
CLIMATE CHANGE AND REGIONAL/LOCAL RESPONSES

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***Itajuba yansanae* Gen and SP NOV of Gnetales, Araripe Basin (Albian-Aptian) in Northeast Brazil**

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1. Introduction

This paper provides a description of the morphology and anatomy of a fertile fossil, related to gnetalean lineage, which has been named *Itajuba yansanae*. A conclusion has been drawn regarding the paleoclimate when this taxon proliferated. It was collected in the Araripe basin in Brazil (Fig. 1), in the sedimentary rocks of the Santana Formation [1].

1.1. General considerations of paleoflora of the Crato Member of the Santana Formation

It is well known that during the deposition of the Crato Member, semi-arid paleoclimatic conditions prevailed in the northeast of Brazil and influenced the Araripe Basin [1, 2, 3, 4]. The presence of a system of lakes associated with the deposition of the Santana Formation may have favoured the maintenance of a more humid microclimate than the semi-arid conditions prevailing in the surrounding region, or at least a wetter season [5].

The paleoflora of the Santana Formation is famous around the world, since it represents one of the best-preserved records of the Aptian in tropical Gondwana [2, 3, 4, 5]. The assembly of macrofossils of this paleoflora [6] is composed of approximately 35% Pteridophytes, of the orders Filicales, Lycophytes, and Sphenophytes; 50% “gymnosperms” of the orders Gnetales, Coniferales, Cycadales, Bennettitales and some Pteridospermales [4, 7-15; among others] and 17% angiosperms related to the ‘ANITA’ lines Magnoliids, Monocots and Eudicots [16-19]. The paleoflora may reflect the presence of forest near the margins of a lacustrine system, as well as aquatic macrophytes inhabiting the lake [2; 3, 17- 19]; moreover, the fossils may represent

a succession of vegetation which grew there during the deposition of the bodies of limestone of the Crato Member.

2. Geologic location

The Araripe Basin, located between the states of Ceará, Piauí and Pernambuco in the Northeast of Brazil (Figure 1), is approximately 9,000 km² in area and 1,700m in width. Its geologic evolution is related to the fragmentation of the paleocontinent of Gondwana and the consequent opening of the southern Atlantic [1, 2].

In this study, we utilize the lithostratigraphic division proposed by Assine [1] for the Araripe basin, since it is the product of years of study by various authors, including the Brazilian Petroleum Industry (PETROBRAS), rather than the lithostratigraphic scheme proposed for the same layers by Martill [20]. Moreover, the stratigraphy is easily correlated with the geology of other Cretaceous basins in the northeast of Brazil (Parnaíba, Potiguar, Jatobá, Tucano, etc.).

The sedimentary rocks of the Aptian-Albian sequence of the Araripe Basin were deposited during a post-rift event which reactivated the subsidence of the area of the basin. This sequence is composed of the Barbalha Formation (lower portion) and Santana Formation (upper portion), which are most clearly exposed in the cliffs of the tableland of Araripe [1]. The Santana Formation represents the end of the second sedimentation cycle of the sequence, with an upward decrease in grain size, terminating with the deposition of the layered micritic limestone of the lower Crato Member. This limestone is found in discontinuous banks up to 60 meters in thickness, laterally interlinked with shales. At times, layers of gypsum are found above the limestone; these are known as the Ipubi beds. In the other locations, the sedimentary rocks of the Crato Member are in discordant contact with the upper member of the Santana Formation or Romualdo Member [1].

3. Materials and methods

The fossils studied consist of compressions permineralized with iron oxides, giving them a reddish brown colouration, which clearly distinguishes them from the micritic limestone matrix of the Crato Member. As in the case of the plant fossils described by Kunzmann *et al.* [4], only some branches of the fossils have preserved anatomical details. The specimens are associated with cranial and post-cranial fragments of small Osteichthyes. The specimens studied (MPMA 30-0042.03 A and B) were collected from laminated layers of limestone in the Pedra Branca Quarry near Nova Olinda in the Brazilian state of Ceará, and constitute part of the scientific collection of the Paleontological Museum of Monte Alto “Prof. Antonio C. Arruda-Campos”, in the municipality of Monte Alto, in the state of São Paulo in Brazil.

The morphological study of the specimens was made using an Axiocam 5.0 attached to a Zeiss Stemi SV6C stereomicroscope, and digital images of the fossil specimens were also registered

