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Palynological evaluation of the Famennian *Protosalvinia* (*Foerstia*) Zone in the Amazon Basin, northern Brazil: a preliminary study

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Abstract

Miospore assemblages recovered from a shallow borehole (Caima PH-2) and outcrops near the Tapajós River (Itaituba area), on the southern margin of the Amazon Basin, permit the correlation of the *Protosalvinia* Zone in this region with the equivalent of the uppermost part of the VCo miospore Zone in the eastern USA. Therefore it is dated as late (not latest) Famennian (*postera* to early *expansa* conodont Zones).

The *Protosalvinia* Zone also exists in the eastern USA but cannot be considered there as one single floral zone, its age varying, from place to place, from the middle to the late (not the latest) Famennian (one of the *marginifera* Zones to one of the *expansa* conodont Zones).

As demonstrated in well 1RX1AM, miospore evidence points to an important intraformational gap separating the lower and upper parts of the Curiri Formation. The lower section (which contains the *Protosalvinia* Zone) lacks diamictites, and rests conformably on the upper, non-radioactive shales of the uppermost Barreirinha Formation, of similar late Famennian (VCo) age. The 'upper Curiri unit' contains diamictites, and invariably displays a latest Famennian (late 'Strunian', LE–LN) age; it may constitute the whole formation in areas where 'lower Curiri' strata are missing, due to either erosion or non-deposition.

eywords: *Protosalvinia* (*Foerstia*); miospores; Famennian; Amazon Basin; Brazil

1. Introduction

The lower part of the Curiri Formation, basal Curuá Group, in the Amazon Basin, is a silty/shaly succession of variable thickness (0 to ca. 100 m). It includes the entire *Protosalvinia* Zone in that region, and is distinguished from the overlying parts of the formation by the general absence of diamictites[1]. In this section, *Protosalvinia* (*Foerstia*) is often associated with the trace fossil *Spirophyton*. Due to its occasionally high concentration, sometimes attaining as much as 50% of the total rock

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[1] We do not agree with the opinion of Niklas et al. (1976) who admit diamictites and quartzose subgraywackes as some of the lithologic constituents of the lower Curiri unit (e.g., in boreholes of the Manaus Platform area). Diamictites, regardless of higher or lower positions within the Curiri Formation, invariably display the same latest Famennian (LE–LN) age wherever dated by miospores (Loboziak and Streel, 1992; Loboziak et al., 1993;

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composition (Caputo, 1984), and its wide regional distribution, *Protosalvinia* (*Foerstia*) is a useful stratigraphic tool to detect and correlate this unit.

Niklas et al. (1976) and Caputo (1984) proposed an early Famennian age for the *Protosalvinia* Zone of Brazil based on correlation with occurrences of the genus known at that time in eastern North America. There have been no previous palynological age determinations for the *Protosalvinia* Zone in the Amazon Basin. The entire Curiri Formation has been generally assigned an age within the Famennian–'Strunian' range according to most recent workers (Daemon and Contreiras, 1971; Carozzi et al., 1973; Daemon, 1974, 1976; Caputo, 1984; Quadros, 1985; Streel, 1986). In terms of the Petrobras operational biozonation, the whole formation has been ascribed a single broad palynozone, i.e., the biostratigraphic interval VII of Daemon and Contreiras (1971) and followers. This biozone was originally referred to the latest Famennian because interval VII was believed to be characterized by the appearance of the miospore species *Retispora lepidophyta* (Daemon and Contreiras, 1971, p. 81; Daemon, 1974, pp. 550, 572). Daemon (1974, p. 579) includes the *Spirophyton* and *Protosalvinia* occurrences of the lower Curiri within the basal part of interval VII, so implying a same latest Famennian age for both the *Protosalvinia* Zone and the upper part of the formation.

Based on Streel's (1986) belief that most of the Famennian would be missing in northern Brazilian basins, Grahn (1992, fig. 2) suggested the presence of a wide gap within the Curiri Formation. According to him, the lower part of the formation, characterized by the *Protosalvinia* Zone and considered to be early Famennian in age, would rest conformably on the upper Barreirinha Formation, of late Frasnian/earliest Famennian age. Above the gap, the remainder of the Curiri Formation plus the lower part of the overlying Oriximiná Formation (both containing diamictites) were assigned to the uppermost Famennian. The concept of this intraformational break was also adopted by Loboziak et al. (1996). However, these latter predicted a younger age for the lower Curiri unit, i.e., late Famennian, corresponding to the *Diducites versabilis–Grandispora cornuta* (VCo) Oppel Zone. They based their age inference on similar miospore datings for the underlying section, i.e., the upper part of the Barreirinha Formation.

New miospore evidence provided by this study largely confirms Loboziak et al.'s viewpoints. Besides, the present investigation allows some new insights into the age problem of the lower part of the Curiri Formation and the magnitude of the gap which separates it from the upper part of the unit. This was facilitated by the continued recognition of Western European-defined miospore zones in the Amazon Basin. Such a procedure, pioneered in the basin by Loboziak et al. (1993), permits direct correlation of the local sections with the type marine Devonian of the Ardenne–Rhenish regions in Western Europe, where miospore zonal successions are accurately calibrated by means of the standard conodont biozonation (Streel et al., 1987).

2. Materials and methods

Biostratigraphic results presented herein are mainly based on the detailed palynological investigation of 39 core samples taken from the upper part of the shallow borehole Caima PH-2, drilled near the left bank of the Tapajós River in the Itaituba area, southern margin of the Amazon Basin (Fig. 1). The studied section, ca. 41 m thick, extends from the lower Curiri unit (which crops out at the borehole site) down to the Curiri/Barreirinha formational boundary. It corresponds to a portion of the *Protosalvinia* Zone, as specimens of this fossil plant have been recovered from the depth interval 9.22–14.24 m, and *Spirophyton* occurs down to at least 32.97 m. In addition, an outcrop sample bearing *Protosalvinia*, taken from the Tapajós riverbank adjacent to the

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Loboziak, unpubl. data). Therefore, they are herein regarded as part of the 'upper Curiri unit', and interpreted to lie unconformably on older Famennian silty/shaly sections of either the 'lower Curiri' or upper Barreirinha Formations, depending on the local extent and nature of the intervening gap (whether non-depositional or erosional).

