Primitive Vascular Plants and Microfossils from the Río Seco de los Castaños Formation, San Rafael Block, Mendoza Province, Argentina

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Abstract In this contribution we describe fossil plant remains from Río Seco de los Castaños Formation, at San Rafael Block, Mendoza Province, Argentina. The fossil plants comprise non-forked and forked axes without or with delicate lateral expansions, which are assigned to *Bowerophylloides cf. mendozaensis* and *Hostinella* sp. We refer them to primitive land plants and discuss about their systematic affiliation. Furthermore, we mention the presence of a diverse acritarch assemblage present in the same lithostratigraphic unit. On the basis of the taxonomical information and stratigraphic correlation, we could infer that Río Seco de

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los Castaños Formation has an Early Devonian age. The taphonomical conditions of this fossil association would indicate that the plants were transported some distance from their presumed coastal and riverbank habitats. Finally, studying the amount and the percentage of kaolinite within charcoal levels, warm to cool temperate paleoclimatic conditions were deduced.

Keywords Vascular plants · Microfossils · Lower Devonian · San Rafael block · Mendoza

1 Introduction

The main focus of this chapter is the study of the first record of primitive vascular plants from Río Seco de los Castaños Formation (RSC) that is one of the "pre-Carboniferous" units of the San Rafael block (González Díaz 1972, 1981). Based on the stratigraphical and paleontological evidence, the age of this formation is considered between the Late Silurian and Early Devonian. The fossil remains described here were found at Atuel River Creek, where the type section of RSC is located about 12 km NE of El Nihuil town (Fig. 1).

At this outcrop the unit comprises near 600 m of marine siliciclastic sedimentary rocks, mainly green sandstones and grey mudstones (Fig. 2). The fossiliferous stratum with fossil plants is placed 60 cm above a charcoal bed. This charcoal is interbedded with a massive sandstone body, and it is composed of a mixture of silty-quartz, illite-kaolinite clays and amorphous organic matter (Morel et al. 2006; Manassero et al. 2009). In order to study the origin of the charcoal, three kinds of analyses were done: Total Organic Carbon (in ACME Lab, Canada), isotopic deviation of ^{13}C (=δ ^{13}C) in Activation Laboratories LTD, Ontario, Canada and pyrolysis quantification (in GeoLab Sur S.A., Buenos Aires, Argentina).

The sedimentary rocks which contain the fossil plants were interpreted as deposits of suspension and fall out from low density turbidity currents in a distal platform (Manassero et al. 2009). The paleoenvironmental conditions are shallow marine water near the coastline as can be inferred from the taphonomical attributes of the fossil plants. A similar siliciclastic environment has been recognized in the Upper Silurian-Lower Devonian Villavicencio Formation of southern Precordillera (Edwards et al. 2001). However, the RSC unit has two distinctive sedimentological characteristics: conglomerate channels and organic-matter-rich beds.

The plant debris comprises non-forked and forked axes without or with delicate lateral expansions. Sporangia were not preserved in any sample. Although these plants were previously assigned to lycophytes (Morel et al. 2006, 2007), here we discuss their possible filiations and systematic relationships.

