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

**Category: Stratigraphy**

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**Short title: Frasnian biostratigraphy at Ben Zireg (Algeria)**

**Abstract**

The Ben Zireg anticline NW of Bechar yields the so far 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 through late Frasnian. As the early Frasnian is not represented, the succession rests conformably on an indifferiated, probably late Givetian substrate. Fine-scaled conodont biostratigraphy reveals a continuous sequence of Montagne Noire Zones 5

to 13, superseded by the earliest Famennian *triangularis* Zone.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 Ancyrorellids 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 Tafilalet platform, and contrast with those from the Marhouma trough and the Maider basin. Unlike other Frasnian successions S 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.

Key-words: Frasnian, conodont biostratigraphy, biofacies, depositional environment, northwestern Algerian Sahara

## 1. Introduction

The Ben Zireg area at 50 km NE of Bechar township constitutes the north-eastern most 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 N and W of Djebel Antar (Weyant, 1988) (Fig. 1a) in comprising a well exposed, almost complete succession of marine sediments from Cambrian-Ordovician

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through Early Carboniferous. As such the Ben Zireg section is a reference for the northern margin of epicontinental Sahara in SW Algeria, at 200 km in distance from the Palaeozoic of the Ougarta region further to the South (Fig. 1a). A major contribution to its structure and stratigraphy by Pareyn (1961) was mainly devoted to the Carboniferous, whereas apart from a few scattered data, the Devonian, and Frasnian in particular, remained largely unstudied regards biostratigraphical subdivision and sedimentary development.

After the first recognition of Devonian fossils at Ben Zireg by Flamand (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. This taxon, however, is now restricted to the Latest Givetian since the definition of Frasnian stage boundaries by SDS/IUGS (Klapper, Feist & House, 1987, 1993). The presence of Frasnian strata was definitely established when Massa et al. (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 Tafilalet area (e.g. Belka et al., 1999), no more work was carried out to evaluate the extent and completeness of the early Upper Devonian in the Algerian part of northern Sahara.

This study aims establishing fine-scaled conodont biostratigraphy and biofacies as well as sedimentary dynamics of the Ben Zireg section to emphasise the importance of its pivotal position between Frasnian sections on both sides of the Main Atlas fault, i.e. the allochthonous Hercynian Meseta of Central Morocco, and their eastern prolongation into the Algerian Hercynian Tifrit Horst, and cratonic Gondwana sections both in SW Algeria (Marhouma) and Tafilalet / 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 orogeny (e.g. Allary et al., 1976), the Palaeozoic deposits of the western Sahara platform north of the Precambrian Reguibat shield (Fig. 1a) remained generally only weakly deformed to wide synclinal and narrower anticlinal structures, where Devonian sedimentation rates reflect basin and ridge depending depositional environments (Elmi & Ameur, 1984; Conrad, Massa & Weyant, 1986; Wendt et al., 2006). Exposures of the north-eastern Bechar basin close to the Atlas fault are more intensely folded to form narrow W-E trending anticlinal structures, often over-thrusted to the N, and these features along with the occurrence of synorogenic wildflysch sediments with olistolithes of various ages characterising the Dinantian of Ben Zireg (Pareyn, 1961) might indicate dynamic relations to the Maghrebien variscan belt in the north.

In this context the Ben Zireg Palaeozoic forms 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 sub-parallel to the Main Atlas fault and, affecting also the Cretaceous cover, may belong to the alpine transform system. The eastern end of the structure is framed by a prominent ridge of some 200m of Middle through Late Devonian carbonates easily accessible from the S where the road-truck from Ben Zireg station to Taghit runs along the Oued Ben Zireg shortly before it bends to the S (Fig.1b). The investigated section in the Frasnian is situated on the steep southern flank of the Devonian ridge along a southerly directed, deeply incised gorge (coordinates: N 31° 54' 39.4" W 001° 47' 58.8", Fig. 1b).

3. Material and Methods

One single section was logged in detail and thirty-seven 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 under 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 feature 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. The sulphic acid (10%) was used to dissolve iron-and pyrite-rich samples (beds BZ1A and 1C and BZ2). The insoluble residue was then rinsed through two sieves (1mm and 100µm). Residue smaller than 1 mm were dried and handpicked under 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). Some of these elements were identified at the specific level for biostratigraphy. In this paper the biostratigraphic zonations are those of Klapper (1989, 2007a) for the Frasnian and Klapper (2007b) and Schülke (1999) for the lowermost Famennian.

