatus* and *Schmidtognathus latifossatus*. This association indicates an age from the base of the latifossatus (topmost middle Givetian) through the top of the cristatus-ectypus Zone (upper Givetian) (Aboussalam, 2003) (Figs 2 and 5).

The following level BZ1A indicates MN Zone 5 due to the occurrence of *Palmatolepis punctata*. This level coincides with the base of the middle Frasnian stage (Becker & House, 2000*a*). *Polygnathus dubius* and *Po. decorosus* also occur within this zone.

The MN Zone 6 is identified with the entry of *Ancyrodella gigas* form 2 in bed BZ2. *Icriodus symmetricus*, *Po. decorosus* and *Po. dubius* are also present in this zone.

The occurrences of both *An. lobata* and *An. curvata* (early form) in bed BZ4B.1 mark the base of the MN Zone 7.

The undifferentiated MN Zones 8–10 are identified by the co-occurrence of *Pa. hassi* (*sensu lato*) (after Bultynck, Helsen & Hayduckiewich, 1998), *Ag. coeni* and *Pa. ljaschenkoae* together with *Pa. kireevae* from bed BZ6 to bed BZ7A. The conodont association is completed by *Pa. amplificata* in bed BZ7 and *Po. zinaidae* and *Po. aequalis* in bed BZ7A.

The base of the MN Zone 11 is defined by the first occurrence of the marker *Pa. feisti* in bed BZ8 and corresponds to the base of the upper Frasnian substage (Becker & House 1998).

The presence of the MN Zone 12 is attested in bed BZ12A with the first appearance of *Pa. winchelli*, index-species of the zone.

The presence of the marker *Pa. bogartensis* in bed BZ13 allows the base of MN Zone 13 to be determined. The level BZ13A.1 yields *Pa. ederi* and *Ag. asymmetricus*, and *Pa. brevis* and *Pa. boogaardi* occur in bed BZ14. The co-occurrence of *Pa. beckeri* and *Pa. juntianensis* is recorded in bed BZ15 at MN Zone 13.

The occurrences of *Pa. ultima* and *Pa. triangularis* in Bed BZ16 indicate the Famennian stage (early *triangularis* Zone) (Klapper, 2007*b*). Other species present are *Pa. subperlobata*, *Pa.* sp. B, *Pa. quadrantinodosalobata praeterita, Po. angustidiscus*, *Po*. cf. *politus* and *Ic. alternatus.* In our record, *Pa.* cf. *spathula* occurs slightly before the first known appearance of *Pa. spathula* (late *triangularis* zone; Schülke, 1999).

4.c. Temporal calibration of terminal Frasnian black shales

Temporary dysoxic events are recorded by several thin intervals of black shale deposits that occur throughout the section, especially at the top of the succession where a 30-cm-thick discrete black shale level (between BZ15C and 15D) is developed. The Lower Kellwasser is known to occur at the boundary between MN Zone 12 and MN Zone 13 (Girard & Renaud, 2007). At Ben Zireg the Lower Kellwasser event is located at the end of sedimentary cycle 12 and the beginning of cycle 13, coinciding with the entry of the marker *Palmatolepis bogartensis*. It is not defined by a distinct horizon, but rather constitutes a 2-m-thick

