Research paper

Palynostratigraphy of the Zorritas Formation, Antofagasta region, Chile: Insights on the Devonian/Carboniferous boundary in western Gondwana

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ABSTRACT

The Middle Member of the Zorritas Formation in the Antofagasta region of northern Chile, yielded terrestrial and marine palynomorph assemblages which span the Devonian/Carboniferous boundary. The assemblages show a clear predominance of terrestrial palynomorphs with 70 miospore species, 18 marine phytoplankton species, two non-marine algae and one chitinozoan species, all coming from 15 productive levels. Palynomorphs are poorly preserved and most of them are reworked. Three palynological associations are recognized based on miospores. These are assigned to the Tournaisian–Visean, Tournaisian and probable latest Famennian. Age assignments are discussed in the frame of the spore zonal schemes established for Euramerica and western Gondwana. The stratigraphical distribution of spores allows the identification of the probable position of the Devonian/Carboniferous boundary within the Zorritas Formation. This system boundary is proposed for the first time in Palaeozoic sedimentary rocks of northern Chile. The presence of Gondwanan typical miospore species indicates affinities with this palaeocontinent even though the Tournaisian and Tournaisian–Visean miospore associations support the cosmopolitanism already suggested for the early Carboniferous flora. The significant number of reworked palynomorphs together with the sedimentological analysis of the studied sections, suggest that these deposits were severely impacted by the climatic change and major sea level fluctuations. Similar conditions were recorded in coeval western Gondwana basins.

1. Introduction

Sedimentary Palaeozoic rocks are very scarce in northern Chile. Cecioni and Frutos (1975) were the first to provide information about the Zorritas Formation, a nearly 2600 m thick siliciclastic sequence deposited in a mainly marine environment. Next, Davidson et al. (1981) and Boucot et al. (2008) suggested a Devonian age for this formation. Isaacson et al. (1985) and Dutro and Isaacson (1990) distinguished a transition, based on braquiopod determinations, between the Devonian and the Carboniferous into the Zorritas Formation. Niemeyer et al. (1997) distinguished and mapped three members in this stratigraphic unit (Fig. 1a,b,c) and proposed the presence of the Devonian/Carboniferous transition within the Middle Member. The presence of the systemic boundary in the upper part of the Middle Member of the unit was suggested by Rubinstein et al. (1996) based on palynological studies.

The studied section of the Zorritas Formation ranges from the latest Devonian to the early Carboniferous. During this time interval, important changes in the biosphere and therefore in the biota took place. Climatic change and major sea level fluctuations are revealed by stratigraphic discontinuities and large amounts of reworked palynomorphs, particularly in South American basins.

Even though the Devonian was climatically interpreted as a relatively warm period, the latest Devonian displayed the first evidences of long-term and intermittent upper Palaeozoic glaciations that extend until the Permian (Torsvik and Cocks, 2013). The earliest glaciogenic rocks were found in the Famennian of South
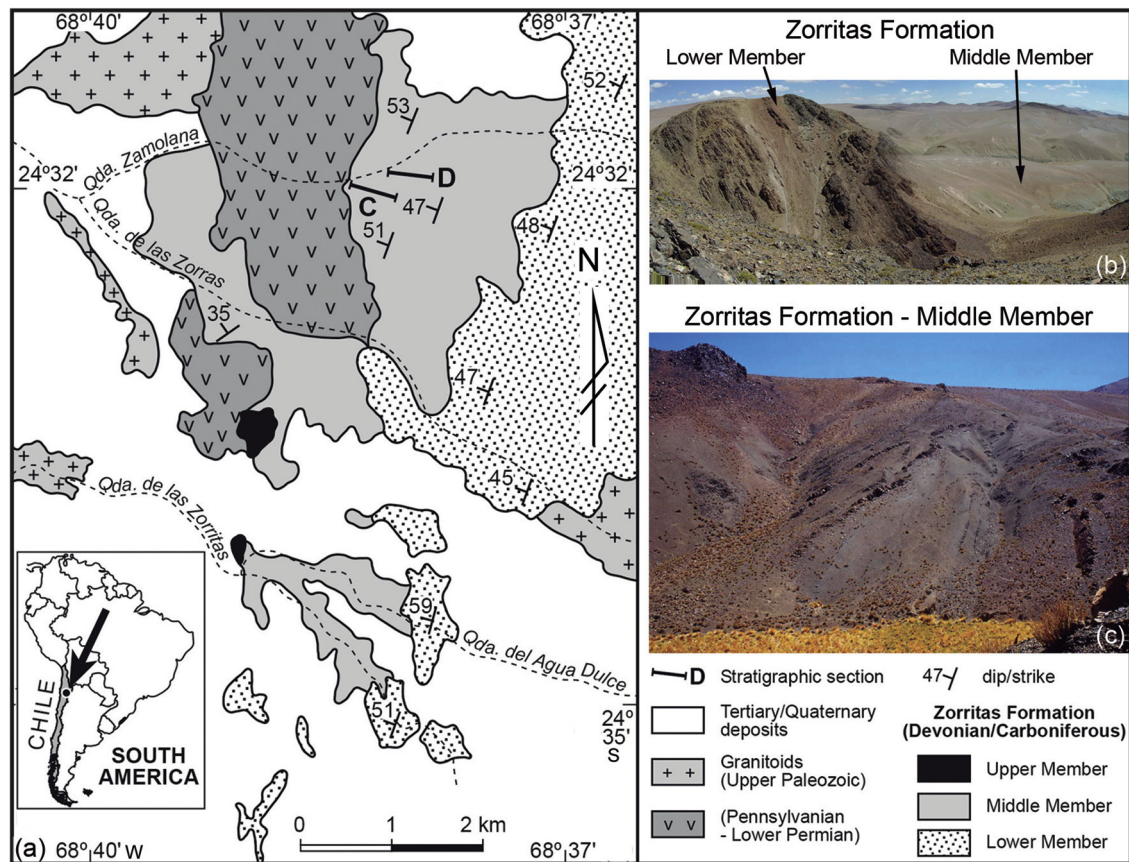
Figure 1. (a) Geographical and geological map of the studied area, in the Antofagasta region of northern Chile. C and D: stratigraphic sections of the Quebrada Zamolana. (b) Upper part of the Lower Member composed of coarse quartzarenites and the Middle Member dominated by claystones and siltstones. (c) The Middle Member with intercalations of fine grained sandstones and a few conglomerate beds.

America (from Venezuela or northern Brazil to central Argentina), Africa and the United States (e.g. Appalachian Basin) (Caputo et al., 2008 and references therein), thus suggesting that the Neo-Devonian cooling was a global event involving most of western Gondwana and even partially reaching Laurussia. Consequently, the Rheic Ocean was narrower than previously supposed (Caputo et al., 2008). Noteworthy, in the Andean region of Argentina, Peru and Bolivia, Famennian glacially-influenced sediments have also been identified (Caputo and Ponciano, 2010). The only Tournaisian sediments of possible glacial origin in western Gondwana were recorded from Brazil thus making the extension of the glaciation in this region less evident during the early Mississippian (Caputo et al., 2008). Transgressive and regressive sequences of non-marine, nearshore or offshore deposits outside the glaciated areas may have been produced by the alternation of glacial and inter-glacial phases (Caputo et al., 2008). The precise timing of ice centres waxing and waning during the glacial episode has been interpreted as influenced by basin dynamics, topographic barriers, glaciation styles and other local factors (López-Gamundí and Buatois, 2010).

The first results related to the stratigraphy and palynology of the Devonian/Carboniferous boundary in the Zorritas Formation, were anticipated based on a single palynological productive level (sample Z128 in Fig. 2) by Rubinstein et al. (1996), Niemeyer et al. (1997), and Niemeyer and Rubinstein (2000). Even though this level yielded a badly preserved mainly terrestrial palynomorph assemblage, the contained spores allowed the assignment of this stratigraphic level to the Tournaisian, correlating it with the western European *Vallatisporites verrucosus-Retusotriletes incohatus* (VI) spore zone. This spore zone is considered the basal one of the Carboniferous

(Higgs et al., 1988a). The marine phytoplankton was represented by scarce specimens of simple forms (*Michrystridium* sp., *Veryhachium* sp.) without any stratigraphic value.

The present contribution provides new information, displaying richer and more diverse palynological assemblages coming from 15 productive levels obtained from a new field work of the same stratigraphic unit. The palynological assemblages comprise mio-spores and subordinated organic-walled phytoplankton.

The biostratigraphic usefulness of miospores for the late Dev-onian–early Carboniferous has been recognized particularly in Euramerica, where most of the miospore biozonations utilized worldwide come from.

In fact, the Devonian/Carboniferous boundary is possibly the Palaeozoic systemic boundary best defined based on miospore biozonations. One of the most remarkable palynological events in coincidence with this boundary which can be recognized world-wide is the extinction of *Retispora lepidophyta* (Clayton, 1996).

Two main miospore zonation schemes have been erected for the Devonian. Firstly, the Richardson and McGregor (1986) one has been defined for the Old Red Sandstone continent and adjacent regions. Afterwards, the Streel et al. (1987) miospore zonation has been defined for the Ardenne-Rhenish regions. These schemes developed for Euramerica were subsequently applied for the Devonian of western Gondwana.

