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The *Normalograptus persculptus* Biozone in the Eusebio Ayala Formation: A new Hirnantian-Llandovery sequence with graptolites and trilobites in the Paraná Basin of Eastern Paraguay

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ABSTRACT

In this contribution we report a low diversity graptolite-trilobite fauna from the Eusebio Ayala Formation (Itacurubí Group) exposed at the intracratonic Paraná Basin of eastern Paraguay. Analyzed sections are composed dominantly of red micaceous mudstones with intercalations of purple sandstones located about 60 km east of Asunción City. Shelly faunas such as brachiopods, bivalves, gastropods and cephalopods are abundant at many exposures. The graptolites *Normalograptus persculptus* (Elles and Wood), *Normalograptus normalis* (Lapworth) and *Normalograptus medius* (Törnquist), and the dalmanitid trilobite *Mucronaspis* sp. are described herein. Since these taxa are characteristic elements of the *N. persculptus* Biozone, the successions studied are assigned to the Hirnantian-Llandovery transition. The Eusebio Ayala Formation is correlated with coeval, postglacial units of South America and Africa in southwestern Gondwana, and the palaeobiogeographical implications of its faunas are discussed.

Keywords: Graptolites; Trilobites, Paraná Basin of Eastern Paraguay; Eusebio Ayala Formation; *Normalograptus persculptus* Biozone; Hirnantian-Llandovery transition.

INTRODUCTION

The Lower Palaeozoic Itacurubí Group (Harrington, 1972) is exposed along the western border of the intracratonic Paraná Basin of eastern Paraguay and comprises, from base to top, the siliciclastic Eusebio Ayala, Vargas Peña, and Cariy Formations. This *c.* 350-m-thick sequence was traditionally assigned to the Llandovery (*e.g.* Harrington, 1950; Wolfart, 1961; Dyck, 1991; Benedetto *et al.*, 1992; 2002; Galeano Inchausti and Poiré, 2006; Uriz *et al.*, 2008a, b and references therein) on the basis of its abundant marine fossil record (graptolites, trilobites, brachiopods, bivalves, gastropods, nautiloids, tentaculitids, crinoids, ichnofossils). In addition, Llandovery palynofacies assemblages dominated by acritarchs, chitinozoans and miospores were described by Steemans and Pereira (2002).

On a global scale, Ordovician pelagic graptolites expanded in abundance and species diversity during the Katian Stage but they were affected by a dramatic extinction episode in the Hirnantian Stage (Melchin and Mitchell, 1991; Melchin *et al*., 1998). A model explaining the influence of ecological factors on graptolite extinction and diversification during the latest Ordovician mass extinction event was discussed by Finney *et al*. (2007). After Hirnantian crisis, taxonomic diversity increased rapidly from

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a low number of species in the *N. persculptus* Biozone to about 60 species in the *Normalograptus acuminatus* Biozone.

The objective of the present contribution is to describe new graptolites and trilobites from classic localities of the Eusebio Ayala Formation that proved to be assignable to the *Normalograptus persculptus* Biozone. Because the Ordovician-Silurian boundary interval represents a time slice with relevant palaeoclimatic and evolutive implications (Cocks, 1985; 2001), the sections studied are compared with coeval, postglacial units of southwestern Gondwana and the palaeobiogeographic significance of their faunas is discussed.

(FIGURE 1)

GEOLOGICAL SETTING AND STRATIGRAPHY

The South American Paraná Basin extends from the Asunción arch as a western boundary near the Paraguay River, to the south and southeast of Brazil, the central region of Uruguay, and northeastern Argentina. The geological evolution of this intracratonic basin was influenced by the geodynamics of southwestern Gondwana, with compressional stresses derived from an active convergent margin (Milani and de Wit, 2007). During the Late Ordovician–Lower Devonian, the basin was filled by continuous and thick siliciclastic sequences. In eastern Paraguay, a major extensive tectonic event controlled by NW-trending faults ('Asunción rift') took place during post-Palaeozoic times, developing a conspicuous morphologic graben structure (Ypacaraí graben) (Figure 1). The subsidence of blocks has led to depocenters within the western border of the Paraná Basin, as well as the distribution of younger sedimentary facies. This distensive structural process exposed the Palaeozoic sedimentary sequences, and partially its Precambrian basement. The Ypacaraí graben has a general orientation NW-SE and bears a well known rift-related alkaline magmatism. The pre-Carboniferous units are widely exposed along the south-western edge of the graben, constituting a sub-horizontal cratonic sedimentary sequence that overlies Precambrian rocks. The Ordovician *c*. 700-m-thick Caacupé Group (Harrington, 1972) is the basal sedimentary unit, which includes, in ascending order, the Paraguarí, Cerro Jhú and Tobatí Formations, and is composed of conglomerates and coarse-grained sandstones that culminate with tillite deposits linked to the Upper Ordovician glacial event. The Itacurubí Group (Harrington, 1950; 1972), mainly of Early Silurian age, overlies these glacial deposits and is composed of the Eusebio Ayala, Vargas Peña, and Cariy Formations (Figure 2). It represents a complete transgressive-regressive cycle, in which the sandstones of the Eusebio Ayala Formation mark the base of the series. In the study area, the Itacurubí Group is locally covered by either Cretaceous-Tertiary rocks (Asunción Group) or Quaternary alluvial deposits.

(FIGURE 2)

The *c*. 5-7-m-thick Eusebio Ayala Formation is composed of yellowish, brownish, reddish to purple micaceous sandstones with intercalated mudstone-siltstone beds and ferruginous levels. The sandstones are laminated, and wave-cross stratifications are frequent. Reddish fine sandstone levels bearing fossils have stratigraphical surfaces plenty of detrital micas (see a petrographic detail in Figure 3). Clasts are subrounded, with moderate sorting. Sedimentary rock fragments (microcrystalline chert) are present and secondary hematite cement is widespread, filling available porosity. Mudstones and siltstones show bioturbation rates and wavy-linsen structures. The Eusebio Ayala

Formation contains invertebrate fossils that developed in a shallow marine environment at the beginning of the latest Ordovician-early Silurian flooding event (Milani and de Wit, 2007).

FIGURE 3

PALAEOBIOLOGICAL CONTENT

New graptolite faunas from the Eusebio Ayala Formation were found in a series of clay quarries (Santa Elena, 25º23'27" S-57º18'54"W; Galeano, 25º23'33"S-57º18'22"W; Western Itauguá, 25º22'25"S-57º20'08"W) around Itauguá city, about 60 km east of Asunción, where the 'Asunción rift' defines the western border of the Paraná Basin. In addition, a trilobite assemblage was collected from the type locality of the formation near Eusebio Ayala city (Figure 1). General orientations of the strata range from N139º to 145º, dipping 12º to 32ºSE. The base of the formation is not exposed in the sections studied but diamictite deposits have been reported in drill holes from the Santa Elena area (see below). The Eusebio Ayala unit is overlain by a transgressive surface characterized by the presence of iron rich levels. The stratigraphic positions of all specimens described herein were assessed after Uriz *et al.* (2008a, b) and Alfaro *et al.* (2010) based on lithostratigraphic correlation. Graptolites show a low diversity, being *Normalograptus persculptus* (Elles and Wood), *Normalograptus normalis* (Lapworth) and *Normalograptus medius* (Törnquist) the most dominant forms. Similarly, trilobites are scarce and restricted to *Mucronaspis* sp. (Dalmanitidae) from the Eusebio Ayala locality and two incomplete and poorly preserved homalonotid pygidia (not figured). Associated shelly faunas (bivalves, gastropods) are currently under study.

