

What do latest Famennian and Mississippian miospores from South American diamictites tell us?

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Abstract Cores from shallow boreholes penetrating the Mississippian Poti Formation, in the western margin of the Parnaíba Basin, contain dark grey diamictites which are extremely rich in well-preserved palynomorphs. Eighty-eight miospore taxa have been identified, and almost half of these are obviously reworked. The presence of these early Late Viséan-age diamictites might possibly contradict the accepted climatic implications of the Paraca Flora, which is also recorded in the Poti Formation. However, a time span of ca. 4 Ma, corresponding to almost the entire Late Viséan, probably allowed the warmer-climate Paraca Flora to exist between the early Late Viséan and Serpukhovian ice ages. Cores from a deep borehole penetrating the upper Cabeças strata of latest Famennian age, in central Parnaíba Basin, contain tillites and varve-like rhythmites, usually laminated siltstones and sandstones, with scattered clasts. Forty-one miospore taxa have been identified from these diamictites and associated siltstones, most of which (70 %) were reworked from Middle and Upper Devonian sediments. An

18-m-thick diamictite section in the lower portion of the Itacua Formation at Bermejo, southeast Bolivia, was reported to display the three successive Strunian miospore zones (LL–LE–LN) established in Western Europe, and thus interpreted as a composite that records several deglaciation events occurring over 3 million years. However, we challenge the presence of the three successive Strunian miospore zones in the Bolivian diamictites which for us correspond only to parts of the LE and LN zones. In Western Europe, the same shorter interval of the miospore zonation corresponds to a period of lower sea-surface palaeotemperatures based on oxygen isotopes from conodont apatite ($\delta^{18}\text{O}_{\text{phosph}}$) as well as a conspicuous sea-level change. Conodont data suggest a much shorter time span (100,000 years) for the highest LE and the LN interval encompassing the Hangenberg and Drewer Sandstones. On the other hand, the Itacua Formation (Bolivia), sampled 33 m and 58 m above the base of the formation, more likely testifies to multiple glacial–interglacial events featuring a superposition of latest Famennian and Mississippian diamictites.

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Introduction

Late Devonian- and Mississippian-age diamictites have been described from several regions of South America. However, controversy has arisen regarding their actual age and different climatic versus sedimentological interpretations. We present here two miospore-based case studies focusing, respectively, on early Late Viséan and latest Famennian diamictites of the Parnaíba Basin (northeastern Brazil), together with a re-evaluation of a previously described Famennian Bolivian diamictite.

Middle Mississippian glacial deposits of the Parnaíba Basin

In the Parnaíba Basin, the Poti Formation contains evidence of glacial and periglacial deposition in the Paleozoic outcrop belt of the basin's western margin, as well as periglacial deposition on the southeastern margin (Caputo et al. 2008). The formation consists of two superposed units. The lower unit comprises sandstones and rare conglomerates, whereas the upper one is primarily argillaceous. Diamictites with striated pebbles are observed to grade laterally into distal mudrock successions.

The lower stratigraphic boundary of the Poti Formation (Fig. 1), with the underlying Longá Formation (Strunian to early Late Tournaisian; cf. Grahn et al. 2001), seems to be conformable in outcrops, but, in fact, corresponds to a parallel unconformity as demonstrated by palynological studies (Melo and Loboziak 2000). Its upper boundary is likewise unconformable, with the overlying Piauí Formation (Middle Pennsylvanian; Dino and Playford 2002a), the basal conglomerate of which consists of a large number of quartz, quartzite, and sandstone boulders, enclosed within a sandy matrix without any preferential orientation. Many of these clasts resulted from the erosion of the Poti Formation.

Clasts in the Poti diamictites are mainly characterised by angular quartz grains, mica-schist, quartzite, gneiss, sandstone pebbles, and boulders disseminated within a compact silty-argillaceous, micaceous, and sometimes calciferous massive matrix. The relative abundance of basement clasts, in sandstones and diamictites along the outcrop belt of the Poti Formation, indicates that the primary source for these rock fragments was the Central Brazilian Shield.

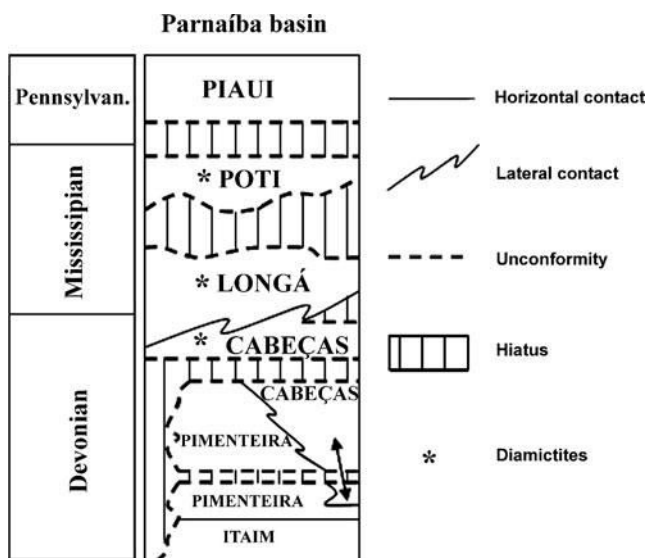


Fig. 1 Lithostratigraphy of the Parnaíba Basin (redrawn from Caputo et al. 2008)

Kegel (1954) dated the basal portion of the formation as early Carboniferous, based on several species of the bivalve *Edmondia*, and Dolianiti (1954) attributed the upper unit to the early Carboniferous based on macrofloral evidence. Using sporomorph evidence, Müller (1962) considered the formation to be Mississippian in age, Andrade and Daemon (1974) dated it as Viséan, and Melo and Loboziak (2000) assigned the Poti Formation to the early Late Viséan, correlating it with two successive West European palynozones, namely, the *Perotrilites tessellatus*–*Schulzospora campyloptera* (TC) and *Raistrickia nigra*–*Triquitrites marginatus* (NM). Melo and Loboziak (2003) referred the Poti Formation to the early Late Viséan Mag palynozone, erected by them in the Amazon Basin (upper Faro Formation and equivalent parts of the Oriximiná Formation).

Based on the fossil megaflora, which is dominated by pteridosperms, with some arboreal lycopsids and associated sphenopsids, Iannuzzi and Pfefferkorn (2002) assigned a Late Viséan age to the Poti Formation. This megaflora is related to the Paraca floral kingdom and consists of a warm to temperate climate floral belt (between 30° and 60°S) with a circum-Gondwanan distribution that developed within a non-glacial context, extending from northern South America to Australia, during the Late Viséan and Early Serpukhovian.

Miospores from the Tocantins River diamictites

Cores from shallow boreholes penetrating the Mississippian Poti Formation, drilled for the construction of a dam on the Tocantins River (western margin of Parnaíba Basin), include sandstones, siltstones, and dark grey diamictites. Palynomorphs were extracted from 30 samples taken from seven shallow wells drilled through diamictite sections ca. 26 m thick (Fig. 2). All samples proved extremely rich in well-preserved palynomorphs, and each prepared slide contains several thousand miospores. Both Devonian and Mississippian miospores are present, not only in the diamictites, but also in samples collected from silty strata above the diamictites.

Eighty-eight miospore taxa were identified from the diamictites and associated siltstones. Of these, 15 taxa (17 %) (Table 1) are Late Viséan markers such as *Schulzospora* sp. and *Raistrickia nigra*; 37 taxa (42 %) (Table 1) could be Late Viséan, but are also known from the Mississippian or even the latest Famennian (annotated species list 1); 35 taxa (41 %) are obviously reworked (Table 2): 18 (22 %) from the Tournaisian or Upper Devonian and 17 taxa (19 %) from the Upper or Middle Devonian. Most of the acritarchs observed are presumably reworked from the Devonian, except some morphologically simple acanthomorphs and ver-yhachids, which could be Carboniferous. Melo and Loboziak (2003) assigned the Poti Formation assemblages

S101 20,56-20,66 (5) silt 28,16-28,27 (6) silt	S103 11,26 (1) 24,14 (2) 27,68 (3) 29,62 (4)	S202 12,71,12,83 (12) silt 20,05 (13) 22,94 (14) 32,16 (15) 33,77 (16)	S203 14,53-14,63 (17) silt 16,86 (18) 19,30 (19) 22,81 (20) 23,86 (21)	S204 16,60 (22) 32,32 (23) 34,50 (24) 58,93 (25)	S205 12,87-12,96 (26) silt 25,88 (27) 40,29 (28) 40,85 (29) 56,66 (30)	S208 11,77-11,91 (7) silt 18,35 (8) 35,36 (9) 38,15 (10) 44,65 (11)
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Fig. 2 Studied samples from the Tocantins River shallow boreholes drilled in the Upper Viséan of the Parnaíba Basin. *S* Shallow borehole identification. No. of palynological slide shown in parentheses

to the Late Viséan *Cordylsporites magnidictyus* (Mag) palynozone, which is now re-assigned to the *Reticulatisporites magnidictyus* Zone following the latest taxonomic review of the eponymous species (Dino and Playford 2002b).

The Cortaderas Formation of the Rio Blanco Basin (Argentina), also contains glacial deposits. Pérez-Loinaze (2007) defined the Late Viséan MQ (*magnidictyus*–*quasi-gobbettii*) palynozone here, which she considered to be correlative of the Mag palynozone of Brazil. The age of the MQ Zone is now constrained by radiometric data (335.99 ± 0.06 Ma; cf. Césari et al. 2011) which fits with a latest Holkerian or earliest Asbian age determination, according to the Carboniferous time scales of Menning et al. (2006) and Ogg et al. (2008), respectively.

Azcuy and di Pasquo (2005) recorded a low-diversity miospore assemblage from the Ambo Formation, Pongo de Mainique (Peru), which they compared with the early Late Viséan Mag Zone of northern Brazil. The authors stressed the poor preservation of the Peruvian palynoflora and the apparent absence of *Reticulatisporites magnidictyus* in the uppermost part of the Ambo Formation. The first occurrence of small *Schopfipollenites* spp. (attributed to *S. ellipsoides* by Azcuy and di Pasquo 2006) within the uppermost Ambo strata might imply possible correlation with the inception of true *S. ellipsoides* in the AT Zone of Eastern Canada and the NC Zone in Western Europe (the latter corresponding to the Viséan–Serpukhovian transition).