Streel and Loboziak (1996) correlated the upper Devonian miospore zonations of southern Euramerica, northern Euramerica and western Gondwana based on the schemes of Richardson and McGregor (1986), Streel et al. (1987) and Avkhimovitch et al. (1988).
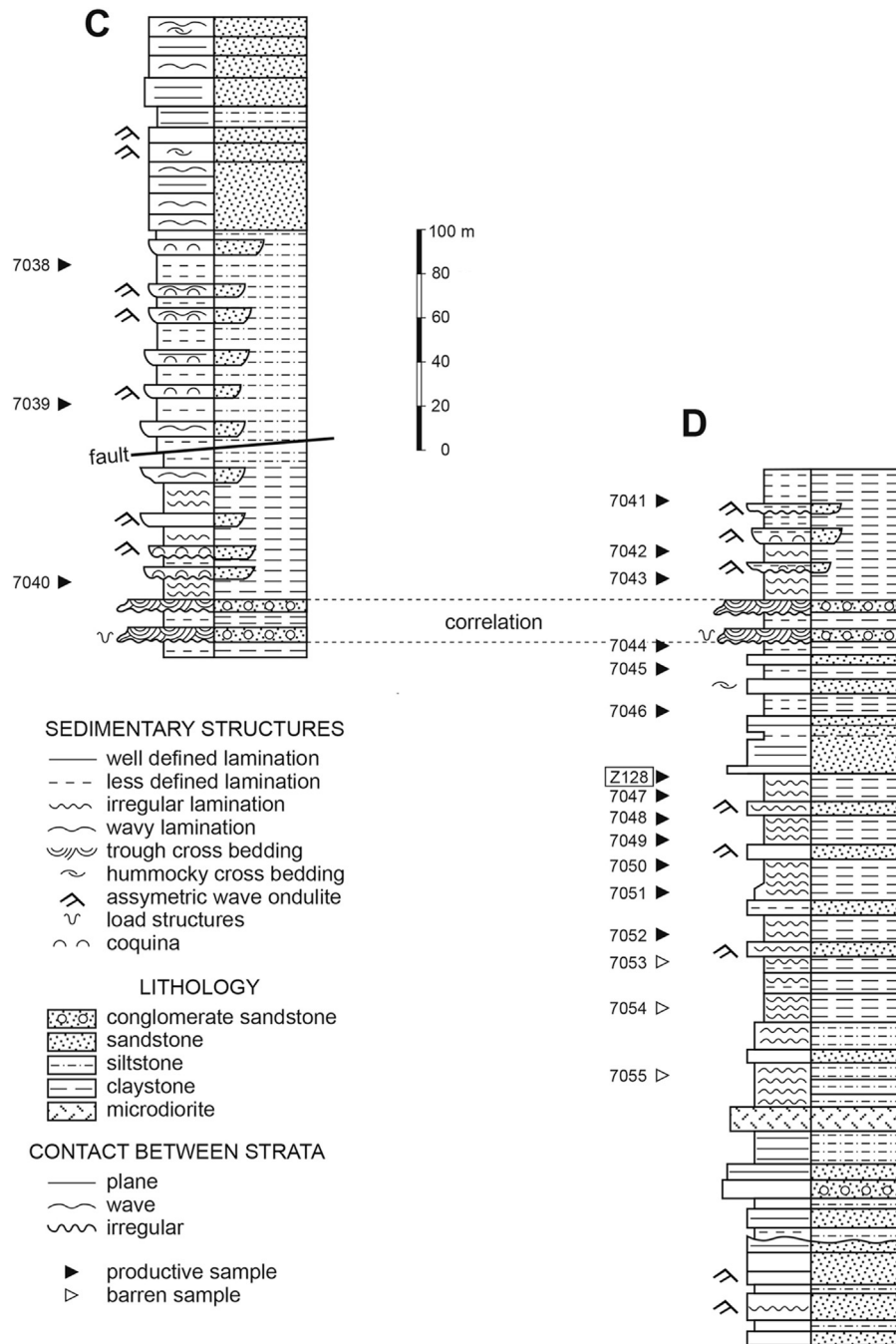
Figure 2. Stratigraphic sections C and D with the location of the studied samples.

Subsequently, Maziane et al. (1999) refined the late Famennian miospore zonation scheme based on studies in eastern Belgium, thus allowing a better correlation with other regions of Europe and North America.

Regarding the late Devonian–early Carboniferous, miospore zonations have been proposed for different regions and paleocontinents. The miospore zonal scheme of Higgs et al. (1988a) was established based on palynological studies of Ireland involving the late Famennian or "Strunian" and Tournaisian. Additionally, Higgs et al. (1988a) correlated their miospore zonation with previous British and Irish zonation schemes (Neves et al., 1972; Clayton et al., 1974, 1977). This zonation has been further applied to western European and Euramerican microfloras.

Nevertheless, owing to certain inaccuracies in the correlation of regional miospore successions with Euramerican palynozones, a new Devonian–early Carboniferous miospore zonation for the Amazon Basin was proposed by Melo and Loboziak (2003).

This zonal scheme is also applicable to other coeval Brazilian and western Gondwana basins.

The extinction event underwent by miospores near the Devonian/Carboniferous boundary also affected marine organic-walled phytoplankton. As a consequence, scarce cosmopolitan species, mainly small and morphologically simple taxa, survived the late Devonian–early Carboniferous transition (Clayton et al., 2002). The drastic reduction of the fossil marine phytoplankton related to this systemic boundary, marks the beginning of the "Phytoplankton

Blackout" that extends approximately until the late Triassic (Riegel, 2008).

Early Carboniferous phytoplankton has been recorded at equatorial and high latitudes, thus suggesting that there is no relationship between their diversity and the palaeolatitudinal position (Mullins and Servais, 2008). Even though several hypotheses have been proposed to explain the decline of the phytoplankton, the latter authors interpreted that this decline could be related to the sparse detailed studies on the Carboniferous phytoplankton in stratigraphically continuous sequences. More recently, Servais et al. (2015) interpreted the collapse of acritarchs around the Devonian/Carboniferous boundary as a consequence of the decrease of cyst-producing phytoplanktonic organisms; therefore the lack of cyst in the fossil record. Moreover, the Tournaisian has yielded the most diverse acritarch assemblages of the Carboniferous while the Visean assemblages have proven to be low diverse (Mullins and Servais, 2008 and references therein).

The goal of this paper is to report late Devonian?–Mississippian palynological assemblages of the Zorritas Formation and to propose, for the first time for northern Chile, the probable position of the Devonian/Carboniferous boundary. Such data would contribute to the knowledge of this controversial systemic boundary in western Gondwana.

2. Geological setting

The Zorritas Formation was deposited into a shallow-marine platform in a nearly north-south trending basin in the eastern part of the Antofagasta region (Bahlburg et al., 1988; Niemeyer et al., 1997). The Lower Member of the Zorritas Formation (Fig. 1b) is formed by a monotonous succession 1325 m thick of white to light grey and coarse to very coarse quartzarenites deposited in a marine tidal environment. The Middle Member (Fig. 1b,c) is composed of a 1313 m thick sequence of grey to green claystones and siltstones with intercalations of fine grained sandstones of the same colour and a few conglomerate beds. It was deposited in an internal platform environment of lower shoreface dominated by storm waves. The Middle Member is a coarsening up sequence which shields reddish sandstones on the top, thus indicating a regression in its upper part. The Upper Member does not exceed the 40 m of thickness and has a very restricted areal distribution (Fig. 1a). It is lensoid and formed by very fine grained brown to dark red sandstones with cross bedding and small channels. It overlies the Middle Member by means of an erosive rugged contact. A fluvial environment of deposition has been suggested for this member. Thus, the whole sequence of the Zorritas Formation represents a complete cycle of transgression-regression. This formation is covered in angular unconformity by Pennsylvanian to lower Permian volcaniclastic terrestrial deposits.

The detailed stratigraphy and lithology of the Zorritas Formation's Middle Member are displayed in Fig. 2.

The scarcity of fossils in the section, due to the marginal marine settings, hinders the biostratigraphic constraining of this sedimentary succession. Nevertheless, brachiopods from the upper part of the Lower Member indicate an Eifelian–Givetian or even Frasnian age for the bearing levels. A goniatite assigned to the Famennian was found in the basal part of the Middle member while the upper part of the Middle Member, dominated by sandstone beds, yielded a brachiopod fauna considered as Tournaisian (Niemeyer et al., 1997 and references therein).

3. Material and methods

Forty-eight palynological samples of the Zorritas Formation were analysed from the Quebrada Zamolana and the Quebrada del Agua Dulce (Fig. 1a). However, the only productive samples came from two stratigraphic sections of the Quebrada Zamolana. These, labelled C and D (Fig. 1a), cover the Middle Member of the formation. Along these two sections, palynological samples correspond to dark grey to green claystone to siltstone lithologies (Fig. 2).

From the 16 productive levels, sample Z128 was previously studied (Rubinstein et al., 1996).

Samples were processed in the Paleopalynology Laboratory of the Instituto Argentino de Nivología, Glaciología y Ciencias Ambientales, Centro Científico Tecnológico CONICET Mendoza, using standard HCl-HF-HCl acid maceration techniques. The residues were oxidized 15 to 30 min with a Schulze solution (HNO_3+KClO_3) and were sieved using a 10 μm mesh. The palynomorphs were mounted in glycerine jelly as permanent palynological slides and examined using light microscopy.