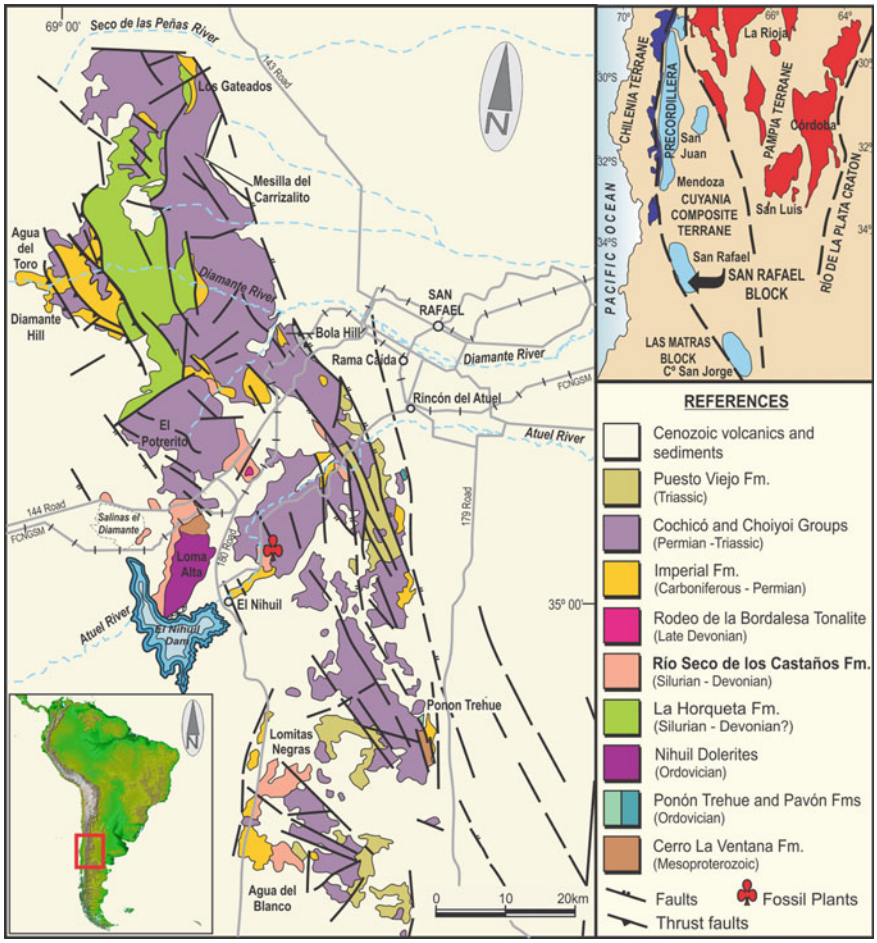

Fig. 1 Geological sketch map of the San Rafael BlockSan Rafael Block, showing the outcrops of the Río Seco de los Castaños Fm. The *red symbol* indicates the fossil plants locality

2 Paleontological Background

The paleontological contributions about RSC are scarce. The first reference corresponds to the coral *Pleurodyctium* sp. by Di Persia (1972) found in Agua del Blanco region, but lacks an original description. Pöthe de Baldis (1999) in an unpublished report has mentioned a palynological association, in the type section of the RSC unit at Atuel creek, and in the same sequence where the plant debris was found. Those palynomorphs have a very high-grade of thermal alteration (<4 of Staplin scale) making the generic assignment relatively difficult. Acritarchs, algae prasinophytes, and probably plant spores were recognized, which are listed below and reproduced in Fig. 3.