SYSTEMATIC PALAEONTOLOGY

The specimens documented herein are deposited in the Department of Invertebrate Palaeontology at the Museum of La Plata (MLP), Argentina. MLP 32916 to 32964. Graptolites were studied under alcohol or glycerin with a binocular microscope. Trilobites were whitened with magnesium oxide prior to photography.

a. Graptolites

Family NORMALOGRAPTIDAE Štorch and Serpagli, 1993
Genus NORMALOGRAPTUS Legrand, 1987
Normalograptus persculptus (Elles and Wood, 1907)
(Figure 4, a-s; Figure 6, a-k)

1865 *Diplograptus persculptus* (Salter), Salter, p. 25 (see Strachan 1971).
1866 *Diplograptus (Glyptograptus) persculptus* Salter; Elles and Wood, p. 257, pl. 31, fig. 7a–c; text-fig. 176a–b.
1929 *Glyptograptus aff. persculptus* Salter; Davies, p. 10, text-fig. 11A. p.
1929 *Glyptograptus persculptus* mut.; Davies, p. 11, text-figs 11, 13, 16–18 [non text-figs 12, 14, 19? (= *N. parvulus* (H. Lapworth))].
1929 *Glyptograptus persculptus* mut. omega, Davies, text-figs 15, 20.
1930 *Glyptograptus bohemicus* Marek, p. 7, pl. 1, figs 1–4.
1975 *Glyptograptus persculptus* (Salter); Bjerreskov, p. 30, text-fig. 11a–c.
1977 *Glyptograptus persculptus* (Salter); Rickards *et al.* pl. 2, fig. 4; text-figs 8, 53.
1980 *Glyptograptus? persculptus* (Salter) forma B; Koren' (in Apollonov *et al.*. 1980), p. 150, pl. 45, figs 1–6; pl. 46, figs 1–6; text-fig. 45a–zh.
1983 *Glyptograptus persculptus* (Salter); Williams, p. 622, pl. 66, figs 1–3.

1983 *Glyptograptus cf. persculptus* (Salter); Mu and Ni, p. 162, pl. 1, fig. 12; text-fig. 4a.

1983 *Glyptograptus persculptus* (Salter); Koren' *et al.* p. 144, pl. 42, figs 4–10; pl. 43, figs 1–6; text-fig. 54.

1984 *Glyptograptus persculptus* (Salter); Chen and Lin, p. 193, pl. 1, figs 1–6; pl. 2, figs 3–9; text-fig. 1.

1984 *Glyptograptus persculptus* (Salter); Lin and Chen, pl. 1, figs 1–2.

1984 *Glyptograptus? persculptus* (Salter); VandenBerg *et al.*., p. 10, figs 8–9.

1994 *Normalograptus? persculptus* (Elles and Wood); Zalasiewicz and Tunnicliff, p. 704, fig. 5a–c.

1996 *Normalograptus persculptus* (Elles and Wood); Štorch and Loydell, p. 872, text-figs 3–5.

1998 *Normalograptus persculptus* s.l. (Elles and Wood); Underwood *et al.* p. 103, fig. 5S?, U [non fig. 5T, V, W?(= *N. parvulus* (H. Lapworth 1990)].

Material

Forty-eight well preserved specimens. Most rhabdosomes are raised and fully or partially replaced by iron oxides, which give them reddish or blackish colors. Specimens replaced by iron oxides retain fine morphological details (*e.g.* medium septum inclusion). Only two specimens are complete; most colonies are represented only by proximal, medium or distal fragments.

Description

Complete rhabdosomes have a length of 18 - 24.5 mm and a width of 0.8 - 1.1 mm at the first thecal pair. Their width increases to 1.4 - 1.5 mm (in relief colonies) and 1.9 mm (in flattened specimens) in the initial 5 mm (maximum distal width). The sicula adopts a conical shape; it is in relief, with a length of 0.5 - 0.9 mm on the obverse side of the colony. The diameter of the sicular aperture is 0.20 mm. The Th11 grows below the sicular aperture and then bends sharply upward, while the Th12 grows up along its length, giving an asymmetrical appearance to the proximal end of the colony. Thecae have a length of 0.9 - 1.9 mm, being the most common range from 1.3 to 1.4 mm. Thecal excavations occupy a quarter of the width of the rahbdosome in flattened specimens, and a third in relief colonies; they present a double sigmoidal curvature and an overlap of half the thecal length. Supragenicular walls are straight or slightly inclined to the central axis of the colony. Proximal thecae are 9 - 14 in 10 mm and distal thecae are 9 - 11 in 10 mm. The medium septum is markedly undulating proximally, becoming straight distally. Two specimens have a nema with a maximum length of 4.7 mm.

Discussion

The forms described above resemble those of *Normalograptus persculptus* according to Elles and Wood (1907; 1918) in the general appearance of the rhabdosome, although the former slightly differ in having a somewhat thinner exoskeleton and a wider thecal spacing. Davies (1929) alluded to the high degree of morphometric variation produced by these morphologically similar forms. Recently, Blackett *et al.* (2009) defined four graptolite morphospecies by morphometric analysis of numerous specimens from the *persculptus* and *acuminatus* Biozones of Wales. On the other hand, Koren and Rickards (1996) proposed the monotype genus *Persculptograptus* regarding "*Glyptograptus persculptus*" as its type species, which is characterized by having thecae with a double sigmoidal curvature and a corrugated medium septum. Although the material collected from the Eusebio Ayala Formation does not seem to include well defined morphotypes, the largest specimens are consistent with the basic morphology of materials described by Elles and Wood (1907) and Koren and Rickards (1996). Morphological variability of Upper Ordovician graptolites have been largely discussed in the literature (*e.g.* Legrand,

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1996; Underwood *et al*., 1998; Koren and Bjerreskov, 1999). According to some authors, *N. persculptus s.s*. is restricted to its eponymous biozone (Upper Hirnantian) (Melchin *et al*., 2003), whereas Chen *et al*. (2005) consider that *N. persculptus* ranges from the Upper Hirnantian to the Lower Rhuddanian. As discussed by Delabroye and Vecoli (2010), the *Normalograptus* vs. *Persculptograptus* synonymy is still a matter of debate.

In southwestern Gondwana, *Normalograptus persculptus* (Elles and Wood) was described from the Hirnantian Stage of different localities of the Argentinian Precordillera (Levy and Nullo, 1974; Cuerda *et al.,* 1988a, b; Peralta and Baldis, 1990; Astini and Benedetto, 1992; Brussa *et al*., 1999; Peralta and Finney, 2002). The *N. persculptus* Biozone is well represented in the Don Braulio Formation (Villicum range, Eastern Precordillera; Peralta and Baldis, 1990; Peralta and Carter, 1999), the Talacasto area at the base of the La Chilca Formation (Central Precordillera; Cuerda *et al*., 1988b), and the Rio Escondido section (Cerro del Fuerte; Benedetto, 1986; Rickards *et al*., 1996).