Among the platform P1 elements, different genera can be recognised that are supposed 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 the 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 ancyrorellids. Together with *Polygnathus* they are considered as ubiquitous, with a slight preference for deep environments for *Polygnathus* whereas Ancyrorellids would prefer shallow ones (Sandberg et al., 1992; Sobstel et al., 2006). The variations of relative abundances of these 5 different genera were investigated through the Ben Zireg section. The relative abundances of the four groups (*Palmatolepis*, *Icriodus*, *Polygnathus* and ancyrorellids) are represented as percentage of the total assemblage.

## 4. Results

### 4.a. Lithostratigraphy

The Frasnian deposits at Ben Zireg section are 26.5 metres thick, between sample BZ1 (Givetian) and sample BZ16 (early Famennian) (Fig. 2). Sedimentary rocks display a rhythmic pattern characterized by cm to dm-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). Sedimentary cycles are limited at top and bottom by thick, argillaceous carbonates or dark claystones. Between, twenty couplets are generally found, 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 of our knowledge, 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 to 9 and 11 to 12 are 1 to 2m thick, whilst the cycles 10 and 13 to 15 are 2.5 to 3.5 m thick. The facies are rather homogenous with rare macrofossil remains, but slight differences can be depicted, from bottom to top:

1) Above sample BZ1 is a cm-thick iron crust. Between 0.6 and 4m above the base of the section, there are interbedded cm to dm thick massive, greyish to brownish micritic limestones and cm to dm thick argillaceous limestones. The first beds above the hard-ground are cherty and ferruginous (BZ 1b). The massive limestones are tentaculid-rich wackestones. The top of some beds can be coated by iron hydroxydes. Limestones display a discrete nodular structure and some pyrite cristals.

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



(tentaculids, entomozoan crustaceans, pelagic molluscs). They also yielded foraminifers in residues obtained for conodont extraction. Some cm-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 limestones. These are mudstones with some pelagic organisms (tentaculids, entomozoan crustaceans, pelagic molluscs) and some benthic ostracods (Fig. 4e).

5) Between 19.5 and 26.5m above the base of the section deposits are dominant pinkish to greyish pseudo-nodular limestones and interbedded argillaceous micrites (Fig. 4b).

Limestones are tentaculid 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 14 d with *Acuticryphops acuticeps*; Fig. 4f). The uppermost part of the Frasnian deposits consists of a 30 cm thick black shale level overlain by 35 cm bed of plane-laminated, grain-sorted, pinky calcisiltite between samples BZ15c and BZ16 (Fig. 4c). The significance of this reddish calcisiltite remains enigmatic. It could have resulted in turbidite current activity carrying detrital carbonates and iron oxides of possibly of continental origin into the offshore domain.

#### *4.b. Biostratigraphy*

Distribution of conodont platform elements is given on Fig. 2, and some biostratigraphic species are presented on the Fig. 5. Genera abundance per level is listed on Table 1.

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The first level (BZ1) delivered *Polygnathus linguiformis linguiformis* (gamma morphotype), *Po. linguiformis mucronatus*, *Po. linguiformis weddigei*, *Po. pseudofoliatus* and *Po. latifossatus* indicating the Givetian (Aboussalam, 2003).

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 (Becker & House, 2000a). *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*, *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 MN Zone 8 is identified by the co-occurrence of *Pa. hassi* and *Ag. coeni*.

An undifferentiated MN Zone 9-10 is discriminated from bed BZ7 to bed BZ7A by the presence of *Pa. ljaschenkoae* together with *Pa. kireevae*. The conodont association is composed by *Pa. amplificata* in bed BZ7, *Po. zinaidae* and *Po. aequalis* in bed BZ 7A which have their first occurrences during this interval.

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 discriminating the basis of MN Zone 13. Thereafter, 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.

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3 The occurrences of *Pa. ultima* and *Pa. triangularis* in Bed BZ16 indicate the Famennian stage  
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5 (early *triangularis* Zone) (Klapper, 2007b). Other species present are *Pa. subperlobata*, *Pa. sp.*  
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7 *B*, *Pa. quadrantinodosalobata praeterita*, *Po. angustidiscus*, *Po. cf. politus* and *lc. alternatus*. In  
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9 our record, *Pa. cf. spathula* occurs slightly before the first known appearance of *Pa. spathula*  
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11 (late *triangularis* zone, Schülke 1999).  
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#### 18 4.c. Temporal calibration of terminal Frasnian black shales