The palynological slides are housed in the palynological collection of the IANIGLA, CCT CONICET Mendoza, Argentina. Specimens in the slides are located by means of the England Finder coordinates.

4. Palynostratigraphic results

Most of the palynomorphs recovered from both sections of the Zorritas Formation are carbonized, broken and dark brown to black in colour, thus hindering their positive identification at specific level. Seventy miospore species, eighteen marine phytoplankton species, two non-marine algae and one chitinozoan were nevertheless recognized (Figs. 3 and 4).

The complete list of species is displayed in Appendix A.

Miospores show a clear predominance in all the studied levels and are more diverse than phytoplankton as well.

Miospores have been analysed within the framework of the zonation schemes established for western Europe (Clayton, 1985; Streel et al., 1987; Higgs et al., 1988a,b; Maziane et al., 1999) and western Gondwana (Melo and Loboziak, 2003). Their global stratigraphic distribution is shown in Fig. 5.

Based on the identified spores (Figs. 6–8), three palynological associations can be distinguished. These can be assigned to the Tournaisian–Visean, Tournaisian and latest Famennian (Strunian)? (Fig. 3), thus suggesting the position of the Devonian/Carboniferous boundary.

The scarce, poorly preserved and low diverse phytoplankton (Fig. 9) resulting in most of the taxa being left in open nomenclature together with the lack of reliable stratigraphic markers, hinder the use of phytoplankton to support age based in miospore zonation.

Most of the palynomorph taxa of the late Devonian?–Tournaisian palynological associations herein analysed have been considered reworked. A transition to subaerial conditions has already been pointed out for northern Chile basins, beginning for the early Carboniferous, when, according to Bahlburg and Breitkreuz (1993), the Gondwana glaciation set up and global sea-level dropped. Therefore, the occurrence of recycled palynomorphs has been interpreted, as stated by Caputo et al. (2008), as a consequence of sea-level falls that could have removed and then incorporated older sediments into glacial and non glacial-derived strata during the glaciation.

The three miospore associations from the upper to the lower beds are described below, together with the accompanying marine and non-marine phytoplankton and chitinozoans.

4.1. Tournaisian–Visean association (samples 7038 to 7047)

Among the miospore association, there are species that first appear in the Visean. That is the case of *Spelaeotriletes arenaceus* (sample 7041), which is known from western Europe and from the
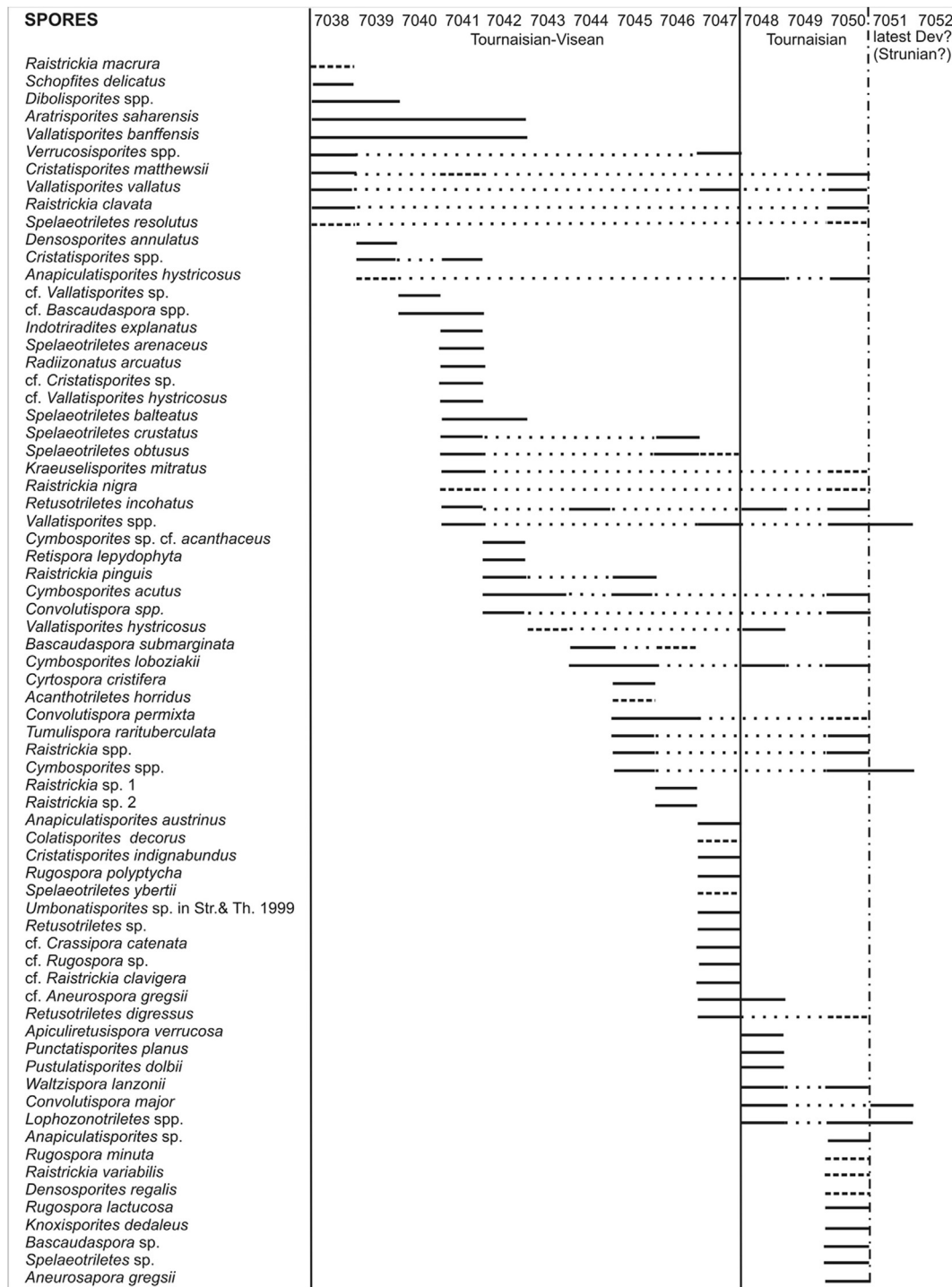
Figure 3. Stratigraphic distribution of miospore species in the studied levels. Positively identified species are indicated in continuous lines; cf. species in dashed lines; supposed stratigraphic range in dotted lines.

Mag Zone of Brazil (Playford et al., 2001; Playford and Melo, 2012 and references therein); *Raistrickia nigra* (as *R.* cf. *nigra* in sample 7041), which occurs from the Visean NM to VF Zones of Britain and eastern Europe and extends to the Namurian (Owens et al., 2004, 2005; Górecka-Nowak and Muszer, 2011); *Raistrickia pinguis* (samples 7042 and 7045), a Gondwanan species first described for the Visean of Australia (Playford, 1971) and also presented in the late Carboniferous of Brazil (Souza and Marques-Toigo, 2003); *Anapiculatisporites austrinus* (sample 7047), first

occurring in the Visean of Australia (Playford and Satterthwait, 1986) and also present in the Visean of Peru (Azcuy and di Pasquo, 2005) and Argentina (Perez Loinaze, 2007); and *Spelaeotriletes ybertii* (as *S.* cf. *ybertii* in sample 7047), which has its oldest record in the lower middle Pennsylvanian of South America (Playford et al., 2001).

This association is also characterized by the presence of several species that range from the Tournaisian to the Visean. They are *Spelaeotriletes balteatus* (samples 7041 and 7042), which is an index
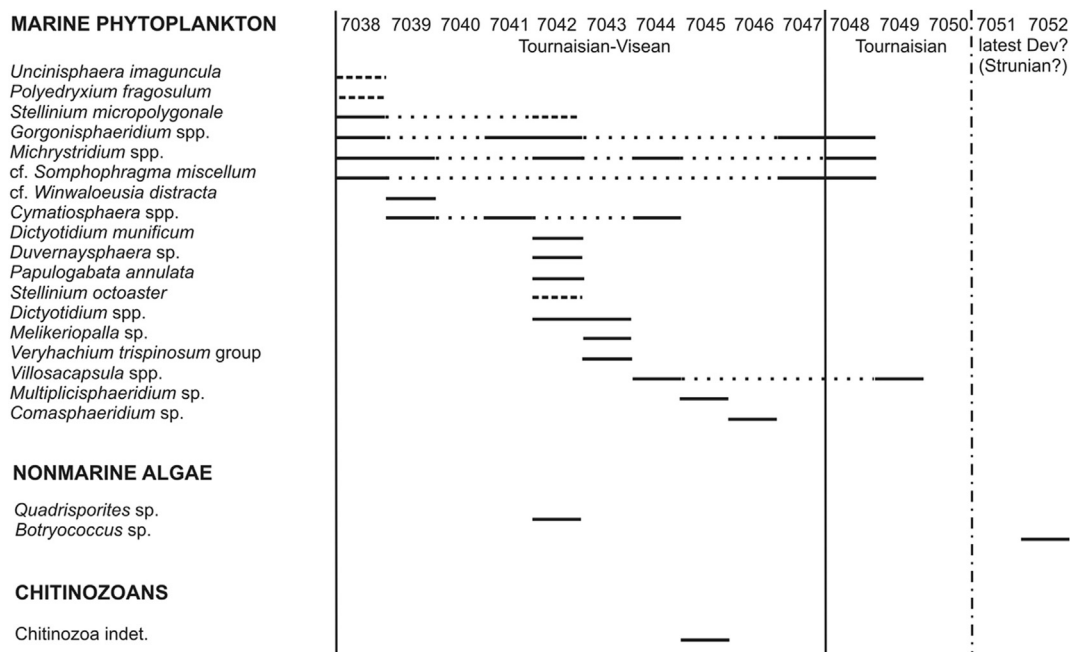
Figure 4. Stratigraphic distribution of marine phytoplankton, nonmarine algae and chitinozoans in the studied levels. Positively identified species are indicated in continuous lines; cf. species in dashed lines; supposed stratigraphic range in dotted lines.

