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Contribution to the Holocene history of Atlantic rain forest in the Rio Grande do Sul state, southern Brazil

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Abstract: This is a paleoclimatic synthesis based on the results of seven cores from the Brazilian Coastal Plain and adjacent low areas (Central Depression and Serra Geral, southern foothill valley) of Rio Grande do Sul, published by different authors. The objective is asses to the Holocene history of the Atlantic rain forest *stricto sensu* (*str. s.*), a dense ombrophilous forest in the extreme southern Brazil. The comparative analysis indicates scarce presence of the first taxa of the Atlantic rain forest *str. s.* at the beginning of the Holocene (probably due to warmer and wetter climate) and sea-level oscillations. Subsequently marsh forest expansion took place after 4,000 BP on the coast, after sea regression and desalination of the soils. In the adjacent low areas from the coast, favored by this warmer and wetter climate without marine influence, expansion of the forest seems to have occurred earlier, at about 4,000 BP. In the Serra Geral southern foothill valleys and Central Depression forest expansion occurred much earlier, at *ca.* 6,000 BP. These data agree with the coastward migration of the Atlantic rain forest *str. s.* from inner continental areas colonizing the Coastal Plain of southern Brazil in the Late Holocene.

Key words: South Brazil; Palynology; Palaeoclimatology; Late Quaternary; Atlantic rain forest.

The Atlantic rain forest *str. s.*, a dense ombrophilous forest, covers the Brazilian coast and adjacent areas from the north to the extreme south (Rio Grande do Sul state). Much attention is devoted to environmental preservation programs due to this forest high biological diversity (to shelter species threatened by extinction) in face of the indiscriminate use of the land. Efforts have concentrated on floristic and faunistic studies and on several ecological aspects focusing on preservation, but very little is known of the past behavior of this forest, which would be essential for the understanding of its present-day distribution and predictions of its natural response to climate change. Although there is a large area involved, there is little information about the Holocene history of this Atlantic data are from one site in the Santa Catarina state (Behling, 1995, 1998; Ybert *et al.*, 2001, 2003) and from seven sites in the Rio Grande do Sul state, including Coastal Plain as well as adjacent low areas (Cordeiro, 1991; Cordeiro & Lorscheitter, 1994; Grala & Lorscheitter, 2001; Lorscheitter & Dillenburg, 1998; Neves, 1991, 1998, 2000; Neves & Lorscheitter, 1995, 1997; Werneck & Lorscheitter, 2001). This paper summarizes paleoecological evidence of these seven sites. The objective is to obtain a general view of the behavior of the Atlantic rain forest *str.s.* in the extreme south of Brazil (its meridional limit) during the last millennia, to provide more information for the preservation programs of this important tropical forest.

The Atlantic rain forest *str. s.* area in Rio Grande do Sul

Sul state was related to climatic changes and associated sea-level oscillations (Villwock & Tomazelli, 1998). The present-day climate along the coast and in the adjacent low areas is characterized by Nimer (1979) as mild mesothermic and very humid. According to Köppen's classification (Moreno, 1961) the regional climate is CFa-humid sub-tropical, with temperatures mitigated by the thermo-regulating action of the Atlantic Ocean and the coastal lake bodies.

This long Coastal Plain (622 km), with a well developed system of coastal lakes and lagoons, produces a rich aquatic vegetation ranging from brackish to fresh water, as described by Irgang (1999). Aquatic macrophyte vegetation is represented by several stages of succession, given very unstable environments. The gentle sloping of the coastal area hastens the filling of water bodies with sediment tending to make them shallow and marshy. In many of these freshwater swampy areas there are marsh forests. These marsh forests are considered an edaphic variant of the Atlantic rain forest of the more firm soils (Rizzini, 1997) present inland from the coast. The marsh forest consists of low trees, about 12 m high, and of a great number of tropical species of the Atlantic rain forest, such as *Coussapoa microcarpa* (Schott) Rizz., *Euterpe edulis* Mart., *Geonoma schottiana* Mart., *Ilex pseudobuxus* Reiss., *Talauma ovata* A. St. Hil., pioneer species such as *Alchornea triplinervia* (Spreng.) Müll. Arg., *Cecropia pachystachya* Trec., *Myrsine umbellata* Mart. ex A.DC., and many other arboreal species such as *Bactris setosa* Mart., *Ficus organensis* (Miq.) Miq., *Myrsine lorentziana* (Mez) Arechav, *Sorocea bonplandii* (Baill.) Burg., Lanj. & Boer, including various Myrtaceae, a rich lower stratum of pteridophytes and a high number of epiphytes: pteridophytes, Bromeliaceae and many Orchidaceae species (Waechter, 1986; Kindel, 2002). Due to frequent rains and poor drainage conditions, the water table lies near or a little above the surface and the soil is rich in organic matter. In many places, mainly at the forest border, *Sphagnum* is present, giving rise to a somewhat peaty soil.