However, identical small praecolpates from the older Mag Zone of Brazil—likewise assigned to *S. ellipsoides* by Loboziak et al. (1991), but later redesignated as *Schopfipollenites* sp. (Loboziak et al. 1998; Melo and Loboziak 2003), have recently undergone taxonomic revision (G. Playford and J.H.G. Melo, in preparation). It is now concluded that the Viséan representatives of *Schopfipollenites* reported from South America are actually distinct from, and thus not necessarily coeval with, *S. ellipsoides*. Moreover, these small forms are now recorded, together with *Reticulatisporites magnidictyus*, from the very base of the Mag Zone in some Amazon Basin sections (G. Playford and J.H.G. Melo, in preparation), and, therefore, are not restricted to the higher parts of the zone as previously indicated (Loboziak et al. 1998).

Lastly, the local absence of *Reticulatisporites magnidictyus* is not age diagnostic per se, because the species also occurs erratically within some Mag sections of northern Brazil (S. Loboziak and J.H.G. Melo, unpublished data).

Furthermore, it is also known to range into Early Serpukhovian-age sections of South America, North Africa, and Australia (Dino and Playford 2002b; Fasolo et al. 2006; Hyam et al. 1997; Loboziak et al. 2000a; Melo et al. 1999; Pérez-Loinaze 2007). Therefore, local non-occurrences of *R. magnidictyus* in the Upper Viséan of South America can be best ascribed to ecofaciological constraints, and, thus, are probably devoid of stratigraphic significance.

In view of the palynological data, and together with the early Late Viséan (late Holkerian to late Asbian) radiometric dating of the Mag Zone (=MQ Zone) diamictites in north-western Argentina, it seems evident that a time span of ca. 4 Ma (corresponding to nearly the entire Late Viséan; cf. Bruckschen and Veizer 1997) allowed the warmer-climate Paraca Flora (Iannuzzi and Pfefferkorn 2002) to exist between the early Late Viséan and Serpukhovian ice ages (Césari et al. 2011).

Latest Famennian glacial deposits of the Parnaíba Basin (Fig. 1)

Sediments deposited under glacial and periglacial conditions in the Parnaíba Basin make up the upper Cabeças section of latest Famennian age. The Cabeças Formation is overlain by the Longá Formation, both conformably (in sites where the lowest Longá strata are end-Devonian transgressive marine shales) and unconformably (in places where the Longá Formation is entirely Tournaisian in age). The upper Cabeças beds, which are placed in the Famennian LVa (*lepidophyta-vallatus*) Zone, and are equivalent to the upper part, or the entire Western European LN (*lepidophyta-nitidus*) Zone (Melo and Loboziak 2001, 2003), contain massive polymict diamictites with subrounded to angular, striated and polished outsized clasts immersed in a silty and clayey matrix (Caputo 1985; Loboziak et al. 1993). The lower Cabeças beds (chiefly sandstones with minor shaly interbeds) are dated as early to late Famennian (Grahn et al. 2006).

The upper Cabeças/lower Cabeças boundary seems to correspond to a relatively minor (3rd to 4th order) unconformity, which thus accounts for the apparent absence of at least the LL Zone (locally also encompassing the VCo and VH zones), unless coeval Famennian sediments are palynologically barren or contain only non-diagnostic palynofloras. However, in parts of the western margin of the Parnaíba Basin where the lower Cabeças sandstone is absent, the

Table 1 Tocantins River shallow drills (Parnaíba). Mississippian recorded species and chronostratigraphy

(See also Figs. 3 and 4)

<i>? Cristatisporites inordinatus</i> 3c	(Menendez and Azcuy) Playford, 1978	? Late Visean–early Namurian	
<i>? Rotaspora</i> sp. 3k		? Presumed late Visean at least	
<i>? Schopfipollenites</i> 4abc		? Late Visean–late Carboniferous	
<i>? Spelaeotriletes ybertii</i>	(Marques-Toigo) Playford and Powis, 1979	? Late Visean to lower Permian	
<i>? Tripartites</i> sp. 4g		? Presumed late Visean at least	
<i>Retusotriletes ?mirabilis</i>		Late Visean	
<i>Anapiculatisporites cf semisentus</i> 3a	Playford, 1971	Late Visean	As early as
<i>Cingulizonates</i> sp		? Presumed late Visean at least	Late Visean
<i>Ductilispora corrugata</i> 4d	Perez-Lonaze, 2005	Late Visean	
<i>Indotriradites</i> sp cf <i>I. dolianitii</i> 3f	Loboziak et al., 1999	Late Visean	
<i>Raistrickia nigra</i> 3j	Love, 1960	Late Visean–basal Namurian	
<i>Schulzospora</i> sp. 3l		Late Visean to Pennsylvanian	
<i>Spelaeotriletes arenaceus</i> 4e	Neves and Owens, 1966	Late Visean to early Westphalian	
<i>Spinozonotriletes hirsutus</i>		Late Visean–early Namurian	
<i>Tumulispora</i> sp. aff <i>Lophozonotriletes muricatus</i>		Late Visean	
<i>? Lycospora pusilla</i>	(Ibrahim) Somers, 1972	Visean to Pennsylvanian	
<i>Procoronaspora butterworthii</i> 3h	Staplin, 1960	Visean	
<i>Densosporites pseudoannulatus</i> 3d	Butterworth and Williams, 1958	Visean–Namurian	
<i>Densosporites triangularis</i> 3e	Kosanke, 1950	Visean–Namurian	As early as
<i>Dibolisporites microspicatus</i> 4f	Playford, 1978	Visean	Undifferentiated
<i>Raistrickia cf ponderosa</i> 4k	Playford, 1964	Mississippian (Cheverie Fm)	Visean
<i>Secarisporites remotus</i> 3m	Neves, 1961	Visean	
<i>Thymospora cymbiformis</i> 4h	Playford and Satterthwait, 1988	Visean	
<i>? Anulatisporites orbiculatus</i> 3b	(Waltz) Playford, 1963	Mississippian	
<i>? Rugospora polyptycha</i>	Neves and Ioannides, 1974	Mississippian	
<i>Colatisporites decorus</i>	(Baradwaj and Venkatachala) Williams, 1973	Mississippian	
<i>Cristatisporites aculeatus</i>		Mississippian (Horton Gr)	
<i>Grandispora uncata</i>	(Hacquebard) Playford, 1971	Mississippian (Horton Gr)	As early as
<i>Indotriradites variabilis</i>		Mississippian?	Undifferentiated
<i>Lophozonotriletes dentatus</i> 3g	Hughes and Playford, 1961	Mississippian	Mississippian
<i>Perotriletes perinatus</i> 4l	Hughes and Playford, 1961	Mississippian	
<i>Raistrickia clavata</i> 3i	Hacquebard, 1957 emend Playford, 1964	Mississippian	
<i>Schopfites angustus</i> 4i	Playford, 1964	Mississippian (Horton Gr)	
<i>Spelaeotriletes cabotii</i>	Utting et al., 1989	Mississippian	
<i>Tumulispora variverrucata</i> 4j	(Playford) Staplin and Jansonius, 1964	Mississippian	
<i>Vallatisporites ?agadesi</i>	Loboziak and Alpern, 1978	Mississippian	
<i>? Raistrickia strumosa</i>	Playford, 1976	BP–PC	
<i>Auroraspora corporiga</i>	Higgs et al., 1988	VI–PC	
<i>Ceratisporites</i> sp. A	in Van der Zwan, 1979	Mid Tournaisian–Visean	
<i>Crassispora maculosa</i>	(Knox) Sullivan, 1964	VI–Namurian A	As early as
<i>Kraeuselisporites hibernicus</i>	Higgs, 1975	HD–CM	Tournaisian
<i>Mooreisporites</i> sp.	in Melo and Loboziak, 2003	BP–PC?	
<i>Spelaeotriletes balteatus</i>	(Playford) Higgs, 1975	BP–NM	
<i>Spelaeotriletes obtusus</i>	Higgs, 1975	VI?–BP	
<i>Spelaeotriletes resolutus</i>	Higgs, 1975	VI?–BP	
<i>Spinozonotriletes impensus</i>	Higgs et al., 1988	HD–PC	
<i>Velamisporites lacertosus</i>	Playford, 1971	Late Tournaisian	

Table 1 (continued)

(See also Figs. 3 and 4)

<i>Cordylosporites marciae</i>	(Winslow) Playford and Satterthwait, 1985	LE–Visean	
<i>Cordylosporites spathulatus</i>	(Winslow) Playford and Satterthwait, 1985	LE–NM	As early as
<i>Tumulispora rarituberculata</i>	(Luber) Playford, 1990	LL–Visean	Uppermost
<i>Vallatisporites vallatus</i>	Hacquebard, 1957	LN–NM	Famennian
<i>Vallatisporites verrucosus</i>	Hacquebard, 1957	LE–NM	

Reference to figures in the first column

Table 2 Tocantins River shallow drills

Reworked species			
Latest Famennian–Tournaisian			
<i>Auroraspora macra</i>	Sullivan, 1968	LL–Pu	
<i>Endoculeospora gradzinskii</i>	Turnau, 1975	LE–CM	
<i>Indotriradites explanatus</i>	(Luber) Playford, 1991	LE–PC	
<i>Plicatispora scoleophora</i>	(Neves and Ioannides) Higgs et al., 1988	LL–CM	
<i>Raistrickia minor</i>	(Kedo) Neves and Dolby, 1967	LL–PC	
<i>Retusotriletes crassus</i>	Clayton et al., 1980	LN–CM	
<i>Retusotriletes incohatus</i>	Sullivan, 1965	?VH–HD?	
<i>Spelaeotriletes crustatus</i>	Higgs, 1975	LL–PC	
Late–latest Famennian			
<i>Retispora lepidophyta</i>	(Kedo) Playford, 1976	LL–LN	
<i>Leiotriletes struniensis</i>	Moreau-Benoit, 1979	VCo–LN?	
<i>Rugospora radiata</i>	(Jushko) Byvsheva, 1985	VCo–LN	
Late Frasnian–mid. Tournaisian			
<i>Cyrtospora cristifer</i> var. A	(Luber) Van der Zwan, 1979	Early Famennian–mid. Tournaisian	
<i>Retusotriletes planus</i>	Dolby and Neves, 1970	Late Frasnian–PC	
Late Frasnian–Famennian			
? <i>Teichertospora torquata</i>	(Higgs) McGregor and Playford, 1990	IVc–LN	
<i>Cornispora varicornata</i>	Staplin and Jansonius in Staplin, 1961	Late Frasnian–early Famennian	
<i>Cyrtospora cristifera</i> var. <i>biloba</i>	(Luber) Van der Zwan/(Kononenko) B. & H.	Famennian	
<i>Geminospora piliformis</i>	Loboziak et al., 1988	BJ–IVc	
<i>Samarisporites</i> sp. E	in Streel and Loboziak, 1987	BJ–IVc	
Mid.–Late Devonian			
<i>Ancyrospora</i> sp.		Mid.–Late Devonian	
<i>Brochotriletes foveolatus</i>	Naumova, 1955	BZ	
<i>Camazonotriletes?</i> <i>concavus</i>	Loboziak and Streel, 1989	AD	
<i>Corystisporites multispinosus</i>	Richardson, 1965	AD–TA	
<i>Cymbosporites catillus</i>	Allen, 1965	AD–IVc	
<i>Cymbosporites cyathus</i>	Allen, 1965	AD–IVc	
<i>Grandispora douglstownense</i>	McGregor, 1974	AP–AD	
<i>Grandispora mammillata</i>	Owens, 1971	ADLem	
<i>Grandispora megaformis</i>	(Richardson) McGregor, 1973	AP–AD	
<i>Grandispora permulta</i>	(Daemon) Loboziak et al., 1999	AD	
<i>Grandispora protea</i>	(Naumova) Moreau-Benoit, 1980	AP–AD	
<i>Grandispora pseudoreticulata</i>	(Menendez and Pothe de Baldis) Ottone, 1996	Mid. Devonian–early Carboniferous?	
<i>Grandispora velata</i>	(Eisenack) Playford, 1971	APVel	
<i>Hystericosporites</i> sp.		Mid.–Late Devonian	
<i>Samarisporites eximius</i>	(Allen) Loboziak and Streel, 1989	APVel–TA	
<i>Samarisporites praetervisus</i>	(Naumova) Allen, 1965	APVel–TA	
<i>Samarisporites triangulatus</i>	Allen, 1965	TA–early Famennian	

