

WHEN IS *Retispora lepidophyta* A RELIABLE PROXY TO DEFINE THE DEVONIAN-CARBONIFEROUS BOUNDARY (DCB)? A REVISION OF THIS BOUNDARY IN SOUTH AMERICA (SAM)

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Abstract

The main objective of this contribution is to update and critically analyze the hitherto published findings of *Retispora lepidophyta* (*RI*), especially those in deposits from South America (SAM). According to records around the world, it is interpreted that the *RI* flora reached a wide paleobiogeographic distribution with a high degree of synchronicity during the last 2 Ma of the Late Devonian. Although, *RI* together with other Devonian taxa are frequently found reworked especially into Mississippian and Pennsylvanian rocks of South America as well as in the Northern Rockies of western North America. In the latter, a controversy remains as to whether or not *RI* is *in situ* in the Early Mississippian strata of the Sappington, Bakken, and Banff formations. The extinction of *RI* together with several terrestrial and marine fossils would have been triggered by a global paleoclimatic change at the end of the Devonian. A global regression of glacio-eustatic origin confirmed by diamictites in South America, Africa, and eastern North America was likely the main factor among others (e.g. diastrophic processes, volcanism, meteoric impact, orbital forcing). At this point it is worthy to be asked "When is *RI* a reliable proxy to define the Devonian-Carboniferous boundary (DCB)?" Could there be a diachronic appearance of *RI* in SAM with respect to its appearance in Europe or other regions of the world? There is

another phrase that also applies in this case: "tell me who you hang out with and I'll tell you how old you are". Therefore, of great importance is to carefully classify all the taxa found along stratigraphic successions of the Famennian - Tournaisian and analyze their stratigraphic range, especially FADs (first appearance datum) of those that are or could be diagnostic. An updating of palynological associations obtained from diamictites from the Cumaná Formation in Isla del Sol, Matilde and Hinchaka Mine and from the Toregua Formation in various sections of the Bolivian mountain range and in the Pando and Manuripi wells, suggested their Early Carboniferous age bearing recycled *RI*. As well, geological evidences such as discontinuities in the sedimentation identified in those sections, due to the effect of local and regional tectonic processes that acted in parallel with glacio-eustasy. Unfortunately in SAM, other proxy data such as conodonts and ammonoids and forams are not found in association with *RI* palynofloras, which are more frequently present in paleotropical-equatorial marine associations rather than elsewhere in southern Gondwana. Moreover, till now, there are very few *RI* palynofloras radiometrically dated but any in South America. Hence, to try to shed light to these uncertainties, a critical revision of the presence of *RI* in diamictites and / or tillites is mandatory to define their time- "*in situ*" or "reworked" character.

1 Introduction

Extinctions of different groups of fossils have occurred in the interval from latest Devonian to the earliest Carboniferous (DCB) reviewed by Kaiser et al. (2016) and Becker et al. (2016). This interval was characterized by a profound change in the biosphere due to the disappearance of typical Devonian groups (e.g., stromatoporoids, trilobites, and conodonts *Palmatolepis*) and the subsequent radiation of new groups in the basal Carboniferous (e.g., *Gattendorfia* ammonoids). Becker et al. (2012) made interpolations of biostratigraphic information of conodonts, ammonoids and foraminifers zones documented in several localities around the world and proposed short durations of only 100–300 kyr for some of those zones (see also Sandberg and Ziegler, 1996). Myrow et al. (2014) established the main event or black shale of the latest Famennian interval lasted between less than 50 and 190 kyr based on geochronological dating of Polish ash layers (see also De Vleeschouwer et al., 2013). New and revised biostratigraphic information from conodonts, ammonoids and foraminifers zones in which biostratigraphic and taphonomic and litho-eco-facies problems discussed or highlighted in many works published especially in the last years (e.g. Aretz and Corradini, 2021, and references therein). A critical revision of the latest Famennian palynofloras documented in Europe was addressed by Strel and Steemans (2020) and Strel and di Pasquo (2022).

In this sense, Kaiser et al. (2016) and Becker et al. (2016) updated biozonation schemes across the DCB based on the first occurrence (FAD) of the Devonian conodont index taxa *Bispathodus ac. aculeatus*, *Bi. costatus*, *Bi. ultimus*, *Siphonodella praesulcata*, *Protognathodus kockeli*. The sudden and global extinction of most of the Devonian conodont groups during the deposition of the “global” Hangenberg black Shale defines the base of the *costatus-kockeli* Interregnum (ckI, Kaiser et al., 2009) (Fig.

1). This is a slightly higher level than the former Middle *praesulcata* Zone, which is poorly defined and diachronous (Corradini, 2008; Kaiser et al., 2016 and references therein). In the Lower Carboniferous, the FAD of *Pr. kuehni*, *Si. bransoni*, *Si. duplicata*, *Si. jii*, *Si. sandbergi* and *Si. quadruplicata* are used for establishing the refined Tournaisian biozones. Despite the ranges of the lineage of *Si praesulcata* - *sulcata* still need a revision, as they represent the extremities of variable morphotypes, with an evolutionary trend towards the increasing of the abundance of the curved morphotypes in younger populations (Kaiser and Corradini, 2011; Corradini et al., 2016; Becker et al., 2016), *Si sulcata* is used as an earliest Tournaisian taxon in most of the more recent DCB works published in the last few years.

The DCB foraminifer zonation is based on calcareous shallow-water groups, while agglutinating taxa, especially of pelagic settings, are long-ranging (e.g. Eickhoff, 1973 in Becker et al., 2016). The European–Russian zonations have been reviewed by Kulagina et al. (2003), Devuyt & Hance in Poty et al. (2006), and Kulagina (2013). They can be correlated into neritic successions of South China (e.g. Hance, 1996; Hance et al., 2011). The uppermost Famennian is roughly characterized by the entry of *Q. kobeitusana* (Mamet et al., 1965; Austin et al., 1970; Conil et al., 1977, 1991). The Belgian DFZ7 (formerly df31 Zone) is defined by the presence of either *Q. kobeitusana* or *Q. konensis* (Devuyt and Hance, in Poty et al., 2006). In the Chanxhe reference section, the base of this zone lies just above the first *Bi. ultimus ultimus* and just before the change from *R. lepidophyta lepidophyta* to *R. lepidophyta minor* (upper LL Zone, Maziane-Serraj et al., 2007).

Strel et al. (2012) and Strel (2015) emphasized that the LE and LVA (LN) Zones may represent lateral facies variants of the same time interval, which has implications for the dating of glacial pulses in South America. The *R. lepidophyta* declined gradually within the

middle/upper crisis interval (middle to upper or 'atypical' LN Zone, HS/HSS; e.g. Avkhimovitch et al., 1988; Higgs et al., 1993; Streel, 1999, 2015), and its extinction defines the base of the VI Zone in the upper part of the *kockeli* Zone, between the Lower and Upper Stockum Limestones of the type area in Europe (Higgs and Streel, 1984, 1994; Higgs et al., 1993). Other important species that disappeared are *Rugospora flexuosa*, *Rugospora radiata*, *Diducites versabilis* and *D. plicabilis* (e.g. Streel, 2015). This correlation was based on data from the Hasselbachtal auxiliary stratotype (Becker et al., 1984) and Stockum (Higgs and Streel, 1984), not on the La Serre GSSP level due to the lack of palynomorphs.

This zonal boundary in the Zigan section on the western slope of the southern Urals, the extinction of *R. lepidophyta* also just predates the entry of *S. (Eo.) sulcata* (s.l., within the middle Gumerov Horizon, Pazukhin et al., 2009). In the Timan, the VI Zone correlates with the shallow-water *Patr. variabilis* Zone (Durkina and Avkhimovitch, 1988). The entries of *Spelaotriletes balteatus* or *Bascaudaspora mischkinensis* are used to define East European basal Carboniferous MB and PMi Subzones (Avkhimovitch, 1993; Byvsheva and Umnova, 1993). The Lower Alum Shale Event coincides with the base of the HD Zone, defined by the entries of *Kraeuselisporites hibernicus* and *Umbonatisporites distinctus* (Higgs and Streel, 1984).

In South America, the DCB characterized in northern basins of Brazil mainly by Melo and Loboziak (2003) and western Bolivia by Lakin et al. (2021), in which late Famennian assemblages bearing *Rl* are documented. Despite these reports of *Rl in situ*, this boundary has been and it is difficult to delimitate especially in Bolivia due to several reasons, such as:

1. Frequent DC unconformable contacts due to diastrophism and/or climatic /sea level changes
2. Difficulty to separate or distinguished the *LL/LE/LN* palynozones

of Europe in South America palynofloras (e.g. Loboziak et al., 1993; Melo and Loboziak, 2003).

3. The entry of *Vallatisporites vallatus* has been used to define the LVa Zone in Brazil (Melo and Loboziak, 2003), as equivalent to the upper part of the LN Zone in Poland (Marynowski and Filipiak, 2007), despite it is a long- ranged species.

4. *Tumulispora malevkensis* has been used to separate an upper division of the earliest Tournaisian PM Subzone in Russia (Avkhimovitch, 1993; Avkhimovitch et al., 1993), which also can be traced in South China (Yang and Neves, 1997: 'Pmr assemblage'). Although, this species is also considered part of a morphon with *T. rarituberculata*, the latter known to appeared from the late Famennian *Rl* assemblages (Playford and Melo, 2012).

5. *Umbellasphaeridium saharicum* is another late Famennian diagnostic taxon of high-latitude microplankton communities with the exception of its occurrence in North America (Vavrdová and Isaacson, 1999). Wicander and Playford (2013) commented (p. 623) on the occurrence of *Umbellisphaeridium deflandrei* or *U. saharicum* from North America reported by Molyneux et al. (1984) from the Strunian Bedford Shale, and from five localities by Wood (1984). However, Wood (1984) considered that the only genuinely *in situ* specimens of *U. deflandrei/U. saharicum* came from the Famennian Chattanooga Shale, Tennessee (Reaugh, 1978) and from undifferentiated black shale, thought to be the Cleveland Shale of northern Ohio. Those from the other three localities (Bedford Shale) remain suspect and could well be judged remanié, because they occur only where reworked Lower-Middle Silurian acritarchs are present (Wood, 1984).

6. The absence or infrequent presence of other diagnostic microfossils/ megafossils, which could help to control the stratigraphic range of associated palynomorphs preventing the application with certainty of the biostratigraphical schemes adopted from

Northern Hemisphere (e.g. Higgs et al., 1988) in SAM.

7. Reworking of *Rl* and other Devonian palynomorphs is a recurring problem in Carboniferous deposits in SAM (di Pasquo and Azcuy, 1997; Streel et al., 2000; di Pasquo, 2003, 2009b; Azcuy and di Pasquo, 2005; di Pasquo et al., 2015b, 2019a; Playford and Melo, 2012; Playford et al., 2012; di Pasquo and Streel, 2022) and elsewhere (e.g. Bless and Streel, 1976; Streel and Bless, 1980; Playford and McGregor, 1993; Playford, 1993). di Pasquo (2007c) indicated that critical palynotaxonomic revisions of the DCB interval in Bolivia and other regions of South America are needed to avoid extending the range of important or diagnostic taxa across this boundary. The latter is an important trouble shared by late Famennian – Tournaisian deposits in South America especially in diamictites bearing *Rl* but lacking independent diagnostic fossils to give a more accurate dating.

Aretz et al. (2021) compiles relevant DCB information from most of the continents including some examples from Chile (e.g. Rubinstein et al., 2017), not commented herein, and others from Brazil and Bolivia. Although, they did not referred to those critical revisions of several localities from Bolivia that demonstrated the presence of Devonian reworked palynomorphs into Mississippian and Pennsylvanian cycles mentioned above (see also di Pasquo et al., 2015b, 2019a). The reworking of palynomorphs is well-known to occur all along the Phanerozoic, and also other microfossils like conodonts are feasible to be reworked, and especially this issue becomes more relevant across short time intervals like this one around the late Famennian – early Tournaisian. For example, Macke and Nichols (2007) interpreted assemblages with *Siphonodella sulcata* and *S. praesulcata* documented in western USA as reworking mixtures (see also Gorozhanina et al., 2010; Iannicelli, 2019). Other issues precluding accurate datings of the DCB are wrong or misinterpreted taxonomic

assignments of illustrated taxa and also, the use of not illustrated taxa listed in abstracts that should be considered with caution (see di Pasquo, 2006, 2007c; di Pasquo and Streel, 2022).

Therefore, these are reasons that have prevented the accurate dating of deposits considered of late Famennian and early Tournaisian in age in SAM. Diamictitic deposits of Bolivia and other places in SAM dated as late Famennian based on the presence of *Rl* as the main diagnostic taxon should need to be re-considered, if possible younger ages could be due to the co-occurrence of taxa with ranges extended into the early Tournaisian (e.g. *Cordylosporites marciae*, *Retusotriletes maculatus*), were disregarded. Even worse, some early Tournaisian taxa such as *Rugospora polyptycha*, *Umbonatisporites distinctus*, *Cristatisporites peruvianus* and *Densosporites spitsbergensis*, present in those deposits with *Rl* ignored, and would need more attention as highlighted by di Pasquo and Azcuy (1997).

Palynologic information from several localities of Bolivia where *Rl* is found reworked into younger Carboniferous deposits not fully published yet, and also a critical revision of selected literature mainly from Bolivian and Brazilian DCB palynofloras is attempted herein in the light of more recent information to contribute to the unravelling of the DCB.

2 Brazil

Melo and Loboziak (2001, 2003) proposed a zonal scheme for the Devonian-Carboniferous of northern basins of Brazil. The latest Famennian assemblages of the Amazon Basin is often, characterized by the joint occurrence of *R. lepidophyta* and *Kraeuselisporites explanatus* (*LE*, Streel et al., 2000; Melo and Loboziak, 2003). Two Interval Zones are concerned. The *LE* with the FOB of *R. lepidophyta* but also containing *Vallatisporites verrucosus*. Many additional species of the genera *Convolutispora*, *Corbulispora*, *Cristatisporites*,

Cymbosporites, *Densosporites* and *Verrucosiporites* also occur in the *LE* strata. All those taxa range upwards into the succeeding *LVa* (*R. lepidophyta-V. vallatus*) Interval Zone but containing also *Verrucosiporites nitidus* and many persist even higher. See Figure 2. Diamictites and glacio-marine strata are common in these intervals, which are equivalent to those in North Brazilian Parnaíba and Solimões basins (see Caputo and Soares, 2019).