As a whole, the Rio Grande do Sul Atlantic rain forest *str. s.* (Teixeira & Coura Neto, 1986) spreads southward along the coast, from the extreme north (Torres region, Fig. 1), diminishing gradually until disappearing south of 32°S. It also spreads westward penetrating into the eastern slopes of Serra Geral mountain and, along *ca.* 30° S, into the lowlands that cut across Rio Grande do Sul, i.e., the Central Depression and the adjacent southern foothill valleys of Serra Geral (Baptista, 1967). As in the Coastal Plain, the species of this forest gradually disappear towards the interior of the continent (Fig. 1). Through the analysis of present-day local flora but without giving chronological evidence Rambo (1950, 1951, 1961) concluded that Atlantic rain forest reached Rio Grande do Sul from the north of the coast (Torres region) and spread south and westwards.

STUDIED SITES

The distribution of the sites (Fig. 1) is related to the present-day Atlantic rain forests marshes and present-day lagoons.

1. Adjacent low areas of the Coastal Plain

Site 1. Serra Velha, 29°36' S-51°38' W (Grala & Lorscheitter, 2001), marsh forest, valley from southern foothills of Serra Geral.

Site 2. Guaíba, 30°11' S-51°22' W (Neves 1998, 2000), marsh forest, Central Depression.

2. Coastal Plain

Site 3. Terra de Areia, 29°33' S-50°03' W (Neves, 1991; Neves & Lorscheitter, 1995), marsh forest, inner portion of the northern coast, near the Serra Geral cliffs.

Site 4. Faxinal, 29°21' S-49°45' W (Werneck & Lorscheitter, 2001; Lorscheitter & Werneck, *m.s.*), marsh forest, northern coast, 2 km from the shoreline, Torres.

Site 5. Tramandaí Lagoon, 29°57' S-50°10' W (Lorscheitter & Dillenburg, 1998), lagoon, northern coast.

Site 6. Patos Lagoon, 30°50' S-50°59' W (Cordeiro, 1991; Cordeiro & Lorscheitter, 1994), northern portion of the long lagoon.

Site 7. Capão do Leão, 31°47' S-52°15' W (Neves & Lorscheitter, 1997; Neves, 1998), marsh forest, southern coast.

MATERIAL AND METHODS

The Hiller sampler was used for forest mud and vibracorer for lagoonal sediments to obtain the cores. The samples were prepared at the palynology laboratory (Botany Department, UFRGS) using the same method, enabling comparable results.

The chemical pre-treatment of the samples consisted of HCl, HF, KOH and acetolysis (Faegri & Iversen, 1989) and filtering in a 250 μm screen. *Lycopodium clavatum* tablets were added (Stockmarr, 1971) to most of the samples, to calculate palynomorph concentration. The slides were mounted in glyceroljelly. Pollen identification relied on the reference collection of the palynology laboratory and on pollen and spore atlases (Heusser, 1971; Markgraf & D'Antoni, 1978; Wingenroth & Heusser, 1983; Roubik & Moreno, 1991; Lorscheitter *et al.*, 1998, 1999, 2001, 2002; Pire *et al.*, 1992, 1998, 2001). Whenever possible, a minimum number of 500 pollen grains and 100 exotic *L. clavatum* spores was counted simultaneously in each sample. Other palynomorphs were counted separately, while trying to reach the minimum numbers. The quantitative analysis took into consideration relative frequency (%) and concentration (grains/cm^3). Composite and detailed palynological diagrams permitted paleoenvironmental reconstruction. For chronological control conventional ^{14}C dates were used. This synthesis discusses and illustrates only the main parts of original percentage and/or concentration diagrams, extracted from the references (Fig. 2), in order to give a summary of the principal events of the last millennia. More detailed informations about the sites can be found in the cited references.