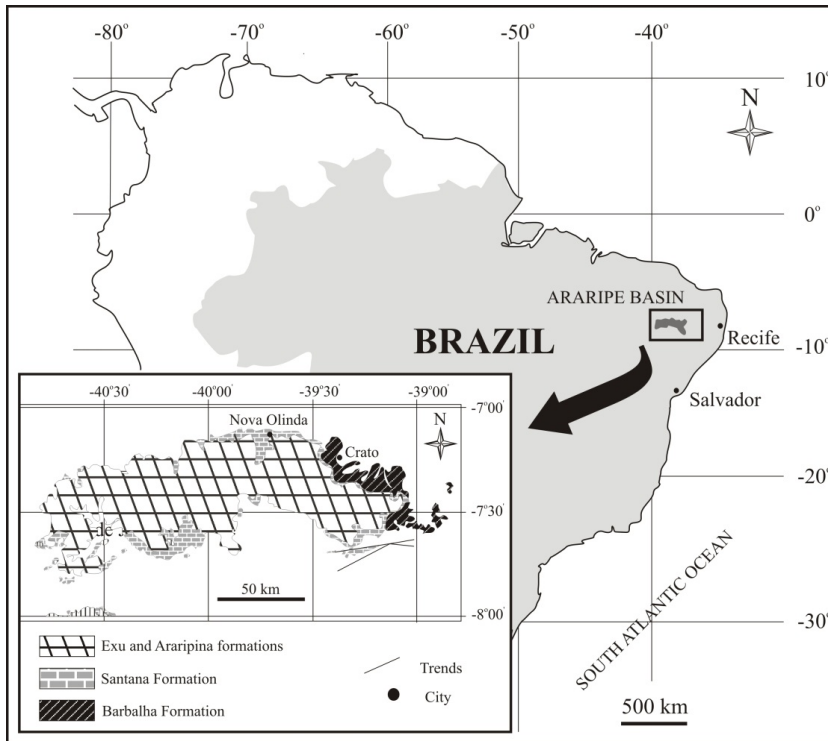


Figure 1. Location Map of the Araripe basin in Brazil.

with a Sony Alfa 1 camera (70mm lens). The lower part of specimen MPMA 30-0042.03 B was coated with gold and scanned using a LEO 430i Scanning Electron Microscope (SEM) of the Microscopic Laboratory of the Institute of Geosciences of UNICAMP and the JEOL-6360 Scanning Electron Microscope of the Institute of Chemistry of UNICAMP to obtain the longitudinal and cross section photographs.

The vessel density per mm^2 was measured for a random cross section, and the larger diameters of 50 vessels and tracheids were also measured.

In the present paper, the classification systems of the plant kingdom of Frey [21] and Kubitzki [22] were used.

4. Systematic palaeontology

Subkingdon Embryobionta Cronquist, Takhtajan and Zimmermann, 1966

Division Tracheophyta Sinnott, 1935 ex Cavalier-Smith, 1998



Figure 2. Photographs of external morphology of *I. yansanae*, showing vegetative characteristics: 1, overall view of sympodial branching, with terminal female cones and striated stems; 2, detail of View 1 showing striated stem (SS) and branching nodes (WB). Scale bars equal: 200mm in 1 and 100mm in 2.

Subdivision Spermatophytina Cavalier-Smith, 1998

Order Gnetales Luerssen, 1879

Genus *Itajuba* new genus

Figures 2, 3, 4, 5 and 6

Type species. *Itajuba yansanae*

Diagnosis. Plant with branch system bearing terminal female cones with striate stem at internodes. Main stem woody, with swollen nodes. Xylem consisting of vessels and tracheids, with tracheids more abundant than vessels; both with alternately distributed bordered pits. Long thin fibre-tracheids. Uniseriate rows of vascular rays composed of procumbent cells.

Reproductive shoot with ovulate cones in terminal branchlets, 1 ovulate/seed per cone, surrounded by pairs of bracts. Ovate seed with ornamented external surface.

Etymology. From Ita (stone), Juba (yellow) in Tupí-Guarani, since the laminated limestones of the Crato Member of the Santana Formation of the Araripe Group are yellow.

Itajuba yansanae new species

Figures 2, 3, 4, 5 and 6

Diagnosis. Sympodial branch system bearing terminal female cones with striate stem between all internodes with swollen nodes. Branches opposite-decussate. Xylem composed predominantly of tracheids, with a few vessels (approximately 40 per mm²), both with helical thickenings; alternately distributed bordered pits. Long, thin fibre-tracheids. Uniseriate rows of vascular rays composed of procumbent cells. Reproductive shoot with female cones in terminal branchlets, 1 ovule/seed per cone, surrounded by two pairs of connate bracts. Ovate seed with ornamented external surface.

Description. Vegetative characteristics. Branches opposite-decussate, longitudinally striated and apparently leafless at maturity; sympodial branches (up to 6 orders) bearing organically connected female cones; more than 540mm long (Figures 2 and 3). Main axis woody, at least 225mm long and from 7.5 to 11.5mm wide with thickening at nodes.

Lower portion of branches thicker, at times preserving anatomical features of secondary xylem, such as vessels and tracheids. Following opposite-decussate branches considered to be of inferior orders. Second-order branches reach lengths of 145-205mm between nodes, with widths between 2.5 and 4mm. Third-order branches reach lengths of 56-125mm between nodes, with a width of 2mm. Fourth-order branches have a length of 6-56mm and a width of 1mm. Fifth-order branches 2-21mm long and 0.5mm wide, and those of the sixth orders bear organically connected female cones (Figures 3 and 4) and possibly ephemeral leaves.