The next *Radiizonates arcuatus-Waltzisporea lanzonii* (*AL*) Interval Zone of early Tournaisian succeeding the *LVa* Zone correspond to the *LOB* of important Late Devonian miospores headed by *R. lepidophyta*. This unit is characterized by a proliferation of miospores with simple morphology (e.g. *Rugospora minuta*) and laevigate forms. In certain *AL* Zone section and even in higher Tournaisian and Visean intervals, *R. lepidophyta* and some of its latest Famennian associates may still persist (usually in reduced numbers) due to recycling processes (Melo and Loboziak, 2003).

Playford and Melo (2012) published a taxonomic study of the Mississippian Oriximaná and Faro formations from Amazonas, a detail comparison with previous Brazilian studies and with other Gondwanan microfloras. They summarised in their Figure 6 (page 145) different palynozonal ages established to the Petrobras well 2-LF-1AM based on several authors including the Curiri Formation bearing the *RI-LVa* (*in situ*) zones by Melo and Loboziak (2001, 2003). Other occurrences of the *LE* Zone in Brazil concern diamictite-bearing sections of the Jandiatuba and Uere Formations in the Solimões Basin (Loboziak et al., 1994 a, b) and Cabeças Formation in the Parnaíba Basin (Loboziak et al., 1992, 1993; Loboziak and Melo, 2000, 2002). In all these regions the base of the late Famennian section is underlain by a major hiatus of variable magnitude, which separates the *LE* Zone (or the *LVa* Zone) from older rock units ranging in age from Precambrian to late Famennian (see also Grahn et al., 2001; Streel et al., 2000;

Grahn et al., 2006). Devonian reworked palynomorphs including *RI* were documented in Tournaisian and Visean assemblages in Brazil (see also Loboziak et al., 1995; Loboziak and Melo, 2000, 2002; Playford et al., 2012; di Pasquo and Iannuzzi, 2014), as occurs in Bolivia addressed herein. Morphological anomalies of several abnormal acritarchs documented along continuously cored shallow borehole (e.g., Caima PH-2, 375 core samples along 137 m drilled on the left bank of the Tapajós River) close to the Devonian/Carboniferous boundary of the Amazon Basin, were interpreted as responses to severe disturbances of the marine ecosystems possibly related to glacio-marine conditions, so extensively developed over much of the Amazon Basin and other northern Brazilian regions (see Le Hérissé, 2001). Grahn et al. (2001) attributed to the late Famennian *LE-LN* zones of the lower part of the Longá Formation and the upper part to the Tournaisian *BP-PC* zones, and in between, a possible discontinuity.

3 Bolivia

Tectonic movements and paleogeographic changes triggered by paleoclimatic fluctuations in the context of Late Paleozoic Ice Age (LPIA) occurred since the late Devonian and especially, during the Carboniferous affecting all around the World (see Golonka, 2020; Scotese et al., 2021). In western Bolivia-Argentina, the regional extension of the tectonic movements (equivalent to the Tatarenda-Chiriguana phases) closed the Famatinian Cycle (Lower Paleozoic) and started the Gondwanan (Upper Paleozoic) one in the central part of Argentina (e.g. Starck and del Papa, 2006), equivalent in Bolivia to the Cordilleran Cycle of the Sub-Andean range in Bolivia (Suárez Soruco, 2000). Evidences of their impact are the erosion of thick Devonian successions, expressed through the reworking of palynomorphs of that age into younger Lower and Upper Carboniferous deposits (e.g., di Pasquo, 2003; Starck and del Papa, 2006).

In this section, a revision of palynofloras around the DCB is addressed herein based on unpublished information presented in congresses indicated in Figure 3 along with few recent publications.

3.1 Bolivian Altiplano

Lakin et al. (2021) documented the Devonian/Carboniferous Boundary (DCB) interval Bolivian Altiplano using sedimentology, palynology, total organic carbon and bulk $\delta^{13}\text{C}_{\text{org}}$. The Colpacucho Formation is a Late Devonian shelfal-marine siliciclastic sequence. It is overlain in the study area by a unit of coarse sandstones and sandy diamictites, interpreted as a glaciomarine unit of very latest Famennian age (7 km wide and 60–120 m thick) with a variably incisive basal contact (<100 m). The last occurrence of *Retispora lepidophyta* and *Umbellasphaeridium saharicum* phytoplankton are main significant palynological changes registered 12 m above the flooding surface over which the offshore marine Kasa Formation of Mississippian age deposited. Following these authors marine and terrestrial palynological extinctions are synchronous with a 2 ‰ positive carbon isotope excursion interpreted to be reflective of changes in organic matter delivery and preservation during an interval of environmental stress of a short glacial episode.

3.2 Isla del Sol, Mina Matilde and Hinchaka sections

Díaz Martínez et al. (1993, 1999) referred to the Famennian glaciation of western Gondwana, based on the palynologic information from diamictites of the Cumaná Formation (Vavrdová et al., 1991, 1993) at Isla del Sol and Mina Matilde and Hinchaka sections (Fig. 4).

Vavrdová et al. (1993) presented the palynologic result of two sections in the Titikaka lake area, and established a Famennian *Rl* interval for the samples IS 2 and IS 3 (Isla del Sol) and MM4a and 9a (Mina Matilde), due to the presence of this taxon along with *Kraeuselisporites*

explanatus, *Raistrickia macrura*, *R. spathulata*, *R. variabilis*, *Retusotriletes incohatus*, and the acritarch *Umbellasphaeridium saharicum*.

The samples MM4a and 9a also document important taxa associated to *Rl* such as *Verrucosisporites nitidus*, *Lophozonotriletes malevkensis*, *Knoxisporites literatus*, *Cordylosporites marciae* and *Convolutispora vermiformis*. In the sample MM9b species with Tournaisian ranges such as *Densosporites spitsbergensis*, *Grandispora conspicua*, *G. echinata*, *Spelaeotriletes obtusus*, *S. pretiosus*, *Rugospora polyptycha*, *Tumulispora rarituberculata* and *Cyrtospora cristifera* allowed the attribution an early Tournaisian age of VI Zone to this assemblage. Other Devonian species associated to those spore taxa, include numerous acritarchs that were considered indigenous. *Rl* is absent. Díaz Martínez et al. (1999) cited also the presence of *Dibolisporites distinctus*, another exclusive species of Tournaisian in Europe and Australia.

Díaz-Martínez et al. (1999) described a section at Hinchaka and its palynologic content of samples HI2-HI4 from a diamictite of Cumaná Formation characterized by poor in palynomorphs bearing *Rl*, *Convolutispora vermiformis*, *Cordylosporites marciae*, *Kraeuselisporites explanatus*, *Raistrickia macrura*, *R. spathulata*, *Spelaeotriletes resolutus*, *S. obtusus*. It was akin to the *R lepidophyta* – *K explanatus* (LE) Zone. Overlying, the sample HI6 yielded *Raistrickia clavata* and *D. spitsbergensis* was assigned to the early Tournaisian VI Zone.

It must be mentioned that several acritarchs and other palynomorphs recycled from the Devonian *sensu lato* are associated to the indigenous taxa in all the samples of the three localities.

di Pasquo and Azcuy (1997) and di Pasquo (2003) warned about the presence of Devonian olistoliths intercalated in Mississippian and Pennsylvanian successions locally, and also, clasts of very different sizes into the diamictites yielding different Devonian

ages through specific palynologic analysis (including *Rl* assemblage, data mostly unpublished). Streel (2008) referred to the early Tournaisian age of sample 9b as it might belong to the uppermost Famennian (LN* Zone in Streel and di Pasquo, 2022). This may prove to be important because the Tournaisian part of Glacial Episode 1 of Lopez-Gamundi (1997, in Iannuzzi and Pfefferkorn, 2002) is based on this material. Samples M9a and M4a of the Colpacucho Formation belong to the “late” latest Famennian LN Zone and should indicate that the thick sandy part of that formation does correspond to a gap between the Cumaná and Kasa formations in the two sections in Figure 4, however, correlations are shown differently by the authors. Whether these correlations confirmed, then the succession LE-LN will prove to be unusable in this area. The scarcity of the miospore *Verrucosporites nitidus* might render the distinction between these two zones unrealistic in the northern Brazil basins (Melo and Loboziak, 2003). It was the reason why they subsequently selected *Vallatisporites vallatus* as a marker for the LN Zone (see LVa in Fig. 2), which has been proved (Streel and Traverse, 1978; Higgs and Streel, 1984) to first occur in the highest part of the *Retispora lepidophyta* range.

Therefore, a critical taxonomic revision of these sections is recommended due to the importance of finding palynoassemblages bearing *Rl in situ* in Bolivia to be compared with certainty with those from Brazil and from elsewhere in northern Hemisphere, as further discussed in this contribution.

3.3 Los Espejos Range between Santa Cruz de la Sierra – Cochabamba

The Bermejo river outcrop studied by Pérez Leyton (1990) between Bermejo-La Angostura in the highway connecting Santa Cruz de la Sierra – Cochabamba, revealed a great diversity of

spores, acritarchs and chitinozoans species in the Itacua (ex Saipurú Formation, turbiditic resedimented diamictites with glacial influence) and the unconformably underlying Los Monos/Iquiri formations. The biostratigraphic interpretation including the assignment to *Rl* zones given by Pérez Leyton (1990) was revised and changed in Pérez Leyton (1991), shown in Figure 5, and the main composition of three samples of the Itacua Formation is addressed below, whereas the lower M18 is composed of older Givetian-Frasnian reworked palynomorphs by Pérez Leyton (1991):

M19. *Colatisporites decorus*, *Rugospora radiata*, *Retusotriletes planus*, *Knoxisporites* sp. and *Cristatisporites* sp. (scarce specimens), whereas reworked spores from the Devonian and acritarchs are abundant especially *U. saharicum*. *Verruciretusispora famenensis* cited for the late Famennian of Algeria (Attar et al., 1980) and absence of *Rl* were used to attribute this sample to VCo Zone of Streel et al. (1987).

M12 - 13. Notably rich in diverse palynomorphs among them, bearing *Rl*, *Colatisporites decorus*, *Cordylosporites glumaceus* (= *C. marciae*, *Dictyotriletes fimbriatus*, see Playford and Dino, 2012), *Cristatisporites echinatus*, *Cyrtospora cristifera*, *Knoxisporites literatus*, *Kraeuselisporites explanatus*, *Raistrickia spathulata*, *Tumulispora rarituberculata*, *Vallatisporites verrucosus*, and the chlorophycean *Botryococcus*.

This assemblage was akin to the late Famennian LE Zone of Streel et al. (1987) and a younger age was rejected due to the absence of index taxa such as *Spelaeotriletes balteatus*, *S. pretiosus*, *Umbonatisporites* spp., *Aratrisporites saharensis*. Although, today, *A. saharensis* and *S. pretiosus* are also recognized in *Rl* palynofloras, whereas *Colatisporites decorus* and *Cristatisporites echinatus* are documented since the Tournaisian (see Higgs et al., 1988; Playford and Melo, 2012). Hence, di Pasquo and Azcuy (1997) indicated with certainty an Early Carboniferous age most likely mid

Tournaisian, for the three samples M19, 12 and 13 of this diamictitic deposit of Itacua Fm, and the separation of indigenous and reworked set of palynomorphs. A revision of this outcrop by Streel et al. (2012) did agree with the presence of Mississippian spores in this diamictitic unit.

From the same area of this Bermejo outcrop described above, more diamictitic deposits are exposed along the La Angostura- Bermejo- Samaipata- Mairana highway in the Espejos Range, west of Santa Cruz de la Sierra. Wicander et al. (2011) have studied the palynologic content of a diamictite at Lajas area and it was correlated to the LL and LE zones due to the absence of *Verrucosiporites nitidus* and to LN zone bearing exotic blocks. Streel et al. (2012) disagreed with this zonal correlation and age given to this deposit in view of the doubtful distribution of taxa along the samples. These different ages are not necessarily in contradiction and might well depend on the importance of the hiatus separating the diamictitic beds of the Itacua Formation from underlying Givetian-lower Famennian Los Monos/Iquiri formations (see di Pasquo et al., 2015a).

In this same area, as part of a major Carboniferous-Permian project in Bolivia between 2007 and 2009 (undertaken by geologists from different countries and funded by Spain), palynologic investigations were carried out to look for the DCB and to test the Pennsylvanian biostratigraphic scheme (KA, RS, BC, MR and TB zones) of di Pasquo (2003) in the central portion of the Tarija-Chaco Basin and its aid in chrono-stratigraphic discrimination of several diamictitic intervals across the same highway above. First results were presented by di Pasquo and Anderson (2012) in which different Devonian, Carboniferous and less frequently Permian rocks (at La Angostura) cropping out to the west up to Mairana were sampled and dated (See Figs. 3, 6.A). The stratigraphic units are generally in faulted contact and structural repetition of units

is quite common. Even though this work is still not published in full length, it demonstrates that the Devonian to Pennsylvanian biostratigraphic zones identified allowed the reconstruction of complex tectonic successions, and *Rl* was found as part of reworked set of palynomorphs (See Fig. 6.C) in diamictites of the Tarija Formation assigned to the Pennsylvanian BC Zone (See Fig. 6.B), below the Escarpment Formation. Major shifts in LPIA paleoclimate during the Pennsylvanian across the Tarija-Chaco Basin and tectonic processes explain the erosion of Devonian and Mississippian deposits.

Other diamictites of the Itacua Formation studied by di Pasquo (2007 b) were akin to the early Visean at Balapuca (see further below, Fig. 3) and allowed the recognition of a hiatus with the underlying Givetian-lower Famennian Los Monos/Iquiri formations (see also di Pasquo et al., 2015a). In this sense, in agreement with comments addressed by Streel (2008) and Streel et al. (2012), new palynologic analysis of the diamictite section interpreted as late Famennian age by Wicander et al. (2011), and the well-stratified layers of mid- Devonian at Piray creek is currently ongoing (Fig. 7).

3.4 Macharetí creek

Di Pasquo (2008, Fig. 8) provided palynologic information of the Iquiri and Itacua formations at Macharetí (63° 24' 09" W, 20° 47' 50" S), located in the Aguara Güe range, southeastern Bolivia.

This study (still unpublished) was presented in a scientific event but and therein, still unpublished, and it was referred to the same occurs with other palynostratigraphic surveys to look for the DCB in Bolivia, carried out in 1998, 2000 and 2007/2008 to look for the DCB in Bolivia, in several localities such as Alarache, Canaletas, Samaipata, Angosto del Pilcomayo, Bermejo, Lajas, Caigua, Los Monos and Taputá (see Fig. 3, di Pasquo, 2008).