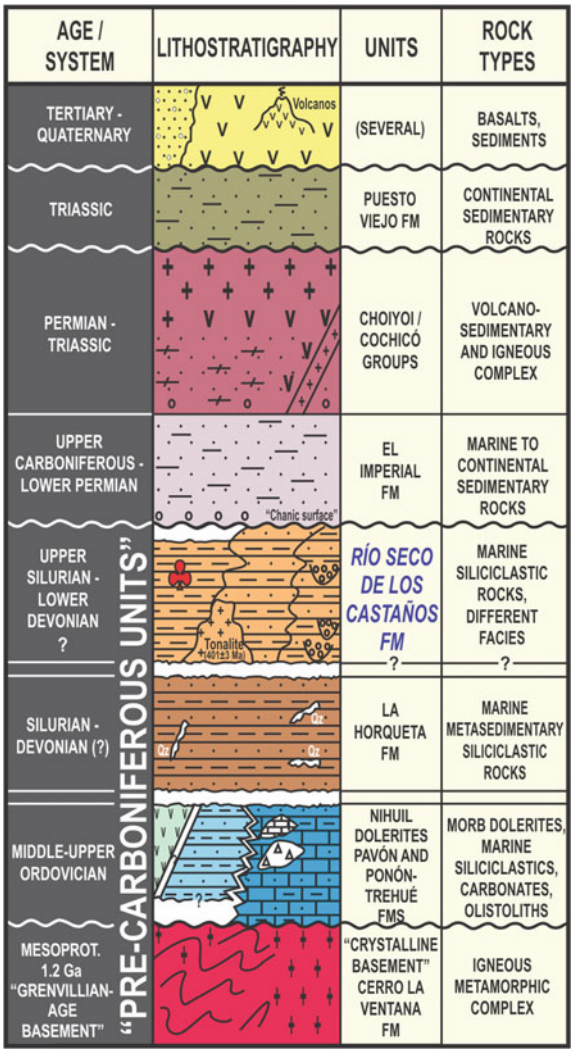

Fig. 2 Stratigraphic column of the San Rafael Block

Acritarcha: *Ammonidium alloiteaui* (Deunff) Deunff, *Ammonidium* cf. *Ammonidium hydraferum* (Stockmans and Williére) Pöthe de Baldis, *Lophosphaeridium* sp., *Micrhystridium* sp. aff. *Micrhystridium stellatum* Deflandre, *Protoleiosphaeridium* sp., *Veryhachium trispinosum* (Eisenack) Stockmans and Williére.
Prasynophyceae: *Veliferites* sp. cf. *Veliferites jachalensis* Pöthe de Baldis, *Cymatiosphera* sp.
Plant spores: *Streelispora*?

Although the palynomorph elements are not diverse, the presence of acritarchs would indicate a shallow marine paleoenvironment, near the coast as it is suggested