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20 Temporary dysoxic events are recorded by several thin intervals of black shale deposits that  
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22 occur throughout the section, especially at the top of the succession where a 30 cm thick  
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24 discrete black shale level (between BZ 15 C and 15D) is developed. The Lower Kellwasser is  
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26 known to occur at the boundary between the MN zone 12 and MN zone 13 (Girard &  
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28 Renaud 2007). At Ben Zireg the Lower Kellwasser event is located at the end of sedimentary  
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30 cycle 12 and beginning of cycle 13, coinciding with the entry of the marker *Palmatolepis*  
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32 *bogartensis*. It is not defined by a distinct horizon but rather constitutes a two metres-thick  
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34 succession of dark micritic limestones and few black shales. In this interval the percentage of  
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36 *Icriodus* elements increases (Fig. 6). The Upper Kellwasser horizon that comprises at Ben  
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38 Zireg black shale deposits in its lower part and reddish calcisiltites in its upper part (BZ 15C  
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40 and D), represents the uppermost part of MN Zone 13 before being superseded by basal  
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42 Famennian strata (BZ 16). As the most basal part of the lower *triangularis* Zone has not been  
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44 established, a small depositional gap might exist. This gap might be related to a sea-level  
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46 instability, materialized by the pinkish detrital level. Such instability is often recorded at the  
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48 top of the Upper Kellwasser horizon event (i.e. Girard & Renaud, 2007; Schindler, 1990).  
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3                   4.d. Biofacies  
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5                   Numerous studies using the biofacies approach were performed through the Frasnian, from  
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7                   very different parts of the world, showing that the assemblages were dominated by  
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9                   *Polygnathus* during the early and middle Frasnian and then by *Palmatolepis* at the end of the  
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11                  Frasnian (e.g. Morocco: Lazreq, 1999; China: Ji & Ziegler 1993; USA: Sandberg et al., 1989;  
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13                  Russia: Ovnatanova et al., 1999). At Ben Zireg, three biofacies have been distinguished from  
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15                  bottom to top (Fig. 6): polygnathid-icriodid, polygnathid-ancyrodellid and then palmatolepid-  
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17                  polygnathid. Several peaks of *Icriodus* occur successively in Zone MN5 and through MN8 to  
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19                  MN10 zones. Ancyrodellids are never dominant but their percentage can reach more than  
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21                  20% of the assemblage at the end of Zone MN11 and during Zone MN12.  
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24                  The change from relatively shallow-water polygnathid-icriodid and polygnathid-ancyrodellid  
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26                  to deep-water palmatolepid-polygnathid biofacies through the Frasnian correlates with  
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28                  conclusions of Johnson, Klapper & Sandberg (1985) and trends in conodont biofacies that  
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30                  have been observed globally.  
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39                  5. Interpretations and Discussion  
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41                       5.a. Biostratigraphy and depositional environment  
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43                   The fine-scaled conodont stratigraphy in the Ben Zireg section bears witness to a  
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45                   considerable stratigraphic hiatus at the base of the section. The underlying bed (BZ1) yields a  
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47                   Givetian, probably late Givetian conodont association where no typical Frasnian elements  
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49                   are found. This age attribution is emphasised by the occurrence of *Pharciceras* at Ben Zireg  
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51                   mentioned by Menchikoff (1936) but not recovered since (Massa et al., 1965). As the  
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53                   superseding bed (BZ1B) already yields *Pa. punctata*, the entire early Frasnian is missing (i.e.  
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55                   MN Zone 1 to MN Zone 4).  
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The interval of Zones MN5 to MN10 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 to 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 bottom to top of the section. Deposits of Zone MN13 reach a thickness of 9 metres that correspond to one third of the total thickness of the section.

The resumption of the Middle Frasnian sedimentation is neither marked by erosional feature nor transgressive deposits. Noticeable is only the presence of ferruginous cherty beds just above the iron crust (bed BZ 1b). Sedimentary rocks are condensed in the lower part of the section (cycles 1 to 6 with frequent iron 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 autochthonous 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 15.5m yield bioturbation features, rare pelagic organisms, abundant foraminifers, benthic ostracods and numerous *Icriodus*. These indicate that the corresponding sediments were probably deposited at shallower depth than both the overlying and underlying ones. The interval 4) during the MN 13 Zone interval indicates a return to deeper outer ramp

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setting. Noticeable is the presence of some soft pebbles 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 Mahrouma section (Ougarta area) by Mahboubi *et al.* (2013a and b; Fig. 6).

The Marhouma section is distinct from Ben Zireg in the lower part of the Middle Frasnian 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 MN11 Zone (base of the Upper Frasnian), second by an obvious increase of *Palmatolepis* till the Frasnian/Famennian boundary.

In detail, a slight shallowing is indicated during early late Frasnian (MN Zones 11-12) in both sections due to the obvious increase of Ancyrodellids. As depositional environments are different, *i.e.* submarine rise vs subsiding basin, this trend seems independent from local setting dynamics.