species of the BP Zone of Britain and the BL Zone of Brazil and extends to the CM Zone (Higgs et al., 1988a; Brittain and Higgs, 2007) and the Mag zone (Melo and Loboziak, 2003; Playford et al., 2012) respectively; *Kraeuselisporites mitratus* (samples 7041, cf. in 7050), that ranges from the PC and PD zones to the NM and Mag zones in western Europe and Gondwana (Higgs et al., 1988a; Melo and Loboziak, 2003; Azcuy and di Pasquo, 2005); and *Cristatisporites indignabundus* (sample 7047), of the Tournaisian–Visean of Europe, USA and Brazil (Souza et al., 2003; Azcuy and di Pasquo, 2005; Amenábar et al., 2007 and references therein). *Raistrickia clavata* (sample 7038 and 7050), *Colatisporites decorus* (cf. in sample 7047) and *Raistrickia clavigera* (doubtful assignment in sample 7047) range from the highest Tournaisian (PC/PD and CM zones) to the Mag Interval Zone (Higgs et al., 1988a; Melo and Loboziak, 2003; Playford and Melo, 2012 and references therein). *C. decorus* (cf. in sample 7047) first occurs within the PD Zone, while being as well one of the index species of this spore zone.

Species of this association ranging from the late Devonian to the Visean, from Rle/LE to Mag/TC-NM zones, are *Vallatisporites banffensis* (samples 7038 to 7042) (Ravn et al., 1994; Playford et al., 2012), *Vallatisporites vallatus* (samples 7038, 7047, 7050), *Densosporites annulatus* (sample 7039) and *R. incohatus* (samples 7041, 7044, 7050) which is one of the nominal species of the VI Zone (Higgs et al., 1988a; Clayton and Turnau, 1990; Playford and Melo, 2012 and references therein). Species recorded from the LL Zone to the Mag Zone or Visean s.l. are *Bascaudaspora submarginata* (samples 7044, cf. in 7046) (Higgs et al., 1988a; Azcuy and di Pasquo, 2005; Dueñas and Césari, 2006) and *Cyrtospora cristifer* (sample 7045) (Clayton and Turnau, 1990; Playford et al., 2012 and latest Frasnian–early Famennian of Euramerica according to Playford and McGregor, 1993). *Indotriradites explanatus* (sample 7041) is a cosmopolitan species that first appears in the LE Zone (index species) ranging to the late Tournaisian or early Visean (Playford, 1991, 1993; Playford and Melo, 2012).

Aratrisporites saharensis (samples 7038 to 7042) and *Radiizonatus arcuatus* (sample 7041) are especially relevant because they are palaeogeographic markers of Gondwana. Both of them first

appear in the Strunian Rle/LE and Lva zones respectively and extend to the Visean (Mag/NM zones) (Melo and Loboziak, 2003; Playford et al., 2012; Playford and Melo, 2012).

There are species with stratigraphic ranges restricted to the Carboniferous such as *Acanthotriletes horridus* (Mississippian), *Retusotriletes digressus* (Tournaisian), *Spelaeotriletes* cf. *resolutus* (VI-PC zones), *Rugospora polyptycha* and *Schopfites delicatus* (HD-CM zones), *Convolutispora permixta* (PC-CM zones) and *Anapiculatisporites hystricosus* (PD-CM zones). Species ranging from the latest Devonian to the Tournaisian are *Cristatisporites matthewsii*, *Spelaeotriletes crustatus* and *Raistrickia macrura* (LL-PC zones), *Spelaeotriletes obtusus* (LE-BP zones), *Cymbosporites acutus* (Strunian–Tournaisian), and *Tumulispora rarituberculata* (late Famennian–early Carboniferous) (see Hacquebard, 1957; Playford, 1964, 1976; Higgs et al., 1988a; Clayton and Turnau, 1990; Playford and McGregor, 1993; Melo and Loboziak, 2003; Dueñas and Césari, 2006; Amenábar et al., 2007; Playford et al., 2012; Playford and Melo, 2012).

The genus *Umbonatisporites*, represented in the studied section by *Umbonatisporites* sp. in Streel and Theron (1999) has been considered by these authors as a typical Tournasian genus. However, it is known since the Rle Zone of Brazil (Melo and Loboziak, 2003).

Cymbosporites loboziakii ranges from the AL to the PD zones in Brazil (Melo and Loboziak, 2003), though it has been recorded from the latest Devonian in Africa (Playford and Melo, 2012).

This association is also composed of late Devonian species, herein considered as reworked. *Vallatisporites hystricosus* ranges from the *V. hystricosus* Interval Zone (Hys) of Brazil to the LN Zone. Its occurrences in the Tournaisian have been considered as reworked (Melo et al., 1999; Melo and Loboziak, 2003; Wicander and Playford, 2013).

Cymbosporites acanthaceus, *Crassipora catenata* and *Aneurospora greggsii* are late Devonian species without youngest records (Streel in Becker et al., 1974; Obukhovskaya et al., 2000; Melo and Loboziak, 2003; Streel, 2009). Furthermore, in this study, they have been classified with doubts because of their bad preservation.
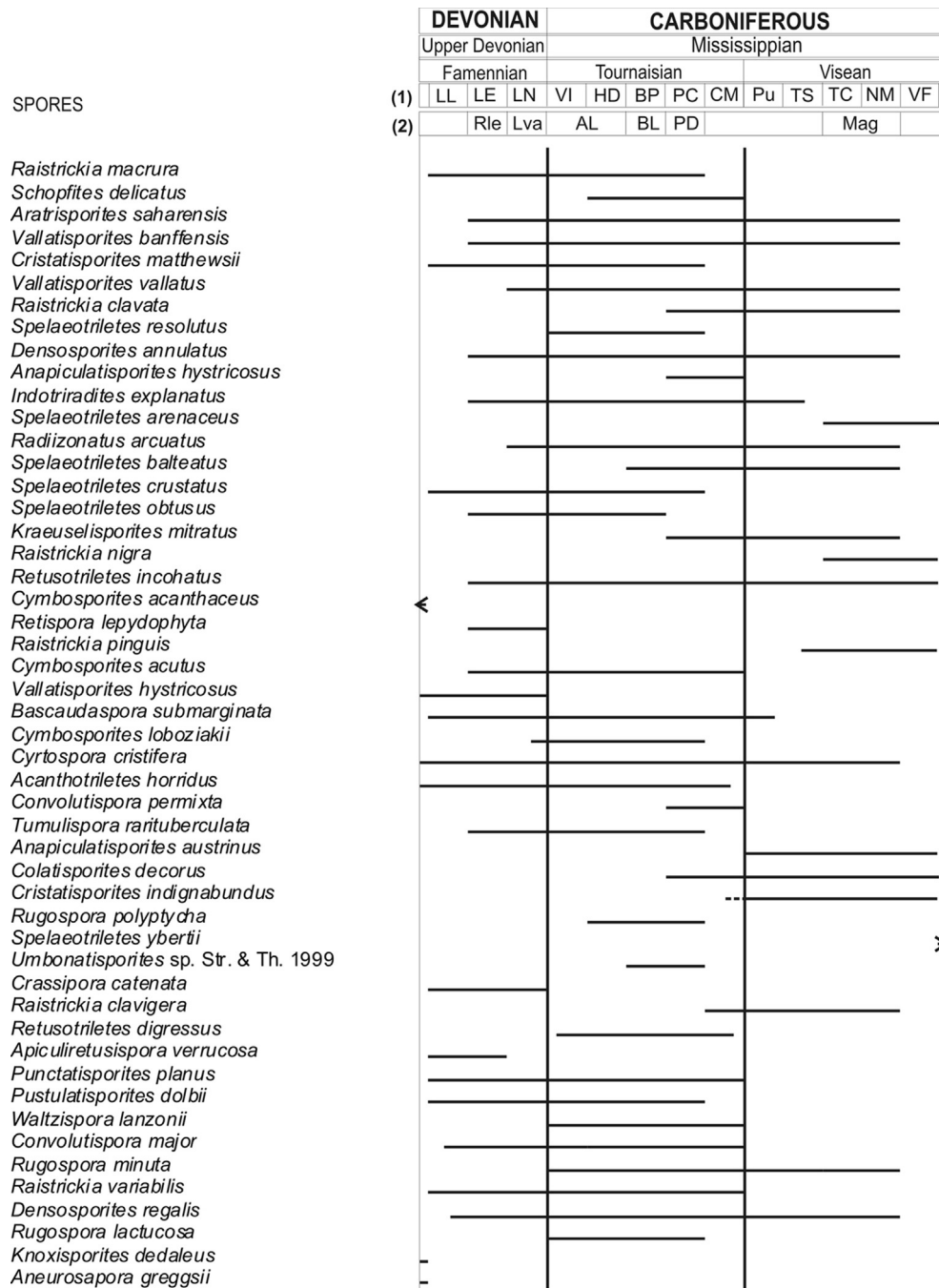
	DEVONIAN	CARBONIFEROUS					
	Upper Devonian	Mississippian					
	Famennian	Tournaisian			Visean		