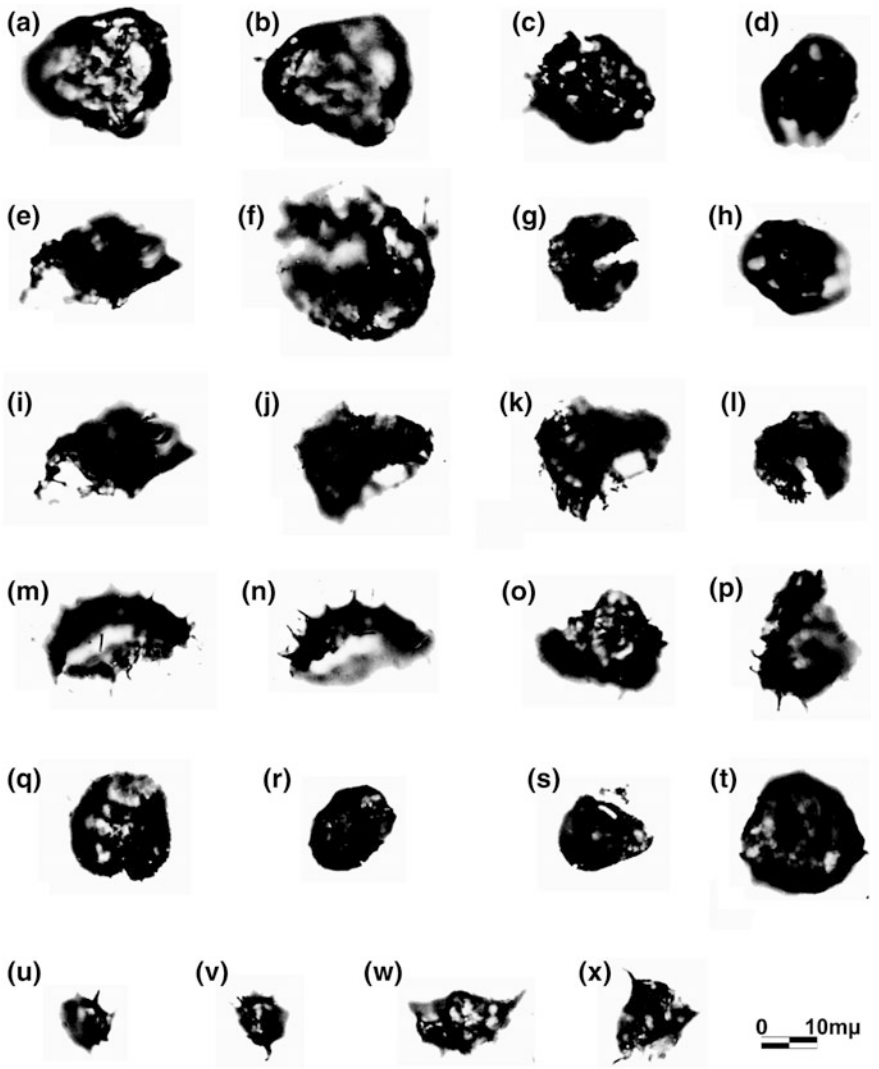

Fig. 3 Microfossil assemblage after Pöthe de Baldis (1999). **a** and **b** *Streelispora* sp.; **c**, **d** and **h** Spores?; **e** and **i** *Veliferites jachalensis*; **f** *Cymatiosphaera* sp.; **g** and **l** Spores?; **j** and **k** *Duvernaysphaera*? sp.; **m** and **n** *Ammonidium* sp. cf. *Ammonidium hydraferum*; **o** and **p** *Ammonidium* sp. cf *Ammonidium alloiteaui*; **q** *Lophosphaeridium* sp.; **r** and **s** *Protoleiosphaeridium* sp., **t** *Micrystridium* sp.; **u** and **v** *Micrystridium* sp. cf. *Micrystridium stellatum*; **w** and **x** *Veryhachium trispinosum*

by the presence of some spores. The presence of *Veliferites* sp. cf. *Veliferites jachalensis* Pöthe de Baldis, would imply a Late Silurian age for this association, since this taxon is known from the Silurian (Ludlow) of the Argentine Precordillera (Los Espejos Formation).

It is important to mention that the palynoflora studied by Rubinstein (1997) from outcrops located near the 144 road at km 702 and assigned to 'La Horqueta Formation' by this author, were afterwards considered as part of the RSC sensu González Díaz (1981) based on sedimentary rock attributes and the presence of the ichnofacies of *Nereites-Mermia* (Cuerda and Cingolani 1998, Poiré et al. 2002 and discussion in Manassero et al. 2009). Rubinstein (1997) described the following Upper Silurian palynoflora:

Ammonidium ludloviense (Lister) Dorning (1981)
Dactylofusa cabotti (Cramer) Fensome et al. (1990)
Dactylofusa striatifera (Cramer) Fensome et al. (1990)
Evittia denticulata denticulata (Cramer) Le Hérissé (1989)
Fimbriaglomerella divisa Loeblich Jr. and Drugg (1968)
Leiofusa estrecha Cramer (1964)
Tylotopalla sp. cf *T. pyramidalis* (Lister) Dorning (1981)
Baltisphaeridium spp.
Leiofusa sp.
Leiosphaeridia spp.
Retisphaeridium sp.
Veryhachium? sp.

This association shares some genera with the assemblage mentioned by Pöthe de Baldis (1999), such as *Ammonidium* and *Veryhachium.*