5.c. Gaps at the Givetian/Frasnian transition

Occurrences of gaps in the later Devonian, and 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 N and W of Ben Zireg where Lower Viséan conformably supersedes various levels from Tournaisian to Late Emsian (Weyant, 1988), bearing witness of the marked diachronism of the omission. Whether the latter is due to

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3 syntectonic mouvements as Weyant (1988) claims or results from current induced erosion or  
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5 influence of differentiated submarine scenery into sea-mounts and depressions is up to  
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7 debate.  
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10 The Ben Zireg section can be compared with other conodont-dated sections in Algeria and  
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12 Morocco (Fig. 6). Whereas in the basinal Marhouma section the Givetian-Frasnian transition  
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14 is presumably complete (Göddertz, 1987; Mahboubi et al., 2003 a), various sections on the  
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16 Tafilalet platform exhibit hiatuses (Becker & House, 2000b): Jebel Mech Irdane (*latifossatus-*  
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18 *semialternans* – MN 4 zones, Ebert, 1993; Walliser, 2000; Aboussalam, 2003), Jebel Amelane  
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20 (MN 1-6 zones, Becker & House 2000a), Bou Tchrafine (lower part of the MN zone 5, Becker  
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22 & House, 2000b; Aboussalam, 2003) and Hamer El Khdad section (*disparilis*-MN zone 4,  
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24 Gouwy, Haydukiewicz & Bultynck, 2007). In these areas, the extent of the gap is variable and  
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26 may range between the Givetian *disparilis* zone and the Frasnian MN zone 6. Hiatuses in the  
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28 same time interval were also noted in northern Morocco, France, Germany and Austria,  
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30 implying a supra-regional distribution (summarized in Table 1 of Hüneke, 2006). These  
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32 hiatuses have been interpreted as the result of a strong current-induced erosion, often  
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34 occurring within lower parts of fossil contourite units (Hüneke, 1995; 2006).  
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37 However, possible contourite deposits were not yet identified at Ben Zireg, and current  
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39 activity is not obvious as no sorting of conodont assemblages were observed, and  
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41 accumulations of benthic biotritus do not occur. Instead, we favour the interpretation that  
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43 these hiatuses and condensation features resulted from depositional conditions on off-shore  
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45 submarine rises under slow sedimentation rates with numerous episodes of non-  
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47 sedimentation, sub-marine dissolution and abrasion of bedding surfaces marked by residual  
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49 iron-rich incrustations and hard-grounds.  
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*5.d. Accumulation rates*

Interbasinal correlation with the South Marhouma section reveals that the Middle Frasnian interval is at least four times thicker than 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 Zones 11-13. This was also the case in Marhouma and in the Anti-Atlas and Meseta domains (Wendt and Belka, 1991, Gouwy, Haydukiewicz & Bultynck, 2007; Lazreq, 1999) (Fig. 7). At the end of the Upper Frasnian, deposits tend to homogenize in thickness over wide areas, which may reflect more uniform depositional conditions and less differentiated subsidence rates, both in 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 characterising the Central Moroccan Hercynian Meseta near Mrirt (Lazreq, 1999). In contrast, South of the Main atlas Fault, the upper Frasnian both in platform and basin settings of the Tafilalet 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 late Frasnian and extends into the lower Famennian is termed by Wendt and Belka (1991) "Upper Kellwasser member".

The Ben Zireg section differs from all other known sections of SE Morocco and adjacent north-western Algerian Sahara in the persistence of well-oxygenated carbonate sedimentation throughout the Late Frasnian and Early Famennian 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 witnesses for normal oxygenated level bottom conditions at Ben Zireg.

These "Hercynian" aspects of late Frasnian lithology and fauna bear evidence of closer palaeogeographic relations to the Frasnian of the Maghrebid hercynides than any other area South of the Atlas Fault.

## Conclusions

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

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The lithological succession is one of largely oxygenated, fine-grained carbonates of the off-shore realm that are condensed in its lower part to continuously gain in importance when sedimentation rates increase. The latest Frasnian MN Zone 13 is the thickest one. Initial depositional environment was that 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 S of the Atlas Fault where the Kellwasser horizons cannot be distinguished lithologically within a uniform shale/limestone succession of Kellwasser-like kind. Conversely, it is identical with equivalent sections characterizing terrains of the European and Maghrebien 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, *i.e.* the notable increase of Ancyrodellids at the beginning of the late Frasnian, follows the global trend independently from local conditions linked to subsidence or paleogeographic constraints.

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### Figure and table captions

**Figure 1.** Main Palaeozoic outcrops in north-west 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; (b) investigated section in the Ben Zireg anticline (after Pareyn, 1961).

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

**Figure 3.** Exposure of the Ben Zireg succession from the Givetian to the Famennian showing 15 sedimentary cycles. Numbers correspond to sedimentary cycles. The Frasnian/Famennian

boundary is located on top of the Upper Kellwasser horizon, and coincides with the top of cycle 15. The scale is given by B. Meyer-Berthaud who is 1.55 m-high on the up-right.