(FIGURE 4)

Normalograptus normalis (Lapworth, 1877)
(Figure 5, h-p)

1877 *Climacograptus scalaris* var. *normalis* Lapworth, p. 138, pl. 6, fig. 31.
1906 *Climacograptus scalaris* var. *normalis* Lapworth; Elles and Wood, p. 186, pl. 26, fig. 2a–g; text-fig. 119a–d.
1929 *Climacograptus scalaris* var. *normalis* Lapworth; Davies, figs 28, 31.
1934 *Climacograptus scalaris* var. *normalis* Lapworth; Hsü,p. 60, pl. 4, fig. 8a–i.
1948 *Climacograptus scalaris* var. *normalis* Lapworth; Waern, p. 449, fig. 5, pl. 26, fig. 1.
1952 *Climacograptus scalaris normalis* Lapworth; Münch, p. 50, fig. 5a–b.
1965 *Climacograptus scalaris normalis* Lapworth; Stein, p. 157, pl. 14, fig. C; text-figs 13i, 14a–e.
1970 *Climacograptus normalis* Lapworth; Rickards, p. 28, pl. 1, figs 1, 7–8; text-fig. 13, figs 7–8.
1974 *Climacograptus normalis* Lapworth; Hutt, p. 19, pl. 1, figs 8–9; pl. 2, figs 1–4.
1983 *Climacograptus normalis* Lapworth; Mu and Ni, p. 168, pl. 2, fig. 5.
1983 *Climacograptus normalis* Lapworth; Williams, p. 611, text-figs 3a–e, 4a–e, 7g.
1983 *Climacograptus normalis* Lapworth; Koren' *et al*.., p. 133, pl. 37, figs 1–6, 11; pl. 38, figs 1–5; text-fig. 48.
1984 *Climacograptus normalis* Lapworth; Chen, p. 40, pl. 2, figs 15–16; pl. 3, fig. 1; text-fig. 3i.
1993 *Normalograptus normalis* (Lapworth); Štorch and Serpagli, p. 23, pl. 1, figs 3, 7?, 8; pl. 2, fig. 5; pl. 5, fig. 8; text-fig. 71m?, n.
1994 *Normalograptus normalis* (Lapworth); Zalasiewicz and Tunnicliff, text-fig. 6o.
2000 *Normalograptus normalis* (Lapworth); Koren' and Melchin, p. 1101, fig. 7.14.

Material

Twenty-four poorly preserved specimens were collected in association with *Normalograptus persculptus*. They are conserved in total or partial relief, replaced by iron oxides. Only two colonies are complete, whereas other specimens are represented by biserial or proximal ends.

Description

Specimens studied reach a maximum length of 15 mm. Most colonies preserve their proximal portion. The width is 0.8 to 1.1 mm at the first pair of libraries, widening to 1.2-1.6 mm distally. The sicula has a length of 1.1 to 1.3 mm. The virguella is not preserved in most of the colonies. The proximal end of the rhabdosome shows a typical

normalograptid pattern, which gives an asymmetric appearance to this part of the colony. Alternating thecae are like those of the climacograptids, with an acute geniculum, straight supragenicular walls parallel to rhabdosomal axis, and deep semicircular openings occupying 1 / 3 - 1 / 4 the width of the rhabdosoma. Proximal thecae are 13-15 in 10 mm, decreasing to 12 distally. One specimen preserves a full medium septum, with a nema up to 2 mm in length.

Discussion

Specimens from the Eusebio Ayala Formation agree fairly well with material from Great Britain described by Hutt (1974) and Rickards (1970), except that the Paraguayan colonies have a higher thecal concentration. Rickards *et al.* (1996) described very similar specimens from the Ordovician Silurian boundary interval of the Argentinian Precordillera. Similarly, Cuerda *et al.* (1988a, b) described *Normalograptus normalis* from the *N. persculptus - Atavograptus atavus* Zones of Talacasto, San Juan, Argentina, and Chen *et al.* (2005) reported it from the *Normalograptus persculptus* Biozone (Lungmachi Formation) of China.

<center>

Normalograptus medius (Törnquist, 1897)
(Figure 4, a-g; Figure 6, l)

</center>

1897 *Climacograptus medius* Törnquist, p. 7, pl. 1, figs 9–15.
1906 *Climacograptus medius* Törnquist; Elles and Wood, p. 189, pl. 26, fig. 4a–f; text-fig. 122a-c
1970 *Climacograptus medius* Törnquist; Rickards, p. 30, pl. 1, fig. 2.
1974 *Climacograptus medius* Törnquist; Hutt, p. 19, pl. 1, fig. 3.
1975 *Climacograptus medius* Törnquist; Bjerreskov, p. 24, text-fig. 9c.
1983 *Climacograptus medius* Törnquist; Williams, p. 616, text-fig. 5f–i.
1984 *Climacograptus medius brevicaudatus* Churkin and Carter; Lin and Chen, p. 212, pl. 4, figs 1–2.
1993 *Normalograptus medius* (Törnquist, 1897); Štorch and Serpagli, p. 23, pl. 5, figs 1, 7; text-fig. 7D, O.
1998 *Normalograptus medius* (Törnquist, 1897); Underwood *et al.*, fig. 5J.

Material

Eleven poorly preserved specimens of this species were recognized in the Eusebio Ayala Formation. They are replaced by iron oxides and preserved in partial relief or flattened. Only four colonies are complete.

Description

Rhabdosomes are between 10 and 18.5 mm long. The proximal width varies from 0.8 to 1.2 mm, widening to 1.6 to 2 mm in medial-distal levels, reaching a maximum width of 2.1 mm. The proximal end is typically rounded and asymmetrical. Thecae are of climacograptid type, with a sharp geniculum, straight and short supragenicular walls 0.50 to 0.70 mm in length, and deep aperture excavations occupying 1/3 the width of the rhabdosome. Thecae concentration is 14 in 10 mm at the proximal end of the rhabdosome, decreasing to 12 mm distally.

Discussion

These specimens conform with the concept of *Normalograptus medius* in rhabdosome dimensions, thecal concentration, and shape of the proximal thecae (see descriptions of

Rickards, 1970; Hutt, 1974; Štorch and Feist, 2008)**,** and partially agree with specimens from the *N. persculptus* Biozone of China described by Chen *et al.* (2006).

In southwestern Gondwana, Rickards *et al.* (1996) described very similar specimens from Cerro del Fuerte region (Precordillera of San Juan, Argentina). Cuerda *et al.* (1988a) also mentioned this form in the *N. persculptus* and *atavus* Biozones of the Talacasto Creek (San Juan, Argentina).

(FIGURE 5)

(FIGURE 6)

b. Trilobites

Family DALMANITIDAE Vodges, 1890
Subfamily MUCRONASPIDINAE Holloway, 1981
Genus MUCRONASPIS Destombes, 1963
Mucronaspis sp.
(Figure 7, a-h)

Material

Four fragmentary cephala, 1 incomplete thorax, 2 thorax-pygidia and 6 pygidia. Some specimens show indications of distortion.

Description

Cranidium slightly convex, with rounded anterior margin. Glabella large, moderately elevated above genal region, well defined by narrow and gentle impressed axial furrows, expanding weakly between S1 furrow and anterior end of palpebral lobe and strongly thereafter, broadly rounded anteriorly; occipital ring decreases in length adaxially; occipital furrow transverse, deepest at sides and shallow on midline; lateral glabellar furrows disconnected at middle, in contact with axial furrows; S1 and S2 furrows narrow, almost normal to axis; L1 lobe as long as L2; S3 furrow oblique, wide, quite deeply impressed, expanding adaxially; L3 shorter (ax.) than L2 at inner margin, expanding (exsag.) adaxially; inner ends of glabellar furrows joined by a very faint longitudinal furrow; frontal lobe large, subrhombic in outline, more than half the length of the glabella. Palpebral lobe semicircular, about 0.4 length of cranidium, extended between S3 and S1 furrow.

Thorax with 10 segments; axis slightly tapering backwards, width about 0.3 of total width of thorax; pleurae with oblique furrow, ending in spines curved backwards; on more posterior segments pleural tips turned progressively more strongly backwards and spines increase in length.

Pygidium subtriangular-parabolic in outline, 1.5 times as wide as long (sag., excluding mucro), moderately convex. Axis narrow, tapering backwards, with ?9 visible axial rings, delimited by narrow axial furrows; axial rings not defined on the posteriormost part of the axis that merges with a mucro; pleural fields only slightly downsloping, with 7 pairs of conspicuous pleural and interpleural furrows of similar depth; these furrows are oblique and strongly flexed backwards distally; border furrow absent; border very narrow, fairly flat to concave; lateral margin entire; posterior mucro subcircular in cross-section (partially preserved).

