# THE EARLY PERMIAN COAL-BEARING SUCCESSION OF THE PARANÁ BASIN IN SOUTHERNMOST BRAZIL: DEPOSITIONAL MODEL AND SEQUENCE STRATIGRAPHY

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**ABSTRACT** This study shows a stratigraphic analysis with emphasis on the coal-bearing strata of the Early Permian package in southernmost Brazil (Paraná Basin). The studied interval comprises the Early Permian lithostratigraphic units Itararé, Rio Bonito, Palermo and Irati (base). Eight facies associations are recognized, and are presented within a third order stratigraphic framework, linked by systems tracts, limited by flooding surfaces and sequence boundaries. Some of the South-Brazilian coal seams were originated in fluvial settings, but the most important coals were deposited in a lagoon-barrier system.

*Keywords*: South America, Early Permian, Paraná Basin, sequence stratigraphy, Coal environment

**INTRODUCTION** The southern region of Brazil, comprising Santa Catarina and Rio Grande do Sul states (Fig.1), has been known for its abundant and economically important coal seams since the beginning of the century (White 1908). The southernmost state of Rio Grande do Sul has the majority of the coal reserves, and the Santa Catarina State shows the greatest production (DNPM 1996). This paper is a synthesis and shows the state-of-art of the stratigraphic and organo-petrographic studies on the coal-bearing interval, presenting a stratigraphic overview which summarize (1) the facies and environments, (2) the sequence stratigraphy of the coal-bearing strata and (3) a discussion of coal characteristics within the depositional model. The data were obtained from well logs and cores, supplied by the Brazilian agency CPRM (Geological Survey of Brazil).

**GEOGRAPHICAL AND GEOLOGICAL CHARACTERIZATION OF THE STUDIED AREA** The study area is part of a tectonic unit from southwestern Gondwana known as the Paraná Basin, a large intracratonic basin located in the central-eastern part of the South-American Platform (Fig. 1), covering a surface area about 1,700,000 km$^2$. Milani *et al*. (1994) recognize six second order depositional sequences. The study interval is located within the third sequence, namely the Carboniferous/Eo-Triassic Sequence, the thickest sequence of the basin (2800 m).