**Figure 4.** Upper Devonian facies types of Ben Zireg section (Algeria). Os – benthic ostracods; Tr – trilobite; Ra – Radiolarian; Te – Tentaculite (*Homoctenus*).

- (a) View of the ferruginous limestone unit (7<sup>th</sup> cycle)
- (b) View of the thin to thick-bedded grey nodular limestone (13<sup>th</sup> cycle)
- (c) Upper Kellwasser horizon (UKW) composed of a lower part with black shales (to the left) and a upper part of pinkish calcisiltites (BZ15D). BZ16 correspond to the lowermost Famennian. The UKW is 0.65 m-thick.
- (d) Tentaculid wackestone (Bed BZ6C, MN Zone 8).
- (e) Ostracods 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).

**Figure 5.** Significant conodonts from the Ben Zireg section:

- (a) *Ancyrodella gigas* Youngquist, 1947 form 2 (Bed BZ2); (b) *Polygnathus pseudofolius* Wittekindt, 1866 (Bed BZ1); (c) *Polygnathus linguiformis linguiformis* Hinde, 1879 gamma morphotype, Ziegler et al. 1976 (Bed BZ1); (d) *Ancyrodella curvata* (Branson & Mehl, 1934) early form (Bed BZ5B); (e) *Ancyrodella lobata* Branson & Mehl, 1934 (Bed BZ6); (f) *Ancyrognathus triangularis* Youngquist, 1945 (Bed BZ11); (g) *Palmatolepis kireevae* Ovnatanova, 1976 (Bed BZ8); (h) *Palmatolepis ljaschenkoae* Ovnatanova, 1976 (Bed BZ6); (i) *Ancyrognathus coeni* Klapper, 1990 (Bed BZ11); (j) *Palmatolepis feisti* Klapper, 2007a (Bed



BZ8); (k) *Palmatolepis punctata* (Hinde, 1879), (Bed BZ2); (l) *Palmatolepis jamieae* Ziegler & Sandberg, 1990 (Bed BZ10B); (m) *Palmatolepis bogartensis* (Stauffer, 1938), (Bed BZ13); (n) *Palmatolepis boogaardi* Klapper & Foster, 1993 (Bed BZ14D.1); (o) *Palmatolepis hassi* Müller & Müller, 1957 (Bed BZ6B); (p) *Palmatolepis* cf. *spathula* Schülke, 1995 (Bed BZ16); (q) *Palmatolepis ultima* Sannemann, 1955 (Bed BZ16); (r) *Palmatolepis subperlobata* Branson & Mehl, 1934 (Bed BZ16); (s) *Palmatolepis winchelli* Stauffer, 1938 (Bed BZ10A); (t) *Palmatolepis triangularis* Sannemann, 1955.