Discussion

The dalmanitid described above bears deep pleural and interpleural furrows on the pygidium, with their distal parts strongly flexed backwards. In addition, the posterior segments of the thorax are characterized by having prominent and strongly turned backwards pleural spines. Such characters are diagnostic of the Subfamily Mucronaspidinae (see Holloway, 1981). Although the specimens examined are fragmentary, the rear part of the pygidium show clear indications of a caudal projection (mucro), pointing out morphological correspondence with *Mucronaspis* Destombes, 1963. This genus is a very common element of the widespread latest Ashgill (Hirnantian) *Hirnantia* shelly fauna, with only punctual occurrences in the post-Ordovician (Cocks and Fortey, 1997). In western Gondwana, the latest Ordovician records include those from South Africa and the Argentinian Precordillera (e.g., see Cocks and Fortey, 1986; Benedetto *et al*., 2009 and references).

The presence of a wide and shallow glabellar furrow S3 distinguishes *Mucronaspis* sp. from the the widespread species *M*. *mucronata* (Brongniart), from the Ashgill of Great Britain, Scandinavia, Poland, Bohemia and southeastern Asia (e.g. Temple, 1952; Kielan, 1959; Ingham, 1977; Owen, 1982; Cocks and Fortey, 1997); from *M*. *sudamericana* (Baldis and Blasco, 1975), from the Hirnantian of the Precordillera of San Juan, Argentina; and from *Mucronaspis itacurubensis* (Baldis and Hansen, 1980), from the Llandovery of eastern Paraguay (see Jell and Adrain, 2003). *Mucronaspis olini* (Temple), from the latest Ordovician of Sweden, Great Britain, Poland and South Africa (e.g. Temple, 1952; Kielan, 1959; Cocks and Fortey, 1986) has, in addition, shorter (exsag.) palpebral lobes.

(FIGURE 7)

IMPLICATIONS OF THE STUDIED FAUNA WITHIN THE ITACURUBI GROUP

As shown in the composite graptolite-trilobite range chart (Figure 8), the Hirnantian-Rhuddanian transition of the upper part of the Eusebio Ayala Formation contains low-diversity graptolites assignable to the *Normalograptus persculptus* Biozone. As noted above, the record of the trilobite *Mucronaspis* sp. provides additional evidence in favor of a latest Ordovician or Ordovician-Silurian transition age. Late in the Early Llandovery, the record of more varied graptolites and the appearance of several trilobite species in the Vargas Peña Formation (Tortello *et al*., 2008 and references therein) mark the incoming of diverse faunas coinciding with the maximum flooding in the lower Palaeozoic Paraná Basin, suggesting that improving environmental conditions favored such biotic radiation. The influx of new taxa probably also indicates the establishment of warmer water conditions in the basin. *C. innotatus brasiliensis*, which appears to be endemic to South America (Underwood *et al*., 1998), was also recorded in the sequence. The distribution of graptolite taxa in the Itacurubí Group shows a succession of distinct faunal events that was also documented in other basins of South America and Africa, reflecting the exceptional environmental changes that took place in southwestern Gondwana during Hirnantian-Llandovery times.

(FIGURE 8)

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DISCUSSION ON PALAEOBIOGEOGRAPHY AND CORRELATION

'The Great Ordovician Biodiversification Event' (see Webby *et al.*, 2004) of marine organisms is the result of the combined effects of several geological and biological processes, linked to the great palaeogeographic continent dispersion during the lower Palaeozoic. Major ecological and evolutionary changes led to the "explosion" of zooplankton organisms, probably favored by an increase of phytoplankton and a great addition of substantial nutrients to the oceans given by intense volcanic activity. These palaeobiogeographic conditions changed at the Late Ordovician (Hirnantian) which led to extensive glaciations and a glacioeustatic sea-level drop in Gondwanan areas. This climate system affected many groups of marine organisms and promoted the extinction (or severe changes) of a significant number of them. Graptolites suffered nearly complete extinction during the Hirnantian Stage, coincident with a sea-level fall. Diverse populations of the Dicranograptidae-Diplograptidae-Orthograptidae (DDO) fauna decreased with a major turnover at this time to only one genus. *Normalograptus* (Finney *et al.*, 2007; Kaljo *et al.*, 2008; Delabroye and Vecoli, 2010) (=*Persculptograptus sensu* Koren' and Rickards, 1996) is known to have passed through the Hirnantian. The post-extinction radiation, with a sea-level rise from Late Ordovician into the Silurian, developed entirely from these normalograptid species (Melchin and Mitchell, 1991). A certain exception is found in the Late Ordovician of the upper Yangtze region, China (Chen *et al.*, 2005), where graptolites show more diversity in contrast to other regions for this interval. Therefore, it is possible an adjusted biostratigraphical analysis of the Hirnantian Stage where two biozones have been recognized: *Normalograptus extraordinarius-Normalograptus ojsuensis* at the base, and *Normalograptus persculptus* towards the top. For these reasons, the new record of normalograptid forms in Paraguay is of particular interest.

In Western Gondwana the existence of diamictites associated with glaciofluvial and glaciomarine sediments denotes the presence of a large field of ice that could have covered most of Africa and South America (Figure 9). Its South Pole would have been located in west-central Africa (Underwood *et al.,* 1998; Cocks, 2001; Ghienne, 2003; Ghienne *et al*., 2007; Legrand, 2009; Benedetto, 2010). The ice-sheet also reached the Ibero-Armorican domain that was still attached to the Gondwana landmass (Gutierrez Marco *et al*., 2010). In South Africa, Late Ordovician glacial deposits are found in the Pakhuis Formation in the Western Cape Fold Belt (Young *et al.,* 2004; Milani and de Wit, 2007). The black shales of the Soom unit have been assigned to the Late Ordovician *persculptus* graptolite Biozone (Vandenbroucke *et al.*, 2009) and are recognized for the exceptional preservation of marine fossils.

In South America, there are evidences of the record of this glacial event in the Central Andean Basin, in the Precordillera region (Cuyania terrane), Amazonas, Parnaíba and Paraná intracratonic Basins. In Peru, Bolivia and northwestern of Argentina, as part of the Central Andean Basin, identification of diamictites and an erosional surface near the Ordovician-Silurian boundary characterizes the setting of glaciogenic environment that would have extended to Silurian times (Benedetto *et al.*, 1992; Díaz-Martínez, 1997; Astini, 2002; Díaz-Martínez and Grahn, 2007). These glaciogenic conditions are recognized in the Late Ordovician levels of the Zapla and in the lowermost levels of the Lipeón Formations (Monaldi and Boso, 1987; Monteros *et al*., 1993; Martínez, 1998) and in southern Bolivia equivalent units (Schönian *et al*., 1999; Schönian and Egenhoff, 2007).

In the Precordillera region, as a part of the Cuyania terrane, of San Juan, Argentina, tillite levels were recorded at the base of the Don Braulio Formation (Astini, 1999;

Peralta and Carter 1999; Astini, 2001). Benedetto (1986) recognized a brachiopod association at the base of this unit referred to the Hirnantia fauna, while Peralta and Baldis (1990) described *N. persculptus* to the top of the sequence, unable to establish the Ordovician-Silurian boundary in the absence of fossils of *P. acuminatus-A. atavus* Biozones. Also in the regions of Talacasto and Cerro del Fuerte-Cerro La Chilca (San Juan) it was possible to define the boundary between both systems by the presence of the *P. acuminatus* and *N. persculptus* Biozones (Astini and Benedetto, 1992; Rickards *et al.*, 1996).

Over the Río de la Plata craton (Tandilia System, Argentina), the presence of a diamictite level was mentioned in the Balcarce Formation. Zimmermann and Spalletti (2009) based on mineralogical provenance studies suggested a possible Hirnantian age for this glacial event. In the Amazonas and Parnaíba intracratonic basins, northeast Brazil, there are potential tillite deposits referring to the Late Ordovician showing a glaciogenic regime (Boucot, 1988).