At Macharetí, five samples collected from a ca. 50 m thick section of the Iquiri Formation, bearing decimetric

to metric banks of fine and medium sandstones with current and bioturbation structures, and centimetric to decimetric shales, laminated or massive. Palynologic analysis of two fertile samples yielded abundant, diverse and well-preserved palynomorphs (80% spores and microplankton) and phytoclasts (20% with tracheids, cuticles and black particles) of yellow to orange color in general. Among the species with stratigraphic importance are *Acinosporites eumammillatus*, *Verrucosporites bulliferus*, *Pseudolunulidia imperatrizensis*, *Umbellasphaeridium companulatum*, which allow the association to be attributed to the Frasnian.

Overlying in pseudoconcordance, the Itacua Formation comprises a greenish diamictite bearing sandy matrix (ca. 3 m) followed by another diamictite (ca. 5 m) with gray clayey matrix from which another fertile sample comes. It is composed of phytoclasts (50% with tracheids, cuticles and black particles) and abundant and diverse palynomorphs (50%) with notable differences in their preservation (e.g., complete and fragmented palynomorphs, some pyritized and TAI colors from orange to black). The main diagnostic species are *Foveosporites appositus*, *Secarisporites undatus*, *Retusotriletes mirabilis*, *Densosporites triangularis*, and *Lophozonotriletes dentatus*, which support an early Visean age for the association (di Pasquo, 2008). Some of these species were also recorded in associations of this age in the Malimán Formation of western Precordillera Argentina (e.g. Amenábar et al., 2009) and elsewhere in Bolivia (see di Pasquo et al., 2019a, 2019b). *Grandispora pseudoreticulata*, *Ancyrospora* spp., *Arkonites bilixus*, *Petrovina connata*, *Gorgonisphaeridium ohioense* are reworked from mid-late Devonian rocks. The absence of *R1* and other associated taxa suggest the existence of an unconformity involving erosive and non-depositional hiatus at this locality. The succession above continues with whitish

sandstones, black pelites, greenish-purple diamictites and grayish-purple shales of the Macharetí Group and several samples taken in 2000 and 2007 were all barren.

3.5 Balapuca

Potential DCB stratigraphical units bearing palyno-associations in Bolivia are associated to diamictites of the Itacua Formation (previously also called Saipurú Formation, see Azcuy and di Pasquo, 2000), which are overlying Devonian layers generally in unconformable contact. One of these sections at Balapuca develops the Givetian-Frasnian Los Monos and Iquiri formations unconformably, followed by diamictites of the Itacua Formation, which is also unconformably followed by the early Pennsylvanian Macharetí Formation (see di Pasquo, 2003). The palynologic analysis of the Devonian-Mississippian interval carried out by di Pasquo (2007a, 2007b) allowed the attribution of the diamictites to the Lower Carboniferous due to the appearance of Visean taxa mainly known from Australia and Europe and North America, such as: *Anapiculatisporites concinnus*, *Apiculatisporis hacquebardi*, *Convolutispora insulosa*, *Convolutispora varicosa*, *Convolutispora florida*, *Convolutispora tessellata*, *Crassispora scrupulosa*, *Colatisporites decorus*, *Cyclogranisporites australis*, *Dibolisporites microspicatus*, *Endoculeospora larga*, *Foveosporites appositus*, *Granulatisporites granulatus*, *Kraeuselisporites dolianitii*, *Punctatisporites springsurensis*, *Raistrickia intonsa*, *Schopfites clavigera*, *Spelaeotriletes tuberosus*, *Secarisporites undatus*, *Verrucosporites microtuberosus*, *Waltzispota polita*.

Some other taxa like *Apiculiretusispora semisenta*, *Dibolisporites medaensis*, *Dibolisporites microspicatus*, *Grandispora notensis*, *Leiotriletes ornatus*, are known from Tournaisian palynofloras, whereas *Auroraspora macra*, *Auroraspora solisorta*, *Cordylosporites glumaceus* (= *C. marciae*), *Pustulatisporites dolbii*, are also

recorded in late Famennian *Rl* assemblages (e.g. Playford and McGregor, 1993; Playford, 1993; Amenábar et al., 2009). Another taxon is *Cristatisporites peruvianus* Azcu y di Pasquo 2005 defined in the late Visean of Peru, which appeared later on in late Tournaisian palynofloras of Argentina (e.g. Milana and di Pasquo, 2019 and references therein) and also in late Famennian *Rl* assemblages in Brazil (see Playford and Dino, 2012; Playford et al., 2012). Unfortunately, *Rl* was not recorded in the assemblage of the Itacua Formation, which unconformably overlies the Givetian-Frasnian Los Monos and Iquiri formations at Balapuca, but it was recovered from the unconformably overlying early Pennsylvanian Machareti Formation (see di Pasquo, 2003). The long-ranging taxa from the late Famennian aforementioned could reflect reworking of earlier Tournaisian deposits whereas a non-deposition interval of late Famennian age could be inferred based on the absence of *Rl* at this locality. Therefore, these complex results require the recognition of native species with narrower ranges to give age to the deposits with certain accuracy, especially in the absence of other micro-megafossils (di Pasquo, 2007 a, 2007b, 2007c).

3.6 Beni Plain (northern Bolivia)

Di Pasquo et al. (2015b) reexamined in detail the Manuripi X-1 and Pando X-1 boreholes as part of a project to investigate the Devonian/ Carboniferous boundary in Bolivia. In the Manuripi X-1 (over Precambrian igneous/metamorphic rocks, see Isaacson et al., 1995), a sedimentary succession of diamictites, shales and sandstones between 1541 m to 1150 m was palynologically analysed (Fig. 9). The whole interval revealed abundant and diverse mixtures of spores (micro and megaspores) and paleomicroplankton taxa well preserved in general. Between 1535 m and 1387 m, indigenous spores *Anapiculatisporites ampullaceus*, *Cordylosporites papillatus*, *Crassispora scrupulosa*, *Cristatisporites*

echinatus, *Dibolisporites setigerus*, *Foveosporites hortonensis*, *Raistrickia ponderosa*, *Reticulatisporites waloweekii*, *Secarisporites undatus*, *Spelaeotriletes balteatus*, and *Vallatisporites ciliaris*, indicate a mid to late Tournaisian age that is partially correlated to the *Spelaeotriletes pretiosus-Colatisporites decorus* Zone of Brazil and *S. pretiosus-Raistrickia clavata* and *Schopfites claviger-Auroraspora macra* Zones of Europe (di Pasquo et al., 2019a).

The overlying interval of 300 m is attributed to the Visean based on FAD's of indigenous spores (e.g. *Crassispora kosankei*, *Cristatisporites peruvianus*, *Cristatisporites menendezii*, *C. stellatus*, *Cordylosporites* (*Reticulatisporites*) *magnidictyus*, *Foveosporites pellucidus*, *Indotriradites viriosus*, *Lycospora noctuina*, *Punctatisporites aerarius*, *Velamispores australiensis*, *Verrucosisporites quasigobbettii*, *V. gregatus*, *V. roncadorensis*, *V. morulatus*, *V. iannuzzii*, *Vallatisporites agadesensis*) (di Pasquo et al., 2015b, 2019a). Figs. 10-11

Di Pasquo (2015, see also di Pasquo et al. 2019a) documented for the first time in South America, the megaspore *Lagenicula mixta* (Lepidocarpaceae) in core samples from the Pando X-1 (Fig. 12) and Manuripi X-1, northern Bolivia. From the latter, the lowest sample analysed bearing this megaspore is at a depth of 1535-1536 m, and it is well represented at 1521 m. *Lagenicula mixta* has a single published occurrence from the mid-Tournaisian (Early Mississippian) of Ohio, USA (Wellman et al., 2009) and together with a scarce record of *Neoraistrickia loganensis* in Manuripi X-1 at 1455 m confirm the age mentioned above (Fig. 13).

In the Pando X-1 (drilled to the metamorphic basement at 1981 m), this megaspore first appears at a depth of 1355 m just over the reinterpreted DCB proposed by di Pasquo et al. (2015b, 2019a), who indicated the same age of the Manuripi X-1 aforementioned to the interval between 1360 m and 1090 m of

the Pando X-1, due to same palynologic features. Figure 12

A terrestrial link between North America and northern South America is indicated by di Pasquo (2015), due to mutual occurrence of the megaspore *Lagenicula mixta* and *Neoraistrickia loganensis* (Winslow) Coleman and Clayton (see Playford and Melo, 2009) and other indigenous microspores (e.g., *Vallatisporites ciliaris*, *Cristatisporites echinatus*, *Reticulatisporites waloweekii*). Tectonic changes in the paleoequatorial zone especially during the early Mississippian and the global sea level lowering triggered by glaciations are consistent with a very narrow Rheic ocean during the Carboniferous (see also Golonka, 2020). This scenario enhanced a terrestrial link between Northern and Southern America widening the inroads for the dispersion of Tournaisian and Visean floras as widely discussed in many works (cf. Playford and Melo, 2009, 2010; Pfefferkorn et al., 2014).

Together with these indigenous spores and algal remains there are abundant reworked palynomorphs (spores, acritarchs, chitinozoans, scolecodonts). Among diverse list of Devonian reworked taxa (e.g. microplankton *Ammonidium garrasinoi*, *Bimerga bensonii*, *Evittia sommeri*, *Maranhites* spp., *Pyloferites pentagonalis*, *Umbellasphaeridium saharicum* and spores *Grandispora pseudoreticulata*, *Hystricosporites porrectus*, *Kraeuselisporites explanatus*, *Samarisporites triangulatus*), *R. lepidophyta* is scarcely present in the first 100 m whereas in the remaining 300 m is more frequent to abundant between 1432 m and 1387 m and less frequent to scarce up to 1151 m (di Pasquo et al., 2019a). Figure 14.

Also, di Pasquo et al. (2015b) scarcely documented *Waltzisporea lanzonii*, an early Tournaisian species in Brazil (cf. Playford and Melo, 2010, 2012; Playford et al., 2012), is reworked into the late Visean assemblages of both Pando and Manuripi wells. Therefore, reworked species with ranges between late

Famennian – early Tournaisian (e.g., *Cyrtospora cristifera*, *Kraeuselisporites explanatus*, *Convolutispora major*, *Knoxisporites concentricus*) confirms that both the Strunian and the Early Tournaisian have been deposited in this region of Bolivia. Paleogeographical changes (Chiriguana or Chanic Orogeny) since late Devonian, and the glacial/interglacial processes that occurred between the middle Tournaisian and the Visean, would have been the main cause of the exposure and erosion of these sediments. Finally, Figure 15 summarised previous different interpretations of the DCB interval in the Pando X-1, and highlights the difficulties to find out the more likely age due to high abundance of reworked palynomorphs.

3.7 Encañada de Beu, Beni river

Azcuy and Ottone (1987) obtained palynomorphs from a single sample from the upper section of the Retama Formation in the region of Encañada de Beu at the upper Beni river. These authors attributed these layers to the Early Carboniferous of possibly Visean age mainly on the basis of the taxa *Verrucosisporites nitidus*, *Granulatisporites frustulentus* and *Auroraspora macra*. The presence of other Late Devonian species such as *Grandispora pseudoreticulata*, *Stellinium octoaster*, *Maranhites brasiliensis* and *Retispora lepidophyta* suggested the existence of redeposited palynomorphs and, consequently, of an unconformity below the level studied bearing palynomorphs. Melo (2005) also pointed out that the search for palynofloras with *Rl in situ*, typically in the Toregua Formation and in the undifferentiated Retama Group of northern Bolivia, was unsuccessful, and instead some palynomorphs suggest younger ages such as Tournaisian or Visean.

Based on the finding of the *Nothorhacopteris kellybelenensis* megafloora, a Serpukhovian age was given to the Kaka Formation of the Retama Group (Azcuy and Suárez Soruco, 1993;

Iannuzzi et al., 1998, 2003; Iannuzzi and Pfefferkorn, 2002). A palynological re-study of the aforementioned palynological analysis published by Azcuy and Ottone (1987), allowed the attribution of a Serpukhovian age to the upper section of the Kaka Formation, based on indigenous few pollen grains and spores (Fasolo et al., 2006; for more information see di Pasquo et al. (2022), this volume).

4 Peru

The Ambo Formation at Pongo de Mainique, Madre de Dios Basin of Peru (Azcuy and di Pasquo, 2005), yielded Visean species such as *Apiculiretusispora semisenta*, *Auroraspora macra*, *Bascaudaspora submarginata*, *Colatisporites decorus*, *Convolutispora insulosa*, *Convolutispora* sp. cf. *C. varicosa*, *Crassispora kosankei*, *Cristatisporites indignabundus*, *Densosporites annulatus*, *Dibolisporites microspicatus*, *Granasporites medius*, *Grandispora debilis*, *Leiotriletes ornatus*, *Microreticulatisporites parvirugosus*, *Punctatisporites aerarius*, *Schopfites claviger*, *Verrucosisporites congestus*, *Verrucosisporites morulatus*, *Kraeuselisporites mitratus*, *Cristatisporites peruvianus* and *Waltzispora polita* (see also Azcuy and di Pasquo, 2006). Due to its comparison with biozones in Brazil and Australia, this unit has been given a Late Visean age and correlates with the *Mag* Zone Melo and Loboziak 2003 of the Amazon Basin, based mainly on the presence of the species *Cordylosporites magnidictyus* and *Schopfipollenites ellipsoides*. In general, few reworked forms have been found in the analyzed levels, among which *Retispora lepidophyta* stands out at this locality (Azcuy and di Pasquo, 2005) and also, at Pongo de Cognec (di Pasquo et al., 2019d; for more information see di Pasquo et al. (2022), this volume).

