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Foraminifers and calcareous algae in Brigantian rocks as guides for the recognition of the Viséan-Serpukhovian boundary interval of Morocco

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Foraminifers and calcareous algae in Brigantian rocks as guides for the recognition of the Viséan-Serpukhovian boundary interval of Morocco

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ABSTRACT

Revision of foraminifers, algae and problematic algae of well-known late Viséan formations in the Jerada syncline in the Eastern Meseta, Azrou-Khenifra Basin in the Central Meseta and Oued Cherrat in the Western Meseta, suggests that the recognition of the chronostratigraphic units within this period lacks most of the foraminiferal markers in the Western European foraminiferal biozonations. Many taxa recorded in the Moroccan Meseta are considered as late Asbian guides in Western Europe, but in the Meseta, they are first recorded in the early Brigantian. Although some foraminiferal taxa are proposed as guides for the early Brigantian in Morocco, this substage is far more easily recognized by the algal and problematic algal assemblages. In contrast, the late Brigantian, and thus, the equivalent to the lower part of the Serpukhovian, is recognized by typical foraminifers that have been also recorded in Western Europe. Moreover, the algae do not display any significant change at this level. The unusual and unrepresentative foraminiferal assemblages recorded from the Brigantian in Morocco, suggest that most of the numerous outcrops and sections ascribed to the late Asbian in the literature should be revised because, as is demonstrated in a few cases in this study, those outcrops probably belong to younger Brigantian chronostratigraphic units.

KEY WORDS
Biostratigraphy,
Moroccan Meseta,
endothyrids,
Algospongia,
dasycladales,
Namurian.

RÉSUMÉ

Foraminifères et algues calcaires dans les roches brigantiennes comme guides pour la reconnaissance de l'intervalle de la limite Viséen-Serpukhovien du Maroc.

Une révision des foraminifères, des algues et des algues problématiques dans les formations bien connues du Bassin de Jérada (Méséta orientale), du Bassin d'Azrou-Khenifra (Méséta centrale) et de l'Oued Cherrat (Méséta occidentale), révèle que l'identification des unités chronostratigraphiques durant le Viséen supérieur est rendue difficile par l'absence fréquente des foraminifères-guides dont on dispose dans les biozonations d'Europe occidentale. La plupart des taxons trouvés dans la Méséta marocaine pourraient être considérés comme des guides de l'Asbien supérieur, tels qu'en Europe occidentale, mais dans la Méséta ils ne se rencontrent qu'au cours du Brigantien inférieur. Bien que des foraminifères aient été proposés comme guides du Brigantien inférieur au Maroc, ce sous-étage se caractérise plus aisément par les assemblages d'algues et d'algues problématiques. Au contraire le Brigantien supérieur, et donc la base du Serpukhovien, est facilement reconnaissable grâce à des foraminifères qu'on trouve aussi en Europe occidentale, alors que les algues ne montrent aucun changement significatif durant cette période. Les associations typiques et atypiques de foraminifères qu'on trouve au Brigantien incitent à penser que nombre de coupes et d'affleurements attribués à l'Asbien supérieur, dans la littérature marocaine, sont à reviser, car, comme cela est prouvé en quelques cas par cette étude, de tels affleurements pourraient appartenir à des unités chronostratigraphiques plus récentes du Brigantien.

MOTS CLÉS
Biostratigraphie,
Méséta Marocaine,
endothyridés,
Algospongia,
dasycladales,
Namurien.

INTRODUCTION

The Variscan Orogeny in the Moroccan Meseta, north of the High Atlas Mountains (Fig. 1) has been widely studied, and numerous publications have focused on different aspects, including lithostratigraphical, tectonic and palaeontological research syntheses (e.g. Hoepffner *et al.* 2005, 2006; Michard *et al.* 2008, 2010). The succession from the Tournaisian Stage (Lower Mississippian) is sparsely distributed in the Meseta, such as at Bou Khadra (Habibi 1989), whereas in other inferred Tournaisian successions, the main criteria for this assignment were their lithological similarities or the presence of reworked Famennian-early Tournaisian conodonts in conglomerates recorded in nappes (e.g. Faik 1988; Bouabdelli 1989; Becker *et al.* 2020). Rocks belonging to the early and mid Viséan substages (Middle Mississippian) are also rare (Cózar *et al.* 2020b), whereas the late Viséan is widely distributed. The Namurian (including the Upper Mississippian and Lower Pennsylvanian) successions are also common, although due to their predominant siliciclastic character, there is weak biostratigraphic data to support their precise stratigraphical distribution.

As mentioned above, the upper Viséan rocks are common, and although comprising a predominance of siliciclastic materials, they frequently contain interbedded limestones (in platform facies), as well as calciturbidites and carbonate olistolites. Numerous publications contain biostratigraphic analyses of upper Viséan limestones, based principally on foraminifers in the Moroccan Meseta, including many unpublished Ph.D. projects. In addition, some other sections previously considered as early and mid Viséan, are now recognized to be of late Viséan age (Cózar *et al.* 2020a, b). The transition into the Namurian is more unusually recorded in carbonates, e.g. Akerchi Formation (Termier 1936; Verset 1983; Berkhli & Vachard 2001; Cózar *et al.* 2008b), and, the record of Bashkirian carbonates is even rarer (Bensaid *et al.* 1979; Ghfir 1993; Cózar *et al.* 2011). Hence, the vast majority of the carbonates in the Moroccan Meseta are assigned to the late Viséan, although there are two pending issues in establishing their precise biostratigraphy: 1) to contrast the reliability of some taxa for the subdivision of the late Viséan in Morocco; and 2) owing to the fact that the old zonations in Morocco used a classical Western European lithostratigraphical subdivision with Viséan and Namurian, the recognition of the Viséan-Serpukhovian boundary, as currently defined valid international stages, is challenging.

A mixed foraminiferal/algal biostratigraphical zonation was proposed for the lower Carboniferous of Morocco by Vachard & Tahiri (1991), and subsequently updated (e.g. Vachard & Berkhli 1992; Berkhli & Vachard 2001), with its most recent revision published by Izart *et al.* (2017) (Fig. 2). This zonation, and evolution, contains their own proposed regional markers, and includes the most representative lithostratigraphical formations or sections containing the fossil guides. However, some guide fossils are considered inadequate for the early and mid Viséan due to conflicting biostratigraphy (Cózar *et al.* 2020a, b). In the late Viséan, fossil guides used in the zonal schemes are varied, comprising a mixture of well-known worldwide foraminifers (e.g. *Archaediscus karreri* Brady, 1873, *Pseudoendothyra struvei* (von Möller, 1879) and *Howchinia bradyana* (Howchin, 1888 emend. Davis, 1951), problematic algae (e.g. *Stacheoides tenuis* Petryk & Mamet, 1972 and *Ungdarella uralica* Maslov, 1956), red algae (*Neoprincipia tethysiana* Cózar & Vachard,

2003) and unpublished endemic foraminifers restricted to some regions of Morocco (e.g. *Rectoendothyra jeradaensis* Berkhli, 1993 nom. nud. and *Monotaxinoides chantonae* Berkhli, 1993 nom. nud.) (see Izart *et al.* 2017). The use of such uneven fossil guides for the biozonation can be attributed to the apparent delay, absence, or poverty in the key foraminiferal taxa recorded in European zonations for this interval (e.g. Lipina & Reitlinger 1971; Conil *et al.* 1980, 1991; Jones & Somerville 1996; Kulagina *et al.* 2003).

In Western Europe, in Belgium, the entire late Viséan is included in the Warnantian regional substage (Poty & Hance, 2006), whereas in Britain, it is subdivided into the Asbian and Brigantian regional substages (George *et al.* 1976) (Fig. 2). These latter authors selected the Brigantian boundary stratotype at Janny Wood, Kirkby Stephens, in shallow-water facies, with macrofauna and microfauna representative of the so-called D_2 Zone. In a first attempt of correlation with the deeper-water biozonations based on ammonoids, they correlated the base of the Brigantian with the P_{1a} subzone, characterized by the first occurrence of *Posidonia becheri* Bronn, 1828 and *Goniatites crenistria* Phillips, 1836. Riley (1993), Herbig (1998) and Herbig *et al.* (1999) noted that the base of the Brigantian should be considered as the P_{1b} subzone (Fig. 2), characterized by *Goniatites striatus* (Sowerby, 1814). In recent studies in Britain, it is currently assumed that the base of the Brigantian is located at the base of the P_{1b} subzone, which coincides with the original D_2 Zone defined for shallow-water facies (Waters *et al.* 2011).

In addition, recent studies have demonstrated that the Viséan-Serpukhovian boundary does not coincide with the traditional Viséan-Namurian boundary (Cózar & Somerville 2014, 2016, 2021a). The most recent analysis of foraminiferal assemblages suggests that the Viséan-Serpukhovian boundary is located at the early/late Brigantian boundary, approximately at the base of the P_{2a} ammonoid zone (Cózar *et al.* 2019; Nikolaeva *et al.* 2020; Cózar & Somerville 2021a), assuming the base of the Serpukhovian as it is currently defined, at the base of the Tarusian Russian Substage (Fig. 2). Depending on the characteristics of each basin, fossil assemblages present particularities, and currently, the base of the Serpukhovian is being investigated for the definition of a GSSP section and point (see Aretz *et al.* 2020). A candidate boundary selected as possible base of the Serpukhovian is located in an intermediate position of the Venevian Russian Substage (Fig. 2). However, it cannot be definitively recognized without the occurrence of the conodont *Lochriea ziegleri* Nemirovskaya, Perret & Meischner, 1994. This taxon could be used potentially in the future for the definition of the GSSP for the base of the Serpukhovian, although currently, this has not been formally ratified, and thus, the First Appearance of *L. ziegleri* (FALz), may or may not form the future marker for the base of this stage. One of the main problems is possible diachronism in the first occurrence of this species, which needs to be solved still (Herbig 2017). This conodont occurs in Britain in levels of the P_{1d} subzone in a minor cycle composed of the Single Post/Cockleshell limestone, which most authors attributed to the Tynebottom cycle (Sevastopulo & Barham 2014; Herbig 2017; Cózar *et al.* 2019; Aretz *et al.* 2020; Nikolaeva *et al.* 2020; Cózar & Somerville 2021a, b; and references therein), and thus, assigned the upper part of the early Brigantian. However, this minor cycle is not present in many regions of Britain, and thus, the typical foraminiferal taxa occurring in those horizons are only recorded from limestones assigned to the P_{2a} subzone, which complicates notably the recognition of those levels. Readily, without the occurrence of *L. ziegleri*, this level can be only inferred by other accompanying taxa, such as some auxiliary foraminifers are more frequently recognized in limestones spanning this boundary interval (Cózar *et al.* 2019; Cózar & Somerville 2020a, 2021a, b). Owing to this uncertainty, this interval correlated with levels supposedly yielding *L. ziegleri* are recognized here as the early-late Brigantian transitional bed (ELBT).

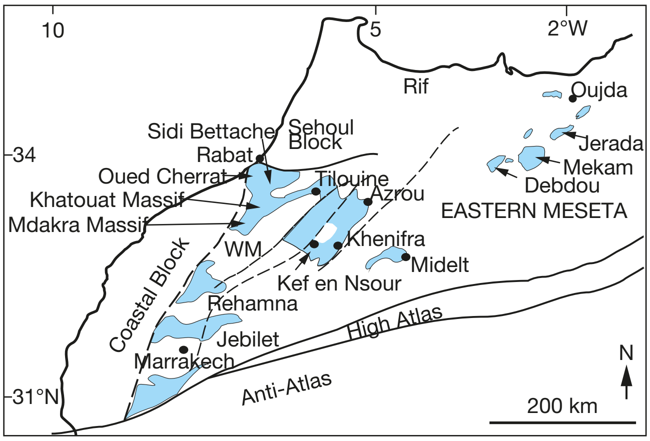
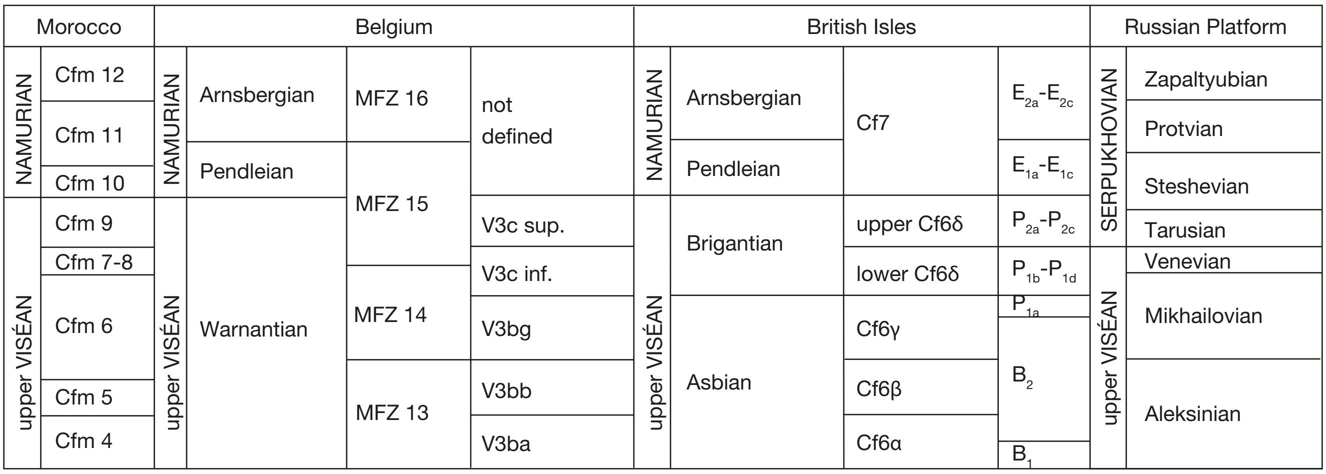


Fig. 1. — Location of the main Carboniferous basins in the Moroccan Meseta. Abbreviation: **WM**, Western Meseta.