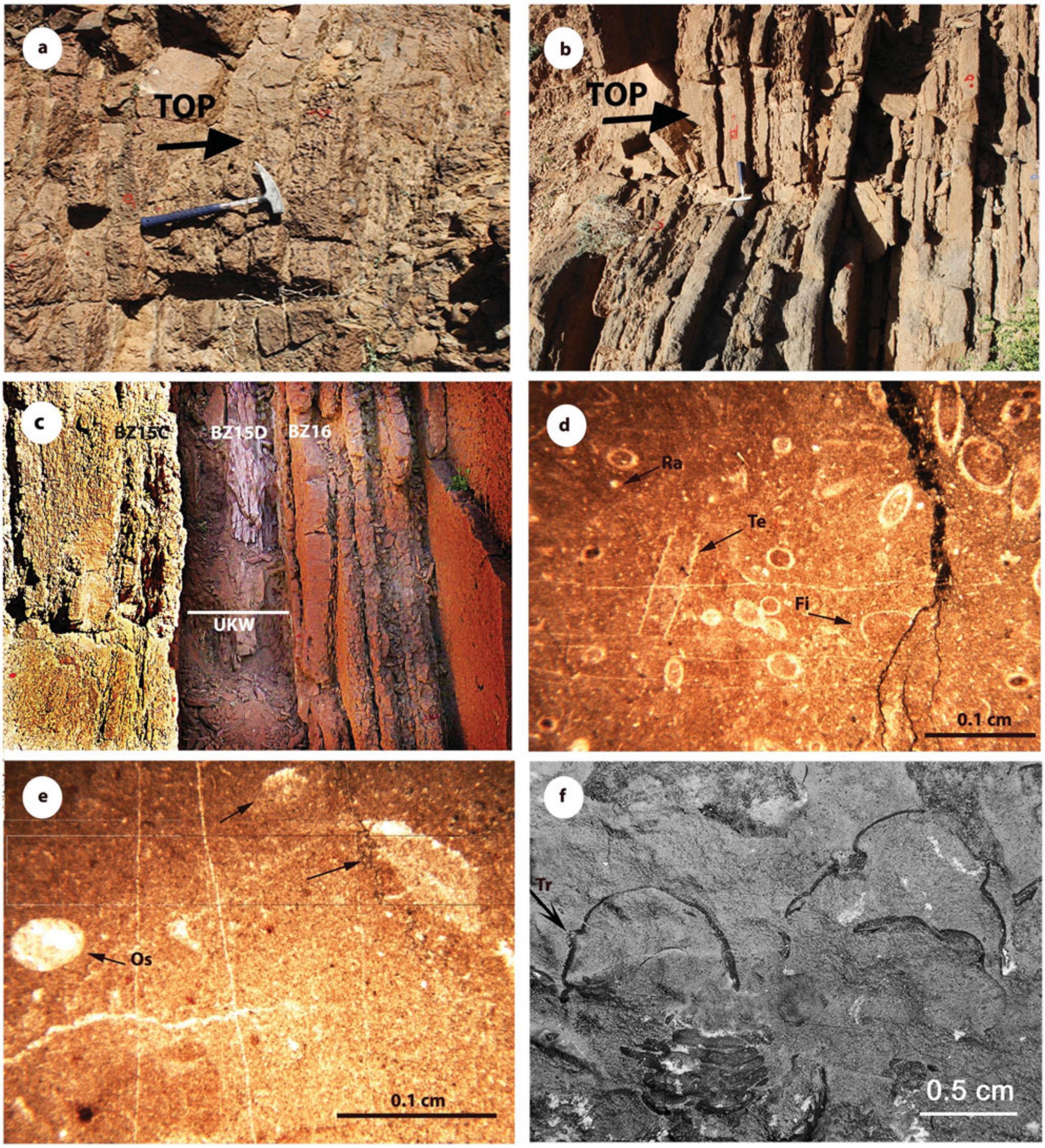

Figure 4. (Colour online) Upper Devonian facies types of Ben Zireg section (Algeria). Os – benthic ostracods; Tr – trilobite; Ra – radiolarian; Te – tentaculite (*Homoctenus*); Fi - Filaments. (a) View of the ferruginous limestone unit (7th cycle). (b) View of the thin- to thick-bedded grey nodular limestone (13th cycle). (c) Upper Kellwasser horizon (UKW) composed of a lower part with black shales (to the left) and an upper part of pinkish calcisiltites (BZ15D). BZ16 corresponds to the lowermost Famennian bed. The UKW is 0.65 m thick. (d) Tentaculite wackestone (Bed BZ6C, MN Zone 8). (e) Ostracod mudstone with unsculptured benthic specimens (Bed BZ13A, MN Zone 13). (f) Surface of mudstone slab with trilobite sclerites of *Acuticryphops acuticeps* (Kayser, 1889). Pointed glabella and reduced size of eye-lobe with few prominent lenses (arrow) are characteristic (Bed BZ14D, MN Zone 13).

succession of dark micritic limestones and few black shales. The percentage of *Icriodus* elements increases in this interval (Fig. 6). The Upper Kellwasser horizon, comprising black shale deposits in its lower part and reddish calcisiltites in its upper part (BZ15C and D) at Ben Zireg, represents the uppermost part of MN Zone 13 before being superseded by basal Famennian strata (BZ16). As the most basal part of the lower *triangularis* Zone has not been established, a small depositional gap might exist. This gap might be related to a sea-level instability, materialized by the pinkish detrital level. Such instabilities are often recorded at the top of the Upper Kellwasser horizon event (i.e. Girard & Renaud, 2007; Schindler, 1990).