5 Paraguay

Pöthe de Baldis (1974) described an assemblage (sample at 1222 m) from the Picuiba borehole that was indicated as mid- Devonian but later, redescribed and dated as Famennian due to the presence of *Retispora lepidophyta*, and frequent species of *Densosporites* and other verrucate and apiculate spores, not illustrated and only mentioned in the abstract, found together with prasinophytes like *Maranhites* and *Polyedryxium*. Instead, new acritarchs (*Duvernaysphaera jelinii*) and chitinozoans (*Ancyrochitina spinosa*, *A. bispinosa*, *Cladochitina striata*) species were described from two samples at 1222 m and 1165 m by Pöthe de Baldis (1979). Therefore, a detail revision of this borehole is recommended before taking it to account as a Famennian interval. An update of the taxonomic status of phytoplankton species illustrated and especially, the identification of the mentioned abundant spores not studied till today. In the context of the Devonian-Permian researches carried out by di Pasquo in SAM since her Ph.D. (see di Pasquo, 1999 in 2003), she tried to find these samples studied by Pöthe de Baldis but she failed and also, she did not get new samples from this Picuiba borehole even trying to involve some academic researchers of Paraguay, after several attempts since 2000.

6 Argentina

Up to now, *Rl* is still absent in western Precordillera of Argentina (see Amenábar et al., 2009; Valdez et al., 2020) and it is found as part of the reworked palynomorphs into Mississippian and Pennsylvanian deposits of the southern portion of the Tarija Basin widely extended in Bolivia (see di Pasquo, 2003, 2009b).

7 Final remarks

Despite exclusive taxa of the late Famennian *Retispora lepidophyta* assemblages in the world are few (Fig. 17), and that both palynomorphs and conodonts can be reworked into

SLIGHTLY younger deposits, we need to keep on doing efforts to apply new techniques and find new sections that can help to discriminate indigenous from reworked fossils across the late Devonian to Mississippian interval. In this way, we will be able to answer with more accuracy ...

“When *Rl* is a reliable proxy to define the Devonian-Carboniferous boundary considering the concept “tell me who you hang out with and I’ll tell you how old you are” and evaluate the synchronicity of *Rl* in SAM with respect to its appearance in Europe or other regions of the world.

As a summary of the information discussed, the erroneous assignment of layers to the Famennian based on « reworked Famennian species » instead of attempting to recognize Tournaisian taxa as those indigenous that would give this age to the assemblage, has contributed to wrongly extend the range of Tournaisian taxa. The same problem is also known to occur with conodonts, such as *S. praesulcata* and *S. sulcata* that are considered a “lineage” morphologic transition hiding or preventing their use in the delineation of the DCB, especially when *S. praesulcata* can or could be considered as reworked into *S. sulcata* assemblages. Hence, despite we should be able to discriminate this situation from the screening of different publications, it is somewhat difficult.

Other problems not easy to disclose are for example, the accurate taxonomic classification of several taxa bearing intraspecific and also, interspecific morphologic variations that preclude their use as diagnostic taxa and especially, those with ranges continuing in the early Mississippian, or having iachronic ranges due to time involved in migration, or poor temporal dating of bearing strata. For example, *Gorgonisphaeridium winslowiae* appears before *Rl* FAD in the VH Zone of the Sappington Formation after di Pasquo et al. (2019c). Another example is the appearance of *Umbellasphaeridium saharicum* just before *Rl* FAD in the

Protosalvinia Floral Stage characterized by Matsumura et al. (2022).

Another discrepancy between the age given to a certain deposit with similar or equal lithologic aspect can occur when the deposit was interpreted as such a formational unit that is considered of such age in a different place, and by transposition in this place it should have or is akin to that same age. But, age given by fossils found in this deposit of this place can disagree with that age.

This kind of stratigraphic disagreements are relatively frequent in the literature and should be avoided for example, because even the lithology and probably the succession in one place can be similar to that of another place, the age given by the fossils found in both places can indicate a different time of deposition. This is a big trouble between geologists that do not trust age given by fossils and extrapolate ages based on one lithostratigraphic section to other sections lacking biostratigraphic control.

There are lots of examples summarised in this contribution related to palynoassemblages bearing *Rl* in diamictites, but in several sections this taxon along with many others are reworked from older strata and in some samples it is somewhat difficult to support a younger age than late Famennian, because the possible indigenous taxa are long-ranging or even not good for dating. Moreover, the lack of other fossils that independently can give an age to this type of samples or strata, then, makes *Rl* a weak biostratigraphic marker of the latest Devonian (indicated as indigenous or *in situ* taxon) in such situation.

As aforementioned herein, it is well-known that between upper Devonian and Tournaisian especially in South America, Africa, and eastern North America occurred global glacio-eustatic events confirmed by the recurrent presence of diamictites in many Tournaisian and Visean deposits up to the Upper Carboniferous of northern basins of SAM bearing reworked palynomorphs mainly from Devonian rocks (Fig. 18). The

current knowledge of the late Famennian-Tournaisian palynofloras and its chronostratigraphy in SAM is still very precarious, and especially in Bolivia, Peru and Argentina the recovery of “indigenous *Rl* palynoassemblages” as addressed in Lakin et al. (2016) and Aretz et al. (2021), can be argue (see also di Pasquo and Azcuy, 1997; Strel and di Pasquo, 2021). Palynologic studies of Devonian, Mississippian and Pennsylvanian deposits from western Argentina demonstrated that *Rl* is absent either indigenous or reworked suggesting that it did not reach/colonize this region (see di Pasquo, 2003; Amenábar et al., 2009). Grahn (2005) recognized that at the end of the Famennian when a glaciation took place, the chitinozoans disappeared from western Gondwana in the *Vallatisporites hystricosus* (VH) Interval spore Zone Melo and Loboziak (2003) before the *Retispora lepidophyta* – *Vallatisporites vallatus* (LVa) Interval spore Zone Melo and Loboziak (2003, see Grahn and Paris, 2011).

Among the many examples of DCB known in the literature outside South America, it is included herein a recent finding of early Tournaisian conodonts associated to *Rl* at Antelope Valley in Montana, USA (Fig. 19). This fact confirms previous documentation of an early Mississippian age given by blastoid fossils (echinodermata) in a unique, fossiliferous channel sandstone at Antelope Valley. A conodont *Siphonodella* cf. *S. hassi* having nodose ornamentation and rostral ridges of Early Mississippian age was identified in the same strata with blastoid fossils (see Rice, 2021). Therefore, the appearance of *Rl* assemblage in an interbedded shale layer documents once again, a controversy whether *Rl* is “in situ” into younger Tournaisian time or, should be interpreted as another palynoassemblage bearing reworked taxa from Famennian rocks triggered by global regression of glacio-eustatic origin confirmed by diamictites in South America, Africa, and eastern North America (Rice, 2021; di Pasquo et al., 2021).

In the context of DCB, di Pasquo et al. (2022) well- demonstrated that the fluorescence of palynomorphs is not a helpful tool to discriminate their provenance, i.e. *in situ* (indigenous) from reworked taxa (those redeposited from erosion of rock-deposits of previous cycles of deposition). For this reason, the criteria recommended are the careful specific systematic allocation of taxa, and their most agreed / checked age (biochron) together with the paleobiologic/ ecologic affinities of the indigenous (autochthonous) taxa to propose accurate age and palaeoenvironment reconstruction. Analyses of abundance and state of preservation are auxiliary features to consider in the identification of reworked taxa.

Hence, as commented herein, the distinction of the possible reworked taxa from the native group in any sample is mandatory to prevent wrong interpretations of the deposit bearing those palynomorphs. More efforts are needed to find out sections or boreholes with a continuous DC passage based on many more productive samples than a few, in which similar quantitative analyses of morphologic variations including malformation of *Rl* and allied species to those made in northern Hemisphere can be feasible in SAM (cf. Strel and di Pasquo, 2022). Although, the preservation of continuous strata recording biotic changes across the DCB in western margin of SAM was controlled, severely restricted or precluded due to active tectonic processes and paleoclimatic and sea level shifts, beyond other phenomena (e.g., active volcanism, meteoric impacts, changes in ozone layer to protect life from UV emission). Therefore, the correct recognition of in situ and reworked taxa in each sample may also, improve interpretations of diachronisms associated to evolution of taxa and migration processes, as well as indicate the development of unconformities and help to evaluate the time of the gap involved and characterize their nature, i.e. whether they were

originated by eustatic, climatic and /or tectonic events (Streel and Bless, 1980; Azcuy and di Pasquo, 1997; di Pasquo et al., 2022).

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List of taxa with their authorities

Conodonts

- Bispathodus ac. aculeatus* (Branson & Mehl)
Bispathodus costatus (Branson)
Bispathodus ultimus (Bischott)
Protognathodus kockeli (Bischoff)
Protognathodus kuehni Ziegler & Leuteritz
Siphonodella bransoni Ji
Siphonodella duplicata (Branson & Mehl)
Siphonodella jii (= *Siphonodella hassi* by Ji 1985 in Becker et al., 2016, and Rice, 2021, appendix F).
Siphonodella praesulcata Sandberg
Siphonodella sandbergi Klapper
Siphonodella sulcata (Huddle)
Siphonodella quadruplicata (Branson & Mehl)

PLANT

Nothorhacopteris kellybelenensis Azcuy & Suárez Soruco emend. Azcuy et al.

CHITINOZOAN

- Ancyrochitina spinosa* Eisenack
Ancyrochitina bispinosa Pöthe de Baldis
Cladochitina striata Pöthe de Baldis

MICROPLANKTON

- Ammonidium garrasinoi* Ottone
Arkonites bilixus Legault
Bimerga bensonii Wood
Duvernaysphaera jelinii Pöthe de Baldis
Evittia sommeri Brito
Gorgonisphaeridium ohioense (Winslow) Wicander
Maranhites brasiliensis (=junior synonym of *Maranhites mosesi* (Sommer) Brito emend. González)
Petrovina connata Oliveira & Burjack
Pseudolunulidia imperatrizensis (Brito & Santos) Brito & Quadros
Pyloferites pentagonalis Quadros
Stellinium octoaster (Staplin) Jardiné et al.
Umbellasphaeridium companulatum Oliveira & Burjack
Umbellasphaeridium saharicum Jardiné et al.
- #### SPORES
- Acinosporites eumammillatus* Loboziak, Streel & Burjack
Anapiculatisporites ampullaceus (Hacquebard) Playford
Anapiculatisporites concinnus Playford
Apiculatisporis hacquebardi (Playford) di Pasquo
Apiculiretusispora semisenta (Playford) Massa, Coquel, Loboziak & Tagordeal-Lantz
Aratrisporites saharensis Loboziak, Clayton & Owens 1986
Auroraspora macra Sullivan
Auroraspora solisorta Hoffmeister, Staplin & Malloy
Bascaudaspora mischkinensis Avkhimovitch et al.
Bascaudaspora submarginata (Playford) Higgs et al.
Colatisporites decorus (Bharadwaj & Venkatachala) Williams in Neves, Gueinn, Clayton, Ioannides, Neville & Kruszezwska

- Convolutispora ampla* Hoffmeister, Staplin & Malloy
Convolutispora florida Hoffmeister, Staplin & Malloy
Convolutispora harlandii Playford
Convolutispora insulosa Playford
Convolutispora major Turnau
Convolutispora tessellata Hoffmeister, Staplin & Malloy
Convolutispora varicosa Butterworth & Williams
Convolutispora vermiformis Hughes & Playford
Cordylosporites glumaceus (Byvsheva) emend. Playford & Melo (= *Cordylosporites marciae*, *Dictyotriletes fimbriatus*, see Playford and Dino 2012)
Cordylosporites (*Reticulatisporites*) *magnidictyus* (= *Reticulatisporites magnidictyus* Playford & Helby)
Cordylosporites papillatus Playford & Satterthwait
Crassispora kosankei (Potonié & Kremp) Bhardwaj emend. Smith & Butterworth
Crassispora scrupulosa Playford emend. Playford & Satterthwait
Cristatisporites echinatus Playford
Cristatisporites indignabundus Potonié & Kremp
Cristatisporites menendezii (Menéndez & Azcuy) Playford emend. Césari
Cristatisporites peruvianus Azcuy & di Pasquo
Cristatisporites stellatus (Azcuy) Gutiérrez & Limarino
Cyclogranisporites australis Azcuy
Cymbosporites loboziakii Playford & Melo
Cyrtospora cristifera (Luber & Waltz) Van der Zwan
Densosporites annulatus (Loose) Smith & Butterworth
Densosporites (= *Cristatisporites*) *spitsbergensis* Playford
Densosporites triangularis Kosanke
Dibolisporites distinctus Lele
Dibolisporites medaensis Playford
Dibolisporites microspicatus Playford
Dibolisporites setigerus Playford & Satterthwait
Diducites plicabilis (Kedo) van Veen
Diducites versabilis (Kedo) van Veen
Endoculeospora larga (Playford) di Pasquo
Foveosporites appositus Playford
Foveosporites hortonensis Azcuy
Foveosporites pellucidus Playford & Helby
Granasporites medius (Dybová & Jachovicz) Ravn, Butterworth, Phillips & Peppers
Grandispora conspicua Playford
Grandispora debilis Playford
Grandispora echinata Hacquebard
Granulatisporites frustulentus Playford
Granulatisporites granulatus Ibrahim
Grandispora notensis Playford
Grandispora pseudoreticulata (Menéndez & Pöthe de Baldis) Ottone
Hystricosporites porrectus Allen
Indotriradites dolianitii (Daemon) emend. Loboziak et al. (= *Kraeuselisporites* after Azcuy and di Pasquo, 2005)
Indotriradites viriosus Melo & Playford
Knoxisporites concentricus (Byvsheva) Playford & McGregor
Knoxisporites literatus (Waltz) Playford
Kraeuselisporites explanatus (Luber) Azcuy & di Pasquo (= *Indotriradites explanatus*)
Kraeuselisporites hibernicus Higgs
Kraeuselisporites mitratus Higgs
Lagenicula mixta Wellman et al. in di Pasquo (2015, reassigned as *Lagenoisporites magnus* after Quetglas et al., 2019)
Leiotriletes ornatus Ischenko