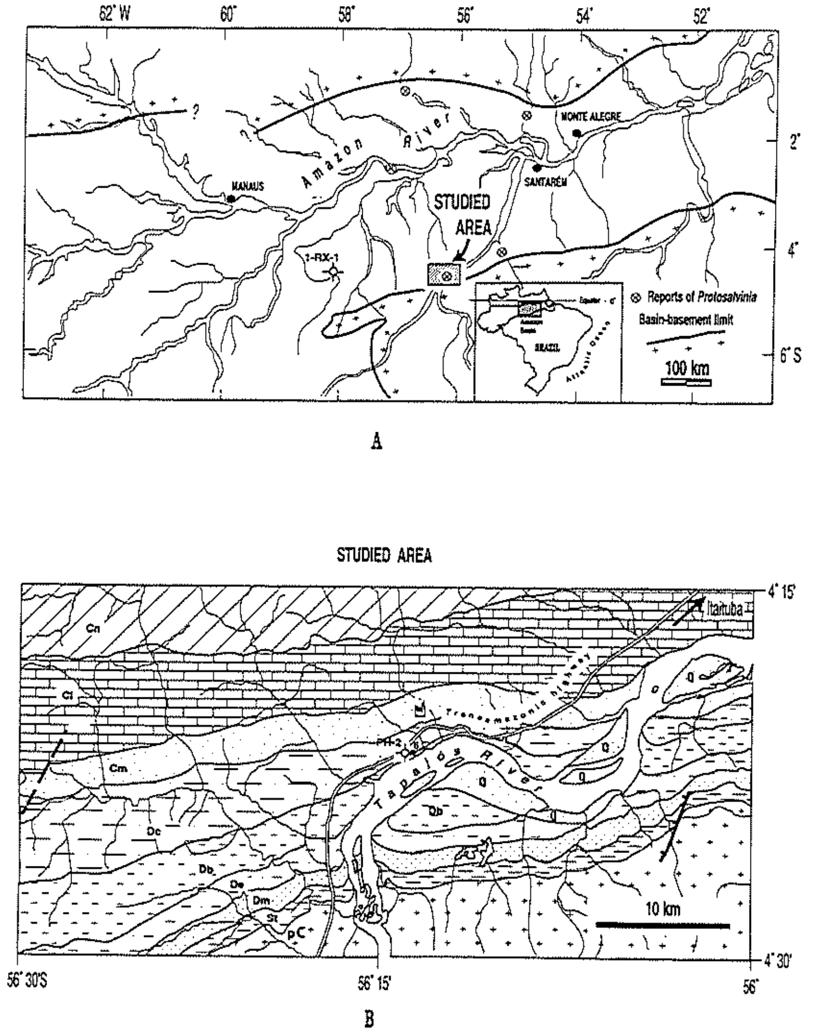


Fig. 1. (A) Regional location of the Itaituba studied area and of the 1RX1AM borehole. Locations of *Protosalvinia* occurrences are according to Niklas et al. (1976). (B) Local geological sketch of the Itaituba area (*PH-2* = site of borehole Caima PH-2; *6* = Tapajós riverbank outcrop sample): *Q* = Quaternary deposits; *Cn*, *Ci*, *Cm* = Nova Olinda, Itaituba and Monte Alegre Formations (Carboniferous); *Dc*, *Db*, *De*, *Dm* = Curiri, Barreirinha, Ererê and Maecuru Formations (Devonian); *St* = Trombetas Group (Silurian); *pC* = Precambrian crystalline basement.

borehole site, was also submitted to palynological investigation.

A supplementary reference section was provided by cores 118 through 121 of well 1RX 1AM (2407–2423.6 m), some 150 km to the west, allowing investigation of the contact between the lower Curiri unit (lacking diamictites) and younger Curiri strata.

All studied samples have been processed for palynological inspection according to Petrobras standard laboratorial procedures described by Quadros and Melo (1987). Investigations were carried out with the help of a conventional (transmitted light) optical microscope, and photographs were taken on a Nomarsky interference contrast microscope.

Most samples have yielded variable amounts of well preserved miospores and microphytoplankton of Late Devonian age. Only a few samples were found to contain fragmentary chitinozoans (below 34 m in Caima PH-2 borehole), which in most cases are too poorly preserved to allow proper identification. The dominant fraction in the organic residue consists of land plant microdebris (miospores and cuticle scraps) and acritarchs, both in situ and reworked. Nearshore to shallow shelf marine sedimentary settings can be inferred for most of the sampled interval based on the nature of the organic residue.

3. Palynological results

3.1. *Miospores*

3.1.1. *Borehole Caima PH-2*

Fig. 2 shows the main miospore taxa identified in this study and their stratigraphic distribution in the most fossiliferous samples of the interval between 7.80 m and 39.90 m of borehole Caima PH-2.

Other taxa have also been identified, but they are rather rare. Amongst them are *Auroraspora macra*, *Cristatisporites imperpetuus* and *C. lupinovitchii*, *Lophozonotriletes lebedianensis* and *L. tylophorus*, as well as various *Cymbosporites* spp.

Also present are a few taxa known from the Middle Devonian and Frasnian, whose presence in the studied section is ascribed to reworking. The main ones include *Geminospora lemurata*, *G. piliformis* and *G. punctata*, *Chelinospora timanica*, *Samarisporites triangulatus* and *Grandispora incognita*.

One single miospore assemblage characterizes all the investigated samples in the Caima PH-2 borehole, with the almost continuous presence of *Rugospora radiata*, a guide species of the late Famennian. According to Byvsheva (1985), this taxon had been incorrectly named *Rugospora flexuosa* by Western European palynologists for many years (Becker et al., 1974). Thus, the first occurrence of *Rugospora radiata* characterizes the *Rugospora flexuosa–Grandispora cornuta* Assemblage Zone in the zonal scheme proposed by Richardson and McGregor (1986) for the Old Red Sandstone Continent and adjacent areas. Its first occurrence also defines the base of the *D. versabilis–G. cornuta* (VCo) Oppel Zone, erected by Streel et al. (1987) in the type marine Devonian of the Ardenne. *Grandispora cornuta*, another guide species of this Oppel Zone, is present but rare in the Caima borehole.

The absence of *Retispora lepidophyta*, which characterizes the overlying miospore zones of the terminal part of the Devonian, allows confirmation that the single miospore assemblage identified in this borehole belongs to the VCo Zone.

The occurrence, from near the base of the investigated interval, of *Vallatisporites hystricosus* is also significant. So far, this taxon has not been recorded below the oldest occurrence of *Retispora lepidophyta* in the type region of the Ardenne. However, *V. hystricosus* (= *V. pusillites* in the usage of several authors) seems to be already present in sections equivalent to the upper part of the VCo Zone in several regions of the eastern USA (Streel and Traverse, 1978; Richardson and Ahmed, 1988; Streel and Schlecker, 1990) and North Africa (Streel, 1986; Streel et al., 1988, p. 115).

The irregularity of the presence or of the abundance of *Vallatisporites* spp. is a well known palynological feature of layers adjacent to the Devonian/Carboniferous boundary (Streel, 1971; Warg and Traverse, 1973). In particular, the abundance of *V. hystricosus* seems to be facies-controlled, and was associated by Streel and Schlecker (1990) with the existence of near-coastal swamp environments.