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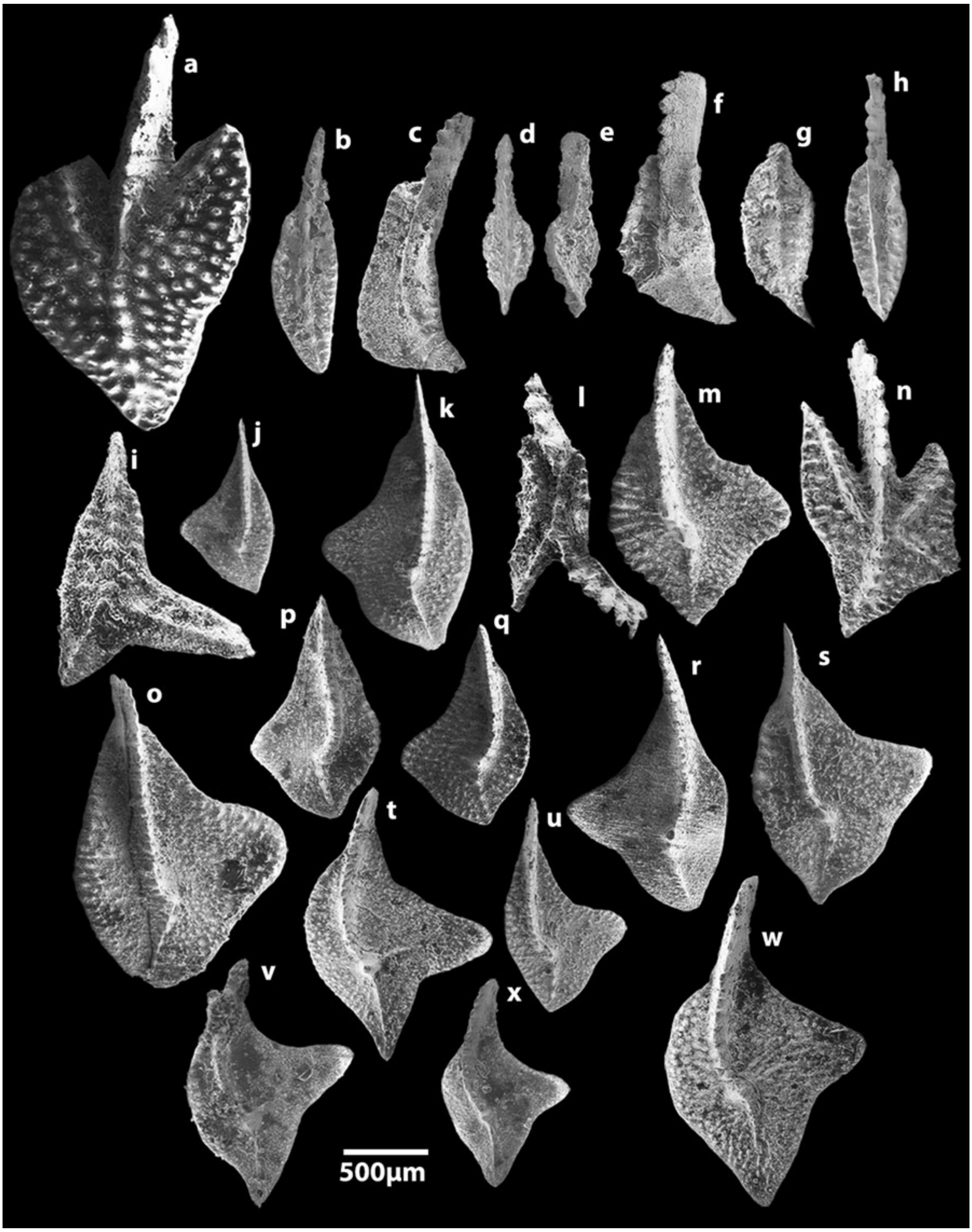