- Lophozonotriletes dentatus* Hughes & Playford
Lophozonotriletes malevkensis (Naumova) Kedo (= *Tumulispora malevkensis* (Naumova) Turnau)
Lycospora noctuina Butterworth & Williams
Microreticulatisporites parvirugosus Staplin
Neoraistrickia loganensis (Winslow) Coleman & Clayton (see Playford and Melo, 2009)
Punctatisporites aerarius Butterworth & Williams
Punctatisporites springsurensis Playford
Pustulatisporites dolbii Higgs, Clayton & Keegan
Radiizonates arcuatus Loboziak, Playford & Melo
Raistrickia baculosa Hacquebard
Raistrickia clavata Hacquebard emend. Playford
Raistrickia intonsa Playford & Satterthwait
Raistrickia macrura Helby
Raistrickia ponderosa Playford
Raistrickia spathulata Higgs
Raistrickia variabilis (Dolby & Neves) Higgs et al.
Reticulatisporites magnidictyus Playford & Helby
Reticulatisporites waloveekii Ravn
Retispora lepidophyta (Kedo) Playford
Retusotriletes incohatu Sullivan
Retusotriletes maculatus McGregor & Camfield
Retusotriletes mirabilis (Neville) Playford
Retusotriletes planus Dolby & Neves
Rugospora flexuosa (Juschko) Byvscheva
Rugospora minuta Neves & Ioannides
Rugospora polyptycha = *Velamisporites polyptychus* (Neves & Ioannides)
Rugospora radiata (Juschko) Byvscheva
Samarisporites triangulatus Allen
Schopfpollenites ellipsoides (Ibrahim) Potonié & Kremp
Schopfites claviger (= *Raistrickia clavigera* (Sullivan) Playford & Satterthwait)
Secarisporites undatus Playford
Spelaeotriletes balteatus (Playford) Higgs
Spelaeotriletes obtusus Higgs
Spelaeotriletes pretiosus (Playford) Utting
Spelaeotriletes resolutus Higgs
Spelaeotriletes tuberosus Utting
Tumulispora rarituberculata (Luber) Playford
Umbonatisporites distinctus Clayton
Vallatisporites ciliaris (Luber) Sullivan
Vallatisporites microgalearis Hibbert & Lacey
Vallatisporites vallatus Hacquebard
Vallatisporites verrucosus Hacquebard
Velamisporites australiensis (Playford & Helby) di Pasquo et al. (= *Rugospora* (*Wilsonites*) *australiensis* (Playford & Helby) Jones & Truswell)
Velamisporites rugosus Bharadwaj & Venkatachala
Verruciretusispora famenensis Coquel & Moureu-Benoit
Verrucosisporites bulliferus (Taugourdeau-Lantz) Richardson and McGregor
Verrucosisporites congestus Playford
Verrucosisporites gregatus Pérez Loinaze
Verrucosisporites iannuzzii di Pasquo in di Pasquo and Iannuzzi
Verrucosisporites microtuberosus Smith
Verrucosisporites morulatus (Knox) Potonié & Kremp emend. Smith & Butterworth
Verrucosisporites nitidus Playford
Verrucosisporites quasigobbettii Jones & Truswell
Verrucosisporites roncadorensis di Pasquo in di Pasquo and Iannuzzi
Waltzispora lanzonii Daemon

Waltzisporea polita (Hoffmeister, Staplin & Malloy) Smith & Butterworth

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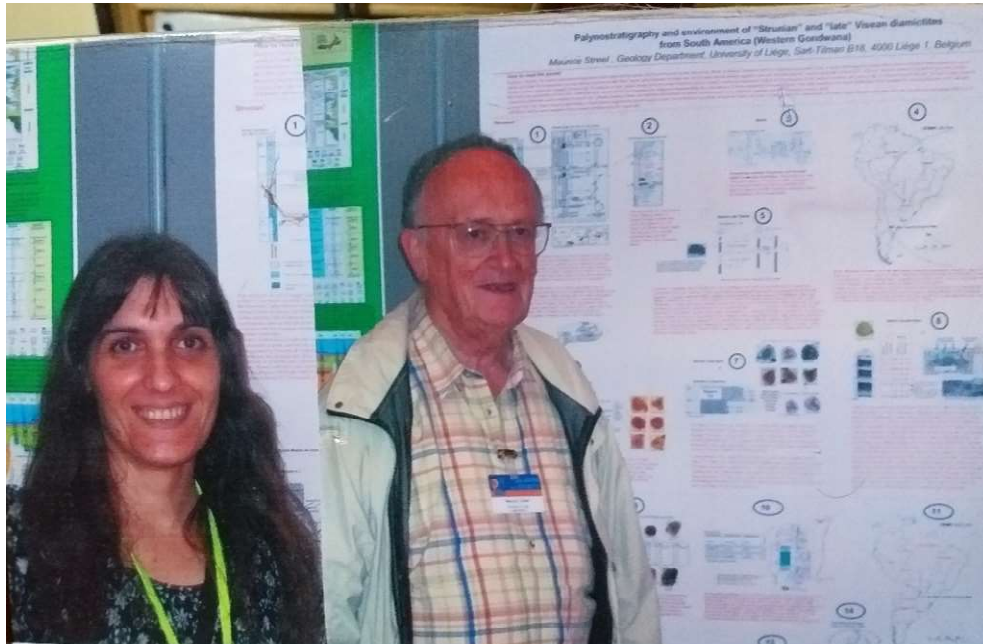
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The picture illustrates the time shared by Maurice and Mercedes looking at his poster presentation (see <http://hdl.handle.net/2268/126324>) during the International Palynological Congress held in Bonn (Germany).

		Europe, N-America standard conodont zonation; Sandberg et al. (1978); Ziegler & Sandberg (1990)	S-W Europe conodont zonation; Kaiser et al. (2009)	
Middle Tournaisian		<i>isosticha -</i>	<i>isosticha -</i>	
		Upper <i>crenulata</i>	Upper <i>crenulata</i>	
		Lower <i>crenulata</i>	Lower <i>crenulata</i>	
		<i>sandbergi</i>	<i>quadruplicata</i> <i>sandbergi</i>	<i>hassi</i> Zone = <i>jii</i> Zone after Becker et al. (2016)
Lower Tournaisian		Upper <i>duplicata</i>	<i>hassi</i>	<i>jii</i>
		Lower <i>duplicata</i>	<i>duplicata</i> <i>bransoni</i>	
		<i>sulcata</i>	<i>sulcata/kuehni</i>	
————— DCB —————				
Upper Famennian		Upper <i>praesulcata</i>	<i>kockeli</i>	
		Middle <i>praesulcata</i>	<i>ckl</i>	← onset of the Hangenberg mass extinction Event
		Lower <i>praesulcata</i>	<i>praesulcata</i>	

Figure 1. Conodont biozones at the DCB in North America and Europe, and refinement of European biozones, *ckl*=*costatus-kockeli* Interregnum taken from Kaiser et al. (2016, see also Becker et al., 2016).

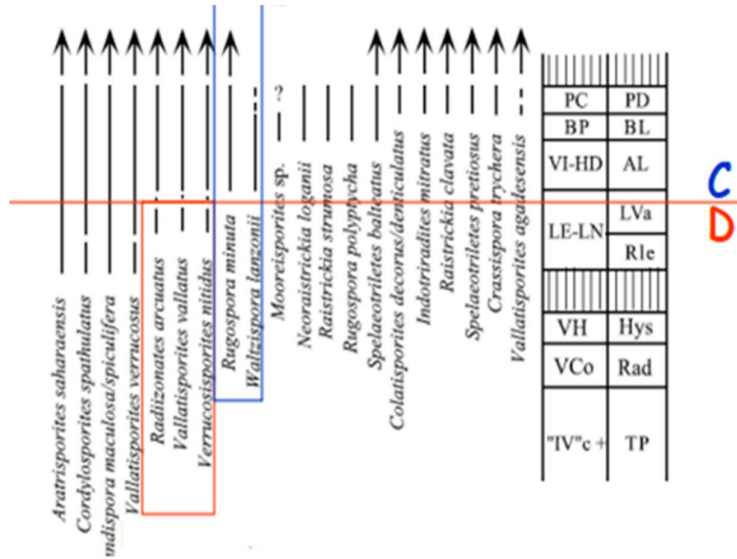


Figure 2. Zonal scheme for the Devonian-Carboniferous of northern basins of Brazil (Melo and Loboziak, 2003).

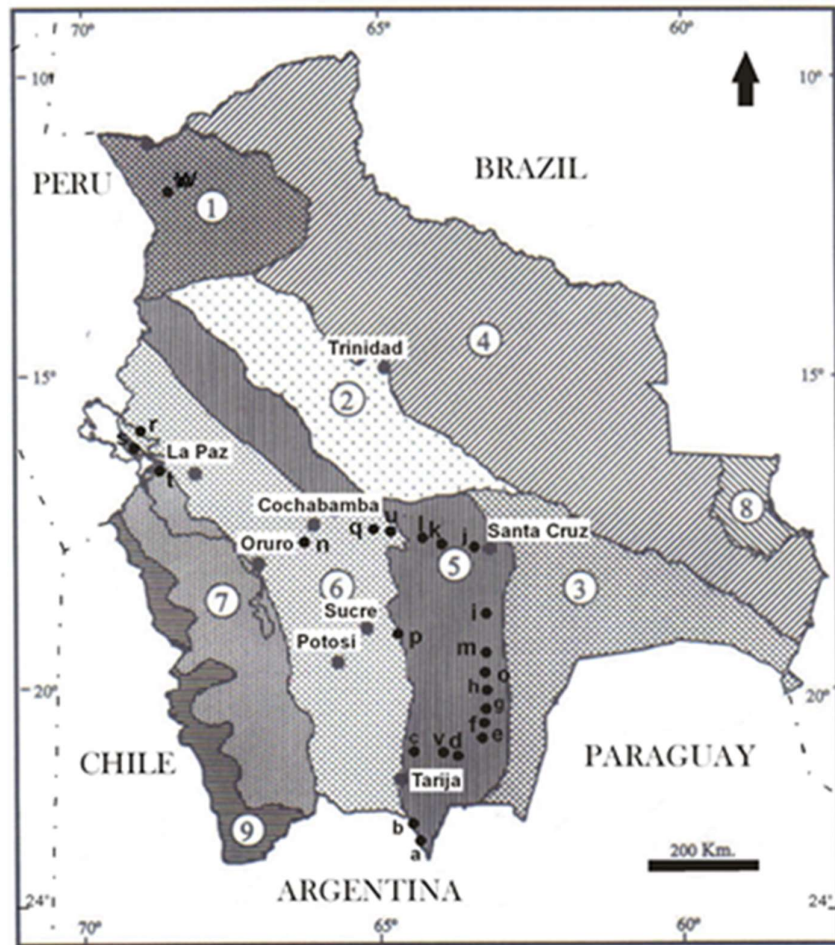


Figure 3. Upper Paleozoic Geological Provinces of Bolivia (after Suárez Soruco, 2000): 1- Madre de Dios, 2- Beni, 3- Chaco and Chaco-Salta plains, 4- Guaporé Craton, 5- Subandean Range, 6- Eastern Range, 7- Altiplano, 8- Pantanal, 9- Western Range. Localities sampled and studied (modified from di Pasquo, 2008 and di Pasquo and Anderson, 2012). a- Balapuca (di Pasquo, 2003, 2007 a, 2007b; di Pasquo et al., 2017), b- Alarache, c- La Yesera (di Pasquo et al., 2015a; Noetinger et al., 2018), d- Canaletas, e- Los Monos (di Pasquo et al., 2015a; Noetinger et al., 2018), f- Angosto del Pilcomayo, g- Caigua, h- Macharetí (di Pasquo, 2008), i- Taputá, j- río Bermejo, k- Samaipata. Devonian – Permian localities sampled in 2007-2008: a- Balapuca (di Pasquo et al., 2015a, 2017; Noetinger et al., 2018), c- La Yesera (di Pasquo et al., 2015a; Noetinger et al., 2018), d- Canaletas, h- Macharetí, k-l - Samaipata-Mairana (di Pasquo and Anderson, 2012), m- Saipurú, n- Apillapampa (di Pasquo and Grader, 2012), o- Parapetí, p- Zudañez (di Pasquo et al., 2019b), q- Pasorapa, r- Yampupata, s- Via Molino, t- Siripaca, u- El Tunal, v- Narvaez. Boreholes (Core samples obtained by di Pasquo in 2000): w- Pando X-1 (di Pasquo, 2009a), x- Lliquimuni X-1, y- Yapacani, z- Tacuaral, w- Pando X-1 and Manuripi X-1 (core samples collected by di Pasquo during stays at Idaho in 2009 and 2011 along with Peter Isaacson and George Grader, see di Pasquo et al., 2015b, 2019a). Rio Piray section (k-l) in La Angostura-Bermejo-Samaipata-Mairana highway in the Espejos Range, west of Santa Cruz de la Sierra. For more references see di Pasquo et al. (2022, this volume).

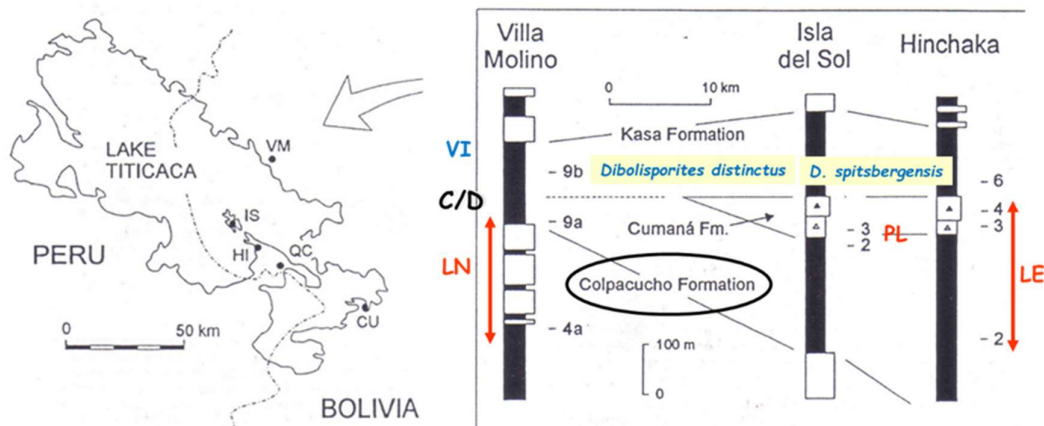


Figure 4. Correlation of DCB sections in the Titicaca Lake region after Díaz Martínez et al. (1999). The “indigenous” taxa in the RI and VI assemblages mixed with other reworked from the Devonian s.l., characteristic of the diamictites in SAM, can preclude accurate datings of those microfloras.