Female reproductive structures. Fertile branches, jointed and longitudinally striated between whorls; 5.9-15.7mm in length. Female cones on terminal branches, 3.6-5.3mm in length and 2.6-2.8mm in width, enclosed by two pairs of sharply pointed bracts connated at the base and extending to or beyond the reproductive structure bearing a single ovule (Figures 3.1 – 3.4). Micropylar tube short and straight, 0.5 mm long. Ovate seed 3mm in length and 2.8mm in width; surface ornamented with apparent projections (Figures 3.6 and 4.1).

Anatomical characteristics. Cross-section. Composed of vessels and tracheids, with the latter much more abundant than the former, vessel density of 40 per mm² (Figure 5). At the widest point vessels of 22-55µm and tracheids 7-19µm. Walls of the vessels and tracheids with width of 1.5-4µm. Vascular. Uniseriate rows of vascular rays of procumbent cells. (Figure 5.1). Tangential section. Vessels and tracheids with helical thickenings (Figure 6). Borderer pits with wide, rounded openings (Figure 6.3) distributed alternately; thin fibre-tracheids, although not very clear, located around vessels and tracheids (Figure 6.7).

Etymology. From Yansan, female goddess of war governing spirits.

Holotype. MPMA 30-0042.03 A

Other materials examined. MPMA 30-0042.03 B

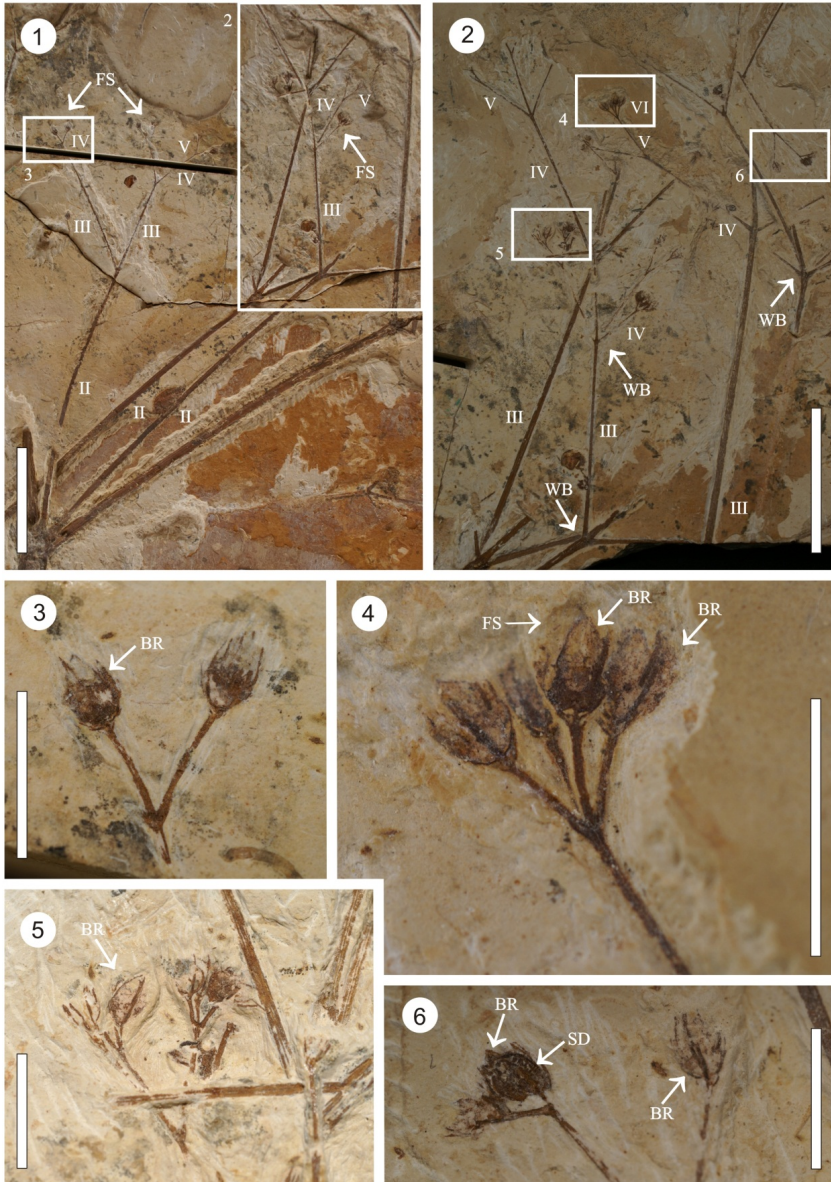


Figure 3. Photographs of external morphology of *I. yansanae* and female cones; 1, right-hand side branch bearing female cones (FS) organically connected to branch; 2, detail of View 1 showing reproductive structures and higher order branches (WB); 3, detail of stem of the sixth order bearing female cone organically connected and surrounded by

bracts (BR); 4, female cone (FS) showing pairs of bracts (BR) with connate bases and pointed tips; 5, female cone showing bracts (BR) protecting female reproductive structures; 6, detail of seed (SD) showing surface crosswise ornamentation with protuberances still surrounded by bracts (BR). Scale bars equal: 50mm in 1 and 10mm in 2,3,4,5 and 6.