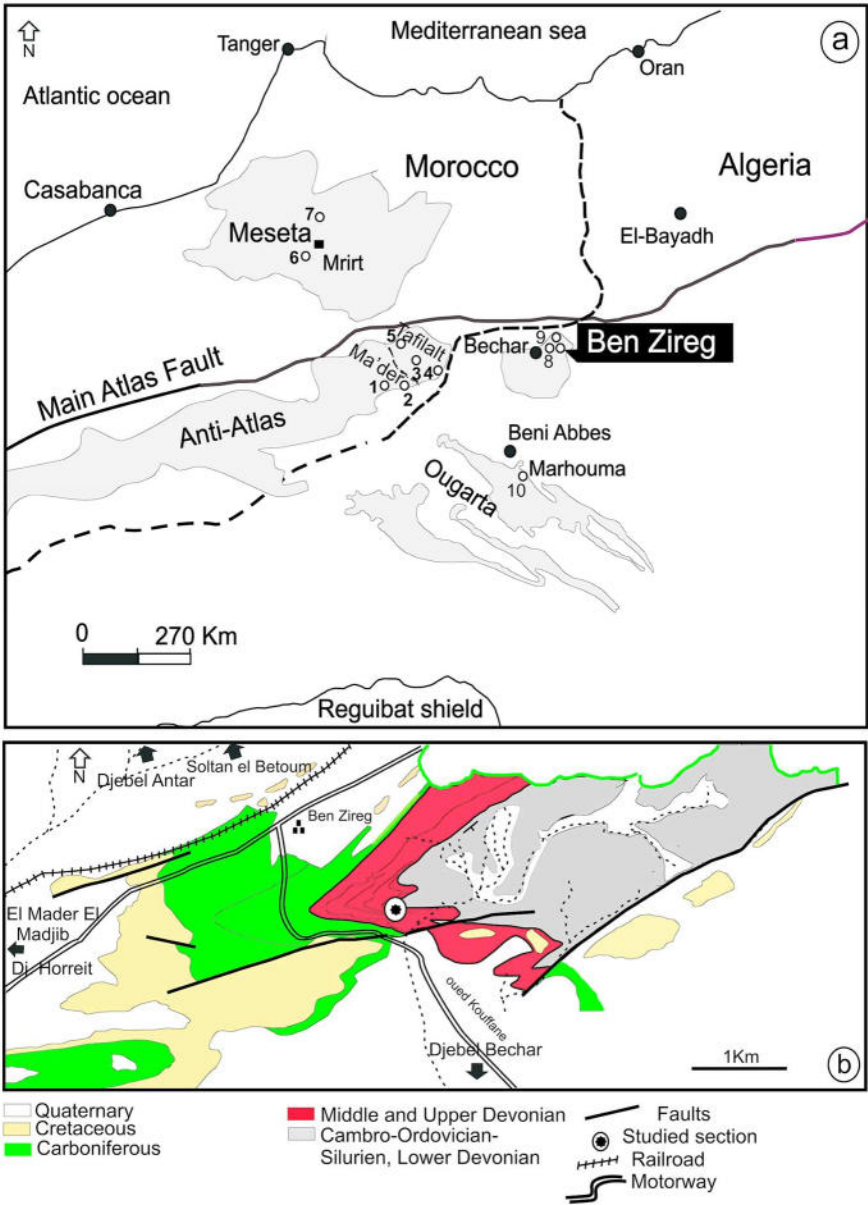
**Figure 6.** Percentage of conodont genera at Ben Zireg (left) and at the South Marhouma section (right) and fine-scaled correlation between these sections based on the detailed biostratigraphical frame. Po = Polygnathid biofacies; Po-Ic = Polygnathid-Icriodid biofacies; Po-An = Polygnathid-Ancyrodellid biofacies; Pa-Po = Palmatolepid-Polygnathid biofacies. G = Givetian; t. = *triangularis*.

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

**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*; An- *Ancyrodella* and *Ancyrognathus*; Ic-*Icriodus*.

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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
<i>BZ14C</i>	<i>90</i>	<i>22.5</i>	<i>4</i>	<i>8</i>	<i>1</i>		<i>13</i>
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
<i>BZ8A</i>	<i>140</i>	<i>11.25</i>	<i>8</i>	<i>4</i>		<i>5</i>	<i>17</i>
BZ8	875	8.75	12	20	7	43	82
<i>BZ7A</i>	<i>170</i>	<i>9</i>	<i>4</i>	<i>7</i>	<i>1</i>	<i>3</i>	<i>15</i>
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
<i>BZ5B</i>	<i>150</i>	<i>5.25</i>		<i>4</i>	<i>4</i>		<i>8</i>
BZ5	730	5.75		66		4	70
BZ4B.1	1120	5.25		79	6	40	125
<i>BZ4B</i>	<i>267</i>	<i>5</i>		<i>14</i>		<i>1</i>	<i>15</i>
<i>BZ3C</i>	<i>580</i>	<i>3.25</i>		<i>6</i>		<i>1</i>	<i>7</i>
BZ3	610	3	2	12		12	26
<i>BZ2C</i>	<i>347</i>	<i>2.25</i>		<i>2</i>		<i>3</i>	<i>5</i>
BZ2	1083	1.75	2	13	2	17	34
<i>BZ1C</i>	<i>1037</i>	<i>1</i>		<i>3</i>			<i>3</i>
BZ1A	715	0.5	1	48	1	4	54
<i>BZ1</i>	<i>800</i>	<i>0</i>		<i>27</i>		<i>1</i>	<i>28</i>