Third column: Miospore zonation after Streel et al. 1987 and Higgs et al. 1988

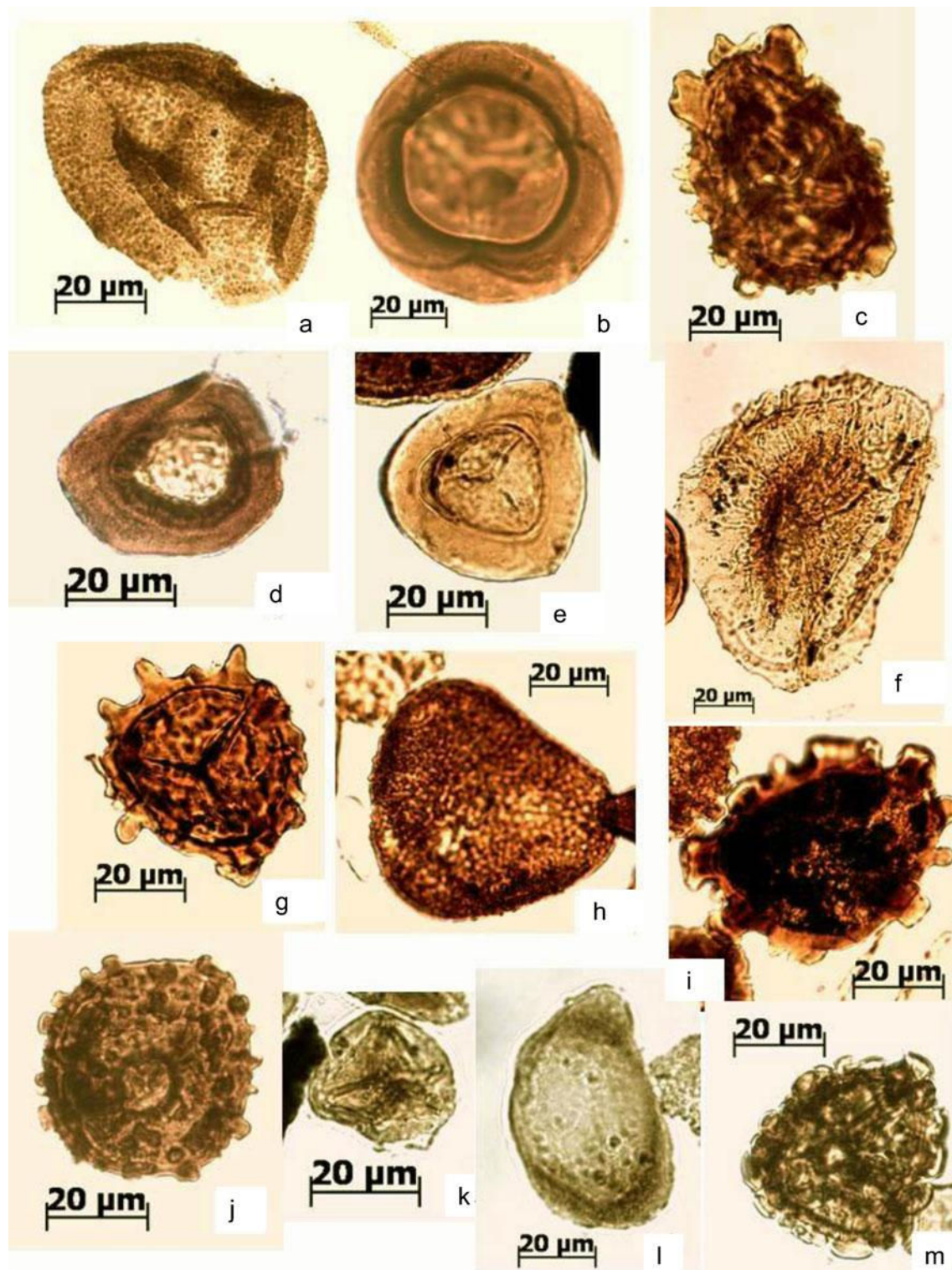


Fig. 3 See annotated species list No. 1. All specimens located by sample, slide number and England-Finder coordinates in annotated species lists. **a** *Anapiculatisporites* cf. *semisentus* Playford, 1971. **b** *?Anulatisporites* cf. *A. orbiculatus* (Waltz) Playford, 1963. **c** *?Cristatisporites inordinatus* (Menendez and Azcuy) Playford, 1978. **d** *Densosporites pseudoannulatus* Butterworth and Williams, 1958.

e *Densosporites triangularis* Kosanke, 1950. **f** *Indotriradites* sp. cf. *I. dolianitii* Loboziak et al., 1999. **g** *Lophozonotriletes dentatus* Hughes and Playford, 1961. **h** *Procoronaspora butterworthii* Staplin, 1960. **i** *Raistrickia clavata* Hacquebard, 1957 emend Playford, 1964. **j** *Raistrickia nigra* Love, 1960. **k** *Rotaspora* sp. **l** *Schulzospora* sp. **m** *Secarisporites remotus* Neves, 1961

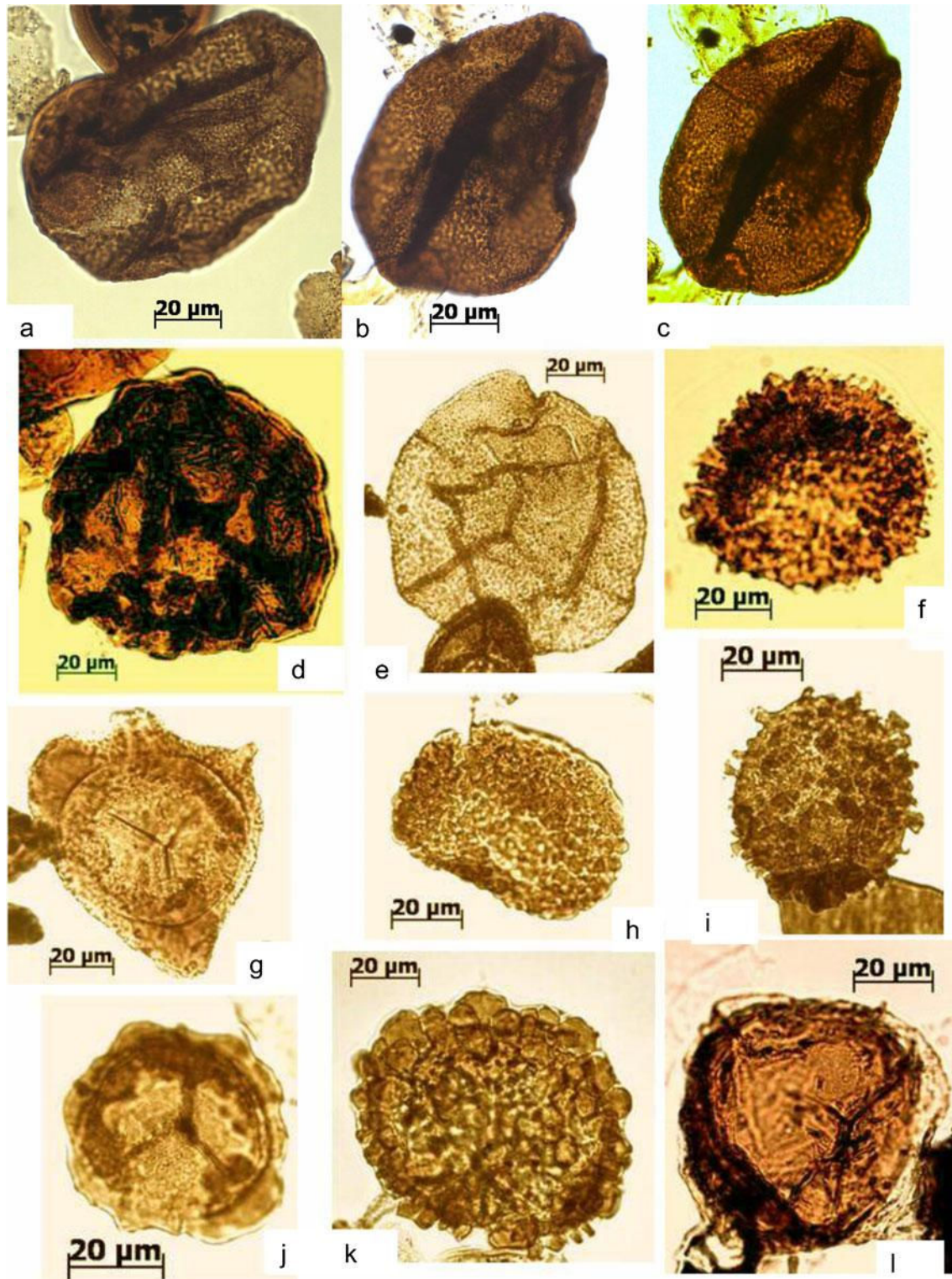


Fig. 4 See annotated species list No. 1. All specimens located by sample, slide number and England-Finder coordinates in annotated species lists. **a–c** *Schopfipollenites?* sp. **d** *Ductilispora corrugata* Pérez-Loinaze, 2005. **e** *Spelaotriletes arenaceus* Neves and Owens, 1966. **f** *Dibolisporites microspicatus* Playford, 1978. **g** *Tripartites?* sp.

h *Thymospora cymbiformis* Playford and Satterthwait, 1988. **i** *Schopfites augustus* Playford, 1964. **j** *Tumulispora variverrucata* (Playford) Staplin and Jansonius, 1964. **k** *Raistrickia* cf. *R. ponderosa* Playford, 1964. **l** *Perotriletes perinatus* Hughes and Playford, 1961

upper Cabeças glaciogenic strata rest erosionally on increasingly older rocks (Devonian through Precambrian; Loboziak et al. 2000b). Varve-like rhythmites, usually laminated siltstones and very fine sandstone couplets with scattered clasts, are known from well cores within diamictites and associated shales (Carozzi et al. 1975, pl. XVI.E-F; Caputo 1985, fig. 13; Caputo and Crowell 1985, fig. 11; Streel et al. 2001, pl. 1.A, pl. 2).

