# The stratigraphic significance of the Solenoid Complex in the Permian of Gondwana

*O significado estratigráfico do Complexo Solenoide no Permiano do Gondwana*

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## Abstract

The Solenoid Complex comprises a fossil wood assemblage with stratigraphic distribution restricted to the middle-late Kungurian, present in Western (Irati Formation, Paraná Basin, Brazil) and Eastern (Upper Barakar Interval of the Indian basins) Gondwana. Its occurrence seems to be related to the adaptation of certain plant groups to paleoenvironmental stress in lowland niches of coastal areas subject to salinity variation. The disappearance of these forms in the latest Kungurian is probably linked to the cessation of these conditions, which is confirmed by the sedimentary record. The here designated "Solenoid Complex Zone" correlates with the acme in diversification of striate and taeniate patterns especially in bisacatte pollen grains, but also in monosacatte ones, reflecting important tectonically and climatically driven changes in the vegetational pattern. The waning icehouse stage during the Permian was an important factor to the development of similar vegetation patterns in Western and Eastern Gondwana in the latitudinal belt of 40° – 55°.

**Keywords:** Stratigraphic correlation; Biostratigraphy; Fossil wood; Kungurian; India; Brazil.

## Resumo

O Complexo Solenoide compreende um conjunto de lenhos fósseis com distribuição estratigráfica restrita ao Kunguriano médio-superior, presente no Gondwana Ocidental (Formação Irati, Bacia do Paraná, Brasil) e Oriental (Intervalo Barakar Superior de bacias da Índia). A sua ocorrência parece estar relacionada à adaptação de determinados grupos vegetais ao estresse paleoambiental em terras baixas de áreas costeiras sujeitas a variações de salinidade. O desaparecimento dessas formas no topo do Kunguriano está provavelmente relacionado à cessação de tais condições, o que é confirmado pelo registro sedimentar. A "Zona do Complexo Solenoide" aqui designada correlaciona-se com o clímax na diversificação de padrões estriados e teniados principalmente em polens bissacados, mas também em monossacados, refletindo importantes modificações no padrão vegetacional relacionadas à evolução climática e a processos tectônicos. O declínio do estágio *icehouse* durante o Permiano foi um fator importante para o desenvolvimento de padrões florísticos similares no leste e oeste do Gondwana em uma faixa latitudinal entre 40° – 55°.

**Palavras-chave:** Correlação estratigráfica; Bioestratigrafia; Lenhos fósseis; Kunguriano; Índia; Brasil.

## INTRODUCTION

During the Permian interval, Pangaea was a relatively diverse region in terms of climate and topography. Global geographic patterns of Permian climates were reconstructed by Rees et al. (2002), showing a significant latitudinal climate gradient, similar to the modern interglacial situation. Paleobotanical data (Ziegler, 1990; Cúneo, 1996; Ziegler et al., 2003) based mainly in compression-impression fossils of leaves, reproductive structures and seeds have shown that the provinciality of Gondwana changed significantly during the course of the Permian, mainly influenced by paleogeographic and paleoclimatic parameters (Rees et al., 2002). Potential macroplant associations are mainly the several taxa of the *Glossopteris* Flora, represented by woody and non-woody plants. Nevertheless, since the Gondwana Supercontinent comprised a huge landmass including all the continents of the Southern Hemisphere and India, a degree of provincialism in floral composition is expected in different paleoclimatic belts.

Silicified woods, subject of the present study, are found within rocks of Permian succession in Gondwana, carrying relevant information for plant taxonomy, paleoecology and paleoclimatology. Nevertheless, this kind of fossils is not usually considered of stratigraphic relevance because descriptions have focused mainly on single specimens rather than on fossil assemblages from determined horizons (e.g. Iannuzzi et al., 2010).

In an attempt to contribute to an extensive correlation project concerning Indian and Brazilian Gondwana during the Permian, the present study aims to summarize information about fossil wood taxa of the Western and Eastern Gondwana from the Barakar Stage of Damuda Group (India) and the Irati Formation of Paraná Basin (Brazil) in the middle-late Kungurian. Woods from some localities for this time interval have been described by many authors in both regions (as synthesized by Merlotti and Kurzawe, 2011 and Prasad, 1982), featuring in some cases preserved central pith.