3.1.2. *Tapajós riverbank outcrop sample*

The miospore assemblage identified in this sample contains: *Diaphanospora rugosa*, *Diducites mucronatus*, *Leiotriletes struniensis*, *Retusotriletes* sp., *Rugospora bricei*, *Rugospora radiata*, *Teichertospora torquata*, *Vallatisporites hystricosus* and *Vallatisporites* sp. cf. *V. anthoideus*.

This assemblage is similar to that described from the Caima PH-2 borehole. The joint occurrence of *Rugospora radiata* and *Vallatisporites hystricosus*, along with the absence of *R. lepidophyta*, also indicate that this sample belongs to the upper part of the VCo Oppel Zone.

As in the Caima PH-2 borehole samples, several

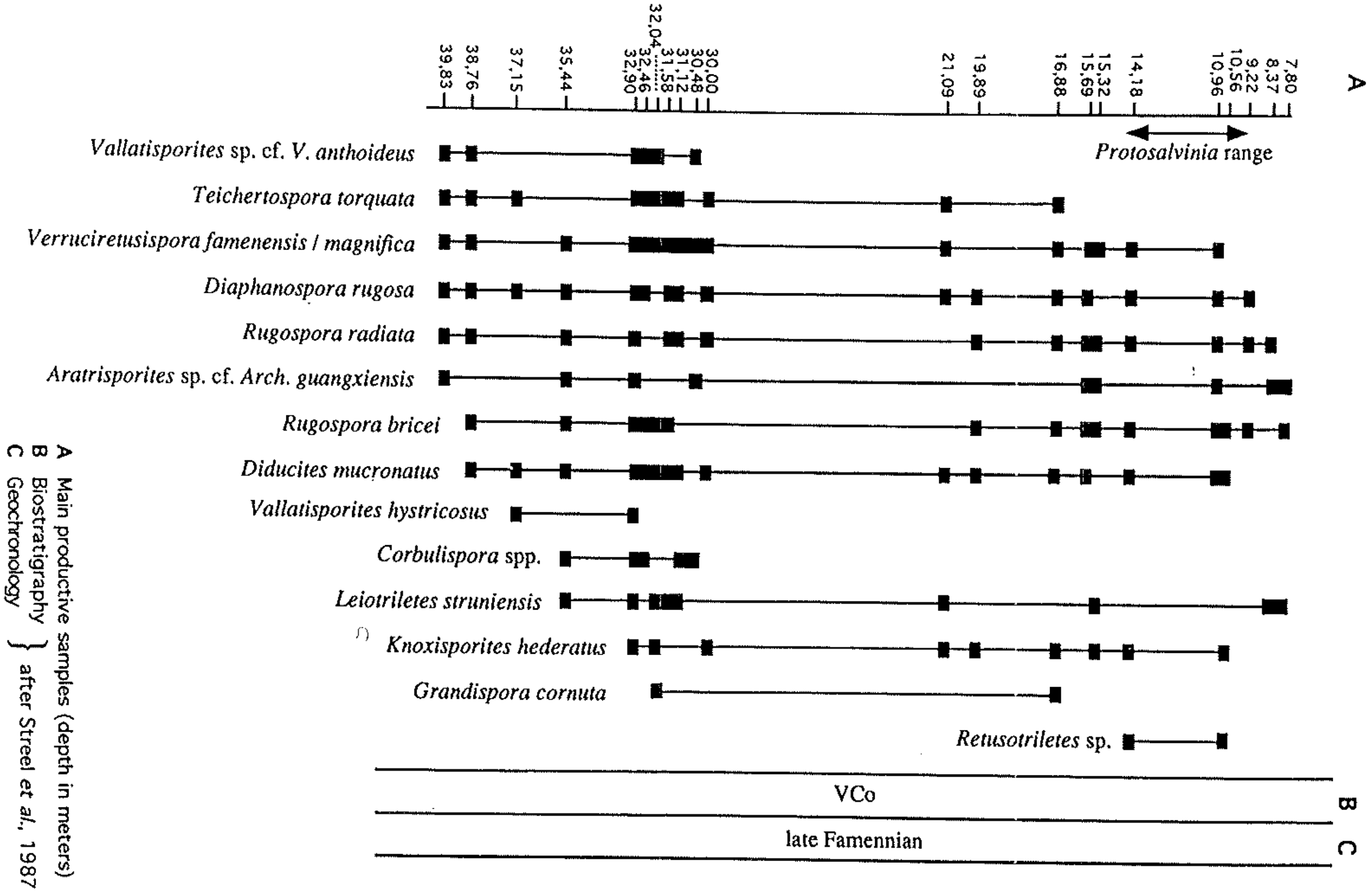


Fig. 2. Miospore distribution in borehole Caima PH-2.

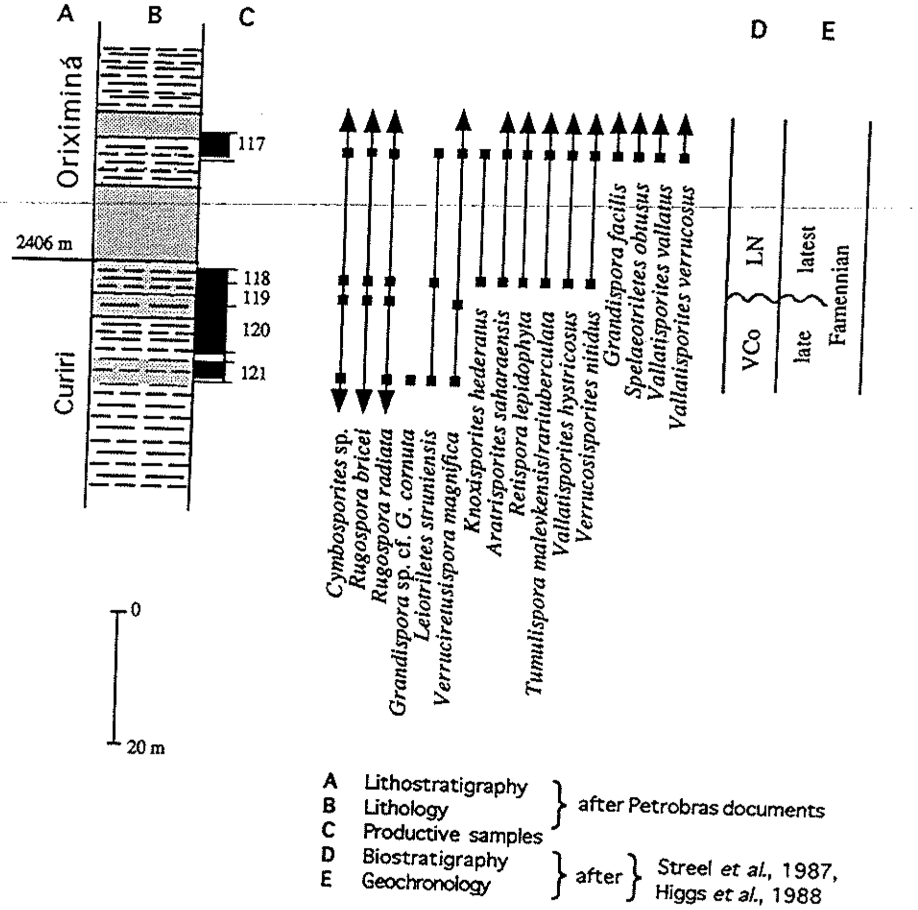


Fig. 3. Miospore distribution in borehole 1RX1AM.