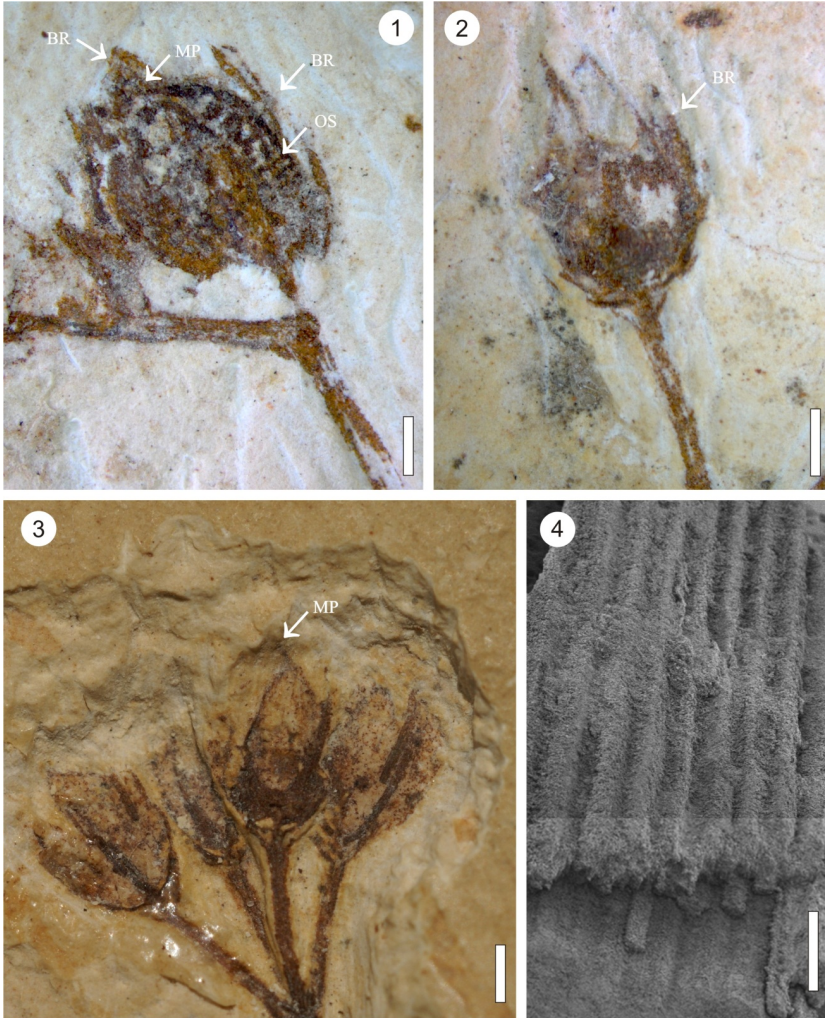


Figure 4. Photographs of external morphology of *I. yansanae* showing female cones and seed: 1, seed associated with *I. yansanae* showing ornamented surface (OS), possible micropyle (MP) and bracts (BR); 2, female cone surrounded by connate bracts (BR); 3, female cone showing bracts and a micropyle (MP); 4, SEM images of longitudinally striated stem. Scale bars equal: 1mm in 1, 2, 3 and 4.

Occurrence. Between the urban centres of Nova Olinda and Santana do Cariri, in the Pedra Branca Quarry in the state of Ceará in Brazil. Lower level of the Crato Member (Aptian), of the Santana Formation, in the Araripe Basin.

Comparison and Discussion. To facilitate comparisons, two Tables (Tables 1 and 2) were elaborated, one for morphological aspects and the other for anatomy.

The specimens studied had an external morphology similar to the fossil taxa related to the Gnetales [23] including opposite-decussate branches longitudinally striated between nodes, terminal female cones, ovules/seed surrounded by bracts, seeds externally ornamented; as well as similar anatomical characteristics, such as the presence of vessels, tracheids and fibre-tracheids and the diameter of the vessels and tracheids.