It is important to emphasize that the distinction between primary xylem, secondary xylem and pith is purely conceptual, since these structures are components of a single unit, the wood (Mussa, 1982). It should also be pointed out that the diagnostic characters of secondary wood allow distinctions between higher taxonomic categories, and they have currently been used in this way, but their value in phytogeographic and/or stratigraphic correlations in Permian Gondwana is not well defined (Bamford and Philippe, 2001). Additionally, the morphology and the composition of the pith reflect both the ecological dynamics and the phenotypic features found in a systematic study (Mussa, 1982) and are here believed to constitute useful criteria for the identification of phytogeographic and stratigraphic distribution range of Paleozoic fossil gymnosperm woods, as mentioned by

Pant and Singh 1987). For such reasons, only woods presenting complete steles are used for correlations in this study.

In order to test the results obtained in the present research, fossil wood characters are compared to phytostratigraphic and palynostratigraphic data from the same interval in both India and Brazil.

## GEOLOGICAL CONTEXT

### Brazil

The Paraná Basin (1,700,000 km$^2$) is an intracratonic basin spanning southern Brazil, southeastern Paraguay, northeastern Argentina and northern Uruguay. Its basement consists of Paleoproterozoic and Mesoproterozoic rocks of the La Plata Craton and Neoproterozoic mobile belts. According to Milani et al. (2007), six supersequences have been identified from the Ordovician to the late Cretaceous based in sequence stratigraphy.

The second-order transgressive/regressive cycle (Gondwana I Supersequence) includes rock packets that were previously recognized as units in lithostratigraphic classification (Schneider et al., 1974). The deposition begins with a basal transgressive interval (Itararé Group), which is overlain by fluvio-paralic and lagoon back-barrier systems, where peat deposition generated expressive coal seams and rich plant assemblages have been described for roof shale levels (Jasper et al., 2006; Guerra-Sommer et al., 2008; Simas et al., 2013), continues with marine facies association (Rio Bonito Formation) followed by the maximum flooding interval (Palermo Formation). The subsequent rock packet (Irati Formation) documents an unique moment in the evolution of the basin into the onset of its intracratonic configuration, when an effective restriction on the water circulation between the synclines and Panthalassa Ocean occurred, culminating in a hypersaline environmental context and a progressive closure of the marine incursions from the west. Under these conditions, carbonates and evaporites accumulated predominantly in the northern part and in bituminous shales in the southern part of the basin. The overlying regressive package represents a continental trend, topped by fluvio-eolian deposits in the latest Permian (Milani et al., 2007).

### India

In India, the Permian deposits occur in peninsular as well as extrapeninsular regions, mostly resting directly on the Archean basement rocks. In the peninsular part, Permian deposits occur along river valleys (Damodar, Son-Mahanadi, Warddha-Godavari, Satpura and Rajmahal basins), besides several other smaller basins (Maheshwari, 1992). The early

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Permian (according to Singh et al., 2007) Barakar Stage, subject of the present study, overlies the lowermost Permian unit, the post-glacial strata of Talchir Series (Lele, 1976; Tiwari, 1974; Tiwari and Tripathi, 1988; Pant and Nautiyal, 1987), which is composed of boulder beds, greenish sandstone, varve and rhythmite (Jha, 2006). The Barakar Stage is the earliest depositional cycle of the Damuda Series and is comprised of feldspathic sandstones, grey and carbonaceous shales associated to thick coal seams (Mitra, 1991; Srivastava, 1992; Singh et al., 2007). Peat deposition has been related to typical paralic (coastal marine to deltaic) systems (Goswami et al., 2006), suitable for the formation of coal during a cool, markedly seasonal climatic regime. The overlaying Kulti Formation, the Barren Measures of latest early Permian age, is characterized by ironstone shale and concretions and devoid of coal seams (Jha, 2006; Chandra and Chandra, 1988). The Raniganj Stage corresponds to the uppermost coal bearing horizon (Guadalupian-Lopingian).