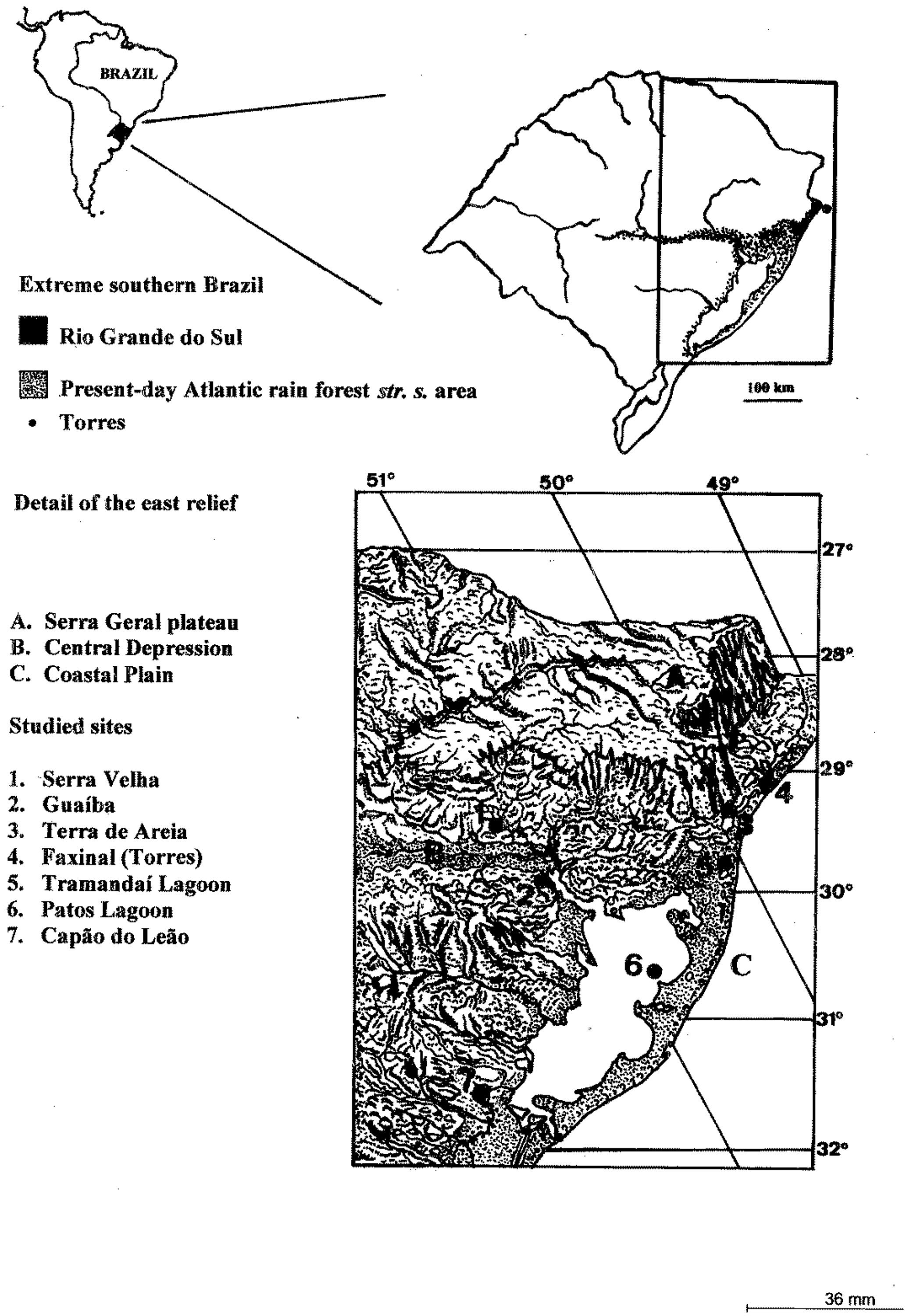


Fig. 1. Distribution of present-day Atlantic rain forest *str. s.* in Rio Grande do Sul state and the location of the studied sites.

RESULTS AND DISCUSSION

The palynomorphs were grouped according to distinct environments (Tab. 1) and their comparative analysis in the seven records (Fig. 2) shows the following results:

1. Adjacent low areas of the Coastal Plain

Site 1. Serra Velha

10,000-6,000 BP (zone I-lower zone III). Phase dominated by herbaceous marshes, showing a local water body conditions (Alismataceae, *Anthoceros*, *Blechnum*-type, Cyperaceae, Eriocaulaceae, *Isoetes, Myriophyllum, Osmunda, Phaeoceros, Selaginella, Sphagnum* and *Typha*, Grala & Lorscheitter, 2001). About 10,000 BP Poaceae was represented in the region and the first Atlantic rain forest taxa seem to have been rather scarce (low frequencies of *Acacia, Alchornea triplinervia,* Anacardiaceae, *Cecropia, Celtis, Myrsine,* Myrtaceae, *Roupala, Trema micrantha* and Urticales, Grala & Lorscheitter, 2001), but they show a significant expansion throughout the marsh area at about 7,800 to 7,000 BP (Fig. 2). The presence of forest indicators and their expansion is probably related to the warmer and wetter climate in the beginning of the Holocene. The higher frequencies of dry soil indicators are coincident to the forest retraction (Fig. 2).