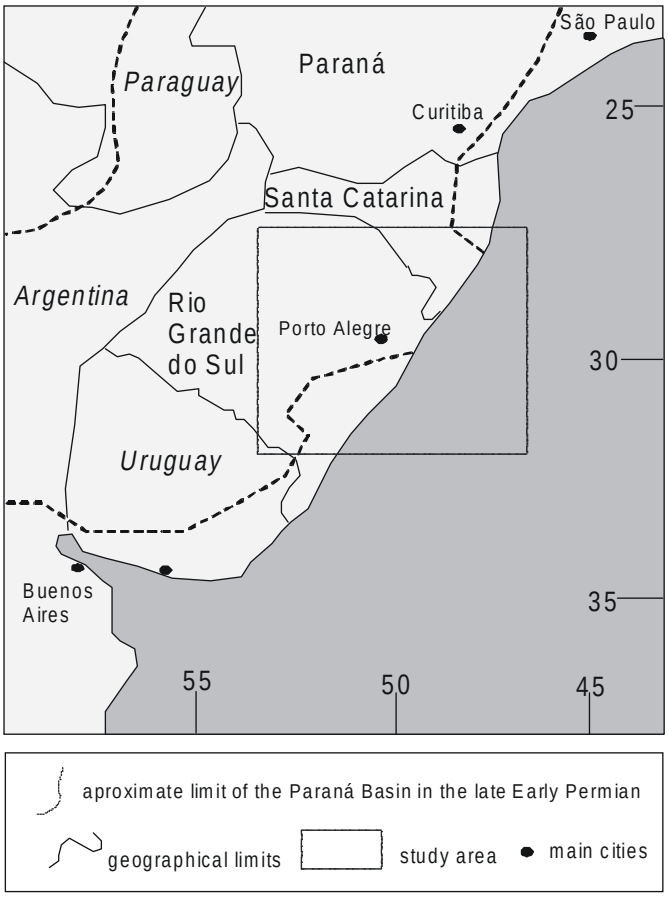


*Figure 1 - Overview of the study area: geographic setting and location map*

**FACIES AND LITHOSTRATIGRAPHY** The coal occurrences are historically assigned to the Rio Bonito Formation, a fluvial to marine sand- and shale-prone lithostratigraphic unit of Early Permian age (Artinskian-Kungurian, see figure 2 for geochronologic and biostratigraphic details). Three members are recognized in the complete section in Santa Catarina (cf. Schneider *et al*. 1974): Triunfo (fluvial and coastal plain), Paraguaçu (marine) and Siderópolis (fluvial and coastal plain). The type section with this tripartite lithostratigraphic division is only found in Santa Catarina, but not in Rio Grande do Sul.

In order to understand the depositional conditions of the coal-bearing sequence and for regional correlation, the entire Early Permian interval in southernmost Brazil (Sakmarian to Kungurian/Ufimian) has been analyzed. This interval comprises the lithostratigraphic units Itararé, Rio Bonito, Palermo and Irati (base) (Fig. 2). As detailed by Holz (1998) and Holz & Vieira (in press), eight facies association (FA's) are recognized in this interval (Table 1). Facies associations III to VI belong to the Rio Bonito Formation, the aim of the present study.

**DEPOSITIONAL SYSTEM OF THE COAL-BEARING STRATA** Some coal seams, very thin (< 0,5 m) and laterally discontinuous, occur in fluvial facies association (see FA-3 in table 1), characterized by orthoconglomerates and coarse to fine subarkose sandstones, with planar and trough cross bedding and fining-upwards cycles, ending in mudstone and coal. The interfluves are characterized by muddy facies with argillaceous coal seams.

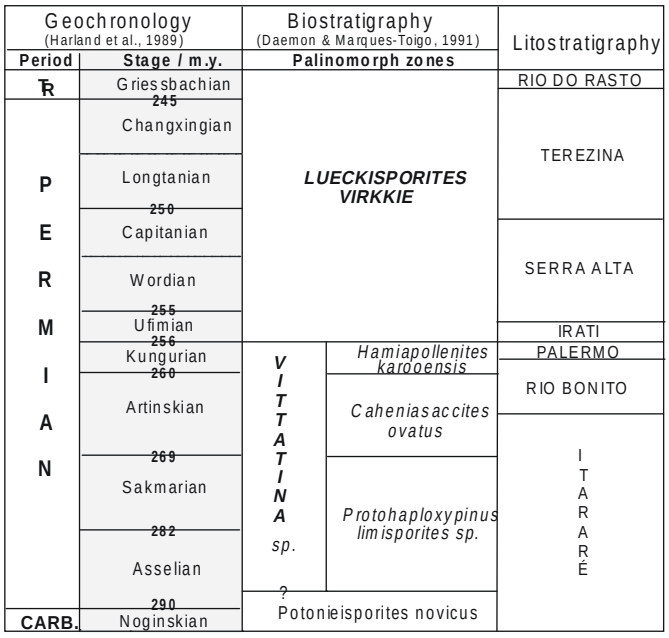


*Figure 2 - Stratigraphic summary of the studied interval (modified from Holz et al. 1999).*

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Thick (up to 2,5 m) and laterally continuous (up to 40 km) coal seams occur in association with fine sandstone and mudstone with lenticular and wavy bedding (see FA-4 in table 01). Paleosoils characterized by nodular mudstone with rootmarks occur in several levels within the mudstone-coal facies. Dip-directed correlation sections show that this coal-bearing facies is laterally and vertically associated with fine to medium quartz-rich sandstones (see FA-5 in table 01), forming units up to 12 meters thickness. The most conspicuous sedimentary structures are tabular cross stratification and planar-parallel bedding, flaser levels, mud drapes and wavy bedding, and abundant swaley and hummocky cross stratification.