Figure 5. Significant conodonts from the Ben Zireg section. (a) *Ancyrodella gigas* Youngquist, 1947 form 2 (UM-BZA-01) (Bed BZ2); (b) *Polygnathus pseudofoliatus* Wittekindt, 1966 (UM-BZA-02) (Bed BZ1); (c) *Linguipolygnathus linguiformis linguiformis* (Hinde, 1879) (gamma morphotype after Bultynck, 1970) (UM-BZA-03) (Bed BZ1); (d, e) *Schmidtognathus latifossatus* Wirth, 1967; upper and lower views (UM-BZA-04) (Bed BZ1); (f) *Linguipolygnathus linguiformis weiddigei* (Clausen, Leuteritz & Ziegler, 1979) (UM-BZA-05) (Bed BZ1); (g) *Linguipolygnathus linguiformis mucronatus* (Wittekindt, 1966) (UM-BZA-06) (Bed BZ1); (h) *Polygnathus decorosus* Stauffer, 1938 (UM-BZA-07) (Bed BZ1); (i) *Ancyrognathus triangularis* Youngquist, 1945 (UM-BZA-08) (Bed BZ11); (j) *Palmatolepis kireevae* Ovnatanova, 1976 (UM-BZA-09) (Bed BZ8); (k) *Palmatolepis ljaschenkoae* Ovnatanova, 1976 (UM-BZA-10) (Bed BZ6); (l) *Ancyrognathus coeni* Klapper, 1990 (UM-BZA-11) (Bed BZ11); (m) *Palmatolepis feisti* Klapper, 2007*a* (UM-BZA-12) (Bed BZ8); (n) *Ancyrodella curvata* (Branson & Mehl, 1934) early form (UM-BZA-13) (Bed BZ5B); (o) *Palmatolepis punctata* (Hinde, 1879) (UM-BZA-14) (Bed BZ2); (p); *Palmatolepis jamieae* (UM-BZA-15) (Bed BZ10B); (q) *Palmatolepis bogartensis* (Stauffer, 1938) morphotype B, Klapper (2007*b*) (UM-BZA-16) (Bed BZ13); (r) *Palmatolepis boogaardi* Klapper & Foster, 1993 (UM-BZA-17) (Bed BZ14D.1); (s) *Palmatolepis hassi* Müller & Müller, 1957 (UM-BZA-18) (Bed BZ6B), *s. l.* after Bultynck, Helsen & Hayduckiewich 1998; (t) *Palmatolepis ultima* Sannemann, 1955 (UM-BZA-19) (Bed BZ16); (u) *Palmatolepis winchelli* Stauffer, 1938 (UM-BZA-20) (Bed BZ10A); (v) *Palmatolepis* cf. *spathula* Schülke, 1995 (UM-BZA-21) (Bed BZ16); (w) *Palmatolepis triangularis* Sannemann, 1955 (UM-BZA-22) (Bed BZ16); and (x) *Palmatolepis subperlobata* Branson & Mehl, 1934 (UM-BZA-23) (Bed BZ16).

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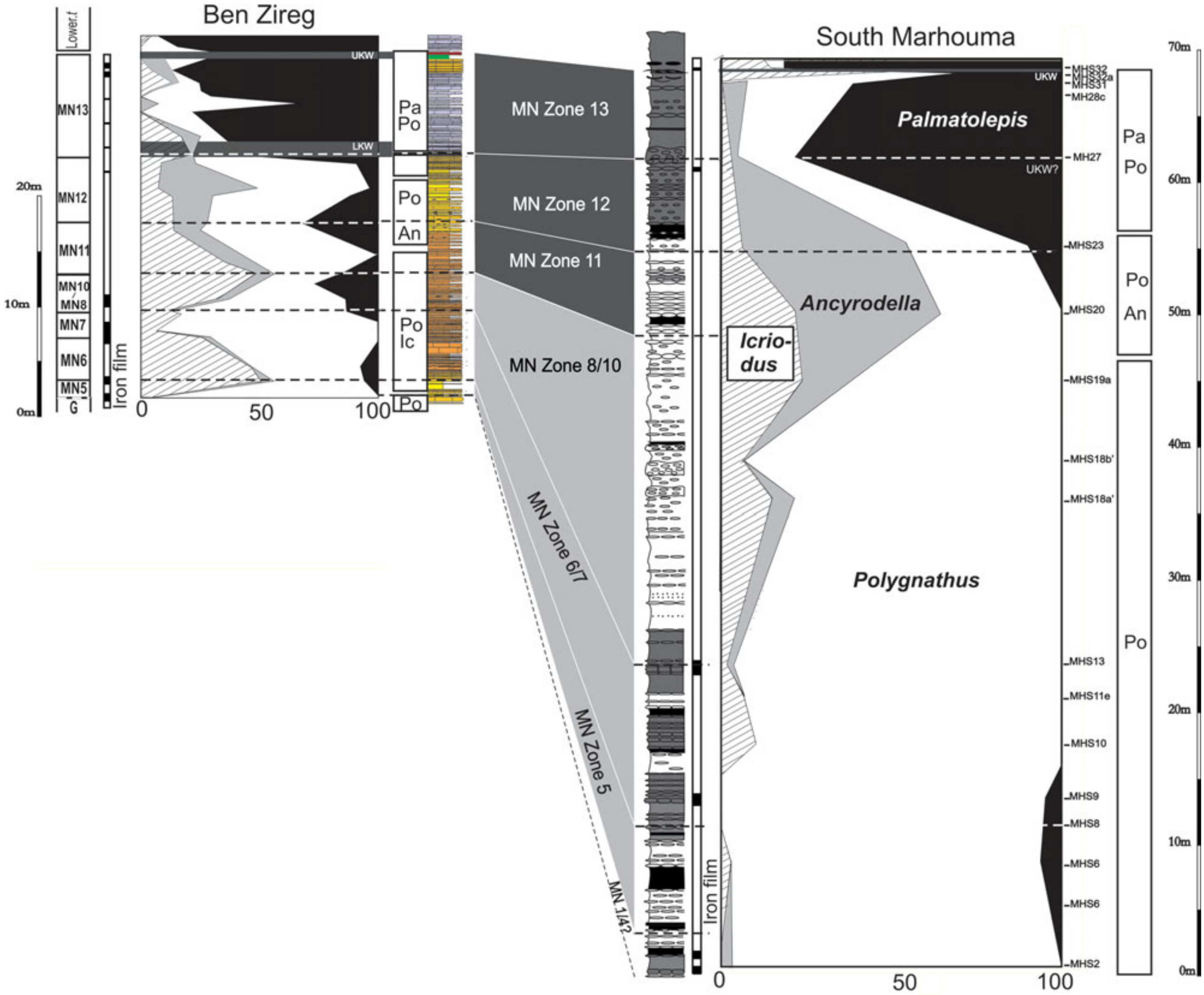