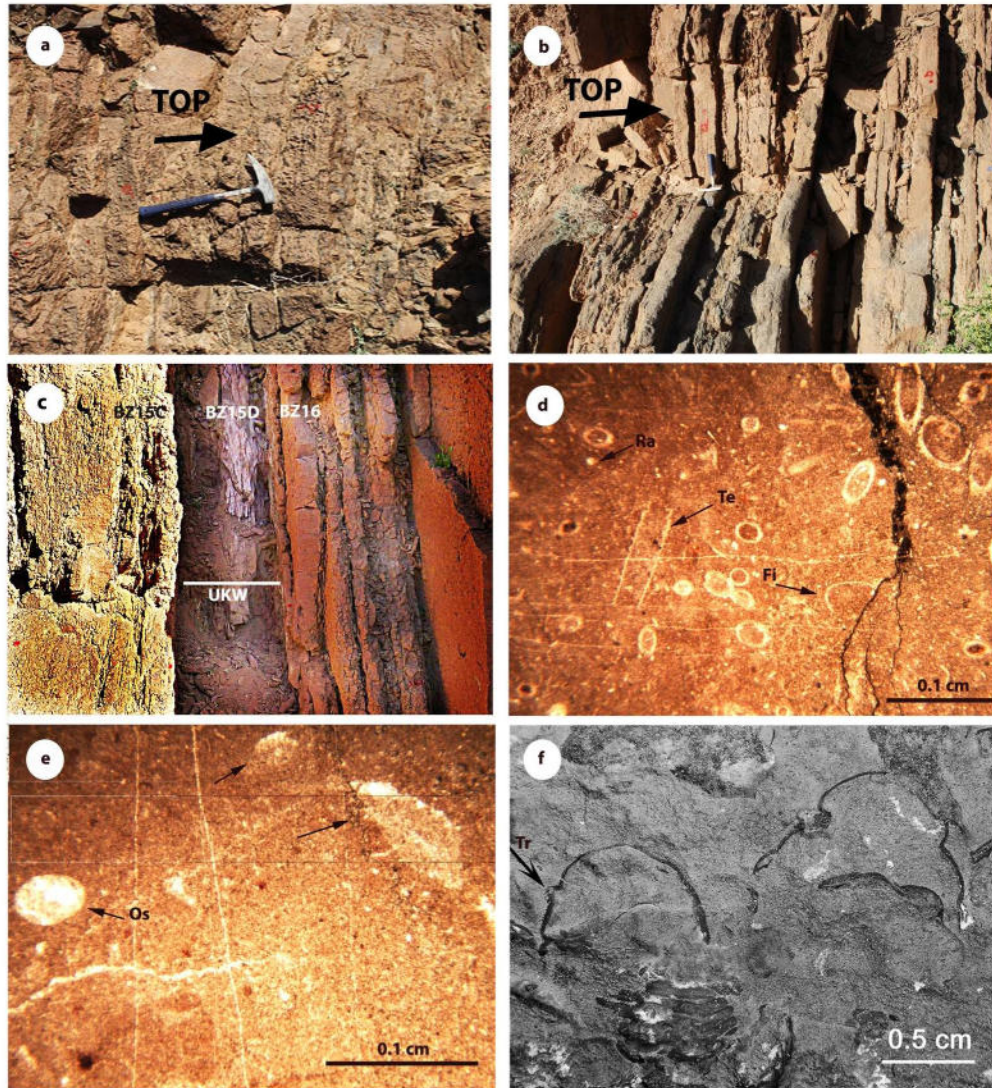
63x87mm (600 x 600 DPI)