(FIGURE 9)

For the Western border of the Paraná Basin (Paraguay), in the studied outcrops bearing *N. persculptus*, *N. medius*, *N. normalis* and *Mucronaspis* sp. within the Eusebio Ayala Formation, typical glacial sediments were not found. However, tillites were reported from drill holes at the Santa Elena area (Figueredo *et al.*, 1995, In: González Núñez *et al.*, 1999). At the base of the drill 50 m of tillites were described, covered by 150 m of sandstones with conglomeratic levels and 200 m of fine sandstones with interbedded shales and claystones. Preliminary palynological studies revealed ages of Upper Ordovician-Lower Silurian for the section between 198 and 385 m (Vergel, 1996, In: González Nuñez *et al.*, 1999). In addition, Steemans and Pereira (2002) described an interesting Llandovery palynologic assemblage on three boreholes from the central part of Paraguay. Uriz *et al.* (2008a) also described an association of graptolites collected from the upper levels of the Eusebio Ayala Formation, which would indicate a Rhuddanian age, probably related to the *vesiculosus-cyphus* (Bohemia, Štorch, 1990) or *Atavograptus atavus* Biozones (Rickards, 1976). Another record that proofs the continental glaciation in other sectors of the Paraná Basin is shown in the Ponta Grossa structural arch in the Apucaran sub-basin (Brazil), where the Iapó Formation, as a part of the 'Río Ivaí Supersequence' (Milani and de Wit, 2007), is essentially composed of diamictites that cover large areas with a thickness of less than 20 m. The first Rb-Sr isotopic analysis performed on samples from the matrix of the Iapó unit yielded ages of 456±6.4 Ma (Upper Ordovician), being interpreted as the maximum sedimentation age (Pereira and Bergamaschi, 2007).

The fossiliferous Paraguayan Itacurubí Group could be a sequence for high-resolution stable isotope chemostratigraphy. Such studies may constraint shallow-water environmental changes associated with mass extinction in Western Gondwana, and to correlate the organic-inorganic carbon isotope excursion models known in the Hirnantian-Early Llandovery of other continents such as Baltica, Laurentia, South China and North Gondwana (Melchin *et al.*, 2003; Finney *et al*, 2007).

FINAL REMARKS

a. A low diversity graptofauna consisting of *Normalograptus persculptus*, *Normalograptus normalis* and *Normalograptus medius*, and the trilobite *Mucronaspis* sp. are described from the Eusebio Ayala Formation in the Western sector of the Paraná Basin (Paraguay).

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b. The co-occurrence of the genus *Mucronaspis* and diagnostic graptolites of the *N. persculptus* Biozone allows us to assign the studied stratigraphical levels to the Hirnantian-Llandovery transition interval.

c. These records also permit to compare the Eusebio Ayala Formation with other basins of South America and Africa and to improve the correlation chart of these high-palaeo-latitude areas of Gondwana.

d. The recognition of graptolites and associated shelly faunas from the Ordovician-Silurian boundary interval in a continuous, undisturbed sequence of the intracratonic Paraná Basin may be a target for isotope high-resolution stratigraphical studies.

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FIGURE CAPTIONS

Figure 1: Geological sketch map near Itauguá town based on Dionisi (1999) and location of quarries in which the fauna was collected.

Figure 2: The exposed units (*c.* 10 m thick) of the Itacurubí Group at the Santa Elena quarry showing the base of the *N. persculptus* Biozone section.

Figure 3: a) Type rock of the reddish sandstone levels of the Eusebio Ayala Fm bearing shelly fauna (brachiopods). Note that the stratigraphical surface is plenty of detrital micas. **b)** Photomicrograph (crossed-nicols) of fine grained sandstone with presence of Qz (Quartz), KF (K-Feldspar) and sedimentary rock fragments (chert) as sub-rounded clasts. Flexured detrital muscovites (Mu) in the matrix and secondary hematite (Fe) are abundant. The sandstone shows moderate sorting. The sample was taken near the San Fernando quarry (25º22'27''S-57º19'47''W).

Figure 4 (a-s) Camera Lucida drawings of representative specimens of *Normalograptus persculptus* (Elles and Wood): **a)** MLP 32916a, **b)** MLP 32917, **c)** MLP 32918, **d)** MLP 32919, **e)** MLP 32920, **f)** MLP 32921, **g)** MLP 32922, **h)** MLP 32923, **i)** MLP 32916b, **j)** MLP 32924a, **k)** MLP 32925, **l)** MLP 32926a, **m)** MLP 32927, **n)** MLP 32928, **o)** MLP 32929a, **p)** MLP 32930, **q)** MLP 32924b, **r)** MLP 32931a, **s)** MLP 32932. Scale: 1 mm between dots.

Figure 5 (a-g) Camera Lucida drawings of representative specimens of *Normalograptus medius* (Törnquist, 1897): **a)** MLP 32929b, **b)** MLP 32933, **c)** MLP 32934, **d)** MLP 32926b, **e)** MLP 32935, **f)** MLP 32936, **g)** MLP 32937, **(h-p)** *Normalograptus normalis* (Lapworth, 1877): **h)** MLP 32938, **i)** MLP 32939, **j)** MLP 32931b, **k)** MLP 32940, **l)** MLP 32941, **m)** MLP 32942, **n)** MLP 32943, **o)** MLP 32944, **p)** MLP 32945. Scale: 1 mm between dots.

Figure 6 (a-k) Microphotographs of *Normalograptus persculptus* (Elles and Wood): **a)** MLP 32928, **b)** MLP 32922, **c)** MLP 32946, **d)** MLP 32918, **e)** MLP 32947, **f)** MLP 32948, **g)** MLP 32949, **h)** MLP 32923, **i)** MLP 32926a, **j)** MLP 32916a, **k)** MLP 32916b and *Normalograptus medius* (Törnquist, 1897): **l)** MLP 32929b. Scale: 1 mm between dots.

Figure 7: *a-h*, *Mucronaspis* sp., Eusebio Ayala Fm. type locality; **a**, fragmentary cephalon and thorax, MLP 32950, x1,9; **b**, fragmentary cephalon, MLP 32951, x1,5; **c**, *fragmentary cephalon*, MLP 32952, x2,4; **d**, *thorax and pygidium*, MLP 32953, x2; **e**, *pygidium*, MLP 32954, x2,1; **f**, *pygidium*, MLP 32955, x2,3; **g**, *pygidium*, MLP 32956, x1,7**; h**, *pygidium*, MLP 32957, x1,5.

Figure 8: Schematic composite graptolite-trilobite range chart for the Ordovician-Silurian boundary interval in the Itacurubí Group of Eastern Paraguay. Note that the Hirnantian-Rhuddanian transition shows low-diversity graptolites and trilobites recorded in the upper section of the Eusebio Ayala Formation. During the Early Llandovery, graptolites and trilobites are incoming of a more diverse fauna. The endemic taxon *C. innotatus brasiliensis* was also recorded in the sequence.