SPORES

(1) LL | LE | LN | VI | HD | BP | PC | CM | Pu | TS | TC | NM | VF

(2) Rle | Lva | AL | BL | PD | Mag

Raistrickia macrura
Schopfites delicatus
Aratrisporites saharensis
Vallatisporites banffensis
Cristatisporites matthewsii
Vallatisporites vallatus
Raistrickia clavata
Spelaeotriletes resolutus
Densosporites annulatus
Anapiculatisporites hystricosus
Indotriradites explanatus
Spelaeotriletes arenaceus
Radiizonatus arcuatus
Spelaeotriletes balteatus
Spelaeotriletes crustatus
Spelaeotriletes obtusus
Kraeuselisporites mitratus
Raistrickia nigra
Retusotriletes incohatus
Cymbosporites acanthaceus
Retispora lepydophyta
Raistrickia pinguis
Cymbosporites acutus
Vallatisporites hystricosus
Bascaudaspora submarginata
Cymbosporites loboziakii
Cyrtospora cristifera
Acanthotriletes horridus
Convolutispora permixta
Tumulispora rarituberculata
Anapiculatisporites austrinus
Colatisporites decorus
Cristatisporites indignabundus
Rugospora polyptycha
Spelaeotriletes ybertii
Umbonatisporites sp. Str. & Th. 1999
Crassipora catenata
Raistrickia clavigera
Retusotriletes digressus
Apiculiretusispora verrucosa
Punctatisporites planus
Pustulatisporites dolbii
Waltzispora lanzonii
Convolutispora major
Rugospora minuta
Raistrickia variabilis
Densosporites regalis
Rugospora lactucosa
Knoxisporites dedaleus
Aneurosapora greggsii

Figure 5. Global stratigraphic ranges of miospore species identified in this study. Correlation with miospore zones of (1) western Europe (Clayton, 1985; Streel et al., 1987; Higgs et al., 1988a,b; Maziane et al., 1999) and (2) Brazil and western Gondwana (Melo and Loboziak, 2003). Spore zones: LL: *Retispora lepidophyta-Knoxisporites literatus*; LE: *Retispora lepidophyta-Indotriradites explanatus*; LN: *Retispora lepidophyta-Verrucosisporites nitidus*; VI: *Vallatisporites verrucosus-Retusotriletes incohatus*; HD: *Kraeuselisporites hibernicus-Umbonatisporites distinctus*; BP: *Spelaeotriletes balteatus-Rugospora polyptycha*; PC: *Spelaeotriletes pretiosus-Raistrickia clavata*; CM: *Schopfites claviger-Auroraspora* macra; Pu: *Lycospora pusilla*; TS: *Knoxisporites triradiatus-Knoxisporites stephanephorus*; TC: *Perotrilites tessellatus-Schulzospora campyloptera*; NM: *Raistrickia nigra-Triquitrites marginatus*; VF: *Tripartites vetustus-Rotaspora fracta*; Rle: *Retispora lepidophyta*; Lva: *Retispora lepidophyta-Vallatisporites vallatus*; AL: *Radiizonates arcuatus-Waltzispora lanzonii*; BL: *Spelaeotriletes balteatus-Neoraistrickia loganii*; PD: *Spelaeotriletes pretiosus-Colatisporitus decorus*; Mag: *Reticulatisporites magnidityus*.