Middle Devonian and Frasnian miospores have been identified including *Archaeozonotriletes variabilis, Chelinospora timanica, Geminospora lemurata, G. piliformis, G. punctata, Samarisporites iangulatus* and *Verrucosisporites bulliferus*.

3.1.3. *Borehole 1RX1AM (cores 118–121)*

From cores 118, 119 and 121 belonging to the uppermost part of the Curiri Formation between 2407 and 2423.6 m, the organic matter is poorly preserved. Miospores are rather rare and highly degraded (Fig. 3).

Two different miospore assemblages are present within this interval, both containing *R. radiata*. In the slides inspected for cores 121 at 2419.2/2423.6 m and 119 at 2410/2414.2 m, this species is associated with *Rugospora bricei, Leiotriletes struniensis, Verruciretusispora magnifica* and a specimen of *Grandispora* sp. cf. *G. cornuta* (in core 121 only). In core 118 at 2407/2410 m the associated taxa are more diverse, including *Retispora lepidophyta* and some other species known to first occur in the upper part of the *R. lepidophyta* zonal range including *Tumulispora malevkensis, T. rarituberculata* and *Verrucosisporites nitidus*. The two lowest samples (cores 121 and 119) belong to the VCo Oppel Zone whilst core 118 corresponds to the younger *Retispora lepidophyta–Verrucosisporites nitidus* (LN) Interval Zone.

The palynological results in borehole 1RX1AM make it clear that the Curiri Formation is here represented chiefly by its lower part only (of VCo age), whereas LN-age strata, equivalent of the 'upper Curiri' elsewhere, are mostly included in the overlying Oriximiná Formation. This case study serves to exemplify the strongly diachronous character of certain Devonian formations as currently identified in some boreholes of the Amazon Basin.

3.1.4. *Short systematic and biostratigraphic notes*

Vallatisporites sp. cf. *V. anthoideus* (Sennova) Braman and Hills, 1992 (Plate I, 3)

Specimens with typical, very short and narrow internal vacual ornamentation on zona, covered by widely to closely spaced or coalesced verrucae or coni.

V. anthoideus ranges from late Frasnian to middle Famennian in the Canadian Northwest Territories and Yukon, where no late Famennian strata are known below those containing *R. lepidophyta* assemblages. The species is known as (?) *Hymenozonotriletes denticulatus* Naumova of McGregor, 1967 in the VCo Zone equivalent of northern America (Richardson and McGregor, 1986, fig. 3, pl. 1a, fig. 2, 3).

Aratrisporites sp. cf. *Archaeoperisaccus guangxiensis* Gao, 1989 (Plate I, 4–5)

Bilateral symmetry, monolete, camerate miospore, with typical raised lips on the proximal surface and perpendicular fold(s) affecting the exoexine on the distal surface. Exine ornamented with small coni and spinae (0.5–1.5 μm).

The cameration in this form is much more developed than in *Archaeoperisaccus*. *Archaeoperisaccus mirandus* and *A. elongatus* figured by Gao (1989, figs. 11–13), do not belong to the genus *Archaeoperisaccus* and might belong to Famennian *Aratrisporites* sp. cf. *Archaeoperisaccus guangxiensis*.

This taxon occurs from Middle to Upper Devonian in several provinces of China.

Retusotriletes sp. (Plate I, 1)

Thick-walled (6–10 μm), smooth retusoid miospore with winged curvaturae.

Diameter: 90–160 μm.

This heavy, large-sized miospore (sometimes in the size range of megaspores) was probably not disseminated a long distance away from its mother-plant. Its local stratigraphic range in the investigated section matches almost exactly that of *Protosalvinia*, from which it may have derived.

3.2. *Acritarchs*

Representatives of nineteen acritarch species have been recovered from shale macerations of core samples from the Caima PH-2 borehole, in the same interval studied for miospores.

Amongst the identified acritarchs, *Umbellasphaeridium saharicum* for instance is a characteristic Famennian taxon in the Amazon Basin (Plate II).

Maranhites insulatus and *M. mosesii* are common in Late Devonian strata of Brazilian Paleozoic basins (Quadros, 1982).

The distribution of other selected acritarch species shown in Fig. 4 gives a general idea of the main assemblage recorded in the studied section.

In conclusion, the identified acritarchs are in general agreement with the Famennian age indicated by *Protosalvinia* and the associated miospores.