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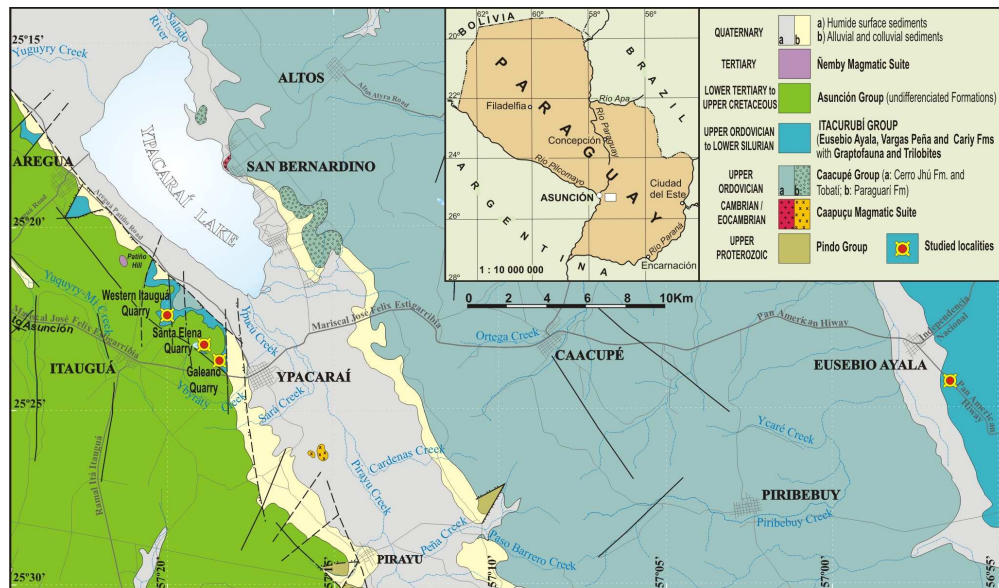
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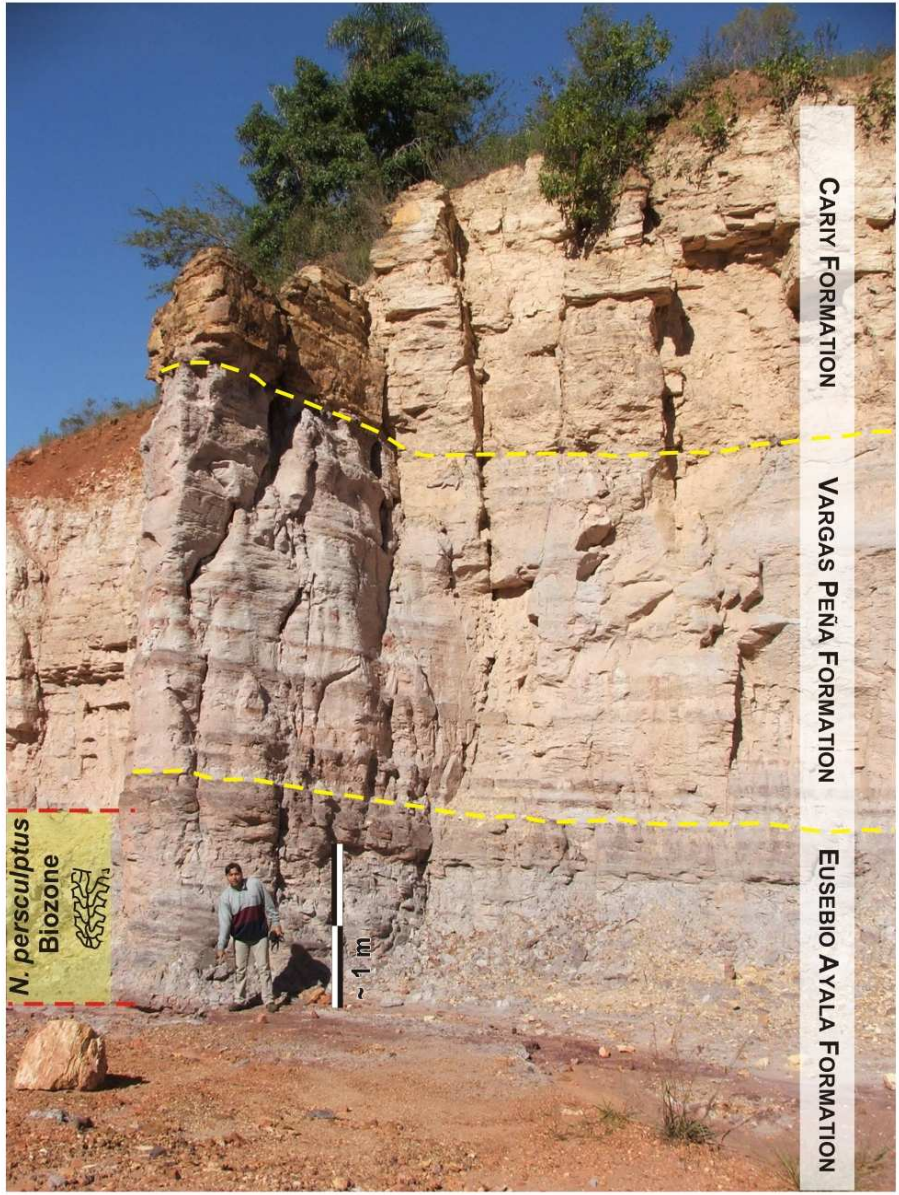48
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