The widespread cosmopolitan *R. lepidophyta* species (sample 7042) is an outstanding marker of the latest Famennian or Strunian. It is a key index species of the western Europe *R. lepidophyta-Knoxisporites literatus* (LL), *R. lepidophyta-I. explanatus* (LE) and *R. lepidophyta-Verrucosisporites nitidus* (LN) interval zones and of the *R. lepidophyta* (Rle) and *R. lepidophyta-V. vallatus* (Lva) interval zones of Brazil. The complete extinction of *R. lepidophyta* is just below the base of the Carboniferous, corresponding to the change from the LN Zone to the VI Zone. Because of the uncertain definition of the VI Assemblage Zone (the nominal species occur in the underlying zone), its base is considered the *R. lepidophyta* LOB (Last Occurrence Biohorizon). Although generally sparse, *R. lepidophyta* may be recorded in post-Devonian strata due to its susceptibility to be reworked (Streel, 2009; Wicander and Playford, 2013 and references therein).
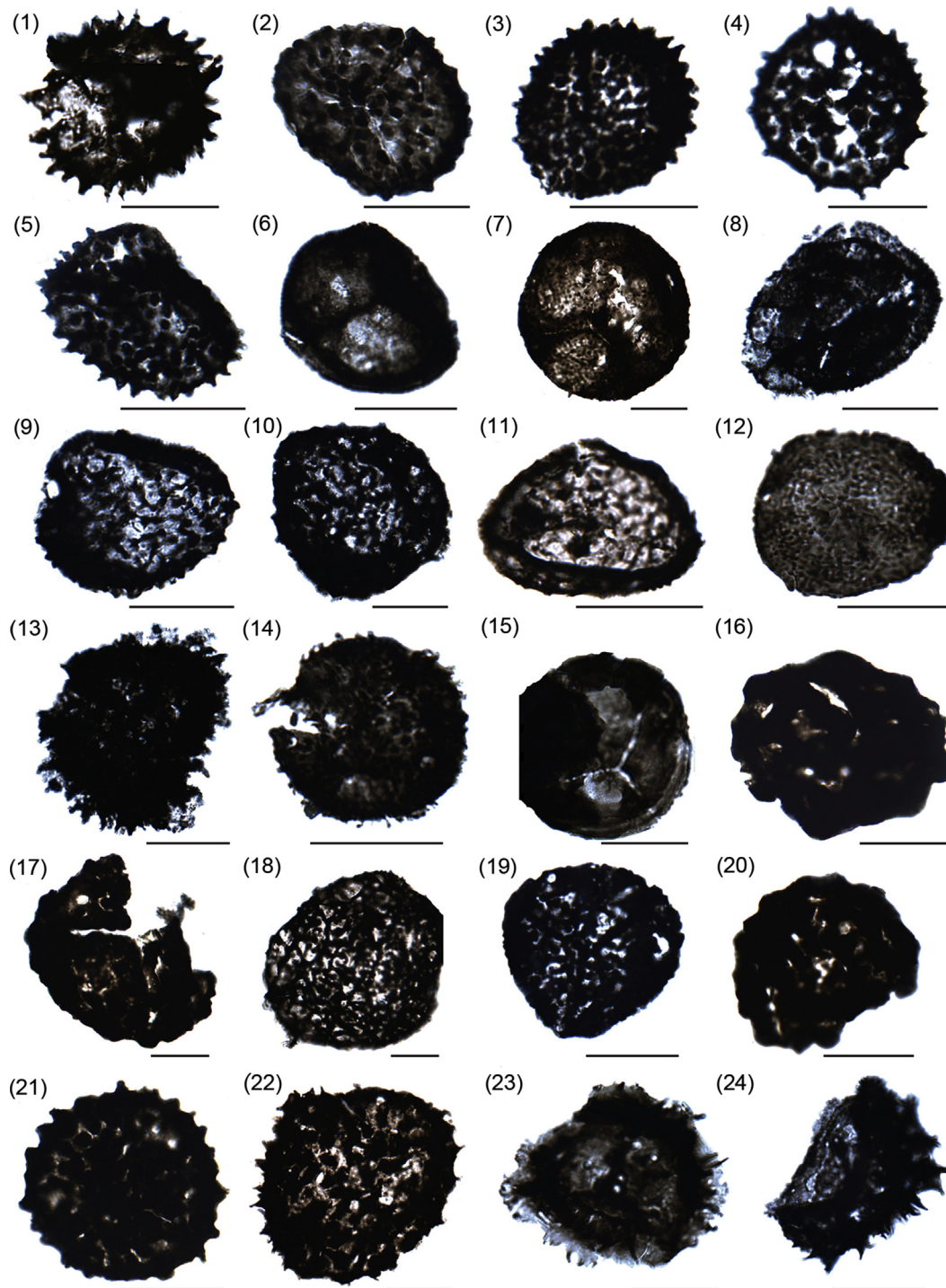
Figure 6. Miospores of the Middle Member of the Zorritas Formation. The scale bars represent 20 μm. (1) *Acanthotriletes horridus* (Hacquebard, 1957); 7045c, D42/3. (2) *Anapiculatisporites austrinus* Playford and Satterthwait, 1986; 7047e, D38/3. (3) *Anapiculatisporites hystricosus* Playford, 1964; 7048a, O25/2. (4) *Anapiculatisporites hystricosus* Playford, 1964; 7050a, M30/0. (5) *Anapiculatisporites* sp.; 7050a, H24/2. (6) *Aneurospora greggsii* (McGregor) Streel in Becker et al., 1974; 7050a, N25/0. (7) *Apiculiretusispora verrucosa* (Caro-Moniez) Streel in Becker et al., 1974; 7048a, O30/1. (8) *Aratrisporites saharensis* Loboziak et al., 1986; 7038b, P23/4. (9) *Bascaudaspora* cf. *submarginata* (Playford) Higgs et al., 1988a,b; 7046e, U28/2. (10) *Bascaudaspora* sp.; 7046e, V4/3. (11) *Bascaudaspora submarginata* (Playford) Higgs et al., 1988a,b; 7044c, U28/2. (12) cf. *Crassipora catenata* Higgs, 1975; 7047e, L34/2. (13) cf. *Cristatisporites* sp.; 7041a, Y32/1. (14) cf. *Raistrickia clavigera* (Sullivan) Playford and Satterthwait, 1986; 7047e, M41/2. (15) *Colatisporites* cf. *decorus* (Bharadwaj and Venkatachala) Williams in Neves et al., 1973; 7047e, E40/3. (16) *Convolutispora major* (Kedo) Turnau, 1978; 7048a, P44/0. (17) *Convolutispora major* (Kedo) Turnau, 1978; 7051a, V39/4. (18) *Convolutispora permixta* Higgs et al., 1988a,b; 7045c, D26/1. (19) *Convolutispora permixta* Higgs et al., 1988a,b; 704e, P26/0. (20) *Convolutispora* spp.; 7050a, Q30/1. (21) *Cristatisporites matthewsii* Higgs et al., 1988a,b; 7050a, Q24/0. (22) *Cristatisporites* cf. *matthewsii* Higgs et al., 1988a,b; 7041a, G49/1. (23) *Cristatisporites indignabundus* (Loose) Staplin and Jansonius, 1964; 7047e, S40/2. (24) cf. *Cymbosporites acutus* (Kedo) Byvscheva, 1985; 7042e, K29/3.
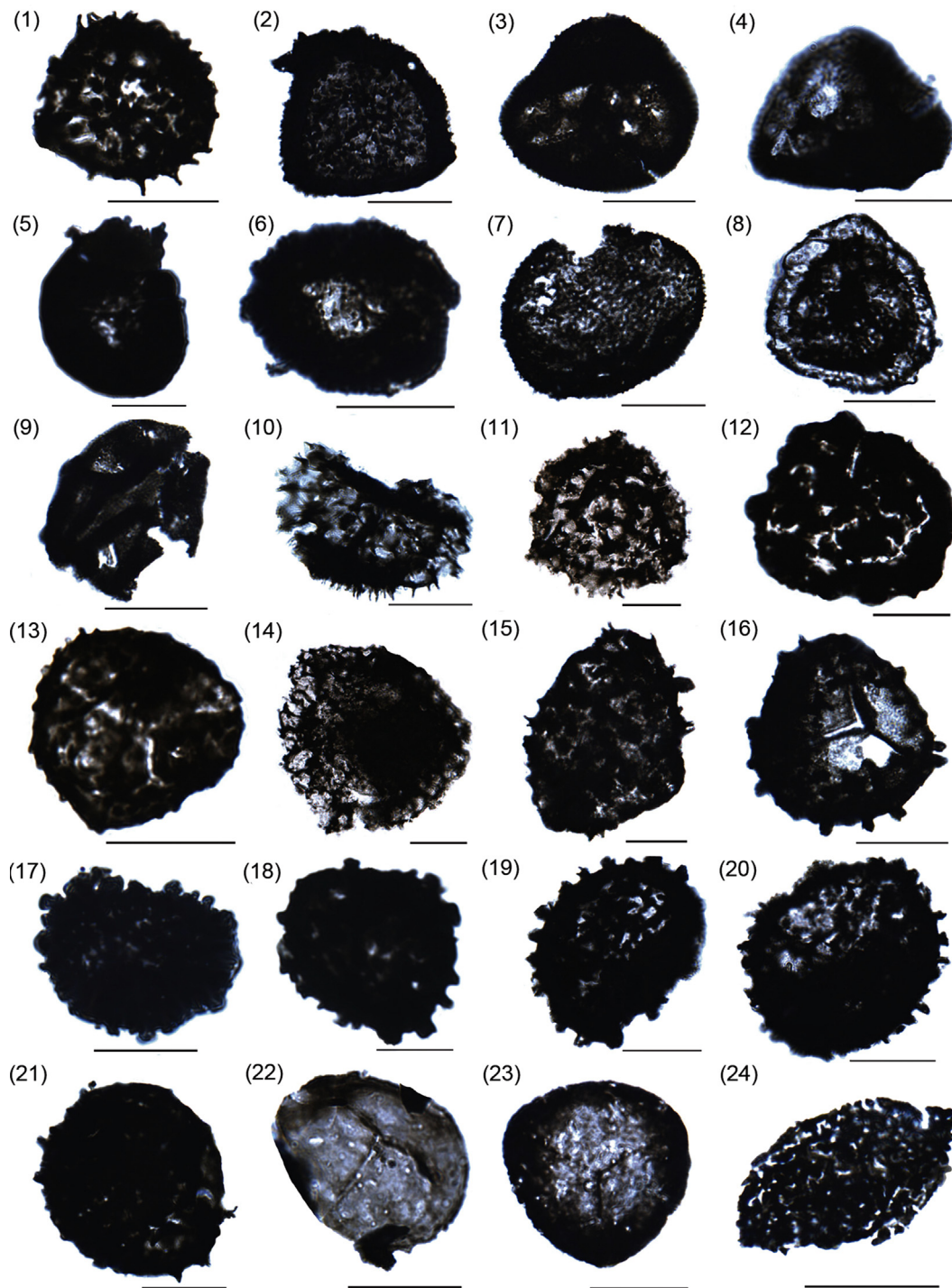
Figure 7. Miospores of the Middle Member of the Zorritas Formation. The scale bars represent 20 μm. (1) *Cymbosporites acutus* (Kedo) Byvscheva, 1985; 7050a, U21/2. (2) *Cymbosporites* sp. cf. *acanthaceus* (Kedo) Obukhovskaya in Obukhovskaya et al., 2000; 7042e, L20/2. (3) *Cymbosporites* spp.; 7050a, C26/1. (4) *Cyrtospora cristifer* (Luber) Van der Zwan, 1979; 7045e, T21/1. (5) *Densosporites annulatus* (Loose) Smith and Butterworth, 1967; 7039a, K24/4. (6) *Densosporites* cf. *regalis* (Bharadwaj and Venkatachala) Smith and Butterworth, 1967; 7050a, R27/3. (7) *Dibolisporites* sp.; 7038a, F43/3. (8) *Indotriradites explanatus* (Luber) Playford, 1991; 7041a, C34/2. (9) *Knoxisporites dedaleus* (Naumova) Moreau-Benoit, 1980; 7050a, S31/0. (10) *Kraeuselisporites* cf. *mitratus* (Higgs) Higgs, 1996; 7050a, F24/0. (11) *Kraeuselisporites mitratus* (Higgs) Higgs, 1996; 7041a, Q28/4. (12) *Lophozonotriletes* spp.; 7048a, K35/1. (13) *Pustulatisporites dolbii* Higgs et al., 1988a,b; 7048a, U24/1. (14) *Radiizonatus