In this study, the biostratigraphy of some sections spanning the late Viséan and younger strata in the Moroccan Meseta has been revised in order to: 1) establish their precise regional biostratigraphy; 2) subdivide the Viséan and the Serpukhovian (the latter as it is currently valid as the equivalent to the base of the Tarusian Substage); and 3) contrast the reliability of the foraminiferal and algal taxa as guides for the subdivision of the late Viséan in the Meseta and to propose new guide taxa. For most of the regional descriptions, original subzones, and stratigraphical subdivisions published by previous authors, some of the biozones are currently disused (e.g. V3bγ and V3c), are correlated with the more recent terminology (Fig. 2). It is not the aim of this study to assess the taxonomic aspects of the foraminifers, and thus, when a taxon can be found in the literature with different names, criteria for distinguishing them are not discussed herein, and both names are included. For completeness, the Moroccan successions of the Meseta are also compared with the foraminiferal assemblages recorded in the Tindouf Basin (Sahara). Biostratigraphically important foraminifers and algae are included in Figures 3 to 9 (a full list of taxa for each section is included in Appendix 1), and summarized in Figure 10. Some selected foraminifers and calcareous algae/problematical algae are illustrated in Figure 11 to 13.



Morocco		Belgium				British Isles				Russian Platform	
NAMURIAN	Cfm 12	NAMURIAN	Arnsbergian	MFZ 16	not defined	NAMURIAN	Arnsbergian	Cf7	E_{2a}-E_{2c}	SERPUKHOVIAN	Zapaltyubian
	Cfm 11										Protvian
			Pendleian	MFZ 15			Pendleian		E_{1a}-E_{1c}		
											Steshevian
	Cfm 10										
upper VISÉAN	Cfm 9	upper VISÉAN	Warnantian		V3c sup.	upper VISÉAN	Brigantian	upper Cf6δ	P_{2a}-P_{2c}		
											Tarusian
	Cfm 7-8				V3c inf.			lower Cf6δ	P_{1b}-P_{1d}	upper VISÉAN	Venevian
				MFZ 14							
	Cfm 6										Mikhailovian
					V3bg		Asbian	Cf6γ	P_{1a}		
									B_2		
				MFZ 13	V3bb			Cf6β			Aleksinian
	Cfm 5										
	Cfm 4				V3ba			Cf6α			
									B_1		

FIG. 2. — Chronostratigraphical and biostratigraphical correlation of the main biozonations in Morocco (Cfm foraminiferal zones based on Izart *et al.* 2017), Belgium (MFZ foraminiferal zones based on Poty *et al.* 2006; V3 zone based on Conil & Lys 1964), British Isles (Cf foraminiferal zones based on Conil *et al.* 1980 in the middle column, and the ammonoid biozones in the right hand column) and Russian stages and substage.

ABBREVIATIONS

ELBT	early-late Brigantian transitional bed;
FALz	First Appearance of *Lochriea ziegleri*.

STUDIED SECTIONS

In the Eastern Meseta, two sections have been selected in the Jerada region, which is in fact, an exposed syncline forming part of a larger basin, including other exposures such as Debdou and Mekam (Fig. 1). The first section is located in the southern flank of the syncline, and corresponds to the Koudiat Es-Senn Formation between the KS1 and KS2 sections of Aretz & Herbig (2008) (34°17'58.6"N, 2°3'17.8"W). The section was selected to avoid the massive microbial-sponge buildups in the formation, which are considered to contain too unfavorable facies for the foraminifers and algae. The second section, in the northern flank of the Jerada syncline, utilises data documented by Vachard & Berkhli (1992) and Berkhli (1993) and used herein.

In the Central Meseta, in the northern part of the Azrou-Khenifra Basin, ten sections of the Tizra Formation have been selected: Tizra 2 (33°33'23.67"N, 5°24'24.28"W), Tizra 3-1 (33°33'16.7"N, 5°24'45.87"W), Tizra 3-2 (33°33'19.41"N, 5°24'43.91"W), Tizra 3-3 (33°33'22.45"N, 5°24'42.68"W), Tizra 4 (33°33'27.63"N, 5°24'29.61"W), Tizra 4-2 (33°33'24.94"N, 5°24'28.62"W), Tizra 5 (33°33'30.10"N, 5°24'10.58"W), Tizra 9 (33°33'25.11"N, 5°24'22.63"W), Tizra 10 (33°33'18.99"N, 5°24'23.94"W) and Tizra 11 (33°33'18.85"N, 5°24'21.03"W). Most of these sections are new, except for Tizra 2, 4 and 5, that were described in Cózar *et al.* (2008b). The Tizra Formation has been selected due to the abundance of carbonates, although because of the predominant microbial buildup facies, many samples are poor in microbiota, and to get more complete microfossils assemblages, many sections have been sampled.

In the southern part of the Azrou-Khenifra Basin, three sections have been selected: Tiouinine 2 at Guergour (32°53'49.02"N, 5°38'51.43"W) (already described in Rodríguez *et al.* 2012), Tabainout at Sidi Amar (32°57'3.14"N, 5°50'33.93"W) (described in Somerville *et al.* 2012) and Kef en Nsour (32°54'23.44"N, 5°58'4.80"W) (same as the Sidi Lamine section in Said *et al.* 2013). The first two sections were measured in the so-called Hsv1 Formation, whereas the third section belongs to the Bou Rifi Formation.

In the western part of the Meseta, in the Oued Cherrat region, two sections were selected: Souk el Had section (33°48'10.29"N, 7°3'21.7"W) in the Machraa Kraret Formation and another section in one of the first quarries in the Alkhoudia band (33°45'6.70"N, 7°2'525.24"W) in the Kef and Nzaha Formation. The first section was studied also by Neqqazi *et al.* (2014), and they also analysed a section in the Alkhoudia band, nearly 2 km to the south of the studied section.

In Tindouf Basin, a representative of the Saharan basins that formed south of the Anti-Atlas Mountains (Fig. 1) on the stable Gondwana platform, the transition between the Betaina and Ouarkziz formations contains the selected stratigraphic interval for this study. The section 2 (28°24'20"N, 9°24'04"W) of Cózar *et al.* (2014a, b) contains the best exposure of those beds.

JERADA SYNCLINE

The succession in the northern flank of Jerada contains a preponderance of volcanic rocks (dacites, tuffs, ignimbrites, volcanic shales) in the lower part of the section, which in part, seem to have been responsible for the low diversity and low abundance of the foraminiferal and algal assemblages. Detailed foraminiferal and algal studies in the region are those of Vachard & Berkhli (1992), Berkhli (1993) and Berkhli *et al.* (1999). The biostratigraphy of the succession was rather precisely established using ammonoids since the early studies (Horon 1952; Owodenko 1976). These authors described outcrops at the base of the succession yielding *Beyrichoceras* Foord, 1913 and *Dimorphoceras* Hyatt, 1884, which should represent the lower part of the Asbian, although

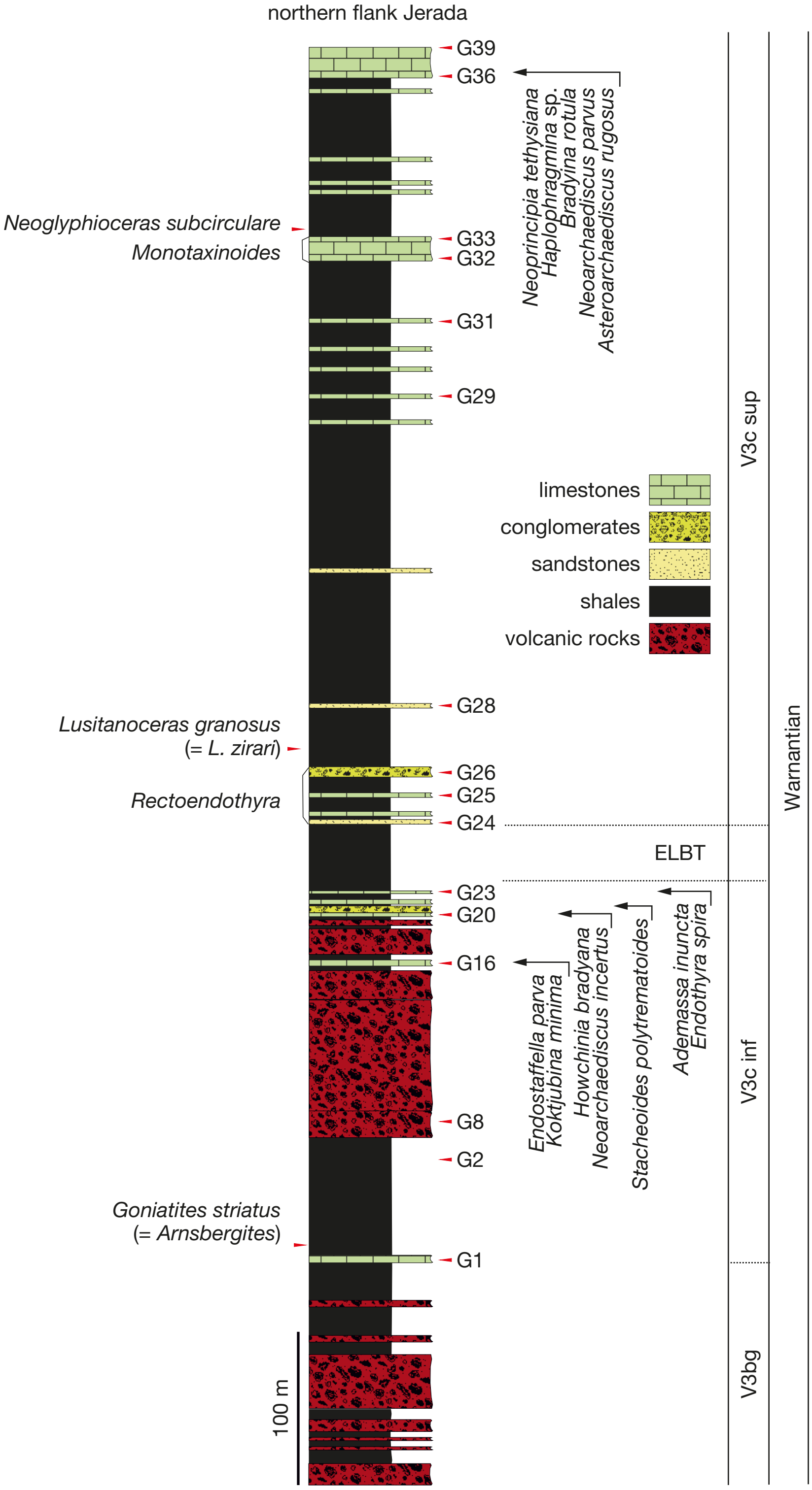


FIG. 3. — Selected first occurrences of the main taxa in the northern flank of the Jerada Syncline. Sample numbers correspond to those in Vachard & Berkhli (1992). Abbreviations: **ELBT**, early-late Brigantian transitional beds; **inf**, inférieur (lower); **sup**, supérieur (upper). Biostratigraphical units in the right hand column as described by Vachard & Berkhli (1992).

Korn & Ebbighausen (2008) revised those identifications, and assigned them as representatives of the *Goniatites crenistria* Zone (P_{1a} subzone), in the latest Asbian (Fig. 2). Higher up in the succession is recorded *Goniatites striatus* (marker for the P_{1b} subzone), although the specimens were reidentified as several species of *Arnsbergites* by Korn & Ebbighausen (2008), which is a genus typically represented in the P_{1b}-P_{1c} subzones (Fig. 3). More than 300 m above, *Lusitanoceras granosus* (Portlock, 1843) was recorded, reidentified as *Lusitanoceras zirari* Korn & Ebbighausen, 2008, which was assigned to the late

Brigantian. Further to the northeast, in the Chebket el Hamra region, Korn & Ebbighausen (2008) recognized also the P_{1c} and P_{1d} subzones, although there, the succession does not contain limestones. Taking into consideration that the FALz lies approximately in the upper part of the P_{1d}, a subzone that is not recognized in the northern flank of the Jerada syncline with limestones, the ELBT might be located approximately between samples G23 and G24 of Vachard & Berkhli (1992) (Fig. 3). Furthermore, the base of the Serpukhovian could be situated in sample G26 above, where ammonoids representative of the P_2 zone were recorded.

Foraminiferal/algal assemblages of levels G16 to G23 are composed of long-ranging taxa in the Viséan, where the "most evolved" taxa are *Praeplectostaffella* cf. *asymmetrica* (Rozovskaya, 1963) (as *Endostaffella*) and *Endostaffella parva* (von Möller, 1879) both first occurring in the mid Viséan according to Rozovskaya 1963, and more commonly during the late Asbian and Brigantian (see *Praeplectostaffella* in Cózar *et al.* 2008a), *Endothyra spira* (a late Viséan taxon; Conil *et al.* 1991; Pille 2008), *Howchinia bradyana* and *Ademassa inuncta* Vachard *in* Vachard, Massa & Strank, 1993 (which are first recorded in the upper part of the late Asbian; Conil *et al.* 1991; Jones & Somerville 1996; Pille 2008). The youngest taxon in this interval recorded by Vachard & Berkhli (1992) is *Neoarchaediscus incertus* (Grozdilova & Lebedeva, 1954), that according to some authors (Conil *et al.* 1991; Poty *et al.* 2006) first occurs near the base of the late Viséan. Thus, taking into consideration the well-known foraminiferal zonations, rocks of this interval should be assigned to the late Asbian. However, from our point of view, true *Neoarchaediscus incertus* are only recorded in the latest Asbian to early Brigantian rocks, and mostly in the late Brigantian of Western Europe and Northern Africa (e.g. Somerville & Cózar 2005; Cózar *et al.* 2006b, 2010, 2014a, 2016b; Vachard *et al.* 2016a).

Most of the interval assigned to the V3c sup. by previous authors has no diagnostic foraminifers in the Jerada Syncline, except for *Rectoendothyra jeradaensis* and *Monotaxinoides chantonae*, two taxa never formally described nor illustrated and hence represent nomina nuda, and were not precisely located (see Berkhli 1993; Berkhli *et al.* 1999). Those genera are usually recorded in Serpukhovian rocks (e.g. Cózar *et al.* 2016a), although other species of *Rectoendothyra* have been recorded from the late Viséan (Vachard *et al.* 2016a), as well as being recorded in this study in the Azrou-Khenifra Basin (see Appendix 1).