The features of facies associations 4 and 5 points to a barrier-lagoon depositional system, where the mires were formed behind barrier island. The muddy facies with coal seams were formed in lagoons during periods of inlet restriction. Insofar, the most important and economically valuable coal seams, as they are exploited in Santa Catarina (*e.g.* Criciúma area) and Rio Grande do Sul (*e.g.* Candiota area), were formed in coastal mires controlled by important base level fluctuations.

**SEQUENCE STRATIGRAPHY OF THE COAL-BEARING STRATA** The detailed stratigraphic framework shown in figure 3, has been established by application of sequence stratigraphy concepts (*e.g.* Van Wagoner *et al.* 1988). The eight facies associations have been ordered into systems tracts, the building blocks of the third-order depositional sequences.

**Sequence 1** The Sakmarian/Artinskian Itararé Group, lithologically characterized by pro-glacial facies associations 1 and 2 (see Table 1), overlies the Proterozoic and Early Paleozoic basement (= sequence boundary SB1, Fig. 3), and is bounded at the top by an unconformity marked by fluvial facies cutting into marine mudstones (= sequence boundary SB2, Fig. 3). No coal occurs in this sequence.

**Sequence 2** It contains the most important coal seams of Rio Grande do Sul state and is bounded by a sequence boundary (SB2) at its base and an unconformity labeled SB 3 at its top. The coal seams are linked to a third order transgressive tract, labeled TST2. The Santa Catarina area, by this time, was mostly a marine embayment formed by the transgression of the "Paraguaçu Sea" (Fig. 3). The Paraguaçu Member registers Lithostratigrafically this transgression, where no coal has formed. The highstand systems tract of sequence 2 (HST2) is marked by progradational coastal sediments with the development of some coal seams in both Santa Catarina and Rio Grande do Sul states.

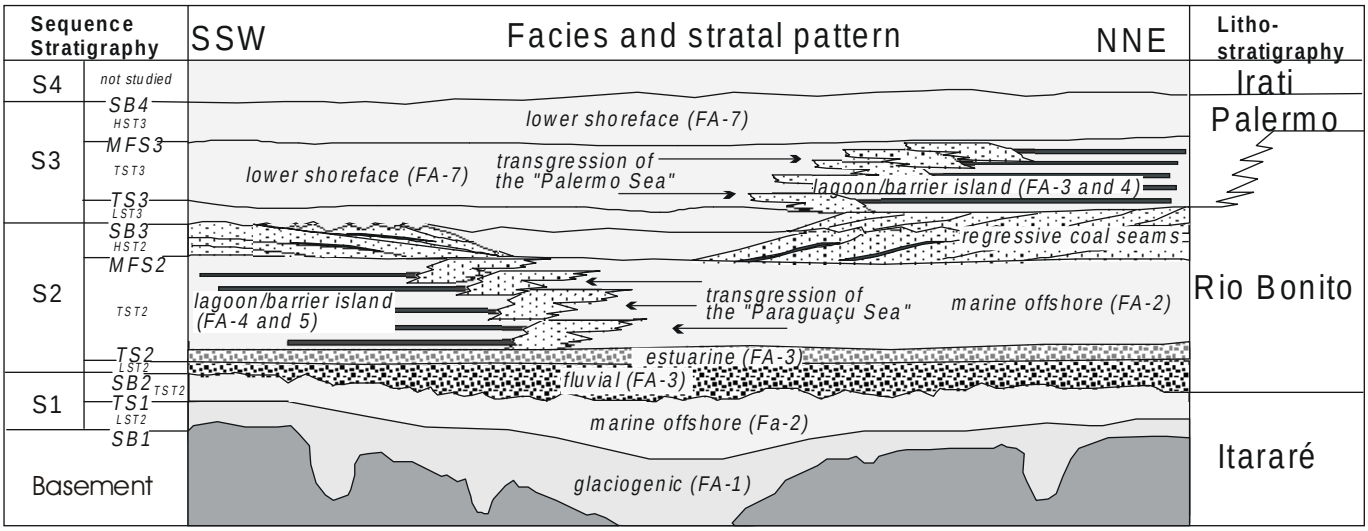


*Figure 3 - Chronostratigraphic framework of the studied interval, showing facies associations, systems tracts, third-order sequences and their lithostratigraphic equivalents, from Holz & Vieira (in press). Key for abbreviations: SB = sequence boundary, TS = transgressive surface, MFS = maximum flooding surface, LST = lowstand systems tract, TST = transgressive systems tract, HST = highstand systems tract*