Discussion of results

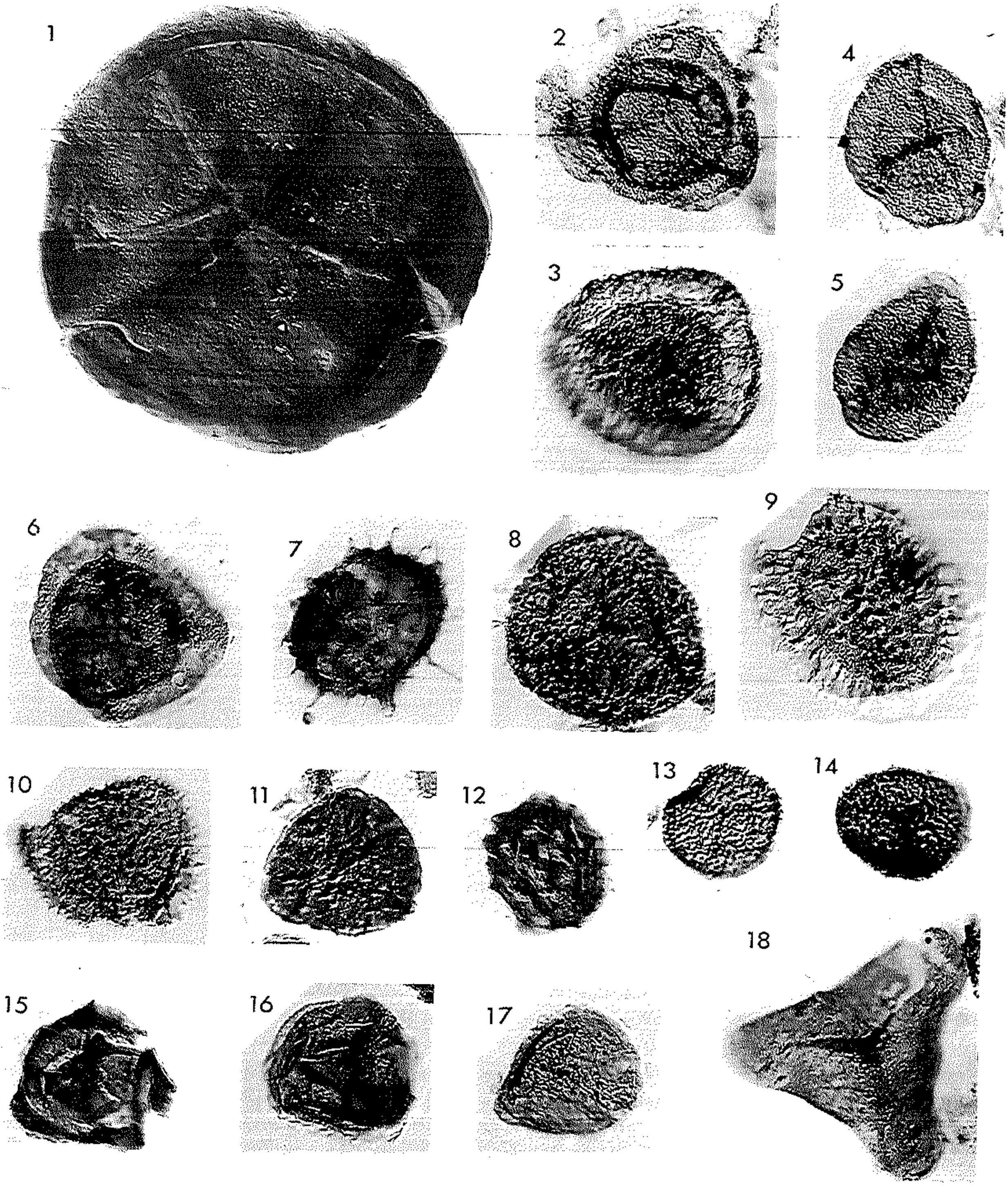
4.1. *Miospore assemblages and their age implications for lithostratigraphic units and the* Protosalvinia *Zone in the Amazon Basin*

Richardson and McGregor (1986, fig. 7) clearly illustrated an apparent discrepancy in the late Famennian conodont–ammonoid and miospore correlations between eastern USA and Belgium. However, Streel and Loboziak (1994, fig. 2) showed that the miospore documentation was obviously better in the New York reference section than in Belgium, whereas the faunal control for the same interval was rather poor in both regions.

Nevertheless, a maximum age corresponding to the latest *marginifera* conodont Zone is possible, although a *trachytera* age cannot be excluded for the base of the VCo miospore Zone.

The first occurrence of *Vallatisporites pusillites* (= *V. hystricosus*) in New York State is noted by

PLATE I



Richardson and Ahmed (1988) in the Cattaraugus Formation, a diachronous formation which is poorly dated by conodonts, but known to belong, by lateral lithostratigraphic correlation, to the ammonoid *Platyclymenia* 'Stufen' or to 'toIII' and 'toIV' of the German stratigraphy (Rickard, 1975). An age equivalence between the upper part of the VCo Zone (with *Vallatisporites hystricosus*) and the *trachytera* or more probably *postera* or even early *expansa* conodont Zones is therefore acceptable.

In the type marine area of the Ardenne, *Retispora lepidophyta* first occurs between two conodont faunas characteristic of the middle and late *expansa* Zones, respectively (Dreesen et al., 1993; Streel and Loboziak, 1994, fig. 6). Four successive miospore terval zones permit the subdivision of the total range of *Retispora lepidophyta* throughout the latest Famennian ('Strunian'). Of these, only the youngest unit, i.e., the *Retispora lepidophyta–Verrucosisporites nitidus* (LN) Interval Zone, has been recognized in borehole 1RX1AM. This biozone corresponds to the middle to late *praesulcata* conodont Zones (Higgs and Streel, 1994).

In the Caima PH-2 borehole, the lower Curiri section contains miospore assemblages of the uppermost VCo Oppel Zone, and hence, is probably of *postera* or early *expansa* 'age'. The occurrence of *Protosalvinia* has been only noted in the upper part of the drilled section (core samples nr. 9(2) to 3(1), between 14.24 and 9.22 m). Miospore assemblages in the same interval are characterized by the presence of *Retusotriletes* sp., a distinctive miospore which might well have been produced by *Protosalvinia* (see Sect. 4.2.).

The *Protosalvinia*-bearing sample taken in the Tapajós riverbank outcrop also corresponds to the upper part of the VCo Zone.

In the borehole 1RX1AM, a poorly preserved VCo miospore assemblage is noted in cores 121 and 119, recovered from the uppermost part of the lower Curiri Formation (devoid of diamictites). No more than 7.2 m above core 119, the VCo Oppel Zone is succeeded in core 118 by the LN Interval Zone, corresponding to the lowest strata of the upper Curiri Formation. Therefore, a major biostratigraphical (and lithological?) break must occur between cores 119 and 118, which encompasses approximately two missing conodont zones (from late *expansa* to middle *praesulcata*), or an estimated time interval of about 0.5 m.y. (Ziegler and Sandberg, 1990).

4.2. *The* Protosalvinia *Zone in Brazil and the eastern USA*

The several species of *Protosalvinia* described in the literature have been revised by Niklas et al.

PLATE I

Except 9, all illustrated miospores are from borehole Caima PH-2 (miospore magnification × 500).

1. *Retusotriletes* sp. Slide 950285: N50, sample 6(1) at 10.56/10.61 m.
2. *Teichertospora torquata* (Higgs) McGregor and Playford, 1990. Slide 950301: U44^3, sample 22(3) at 31.12/31.18 m.
3. *Vallatisporites* sp. cf. *V. anthoideus* Braman and Hills, 1992. Slide 950303: U55, sample 24(3) at 32.04/32.11 m.

5. *Aratrisporites* sp. cf. *Archaeoperisaccus guangxiensis* Gao, 1989.

.. Slide 950286: G61, sample 7(1) at 10.96/11.03 m.