Most foraminifers in the northern flank of Jerada seem to occur outside of their usual biozone, and only rare *Neoarchaediscus incertus* as a marker could establish the early Brigantian age for the succession, as recognized by ammonoids, and the two "undescribed" taxa that might justify the transition into the Serpukhovian, whereas the main part of the assemblages are only representative of the late Asbian. This apparent mismatch of the foraminiferal record is attributed to a confused lithostratigraphy for the northern limb of Jerada. The succession in the southern and northern limbs of Jerada was later defined as composed of the Oued Defla, Çafçaf, Oued El Koriche, Oued Es-Sassi and Koudiat Es-Senn formations, some of them with a higher development of microbial mounds in the southern limb, and clearly with differences in thicknesses (Herbig *et al.* 2006; Aretz & Herbig 2008; Herbig & Aretz 2013). The age of the Oued Defla Formation is not well constrained and it could pre-date the Eovariscan stages (Aretz & Herbig 2008), whereas the radiolarian-bearing cherty beds of the Çafçaf Formation were compared with similar cherty facies in Western Europe spanning the interval of the late Tournaisian-late Viséan. Aretz (2010) recorded the rugose coral *Siphonodendron irregulare* (Phillips, 1836), which ranges from the middle to late Viséan, and this author interpreted it as most probably a middle Viséan age for the Çafçaf Formation, possibly also ranging into the lower part of the late Asbian. The other formations were assigned to the late Viséan in the southern limb (Asbian to mostly early Brigantian) due to the occurrence of the ammonoid P_{1a} subzone in the Oued Es-Sassi Formation (Korn in Aretz & Herbig 2008), whereas Aretz (2010) considered the Oued El Koriche and Oued Es-Sassi formations as probably late Asbian, and the Koudiat-Es-Senn Formation as late Asbian and/or early Brigantian. These authors also recorded the rugose corals *Tizraia berkhlii* Said & Rodríguez, 2007, *Siphonodendron junceum* (Fleming, 1828) and *Dibunophyllum bipartitum* (McCoy, 1849) in the Koudiat Es-Senn Formation, which was compared to the other Brigantian assemblages in Morocco. In addition, at the top of the formation, *Pareynia splendens* Semenoff-Tian-Chansky, 1974 was recorded. However, the reliability of *Pareynia* and *Tizraia* as potentially Brigantian markers was questioned by Aretz (2010) due to the rarity of records, and suggested that there could have been a strong facies-control on their distributions. This lithostratigraphical framework for Jerada allowed Herbig *et al.* (2006) and Herbig & Aretz (2013) to recognise repeated successions in tectonic slides for the northern limb. The clear repetition in the section studied for instance by Berkhli (1993) is located at the base of the section, where two intervals of the predominantly volcanic and volcanosedimentary rocks are observed (Fig. 3). This tectonic problem clarifies the anomalous foraminiferal records observed in the section, and thus, the succession should be revisited, avoiding repetitions.

The intermound facies between KS1 and KS2 buildups of Aretz & Herbig (2008) have been sampled within the Koudiat Es-Senn Formation (Fig. 4). From the base and lower part of the formation, there are recorded *Neoarchaediscus incertus* and *N. parvus* (*Asteroarchaediscus* auct.) (Rauzer-Chernousova, 1948a) and *Asteroarchaediscus termierorum* Vachard *in* Termier, Termier & Vachard, 1975 which suggest at least, the upper part of the early Brigantian age. About 20 m higher in the section, where shales become more abundant, *Neoarchaediscus postrugosus* (*Asteroarchaediscus* auct.) (Reitlinger, 1949), as well as *Neoarchaediscus gregorii* (*Asteroarchaediscus* auct.) replace by (Dain *in* Dain & Grozdilova, 1953) are first recorded, together with *Asteroarchaediscus rugosus* (Rauzer-Chernousova, 1948b) and *A. bashkiricus* (*baschkiricus* auct.) (Krestovnikov & Theodorovich, 1936). *Neoarchaediscus postrugosus* is only recorded at the base of the late Brigantian (Cózar & Somerville 2016, 2020a, 2021a),

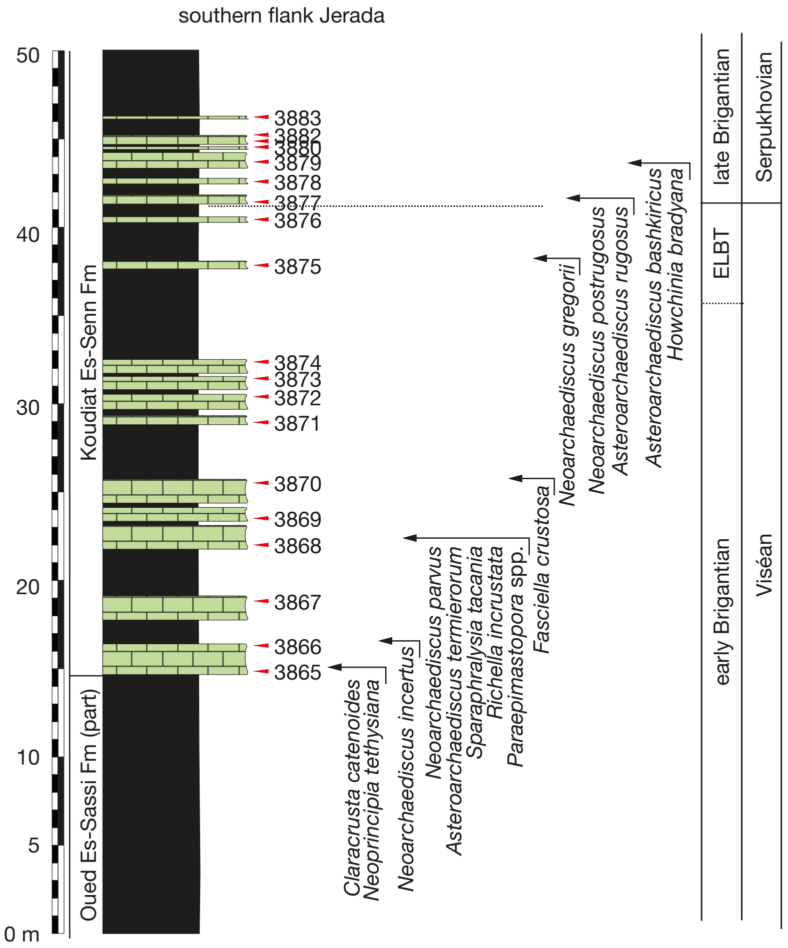


FIG. 4. — Selected first occurrences of the main taxa in the southern flank of the Jerada Syncline. Lithological key see Figure 3.

in levels corresponding to the base of the Serpukhovian in Russia (Gibshman 2003; Gibshman *et al.* 2009).

It is noteworthy, that from the base of this succession, algae and problematic algae are common, whereas in the northern limb they were only recorded in the uppermost levels. Some of these algae (Fig. 4) are commonly associated with Brigantian horizons elsewhere (Cózar & Somerville 2005a, b; Vachard *et al.* 2016b; Cózar *et al.* 2006a). On the other hand, *Claracrusta catenoides* (Homann, 1972), *Sparaphralysia tacania* Vachard in Vachard & Beckary, 1991 and species of *Neoprincipia* are also recorded from the base of the section, also suggesting a Brigantian age (Cózar & Somerville 2005b; Vachard *et al.* 2016b). According to the foraminiferal taxa recorded in the P_{1d} subzone of Britain and Ireland by Cózar & Somerville (2021a, b), levels which might coincide with the ELBT should occur approximately at level Pc3875 (Fig. 4), where *Neoarchaediscus gregorii* is first recorded.

In summary, the early Brigantian in the Jerada Syncline mostly contains late Asbian foraminiferal assemblages, and is more easily recognized by ammonoids (in the northern flank) and calcareous algae (in the southern flank). Only the occurrence of rare *Neoarchaediscus incertus* and *N. parvus* are considered as markers for the early Brigantian in this region with *N. gregorii* in the upper part of the early Brigantian. The presence of *Neoarchaediscus postrugosus, Asteroarchaediscus rugosus* and *A. bashkiricus* indicate younger levels in the late Brigantian (Serpukhovian) (Fig. 4).

SOUTHERN AZROU-KHENIFRA BASIN

The late Viséan is well-known in numerous carbonate sections in the southern part of this basin (e.g. El Houicha 1994; Huvelin & Mamet 1997), some of them being located in the autochthonous succession (Hvs1-Hvs2 formations of Chanton-Güvenç *et al.* 1971), as well as in the allochthonous units, tectonic nappes and gliding nappes (e.g. Verset 1983; Bouabdelli 1989). The three studied sections are from autochthonous units, and they rest unconformably over Ordovician shales in Kef en Nsour and Tabainout (approx. 12 km NE of Kef en Nsour; Fig. 1), and occur in the tectonic window at Guergour (Tiouinine 2 section; 5 km south of Khenifra, Fig. 1).

The succession is characterized by a basal conglomerate-sandstone unit (of variable thickness depending on the outcrop, 0 m to 200 m thick), overlain by massive microbial buildups in Tabainout and Tiounine, whereas in Kef en Nsour accumulated thick-bedded oolitic/bioclastic grainstone deposits (rarely packstone) (Fig. 5).

In Tabainout, the basal bioclastic limestone beds (Fig. 5) are very rich in foraminifers, but also in rugose corals (Chanton-Güvenç & Morin 1973; Aretz & Herbig 2010; Somerville *et al.* 2012; Said *et al.* 2013). Foraminiferal assemblages are rich (Appendix 1), and contain typical late Asbian taxa, including: *Endothyranopsis crassa* (Brady, 1876), *Vissariotaxis compressa* (Brazhnikova, 1956), *Archaediscus karreri* group, *Cepekia* spp., *Ademassa inuncta*, *Euxinita efremovi* (Vdovenko & Rostovceva *in* Brazhnikova, Vakarachuk, Vdovenko, Vinnichenko, Karpova, Kolomiets, Potievskaya, Tostovtseva & Shevchencko, 1967) and *Cribrostomum lecomptei* Conil & Lys, 1964. It is also noteworthy for the occurrence of the alga *Borladella alternans* Cózar, Somerville, Rodríguez & Medina-Varea, 2007, from these basal beds (Appendix 1), a taxon described from limestones assigned to an imprecise late Asbian-Brigantian interval (Cózar *et al.* 2007), and from the top of the Viséan and mostly Serpukhovian (Cózar *et al.* 2018).

Within the microbial facies, it is noteworthy for the occurrence of *Howchinia bradyana* and *Haplophragmina beschevensis* (Brazhnikova *in* Brazhnikova, Vakarachuk, Vdovenko, Vinnichenko, Karpova, Kolomiets, Potievskaya, Tostovtseva & Shevchencko, 1967), as well as the problematic algae *Claracrusta* and *Sparaphralysia*. Compared to other sections studied herein, these microbial facies are now assigned to the early Brigantian (Fig. 5).

The capping beds of the buildups are rather bioclastic rich, and contain *Asteroarchaediscus*, *Biseriella parva* (Chernysheva, 1948) and *Planospirodiscus taimyricus* Sosipatrova, 1962. This assemblage is commonly assigned to the late Brigantian (Cózar & Somerville 2004, 2021b). In the same capping beds, Somerville *et al.* (2012) recorded coral assemblages assigned to the Brigantian.

About 20 metres above the capping beds, thin coarse-grained bioclastic/intraclastic beds (possible calciturbidites) contain *Asteroarchaediscus bashkiricus* (*baschkiricus* auct.) (Krestovnikov & Theodorovich, 1936) and *Endothyranopsis plana* Brazhnikova *in* Brazhnikova, Vakarachuk, Vdovenko, Vinnichenko, Karpova, Kolomiets, Potievskaya, Tostovtseva & Shevchencko, 1967. The latter taxon is recorded in the upper part of the late Brigantian (Vachard & Berkhli 1992). Moreover, in the overlying shales, the ammonoid *Cravenoceras* (identified by S. Nikolaeva) has been recorded by us, which marks the transition into the Namurian. In addition, there are other goniatites recorded in the upper part of the microbial mound complex, but they were only representative of the P_{1b}-P_{1c} subzones (Korn in Somerville *et al.* 2012), which seems to be slightly older than the biostratigraphic age obtained by means of the foraminifers and corals. These ammonoids are clearly in flank facies of the mounds, strongly intraclastic, which suggests a certain reworking, although in situ beds with massive occurrence of ammonoids are not recorded in the core facies. Thus, it could not be clarified if these ammonoids could be also affected by reworking.

Thus, the Tabainout section shows a continuous record of the Brigantian to the basal Namurian, although owing to the poverty of the assemblages, it cannot be clearly subdivided. The most problematic issue concerns the dating of the bioclastic beds at the base of the succession. According to the foraminifers, algae and rugose corals, the assemblages are mostly late Asbian, but they contain, in addition, *Ademassa inuncta* and *Euxinita efremovi*, which although first occurring in the late Asbian (Pille 2008), are more frequently recorded in the Brigantian (Vachard *et al.* 2016a). Thus, these bioclastic beds are likely to be latest Asbian to earliest Brigantian in age.

The Tiouinine 2 section contains a thicker interval of conglomerates-sandstones as the basal unit and a poorly developed microbial-coral reef buildups, whereas Tiouinine 1 only exposes some scarce metres of sandstones and much thicker microbial-coral reef buildups, and Tiouinine 3 contains the flank facies, with breccias and bioclastic/intraclastic packstones (Rodríguez *et al.* 2012). The entire structure constitutes a fringing reef. From the lowest beds of limestone, interbedded with the sandstones in Tiouinine 2 section, foraminiferal assemblages are typically of late Asbian age. However, the alga *Paraepimastopora* is recorded (Fig. 5), which is only known from the Brigantian (Cózar & Somerville 2005a, b; Vachard *et al.* 2016b). In the Tiouinine section 2 (Appendix 1), *Borladella alternans* is first recorded. Similar to Tabainout, no biostratigraphic evidence for the lower part of the succession has been obtained. However, from the base of the reef complex, questionable specimens of *Biseriella* and *Climacammina* occur. Both taxa would suggest the late Brigantian. Furthermore, rugose corals form one of the richest assemblages in Morocco, and include *Tizraia* and *Pareynia*, which in other outcrops in this basin have been only recorded in beds assigned to the late Brigantian, including those of Jerada, and thus confirming, indirectly, the inferred age attributed by foraminifers.