6,000 BP up to the present (zone III). The latest arboreal expansion throughout the marsh began at about 6,000 BP, giving rise to the present-day Atlantic rain marsh forest. The same arboreal pollen is now in great frequencies, besides *Ilex pseudobuxus*, very well represented in this phase (unpublished data). At this phase the higher frequencies of Poaceae probably is due to regional human activity (forest clearing).

Site 2. Guaíba

12,000-6,000 BP (zone I-zone III). This phase shows the pioneer arboreal taxa, with a low regional distribution of forest (low frequencies of Myrtaceae, *Myrsine, Alchornea triplinervia, Cecropia, Roupala* and *Trema micrantha*) (Fig. 2).

6000 BP up to the present (zone IV-zone V): At about 6000 BP began the latest arboreal expansion, giving rise to the present-day forest (Myrtaceae, *Myrsine, A. triplinervia,* and *Cecropia* become the main arboreal pollen components).

2. Coastal Plain

Site 3. Terra de Areia

23,800-4,000 BP (zone I-lower zone IV). As in the other sequences of the Coastal Plain, Atlantic rain forest indicators are found in very much lower concentrations before 4,000 BP (mainly Myrtaceae, *Myrsine, Ilex pseudobuxus,* and *Alchornea triplinervia*) (Fig. 2). The beggining of sequence (zone I) probably is related to a semi-arid climate in the region, according to the rare arboreal pollen (as in Lorscheitter & Romero, 1985 and Roth & Lorscheitter, 1993 for the end of the latest glacial stage). The increase of Myrtaceae and *A. triplinervia* in zone II is not treated here because more informations about date are necessary.

4,000 BP up to the present (zone IV). Without the negative influence of marine transgression (due to the salinity) and favored by the higher temperature and humidity at about 5,000 BP, the marsh forest seems to begin at about 4,000 BP (high concentration of Myrtaceae, *Myrsine, Ilex pseudobuxus* and presence of *Alchornea triplinervia*).

Site 4. Faxinal

7,000-6,000 BP (zone I-zone II). Pioneer arboreal taxa of the Atlantic rain forest already existed in this region according to the low concentration of arboreal pollen (Fig. 2) such as *Acacia,* Anacardiaceae, *Celtis, Ilex pseudobuxus, Myrsine,* Myrtaceae, *Roupala, Trema micrantha* and Urticales, Lorscheitter & Werneck, *m.s.*). Prior to about 7,000 BP (zone I, Fig. 2) there is a phase of marine transgression in the northern Coastal Plain (*Spiniferites mirabilis, Operculodinium centrocarpum,* and microforaminifera in the samples, Lorscheitter & Werneck, *m.s.*), showing that the Holocene marine transgression probably occurred in pulses (Medeanic *et al.*, 2001). This phase is probably correlated to the warmer and wetter climate at about 7,000 BP in Serra Velha (Fig. 2). A rapid marine regression in the Coastal Plain occurred (zone II). Still with some marine influence, the forest was open and probably distributed in patches. The herbaceous marshes are developed (represented especially by *Blechnum*-type, Cyperaceae, *Osmunda,* and *Phaeoceros*; Lorscheitter & Werneck, *m.s.*).

6,000-5,000 BP (zone III-lower zone IV). The sea level increased again, with a maximum Holocene transgression at about 5,000 BP, according to the highest frequencies of the marine indicators in the profile (Fig. 2). In spite of the increase in temperature and humidity at about 5,000 BP, the marine influence seems to become a limiting factor, directly or by edaphic alteration, to the forest expansion. Therefore, the forest distribution soon seems to be altered. On the other hand, taxa of dry sandy soils (including halophytes) developed bordering water bodies and swamps, represented by *Amaranthus*-Chenopodiaceae-

Table 1. Studied palynomorph taxa and the grouping into distinct environments.