Miospores from the well 1-TM-1-MA diamictites (Figs. 1, 5)

The investigated material comes from four samples of core 16 in well 1-TM-1-MA, about 200 km east of the Tocantins River. One of these samples (Caputo 1985; Caputo and Crowell 1985, fig. 11E) is a laminite (varve-like rhythmite) composed of alternating white, very fine sandy layers and dark grey silty layers, each being approximately 0.5 mm thick. Eight layers were macerated separately (Streel et al. 2001). The diamictites and associated siltstones yielded at

least 41 miospore taxa, most of which (29, i.e. 70 %) are reworked from Middle or Upper Devonian sediments. Among the other 12 taxa, *Vallatisporites vallatus* has the youngest first occurrence, at the base of the latest Famennian LVa (*lepidophyta-vallatus*) Zone. The other 11 taxa could also be latest Famennian, but they are known elsewhere to range down into the Famennian. Curiously enough, the reworked Middle Devonian miospores are found only in the diamictite samples, whereas the reworked Late Devonian miospores occur both in the diamictites and laminites.

We propose that the LVa Zone miospores represent the local vegetation of a deltaic and coastal environment that was locally disrupted by advancing lobes of the contemporary ice cap (Carozzi 1980). LVa Zone miospores were distributed on the subaqueous fans and mixed with miospores reworked from underlying Frasnian shales of the upper Pimenteira Formation. Reworked Middle Devonian miospores might have originated from normal and glacial erosion of lower parts of the Pimenteira Formation (Loboziak et al. 2000a).

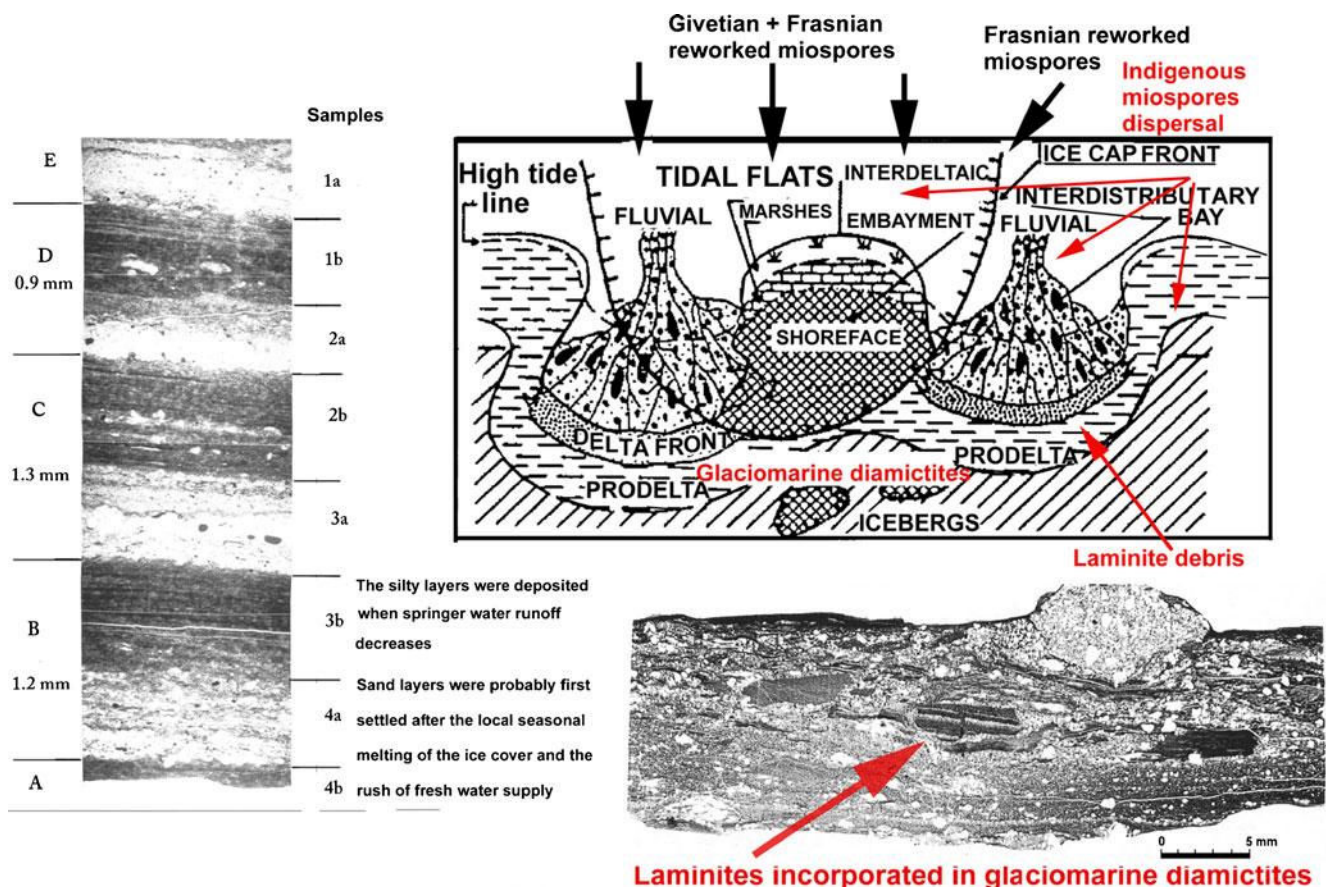


Fig. 5 Latest Famennian glacial deposits of the Parnaíba Basin. The Famennian LVa (*lepidophyta-vallatus*) Zone is characterised lithologically by massive polymict diamictites. The upper Cabeças glaciogenic strata rest erosionally on increasingly older rocks. Varvelike rhythmites of this

unit (usually laminated siltstones and very fine sandstone couplets with scattered clasts) are known from well cores within tillites and associated shales (Carozzi et al. 1975, pl. XVI.E-F; Caputo 1985, fig. 13; Caputo and Crowell 1985, fig. 11; Streel et al. 2001, pl. 1.A, pl. 2)

In the Parnaíba Basin, the LVa Zone characterises latest Famennian-age strata of the upper Cabeças and basal Longá formations in several wells (Grahn et al. 2001, 2006; Loboziak et al. 1992) and outcrops along the Tocantins River valley (Loboziak et al. 2000b). Famennian (pre-Strunian) sandstones of the lower Cabeças Formation are preserved below the LVa diamictite section of well 1-TM-1-MA.

However, in some other localities of the western Parnaíba Basin, the Cabeças glaciation has removed the entire lower Cabeças sandstone plus varied sections of the underlying Pimenteiras Formation (which spans the latest Eifelian through earliest Famennian; fide Grahn et al. 2001, 2006). Near Colinas do Tocantins village, in the western outcrop area (Tocantins State, north-central Brazil), the Cabeças tillites rest directly on the Precambrian metamorphic basement and are succeeded by black shales of the basal Longá Formation (Loboziak et al. 2000b).

Reworked palynomorphs may provide a reliable proxy for the source area of sediments (Streel and Bless 1980), and their occurrence in diamictites has been emphasised for many years in Argentina (di Pasquo and Azcuy 1997; di Pasquo 2007b). Although glacio-marine rhythmites have been described in the Carboniferous of Argentina (del Papa and di Pasquo 2007; Milana and Lopez 1998), no palynomorph analysis for the individual sandy and silty layers has yet been provided.

A quantitative palynological analysis of laminates from well 1-TM-1-MA shows a miospore/miospore + acritarch ratio ranging from 40 to 70 %. The palynomorph concentrations (number of specimens per gram of rock) suggest some rhythmicity as miospores progressively decrease from 4 to 2.5 k in the silty layers and from 2.5 to 1 k in the very fine sandy layers before another cycle starts. This could result from the changing intensity of freshwater currents entering the basin, causing glacio-lacustrine sediments to be deposited from subaqueous fans and related turbidity currents (Ponciano and Della Favera 2009), as well as from the calving of icebergs (Carozzi 1980). Therefore, living parent plants dispersing spores may have coexisted with glacially derived sediments at the margin of some lobes of the contemporaneous ice cap and perhaps even on the debris covering the glacier (Caccianiga et al. 2011).

Are latest Famennian diamictites multiple glacial–interglacial events?

Wicander et al. (2011), working on a 18-m-thick diamictite section in the lower part of the Itacua Formation at Bermejo (Río Lajas, Santa Cruz, southeast Bolivia), recognised three successive Late Devonian miospore zones established in Western Europe: LL (*lepidophyta-literatus*), LE (*lepidophyta-explanatus*), and LN (*lepidophyta-nitidus*). They concluded that the diamictite sequence was a

composite representing several deglaciation events. The diamictites are within a marine succession, and overlie a hiatus coincident with the Itacua/Iquiri Formation boundary, indicative of a lowering of sea-level during the glacial maximum (Wicander et al. 2011). The diamictites were thus interpreted as glaciomarine deposits that accumulated during a time of rising sea-level, i.e. during a deglaciation event.

In Brazil at least, the succession of LE–LN zones is not easily recognised. Instead, that interval is characterised by the successive Rle (*R. lepidophyta*, with, i.a., *Indotriradites explanatus* and *Vallatisporites verrucosus*) and LVa (*lepidophyta-vallatus*) zones (Melo and Loboziak 2001, 2003). The Rle is considered to possibly represent an impoverished variant (ecofacies?) of the LVa in places where *Verrucosisporites nitidus* and *Vallatisporites vallatus* are absent. It should be noted that *V. nitidus* is not always easily identifiable (Turnau et al. 1994), and the single specimen illustrated by Wicander et al. (2011, fig. 5, fig. 2) is unconvincing because its rather widely spaced verrucae sometimes exceed 8 µm in maximum diameter and do not form the negative reticulum diagnostic for this species.