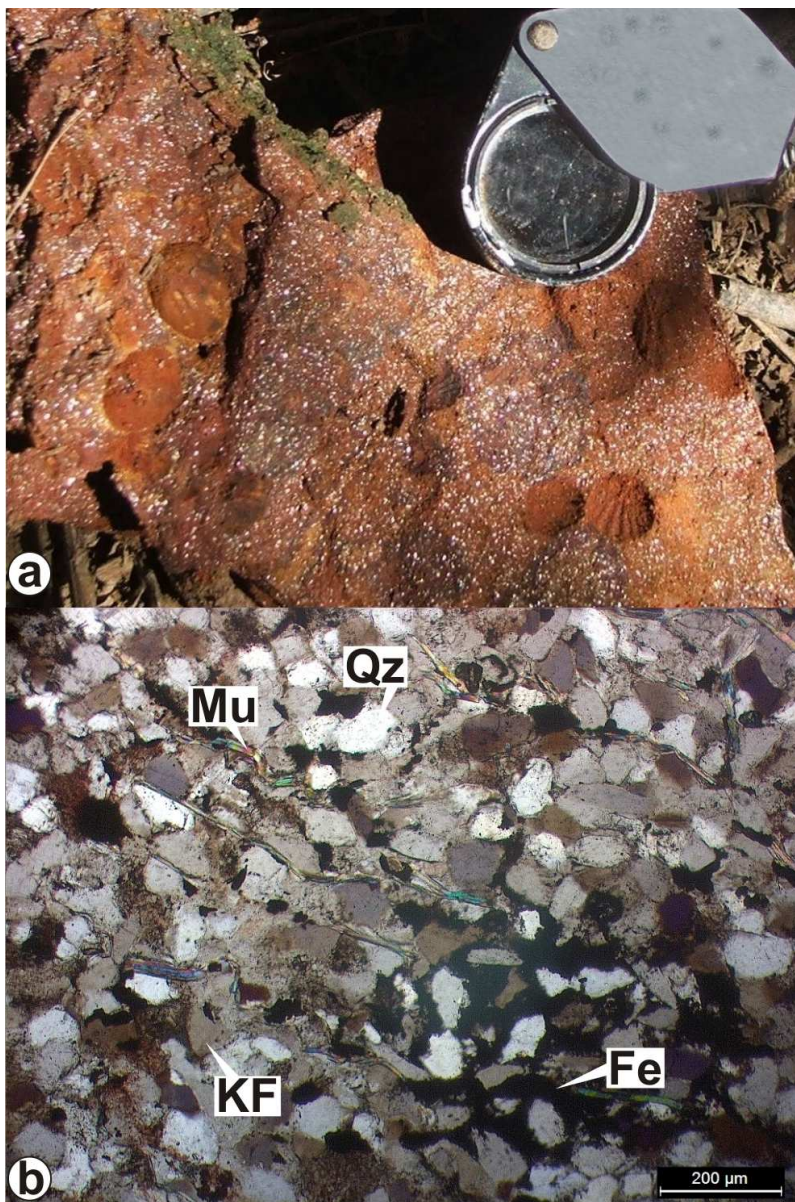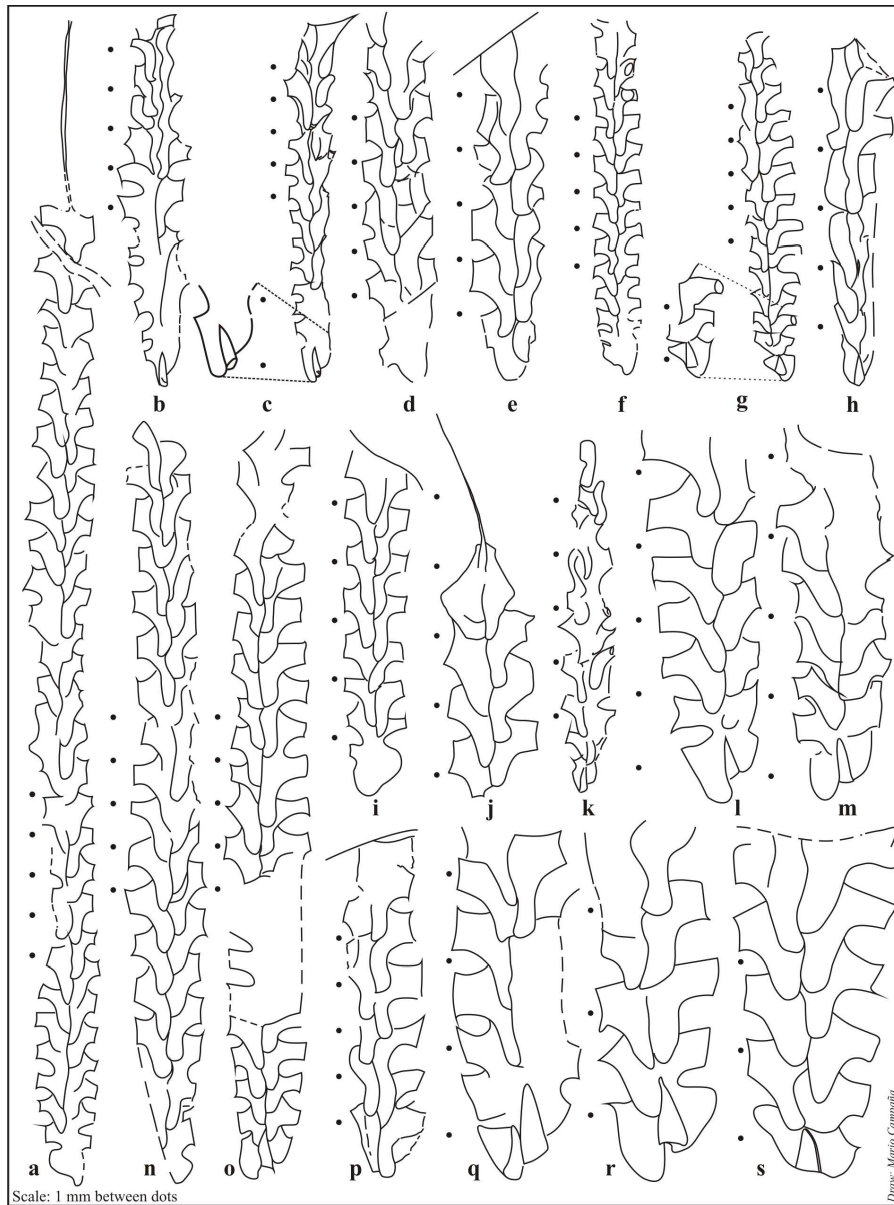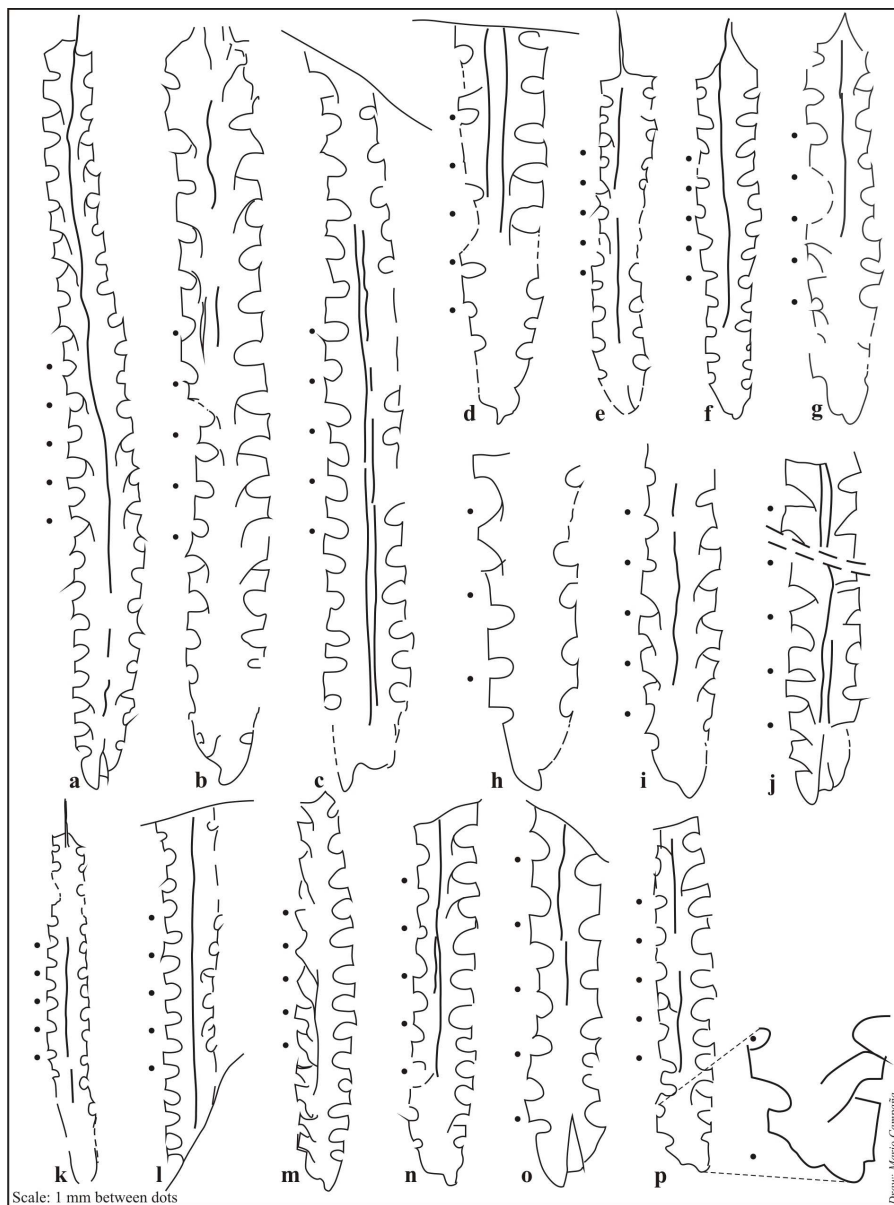
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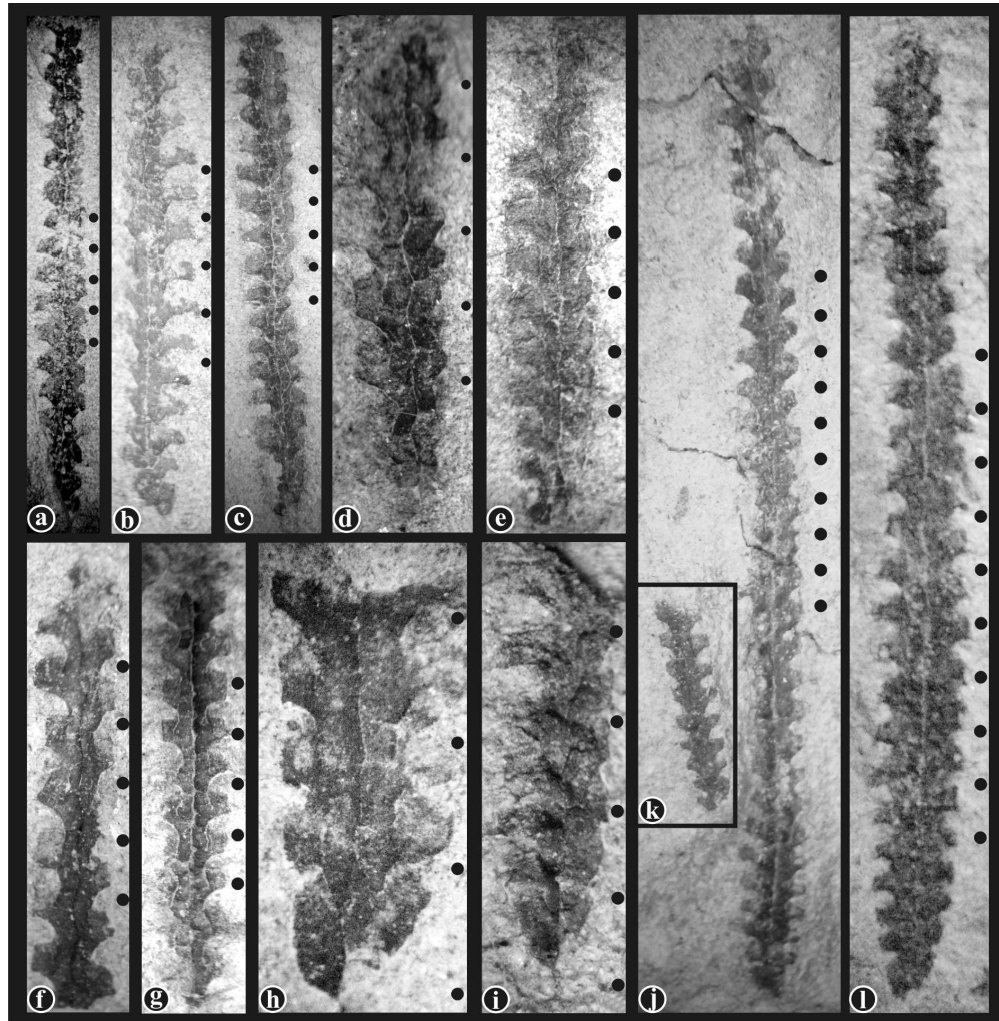