The succession in Kef en Nsour section is the poorest in foraminifers in this region (Appendix 1), and only *Euxinita efremovi*, as mentioned above, suggests that the section might be early Brigantian, with a basal part with conglomerates and breccias which could not be dated. In the upper part of the section is recorded a coral assemblage, mostly representative of the late Asbian (Aretz & Herbig 2010; Said *et al.* 2013), but the occurrence of *Koninckophyllum magnificum* Thomson & Nicholson, 1876 might suggest a Brigantian age, where it is more frequently recorded. Thus, foraminifers and corals contain typical late Asbian assemblages, although the occurrence of rare taxa might suggest that the succession certainly corresponds to the Brigantian. The overlying shales of the Sidi Lamine Formation contain *Goniatites striatus* representative of the P_{1b} subzone (Termier 1936), whereas in the younger Tiberkit Formation, Termier (1936) recorded *Lusitanoceras granosus* (P_{2a} subzone) and *Neoglyphioceras subcirculare* (P_{2b} subzone). This suggests that, in this part of the basin, the carbonates are only present during part of the early Brigantian, whereas the upper part of the early Brigantian and the late Brigantian only occur in the overlying shaley formations, and thus, the transition into the Serpukhovian.

In summary, the transition into the Brigantian in the southern Azrou-Khenifra Basin is only recognized by calcareous algae, rugose corals, and questionably by some rare

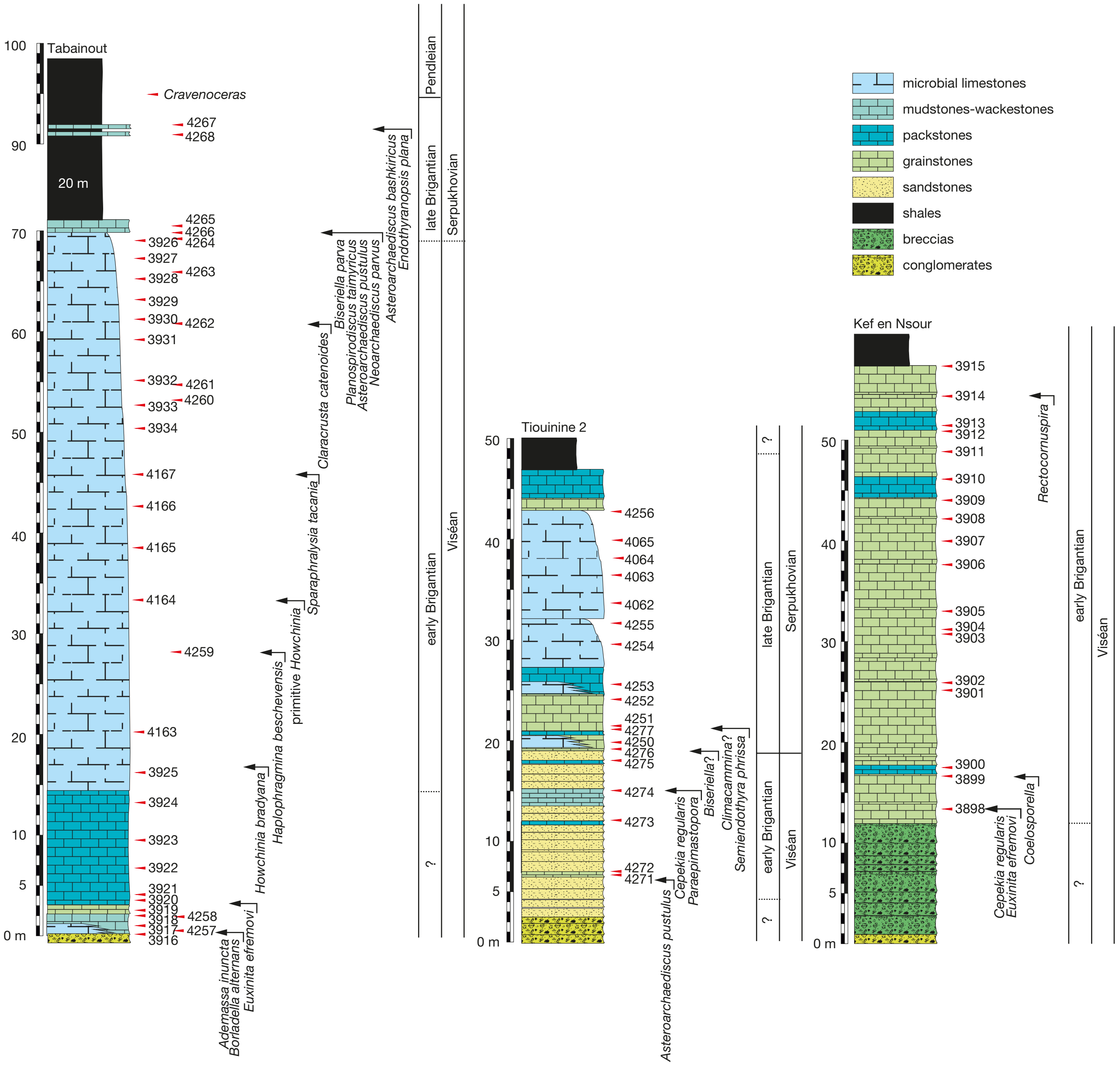


Fig. 5. — Selected first occurrences of the main taxa in the southern Azrou-Khenifra Basin.

foraminifers that are usually more frequent in the Brigantian than in the Asbian. Owing to the poverty in the foraminiferal assemblages, which seem to be facies controlled, the Serpukhovian boundary coincides with major lithological changes, a fact that questions if it should be located in older levels. This paucity in the foraminiferal assemblages also prevents the possible identification of the ELBT.

Northern Azrou-Khenifra Basin

In the northern part of the Azrou-Khenifra Basin the Tizra Formation (*c.* 21 km WNW of Azrou; Fig. 1) comprises abundant carbonates, which in the upper part form the conspicuous continuous ridge. However, the formation as defined by Berkhli & Vachard (2001) and Berkhli *et al.* (2001) also contains hundreds of metres of shales in the lower part, but also with localized and discontinuous development of microbial buildups and oolitic limestones (Fig. 6). At the base of the composite carbonate-rich interval (Tizra 3-1 section), a siliciclastic interval occurs, with sandstones and sandy limestones. This interval contains *Endothyranopsis crassa* and common *Archaediscus* at *angulatus* stage (cf. Pirlet & Conil 1977; Conil *et al.* 1980), which suggest a likely late Viséan age (Conil *et al.* 1980; Cózar *et al.* 2008b).

In the early development of the buildups (Tizra 3 sections; Fig. 6), *Ademassa inuncta* and *Haplophragmina beschevensis* occur, but more evolved foraminifers do not occur.

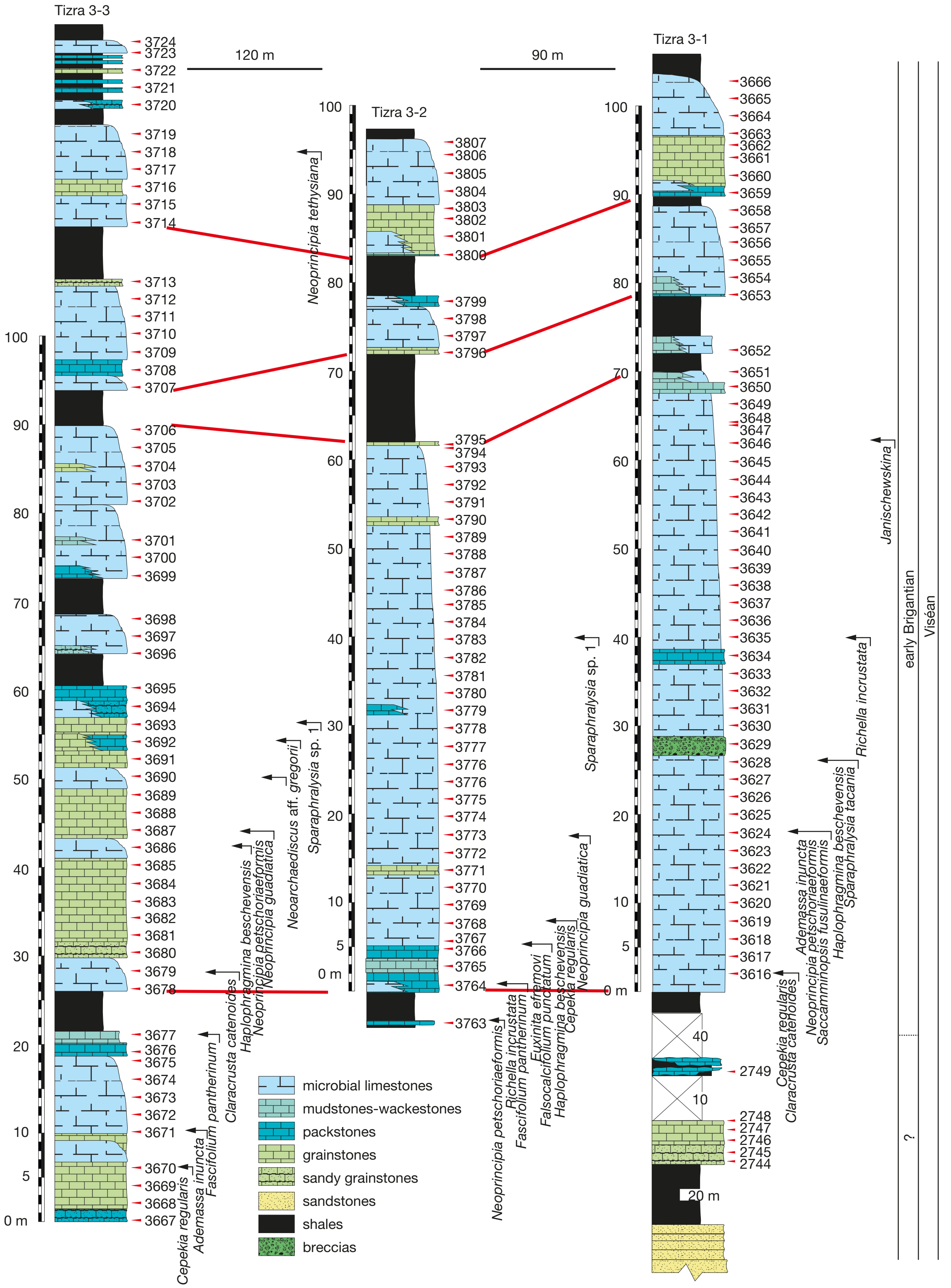


FIG. 6. — Selected first occurrences of the main taxa in the lower part of the Tizra Formation of the northern Azrou-Khenifra Basin.

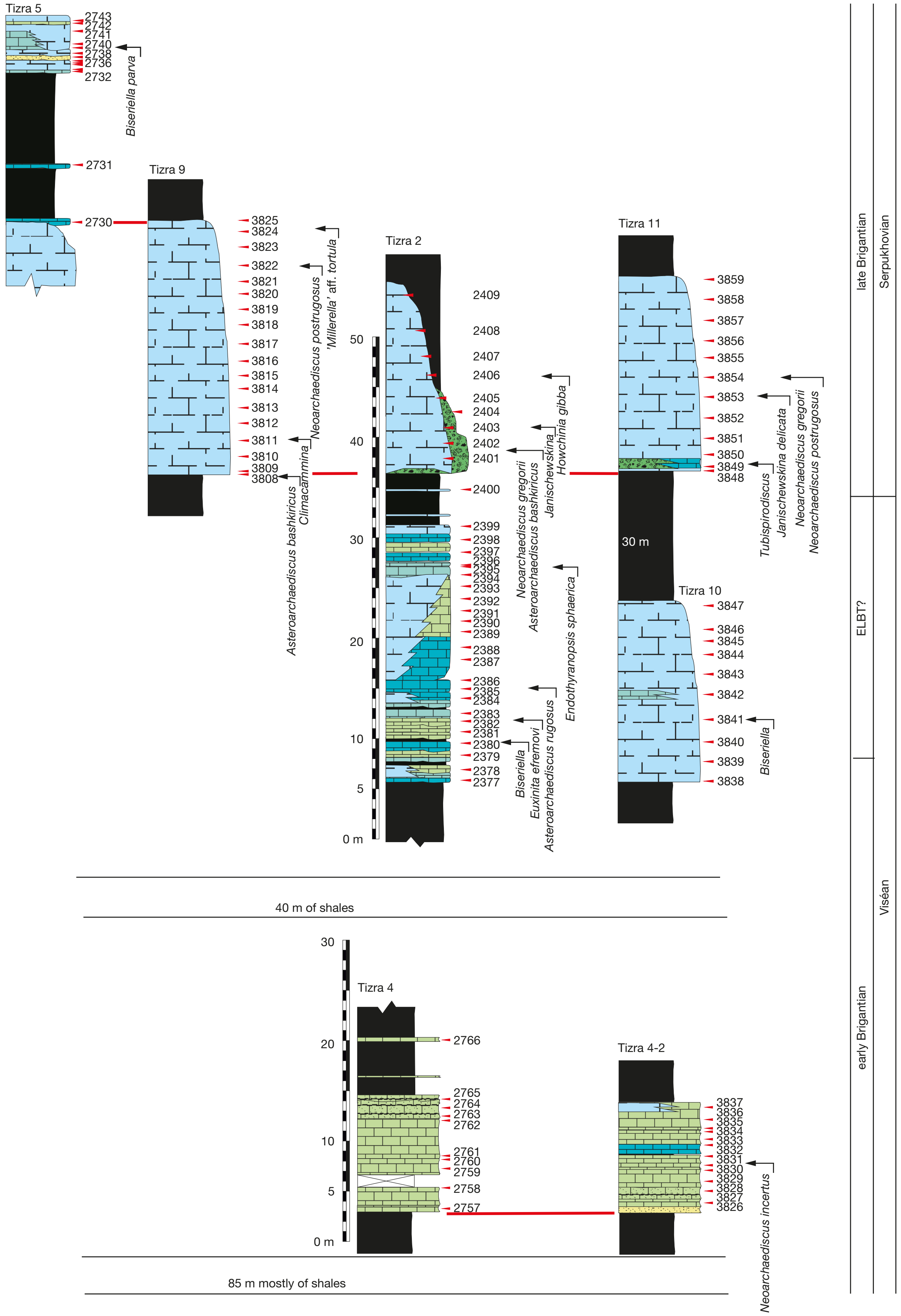


Fig. 7. — Selected first occurrences of the main taxa in the upper part of the Tizra Formation of the northern Azrou-Khenifra Basin. Lithological key explained in Figure 6.