Wicander et al. (2011) furthermore state that the recognition of the LL Zone in the Bermejo sequence is only tentative. They accept that it could also be the LE Zone, because of the scarcity of miospores. The same holds true for the three poorly palyniferous samples assigned to the VCo Zone at the base of the diamictites. This provisional assignment was due to the absence of *Retispora lepidophyta* and the occurrence of *Rugospora radiata*, a species also occurring in the *R. lepidophyta* range.

This lack of definitive zone assignment also applies to the miospore-poor sample M19 of Perez-Leyton (1991), at the base of the same diamictite interval at Bermejo (Río Lajas area), assigned by him to the VCo Zone. It should be noted that *R. lepidophyta* is not abundant in the youngest part of the LN Zone in Western Europe, and the same applies to some uppermost LVa sections of northern Brazil (J.H.G. Melo, personal observations).

Finally, considering that the absence of *V. nitidus* is not necessarily age-diagnostic, we conclude that samples 35–37 (within the exotic block) do not contain the same miospore assemblage as recorded in samples 13–21 (within the “LN” sequence) of Wicander et al. (2011, p. 80). Almost 18 taxa unrecorded in the exotic block are present in the “LN” sequence, but again absent in the “LE” sequence. Therefore, there is no need to resort to soft sediment deformation to explain the lower position of the exotic block in relation to samples 13–21.

In our view, the multiple glaciations and interglacials suggested by Wicander et al. (2011) in the Bermejo diamictites, and supposedly extending through the entire latest Famennian (or Strunian), have not been convincingly demonstrated.

Do the Itacua diamictites represent two superposed glacial events?

Di Pasquo (2007a, b, c) described three samples spaced 1–3 m apart within the Itacua Formation (about 15 m thick) at a locality some 500 km to the south of Bermejo (Santa Cruz), on the Río Bermejo (Balapuca, Department of Tarija, near the Argentina–Bolivia border). She concluded that the entire section was Mississippian in age, and that all the Devonian miospores (66 % of the total palynoflora) were reworked.

Perez-Leyton (1990) illustrated several miospore taxa from the Saipuru (now Itacua) Formation at Bermejo (Santa Cruz), some of which were not published in his 1991 paper. His samples M12 and M13 were from 33 and 58 m, respectively, above the base of the formation, i.e. from stratigraphic levels considerably higher than the 18-m section studied by Wicander et al. (2011) at the same locality and were tentatively attributed to the LE Zone (due to the absence of *V. nitidus*). However, subsequent revision by us has demonstrated the presence of some Mississippian miospores in this palynoflora (see Fig. 6 and annotated species list 2).

Therefore, the Itacua Formation of Bolivia could testify to a succession of glacial–interglacial events, causing Mississippian diamictites to rest directly on latest Famennian ones (Suárez-Soruco and Lobo-Boneta 1983), as also noted in the Solimões Basin of northern Brazil. In the latter, Middle to early Late Tournaisian (PC-age; fide Loboziak et al. 1995), crudely stratified diamictites occur in the upper part of the Jaraqui Member of the Jandiutuba Formation (Eiras et al. 1994). Clasts are randomly oriented and consist of angular to rounded quartz, shale, sandstone, and igneous pebbles. Some diamictite layers are highly deformed and show significant dips. These Tournaisian strata rest disconformably on underlying latest Famennian diamictites and older, non-glaciogenic rocks of the Jandiutuba and Uerê formations (Caputo et al. 2008).

Comparison with European miospore zonation, bathymetry, and geochemical data (Fig. 7)

In recent years, detailed geochemical data have been obtained from Upper and Uppermost Famennian and Lower Tournaisian strata in several localities of central and southern Europe. The data comprise carbon isotope analyses of micrites ($\delta^{13}\text{C}_{\text{carb}}$) and sedimentary organic matter ($\delta^{13}\text{C}_{\text{org}}$), as well as oxygen isotopes from conodont apatite ($\delta^{18}\text{O}_{\text{phosph}}$). The latter was interpreted in terms of sea-surface palaeotemperatures by Kaiser et al. (2008). With the aid of refined conodont stratigraphy (Kaiser et al. 2009), these data have been correlated with both the lithological successions and inferred sea-level changes of the Rhenish Massif (Germany), and can also be correlated with the miospore zonation of the Rhenish Massif and the Ardennes in Belgium (Streel et al. 2000, Higgs et al., in preparation). The

results are summarised in Kaiser et al. (2011) and reproduced here with some modifications (Fig. 7).

These data provide the opportunity to test the hypothesis of the duration, and possible multiple character of the end-Devonian glaciation. In terms of bathymetry, one should note that the major drop in sea-level at the Hangenberg Sandstone level in Germany is confined to the uppermost LN Zone (LN* Zone, characterised by more than 50 % of specimens of *Retusotriletes* and *Apiculiretusispora*; after Higgs et al. 1993). Such major drop in sea-level has no equivalent record elsewhere in the uppermost Famennian and lowermost Tournaisian.

In the uppermost part of the LE Zone, the Drewer Sandstone might correspond to an earlier sea-level fall of lesser magnitude. On the other hand, the two *Retispora lepidophyta* zones below the Drewer Sandstone correspond to times of rather high sea-surface palaeotemperatures, which would be unexpected during an ice age. Additionally, a cooling episode (with low sea-surface palaeotemperatures) at the “Dasberg/Fontin Event” level, around the VCo/VH Zonal boundary, does not correspond to any major sea-level fall. Therefore, it is unlikely that multiple glacial–interglacial events could have persisted for the 3 Ma duration of the combined Strunian LL–LE–LN time interval as suggested by Wicander et al. (2011). The glacial event might as well be characterised by the high LE and LN zones, i.e. by the upper part only of the Strunian.

A much shorter duration of time (100,000 years) has been proposed by Sandberg and Ziegler (1996) for the sequence enclosing the Hangenberg and Drewer Sandstones (Streel 1999, text-fig. 5). The recognition of the LN Zone in the Hangenberg Black Shale (HBS), which overlies the Drewer Sandstone, is based on poorly diversified and scarce palynofloras (Higgs and Streel 1994), in which *Verrucosisporites nitidus* is an erratic component. Even in Ireland (Higgs et al. 1988), where the LN Zone has been defined, *V. nitidus* (usually represented by more finely verrucate variants) is also rather sparse in the basal part of the biozone. Therefore, it is possible that the transitional LE–LN interval, although poorly defined, could correspond to a much shorter duration than the duration accepted for the Strunian.

Conclusions

1. The local absence of *Reticulatisporites magnidictyus* and the presence of small praecolpates (*Schopfipollenites* sp.) in the Tocantins River diamictites are palynological features previously noted in the Viséan Ambo Formation of Peru (and also in some Amazon Basin sections of northern Brazil), and do not necessarily imply a Latest Viséan age for these glaciogenic rocks of the Poti Formation. Moreover, the 4 Ma duration of the entire Late Viséan,

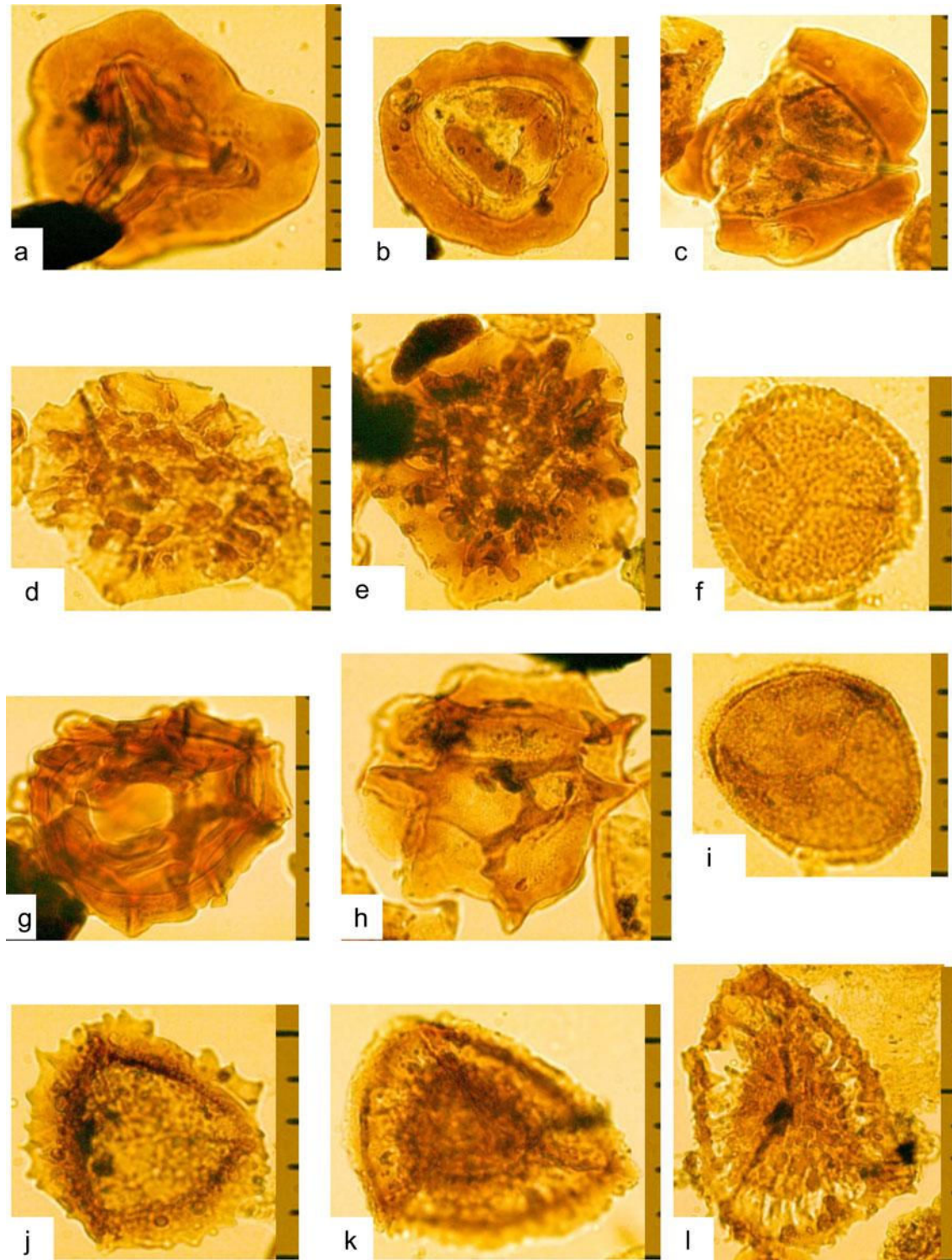
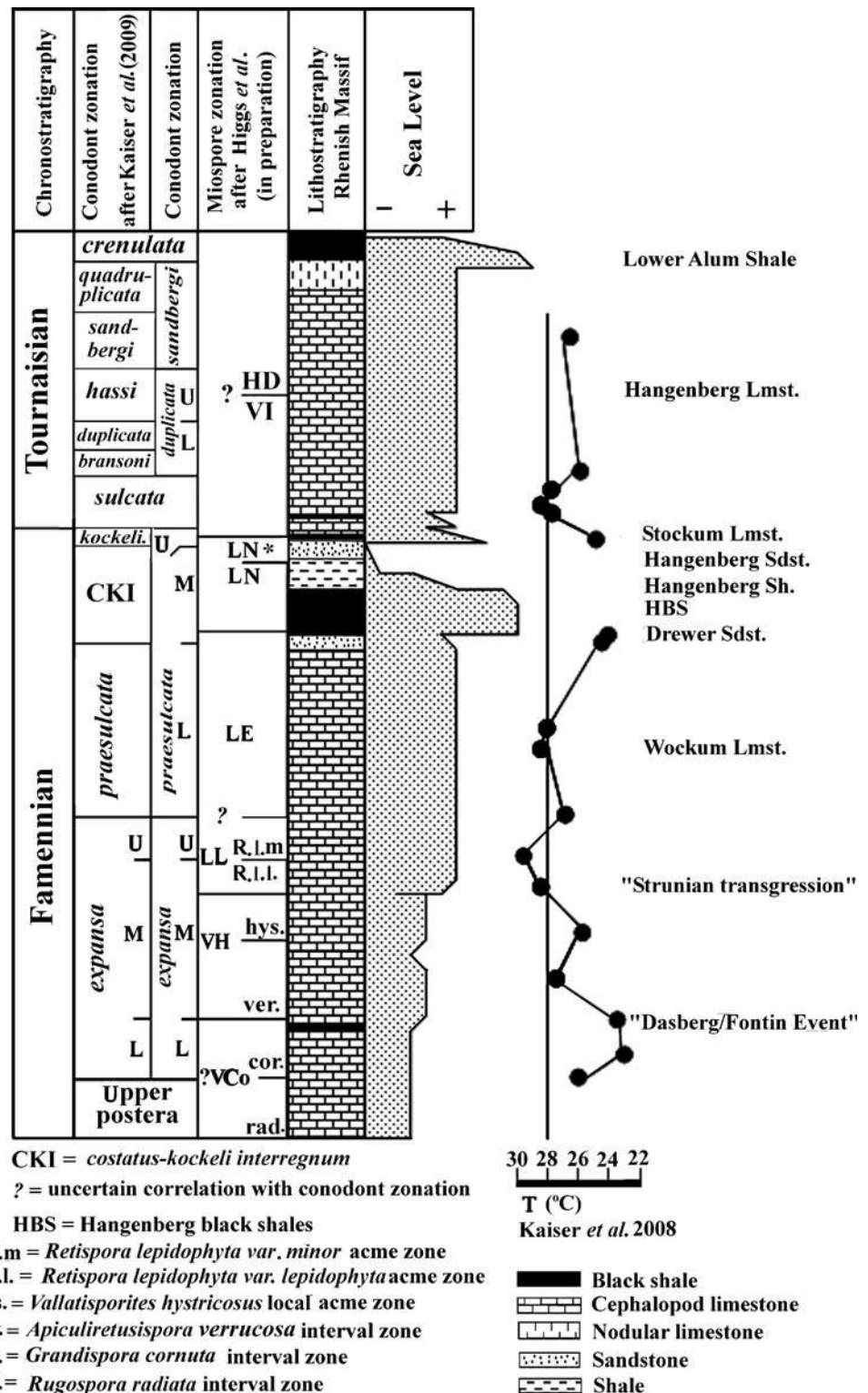