5. Slide 950280: E56^1, sample 1(1) at 7.80/7.84 m.

6. *Diducites mucronatus* (Kedo) Van Veen, 1981. Slide 950305: R47^3, sample 26(3) at 32.90/32.97 m.
7. *Grandispora cornuta* Higgs, 1975. Slide 950293: N52^4, sample 14(2) at 16.88/16.93 m.
8. *Verruciretusispora magnifica* (McGregor) Owens, 1971. Slide 950305: Y64^4, sample 26(3) at 32.90/32.97 m.
9. *Vallatisporites hystricosus* (Winslow) Byvsheva, 1985. Slide 9507138b: Z62^3, Tapajós riverbank outcrop sample.
10. *Cristatisporites imperpetuus* (Sennova) Obukhovskaya, 1986. Slide 950303: 046, sample 24(3) at 32.04/32.11 m.
11. *Rugospora radiata* (Jushko) Byvsheva, 1985. Slide 950299: M55^1, sample 20(3) at 30.00/30.06 m.
12. *Corbulispora vimineus* (Nekriata) Obukhovskaya and Nekriata, 1983. Slide 950304: W56^4, sample 25(1) at 32.46/32.51 m.
13. *Verruciretusispora famenensis* (Kedo) Owens, 1971. Slide 950305: P50^1, sample 26(3) at 32.90/32.97 m.
14. *Cymbosporites* sp. Slide 950304: J57, sample 25(3) at 32.46/32.51 m.
15. *Knoxisporites hederatus* (Ishchenko) Playford, 1963. Slide 950305: Q47, sample 26(3) at 32.90/32.97 m.
16. *Diaphanospora rugosa* (Naumova) Byvscheva, 1985. Slide 950305: V57^4, sample 26(3) at 32.90/32.97 m.
17. *Rugospora bricei* Loboziak and Streel, 1989. Slide 950288: X60, sample 9(2) at 14.18/14.24 m.
18. *Leiotriletes struniensis* Moreau-Benoit, 1979. Slide 950303: O48, sample 24(3) at 32.04/32.11 m.

PLATE II

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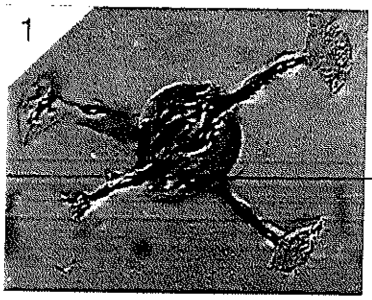

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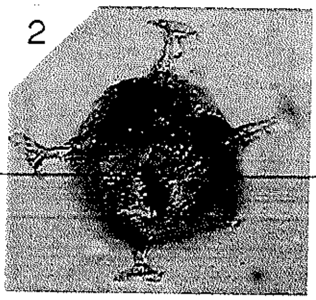

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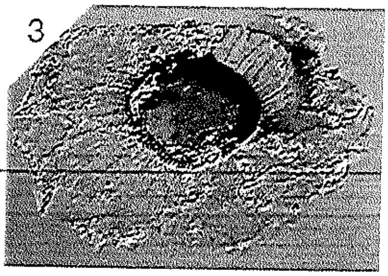

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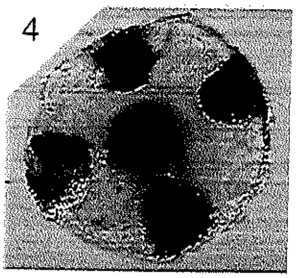

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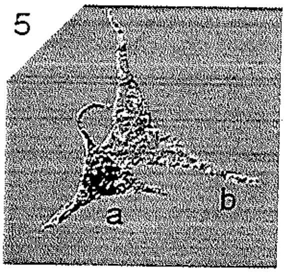

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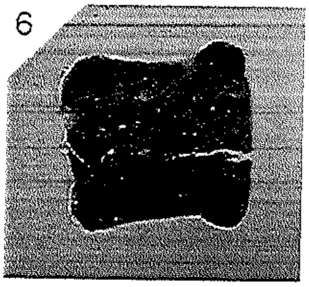

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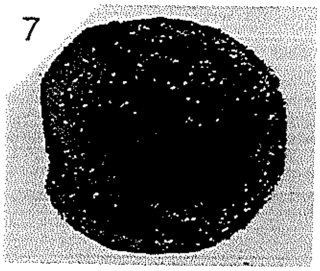

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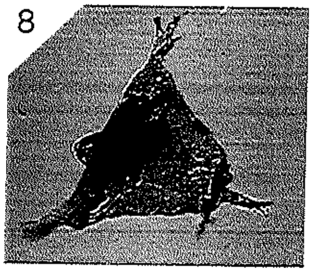

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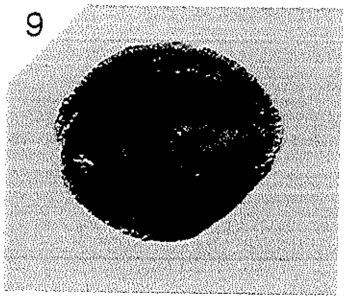

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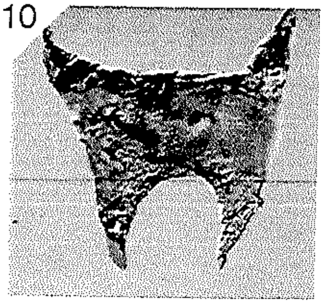

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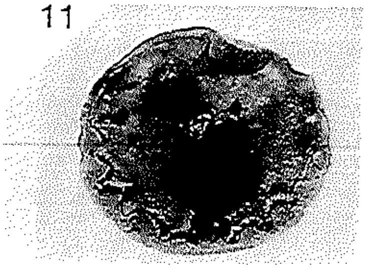

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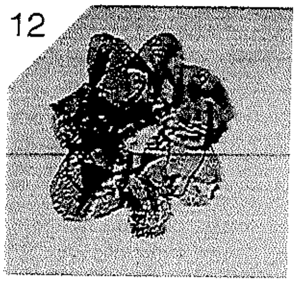

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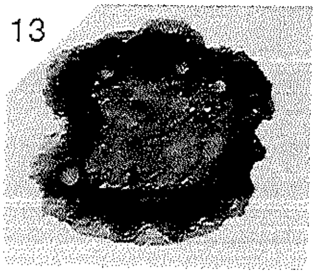

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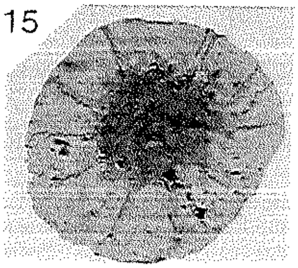

(1976) and Niklas and Phillips (1976). From their study in the Amazon Basin, they concluded that all forms of *Protosalvinia* can be interpreted as ontogenetic stages and ecotypes of one single valid species (*P. braziliensis*). They also noted that miospore tetrads of all forms were indistinguishable. Interesting for the interpretation of the ecology of this fossil plant is the observation that some forms of *Protosalvinia* are more frequent in offshore deposits and might provide an index of relative depth.