## FOSSIL WOODS AS CORRELATION TOOLS

The diversity of the Permian gymnosperm woods in the Paraná Basin reached its climax during the deposition of the Irati Formation. Attempted correlation with sequences of Indian Gondwana, especially those of the Barakar Stage, revealed the difficulty of closer correlations, given the limited data recorded in India in comparison to Brazil. In Indian basins, contrasting with the small number of wood morphogenera so far described, a great diversity of impression/compression plant fossil species, represented by leaves and reproductive structures, has been published (Chandra and Chandra, 1988; Mitra, 1991; Srivastava, 1992; Jha, 2006).

If both Brazil and India have some genera of the lignofloras in common, on the other hand the species are not the same. As already mentioned by Anderson and Anderson (1985) and Bamford (2004), this could be a result of genuine differences or sometimes just exaggerated by taxonomic approaches. Therefore, the generotype is used here as the basis for comparisons, because it reflects more easily recognizable wood types.

Some wood patterns, such as the protoxylem organization, are not employed herein as a decisive feature to distinguish phylogenetically different morphogenera included in the Solenoid Complex. Considering the basifugal acceleration events during the wood development (Chauveaud, 1911; Boureau, 1954), the protoxylem organization changes in different maturation stages of the stem. Consequently, different morphogenera descriptions, which have mainly been based on analysis of single specimens, could correspond to a single wood structural plan. Additionally, the secondary wood morphogenera *Agathoxylon* Hartig and *Australoxylon* Marguerier, which also occur in both Barakar and Irati

sequences (Marguerier, 1973; Mussa, 1982; Merlotti and Kurzawe, 2006), prevent closer correlation by their wide stratigraphic and phytogeographic distribution throughout the whole Permian.

The gymnosperm eusteles from the Irati/Barakar intervals, subject of the present study, have in common a wide pith and a set of xeromorphic features that appear to be used for aeration in low-oxygen environments rather than for water storage (Mussa, 1986).

Among the patterns of gymnosperm steles identified for the interval (Table 1), there is a group of eusteles characterized by a system of secretory canals in longitudinal and radial orientation distributed in a wide pith that, in turn, can be solid or have gaps and cavities. Steles with this peculiar structure were included in the "Solenoid Complex" by Kräusel (1956). The secretory canal system has been considered a morphogeneric attribute by Kräusel and Dolianiti (1958). According to their major anatomical patterns, *Solenobrasilioxylon* Mussa, *Polysolenoxylon* Kräusel and Dolianiti, *Barakaroxylon* (Surange and Maithy) Kulkarni, Maithy and Surange, *Atlanticoxylon* Mussa, *Petalopitys* Mussa, *Ductosolenoxylon* Merlotti and *Solenopitys* Kräusel and Dolianiti were included in a particular group identified by the presence of canals in the pith (Figures 1A to 1E) and endarch or mesarch protoxylem. Mussa (1982), based on anatomic parameters of present-day plants, inferred that in *Barakaroxylon*, *Atlanticoxylon* and *Petalopitys* the canals were mucilaginous (complex), whereas in *Solenobrasilioxylon*, *Solenopitys* and *Polysolenoxylon* the canals were considered not complex. The origin of these structures has been associated with phyllotaxy or regarded as answers to external traumatic processes (Fahn and Zamski, 1970). The presence of canals in the pith structure is considered illustrative of ancestry, linked to systematic and, consequently, to phylogenetic criteria. Nevertheless, the wood assemblage included in the Gondwana Solenoid Complex Zone cannot be related to any particular fossil or recent plant group yet.

The secondary wood of the taxa included in the "Solenoid Complex" is mostly of the *Agathoxylon* type of organization (woods with araucarian radial pitting of the tracheids and araucarioid cross-fields, according to Bamford and Philippe, 2001), rarely showing *Australoxylon* pattern (woods with mixed-type radial pitting and grouped pitting in cross-field (Figures 1F and 1G), according to Marguerier, 1973)).