In this order, the greatest similarity seems to be with *Ephedra*-like fossils, due to the striated stem between nodes, type of the female cone, and the presence of septate vessels, tracheids and fibre-tracheids, as well as the vascular rays with procumbent cells and the diameter of the vessels today found only in this group [24]. Based on the morphological and anatomical similarities, a new genus was proposed (*Itajuba* n. gen.) with the species designated *yansanae* n. sp. This new species was compared (see tables 1 and 2) with other gnetalean fossils found in lithostratigraphic units of the Lower Cretaceous in both the Northern and Southern hemispheres. It was compared with *Drewria potomacensis* Crane et Upchurch [25] from the Aptian of the Potomac Group of Virginia in the USA, and with *Ephedra archaeorhytidosperra* Yang *et al.* [26], *Liaoxia changii* (Cao et S.Q. Wu) Rydin, S.Q. et Friis [27], *L. chenii* Cao et S.Q. Wu [27], *Ephedra hongtaoi* Wang et Zheng [28] and *Siphonospermum simplex* Rydin et Friis [29], all species found in Barremian the Yixian Formation of Lianoning province in northeastern China. Moreover, *I. yansanae* was compared with fossil species related to the order Gnetales and *Ephedra* in the Lower Cretaceous found in the Southern Hemisphere: *Cearania heterophylla* Kunzmann *et al.* [4], *Cariria orbiculiconiformis* Kunzmann *et al.* [12], and a specimen possibly related to *Ephedra* [14], all collected in the same basin in Ceará in layers of the Crato Member of the Santana Formation (Aptian) in the Northeast of Brazil, as well as *Ephedra verticillata* Cladera *et al.* [30], found in the Ticó Formation of the Baqueró Group (Aptian) in Santa Cruz province in the south of Argentina.

Drewria potomacensis [25] had preserved leaves, and differences were found in the reproductive structures, which, although terminal for both, are loose spikes borne in dichasial groups of three in *D. potomacensis*, rather than consisting of terminal solitary female cones with one ovule/seed.

Ephedra archaeorhytidosperra [26] shares the striated stem and single terminal female cones composed of 2 pairs of bracts, although the shape and size are different. Moreover, *E. archaeorhytidosperra* seems to have been a herb, whereas *I. yansanae* seems to have been a woody plant. Such differences would make it difficult to include the samples studied here in this genus.

A comparison of *I. yansanae* with *Liaoxia changii* and *L. chenii* shows that all three have striated stems and terminal female cones, but the bracts of the two species of *Liaoxia* are much larger;

moreover, the female cones in the Chinese species have from 2-10 pairs of bracts, whereas *I. yansanae* have only two.

Ephedra hongtaoi [28] was described to denominate a dioecious plant for which the roots, stems, branches and ovuliferous units are similar in gross morphology to *I. yansanae* with regard to the striated stem between nodes, reduced leaves and terminal female cones, although the morphology of the female cones is somewhat different and the anatomy is at present unknown.

Few comparisons can be established with *Siphonospermum simplex* [29]; although *S. simplex* and *I. yansanae* both have terminal reproductive units surrounded by bracts, the shape and size of these are different. Moreover, the former has a more developed micropylar tube.

Cearania heterophylla [4] has leaves, and the morphology of the reproductive units is also different (Table 1). The anatomical characteristics of the two are similar with regard to the presence of vessels, tracheids, and fibre-tracheids, as well as helical thickenings and alternate pits arranged in rows and longitudinally striated stems. The other species described by [12], designated *Cariria orbiculiconiformis*, may be related to the Gnetales, but it is also quite different from the species described here in terms of the morphology of the reproductive units and the presence of leaves (Table 1). The anatomical characteristics of *C. heterophylla* are similar in relation to the presence of the vessels and tracheids and pits, helical thickenings, although the cross-section of the xylem of both *C. heterophylla* and *Cariria orbiculiconiformis* is unknown, as well as the distribution and number of vessels per mm².

The specimen described by Fanton *et al.* [14] as possibly related to Gnetales is different from the species described here, especially with regard to size (much smaller) and the presence of opposite leaves and cones with more than two pairs of bracts. Both species do have a longitudinally striated stem.

E. verticillata was described for an impression/compression stems [30] has sessile seed-bearing structures either singly or in clusters of the three to five, whereas those of *I. yansanae* are uniformly singular.

The outer seed surface is profusely ornamented by rounded protuberations. Although due to the type of preservation of the fossils studied, this could not be observed in detail, this ornamentation resembles that mentioned by various authors [15, 26, 31-33]. Although not connected organically to the main stem, the seed was attached to a female cone identical to others, organically connected to the main branch. On the other hand, the seed associated with *I. yansanae* is clearly protected by bracts, as can be seen in Figures 3.2, 3.6 and 4.1.

5. Discussion and final remarks

The combination of morphological and anatomical characteristics makes a more complete interpretation of plant fossils. A comparison with present-day representatives of the lineages, when possible, represents one of the basic premises for paleontologic analysis. The anatomy found for *I. yansanae* was thus compared with that of present-day Gnetales, and the conditions