Figure 6. (Colour online) Percentage of conodont genera at Ben Zireg (left) and the South Marhouma section (right), and fine-scaled correlation between these sections based on the detailed biostratigraphical frame. Po – polygnathid biofacies; Po-Ic – polygnathid-icriodid biofacies; Po-An – polygnathid-ancyrodellid biofacies; Pa-Po – palmatolepid-polygnathid biofacies; G – Givetian, t. – *triangularis.*

4.d. Biofacies

Numerous studies using the biofacies approach were performed on Frasnian deposits from very different parts of the world, showing that the assemblages were dominated by *Polygnathus* during early–middle Frasnian time and then by *Palmatolepis* during late Frasnian time (e.g. Morocco: Lazreq, 1999; China: Ji & Ziegler, 1993; USA: Sandberg, Pool & Johnson, 1989; Russia: Ovnatanova, Kuzmin & Menner, 1999). At Ben Zireg, three biofacies have been distinguished from bottom to top (Fig. 6): polygnathid-icriodid, polygnathid-ancyrodellid and palmatolepid-polygnathid. Several peaks of *Icriodus* occur successively in MN Zone 5 and through MN zones 8–10. Ancyrodellids were never dominant, but their percentage reached more than 20 % of the assemblage at the end of MN Zone 11 and during MN Zone 12.

The change from relatively shallow-water polygnathid-icriodid and polygnathid-ancyrodellid to deep-water palmatolepid-polygnathid biofacies through the Frasnian sediments correlates with the conclusions of Johnson, Klapper & Sandberg (1985) and the globally observed trends in conodont biofacies.

5. Interpretation and discussion

5.a. Biostratigraphy and depositional environment

The fine-scaled conodont stratigraphy in the Ben Zireg section bears witness to a stratigraphic hiatus at the base of the section. Between beds BZ1 (late Givetian) and BZ1A (middle Frasnian), the gap extends at least from the top of the *cristatus-ectypus* Zone to the base of MN Zone 5. However, it could begin earlier at the top of the *latifossatus* Zone at the oldest. The underlying bed (BZ1) yields a Givetian, probably topmost of the middle Givetian, conodont association (*semialternans* Zone) where no typical Frasnian elements occur. The presence of Givetian deposits at Ben Zireg is emphasized by the occurrence of *Pharciceras* mentioned by Menchikoff (1936). As the superseding bed (BZ1A) already yields *Pa. punctata*, the deposits of early Frasnian age are missing (i.e. MN Zones 1–4).

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The interval of MN Zones 5–10 is only 9 m thick, attesting to severe condensation of deposits under slow sedimentation rates. Conversely, sedimentation rates increased considerably thereafter. Indeed, sedimentary cycles 10–15 comprise an interval of 17 m in thickness that represents two-thirds of the entire Frasnian deposits. The sedimentary cycles increase in importance from the bottom to the top of the section. Deposits of MN Zone 13 reach a thickness of 9 m that correspond to one-third of the total thickness of the section.