Fig. 6 See annotated species list No. 2. All specimens located by sample, slide number and England-Finder coordinates in annotated species lists. **a** *Murospora* cf. *M. aurita* (Waltz) Playford, 1962. **b** *Lophozonotriletes concentricus* (Byvsheva) Higgs et al., 1988. **c** *Lophozonotriletes triangulatus* (Ischenko) Hughes and Playford,

1961. **d, e** *Cristatisporites* sp 1 in Perez-Leyton, 1991. **f, i** *Spelaotriletes resolutus* Higgs, 1975. **g, h** *Dictyotriletes flavus* Keegan, 1977. **j** *Indotriradites* cf. *I. mitratus* Higgs, 1975. **k, l** *Vallatisporites banfensis* Staplin and Jansonius, 1974. Scale bar 10 μ m

Fig. 7 Comparison of European miospore zonation, bathymetry, and geochemical data. Oxygen isotopes from conodont apatite ($\delta^{18}\text{O}_{\text{phosph}}$) are interpreted in terms of sea-surface palaeotemperatures by Kaiser et al. (2008). With the aid of refined conodont stratigraphy (Kaiser et al. 2009), these data have been correlated with lithological successions and inferred sea-level changes in the Rhenish Massif (Germany), and with the miospore zonation of the Rhenish Massif and the Ardennes in Belgium (Higgs et al., in preparation). Note the major sea-level fall at the Hangenberg Sandstone level, confined to the uppermost LN Zone. That sea-level fall has no equivalent record elsewhere in the uppermost Famennian and lowermost Tournaisian. In the uppermost part of the LE Zone, the Drewer Sandstone might correspond to an earlier sea-level fall of lesser magnitude. On the other hand, the two *Retispora lepidophyta* zones below the Drewer Sandstone correspond to times of rather high sea-surface palaeotemperatures, which would be unexpected during an ice age



and the early Late Viséan age of the Mag Zone (dated radiometrically in northwestern Argentina), pose no serious contradiction to the climatic implications of the Paraca Flora. These warmer-climate plant assemblages may have thrived during the fairly long interglacial separating the early Late Viséan and Serpukhovian ice ages

2. Among the 30 % of presumably autochthonous miospores found in diamictites and other associated sediments of well 1-TM-1-MA, *Vallatisporites vallatus* has the youngest known first occurrence. It is suggested that the autochthonous latest Famennian palynoflora, characteristic of the LVa (*lepidophyta-vallatus*) Zone, could

thus represent the local vegetation developed in deltaic and coastal environments, which were locally disrupted by ice lobes originating from the contemporaneous ice cap (Fig. 5)

3. A 18-m-thick diamictite section in the lower part of the Itacua Formation (Bolivia) was interpreted by Wicander et al. (2011) to be the result of multiple glacial–interglacial events recurrent during the 3 million years of duration of the combined LL–LE–LN zones. This hypothesis does not fit palaeoclimatic and eustatic evidence from Western Europe, where the standard miospore zonation has been compared to sea-surface palaeotemperature estimates based on oxygen isotopes from conodont apatite ($\delta^{18}\text{O}_{\text{phosph}}$) as well as to sea-level changes. It is concluded that sea surface temperatures remained rather warm for most of the *R. lepidophyta* biochron, except during a major sea-level fall (documented by the Hangenberg Sandstone) restricted to the uppermost LN Zone. These data suggest a much shorter depositional time span (100,000 years) for the lower part of the Itacua Formation than previously considered, corresponding to the upper LE–LN zonal span in Western Europe, and LVa Zone in South America. On the other hand, higher parts of the Itacua Formation contain Mississippian miospores, thus indicating a probable superposition of latest Famennian and Mississippian diamictites, as also noted in the Solimões Basin of northern Brazil

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References

- Andrade SM, Daemon RF (1974) Litoestratigrafia e bioestratigrafia do flanco sudoeste da Bacia do Parnaíba (Devoniano e Carbonífero). Anais do 28º Congresso Brasileiro de Geologia. Porto Alegre 2:129–137
- Azcuy CL, di Pasquo M (2005) Early Carboniferous palynoflora from the Ambo Formation, Pongo de Mainique, Peru. Rev Palaeobot Palynol 134:153–184
- Azcuy CL, di Pasquo M (2006) Additional systematic information on the Early Carboniferous palynoflora from the Ambo Formation, Pongo de Mainique, Peru. Rev Bras Paleontol 9(1):41–52
- Bruckschen P, Veizer J (1997) Oxygen and carbon isotopic composition of Dinantian brachiopods, palaeoenvironmental implications for the Lower Carboniferous of Western Europe. Palaeogeogr Palaeoclimatol Palaeoecol 132:243–264
- Caccianiga M, Andreis C, Diolaiuti G, D'Agata C, Mihalcea C, Smiraglia C (2011) Alpine debris-covered glaciers as a habitat for plant life. Holocene 21(6):1011–1020
- Caputo MV (1985) Late Devonian glaciation in South America. Palaeogeogr Palaeoclimatol Palaeoecol 51:291–317
- Caputo MV, Crowell JC (1985) Migration of glacial centers across Gondwana during Paleozoic Era. Geol Soc Am Bull 96:1020–1036
- Caputo MV, Melo JHG, Streel M, Isbell JL (2008) Late Devonian and Early Carboniferous glacial records of South America. In: Fielding CR, Frank TD, Isbell JL (eds) Resolving the late paleozoic ice age in time and space. Geol Soc Am Spec Pap 441:161–173
- Carozzi AV (1980) Tectonic control and petroleum geology of the Maranhão Basin, Brazil. J Petrol Geol 2(4):389–410
- Carozzi AV, Falkenhein FUH, Carneiro RG, Esteves FR, Contreiras CJA (1975) Análise ambiental e evolução tectônica sin-sedimentar da seção siluro-eocarbonífera da Bacia do Maranhão. Ciência-Técnica-Petróleo, Seção: Exploração de Petróleo, 7, 48 p. + Appendix. (2 vols.)
- Césari SN, Limarino CO, Gulbranson EL (2011) An Upper Paleozoic bio-chronostratigraphic scheme for the western margin of Gondwana. Earth Sci Rev 106:149–160
- del Papa C, di Pasquo M (2007) Paleoenvironmental interpretation and palynology of outcrop and subsurface sections of the Tarija Formation (Upper Carboniferous), northwestern Argentina. J S Am Earth Sci 23:99–119
- di Pasquo M (2007a) Asociaciones palinológicas presentes en las Formaciones Los Monos (Devónico) e Itacua (Carbonífero Inferior) en el perfil de Balacupa, sur de Bolivia. Parte 1. Formación Los Monos. Rev Geol Chile 34(1):97–137
- di Pasquo M (2007b) Asociaciones palinológicas presentes en las Formaciones Los Monos (Devónico) e Itacua (Carbonífero Inferior) en el perfil de Balacupa, sur de Bolivia. Parte 2. Formación Itacua y interpretación estratigráfica y cronología de las formaciones Los Monos y Itacua. Rev Geol Chile 34(2):163–198
- di Pasquo M (2007c) State of the art of the Devonian palynological records in northern Argentina, Southern Bolivia and Northwestern Paraguay. Devonian Land-Sea interaction: Evolution of ecosystems and climate (DEVEC):70–73
- di Pasquo M, Azcuy CL (1997) Palinomorfos retrabajados en el Carbonífero Tardío de la Cuenca Tarija (Argentina): su aplicación a la datación de eventos diastróficos. Revista da Universidade Guarulhos, Geociências 2:28–42
- Dino R, Playford G (2002a) Stratigraphic and palaeoenvironmental significance of a Pennsylvanian (Upper Carboniferous) palynoflora from the Piauí Formation, Parnaíba Basin, northeastern Brazil. Paleontol Res 6(1):23–40
- Dino R, Playford G (2002b) Miospores common to South American and Australian Carboniferous sequences: stratigraphic and phytogeographic implications. In: Hills LV, Henderson CM, Bamber EW (eds) Carboniferous and Permian of the World. Can Soc Petrol Geol Mem 19:336–359
- Dolaniiti E (1954) A flora do Carbonífero inferior de Teresina Piauí. Departamento Nacional de Produção Mineral, Divisão de Geologia e Mineralogia, Boletim 148:1–56
- Eiras JF, Becker CR, Souza EM, Gonzaga FG, Silva JGF, Daniel LMF, Matsuda NS, Feijó FJ (1994) Bacia do Solimões. Boletim de Geociências da Petrobras 8(1):17–45
- Fasolo Z, del Vergel M, Oller J, Azcuy C (2006) Nuevos datos palinológicos de la Formación Kaka (Eoserpukhoviano) en La Encañada de Beu, Subandino Norte de Bolivia. Rev Bras Paleontol 9:53–62
- Grahn Y, Loboziak S, Melo JHG (2001) Integrated miospore-chitinozoan biozonation of the Parnaíba Basin and its correlation with Petrobras (Müller 1962) Silurian–Lower Carboniferous palynozones. In: Melo JHG, Terra GJS (eds) Correlação de Sequências Paleozoicas Sul-Americanas. Ciência-Técnica-Petróleo, Seção: Exploração de Petróleo 20:81–89
- Grahn Y, Melo JHG, Loboziak S (2006) Integrated middle and late Devonian miospore and chitinozoan zonation of the Parnaíba Basin, Brazil: an update. Rev Bras Paleontol 9(3):283–294
- Higgs KT, Streel M (1994) Palynological age for the lower part of the Hangenberg Shales in Sauerland, Germany. Ann Soc Géol Belg 116(2):243–247