Poiré et al. (2002) have recognized different ichnogenera in the Agua del Blanco region, as follows, *Arenicolites, Bergaueria, Cochlichnus, Cruziana, Gordia, Mammlichnus, Palaeophycus, Phycodes, Rusophycus and Teichichnus*. This ichnofacies represents a well oxygenated environment and it is interpreted as a proximal to shallow marine platform, with dominance of subtidal environment. The trace fossils are developed in soft substrates of moderate energy (Manassero et al. 2009). On the other hand, Pazos et al. (2013) documented the ichnogenera on the 144 road (km 702) locality that contains dominantly *Nereites irregularis* Schafhäutl, *Helminthopsis* and less abundant arthropod trackways and grazing traces. Microbial mats are very abundant but clearly not related to *Nereites*. At the Atuel creek locality *Nereites* is also the most abundant ichnofossil but it contains more than one ichnospecies: *Nereites irregularis* and one beautifully preserved specimen of *Nereites cambrensis* Murchinson, the type ichnospecies of the ichnogenus. Other specimens are assignable to the questionable *Nereites delpeyi* Borrouilh, a dubious valid ichnospecies that probably is a junior synonym of *Nereites missouriensis* Weller. Other well preserved trace fossil is *Dictyodora* in upper relief expressions. This ichnogenus (Poiré et al. 1998; Pazos et al. 2013, 2015) contains several ichnospecies, with an apparently ichnostratigraphic value. At the Atuel creek RSC outcrop the ichnogenera *Dictyodora* Weiss is recorded. The ichnospecies recognised include *Dictyodora scotica* and *Dictyodora tenuis*, and a new ichnospecies, *Dictyodora atuelica*. The succession studied by Pazos et al. (2015) contains abundant microbial mats (wrinkle marks), either as extended surfaces or patches.

3 Paleobotany

Division Tracheophyta

Incertae Sedis
Genus ***Bowerophylloides*** Edwards et al. (2001)
Bowerophylloides* cf. *mendozaensis Edwards et al. (2001) (Fig. 4a–f)

Description Impression of delicate herbaceous stem fragments, with dichotomizing sterile axes covered by crowded narrow enations, in spiral arrangement. The bases of enations are fusiform when axes are defoliated. The fossil plants present stems with enations and unbranched axes with irregularly shaped patches. Description is based on 7 fragments, all of which bear enations showing varying degree of fragmentation. No anatomical details have been preserved. Branching is

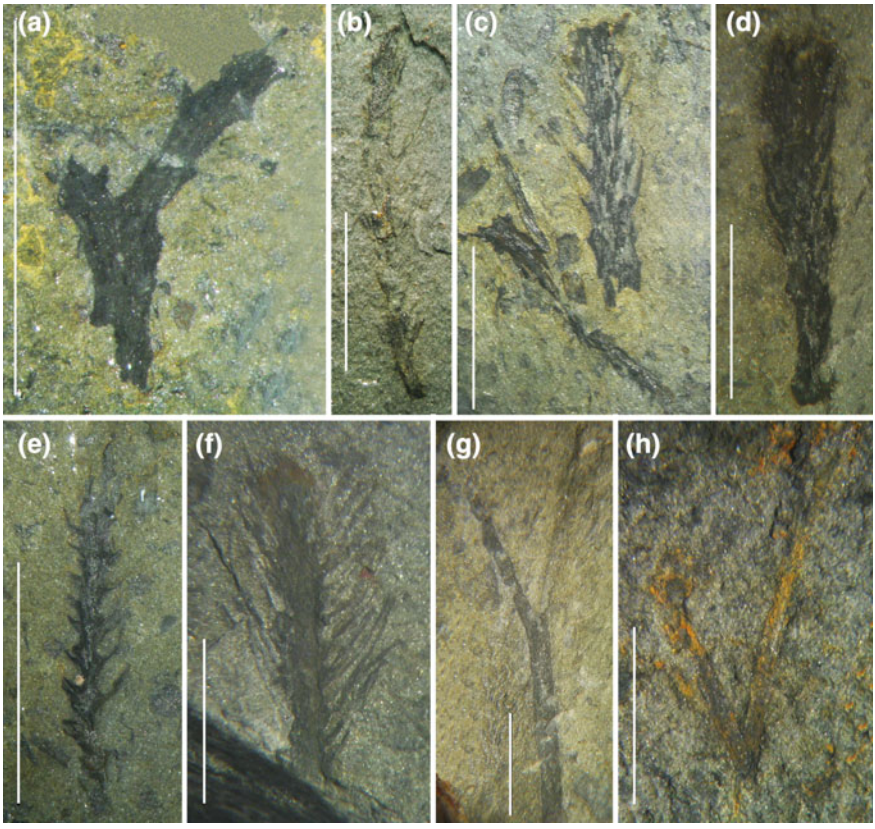

Fig. 4 **a–f** *Bowerophylloides* cf. *mendozaensis* Edwards et al. (2001). **a** LPPB 13814b. **b** LPPB 13816b. **c** LPPB 13817a. **d** LPPB 13829a. **e** LPPB 13818a. **f** LPPB 13830. **g–h** *Hostinella* sp. **g** LPPB 13831. **h** LPPB 13832. *Scale bar* 0.5 cm