*Table 1 - Summary of the facies associations (FA's) recognized in the study area.*

| Facies Association | Description *( * maximum thickness)* | Interpretation |
|---|---|---|
| 1 | muddy and sandy rhytmithes with dropped pebbles, fading ripples, climbing ripples, pebbly mudstones and diamictites; 30 m* | turbidity currents originated the rhytmithes, the conglomerates represent proximal debris flows and tillites (glacial and pro-glacial sedimentation) |
| 2 | dark gray to black mudstone, mostly massive, some lenticular and hummock cross bedding,10 m* | marine deposits, mostly below storm wave base |
| 3 | fine to coarse subarkosean sandstones, with laterally interfingering mudstones and thin coal seams, and sandstones with wavy and lenticular bedding, 40 m* (coal: 0.6 m*) | fluvial environment evolving to estuarine at the top, the coarser portions represent channel deposition, the finer portions and associated coals are floodplain deposits; wavy and lenticular bedded sandstones are estuarine |
| 4 | dark mud- and siltstones, bioturbated, with wavy and lenticular bedding, and thick coal seams; 50 m* (coal: 10 m*) | peat-forming coastal bays |
| 5 | fine to medium quartzitic sandstone, commonly laminated (drapes, wavy, linsen, swaley/ hummocky cross stratification), interfingered with bioturbated mudstones and shales; 65 m* | deposition in a proximal to distal shoreface environment, locally tidal deposits (tidal bars, tidal rhythmites) |
| 6 | marls and siltstones with birdseyes structure, interbedded with thin sandstones with hummocky cross stratification, 6 m* | supratidal environment periodically affected by storms; |
| 7 | gray mudstones, with wavy and lenticular bedding, interfingered with fine to medium sandstones showing wave-truncated lamination, 70 m* | deposition between normal and storm wave base in an offshore region, characterizing a epicontinental sea |
| 8 | black shales interbedded with calcilutites, 10 m* | deposition within restricted marine environment |

**Sequence 3** The sequence boundary SB3 is the base limit of sequence 3. In Santa Catarina State it is marked by fluvio-deltaic input and progradation of a coal forming barrier-lagoon system (the base of the Siderópolis Member), characterizing the lowstand systems tracts deposition (LST3). The transgressive surface TS3 marks the change from progradational to retrogradational sedimentation regime, characterizing the middle and upper portions of the Siderópolis Member, where important coal seams were formed during the transgression of the "Palermo Sea".

In Rio Grande do Sul state the sequence boundary SB3 is commonly marked by supratidal facies (see FA-6 in Table 01), overlain by the distal facies of the retrograding coastal system in the Santa Catarina area (offshore sands and muds of FA-7, see Table 01). These marine facies correspond lithostratigraphically to the Palermo Formation.

**Discussion** As illustrated in the schematic correlation section shown in figure 3, there are two coal-forming retrogradational barrier-lagoon systems, separated in time. The eustatic trend was positive, but tectonics overprinted its signature to sedimentation pattern, because the study area has undergone differential subsidence and tectonic reactivation. The first barrier-lagoon system developed in Rio Grande do Sul state, and at that time the Santa Catarina area was topographically low and characterized by a marine embayment, where the muddy facies is assigned as the Paraguaçu Member. After a base-level fall and the installation of the sequence boundary SB3, an important topographic inversion occurred. The Rio Grande do Sul region was flooded by the ongoing transgression, whereas the Santa Catarina source area was re-activated, with the progradation of coal-bearing sandstones at the base of the Siderópolis Member. In sequence stratigraphy terms, this marks the lowstand systems tract of sequence 3. As the overall Early Permian transgressive trend of sea level was going on, a second retrogradational barrier-lagoon system was installed, forming the sand-coal units of transgressive systems tract TST3 present in Santa Catarina State. Insofar, the analysis of the third order systems tract show that the coals in Rio Grande do Sul and Santa Catarina states are not equivalent in time, nor are the lithostratigraphic subdivision. The marine Paraguaçu Member, as recognized in the type section of the Rio Bonito Formation in Santa Catarina state, is correlative with the transgressive sand-coal units of Rio Grande do Sul state. Insofar, the lithostratigraphic limits are clearly diachronous.