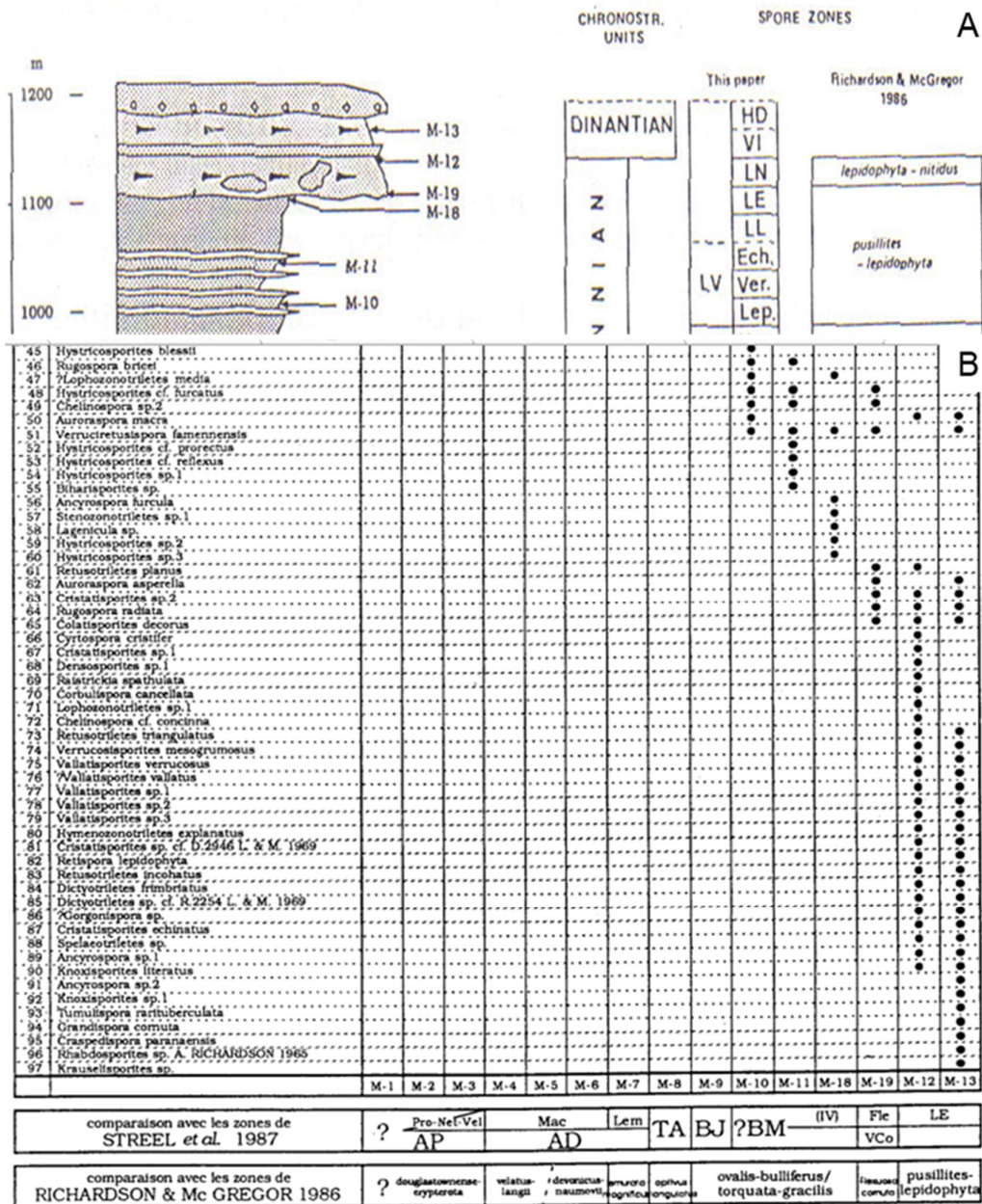


Figure 5. A. Litho-stratigraphic outcrop of the shale/silt/fine sandstones beds of Iquiri and diamictitic Itacua formation from Pérez Leyton (1990) and correlation to spore zones. **B.** Partial chart of vertical distribution of taxa and his revised correlation to spore zones taken from Pérez Leyton (1991).

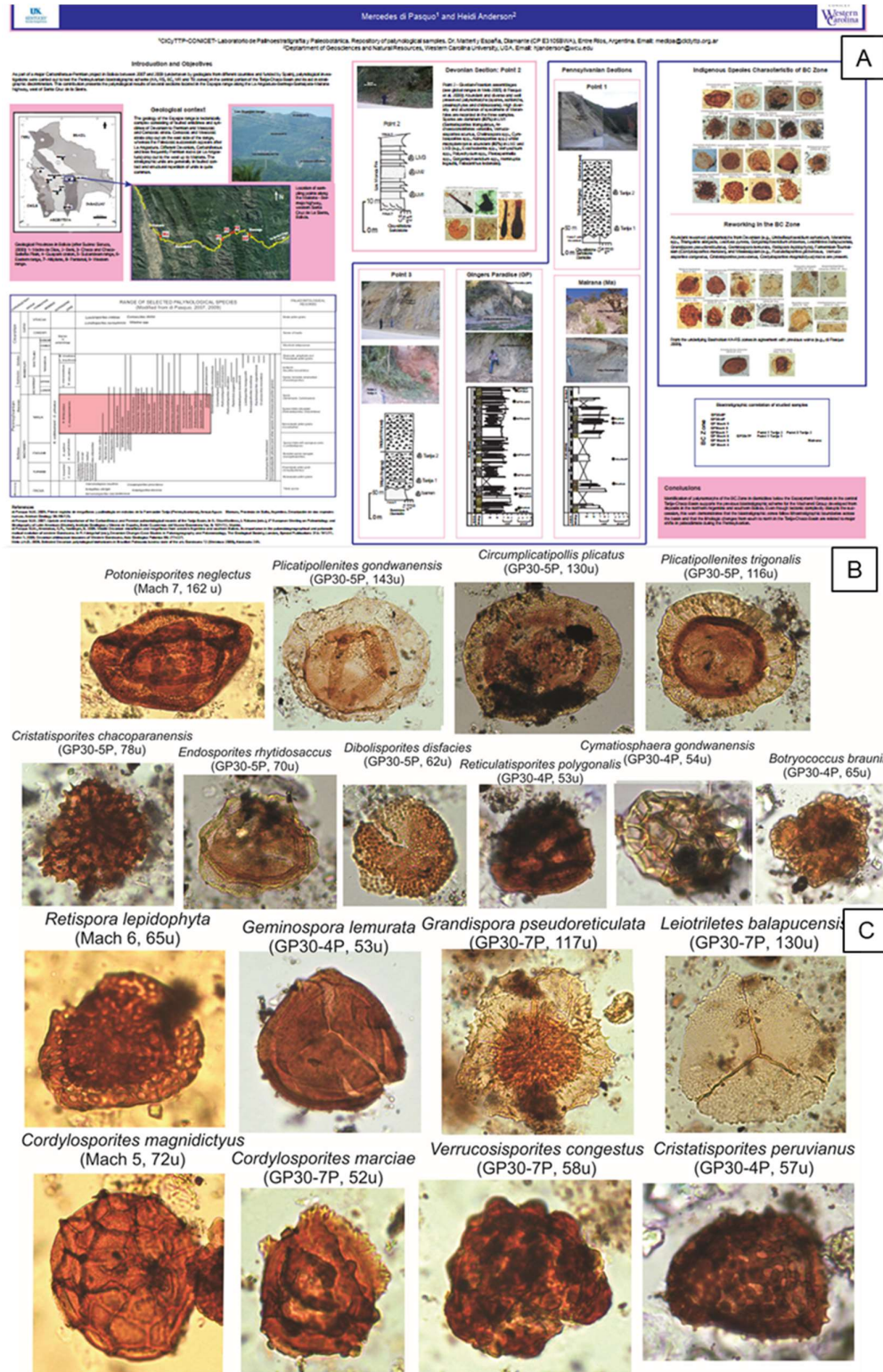


Figure 6. A. Images of the poster presentation of di Pasquo and Anderson (2012). B-C. Enlarged of embedded plates with indigenous (B) and reworked (C) palynomorphs included in this contribution as anticipating a full paper ongoing.



Figure 7. Rio Piray section (see Fig. 3). Field pictures of the Devonian-Carboniferous succession taken by MdP during a field trip carried out in november 2011 along with Dr. Jaime Oller and other geologists (Pluspetrol Bolivia S.A, Santa Cruz de la Sierra, Bolivia). **A.** A disconformable contact between mid- Devonian stratified beds and overlying Carboniferous diamictites respectively. **B-C** and **E-H.** Diamictitic section at both sides of the creek sampled in 2011 (unpublished palynological analysis) that was interpreted as being late Famennian in age by Wicander et al. (2011). **D.** Well stratified layers of mid-Devonian age.



Figure 8. A. Geologic and biostratigraphic information of the DCB at Macharetí creek (southeastern Bolivia) presented by di Pasquo (2008, full text unpublished). B-D. Field pictures showing the boundary between Los Monos/Iquiri and Itacua formations. B. Picture of Jaime Oller taken by di Pasquo in 2000. C. Picture of the same place taken by di Pasquo in 2007. D. Detail of boulders into the diamictite of the Itacua Formation. E-F. Palynomorphs obtained from the matrix of the Itacua Formation. E. Selected indigeous taxa. F. Selected reworked taxa from Givetian-Frasnian (Devonian).

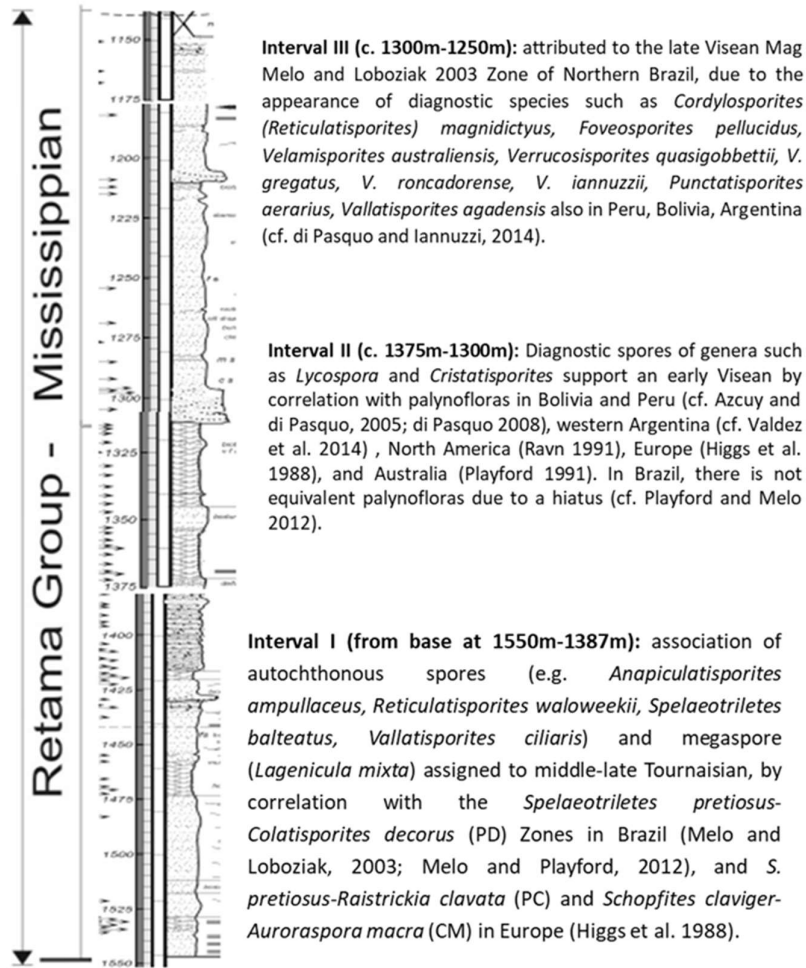


Figure 9. Summary of composition and age of the Manuripi X-1 borehole (see more details in di Pasquo et al., 2019a).

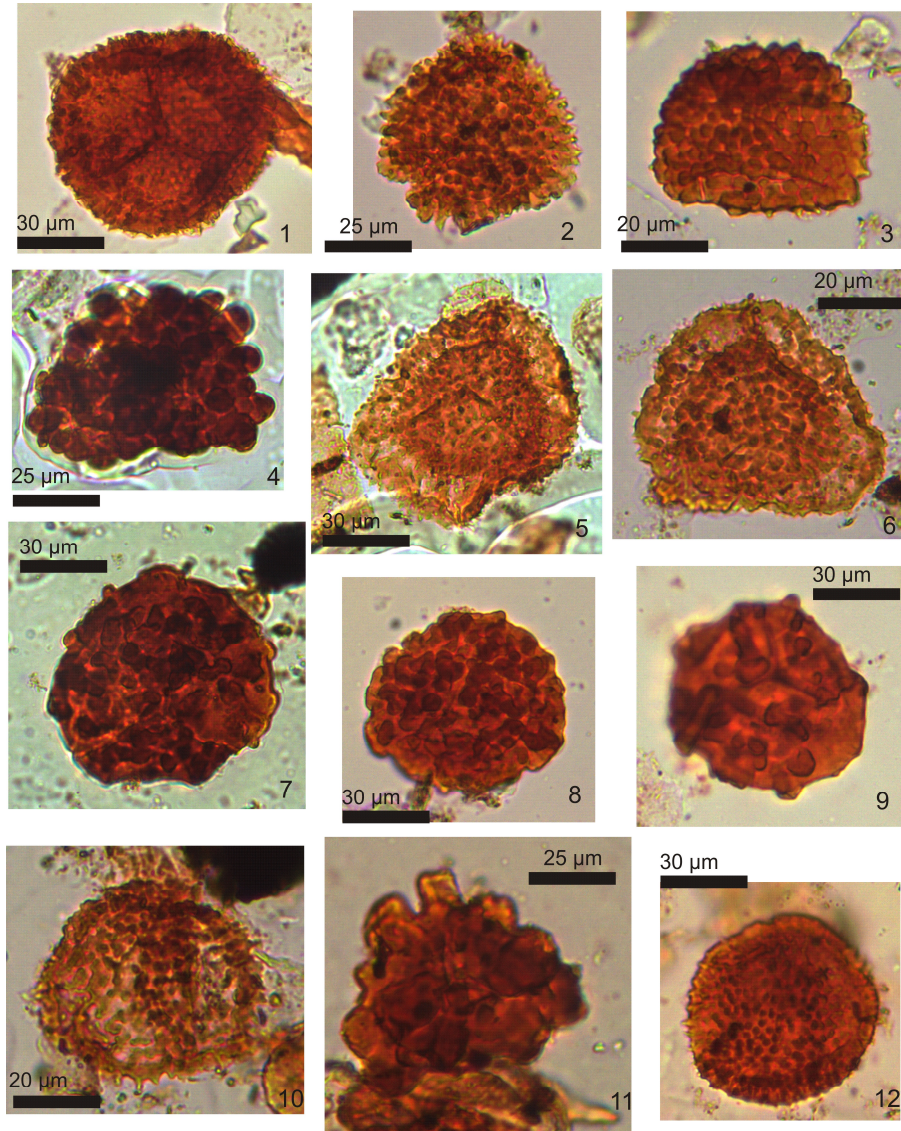


Figure 10. Selected indigenous species of the Manuripi X-1, Interval 1535 m-1438 m. 1. *Crassispora scrupulosa* (CICYTTP-PI 580). 2. *Cristatisporites echinatus* (CICYTTP-PI 579). 3. *Anapiculatisporites ampullaceus* (CICYTTP-PI 580). 4. *Raistrickia ponderosa* (CICYTTP-PI 580). 5. *Vallatisporites ciliaris* (CICYTTP-PI 580). 6. *Vallatisporites microgalearis* (CICYTTP-PI 577). 7. *Raistrickia clavata* (CICYTTP-PI 579). 8. *Raistrickia baculosa* (CICYTTP-PI 565). 9. *Convolutispora harlandii* (CICYTTP-PI 579). 10. *Cymbosporites loboziakii* (CICYTTP-PI 577). 11. *Secarisporites undatus* CICYTTP-PI 577). 12. *Dibolisporites microspicatus* (CICYTTP-PI 576).