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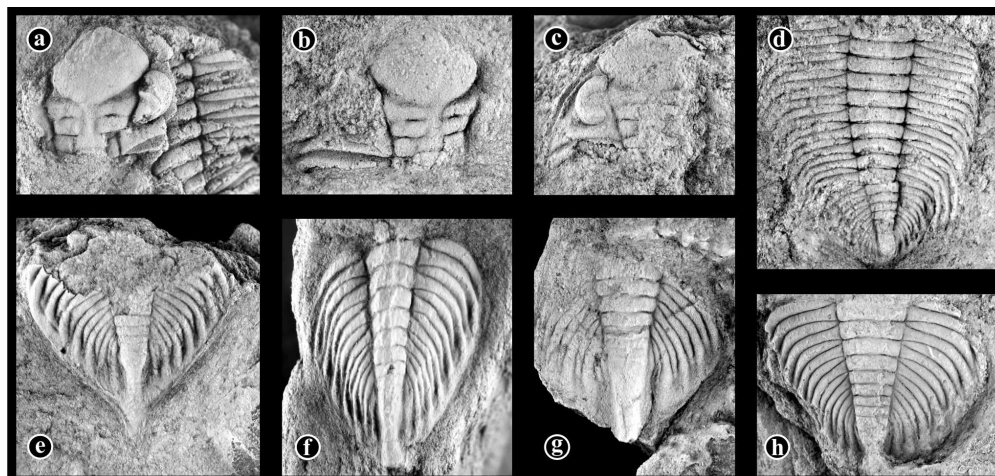
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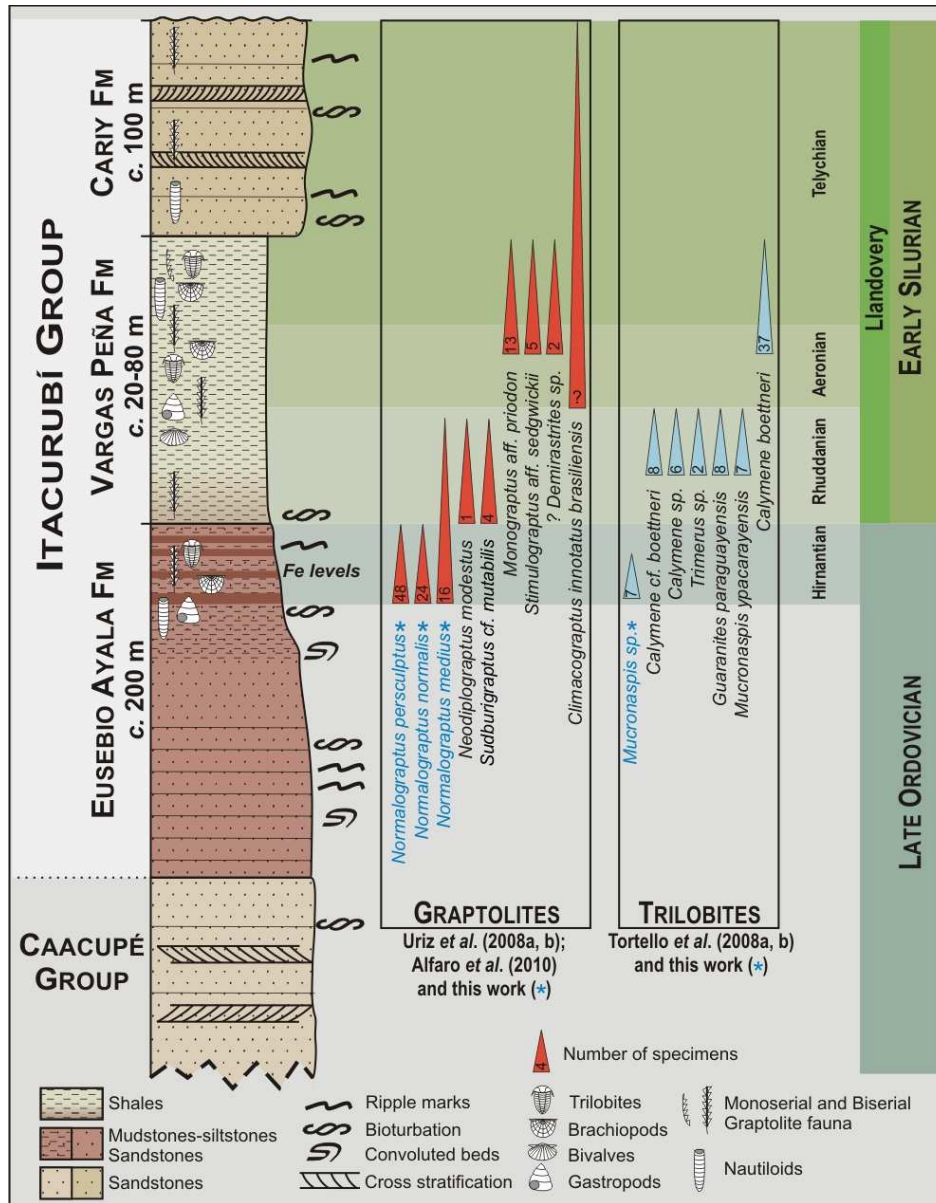31
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