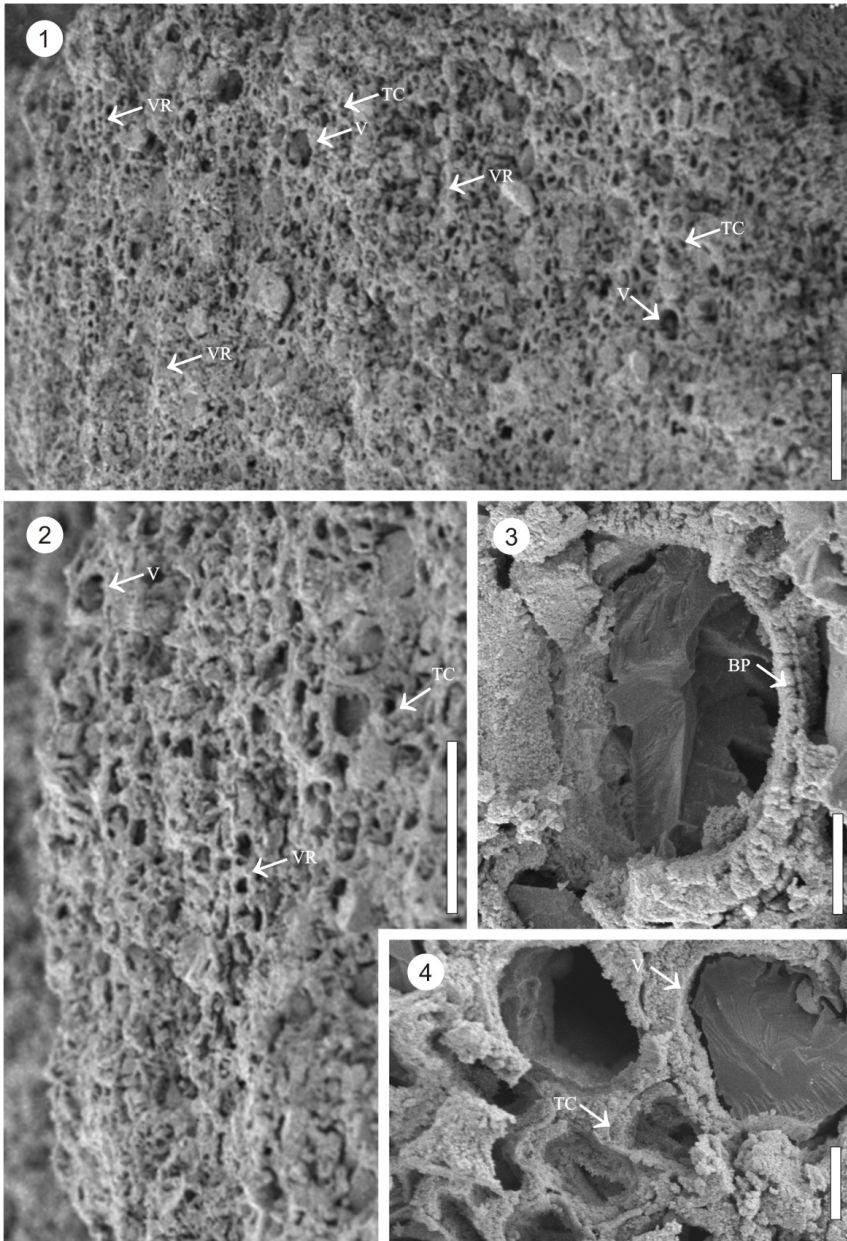


Figure 5. SEM images of anatomy of secondary xylem, cross-section of stem of *I. yansanae*: 1, overall cross-section showing vessels (V), tracheids (TC) and vascular rafts (VR); 2, detail of View 1, showing vessels (V), tracheids (TC) and vascular rafts (VR); 3, detail vessel (V) with bordered pits (BP); 4, detail of vessel (V) surround by tracheids (TC). Scale bars equal: 100 μ m in 1 and 2; 10 μ m in 3 and 4.