Hence, the assemblage might be also assigned to the late Asbian, as suggested previously (e.g. Berkhli 1999; Berkhli *et al.* 2001; Cózar *et al.* 2008b). However, the calcareous algae and algospongia occurring from the lower levels of the main buildups contain *Claracrusta catenoides*, *Fascifolium pantherinum* Vachard, Karim & Cózar in Vachard & Cózar, 2010, several species of *Neoprincipia* (*N. petschoriaeformis* Vachard & Aretz, 2004, *N. claviformis* Vachard & Aretz, 2004, *N. guadiatica* Cózar & Vachard, 2003 and *N. tethysiana*), *Sparaphralysia tacania* (and *Sparaphralysia* sp. 1 cf. Cózar *et al.* 2003), *Falsocalcifolium punctatum* (Maslov, 1956) and *Richella incrustata* Mamet & Roux *in* Mamet, Roux & Nassichuk, 1987. This suite of taxa suggests that the interval corresponds to the early Brigantian (Cózar & Somerville 2005a, b; Cózar *et al.* 2005; Vachard *et al.* 2016b). In addition, the dasycladale taxon *Borladella alternans*, is first recorded (Appendix 1), although its biostratigraphic use as potential marker of the latest Asbian or Brigantian has not been confirmed elsewhere.

Higher up in the composite succession, a discontinuous oolitic bar is recorded (Tizra 4 and Tizra 4-2 sections; Fig. 7), which contains more diverse stellate archaediscids, but not the most evolved species, and thus, this part of the succession is also attributed to the early Brigantian.

In the upper Tizra ridge (represented by Tizra 2, 9, 10 and 11 sections; Fig. 7), a predominance of microbial facies is observed, although laterally, bioclastic/oncolitic packstones are also common (e.g. Tizra 2 section; Fig. 7). In the north of the studied section, the microbial communities built a single massive buildup, but more commonly, two stages of buildup development are observed, separated by shales (Fig. 7). The lower stage (e.g. lower part of Tizra 2 section) contains primitive *Biseriella*, *Asteroarchaediscus rugosus*, and, nearly at the top, *Endothyranopsis sphaerica* (Rauzer-Chernousova & Reitlinger *in* Rauzer-Chernousova, Belyaev & Reitlinger, 1936). These taxa are first recorded in the ELBT (Cózar & Somerville 2020b, 2021b). However, these taxa are usually recorded in the late Brigantian in other regions without those minor cycles or where the limestones are dolomitized (e.g. Cózar & Somerville 2004). Hence, it is not sufficiently clear enough to decide which biozone to assign this interval, as early or late Brigantian (Fig. 7).

Nearly at the base of the second stage in the buildup development (e.g. upper part of Tizra 2, 9 and 11 sections; Fig. 7), a new suite of foraminifers first occurs: *Asteroarchaediscus bashkiricus*, *Climacammina*, *Howchinia gibba* (von Möller, 1879), *Janischewskina delicata* (Malakhova, 1956), *Neoarchaediscus gregorii*, *N. postrugosus*, *Planospirodiscus minimus* (Grozdilova & Lebedeba in Dain & Grozdilova, 1953), and *Tubispirodiscus attenuatus* (*Betpakodiscus* auct.) (Marfenkova, 1978). In addition, *Biseriella parva* is recorded higher up in the youngest Tizra 5 section (Fig. 7). This assemblage can be assigned to the late Brigantian (Cózar & Somerville 2016, 2021a, b), and thus, to the Serpukhovian. Conodonts obtained in the region did not include ornamented *Lochriea*, but the assemblage from these later stage buildups contains typical conodonts recorded in the Serpukhovian assemblages in Russia (Medina-Varea 2017).

In summary, most of the Tizra Formation can be assigned to the early Brigantian, but the upper part is assigned to the late Brigantian (Serpukhovian). The early Brigantian is mostly recognized on the basis of the algal assemblages, whereas the transition into the late Brigantian contains typical foraminiferal markers known elsewhere in Western Europe.

Oued Cherrat

The succession in Alkhoudia (*c.* 30 km SSW of Rabat, Fig. 1) is strongly affected by faults, and contains common shaley intervals and thick intervals of dolomites, and the entire succession is partly affected by dolomitization. There, *Lochriea nodosa* (Bischoff, 1957) was recorded nearly from the base of the Kef an Nzaha Formation (Neqqazi *et al.* 2014), and thus, the succession should be at least, early Brigantian in age. Depending on the quarry section in the region, and also the plausible missing parts due to faults, the succession varies in thickness from 80 m in the northern outcrops (Fig. 8) to 130 m in the south. The foraminiferal assemblages are typically representative of the late Asbian (Appendix 1). In this section, there is no robust Brigantian foraminiferal guide, nor in the upper shalier part of the section, and all the foraminifers could be assigned to the late Asbian (Fig. 2). The most evolved taxa which might be restricted to the Brigantian or younger rocks are *Neoarchaediscus incertus* and *Semiendothyra* (Vachard *et al.* 2016a; Cózar *et al.* 2016a). The stratigraphic range of the latter is still poorly known, and needs to be further investigated. However, there are typical Brigantian calcareous algae from the base, such as *Neoprincipia*, large *Saccamminopsis fusulinaeformis* (McCoy, 1849) and *Sparaphralysia tacania* (Fig. 8).

In the Souk el Had road section (*c.* 26 km SSW of Rabat; Fig. 1), the lower part of the Mechra-el-Kraret Formation can be assigned to the Brigantian, due to the presence of common stellate archaediscids, including *Neoarchaediscus parvus regularis* (Suleimanov, 1948), *N.* cf. *postrugosus* and *Asteroarchediscus termierorum* (Fig. 8). It is also highlighted by common taxa of large *Archaediscus karreri* group. In the middle part of the section is recorded *Endothyranopsis sphaerica*, a taxon which appears close to the base of the late Brigantian (Cózar & Somerville 2021b). This level compares closely with that yielding *Lochriea cruciformis* (Clarke, 1960) by Neqqazi *et al.* (2014), and it can be considered as Serpukhovian (Skompski *et al.* 1995). Slightly higher up in the section, other late Brigantian guides are recorded (*Neoarchaediscus postrugosus*, *Pseudoendothyra globosa* Rozovskaya, 1963).

In summary, most of the early Brigantian strata in the Oued Cherrat region could only be recognized by conodonts and calcareous algae, and typical Brigantian foraminifers only first occur from near the top of the early Brigantian.

Tindouf Basin

The succession in the Saharan Tindouf Basin was studied during the period when investigation of sections to determine the GSSP for the Serpukhovian using FOD of the conodont *Lochriea ziegleri* was in progress (and is still ongoing – see Aretz *et al.* 2020), and before establishing that foraminifers recorded below the Namurian could be correlated with those in the early Serpukhovian in Russia (Cózar & Somerville 2016). Thus, there was a paradigm that the late Brigantian may be regarded as an independent chronostratigraphical unit of the early Serpukhovian (see Cózar *et al.* 2014a, b, c, 2016b).

In the upper part of the Betaina Formation (see Cózar *et al.* 2014b), assigned to the late Asbian, primitive *Neoarchaediscus* and *Archaediscus karreri grandis* Conil & Lys, 1964, are first recorded, similar to that in Britain (Waters *et al.* 2017a, b), whereas the base of the Brigantian is recognized by common *Neoarchaediscus* (Cózar *et al.* 2014a) (Fig. 9). These features are common through the Sahara (Cózar *et al.* 2016b). Within the middle part of the early Brigantian (bed H), more evolved stellate archaediscids first occur, such as *Neoarchaediscus incertus*, *N. parvus*, *N.* aff. *postrugosus*, *Asteroarchaediscus pustulus* (Grozdilova & Lebedeva, 1954) and *A. bashkiricus* (Fig. 9), whereas in the upper part (bed I) are recorded the first questionable *Climacammina* and *Endothyranopsis sphaerica*. Hence, it can be interpreted that those levels are probably the equivalent to the ELBT (Fig. 9).

Higher up in the succession, bed J, the first typical late Brigantian (and thus, Serpukhovian) markers are recorded, *Planospirodiscus taimyricus*, *Biseriella parva* and *Tubispirodiscus* (Fig. 9), an assemblage which is joined in bed K by common *Climacammina* and *Endothyranopsis sphaerica*, as well as *Janischewskina delicata*, *J. gibshmanae* Cózar, Somerville, Sanz-López & Blanco-Ferrera, 2016a and "*Millerella*" *tortula* (= *Zellerinella* = *Paramillerella* = *Plectomillerella* auct.) (Zeller, 1953).

The most remarkable change in the early Serpukhovian is observed in bed M, where *Globivalvulina* spp., *Calcivertella*, *Eostaffellina* spp., and *Insolentitheca horrida* Vachard *in* Bensaid, Termier, Termier & Vachard, 1979, are first recorded. These taxa have been recorded in levels correlated with the Steshevian Substage (see Cózar *et al.* 2016a; Vachard *et al.* 2016a; Cózar *et al.* 2018).

On the other hand, algal assemblages in Tindouf are poor, probably due to the high content of interbedded siliciclastics in the succession, and consequently are comparatively less diverse than the foraminifers, much less diverse and abundant than in the Meseta outcrops. *Claracrusta catenoides* is recorded just below the Brigantian, in bed D, whereas *Paraepimastopora* sp. is the only marker recorded at the base of the Brigantian in bed E. Other important algae are *Neoprincipia tethysiana*, which is first recorded in bed I, whereas *Fascifolium pantherinum* and *Falsocalcifolium punctatum* are recorded from bed J, in the late Brigantian (Fig. 9). It is difficult to validate if the siliciclastic predominance in the succession might also have had an influence on the foraminiferal record, without any other independent fossil group to compare the zonal schemes, although the rugose corals in the region occur usually later than in Europe, and they persisted into the Pennsylvanian (Rodríguez *et al.* 2013; Cózar *et al.* 2014c).

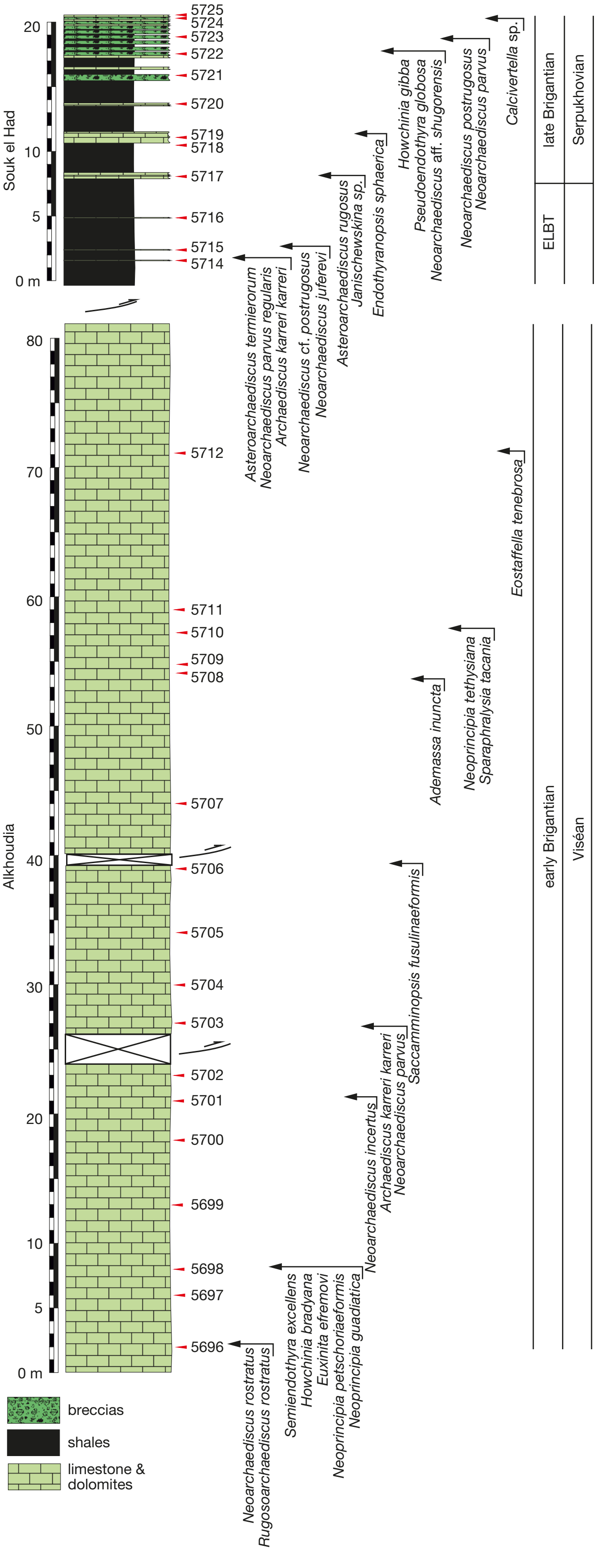


Fig. 8. — Selected first occurrences of the main taxa in Oued Cherrat.