Merlotti and Kurzawe (2011) attributed the stratigraphic position of the solenoid taxon *Ductosolenoxylon* and the non-solenoid taxa *Paulistoxylon*, *Abietopitys*, *Septomedulloxylon*, *Corticoxylon* and *Vertebraria* to the Serra Alta Formation, which overlies the Irati Formation in the southern part of the basin. However, new results obtained by Guerra-Sommer during field expedition revealed that these woods were included in the topmost horizon of the Irati Formation (unpublished data). Therefore, they are included herein.

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**Table 1.** Genera of eusteles described for Indian and Brazilian Gondwana.

| Steles | Brazil | India |
|---|---|---|
| | Irati Formation (Paraná Basin), according to Mussa (1982; 1986) | Upper Barakar Stage, according to Prasad (1982) |
| Vertebraria Complex | *Vertebraria* | *Vertebraria* |
| | *Torosoxylon* | - |
| | *Myelontordoxylon* | - |
| | *Tordoxylon* | - |
| Solenoid Complex (+sclerenchymatous tissue) | *Ductosolenoxylon* | - |
| | *Barakaroxylon* | *Barakaroxylon* |
| | *Solenopitys* | - |
| | *Polysolenoxylon* | *Polysolenoxylon* |
| | *Petalopitys* | - |
| | *Solenobrasilioxylon* | - |
| | *Atlanticoxylon* | *Atlanticoxylon* |
| Solid pith (+sclerenchymatous tissue) | *Taxopitys* | - |
| | *Antarticoxylon* | - |
| | *Taeniopitys* | *Taeniopitys* |
| | *Kaokoxylon* | - |
| | *Brasilestiloxylon* | - |
| | *Kraeuselpitys* | - |
| | *Abietopitys* | - |
| | *Protopodocarpitys* | - |
| | - | *Prototaxopitys* |
| Diaphragm / Lacunae pith (+sclerenchymatous tissue) | *Australoscleromedulloxylon* | - |
| | *Paulistoxylon* | - |
| | *Paranaseptoxylon* | - |
| | *Corticoxylon* | - |
| | *Piracicaboxylon* | - |
| | *Septomedulloxylon* | - |

The morphogenus *Catarinopitys* Mussa, collected from a thick sandstone packet in the base of the coal prone Rio Bonito Formation (Sakmarian) of the Paraná Basin, was not included in this group due to its pith morphology, which is narrow, eccentrical and typically multilobulate.

In extant floras, the presence of secretory canals in the pith occurs as a transitory character, disappearing in mature plant stages. In extant gymnosperms, the presence of canals can be observed only in young branches of *Cephallotaxus*, whereas *Ginkgo* presents this character in the pith during mature stages as well (Jeffrey, 1925). Nevertheless, as pointed out by Fahn and Zamski (1970) and Fahn (1974) and emphasized by Mussa (1982), the presence of canals of traumatic and/or spontaneous origin related to inherited or programmed answers is peculiar to particular plant groups, giving systematic value to this feature.

Steles of the Solenoid Complex were included in the Artinskian-Kungurian interval by Mussa (1986). However, radiometric dating obtained by Santos et al. (2006) resulted in the absolute age of $278.4 \pm 2.2$ Ma for the Irati Formation. This age interval allowed us to attribute a middle Kungurian age deposition for this lithostratigraphic unit according to
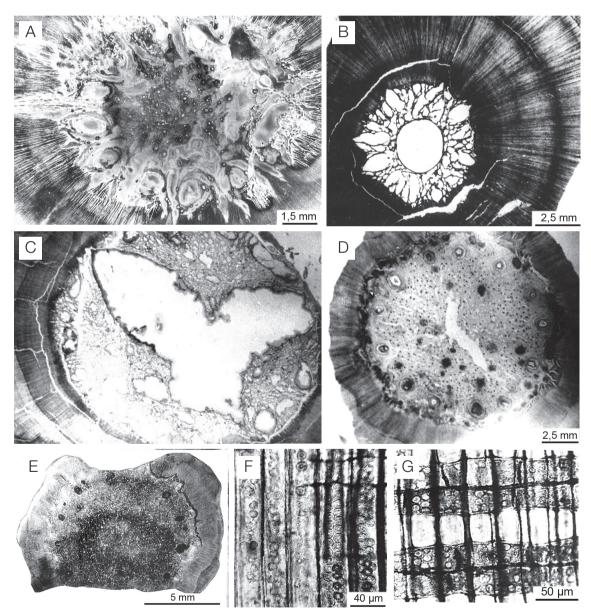
Cohen et al. (2013). Jha (2006) and Singh et al. (2007) inferred a tentative age connotation of later Artinskian (middle Kungurian according to Cohen et al., 2013) for Upper Barakar Stage based in palynological and macroplant data. The stratigraphic range of these fossils in Brazil and India is therefore restricted to the middle Kungurian.