arcuatus* Loboziak et al., 2000; 7041a, V34/0. (15) *Raistrickia* cf. *macrura* (Luber) Dolby and Neves, 1970; 7038b, J24/3. (16) *Raistrickia* cf. *nigra* Love, 1960; 7050a, Q39/2. (17) *Raistrickia clavata* (Hacquebard) Playford, 1964; 7038a, O29/2. (18) *Raistrickia pinguis* Playford, 1971; 7045c, S40/2. (19) *Raistrickia* sp. 1; 7046e, X25/3. (20) *Raistrickia* sp. 2; 7046e, S32/2. (21) *Raistrickia* cf. *variabilis* Dolby and Neves, 1970; 7050a, B27/3. (22) *Retusotriletes digressus* Playford, 1976; 7047e, K22/0. (23) *Retusotriletes incohatus* Sullivan, 1964; 7041a, J35/1. (24) *Rugospora* cf. *minuta* Neves and Ioannides, 1974; 7050a, V26/0.
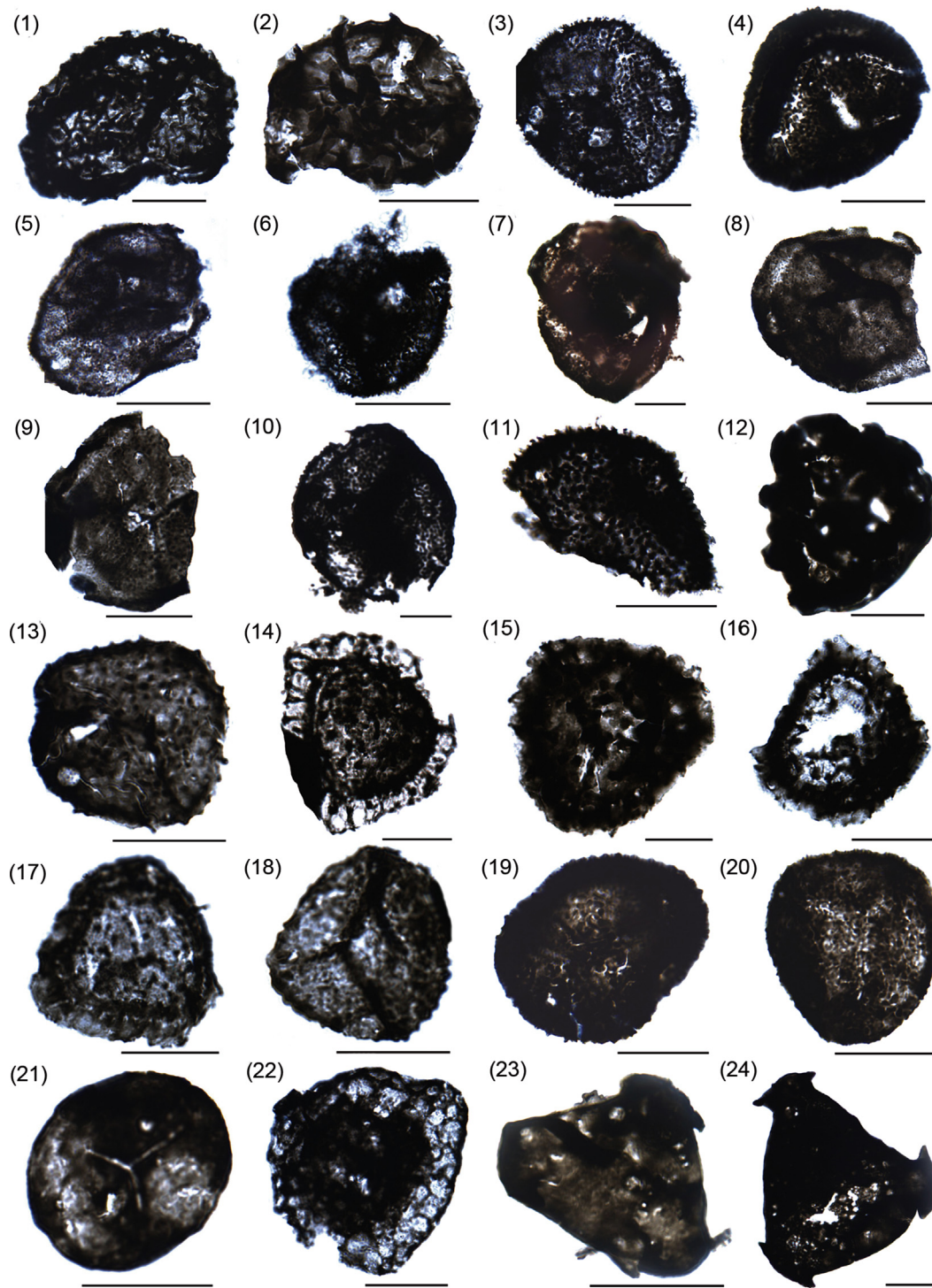
Figure 8. Miospores of the Middle Member of the Zorritas Formation. The scale bars represent 20 μm. (1) *Rugospora lactucosa* Higgs et al., 1988a,b; 7050a, E23/2. (2) *Rugospora polyptycha* Neves and Ioannides, 1974; 7047e, F22/0. (3) *Schopfites delicatus* (Higgs) Higgs et al., 1988a,b; 7038b, O42/2. (4) *Spelaeotriletes* sp.; 7050a, J33/0. (5) *Spelaeotriletes arenaceus* Neves and Owens, 1966; 7041a, U43/3. (6) *Spelaeotriletes balteatus* (Playford) Higgs, 1996; 7041a, D34/0. (7) *Spelaeotriletes* cf. *resolutus* Higgs, 1975; 7038a, U31/3. (8) *Spelaeotriletes* cf. *ybertii* (Marques-Toigo) Playford et al., 2001; 7047e, R24/2. (9) *Spelaeotriletes* cf. *obtusus* Higgs, 1975; 7047e, N34/4. (10) *Spelaeotriletes crustatus* Higgs, 1975; 7046e, M32/2. (11) *Spelaeotriletes obtusus* Higgs, 1975; 7041a, P28/0. (12) *Tumulispora rarituberculata* (Luber) Playford, 1991; 7045c, Q37/0. (13) *Umbonatisporites* sp. in Streel and Theron, 1999; 7047e, Y35/0. (14) *Vallatisporites banffensis* Staplin and Jansonius, 1964; 7038a, Q38/3. (15) *Vallatisporites hystricosus* (Winslow) Wicander and Playford, 2013; 7048a, L32/3. (16) *Vallatisporites vallatus* Hacquebard, 1957; 7050a, H40/3. (17) *Vallatisporites vallatus* Hacquebard, 1957; 7047e, D36/1. (18) *Verrucosisporites* spp.; 7047e, D38/0. (19) *Cymbosporites loboziakii* Melo and Playford, 2012; 7050a, O26/2. (20) *Cymbosporites loboziakii* Melo and Playford, 2012; 7048a, P44/0. (21) *Punctatisporites planus* Hacquebard, 1957; 7048a, H25/2. (22) *Retispora lepidophyta* (Kedo) Playford, 1976; 7042e, Y25/0. (23) *Waltzispora lanzonii* Daemon, 1974; 7050a, A37/0. (24) *Waltzispora lanzonii* Daemon, 1974; 7048a, Y28/0.
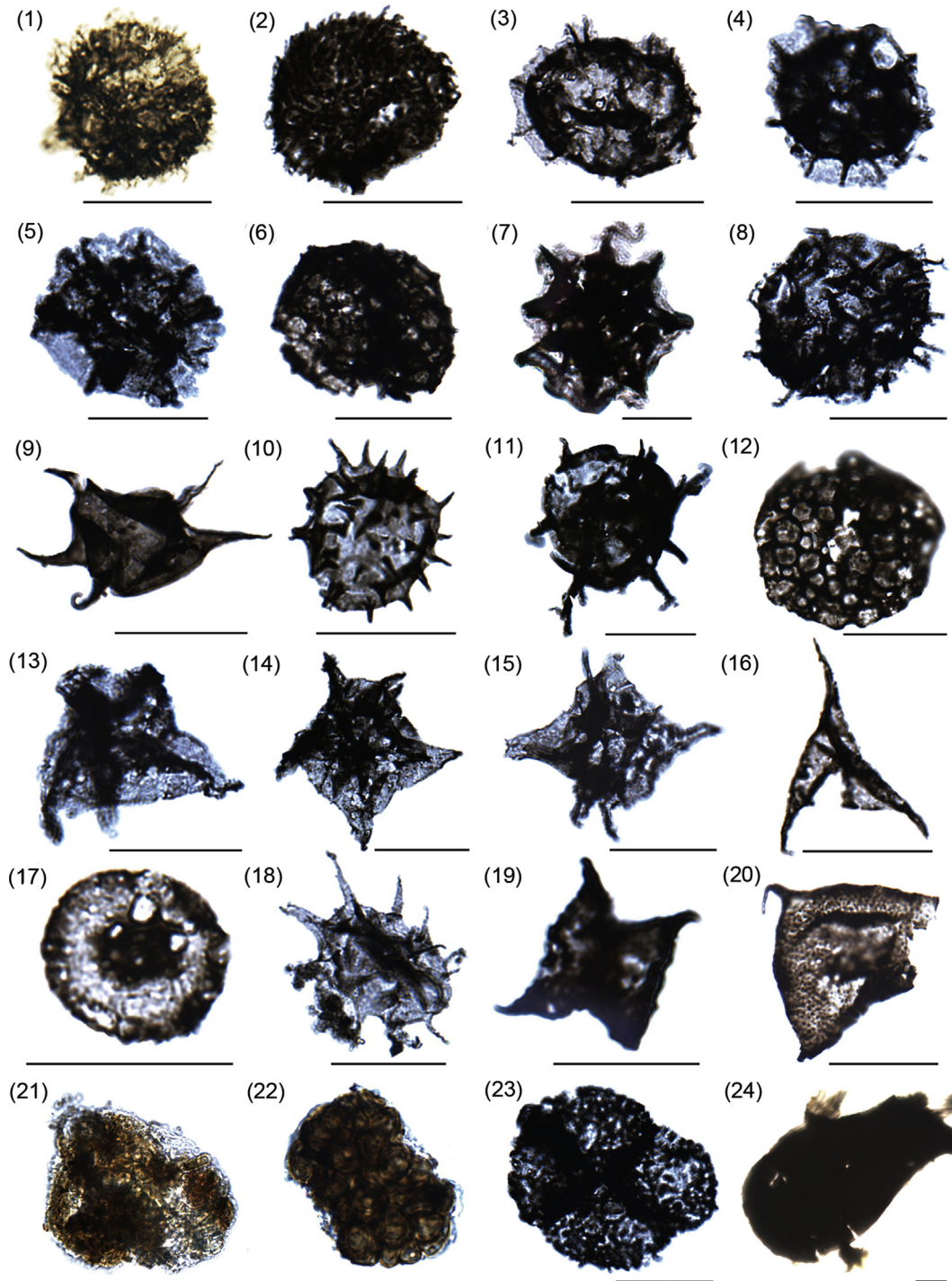
Figure 9. Marine phytoplankton, non-marine palynomorphs and chitinozoan of the Middle Member of the Zorritas Formation. The scale bars represent 20 μm. (1) *Comasphaeridium* sp.; 7046e, N43/3. (2) cf. *Somphophragma miscellum* Playford and Dring, 1981; 7048a, F22/1. (3) *Cymatiosphaera* spp.; 7041a, X27/4. (4) *Cymatiosphaera* spp.; 7039a, N40/4. (5) *Dictyotidium munificum* (Wicander and Wood) Amenábar et al., 2006; 7042e, M26/4. (6) *Dictyotidium* sp.; 7042e, G41/0. (7) *Duvernaysphaera* sp.; 7042e, D21/4. (8) *Gorgonisphaeridium* spp.; 7041a, F25/2. (9) *Michrystridium* spp.; 7042e, S40/3. (10) *Michrystridium* spp.; 7048a, W28/2. (11) *Multiplicisphaeridium* sp.; 7045c, V42/3. (12) *Melikeriopalla* sp.; 7043a, X47/1. (13) *Polyedryxium* cf. *fragosulum* Playford, 1977; 7038a, F23/4. (14) *Stellinium* cf. *micropolygonale* (Stockmans and Willière) Playford, 1977; 7038a, N42/0. (15) *Stellinium* cf. *octoaster* (Staplin) Jardiné et al., 1972; 7042e, J23/0. (16) *Veryhachium trispinosum* group Servais et al., 2007; 7043e, G26/0. (17) *Papulogabata annulata* Playford and Dring, 1981; 7042e, Q42/3. (18) *Uncinisphaera* cf. *imaguncula* Wicander and Playford, 1985; 7038b, M29/0. (19) cf. *Winwaloeusia distracta* Deunff, 1977; 7039e, S39/1. (20) *Villosacapsula* sp.; 7044c, M19/2. (21) *Botryococcus* sp.; 7052a, A38/3. (22) *Botryococcus* sp.; 7052a, B38/0. (23) *Quadrisporites* sp.; 7042e, E36/0. (24) Chitinozoan gen. sp. indet.; 7045c, Z37/0.