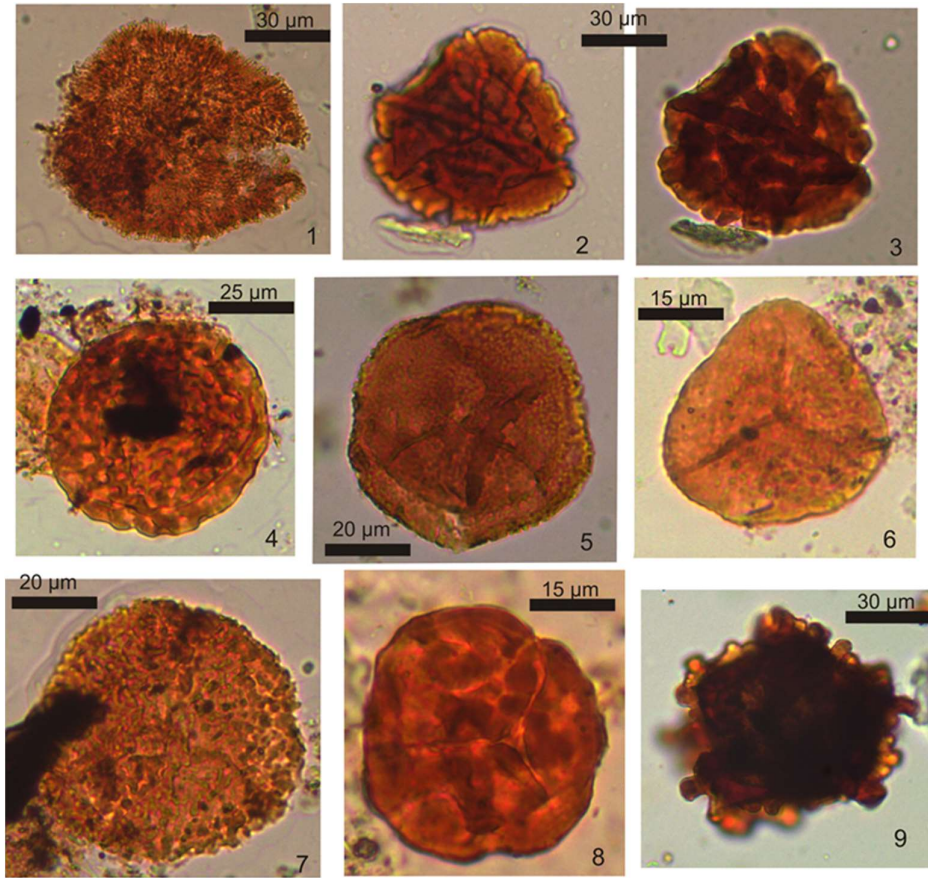


Figure 11. Selected indigenous species of the Manuripi X-1. 1. *Dibolisporites setigerus* (CICYTTP-PI 578). 2-3. *Reticulatisporites waloweeekii* (CICYTTP-PI 578). 4. *Foveosporites hortonensis* (CICYTTP 577-PI). 5. *Spelaeotriletes balteatus* (CICYTTP-PI 573). 6. *Granulatisporites granulatus* (CICYTTP-PI 551). 7. *Convolutispora ampla* (CICYTTP-PI 567). 8. *Convolutispora insulosa* (CICYTTP-PI 565). 9. *Cordylosporites papillatus* (CICYTTP-PI 572).

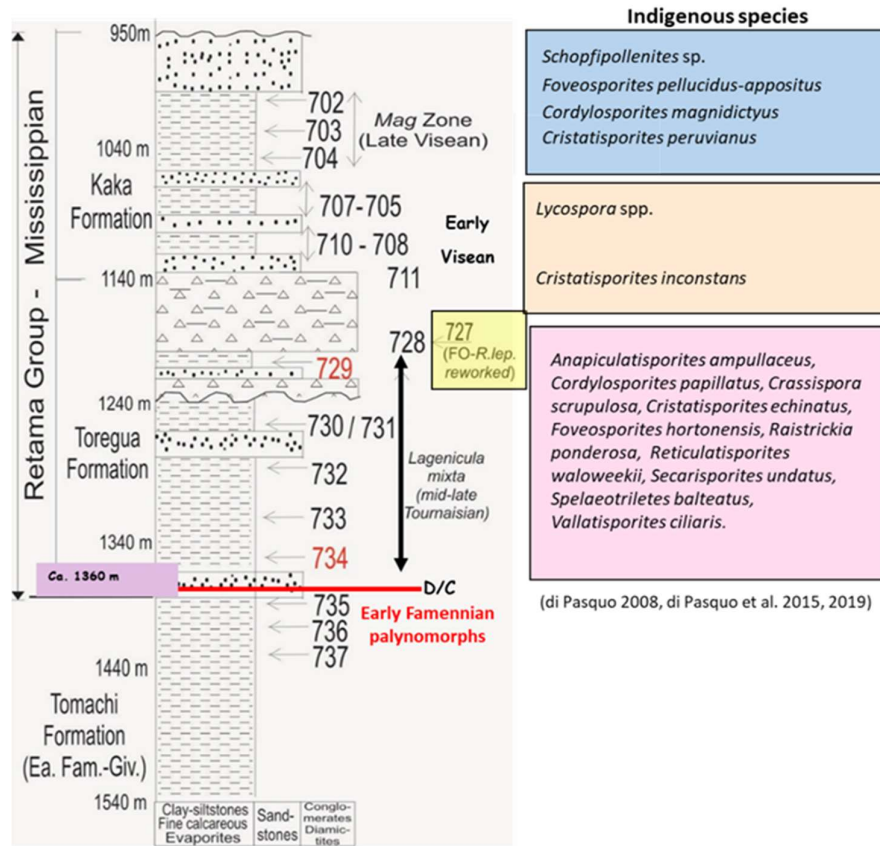


Figure 12. Pando X-1 borehole. Summary of indigenous species documented over the DCB indicated at c. 1360 m depth (after di Pasquo et al., 2019a).

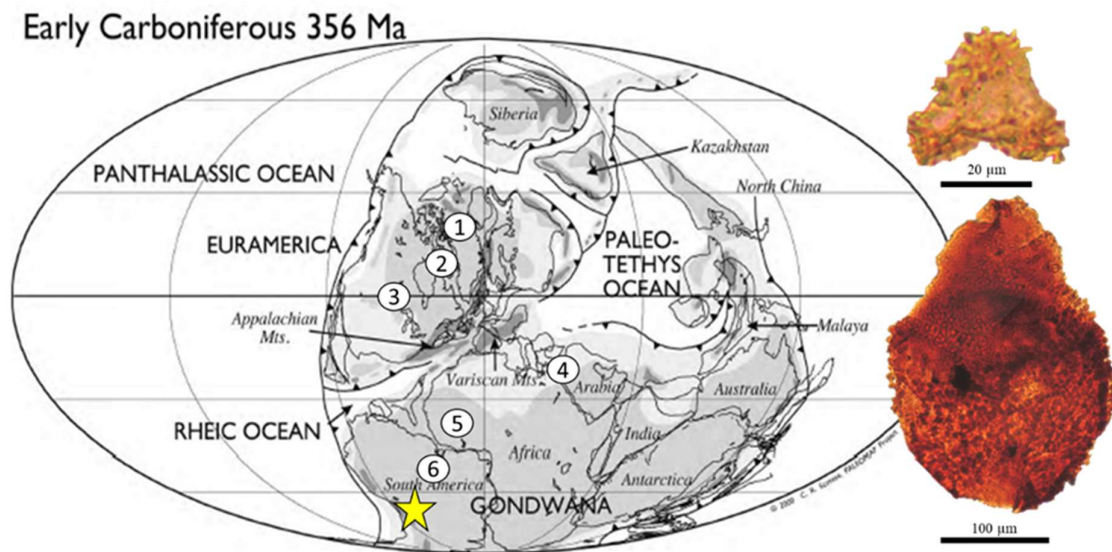


Figure 13. *Neoraistrickia loganensis* and *Lagenicula mixta* after di Pasquo (2015, reassigned as *Lagenosporites magnus* after Quetglas et al., 2019), documented in mid- Tournaisian of Manuripi X-1 well (located in northern Bolivia, see yellow star). The record of *Lagenicula mixta* in number 3 from Ohio (USA, Wellman et al., 2009). Distribution of *Neoraistrickia*

loganensis between Euramerica and northern Africa and elsewhere in western Gondwana, based on references in Playford and Melo (2009), marked by numbers 1-8, as follows: 1-2. United Kingdom. 3. Ohio. 4. Algeria-Libya. 5. Ghana. 6. Brazil.

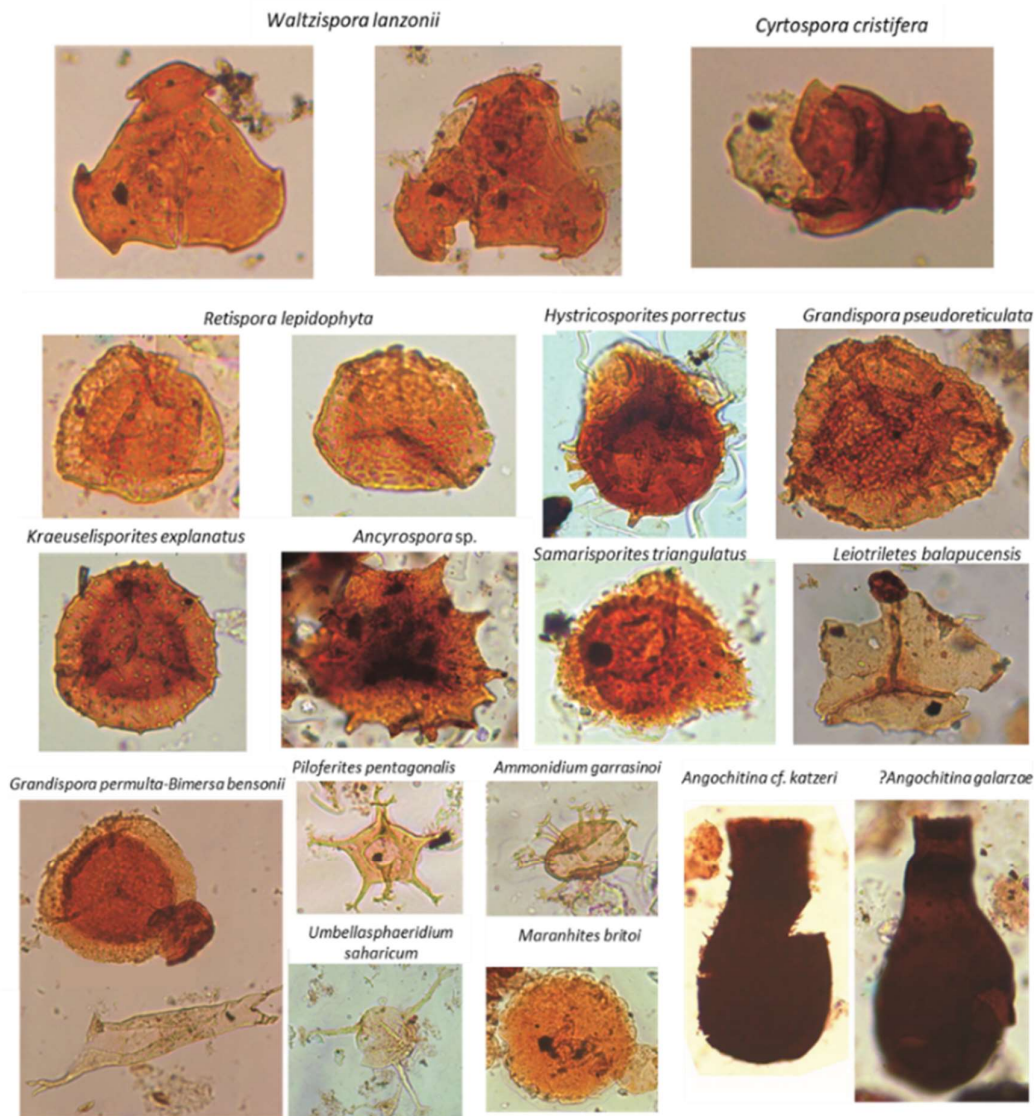


Figure 14. Selected reworked taxa of interval III (*Waltzispora lanzonii*, *Cyrtospora cristifera*) and several taxa reworked in the three intervals (sizes of palynomorphs are not indicated).

References	Interval (mbbp)	Biozone/age
Lobo Boneta, 1991 in S. Soruco 2000	950 – 1100	<i>Verrucosisporites</i> spp.
	1275 – 1340	<i>Retispora lepidophyta</i>
	1654 - 1654	<i>Schizocystia saharica</i>
Mobil, 1992 in S. Soruco 2000	1139 – 1157	Late Famennian-Early Tournaisian
	1247 – 1425	Early-Middle Famennian
	1524 – 1751	Givetian - Middle Famennian
	1771 – 1882	Eifelian
	1906 – 1916	Early to Early Middle Devonian
Pérez Leyton, 1993 in S. Soruco 2000	951 – 985	Visean
	1009 – 1100	Early Tournaisian
	1167	Latest Famennian
	1246 – 1347	Famennian
	1598 – 1935	Gediminan - Emsian
Vavrdová et al., 1996	1095	Tournaisian (VI)
	1167 - 1123	Latest Famennian (LL – LN)
Di Pasquo et al., 2015, 2019	1360 - 1140	Mid- Tournaisian

Figure 15. Different interpretations of the DCB in Pando X-1 well.