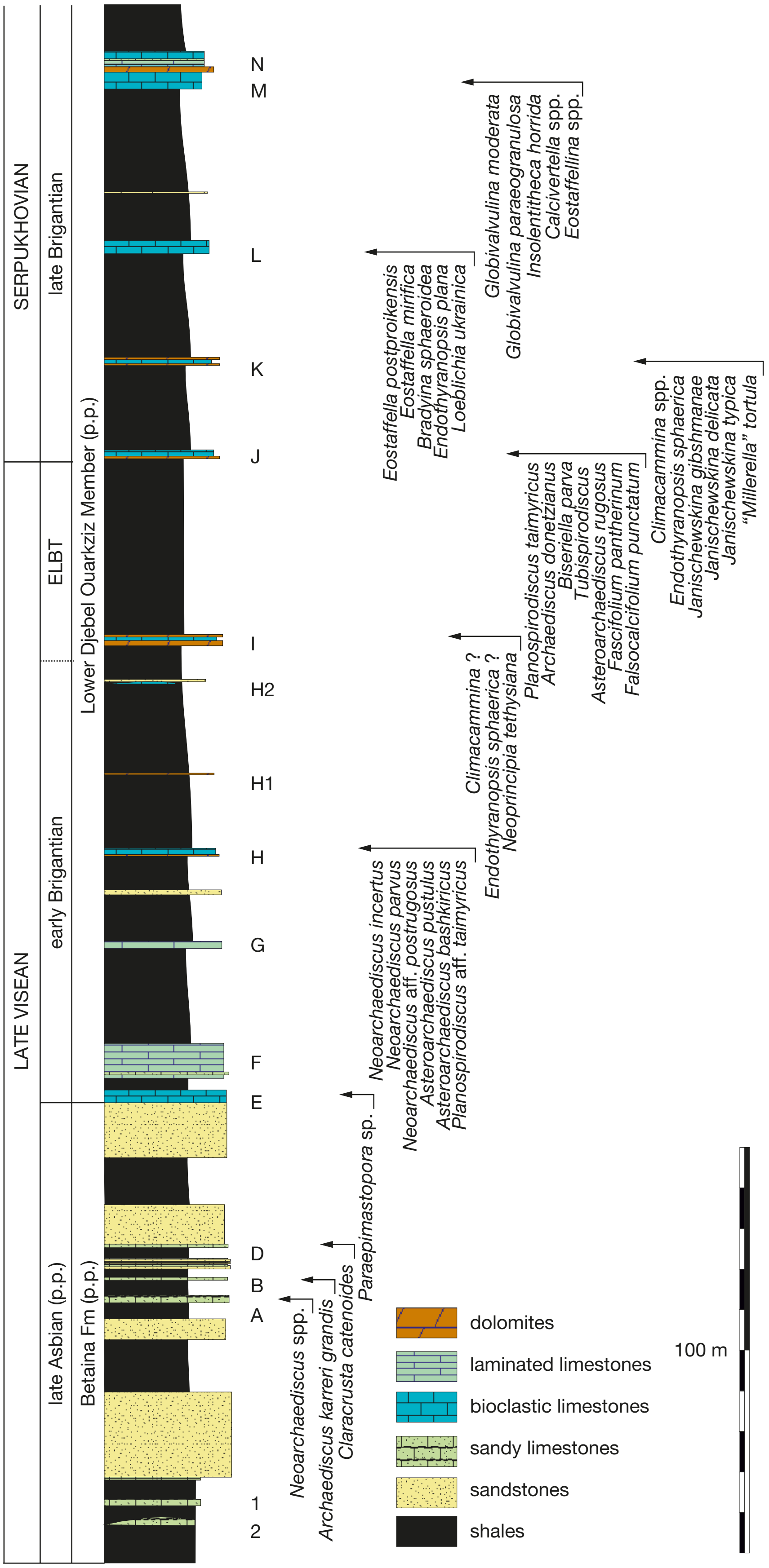


FIG. 9. — Selected first occurrences of the main taxa in the northern limb of the Tindouf Basin.

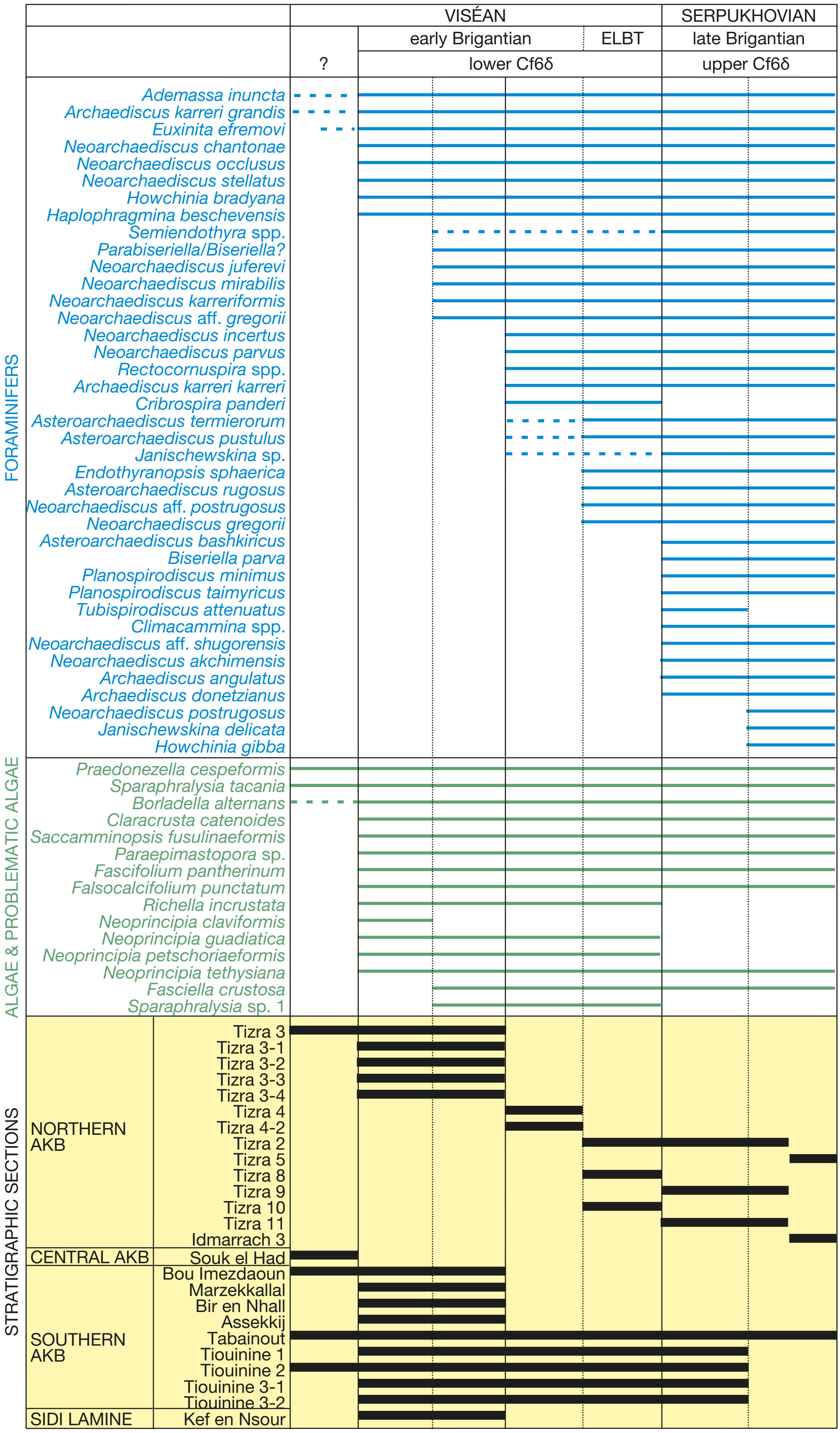


Fig. 10. — Summary of the stratigraphic ranges of selected foraminifers and calcareous algae for the Brigantian in the Moroccan Meseta. Abbreviation: **ELBT**, early-late Brigantian transitional beds.

In consequence, apart for the abundance in stellate archaediscids, there are few similarities in the early Brigantian between the Meseta and the Sahara, with much more evolved foraminifers occurring earlier in the Sahara. This fact is probably related to a better marine connection with the Palaeotethys Ocean of the Saharan basins (such as Tindouf) than with the Meseta, which shows stronger foraminiferal affinities with the southwest of the Iberian Peninsula (Sierra Morena) (Cózar *et al.* 2018; Cózar & Somerville 2021c). Although markers for the recognition of the late Brigantian are roughly similar at the base in both regions, the diversity and numerical abundance are rather higher in the Sahara.

Guides for the recognition of the Brigantian in the Moroccan Meseta

As has been highlighted above, the base of the Brigantian substage is difficult to recognize in the Moroccan Meseta using foraminifers. It is a similar case in England, where, apart from the stratotype section in Janny Wood, it is often difficult to recognize (McLean *et al.* 2018). In addition, similar to Britain and Ireland, the algal assemblages in the Moroccan Meseta are interpreted to be more representative for the recognition of Brigantian substage (Cózar & Somerville 2004, 2005a, b; Cózar *et al.* 2005), in addition to the use of ammonoids, conodonts and rugose corals, when they occur.

This problem does not seem to affect the Gondwana platform, where there are numerous European foraminiferal markers, allowing a more solid subdivision (e.g. Cózar *et al.* 2014a, 2016b). However, this is not the only anomaly detected in the Meseta, because it also contains typical early Viséan foraminifers recorded into the mid Viséan, and in some cases also into upper Viséan successions (Cózar *et al.* 2020a). All those unusual foraminiferal assemblages question whether the Moroccan Meseta was already annexed to Gondwana for the entire Viséan in its current position, or whether it was affected by a certain ecological isolation (by ocean currents, land barriers, insularity, etc.) which allowed these distinct stratigraphic ranges for the foraminifers in the emerging platforms of the Meseta Terrane. Surprisingly, these plausible late occurrences and low diversity (compared with other regions in Europe) are not observed in the calcareous algae.

In order to propose some alternative guides for the Brigantian strata of the Moroccan Meseta, a first step is to clarify which taxa are present in the underlying rocks of the late Asbian. A significant concern is to ensure that the rocks certainly belong to these foraminiferal zones, and that they are not an error of dating. For this issue, continuous successions from the middle Viséan through to the upper Viséan are most desirable, and hence to avoid the fragmentary nature of many outcrops in regions of Morocco, and their plausible incorrect datings. For instance, in the Jbel Moufras and Bouqachmir formations, northeast of Tilouine (Fig. 1), the carbonate outcrops are too fragmentary, and although some of them were equivalent to the late Asbian, they are questionable, due to the absence of reliable markers (see foraminiferal lists in Izart *et al.* 2001), and thus they cannot be used to establish the boundary between the Asbian and the Brigantian.

In Haouz, in the High Atlas, south of Marrakech (Fig. 1), Vachard *et al.* (1991) recognized rocks equivalent to the late Asbian by the incoming of *Neoarchaediscus* sp., whereas the underlying strata, equivalent to the early Asbian, was characterized by rare *Pseudoendothyra struvei*, a proliferation of *Nodosarchaediscus*, rare *Archaediscus karreri* group (all of them still possessing a well-marked microgranular layer), and diversification of the aoujgaliids. Those authors already noted the absence of *Neoarchaediscus* and *Vissariotaxis* from rocks equivalent to the early Asbian, which characterise European biozonations (e.g. Conil *et al.* 1980, 1991; Poty *et al.* 2006).

There are numerous outcrops which could be ascribed to the late Asbian in Rehamna and Jebilet regions (Fig. 1). They are recognized by the presence of *Endothyranopsis crassa*, *Archaediscus karreri* group (still possessing a well-marked microgranular layer), *Endostaffella parva*, *Cribrostomum* sp., *Cribrostomum lecomptei* and *Ungdarella uralica* (see Hollard *et al.* 1977; El Kamel 1987, 2002; El Kamel & El Hassani 2006), without the presence of evolved foraminifers, such as *Neoarchaediscus*, *Bradyina*, *Howchinia*, etc. In the central area of the Azrou-Khenifra Basin, rocks equivalent to this substage has been also recognized by Termier *et al.* (1975), Faik (1988), as well as in the northern part (e.g. Bouabdelli 1989; Berkhli 1999; Berkhli *et al.* 2001; Vachard *et al.* 2006). Similarly, there are some outliers ("boutonnières") north of the Azrou-Khenifra Basin, such as Imouzzer du Kandar, Bhalil, El Hajeb, where the substage has been recognized with similar taxa (e.g. Ouarhache 1987; Ouarhache *et al.* 1991; Berkhli *et al.* 2002).

Hence, accepting the list of taxa previously regarded as reliable markers for the late Asbian, the key foraminiferal genera that can help to recognize the transitional levels into the Brigantian are *Euxinita* and *Ademassa,* whereas *Howchinia* and *Haplophragmina* seem to be recorded from younger basal Brigantian levels (Fig. 10). In the upper levels of the early Brigantian, the stellate archaediscids become common, and can be highlighted by the occurrence of more evolved *Neoarchaediscus*, such as *N. incertus*, *N. parvus*, *N. gregorii* and *N.* aff. *postrugosus*. More primitive forms of *Neoarchaediscus* (*N. stellatus* (Bozorgnia, 1973) (*Rugosoarchaediscus* auct.), *N.* aff. *stellatus*, *N.* aff. *incertus*, *N. occlusus* (Hallett, 1971) (*Rugosoarchaediscus* auct.)*,* etc.), occur from the lower part of the early Brigantian (Fig. 11; see also Cózar *et al.* 2008b, 2011), and they can be even common. Within these assemblages, the first *Semiendothyra* and *Parabiseriella moroccoensis* Cózar & Somerville, 2012 and *Biseriella*? are recorded. In the latter case, it is difficult to distinguish between both genera, but large agglutinated grains in the wall suggest that most of them in this lower part of the succession belong to *Parabiseriella*, although some primitive *Biseriella* seem also to be present.