- Higgs KT, Clayton G, Keegan JB (1988) Stratigraphic and Systematic Palynology of the Tournaisian Rocks of Ireland. Geological Survey of Ireland, Special Paper 7, 93 p
- Higgs KT, StreeL M, Korn D, Paproth E (1993) Palynological data from the Devonian-Carboniferous boundary beds in the new Stockum Trench II and the Hasselbachtal Borehole. Northern Rhenish Massif, Germany. *Ann Soc Géol Belg* 115(2/1992):551–557
- Hyam DM, Marshall JEA, Sanderson DJ (1997) Carboniferous diamictite dykes in the Falkland Islands. *J Afr Earth Sci* 25:505–517
- Iannuzzi R, Pfefferkorn HW (2002) A pre-glacial, warm-temperate floral belt in Gondwana (Late Viséan, Early Carboniferous). *Palaios* 17:571–590
- Kaiser IS, Steuber T, Becker RT (2008) Environmental change during the Late Famennian and Early Tournaisian (Late Devonian-Early Carboniferous): implications from stable isotopes and conodont biofacies in southern Europe. *Geol J* 43:241–260
- Kaiser IS, Becker RT, Spalletta C, Steuber T (2009) High-resolution conodont stratigraphy biofacies, and extinctions around the Hangenberg event in pelagic successions from Austria, Italy, and France. *Paleontogr Am* 63:99–143
- Kaiser IS, Becker RT, Steuber T, Aboussalam SZ (2011) Climate-controlled mass extinctions, facies, and sea-level changes around the Devonian-Carboniferous boundary in the eastern Anti-Atlas (SE Morocco). *Palaeogeogr Palaeoclimatol Palaeoecol* 310:340–364
- Kegel F (1954) Lamelibránquios da Formação Poti (Carbonífero Inferior) do Piauí. Departamento Nacional Produção Mineral, Divisão de Geologia e Mineralogia, Notas Preliminares e Estudos, Boletim 88
- Loboziak S, StreeL M, Caputo MV, Melo JHG (1991) Evidence of West European-defined miospore zones in the uppermost Devonian and Lower Carboniferous of the Amazonas Basin (Brazil). *Geobios* 24(1):5–11
- Loboziak S, StreeL M, Caputo MV, Melo JHG (1992) Middle Devonian to Lower Carboniferous miospore stratigraphy in the central Parnaíba Basin (Brazil). *Ann Soc Géol Belg* 115:215–226
- Loboziak S, StreeL M, Caputo MV, Melo JHG (1993) Middle Devonian to Lower Carboniferous miospores from selected boreholes in Amazonas and Parnaíba basins (Brazil): additional data, synthesis, and correlation. Documents des Laboratoires de Géologie de la Faculté des Sciences de Lyon 125:277–289
- Loboziak S, Melo JHG, Quadros LP, Daemon RF, Barrilari IMR, StreeL M (1995) Biocronoestratigrafia de miósporas do Devoniano Médio-Carbonífero Inferior das bacias do Solimões e Parnaíba (estado da arte). *An Acad Bras Cienc* 67(3):394–395 (Abstract.)
- Loboziak S, Melo JHG, StreeL M (1998) Reassessment of Viséan miospore biostratigraphy in the Amazon Basin, northern Brazil. *Rev Palaeobot Palynol* 104:143–155
- Loboziak S, Melo JHG, StreeL M (2000a) Latest Devonian and Early Carboniferous palynostratigraphy of northern Brazil and North Africa: a proposed integration of Western European and Gondwanan miospore biozonation. *Bulletin du Centre de Recherches Elf Exploration Production* 22(2):241–259
- Loboziak S, Caputo MV, Melo JHG (2000b) Middle Devonian-Tournaisian miospore biostratigraphy in the south-western outcrop belt of the Parnaíba Basin. *Rev Micropaleontol* 43(4):301–318
- Melo JHG, Loboziak S (2000) Viséan miospore biostratigraphy of the Poti Formation, Parnaíba Basin, northern Brazil. *Rev Palaeobot Palynol* 112:147–165
- Melo JHG, Loboziak S (2001) New miospore zonation of Devonian-Early Carboniferous strata in the Amazon Basin: a preliminary account. *Ciência-Técnica-Petróleo, Seção: Exploração de Petróleo* 20:99–107
- Melo JHG, Loboziak S (2003) Devonian-Early Carboniferous miospore biostratigraphy of the Amazon Basin, northern Brazil. *Rev Palaeobot Palynol* 124:131–202
- Melo JHG, Loboziak S, StreeL M (1999) Latest Devonian to early Late Carboniferous biostratigraphy of northern Brazil: an update. *Bulletin du Centre de Recherches Elf Exploration Production* 22:13–33
- Menning M, Alekseev AS, Chuvashov BI, Davydov VI, Devuyt F-X, Forke HC, Grunt TA, Hance L, Heckel PH, Izokh NG, Jin Y-G, Jones PJ, Kotlyar GV, Kozur HW, Nemyrovska TI, Schneider JW, Wang X-D, Weddige K, Weyer D, Work DM (2006) Global time scale and regional stratigraphic reference scales of Central and West Europe, East Europe, Tethys, South China, and North America as used in the Devonian-Carboniferous-Permian Correlation Chart 2003 (DCP 2003). *Palaeogeogr Palaeoclimatol Palaeoecol* 240:318–372
- Milana JP, Lopez S (1998) Solar cycles recorded in Carboniferous glaci-marine rhythmites (western Argentina): relationships between climate and sedimentary environment. *Palaeogeogr Palaeoclimatol Palaeoecol* 144:37–63
- Müller H (1962) Report on palynological results of samples examined from wells in Maranhão. Petrobras Internal Report 229, 44 pp., pl. 1–9. Petrobras/Setor de Exploração/Região de Produção da Bahia, Salvador
- Ogg JG, Ogg G, Gradstein FM (2008) The concise geologic time scale. Cambridge University Press, Cambridge
- Perez-Leyton M (1990) Palynomorphes du Dévonien moyen et supérieur de la coupe de Bermejo-La Angostura (sud-est de la Bolivie). Master Dissertation, Université de Liège, Belgium
- Perez-Leyton M (1991) Miospores du Dévonien moyen et supérieur de la coupe de Bermejo-La Angostura (sud-est de la Bolivie). *Ann Soc Géol Belg* 113(2, 1990):373–389
- Pérez-Loinaze V (2007) A Mississippian miospore biozone for southern Gondwana. *Palynology* 31:101–118
- Playford G (1963) Lower Carboniferous microfloras of Spitsbergen-Part Two. *Palaeontology* 5(4):619–678
- Playford G (1971) Lower Carboniferous spores from the Bonaparte Gulf Basin, Western Australia and Northern Territory. *Bulletin of the Bureau of Mineral Resources. Geol Geophys* 115:1–105
- Playford G (1978) Lower Carboniferous spores from the Ducabrook Formation, Drummond Basin, Queensland. *Palaeontographica* B167:105–160
- Ponciano LCMO, Della Favera JC (2009) Flood-dominated fluvio-deltaic system: a new depositional model for the Devonian Cabeças Formation, Parnaíba Basin, Piauí, Brazil. *An Acad Bras Cienc* 81(4):769–780
- Sandberg CA, Ziegler W (1996) Devonian conodont biochronology in geologic time calibration. *Senck leth* 76(1/2):259–265
- StreeL M (1999) Quantitative palynology of Famennian events in the Ardenne-Rhine Regions. *Abh Geol Bundesanstalt, Wien* 54:201–212
- StreeL M, Bless MJM (1980) Occurrence and significance of reworked palynomorphs. *Meded Rijks Geol Dienst* 32(10):69–80
- StreeL M, Higgs KT, Loboziak S, Riegel W, Steemans P (1987) Spore Stratigraphy and Correlation with faunas and floras in the type marine Devonian of the Ardenno-rhenish regions. *Rev Palaeobot Palynol* 50:211–229
- StreeL M, Caputo MV, Loboziak S, Melo JHG (2000) Late Frasnian-Famennian climates based on palynomorph quantitative analyses and the question of the Late Famennian glaciations. *Earth Sci Rev* 52:121–173
- StreeL M, Caputo MV, Loboziak S, Melo JHG, Thorez J (2001) Palynology and sedimentology of laminites and tillites from the Latest Famennian of the Parnaíba Basin, Brazil. *Geol Belg* 3:87–96
- Suárez-Soruco R, Lobo-Boneta J (1983) La Fase compresiva Eohercínica en el sector oriental de la Cuenca Cordillerana de Bolivia. *Revista Técnica de Yacimientos Petrolíferos Fiscales Bolivianos* IX 1–4:189–202
- Turnau E, Avchimovitch VI, Byvsheva TV, Clayton G, Higgs KT, Owens B (1994) Taxonomy and stratigraphical distribution of *Verrucosisporites nitidus* Playford, 1964 and related species. *Rev Palaeobot Palynol* 81:289–295
- Wicander R, Clayton G, Marshall JEA, Troth I, Racey A (2011) Was the Latest Devonian glaciation a multiple event ? New palynological evidence from Bolivia. *Palaeogeogr Palaeoclimatol Palaeoecol* 305:75–83