The resumption of the middle Frasnian sedimentation is not marked by erosional features or transgressive deposits. Only the presence of ferruginous cherty beds just above the iron-hydroxide crust is noticeable (bed BZ1b). Sedimentary rocks are condensed in the lower part of the section (cycles 1–6 with frequent iron-hydroxide coatings as micro-hard-grounds, phosphatic grains). They display a rhythmic pattern dominated by micritic deposits. Detrital deposits are restricted to a few shaly interbeds. Sediment texture is widely dominated by mudstones and fewer wackestones. The fauna is poorly diversified, mostly represented by pelagic organisms (tentaculites, pelagic bivalves, entomozoan crustaceans, goniatites and conodonts) associated with some autochtonous benthic foraminifers and benthic ostracods, and rare fragments of trilobites and brachiopods in flat mudstone pebbles. These criteria indicate that the Frasnian deposits were emplaced on a distal ramp or distal platform setting (e.g. Franke and Walliser, 1983), below wave action base and very far from emerged areas. Condensation in intervals (1) and lower (2) could indicate a distal submarine rise. The interval (3) between 10.7 and 15.5 m yields bioturbation features, rare pelagic organisms, abundant foraminifers, benthic ostracods and numerous *Icriodus*. These indicate that the corresponding sediments were probably deposited at shallower depths than both the overlying and underlying sediments. The interval (4) during the MN Zone 13 interval indicates a return to deeper outer ramp setting. Noticeable is the presence of some soft pebble-rich levels composed of mudstones with trilobites, indicative of downslope transport.

5.b. Conodont distribution patterns

In order to elucidate the significance of the conodont biofacies, assemblages from Ben Zireg were compared with those established from the Marhouma section (Ougarta area) by Mahboubi, Cornée & Girard (2013*a*) and Mahboubi *et al.* (2013*b*) (Fig. 6).

The Marhouma section is distinct from Ben Zireg in the lower part of the middle Frasnian deposits where a pure *Polygnathus* biofacies prevails. Thereafter, the Marhouma pattern is consistent with the trends of the Ben Zireg section first by a clear increase of the percentage of ancyrodellids during the MN Zone 11 (base of the upper Frasnian) and second by an obvious increase of *Palmatolepis* towards the Frasnian–Famennian boundary.

In detail, a slight shallowing is indicated during early late Frasnian time (MN Zones 11–12) in both sections due to the obvious increase of ancyrodellids. As depositional environments are different, that is, submarine rise v. subsiding basin, this trend seems to be independent of local setting dynamics.

5.c. Gaps at the Givetian–Frasnian transition

Occurrences of Late Devonian gaps, at the Givetian–Frasnian transition in particular, are quite common in sections south of the Atlas Fault. This is most obvious in Devonian outcrops of the Bechar Basin north and west of Ben Zireg where lower Visean conformably supersedes various levels in Tournaisian – upper Emsian deposits (Weyant, 1988), bearing witness to the marked diachronism of the omission. Whether the latter is due to syntectonic movements as Weyant (1988) claims, or is a result of current induced erosion or the influence of differentiated submarine scenery into seamounts and depressions, is open to debate.

The Ben Zireg section can be compared with other conodont-dated sections in Algeria and Morocco (Fig. 7). Although the Givetian–Frasnian transition is presumably complete in the basinal Marhouma section (Göddertz, 1987; Mahboubi *et al.* 2013*b*), various sections on the Tafilalt platform exhibit hiatuses (Becker & House, 2000*b*): Jebel Mech Irdane (*latifossatus–semialternans* Zone – MN Zone 4; Ebert, 1993; Walliser, 2000; Aboussalam, 2003); Jebel Amelane (MN Zones 1–6; Becker & House 2000*a*); Bou Tchrafine (lower part of the MN Zone 5; Becker & House, 2000*b*; Aboussalam, 2003); and Hamer El Khdad section (*disparilis*–MN Zone 4; Gouwy, Haydukiewicz & Bultynck, 2007). In these areas, the extent of the gap is variable and may range between the Givetian *hermanni* zone and the Frasnian MN Zone 6. Hiatuses in the same time interval were also noted in northern Morocco, France, Germany and Austria, implying a supra-regional distribution (summarized in table 1 of Hüneke, 2006). These hiatuses have been interpreted as the result of a strong current-induced erosion, often occurring within lower parts of fossil contourite units (Hüneke, 1995, 2006).

Possible contourite deposits have not yet been identified at Ben Zireg however, and current activity is not obvious as no sorting of conodont assemblages were observed and accumulations of benthic biodetritus do not occur. Instead, we favour the interpretation that these hiatuses and condensation features resulted from depositional conditions on offshore submarine rises under slow sedimentation rates, with numerous episodes of non-sedimentation, sub-marine dissolution and abrasion of bedding surfaces marked by residual hydroxide iron-rich incrustations and hard-grounds.