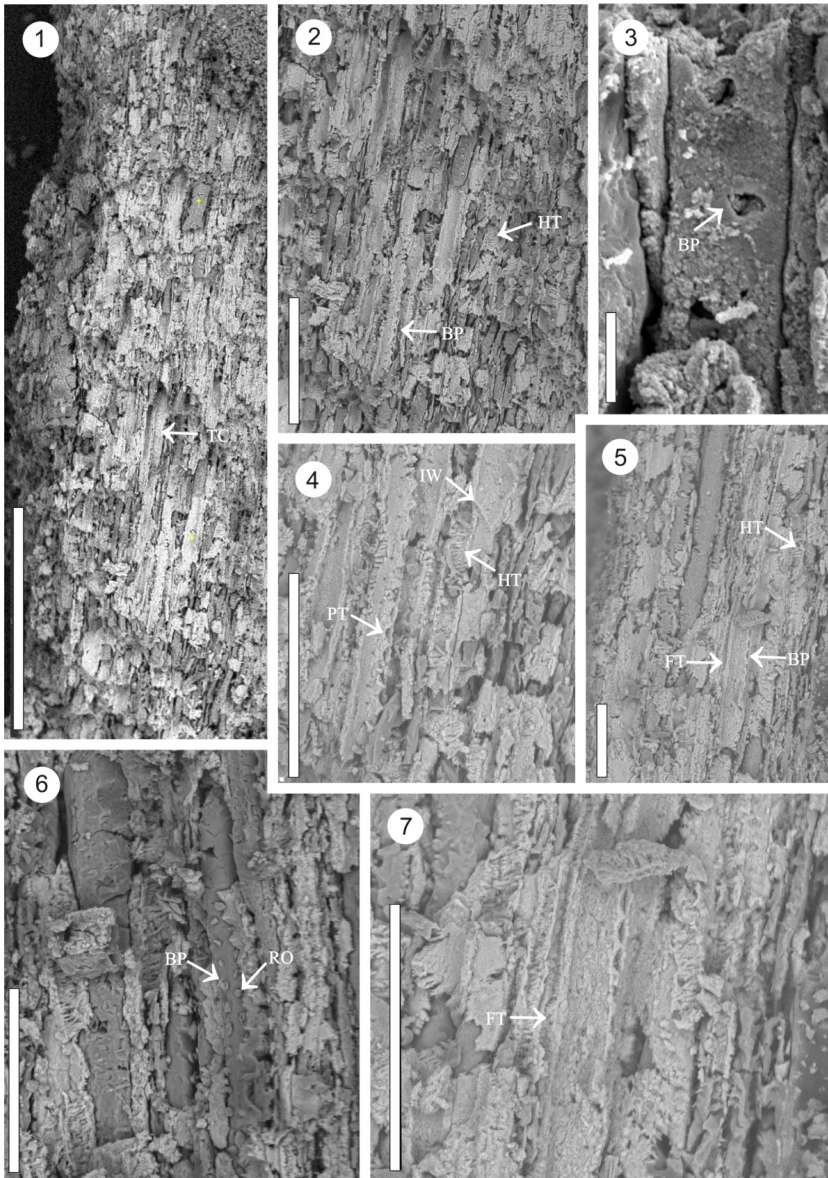


Figure 6. SEM images of anatomy of secondary xylem, tangential section of stem of *I. yansanae*: 1, overall tangential section showing tracheids (TC); 2, detail of View 1, showing tracheids with bordered pits (BP) and helical thickenings (HT); 3, detail of bordered pits (BP); 4, detail of View 2 showing pitted tracheids (PT), helical thickenings (HT) and inclined terminal walls (IW); 5, detail of View 1 showing tracheid with bordered pits (BP) and helical thickenings (HT) and fibre-tracheid (FT); 6, portion of tracheid with two rows of large alternate bordered pits (BP) with rounded openings (RO); 7, detail of View 5 showing long, thin fibre-tracheids (FT). Scale bars equal: 500µm in 1; 200µm in 2; 10µm in 3 and 7; and 100µm in 4, 5, 6 and 7.

of climate in which the fossils flourished were inferred. Thus, the gross morphology and anatomy of *I. yansanae* suggest that it grew in locations with a definite hydric deficit, at least during some seasons of the year; they also suggest, on the basis of other studies conducted in the Araripe Basin, such as the paleopalynological studies [5]. The ephemeral nature of the leaves may have been a defence of the plant to decrease the evaporative surface, with photosynthesis being the function of the new branches [24, 34, 35]. Another indication of the climatic conditions of hydric deficit during at least part of the year is the shortage of vessels elements in relation to the abundance of tracheids in the Gnetales. A study of the near vessellessness in *Ephedra*, [36] showed that variation in the xylem indicates an adaptation for improving the conduction of water. This is physiologically useful, but limited in availability, since tracheids are the vessels for the conduction of water because they avoid the formation of air bubbles or air embolisms. Moreover, present-day species of *Ephedra* with a low density of vessels per mm² have helical thickenings [37]. In the specimens studied here, the ratio of vessels per mm² was only 40 in comparison to the new-world and old-world species of *Ephedra* (1 to 291 and ≤ 20 to 338, respectively) [36, 37]; the helical thickenings of *I. yansanae* can also be interpreted as a consequence of the climate during the deposition of the Crato Member of the Santana Formation, which, as indicated above, would show that despite the system of lakes in the region, the climate was semi-arid.

The phylogenetic implications of the morphological and anatomical characteristics of *I. yansanae* exclude a relationship with any lineage other than that of Gnetales. Given its position in this order, it is closest to an ephedroid-like plant, although since the anatomical details of the seed envelope [27, 29, 31, 38, 39] and the pollen grains are unknown, we cannot prove that it is actually a member of the lineage of the *Ephedra*.