isotomic-dichotomous (in one specimen: LPPB 13814). The largest specimen reaches 10.7 mm. Stem width (excluding enations) ranges from 0.5 to 1.3 mm. Enations in profile attached to the sides of the stem show swollen decurrent bases extending into linear structures that are straight or distally slightly curved. They are inserted at 45–50° angles to the stem. The regular spacing between these enations suggests a regular phyllotaxis, which can be defined as spiral. The bases of enations are subcircular to fusiform in outline, have a central prominence, and range from 0.1 to 0.3 mm wide and 0.2 to 0.3 mm long. The shape of the free distal part of the enations, are probably linear to slightly spatulate (LPPB 13816). Enations show no evidence for a central trace.

Comparisons This material is assigned to *Bowerophylloides mendozaensis* Edwards et al. (2001), because of morphological similarities to material from Villavicencio Formation (Mendoza province; *cf.* Edwards et al. 2001). The specimens described above have sterile axes covered by narrow, elongate projections (enations), directed towards the apex, truncated in the apex, with a maximum length of 0.31 cm and a maximum width of 0.03 cm near the base. Every dimension of these samples agrees with the original material described by Edwards et al. (2001) (Table 1).

This type material of *Bowerophylloides mendozaensis* Edwards et al. (2001) had been originally assigned to *Baragwanathia* (Cuerda et al. 1987). Such identification was rejected because (1) there is little direct morphological similarity with Australian *Baragwanathia* with its elongate flexuous leaves (*e.g.* Lang and Cookson 1935), and (2) there is no anatomical evidence of microphylls.

In RSC samples, it is also impossible to confirm the vascular status of the enations, viz. whether or not they are microphylls, with obvious consequences for unequivocal identification of these fossils as the leafy shoots of lycophytes

Table 1 Comparative table of the RSC plant specimens and type material of *Bowerophylloides*

LPPB	13816a	13818a	13817a	13814b	13822a	13819	13829	13830	*Bowerophylloides* (Edwards et al. 2001)
Axis length above	9.3	7.5	6.9	5.3	7.1	5.0	10.7	9.95	$(3 = n) \times 2.6 + 2.7$ below and above
Axis width	0.5	0.5	1.0	0.9	0.6	0.35	1.26	0.8	1.35 − 1.9 $(4 = n) \times 0.6$ above dichotomy
Enation length	3.1	1.0	0.9	–	0.9	1.5	2.63	4.6–4.4	<2.0 But probably greater
E. basal width	0.3	0.1	0.16	–	0.5	0.3			0.19–0.32
E. basal length	–	–	0.2	0.3			0.57	0.42–0.55	0.27–1.8
"Lamina" width							0.14	0.17–0.22	0.14–0.30
Insertion angle	45–50°	40–45	45–50°		50°	45–50°	40–47°	40–45°	20–35° distally—c50° proximaly

Therefore, the assignation to *Bowerophylloides*, a genus belonging to primitive *incertae sedis* vascular plants, is supported by the following features: (1) *Bowerophylloides* has longer and wider axes but dimensions of the enations are comparable, *i.e*. they fall within the range of the *Bowerophylloides* material, (2) in neither of them is possible to determine a phyllotaxy, but regularity of spacing of emergences in profile, together with the shape of enation bases in face view, suggests a spiral phyllotaxy, (3) angles of insertion of RSC material match with those of the *Bowerophylloides* type specimen, and (4) the material certainly fits the generic diagnosis of *Bowerophylloides*, although spatulate leaves would be needed to allow precise specific identification.