5.d. Accumulation rates

Interbasinal correlation with the South Marhouma section reveals that the middle Frasnian interval is at least

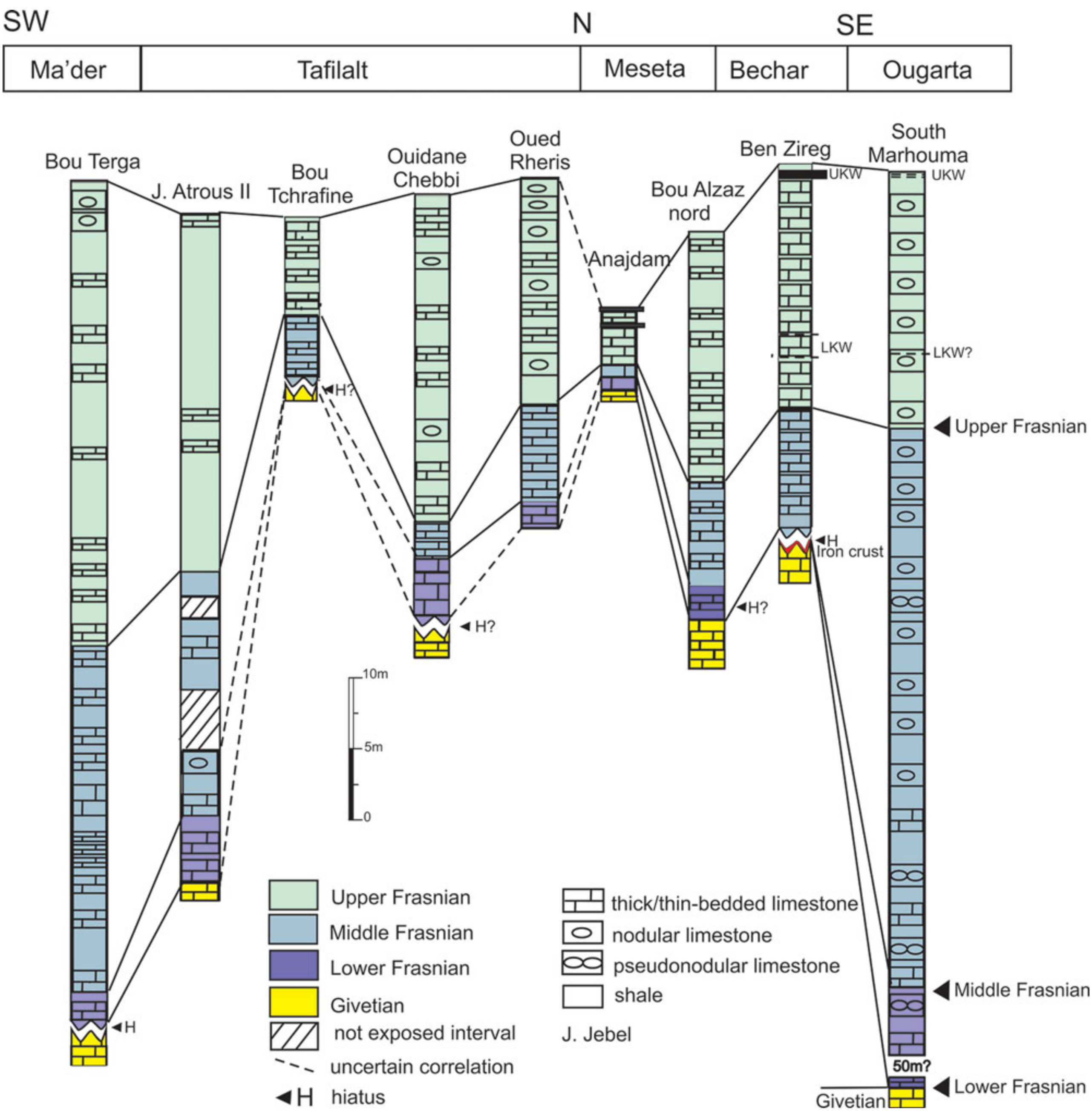

Figure 7. (Colour online) Correlation of selected Frasnian sections from both sides of the Main Atlas Fault (for location see Fig. 1b): Bou Terga, Jebel Atrous II (Gouwy, Haydukiewicz & Bultynck, 2007); Bou Tchrafine (Bultynck & Jacobs, 1981; Bultynck, 1986, 1987; Becker & House, 2000*b*); Ouidane Chebbi (Wendt & Belka, 1991; Belka *et al.* 1999); Oued Rheris (Wendt & Belka, 1991); Anajdam, Bou Alzaz Nord (Lazreq, 1999); South Marhouma (Mahboubi, Cornée & Girard, 2013*a*; Mahboubi & Gatovsky, 2014).

four times thicker there than in the studied section (Fig. 6). This suggests an important accumulation rate that reflects high subsidence in the Ougarta trough, while the Bechar basin suffered condensation (Fig. 7). This is presumably due to voluminous fine-grained detrital influx from the far highlands (i.e. Reguibat shield) into the Ougarta sill.