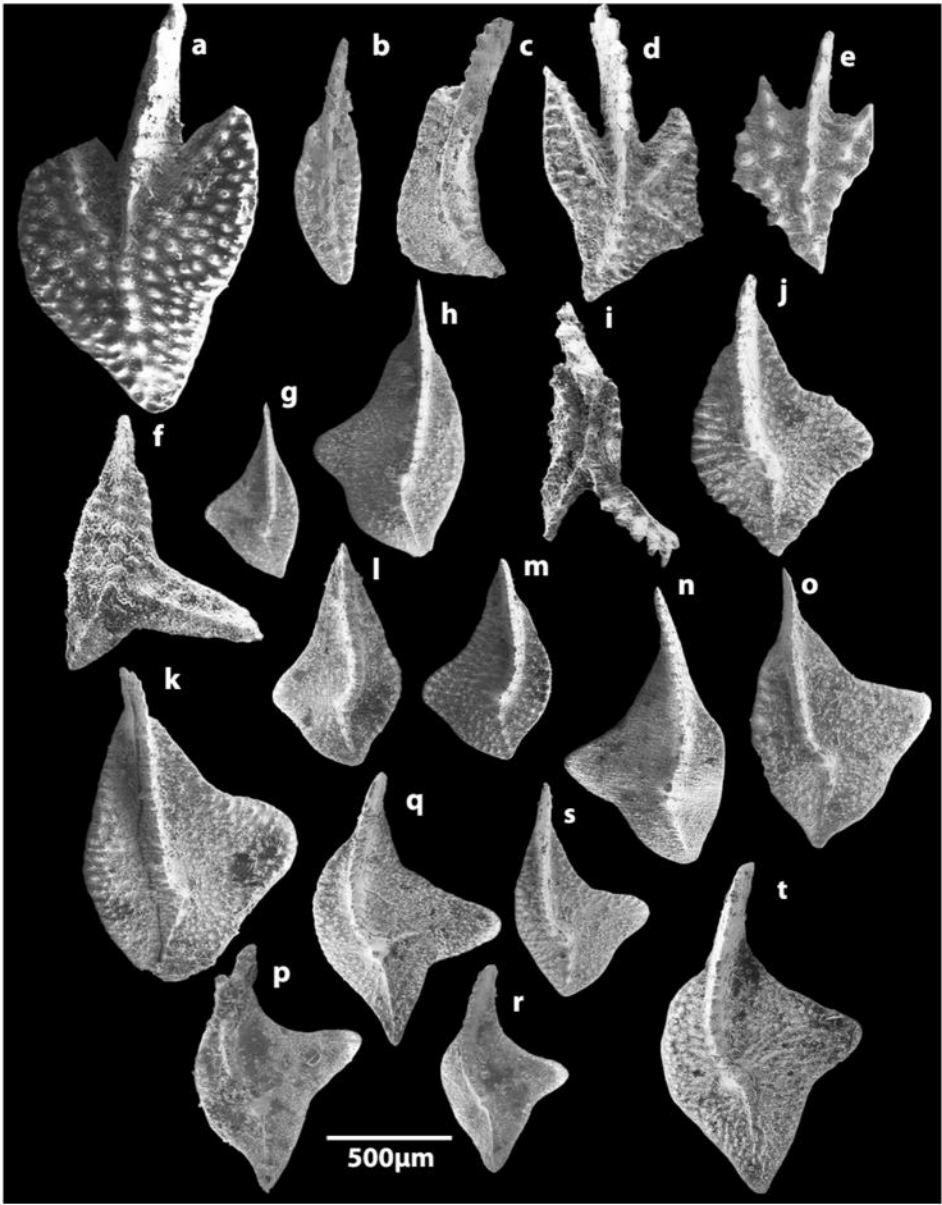


289x80mm (300 x 300 DPI)



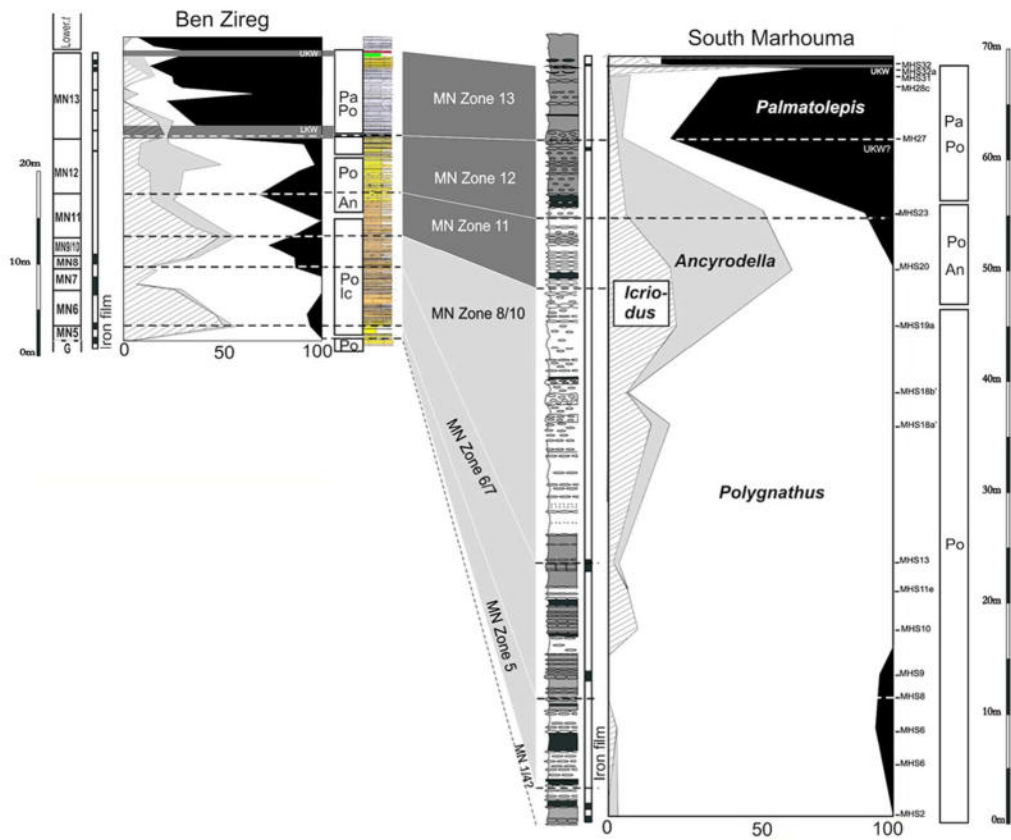


194x212mm (300 x 300 DPI)



140x180mm (170 x 170 DPI)





42x37mm (600 x 600 DPI)