The associated phytoplankton (acritarch and chlorophytes) (Fig. 4) is composed of species that stratigraphically range until the Famennian of Gondwana and Laurussia, such as *Dictyotidium munificum*, *Stellinium micropolygonale* and *Stellinium octoaster* (Clayton et al., 2002). Nevertheless, Wicander and Playford (2013) suggested that *S. micropolygonale* may reach the early Mississippian. *Polyedryxium fragosulum* ranges worldwide from the Pragian to the middle Devonian (Playford, 1977; Rubinstein et al., 2008),

while *Winwaloeusia distracta*, only known from Gondwana, ranges from the early to the late Devonian (Deunff, 1980; Rubinstein et al., 2008). Additionally, *Somphophragma miscellum* and *Papulogabata annulata* are known from the late Devonian of Australia (Playford and Dring, 1981).

All these taxa, with the possible exception of *S. micropolygonale*, could be considered as reworked in the Tournaisian–Visean association.

Representatives of the *Veryhachium trispinosum* Group and the genera *Michrystridium*, *Cymatiosphaera*, *Gorgonisphaeridium*, *Duvernaysphaera*, *Dictyotidium*, *Multiplicisphaeridium*, *Comasphaeridium* and *Quadrisporites* could be autochthonous or recycled taxa.

The single chitinozoan specimen (Fig. 9 (24)) found in level 7045 unquestionably indicates reworking of oldest strata because the extinction of this group took place at the end of the Devonian.

Of the few exclusively Visean species recorded in levels 7038 to 7047, even fewer could be positively identified or considered unquestionable stratigraphic markers. Additionally, there are several taxa that range from the latest Famennian or Tournaisian to the Visean. For these reasons, a Tournaisian–Visean age is suggested for this palynological association.

Taxa with stratigraphic ranges restricted to the Carboniferous could be considered as reworked as well as most of the phytoplankton species. Species with stratigraphic ranges limited to the Devonian, such as *R. lepidophyta*, are considered recycled in coincidence with sedimentological interpretations of the studied sections that evidence a nearshore environment dominated by storm waves in a platform reflecting eustatic sea level changes (Bahlburg and Breitkreuz, 1993).

Supposedly equivalent levels 7043 of section D and 7040 of section C, located just above a conglomerate allowing correlation of both sections, are very poor in palynomorphs.

Level 7043 yielded only recycled species while level 7040 yielded *A. saharensis* and *V. banffensis*, both of which reach the Visean.

4.2. Tournaisian association (samples 7048 to 7050)

This association contains *Waltzispora lanzonii* (samples 7048 and 7050) cronostratigraphically constrained to the Tournaisian (AL to the PD interval zones) and palaegeographically restricted to north-northwestern Gondwana, with records in Brazil, Peru, Argentina, Algeria and Libya (Playford and Melo, 2010, 2012; Playford et al., 2012; Prestianni et al., 2015). Its uncommon records in Visean strata have been considered to be probably reworked (Playford and Melo, 2012 and references therein). Other Carboniferous species are *Rugospora minuta* (cf. in sample 7050), that first appears at the base of the Tournaisian in the VI Zone extending its stratigraphic range to the Visean NM Zone (Higgs et al., 1988a; Melo and Loboziak, 2003; Owens et al., 2005) and *Rugospora lactucosa*, present from the VI to the PC zones. However, the latter species has been described for the latest Devonian LN Zone in Germany (Higgs et al., 1993), although the authors suggest that it would be an anomalous zone in some way transitional in composition to the lowermost Tournaisian VI Zone. This association is also composed of species that range from the Devonian to the Tournaisian. *Punctatisporites planus* first appears in the middle Devonian (Amenábar et al., 2006). Latest Devonian (Strunian)–Tournaisian species are *Pustulatisporites dolbii* (LL-PC zones), *Raistrickia variabilis* (LL-CM zones) (Higgs et al., 1988a; Clayton and Turnau, 1990; Melo and Loboziak, 2003) and the well known from Euramerica and Gondwana *Convolutispora major* (Rle/LE to PD and CM zones) (Playford and Melo, 2012 and references therein). *Densosporites regalis* ranges worldwide from the late Devonian to the Visean (Ravn, 1991; Amenábar et al., 2007).

Species restricted to the late Famennian are *Apiculiretusispora verrucosa*, which is a nominal species of *the V. hystricosus-A. verrucosa* (VH) Zone, and *Knoxisporites dedaleus* (Avchimovitch, 1993; Maziane et al., 1999; Filipiak, 2004). The middle–late Devonian *A. greggsii* is also present (Streel in Becker et al., 1974). All these Devonian spores are considered recycled in the Tournaisian association.

The acritarchs *S. miscellum*, *Veryhachium trispinosun* Group, *Gorgonisphaeridium* spp. and *Michrystridium* spp. would indicate a mostly reworked phytoplankton assemblage.

Even though this association is lower diverse than the youngest one, the presence of the Tournaisian marker *W. lanzonii* allows the assignment of a Tournaisian age to levels 7048 to 7050. Other spores with Tournaisian stratigraphic ranges support this age.

Reworked late Devonian palynomorphs accompanied the association.

4.3. Latest Famennian? association (samples 7051 and 7052)

This association is very poor in palynomorph diversity and abundance, with many species left in open nomenclature (*Vallatisporites* spp., *Cymbosporites* spp., *Lophozonotriletes* spp.). However, the occurrence of *C. major*, which first appears in the Strunian (LE zone), the lack of spores restricted in age to the Carboniferous and the presence of the colonial brackish or freshwater alga *Botryococcus*, with rare pre-Carboniferous records mostly limited to the latest Devonian (Amenábar et al., 2006), would point out to a latest Famennian age for this association.

The Eifelian–Givetian or even Frasnian fauna recorded in the upper part of the Lower Member and the Famennian fauna of the basal part of the Middle Member, just below the lowest palynological assemblages, would support the palynological age-dating.

5. Conclusions

The palynological data analysed in this paper provide a more accurate dating of the probable late Devonian and Mississippian marine deposits of the Antofagasta region, in northern Chile.

Based on the palynological assemblages and, essentially, on the stratigraphic distribution of spores, three palynological associations spanning the Devonian/Carboniferous boundary were documented. These are a Tournaisian–Visean association, a Tournaisian association and a probable latest Famennian association.

The position of this system boundary is proposed for the first time in the studied region.

The Tournaisian and Tournaisian–Visean associations also evidence the lack of provincialism that had already been recognized for the early Carboniferous flora (e.g. Clayton et al., 2002). However, the presence of palaeogeographic markers suggests Gondwanan affinities for the Chilean palynoflora.

The considerable amount of reworked palynomorphs and the stratigraphic discontinuities in the Middle Member of the Zorritas Formation, coincide with what happens in other South American basins seriously affected by the latest Devonian to Mississippian climatic change and major sea level fluctuations.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.gsf.2016.04.005.

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