Within the *Archaediscus karreri* group, species with a poor development of the microgranular layer characterize the Brigantian, with the usually smaller forms (*A. karreri grandis*) typical of the early Brigantian, and the largest forms (*A. karreri karreri* Brady, 1873) in the uppermost early and late Brigantian, but the latter with a negligible microgranular layer (Fig. 11).

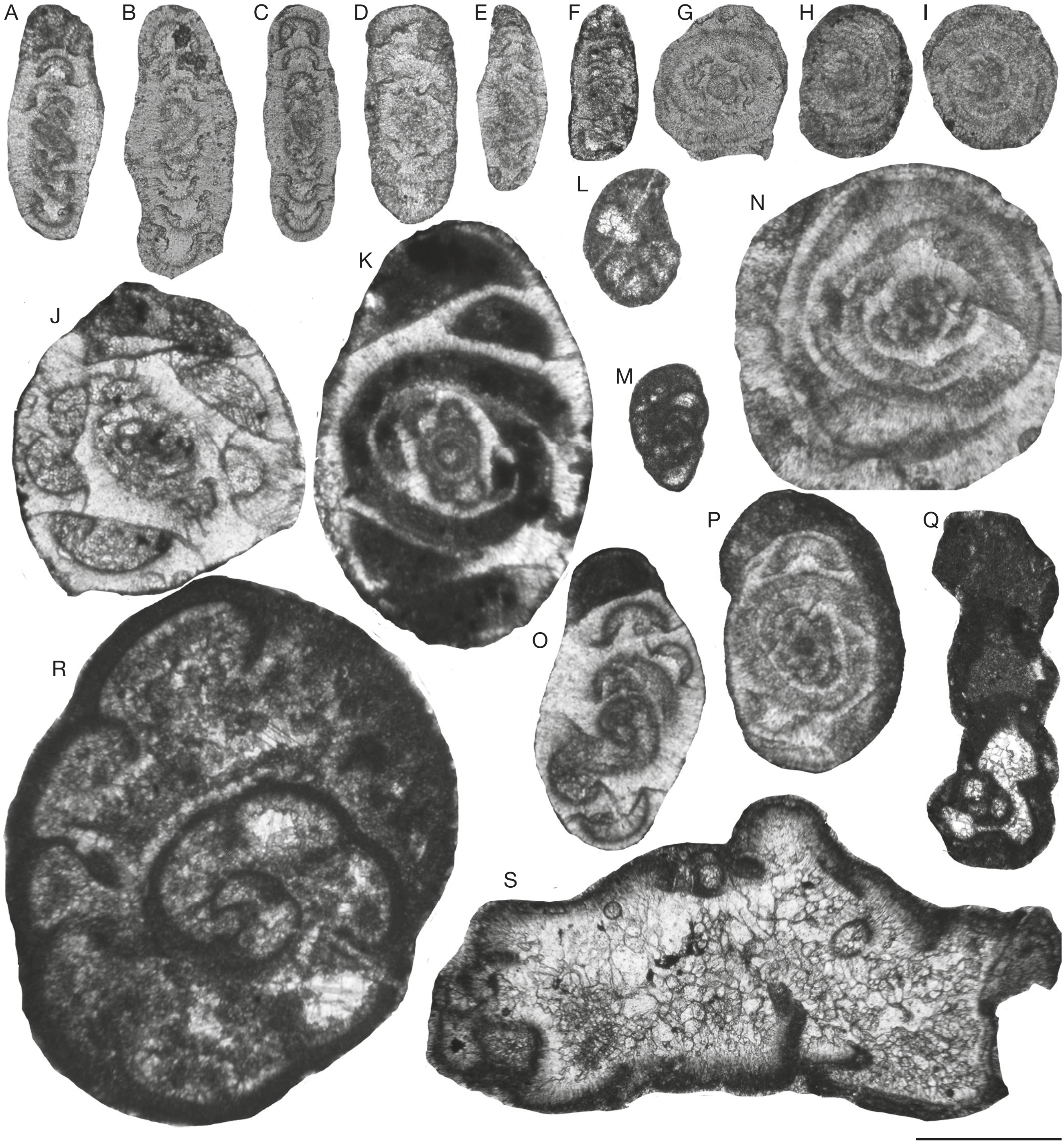


FIG. 11. — Selected foraminifers which first occur in the early Brigantian: **A**, *Neoarchaediscus chantonae* Berkhli, 1993 nom. nud., sample Pc3669, Tizra 3-3 section; **B**, *Neoarchaediscus juferevi* Marfenkova, 1983, sample Pc3815, Tizra 9 section; **C**, *Neoarchaediscus mirabilis* Marfenkova, 1983, sample Pc3815, Tizra 9 section; **D**, *Neoarchaediscus parvus* (Rauzer-Chernousova, 1948), sample Pc3823, Tizra 9 section; **E**, *Neoarchaediscus* aff. *gregorii*, sample Pc3697, Tizra 3-3 section; **F**, *Neoarchaediscus incertus*, sample Pc5716, Souk el Had section; **G**, *Neoarchaediscus occlusus* (Hallett, 1971), sample Pc3882, KS1/KS2 section; **H**, *Asteroarchaediscus termierorum* Vachard *in* Termier, Termier & Vachard, 1975a, sample 3868, KS1/KS2 section; **I**, *Asteroarchaediscus pustulus* (Grozdilova & Lebedeva, 1954), sample Pc3876, KS1/KS2 section; **J**, *Archaediscus karreri karreri* Brady, 1873, sample Pc5714, Souk el Had section, **K**, *Archaediscus karreri grandis* Conil & Lys, 1964, sample Pc3689, Tizra 3-3 section; **L**, *Parabiseriella moroccoensis* Cózar & Somerville, 2012, sample Pc3657, Tizra 3-1 section; **M**, *Euxinita efremovi* (Vdovenko & Rostovtseva *in* Brazhnikova, Vakarachuk, Vdovenko, Vinnichenko, Karpova, Kolomiets, Potievskaya, Tostovtseva & Shevchencko, 1967), sample Pc5699, Alkhoudia section; **N**, *Neoarchaediscus karreriformis* (Reitlinger, 1950), sample Pc3822, Tizra 9 section; **O**, *Nodasperodiscus* sp., sample Pc3778, Tizra 3-2 section; **P**, *Neoarchaediscus stellatus* (Bozorgnia, 1973), sample Pc3868, KS1/KS2 section; **Q**, *Haplophragmina beschevensis* (Brazhnikova *in* Brazhnikova, Vakarachuk, Vdovenko, Vinnichenko, Karpova, Kolomiets, Potievskaya, Tostovtseva & Shevchencko, 1967), sample Pc3651, Tizra 3-1 section; **R**, *Cribrospira panderi* Möller, 1878, sample Pc5700, Alkhoudia section; **S**, *Ademassa inuncta* Vachard *in* Vachard, Massa & Strank, 1993, sample Pc3715, Tizra 3-3 section. Scale bar: A-P, 200 µm; Q-S, 400 µm.

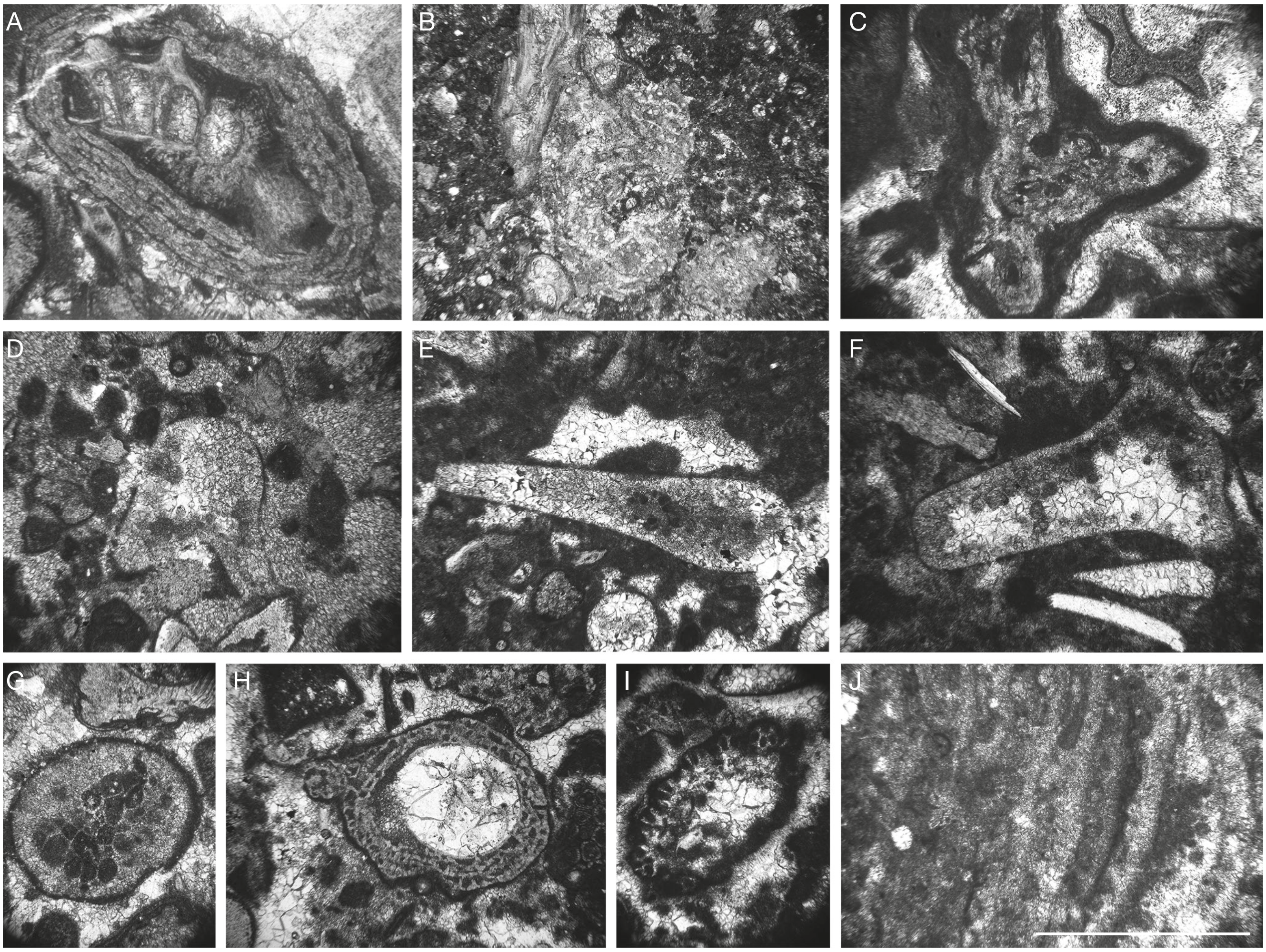


Fig. 12. — Selected algae and problematic algae in the early Brigantian: **A**, *Fasciella crustosa* Vachard, Somerville & Cózar, 2004, sample Pc3775, Tizra 3-2 section; **B**, *Fascifolium pantherinum* Vachard, Karim & Cózar in Vachard & Cózar, 2010, sample Pc3677, Tizra 3-3 section; **C**, *Falsocalcifolium punctatum* (Maslov, 1956), sample Pc3773, Tizra 3-2 section; **D**, *Neoprincipia petschoriaeformis* Vachard & Aretz, 2004, sample Pc3627, Tizra 3-1 section; **E**, *Neoprincipia claviformis* Vachard & Aretz, 2004, sample Pc3621, Tizra 3-1 section; **F**, *Neoprincipia guadiatica* Cózar & Vachard, 2003, sample Pc3626, Tizra 3-1 section; **G**, *Neoprincipia tethysiana* Cózar & Vachard, 2003, sample 3868, KS1/KS2 section; **H**, *Claracrusta catenoides* (Homann, 1972), sample Pc3700, Tizra 3-3 section; **I**, *Borladella alternans* Cózar, Somerville, Rodríguez & Medina-Varea, 2007, sample Pc3706, Tizra 3-3 section; **J**, *Richella incrustata* Mamet & Roux *in* Mamet, Roux & Nassichuk, 1987, sample Pc3641, Tizra 3-1 section. Scale bar: 0.5 mm.

However, the microgranular layer in the recorded specimens is variable, depending on how it is considered by the researcher, the stage of preservation, or even the thickness of the thin-section. Thus, it is difficult to apply universally this criterion, and a detailed re-examination of the so-called *Archaediscus karreri* by the different authors is required for a robust biostratigraphy based on this group.

Within the genus *Asteroarchaediscus*, oblique or poorly preserved sections and small specimens (possibly assignable to *A. pustulus* and *A. termierorum*) are recorded in the upper part of early Brigantian (Figs 10; 11). On the other hand, *Asteroarchaediscus rugosus* is first recorded from the uppermost early Brigantian, whereas *A. bashkiricus* is only recorded in the late Brigantian.

In contrast, some of the endemic taxa proposed by Vachard & Berkhli (1992) from the Jerada Basin, such as *Rectoendothyra jeradaensis* or *Monotaxinoides chantonae* might be useful for local correlations, but owing to their rarity, they cannot be considered as potential markers for other basins in Morocco. Furthermore, neither taxon has been recorded in the southern limb of the Jerada Syncline (Fig. 4).