Opinions differ indeed as to whether this plant was marine (Schopf, 1978) or terrestrial (Gray and Boucot, 1979). The morphology and mode of reproduction were sometimes compared to the wn algae *Phaeophyta* (Niklas and Phillips, 1976).

Gutschick and Sandberg (1991, p. 156) "interpret that *Protosalvinia* grew in marine swamps; its abundant occurrences in black shales resulted from drowning of its habitats and seaward dispersal during major Famennian rises of sea level".

Recent works, however, point to the land plant affinities of *Protosalvinia*, based on such evidence as the presence of lignin-like compounds (Romankiw et al., 1988) and the meiotic nature of tetrads, which display little similarity with tetraspores of extant phaeophyceans (Taylor and Taylor, 1987).

It should be kept in mind that the only parts of *Protosalvinia* preserved in the fossil record are those associated with what appear to be reproductive structures (Romankiw et al., 1988). The spore compartments retain generally complete tetrads. Individual spores are large (250 μm in mean diameter), thick-walled (10 μm) and exhibit a well defined triradiate mark and prominent, winged curvaturae (Niklas and Phillips, 1976, fig. 31). Their heavy exine was interpreted by these authors as an adaptation to resist the periodic desiccation of a possible littoral habitat.

Obviously, the large-sized *sporae dispersae* observed in the Caima PH-2 borehole and the Tapajós riverbank outcrop sample, herein classified as *Retusotriletes* sp., might well correspond to the miospores observed in *Protosalvinia*.

Protosalvinia has been considered in eastern USA to represent one single floral zone and has been used as a virtual time line for regional correlations (Schwietering and Neal, 1978; Hasenmueller et al., 1984; Conkin, 1986). Some correlations indicated a 'middle' Famennian age (*crepida* to *marginifera* conodont Zones) but rely often on poorly documented lateral lithological correlations (Schopf and Schwietering, 1970; Murphy, 1973; Ettensohn et al., 1988).

Gutschick and Sandberg (1991, p. 156) and Sandberg et al. (1994, p. 241) recently demon-

PLATE II. Selected acritarchs from borehole Caima PH-2 (unless otherwise stated, scale bar = 50 μm)

1, 2. *Umbellasphaeridium saharicum* Jardiné, Combaz, Magloire, Peniguel and Vachey, 1972.
1. Slide 950295: Q45^2, sample 16(3) at 19.89/19.94 m.
 Slide 950301: T67^1, sample 22(3) at 31.12/31.18 m.
3. *Pterospermella pernambucensis* (Brito) Eisenack, 1972. Slide 950301: W37, sample 22(3) at 31.12/31.18 m.
4. *Maranhites insulatus* Burjack and Oliveira, 1989. Slide 950304: W53^3, sample 25(3) at 32.46/32.51 m.
5a. *Veryhachium trispinosum* (Eisenack) Cramer, 1964. Slide 950304: X53, sample 17(3) at 20.39/20.45 m.
5b. *Veryhachium trispininflatum* Cramer, 1964. Slide 950304: X53, sample 17(3) at 20.39/20.45 m.
6. *Crassiangulina tessellita* Jardiné, Combaz, Magloire, Peniguel and Vachey, 1972. Slide 950299: Q55, sample 20(3) at 30.00/30.06 m.
7. *Maranhites stockmansii* (Martin) emend. Martin, 1984. Slide 950296: S46^2, sample 17(3) at 20.39/20.45 m.
8. *Evittia sommeri* Brito, 1967. Slide 950307: J42^3, sample 28(6) at 34.14/34.20 m.
9. *Tasmanites* sp. Slide 950307: D41^1, sample 28(6) at 34.14/34.20 m.
10. *Horologinella quadrispina* Jardiné, Combaz, Magloire, Peniguel and Vachey, 1972. Slide 950307: F63, sample 28(6) at 34.14/34.20 m.
11. *Maranhites mosesii* (Sommer) Brito emend. Burjack and Oliveira, 1989. Slide 950304: W53^3, sample 25(3) at 32.46/32.51 m.
12. *Petrovina connata* Oliveira and Burjack, 1990. Slide 950307: B52, sample 28(6) at 34.14/34.20 m (scale bar = 100 μm).
13. *Maranhites lobulatus* Burjack and Oliveira, 1989. Slide 950307: F63, sample 28(6) at 34.14/34.20 m.
14. *Mediocorpore conspicuo* Oliveira, 1991, nom.nud. Slide 950295: P54^1, sample 16(3) at 19.89/19.94 m (scale bar = 100 μm).
15. *Duvernaysphaera radiata* Brito, 1967. Slide 950289: N45, sample10(2) at 14.85/14.90 m.

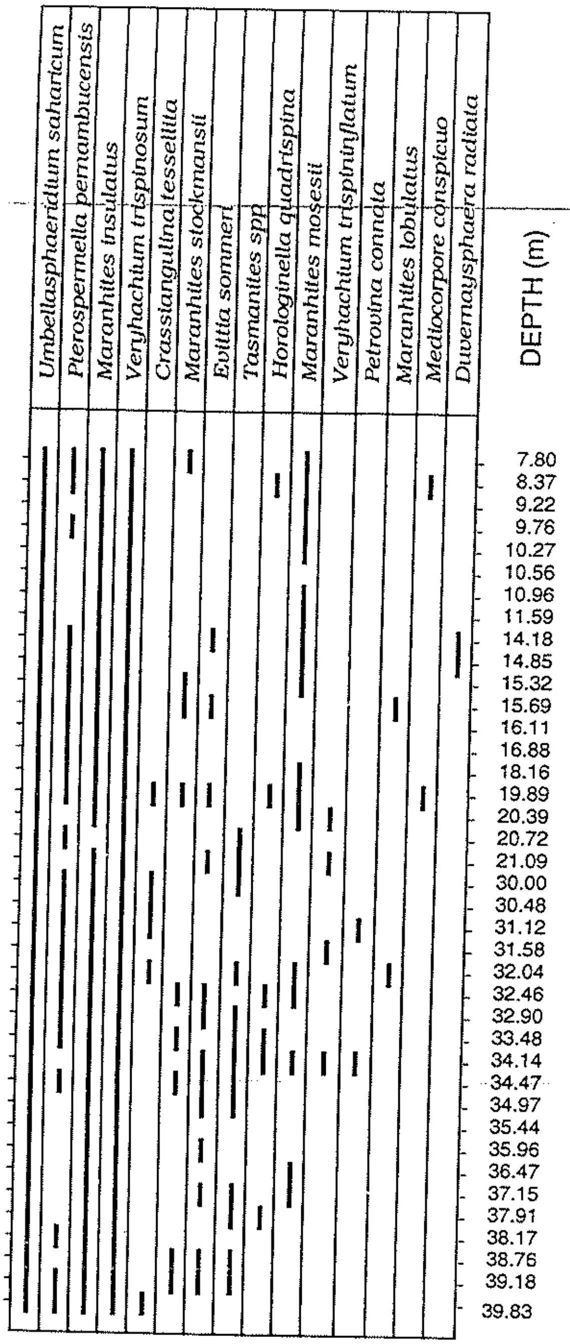

Fig. 4. Acritarch distribution in borehole Caima PH-2.