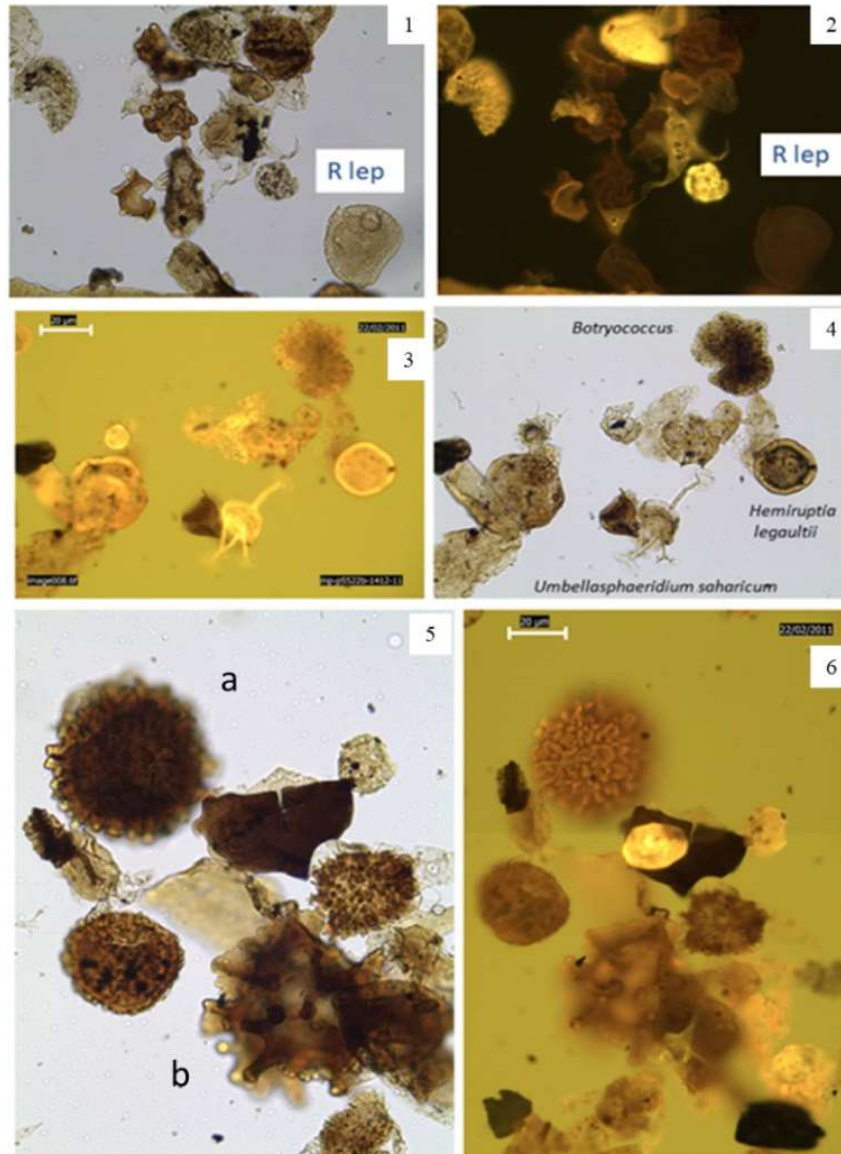


Figure 16. Indigenous and reworked palynomorphs showing differences in autofluorescence color in the same sample CICYTTP-PI 709 at 1132.06 m of the Pando x-1. 1-2. *Retispora lepidophyta* reworked without autofluorescence whereas other acritarchs and prasinophytes are still fluorescent. 3-4. *Umbellasphaeridium saharicum* and other reworked phytoplankton with fluorescence. 5-6. Indigenous spore taxa of the early Viséan with orange fluorescence respect to the more yellow color of reworked phytoplankton.

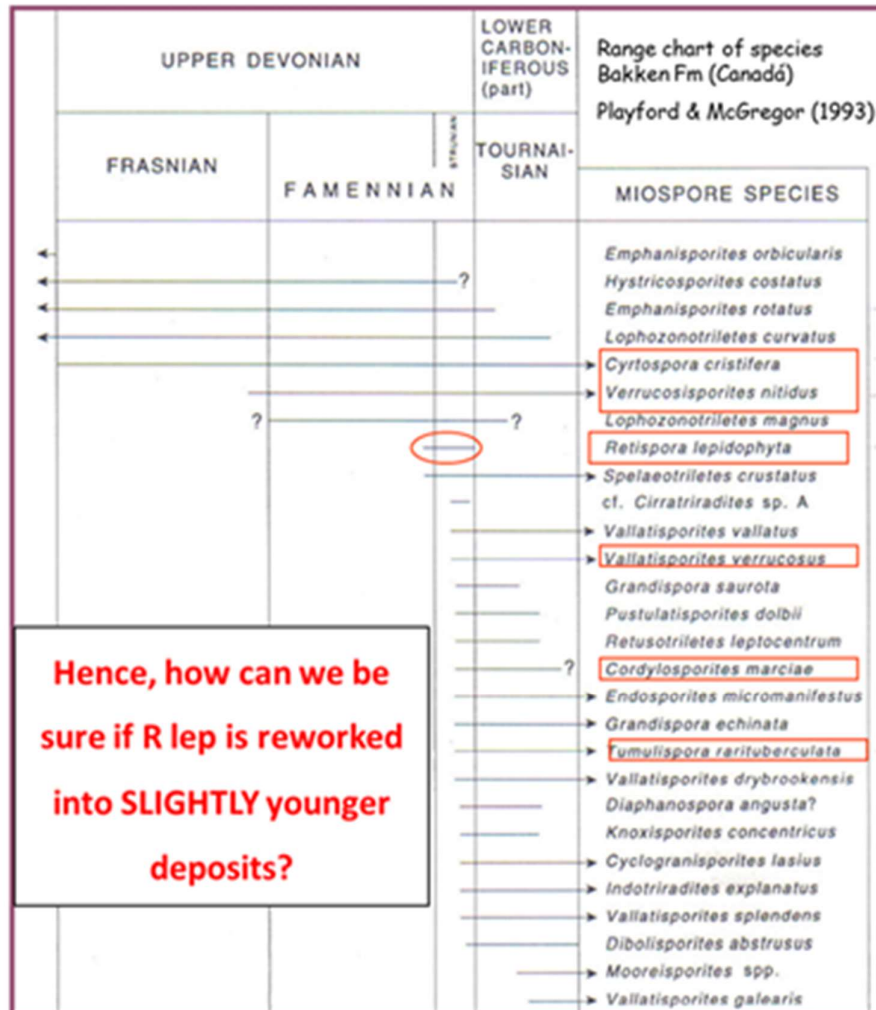


Figure 17. Example of stratigraphic range chart of taxa around the DCB.

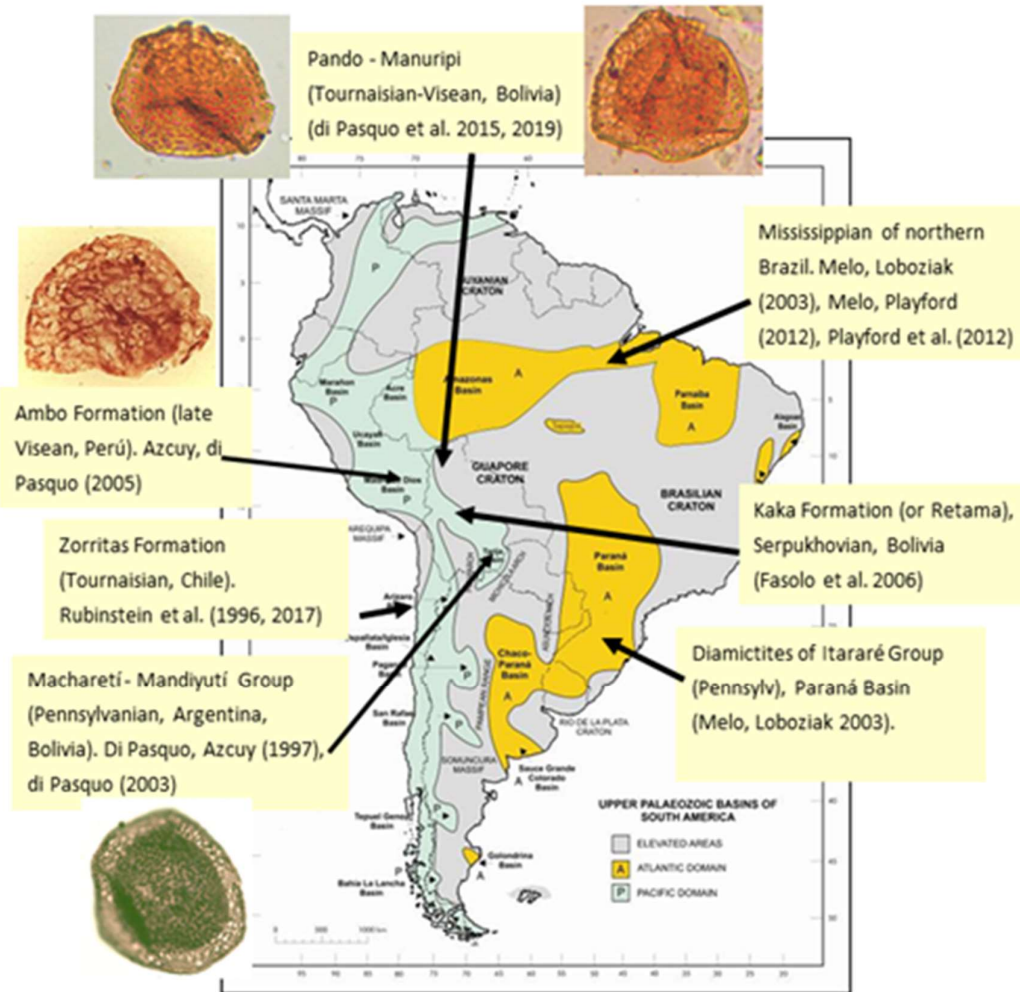


Figure 18. Examples of reworked *Rhynchonella* documented in younger Carboniferous assemblages in South America (map from Azcuy and di Pasquo, 2000).

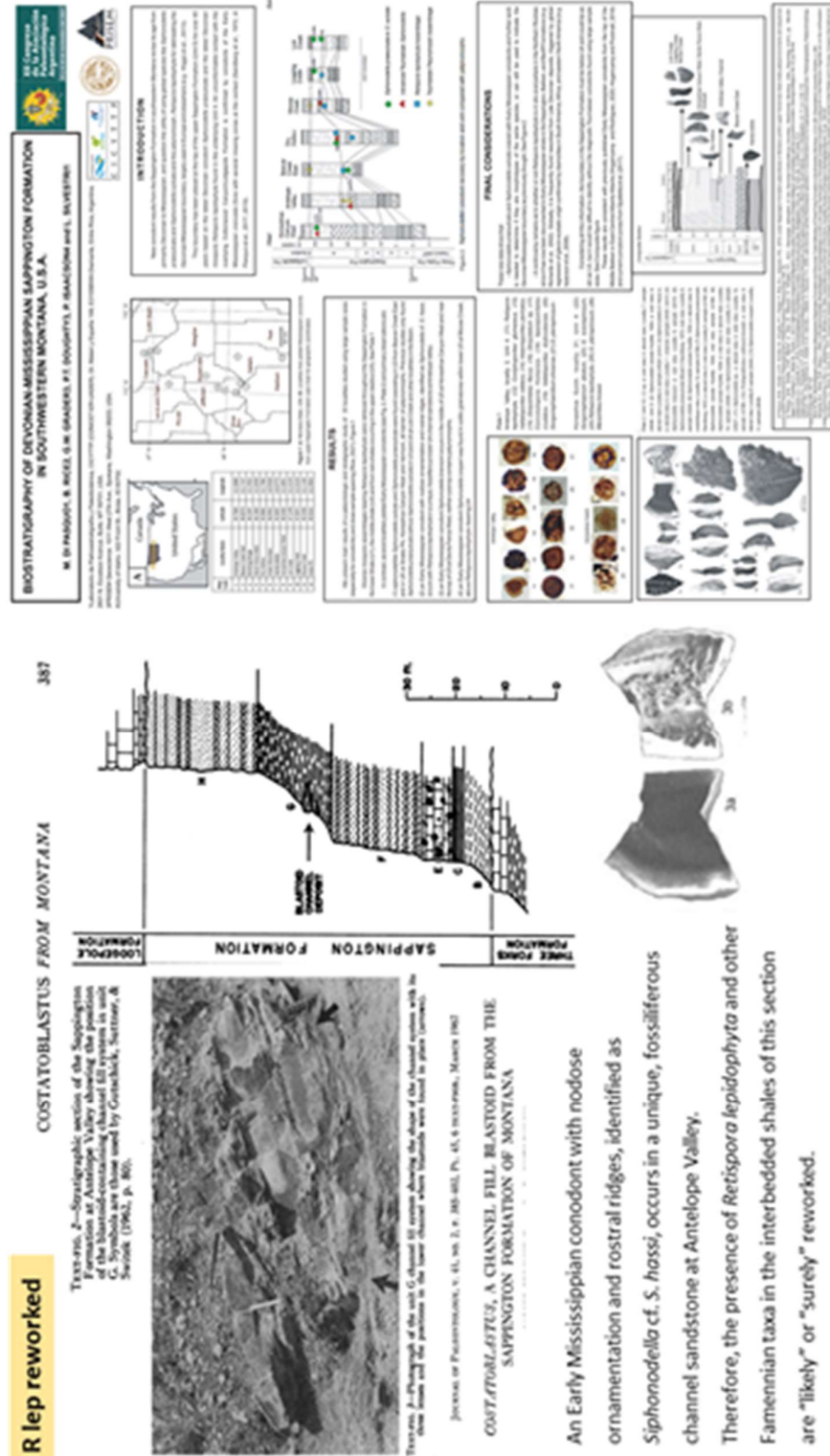


Figure 19. Composite information of the DCB in Montana based on still ongoing study as addressed in the text herein (see also Strel and di Pasquo, 2022).