The phytogeographic distribution of the Solenoid Complex, although associated with distinctive lithologies (organic shales related to coals in India and shales and carbonatic sediments in Brazil), was linked to cyclical, seasonal conditions, usual in confined basins of restrict water circulation and sometimes subject to seasonal hipersalinity (Jha, 2006; Milani et al., 2007). Based on growth ring analyses in fossil woods, Alves and Guerra-Sommer (2005) indicate a "Mediterranean-like climate" during the deposition of the Irati Formation of the Brazilian Paraná Basin. The disappearance from the geological record of woods showing solenoid pattern associated with the pith structure can be linked to changing environmental and/or climatic conditions, which must have occurred at the end of specific cycles of deposition, identifiable within the limits of Barakar-Kulti and Irati-Serra Alta formations.

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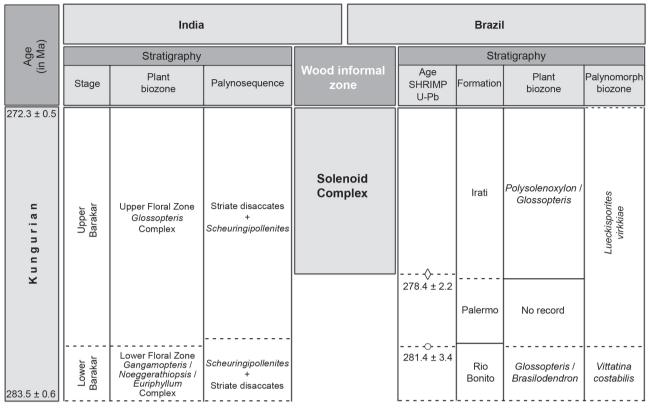Geol. USP, Sér. cient., São Paulo, v. 14, n. 2, p. 139-148, Junho 2014

The comparison between the wood data and phyto and palynostratigraphy schemes for the same interval in Indian and Brazilian basins lead to the establishment of correlations presented in the Figure 2.

According to the palynostratigraphy proposed for the Paleozoic of the Paraná Basin by Souza and Marques-Toigo (2003, 2005), the palynoflora of the Irati Formation is included in the *Lueckisporites virkkiae* Interval Zone. The assemblage is comprised predominantly of bisaccate

(taeniate and non-taeniate) and polyplicate pollen grains. *L. virkkiae* is considered a datum in the Paraná Basin, ranging from its southernmost to the northernmost border. Climatically driven changes in floras appear to have occurred during the transition from the *Vittatina costabilis* Zone (which includes the coal prone rocks) to the *Lueckisporites virkkiae* Zone (Iannuzzi et al., 2010; Simas et al., 2013).

In the correlation chart of chrono and biostratigraphic data by Iannuzzi and Souza (2005), no plant zones were observed



**Figure 1.** Anatomic patterns of the Solenoid Complex in cross-section (A-E) and radial section (F, G): (A) *Polysolenoxylon*; (B) *Atlanticoxylon*; (C) *Petalopitys*; (D) *Solenopitys*; (E) *Barakaroxylon*; (F) *Agathoxylon* type of secondary wood pitting; (G) *Agathoxylon* crossfield pitting.