There are other taxa that have not been used as guides due to: 1) their rarity in the studied sections; 2) their first occurrences seem to be later than in Western Europe; or, 3) their stratigraphic ranges in Morocco are not well constrained. Moreover, some taxa that might be considered also as potential markers for the Brigantian, have been recorded in older rocks in Morocco (Fig. 10). For instance, *Cepekia regularis* Brazhnikova, Rostovtseva & Karpova *in* Brazhnikova, Vakarchu, Vdovenko., Vinnichenko,, Karpova, Kolomiets, Potievskaya, Rostovtseva & Shevchenko, 1967 proposed by Izart *et al.* (2017), has been recorded from the base of the late Viséan in El Goulib (Cózar *et al.* 2020b). Similarly, other taxa that have been also considered as evolved forms that could be useful in recognizing the upper part of the Viséan, are *Endostaffella parva* or *Praeplectostaffella asymmetrica*, but as has been

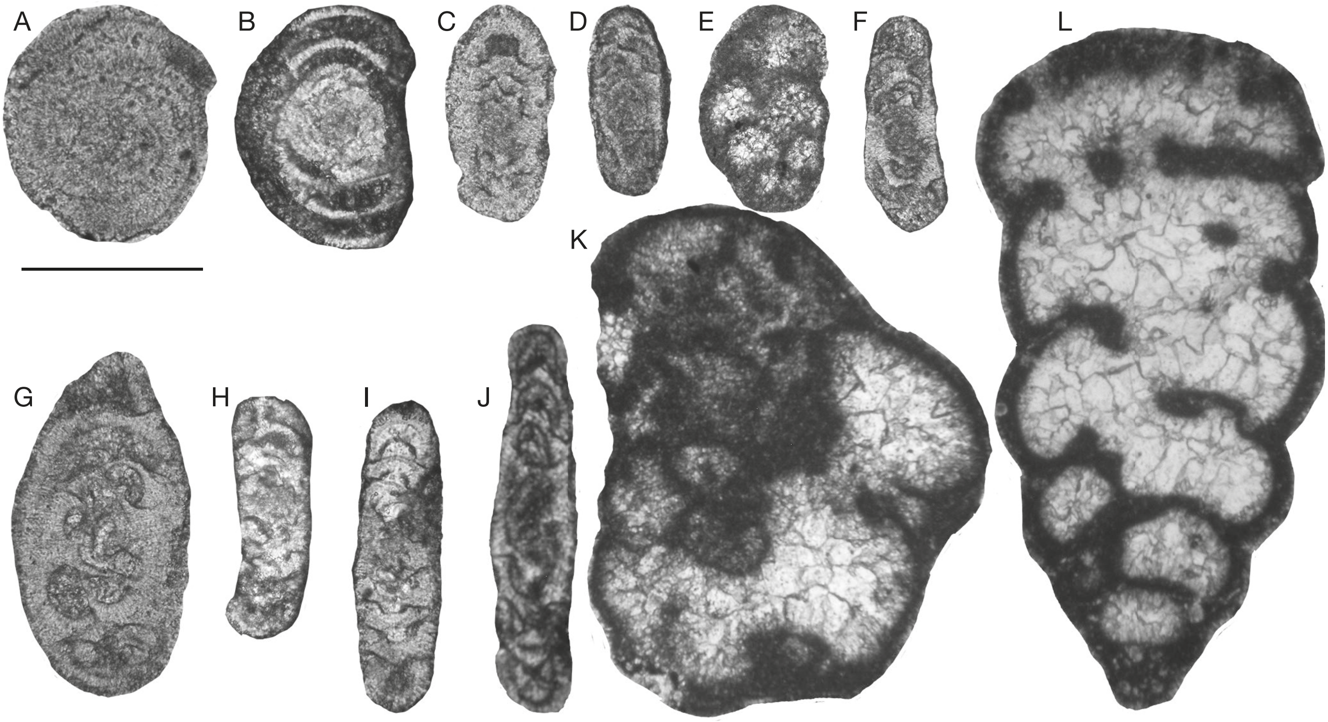


Fig. 13. — Selected foraminifers of the late Brigantian: **A**, *Asteroarchaediscus bashkiricus* (Krestovnikov & Theodorovich, 1938), sample Pc3879, KS1/KS2 section; **B**, *Neoarchaediscus akchimensis* (Grozdilova & Lebedeva, 1954), sample Pc3849, Tizra 11 section; **C**, *Asteroarchaediscus rugosus* (Rauzer-Chernousova, 1948b), sample Pc3812, Tizra 9 section; **D**, *Neoarchaediscus gregorii* (Dain *in* Dain & Grozdilova, 1953), sample Pc3876, KS1/KS2 section; **E**, *Biseriella*? sp., sample Pc3845, Tizra 10 section; **F**, *Neoarchaediscus postrugosus* (Reitlinger, 1949), sample Pc3881, KS1/KS2 section; **G**, *Archaediscus donetzianus* Sosnina *in* Dain & Grozdilova, 1953, sample Pc3848, Tizra 11 section; **H**, *Planospirodiscus minimus* (Grozdilova & Lebedeva *in* Dain & Grozdilova, 1953), sample Pc3849, Tizra 11 section; **I**, *Tubispirodiscus attenuatus* (Marfenkova, 1978), sample Pc3849, Tizra 11 section; **J**, *Neoarchaediscus* aff. *shugorensis* (Chermnykh, 1996), sample Pc3849, Tizra 11 section; **K**, *Janischewskina delicata* (Malakhova, 1956), sample Pc3853, Tizra 11 section; **L**, *Climacammina* sp., sample Pc3815, Tizra 9 section. The size of K and L are reduced by two to show all the typical late Brigantian species. Scale bar: A-J, 200 µm; K, L, 400 µm.

discussed previously, they have been recorded in Morocco and elsewhere in much older rocks. *Cribrospira panderi* (von Möller, 1878) and *Eostaffella ikensis* Vissarionova, 1948 are only recorded in the upper part of the early Brigantian, but they are very rare, and so their first occurrences are of regional character, or even only local. On the other hand, *Bradyina*, a typical marker of the late Asbian in Western Europe, has been rarely recorded from upper Brigantian rocks, and mostly in late Serpukhovian rocks (Cózar *et al.* 2011). The occurrence of *Janischewskina* in the studied sections is exceptional (see Tizra 3-1 in Appendix 1), and thus, owing to its rarity, it cannot be used as a marker.

In addition, the first occurrence of algae and problematical algae such as *Claracrusta*, *Paraepimastopora*, *Sparaphralysia*, *Neoprincipia*, *Fasciella crustosa* Vachard, Somerville & Cózar, 2004, *Fascifolium*, *Falsocalcifolium* and *Richella* are considered as markers of the Brigantian in the Moroccan Meseta (Figs 10; 12). Other questionable algal taxa that also seem to first occur in the Brigantian in Morocco, are *Coelosporella*, *Palaepimastoporella* and large *Saccamminopsis fusulinaeformis* (see Appendix 1), although their stratigraphic range needs to be further investigated. It has to be highlighted that the *Archaeolithophyllum lamellosum* Wray, 1964, recorded in Cózar *et al.* (2008b) is reinterpreted herein as recrystallized *Richella*.

In contrast, the late Brigantian (or early Serpukhovian) is marked by numerous foraminiferal taxa which present similar stratigraphic ranges as in Western Europe (Fig. 10), such as *Climacammina*, *Neoarchaediscus postrugosus*, *Janischewskina* (particularly *J. delicata*), *Tubispirodiscus attenuatus*, "*Millerella*" aff. *tortula*, *Planospirodiscus taimyricus*, *Biseriella parva* and the above-mentioned *Asteroarchaediscus bashkiricus* (Fig. 13; see also Cózar *et al.* 2008b, 2011). Furthermore, *Howchinia gibba* can be also considered a marker for the Serpukhovian in the Meseta. Other taxa that might be useful for the recognition of the Serpukhovian are evolved species of *Archaediscus* (*A. angulatus* Sosnina *in* Dain & Grozdilova, 1953, and *A. donetzianus* Sosnina *in* Dain & Grozdilova, 1953), but their stratigraphic ranges in Morocco need to be further constrained. Unfortunately, we have not detected differences in the algal assemblages in levels within the Serpukhovian, nor significant new first occurrences.

BIOSTRATIGRAPHIC IMPLICATIONS FOR THE MOROCCAN MESETA

Taking into consideration the unusual foraminiferal assemblages recognized for the early Brigantian in the Moroccan Meseta, some concerns can be raised in regard to the published late Asbian datings based on poor foraminiferal assemblages, or outcrops studied only by means of a few spot samples and not detailed measured sections. It is most likely that some (or even many?) of those supposed late Asbian rocks could be confirmed as early Brigantian with further sampling and preparation of more thin sections for investigation. The "poor" assemblages are really difficult to validate, but in some cases, much richer published assemblages allow to question and reinterpret the published biostratigraphy.

In Sidi Bettache (Fig. 1), assemblages spanning the Asbian were recognized by Izart & Vieslet (1988) and Izart (1990), including: *Archaediscus karreri grandis*, common *Nodosarchaediscus* and *Euxinita*. Other outcrops in the region can be assigned certainly to the Brigantian based on the presence of: *Archaediscus karreri karreri*, *Asteroarchaediscus*, *Howchinia* and *Semiendothyra phrissa* (Zeller, 1953). Compared to the assemblages presented in this study, most outcrops of the Sidi Bettache Basin are more likely to be of Brigantian age. In fact, these authors included the succession in Oued Cherrat for the Mechra el Kraret Formation, as equivalent to the Asbian, according to Chalouan (1981), whereas now, the formation is considered as upper early Brigantian and late Brigantian (see above, Souk el Had section; Fig. 8).

The Mellila Formation in the Mdakra Massif (Fig. 1) was assigned to a subzone equivalent to the late Asbian, based on *Howchinia bradyana* and *Ungdarella uralica* as the main markers (Fadli 1990; Vachard & Fadli 1991). The assemblage recorded by those authors also includes *Cribrospira panderi*, *Endostaffella parva*, *Eostaffella ikensis*, *Nodosarchaediscus saleei* (Conil & Lys, 1964), *Neoarchaediscus incertus* and *N. gregorii*. The assemblage can be now reinterpreted as Brigantian, including the level immediately below the late Brigantian, and possibly coinciding with levels correlatable with the FALz. At Beni Sekten (SW margin of the Mdakra Massif), the second and third levels of Fadli (1990), as well as in the Al Qotaybat region in the Khatouat Massif, were also assigned to the equivalent to the Asbian, although, similarly, in the former region, *Neoarchaediscus incertus* and *Archaediscus karreri* occur, and *Neoarchaediscus parvus* occurs in the latter. These taxa question the biostratigraphy assigned to those regions, and they could be more probably Brigantian.

The Bled Mekrach Formation in northern Rehamna (Fig. 1) is a similar case. There are reported foraminifers in the units a and b, but from units c and d, El Kamel (2002) recorded assemblages assigned to an interval equivalent to the late Asbian-Brigantian, including *Endostaffella parva*, *Archaediscus chernoussovensis* Mamet *in* Mamet, Choubert & Hottinger, 1966, *Archaediscus karreri*, *Cribrostomum lecomptei*, *Archaediscus enormis* Schlykova, 1951, and *Biseriella parva*. Furthermore, in the higher levels, unit e, a conodont assemblage was recorded, yielding *Lochriea nodosa* and *L. multinodosa* (Wirth, 1967). The assemblages suggest a continuous record of the Brigantian, possibly including the late Brigantian. Unfortunately, foraminifers were not studied from the youngest levels.

These successions, as well as many other poorer and less well-known sections in the Moroccan Meseta should be resampled in detail in order to establish a much more solid biostratigraphic framework. With the available data, the subdivisions of the late Viséan and the base of the Serpukhovian of the Moroccan Meseta show a biostratigraphy with a low reliability.

CONCLUSIONS

Revision of foraminifers, algae and problematic algae of well-known late Viséan formations in the Jerada Massif in the Eastern Meseta, Azrou-Khenifra Basin in the Central Meseta and Oued Cherrat in the westernmost Meseta, suggests that the recognition of the chronostratigraphic units within this period lacks most of the foraminiferal markers that characterize the Western European foraminiferal biozonations. Most taxa recorded in the Moroccan Meseta could be erroneously considered as late Asbian guides in Western Europe, but in the Meseta, they are first recorded within the early Brigantian (Fig. 10). In the studied sections in the Azrou-Khenifra Basin, there is commonly a basal interval that is locally characterized by the first occurrence of *Ademassa inuncta*, *Archaediscus karreri grandis*, *Euxinita efremovi* and the problematic alga/cyanobacterium *Sparaphralysia tacania*, whose biostratigraphic dating is questionable, either latest Asbian or earliest Brigantian. The first strata unquestionably assigned to the Brigantian are characterized by numerous species of *Neoarchaediscus*, *Haplophragmina*, *Howchinia* and some endemic taxa. The Viséan-Serpukhovian boundary interval, possibly equivalent to levels that should contain the FALz, is characterized by the first occurrence of *Asteroarchaediscus rugosus*, *Neoarchaediscus* aff. *postrugosus*, *N. gregorii*, *Endothyranopsis sphaerica* and primitive *Biseriella*. Strata of late Brigantian age, and thus, readily assigned to the Serpukhovian, are characterized by *Asteroarchaediscus bashkiricus*, *Biseriella parva*, *Planospirodiscus minimus*, *P. taimyricus*, *Tubispirodiscus attenuatus*, and rare specimens of *Climacammina*, whereas in slightly younger rocks, *Neoarchaediscus postrugosus*, *Janischewskina delicata* and *Howchinia gibba* are first recorded.

In contrast, the algae and problematic algae present a completely different distribution, and numerous taxa have been first recorded from the basal levels assigned to the Brigantian (*Claracrusta catenoides*, *Falsocalcifolium punctatum*, *Fascifolium pantherinum*, four species of *Neoprincipia*, *Paraepimastopora* sp., *Richella incrustata* and *Saccamminopsis fusulinaeformis*), with *Fasciella crustosa* and *Sparaphralysia* sp. 1 in slightly younger levels. Most of them extended their stratigraphic ranges up to the Serpukhovian without any significant change.

Hence, the early Brigantian is more easily recognized by means of the algae than with foraminifers in the Moroccan Meseta. The unusual and unrepresentative foraminiferal assemblages recorded from the Brigantian suggest that most of the numerous outcrops and sections ascribed to the equivalent biozones of the late Asbian in the Moroccan literature should be revised because, as has been demonstrated in a few cases in this study, those outcrops most likely belong to younger chronostratigraphic units.

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APPENDIX

Appendix 1. — Foraminiferal, algal and problematic algal distribution of the studied sections. Details of sections Tizra 4, Tizra 2, Tizra 5 were published in Cózar *et al*. 2008b: https://doi.org/10.5852/cr-palevol2023v22a12_s1