Character	Vegetative structures				Reproductive structures			
	Branches		Leaves		Roots			
Species	Type	Dimensions (cm)	Internode (cm)	Shape / Dimensions (mm)	Arrange / Venation	Female (mm)	Male (mm)	Seeds (mm)
<i>Itajuba</i>	Sympodial,	54.5 x	22.5-9 x			3.6-5.3 x		3 x 2.8, ovate
<i>yansanae</i>	dioecious, longitudinally striated	0.75-1.15	4-0.5			2.6-2.8, two pairs of bracts		surface ornamented with projections
<i>Drewria</i>	Monopodial,	Diameter	30	Oblong	Opposite	Short loose		1-2.5 x 1-2
<i>potomacensis</i>	longitudinally striated	1-3		10-20 x 2-6	Parallel with crossveins	spike arranged in groups of three		Flattened, narrowly ovate, apex acute, base rounded

Character	Vegetative structures				Reproductive structures			
	Branches		Leaves		Roots			
Species	Type	Dimensions (cm)	Internode (cm)	Shape / Dimensions (mm)	Arrange / Venation	Female (mm)	Male (mm)	Seeds (mm)
<i>Ephedra archaeorhytidosperma</i>	Opposite, erect, longitudinally striated		0.8-1.4 x 0.5-1	Caducous, triangular and acute, 5 x 2	Verticillate, parallel	Terminal, two to three pairs of bracts		Immature 1,5-4 x 1-1,6. Mature 7.5 – 2.2. Obovate – elongate-ovoid cuspidate apex, surface ornamented
<i>Liaolaxia changii</i>	Shrub(?) with opposite branch and longitudinally striated		8- 4 x 0.5-4			5-6 x 2.5-3 Sessile to pedunculate Compound, obovate, six pairs of bracts or more		0.9-1.1 x 0.3-0.7 Ovate
<i>Liaoxia chenii</i>	Longitudinally striated		9 x 0.1-0.3	Linear 20 x 1-2	Parallel	5-10 x 3-4 obovate, compound; two – six pairs of bracts		
<i>Ephedra verticillata</i>	Longitudinally striated	< 5				Single to five sessile structures		1.8 x 0.8, oval striated surface, with one pair of bracts
<i>Siphonospermum simplex</i>				Linear	Opposite, parallel	Terminals obovate, without bracts, orthotropous ovule		

Character	Vegetative structures					Reproductive structures		
	Branches		Leaves		Roots	Female (mm)	Male (mm)	Seeds (mm)
Species	Type	Dimensions (cm)	Internode (cm)	Shape / Dimensions (mm)	Arrange / Venation			
<i>Ephedra hongtaoi</i>	Shrub	< 26	0.7-4 x 0.4	Highly reduced		Tap root	3 x 2.3, spherical, two pairs of bracts	2.7 x 2.2 In pairs or single
? <i>Gnetales</i>	Shrub dioecious, with opposite branch and longitudinally striated		2-13.5 x 1-2.5	Ovate- oblong, 3-7.5 x 1.5-5	Opposite	Closely together		Spikes (?)
<i>Cearania heterophylla</i>	Herb – shrub, sympodial and longitudinally striated	">65.5		Linear lanceolate-ovate	Coriaceous, parallel	Closely together	Single with many pairs of bracts	
<i>Cariria orbiculiconifomis</i>	Herb – shrub, sympodial and longitudinally striated	16.5-0.5	4.4-4.5 – 0.3-0.5	Oval to oval- orbicular and dorsiventrally flattened; decurrent base. Apex acute-obtuse or obtuse. 8-24 x 5-18mm	Parallel to the leaf margin		4-11 x 1.2-1.5; orbicular compound strobili, a pair of sterile bracts	4-6 x ~1 individual pollen-producing structure with two sterile bract-like
? <i>Ephedra</i> sp.	Shrub dioecious, with opposite branch and longitudinally striate		2-13.5 x 1-2.5	Ovate- oblong, 3-7.5 x 1.5-5	Opposite	Closely together		Spikes (?)

Table 1. Morphological characteristics of species associated with the Gnetales mentioned in the text (Modified from 4, 14, 25-30).

Character	Stem	
	Cortical layer	Wood
Species		
<i>Itajuba yansanae</i>		Cross and tangential sections. Vessels and tracheids with alternate pittings, helical thickenings, fibre-tracheids and uniseriate vascular rays of procumbent cells
<i>Cearania heterophylla</i>	Uniform isodiametric and/or rectangular cells, helical thickenings, circular strands of supporting tissue	Transversal section. Vascular tissue, elongated cells with acute polar ends and helical thickenings, presence of pits arranged in single or two rows. Perforation plates and fibre-tracheids
<i>Cariria orbiculiconiformis</i>	Uniform parenchymatous and rectangular cells	Transversal section. Tracheids with helical thickenings and uniseriate pittings becoming biseriate at the polar ends. Fibre-tracheids

Table 2. Anatomical characteristics of species associated with the Gnetales mentioned in the text [Modified from 4, 12].

6. Conclusions

This paper has described a new species, *I. yansanae* on the basis of morphological and anatomical characteristics. It has been placed systematically in the order Gnetales, since it shares various characteristics with them, including the longitudinally striated stem, thickened nodes giving rise to varying numbers of branches; possibly ephemeral leaves, terminal female reproductive structures protected by two pairs of bracts and seeds externally ornamented with protuberances. The anatomy of the new species includes secondary wood consisting of vessels and tracheids with helical thickenings, fibre-tracheids and bordered pitting. This new species introduced one more taxon which contributes to a better understanding of the diversity of the Crato paleoflora during the Early Cretaceous period (Aptian-Albian).

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