Annotated species list 1 (All slides housed in the palynological slide collection of the Biostratigraphy and Palaeoecology Sector of PETROBRAS Research Centre (CENPES/DIVEX/SEBIPE), Rio de Janeiro, Brazil)

Anapiculatisporites cf. *A. semisentus* Playford 1971. Fig. 3a. Ref. 1/W62

As indicated by Playford (1971), the distal sculpture of *A. semisentus* is too uniform in size and distribution for it be considered as belonging to *Apiculiretusispora* (Streel) Streel 1967. The species is recorded as *Apiculiretusispora semisenta* (Playford 1971) Massa et al. 1980 in the highest part of the Ambo Formation in Peru (Azcuy and di Pasquo 2005). The species is known from Bonaparte wells (Bonaparte Basin) in Western Australia where it is dated as Viséan (by conodonts) and late Viséan (by Foraminifera) (Playford 1971, p. 7)

? *Anulatisporites* cf. ? *A. orbiculatus* (Waltz) Playford 1963. Fig. 3b. Ref. 22/P61-4

A single specimen which fits rather well with the description given by Playford (1963) except that it also shows a very distinct *curvaturae perfectae*, a feature never (to our knowledge) observed in densosporites. *A. orbiculatus* is known from the Mississippian of Eastern Europe and Spitsbergen.

? *Cristatisporites inordinatus* (Menendez and Azcuy) Playford 1978. Fig. 3c. Ref. 15/V50-4

A single specimen which fits rather well with the ornament description of *Ancistrospora inordinata* Menendez and Azcuy 1972 from the Late Viséan–Early Namurian from the Province of La Rioja (Argentina), although the radial amb and laevigate proximal surface is difficult to recognize on our specimen.

Densosporites pseudoannulatus Butterworth and Williams 1958. Fig. 3d. Ref. 1/G62-1

The species has a massive smooth cingulum that is wider than the cingulum of *D. annulatus*. *D. annulatus* first occurs near the base of the Viséan.

Densosporites triangularis Kosanke 1950. Fig. 3e. Ref. 21/F43-2

The species has a subtriangular amb and a cingulum with foveolate dissections.

Densosporites are known to be much more abundant in coals than in shales and therefore its first occurrence might be linked to facies. *Densosporites* become numerically important components from the TC Zone in the Late Viséan until the Pennsylvanian.

D. pseudoannulatus and *D. triangularis* are present in the Viséan and Namurian of Scotland.

Dibolisporites microspicatus Playford 1978. Fig. 4f. Ref. 8/Y62

The species is described from Viséan sediment of the Drummond Basin (Queensland, Australia) and is identified in a few South American papers: i.e., in the highest part (Late Viséan?) of the Ambo Formation in Peru (Azcuy and di Pasquo 2005) and in the early? Viséan of the Tarija Basin (di Pasquo 2007a, b, c).

Ductilspora corrugata Pérez Loinaze 2005. Fig. 4d. Ref. 5/F47-1

Described from the Late Viséan-age Cortaderas Fm. in the San Juan province (Argentina)

Indotriradites sp. cf. *I. dolianitii* Loboziak et al. 1999. Fig. 3f. Ref. 7/L57

Species recorded from Late Viséan-age strata of North Africa, the Middle East and South America.

Lophozonotriletes dentatus Hughes and Playford 1961. Fig. 3g. Ref. 21/B45-4

Species recorded from the Mississippian of Spitsbergen. A badly preserved conspecific specimen is perhaps *Spinozonotriletes* sp. in Sessarego and Cesari (1989) from the El Raton Formation (an equivalent to the Maliman Formation) in western Argentina, a locality with well-documented megafloras thought to belong to the Viséan.

Perotriletes perinatus Hughes and Playford 1961. Fig. 4l. Ref. 25/D53-3

Species recorded from the Mississippian of Spitsbergen.

Procoronaspora butterworthii Staplin 1960. Fig. 3h. Ref. 20/R56-2

Species recorded from the Late Mississippian in Alberta, Canada.

Raistrickia clavata Hacquebard 1957 emend Playford 1964. Fig. 3i. Ref. 7/N53-1

Species recorded in the Euramerican and Gondwanan Mississippian.

Raistrickia nigra Love 1960. Fig. 3j. Ref. 2/F56

A Late Viséan to earliest Namurian species in Western Europe, and also known in Brazil.

Raistrickia cf. *R. clavata* in Duenas and Cesari (2005) in the Llanos Orientales Basin, Colombia, might be conspecific.

Raistrickia cf. *R. ponderosa* Playford 1964. Fig. 4k. Ref. 1/C59

This species is described as characteristic of the ?Viséan Cheverie Formation, Horton Group, Canada. Some specimens in our material show less dense and more verrucate ornaments as in the Namurian? *Verrucosisporites quasigobettii* Jones and Truswell 1992.

Rotaspora sp. Fig. 3k. Ref. 5/F42-4

A single specimen. *Rotaspora* sensu stricto is known from the Namurian of Scotland and is first found in the Late Viséan in Western Europe.

Schopfipollenites? sp. Fig. 4a,b,c. Ref. 25/E57-2 and E58

Two forms with possible longitudinal furrows. Small praecolpates reminiscent of, and possibly conspecific with, the illustrated specimens have been previously reported from other Upper Viséan sections of South America, including the Faro Formation of the Amazon Basin in northern Brazil (Loboziak et al., 1991, 1998; Melo and Loboziak, 2003), the uppermost Ambo Formation in Peru (Azcuy and di Pasquo 2006), and in the partly coeval Kaka Formation in Bolivia (Fasolo et al. 2006).

Schopfites augustus Playford 1964. Fig. 4i. Ref. 1/D64-3

The species is described from the Mississippian undifferentiated Horton Group, Canada.

Schulzospora sp. Fig. 3l. Ref. 1/U46-4

The genus is known from the Late Viséan and Pennsylvanian of western Europe and is identified in a few South American papers: i.e., from the Upper Viséan Cortaderas Formation. (Pérez Loinaze, 2008) in the San Juan province, Argentina.

Secarisporites remotus Neves 1961. Fig. 3m. Ref. 24/M59-1

The species is described from the Namurian B and C of the southern Pennines, England. A close species, *S. undatus*, is described (Playford 1978) from Viséan sediment of the Drummond Basin, Queensland, Australia.

Spelaeotriletes arenaceus Neves and Owens 1966. Fig. 4e. Ref. 25/S50

A species described from the Namurian of England but generally accepted as ranging from Late Viséan to Early Westphalian.

Thymospora cymbiformis Playford and Satterthwait 1988. Fig. 4h. Ref. 26/S58-3

A Viséan monolete species with coarse verrucate to rugulate ornaments described from the Bonaparte Basin, Western Australia.

Tripartites? sp. Fig. 4g. Ref. 13/C52-2

A single specimen of unknown affinity. *Tripartites* might be inappropriate due to the presence of a well-rounded central area. True cingulate genera like *Murospora*, *Simozonotriletes*, *Cincturasporites*, or *Tendosporites* do not seem to fit any better. *Tripartites*-type miospores are known to first occur in the Late Viséan in western Europe.

Tumulispora variverrucata (Playford) Staplin and Jansonius 1964. Fig. 4j. Ref. 9/H46

Lophozonotriletes variverrucatus was described from the Mississippian of Spitsbergen.

Annotated species list 2 (slides housed in the palynological slide collection of the Palaeogeobiology, Palaeopalynology, Palaeobotany Research Unit, Department of Geology, University of Liège, Belgium.)

Cristatisporites sp 1 in Perez-Leyton 1991. Fig. 6d,e

Perez-Leyton 1990: pl. 10, fig 3, slide M12 : N28- 3; fig 4, slide M12: W44. Perez-Leyton 1991: pl. 2, figs. 9–10.

Palynozone M3 (Tournaisian) in Lanzoni and Magloire (1969): No. 3256.

Dictyotriletes flavus Keegan 1977. Fig. 6g,h.

Perez-Leyton 1990: pl. 9, fig. 14, slide M12: T41; fig. 15, slide M12: G39.

BP-PC biozones in Higgs et al. (1988).

Indotriradites cf. *mitratus* (Higgs 1975) Higgs 1996. Fig. 6j. (M13:N29-4).

See another specimen in Perez-Leyton 1990: pl. 12, figs. 1–2, slide M13: M28.

PC biozone in Higgs et al. (1988).

Lophozonotriletes concentricus (Byvsheva) Higgs et al. 1988. Fig. 6b.

Perez-Leyton 1990: pl. 10, fig. 9, slide M13: H42-2.

LE-PC biozones in Higgs et al. (1988).

Lophozonotriletes triangulatus (Ischenko) Hughes and Playford 1961. Fig. 6c

Perez-Leyton 1990: pl. 10, figs. 10–11, slide M13: H31-4.

VI-PC biozones in Higgs et al. (1988).

Murospora cf. *M. aurita* (Waltz) Playford 1962. Fig. 6a.

Perez-Leyton 1990: pl. 10, figs. 13–14, slide M13: H42-4.

Mississippian in Karczewska and Turnau (1974). See also palynozones M4-5 (Viséan) in Lanzoni and Magloire (1969): No. 2894.

Spelaeotriletes resolutus Higgs 1975. Fig. 6 fi

Perez-Leyton 1990: pl. 11, fig 9, slide M13: X31-3; fig. 10, slide M12: P44-1; fig. 11, slide M13: F24-4.

VI-PC biozones in Higgs et al. (1988).

Vallatisporites banffensis Staplin and Jansonius 1974. Fig. 6 kl.

Perez-Leyton 1990: pl.12, figs 15–16, slide M13: R40; fig. 17, slide M12: T27; fig. 18, slide M12: F26-3. Perez-Leyton 1991: pl. 2, figs 27–30.

Palynozones L10-M3 in Lanzoni and Magloire (1969): No. 2891.