Genus ***Hostinella*** Barrande ex Stur 1882
***Hostinella* sp.** (Figure 4g, h)

Description Fragments of axes with dichotomous isotomous branching, usually with little change in diameter of the daughter branches. The axes are branched only once. Some specimens show evidence of central strand (LPPB 13832). The fragments reach 28.1 mm of length, and a width of 0.6–1 mm before dichotomy and 0.6–0.8 mm above dichotomy.

Studied material: LPPB 13831, 13832.

Comparisons Isotomously branching axes are traditionally referred to genus *Hostinella.* This taxon had been used for a variety of naked axes with dichotomous or pseudomonopodial branching with occasionally, bud-like protuberances in the upper angle of the dichotomy (Gensel and Andrews 1984). This genus has not great significance as biological entities, thus the RSC samples cannot be assigned to any group of vascular plants.

4 Discussion

Taphonomical considerations
The plant assemblage presents a low diversity and high fragmentation of the specimens. This can be explained by taphonomical conditions, since the plant debris were preserved in heterolithic siltstone/sandstone strata, inferred as fair weathered deposits in a subtidal coastal environment on a shallow shelf. The plants would have been transported some distance from their presumed coastal and riverbank habitats, for which we have no direct information (Poiré and Morel 1996; Edwards et al. 2009).

Systematic considerations

Despite that *Bowerophylloides mendozaensis* was considered as an enigmatic "leafy" shoot taxon (Edwards et al. 2001), some characters present in the genus confirm that it belongs to a primitive vascular plant. Particularly the enations show evidence of a regular phyllotaxy which can be defined as spiral, and they have a swollen basis that remains attached to the axis. These characteristics could link this taxon to the lycophyte lineage (*cf.* Kenrick and Crane 1997).

Correlations

The low diversity and high fragmentation of this plant assemblage makes difficult the correlation with other coeval paleofloras. The occurrence of *Bowerophylloides*, present in Lower Devonian Villavicencio Formation, would suggest a similar age for RSC fossil assemblage. The microflora of Villacencio Formation (Rubinstein 1993) shows abundant spores and only three species of acritarchs, *Veryachium* cf. *downiei* Stockmans and Willière, *Veryachium* cf. *lairdi* Deunff, and *Micrhystridium* sp. These genera are also present in RSC Formation (see Paleontological background). Even though the biochrons of these acritarch taxa are extended, their presence is another element for correlation.

Charcoal level

The Total Organic Carbon analysis gave a value of 1.08%, which represent an important proportion. The isotopic deviation of ^{13}C (= $\delta\ ^{13}C$) analysis showed a value of −26.3‰. Such a deviation is an average amount of the land vegetation, since the land plants are classified in two main groups: C3 and C4, according to their metabolic photosynthetic mechanism. The 85% of the vascular plants are of C3 type, and show very low values of $\delta\ ^{13}C$, between −22 and −30‰. The plants that generated the charcoal level here analysed are comprised into the last mentioned interval of $\delta\ ^{13}C$ values. Otherwise, the values of C4 plants range between −10 and −14‰, much higher that the amounts obtained in this work. C4 plants correspond to the 15% of land plant and mainly comprise tropical herbs. The pyrolysis quantification analysis is shown in Table 2.

Table 2 Pyrolysis quantification data of the charcoal sample 05CA2

Lab record	Sample	TOC	*S*1	*S*2	*S*3	*T* °C	*S*1/TOC	*S*3/TOC	*S*1/*S*1 + *S*2
			mg/g					O index	Productivity index
LC-07-005	05CA2	0.37	0.01	0	0.29	274 °C	3	78	1

These data indicate severe maturity for charcoal material. The charcoal amount and the record of kaolinite in this bed could indicate, following the paleogeographic reconstruction of Scotese et al. (1999), that the paleoclimatic conditions were warm to cool temperate.

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