| Age (in Ma) | India | | | Wood informal zone | Brazil | | | |
|---|---|---|---|---|---|---|---|---|
| | Stratigraphy | | | | | Stratigraphy | | |
| | Stage | Plant biozone | Palynosequence | | Age SHRIMP U-Pb | Formation | Plant biozone | Palynomorph biozone |
| 272.3 ± 0.5 **K u n g u r i a n** 283.5 ± 0.6 | Upper Barakar | Upper Floral Zone *Glossopteris* Complex | Striate disaccates + *Scheuringipollenites* | **Solenoid Complex** | | Irati | *Polysolenoxylon / Glossopteris* | *Lueckisporites virkkiae* |
| | | | | | 278.4 ± 2.2 | Palermo | No record | |
| | Lower Barakar | Lower Floral Zone *Gangamopteris / Noeggerathiopsis / Euriphyllum* Complex | *Scheuringipollenites* + Striate disaccates | | 281.4 ± 3.4 | Rio Bonito | *Glossopteris / Brasilodendron* | *Vittatina costabilis* |

Kungurian limits after Cohen, Finney and Gibbard (2013); radiometric zircon ages for the Paraná Basin after ○ Mori et al. (2012) and ◊ Santos et al. (2006); Indian stratigraphy modified from Jha (2006) and Singh et al. (2007); Brazilian stratigraphy modified from Souza and Marques-Toigo (2005) and Iannuzzi and Souza (2005).

**Figure 2.** Chart of tentative correlation between India and Brazil establishing the wood informal zone "Solenoid Complex".

for the studied interval in the southern part of the Paraná Basin, whereas, for the northern part, the deposition interval of the Irati Formation is included in the *Polysolenoxylon-Glossopteris* Zone. However, Iannuzzi and Souza (2005) did not mention a leaf assemblage composed mainly of *Glossopteris* and also of *Ginkgophytopsis*, *Ginkgoites*, *Cordaites* and rare *Paracalamites* fragments described earlier for the southernmost part of the basin (Bortoluzzi, 1975; Backeuser et al., 1984), neither the rich lignofloristic assemblage described for the Irati Formation in the southern border of the basin (Merlotti, 2002). The presence of *Brasilodendron* and different species of *Glossopteris* observed for the coal-bearing interval in the southern part of the basin allows its stratigraphic assignment to the *Brasilodendron-Glossopteris* Zone by Iannuzzi and Souza (2005) because these morphogenera constitute diagnostic taxa (Simas et al., 2013), as represented here in the Figure 2. The absence of fossil macroplants in the Palermo Formation is due to the fact that this is the Permian maximum flooding interval in the Paraná Basin.

The "Solenoid Complex" is here proposed as an informal zone, occurring in the northern (São Paulo State) and southern (Rio Grande do Sul State) borders of the Paraná Basin, and also in the Barakar Stage in Indian basins during the middle Kungurian.

The record of *Polysolenoxylon* by Maheshwari (1972) in the intermediate levels of the Lower Mount Glossopteris Formation in Ohio Range, Antarctica (Long, 1965), of Baigendzinian age (late Artinskian) according to Farabee et al. (1991), based on palynological data, indicates that the Solenoid Complex could have also occurred in the Antarctic subcontinent, in age intervals presently corresponding to the Kungurian (according to the criteria of Cohen et al., 2013).

In contrast to the rare impression/compression fossils described from the Irati Formation, abundant plant assemblages are recorded for the Barakar Stage (Chandra and Chandra, 1988; Mitra, 1991; Srivastava, 1992), which allowed the establishment of a phytostratigraphic zonation. The Solenoid Complex can be correlated with the Upper Floral Zone preserved in organic shales associated to the upper coal seams of the Barakar Stage in different Indian basins, mostly represented by several species of *Glossopteris,* some ferns (*Neomariopteris*, *Pecopteris*) and arthrophytes

(*Phyllotheca*, *Sphenophyllum*, *Lelstotheca*) (Goswami et al., 2006). Conversely, *Gangamopteris*, *Euryphyllum*, *Noeggerathiopsis*, *Pallaeovitaria*, *Maheswariophyllum* and *Buriadia*, typical for the Lower Floral Zone associated with shales of the lower coal seams, declined in both diversity and abundance and disappeared at the end of the Barakar coal deposition interval. The increasing and widespread peat accumulation suggests that the climate became comparatively warmer, favoring the rapid growth and diversification of *Glossopteris* and the waning of *Gangamopteris* (Lele, 1976; Tiwari, 1974; Tiwari and Tripathi, 1988; Pant and Nautiyal, 1987; Chandra and Singh, 1992; Srivastava, 1992).