**SEQUENCE STRATIGRAPHIC ORIENTATED DEPOSITIONAL MODEL AND COAL PROPERTIES** Based on the above stratigraphic framework, the team at UFRGS is now working to integrate stratigraphic, organo-petrological and geochemical data to investigate the correlation between the petrologic characteristics of the coal measures and the depositional history as depicted by the forth-order stratigraphic framework. Previous studies on this subject in other coal-bearing basins has conclusively shown that some proprieties of a coal seam, such as vitrinite reflectance, maceral distribution, Gelification Index (GI) and Tissue Preservation Index (TPI) are strongly controlled by the sedimentary regime (progradational, retrogradational or aggradational|), and that any variation in the sedimentation regime results in a related variation of coal seam properties.

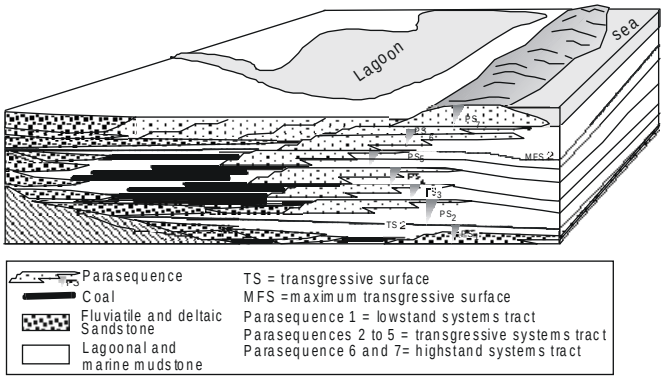


*Figure 4 - Schematic representation of the depositional model for the coals in the Candiota area (modified from Holz et al. 1999)*

The ongoing research focuses at present time on the Bagé/Candiota area, in the southwestern region of the Rio Grande do Sul State. For these areas several correlation sections have been established, applying forth-order sequence stratigraphy and form the database for the integrated analysis. Preliminary results presented by Holz *et al.* (1999) show the correlation between the stratigraphic framework and the analyzed coal parameters. The stratigraphic succession of the coal-bearing interval is composed of four retrogradational parasequence sets, forming the transgressive system tract TST 2 as shown in figure 4. Each of the parasequences contains several coal seams. While the first coal seam of every parasequence set formed under a retrogradational sedimentation regime, with a coastal encroachment in the order of several tens of kilometers, the following coal seams are strongly progradational, as shown in figure 4. The coal characteristics vary according to this stratigraphic interpretation. The vitrinite content and the GI decrease from the first to the last coal seam of every parasequence set, reflecting the gradual modification of the physical and chemical conditions of the successive mires as the sea level oscillated and advanced throughout the 4th order parasequence package. The study shows that coal petrology can be applied not only in order to determine coal type and technological properties, but also as an additional tool for sequence stratigraphic interpretations.

**CONCLUSION** The important economic coal seams of the Rio Bonito Formation, a lithostratigraphic unit here presented in a third order framework, are not linked to fluvio-deltaic environment, but to a barrier/lagoon system. The control on sedimentation and peat accumulation seems to be eustatic, as recorded by many minor flooding surfaces, and tectonic, as indicated by the reactivation of source areas. The important coals in Rio Grande do Sul state were formed earlier than the coals in Santa Catarina state due to inversion in the regional paleophysiography because of tectonic control in the source areas.

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