strated that regional North American occurrences of *Protosalvinia*, at a generic level, cannot be regarded as a virtual time line. In the USA, *Protosalvinia* probably ranges from at least one of the mid-Famennian *marginifera* Zones to one of the late Famennian *expansa* Zones, so implying a time span of no less than 3 m.y. (Ziegler and Sandberg, 1990).

5. Conclusions

In the Amazon Basin, the *Protosalvinia* Zone is confined to the lower section (lacking diamictites) of the Curiri Formation. The late (not latest) Famennian age of this unit is given by the occurrence of miospores of the upper VCo Oppel Zone, i.e., the part of that zone which contains *Vallatisporites hystricosus* (= *V. pusillites* in the usage of Richardson and Ahmed, 1988, and other authors). *Protosalvinia* remains unknown in the older VCo shales which make up the uppermost part of the underlying Barreirinha Formation.

Known in the eastern USA (but so far not in Western Europe), the upper VCo Zone is not well dated by conodonts. A range from the *trachytera* Zone to the early *expansa* Zone is possible, with a greater probability for the upper part of this range. As previously suggested by Richardson and Ahmed (1988, p. 550), this interval, characterized by the earliest occurrence of *V. hystricosus* without any *R. lepidophyta*, possibly bridges a stratigraphic gap in the Famennian miospore succession of Western Europe, located at the VCo/LV zonal transition. In the Amazon Basin, however, the VCo Zone is directly succeeded by the LN Zone, which corresponds to the diamictite-bearing part of the Curiri Formation. This suggests that a biostratigraphical (and lithological?) gap intervenes on the top of the *Protosalvinia* Zone, possibly corresponding to at least two missing conodont zones.

In the eastern USA the *Protosalvinia* Zone is present in black shales at different localities, with different ages ranging from one of the mid-Famennian *marginifera* Zones to one of the late Famennian *expansa* Zones. Thus, the *Protosalvinia* Zone does not represent a virtual time line as formerly believed. Nevertheless, the age of this zone in the Amazon Basin of Brazil probably matches one of the late Famennian ages of the unit in the eastern USA.

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Species listed

Miospores

Aratrisporites saharaensis Loboziak, Clayton and Owens, 1986
Aratrisporites sp. cf *Archaeoperisaccus guangxiensis* Gao, 1989
Archaeoperisaccus elongatus Naumova, 1953
Archaeoperisaccus mirandus Naumova, 1953
Archeozonotriletes variabilis Naumova emend. Allen, 1965
Auroraspora macra Sullivan, 1968
Chelinospora timanica (Naumova) Loboziak and Streel, 1992
Corbulispora vimineus (Nekriata) Obukhovskaya and Nekriata, 1983
Cristatisporites imperpetuus (Sennova) Obukhovskaya, 1986
Cristatisporites lupinovitchii (Avkhimovitch) Avkhimovitch, 1993
Diaphanospora rugosa (Naumova) Byvsheva, 1985
Diducites mucronatus (Kedo) Van Veen, 1981
Geminospora lemurata Balme emend. Playford, 1983
Geminospora piliformis Loboziak, Streel and Burjack, 1988
Geminospora punctata Owens, 1971
Grandispora cornuta Higgs, 1975
Grandispora facilis (Kedo) Avkhimovitch, 1988
Grandispora incognita (Kedo) McGregor and Camfield, 1976
Knoxisporites hederatus (Ishchenko) Playford, 1963
Leiotriletes struniensis Moreau-Benoit, 1979
Lophozonotriletes lebedianensis Naumova, 1953
Lophozonotriletes tylophorus Naumova
Retispora lepidophyta (Kedo) Playford, 1976
Rugospora bricei Loboziak and Streel, 1992
Rugospora flexuosa (Jushko) Streel, 1971
Rugospora radiata (Jushko) Byvsheva, 1985
Samarisporites triangulatus Allen, 1965
Spelaeotriletes obtusus Higgs, 1975
Teichertospora torquata (Higgs) McGregor and Playford, 1990
Tumulispora malevkensis (Kedo) Turnau, 1978
Tumulispora rarituberculata (Luber) Potonié, 1966
Vallatisporites hystricosus (Winslow) Byvsheva, 1985
Vallatisporites pusillites (Kedo) Dolby and Neves emend Byvsheva, 1985
Vallatisporites vallatus Hacquebard, 1957
Vallatisporites verrucosus Hacquebard, 1957
Vallatisporites sp. cf *V. anthoideus* Braman and Hills, 1992
Verruciretusispora famenensis (Kedo) Owens, 1971
Verruciretusispora magnifica (McGregor) Owens, 1971
Verrucosisporites bulliferus Richardson and McGregor, 1986
Verrucosisporites nitidus Playford, 1964

Acritarchs

Crassiangulina tessellita Jardiné, Combaz, Magloire, Peniguel and Vachey, 1972
Duvernaysphaera radiata Brito, 1967
Duvernaysphaera stellata Deunff, 1964
Evittia sommeri Brito, 1967
Horologinella quadrispina Jardiné, Combaz, Magloire, Penigue and Vachey, 1972
Maranhites mosesii (Sommer) Brito emend. Burjack and Oliveira, 1989

Maranhites stockmansii (Martin) emend. Martin, 1984
Maranhites insulatus Burjack and Oliveira, 1989
Maranhites lobulatus Burjack and Oliveira, 1989
Mediocorpore conspicuo Oliveira 1991, nom.nud.
Navifusa cylindrica (Brito and Santos) Combaz, Lange and Pansart, 1967
Petrovina connata Oliveira and Burjack, 1990
Pterospermella pernambucensis (Brito) Eisenack, 1972
Umbellasphaeridium deflandrei Moreau-Benoit, 1967
Umbellasphaeridium saharicum Jardiné, Combaz, Magloire, Peniguel and Vachey, 1972
Veryhachium trispininflatum Cramer, 1964
Veryhachium trispinosum (Eisenack) Cramer, 1964

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