The distribution of the Solenoid Complex in the Barakar Stage can be correlated with the palynoassemblages "Striate disaccates + *Scheuringipollenites*", based on Jha (2006) (Figure 2). Tripathi and Bhattacharya (1997) and Tiwari (2001) concluded that these palynoassemblages reflect the change when the monosaccate-rich palynofloras were replaced by disaccate-rich assemblages. Generally speaking, the typical palynoassemblages from Barakar Formation reflect the proliferation of striate disaccate forms (Goswami et al., 2006).

A latitudinal belt of 40°-55° S (Figure 3) for the Gondwana Solenoid Zone can be inferred for Brazilian and Indian data based on the landmass distribution presented in the paleogeographic maps of the late Cisuralian (Ziegler et al., 1997). However, the absence of polar ice caps during this interval (Ziegler et al., 1997) must have contributed to a milder climate in the temperate biome.

However, woods showing solenoid piths with canals and ducts, as well as secretory and sclerenchymatic cells, and araucarian pitting in the radial walls of the tracheids were described for the lower Motuca Formation in the Parnaíba Basin by Kurzawe et al. (2013a, 2013b). The assemblage is anatomically comparable to the ones discussed in the present study despite the absence of growth rings in the secondary wood in the Parnaíba Basin. Consequently, besides the presence of some foliar genera showing Gondwanan affinities, the occurrence of the Solenoid wood pattern would allow a correlation between the Irati Formation in the Paraná Basin (upper Kungurian) and the lower Motuca Formation (currently included in the middle to late Permian). The Solenoid Zone in this case could occur in a wider climate belt (temperate to subtropical) during the late Cisuralian.
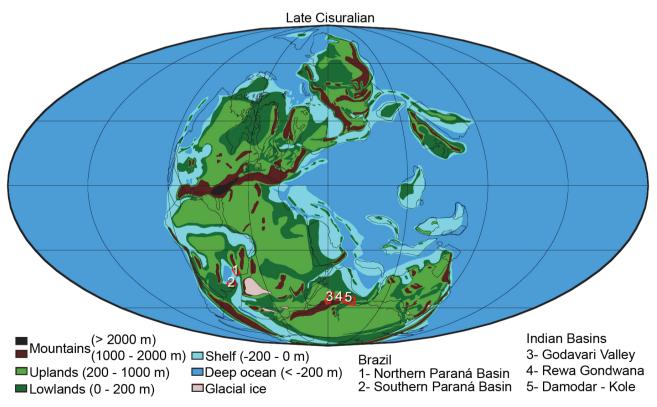


**Figure 3.** Late Cisuralian paleogeography (after Ziegler et al., 1997); basin locations with occurrence of wood included in the Solenoid Complex after Mussa (1982, 1986), Maheshwari (1992) and Srivastava (1992).

## FINAL REMARKS

The Solenoid Complex comprises a group of eusteles characterized by a system of secretory canals in longitudinal and radial orientation, distributed in a wide pith that in turn can be solid or have gaps and cavities. In spite of the paleogeographic distance between Brazilian and Indian Gondwana, the stratigraphic distribution of the Solenoid Complex is restricted to the middle-late Kungurian, occurring in both Western and Eastern Gondwana Realm. Its presence in fossil woods is linked to systematic and phylogenetic approaches and seems to be related to the adaptation of specific plant groups to paleoenvironmental stress in restricted, lowland niches in coastal areas subject to salinity variation. The disappearance of these forms in the latest Kungurian appears to be related to the cessation of these conditions, which is confirmed by the sedimentary record. The here designated "Solenoid Complex Zone" is correlated with the acme of striate pollen grains, reflecting tectonically and climatically driven changes in the floristic composition evidenced in both the Upper Floral Zone of the Barakar Stage and in the Irati Formation of the Paraná Basin (Figure 2). The waning icehouse stage during the Permian was an important factor to the development of similar vegetation patterns in Western and Eastern Gondwana in the latitudinal belt of 40°-55°S inferred for the Solenoid Complex Zone (Figure 3).

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