At Ben Zireg condensation progressively reversed during MN Zones 11–13. This was also the case in Marhouma and in the Anti-Atlas and Meseta domains (Wendt & Belka, 1991; Lazreq, 1999; Gouwy, Haydukiewicz & Bultynck, 2007; Fig. 7). At the end of late Frasnian time, deposits tend to homogenize in thickness over wide areas. This may reflect more uniform depositional conditions and less differentiated subsidence rates, in both platform and basin domains.

5.e. Late Frasnian Kellwasser facies

The terminal Frasnian Upper Kellwasser horizon is defined by an outstanding level of oxygen-depleted carbon-rich black shales that occur intercalated in a succession of normally oxygenated sediments. This is generally the case in European sections of offshore cephalopod limestones (Schindler, 1990), but also in sections characterizing the Central Moroccan Hercynian Meseta near Mrirt (Lazreq, 1999).

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In contrast, south of the Main Atlas Fault, the upper Frasnian deposits in both platform and basin settings of the Tafilalt and Maider regions as well as in the South Marhouma area are exclusively composed of black cephalopod-rich limestones and shales. In these, the two Kellwasser horizons are lithologically difficult to discriminate but are discernable by conodont and goniatite biostratigraphy. This lithological unit of Kellwasser-like facies that starts diachronously at the base or in the lower part of the lower Frasnian stage and extends into the lower Famennian stage is referred to as the 'Upper Kellwasser member' by Wendt & Belka (1991).

The Ben Zireg section differs from all other known sections of SE Morocco and adjacent NW Algerian Sahara in the persistence of well-oxygenated carbonate sedimentation of late Frasnian – early Famennian age in which, similarly to the situation in the Moroccan Meseta, the intercalation of a clearly defined Upper Kellwasser horizon is obvious. Additionally, the presence of the trilobite *Acuticryphops acuticeps*, index of pre-Upper Kellwasser MN Zone 13 in European and Central Moroccan sections, is exceptional as it is unknown from contemporaneous dysoxic deposits of Kellwasser facies in Southern Morocco and Algeria. Its occurrence shortly before the Upper Kellwasser horizon is an indication of normal oxygenated level bottom conditions at Ben Zireg.

These 'Hercynian' aspects of upper Frasnian lithology and fauna bear evidence of closer palaeogeographic relations to the Frasnian section of the Maghrebid Hercynides than to any other area south of the Atlas Fault.

6. Conclusions

The Ben Zireg section is representative of Frasnian deposits on the northern edge of the Algerian Sahara platform, where the lower Upper Devonian stage is generally largely incomplete or even absent from the Bechar Basin. Although deposits of early Frasnian age are missing at Ben Zireg, this section is the most complete as, conformably superseding upper Middle Devonian deposits, all conodont zones of the middle and upper Frasnian stage are represented below the lowest Famennian deposits. Such a fine-scaled biozonation representing MN Zones 5–13 is obtained for the first time in Frasnian sequences of the Algerian Sahara.

The lithological succession is one of largely oxygenated, fine-grained carbonates of the offshore realm that are condensed in its lower part to continuously gain in importance when sedimentation rates increased. The latest Frasnian MN Zone 13 is the thickest zone. The initial depositional environment was one of an offshore submarine rise subsequently smoothed to bottom level at the top of the section.

Both the Lower and Upper Kellwasser events are recorded, the latter being represented by an outstanding horizon of anoxic black-shale deposits intercalated in the normally oxygenated carbonate sequence. This disposition is unique among all other known terminal Frasnian sections south of the Atlas Fault, where the Kellwasser horizons cannot be distinguished lithologically within a uniform Kellwasser-like shale/limestone succession. Conversely, it is identical to equivalent sections characterizing terrains of the European and Maghrebian Variscids. In particular, evidence of instability in the topmost part of the Upper Kellwasser horizon has also been observed in many European sections.

Frasnian conodont biofacies patterns at Ben Zireg, that is, the notable increase of ancyrodellids at the lowermost of the upper Frasnian stage, follows the global trend independently of local conditions linked to subsidence or palaeogeographic constraints.

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