Marine
Dinoflagellate cysts: *Operculodinium centrocarpum* (Deflandre & Cookson) Wall., other cysts, *Spiniferites mirabilis* (Rossignol) Sarjean., microforaminifera.

Dry soil
Amaranthus-Chenopodiaceae-type, *Baccharis*-type, *Gomphrena*, *Plantago*, Poaceae.

Herbaceous marsh
Alismataceae, *Anemia*, *Anogramma-type*, *Anthoceros*, *Azolla filiculoides* Lam., *Blechnum*-type, Cyperaceae, *Cystopteris*-type, Eriocaulaceae, *Huperzia*, *Isoetes*, *Lycopodium alopecuroides* (L.) Cranfill, *Myriophyllum*, *Osmunda*, *Phaeoceros*, *Regnellidium diphyllum* Lindm., *Salvinia*, *Selaginella*, *Sphagnum*, *Typha*.

Forest
Acacia, *Alchornea triplinervia* (Spreng.) Müll. Arg., *Alsophila*, Anacardiaceae, *Cecropia*, *Celtis*, *Ilex pseudobuxus* Reiss, Melastomataceae, Meliaceae, *Microgramma*, *Myrsine*, Myrtaceae, *Roupala*, *Trema micrantha* (L.) Blume, *Tripodanthus*, Urticales.

type, *Baccharis*-type, *Gomphrena*, *Plantago* and Poaceae (Lorscheitter & Werneck, *m.s.*).

5,000 BP up to the present (upper zone IV-zone VI). Marine regression seems to relate to forest retraction, probably due to edaphic alteration, a consequence of the previous transgressive phase. During the desalination of soils after 4000 BP the marshes were gradually recolonized, first with a hydrophytes such *Isoetes* (Fig. 2) followed by other marsh taxa in higher frequencies (*Alimataceae, Anthoceros, Azolla filiculoides, Blechnum*-type, Cyperaceae, Eriocaulaceae, *Huperzia, Myriophyllum, Osmunda, Phaeoceros, Regnellidium diphyllum, Salvinia, Selaginella,* and *Typha*, Lorscheitter & Werneck, in preparation). The transition phase is replaced by forest expansion, with a marked increase in arboreal pollen, giving rise to the present-day forest distribution. The higher frequencies of *Sphagnum* spores are observed with forest development (Fig. 2). In the final sequences of the profile, the increase of arboreal indicators coincides with a higher frequency of diverse pteridophyte taxa (*Alsophila, Blechnum*-type, *Huperzia*, and *Microgramma;* Lorscheitter & Werneck, *m.s.*) comparable to the floristic composition of the present-day Atlantic rain forest *str.s.* in Rio Grande do Sul, described by Waechter (1986), Jarenkow (1994), and Kindel (2002).

Site 5. Tramandaí Lagoon

6,000-5,000 BP (zone I-lower zone III). Large increase of marine indicators (*Operculodinium centrocarpum, Spiniferites mirabilis,* other cysts and microforaminifera) reaching a maximum at about 5,000 BP, when the great transgression in the lagoon ocurred (Fig. 2).

5,000 up to the present (zone III-zone IV). Very significant reduction of the marine indicators up to the disappearance, according to the accentuated marine regression.

Site 6. Patos Lagoon

5,000-4,000 BP (zone I-zone II). Large influence of marine indicators (*Operculodinium centrocarpum, Spiniferites mirabilis,* other cysts and microforaminifera; Cordeiro, 1991) reaching a maximum at about 4,000 BP, showing the great marine transgression in the lagoon. The Bryophytes (*Phaeoceros, Anthoceros,* and *Sphagnum;* Cordeiro, 1991) are frequent in this phase (Fig. 2), showing regional humidity.

4,000 BP up to the present (upper zone II-zone III). Very significant reduction of the marine indicators, showing a great marine regression on the coast (Fig. 2). The Pteridophytes are very expressive (*Blechnum*-type, *Anemia, Anogramma*-type, *Cystopteris*-type, *Selaginella, Lycopodium alopecuroides;* Cordeiro, 1991) indicating very humid environments (Fig. 2).

Site 7. Capão do Leão

6,000-4,000 BP (zone I-zone II). Significant presence of marine taxa (*Operculodinium centrocarpum, Spiniferites mirabilis,* and microforaminifera, Neves, 1998) with a maximum at about 4,000 BP (zone II), indicating the great marine transgression in the region (Fig. 2). The dry soil indicators related to halophytes are significant in this phase (*Amaranthus*-Chenopodiaceae-type

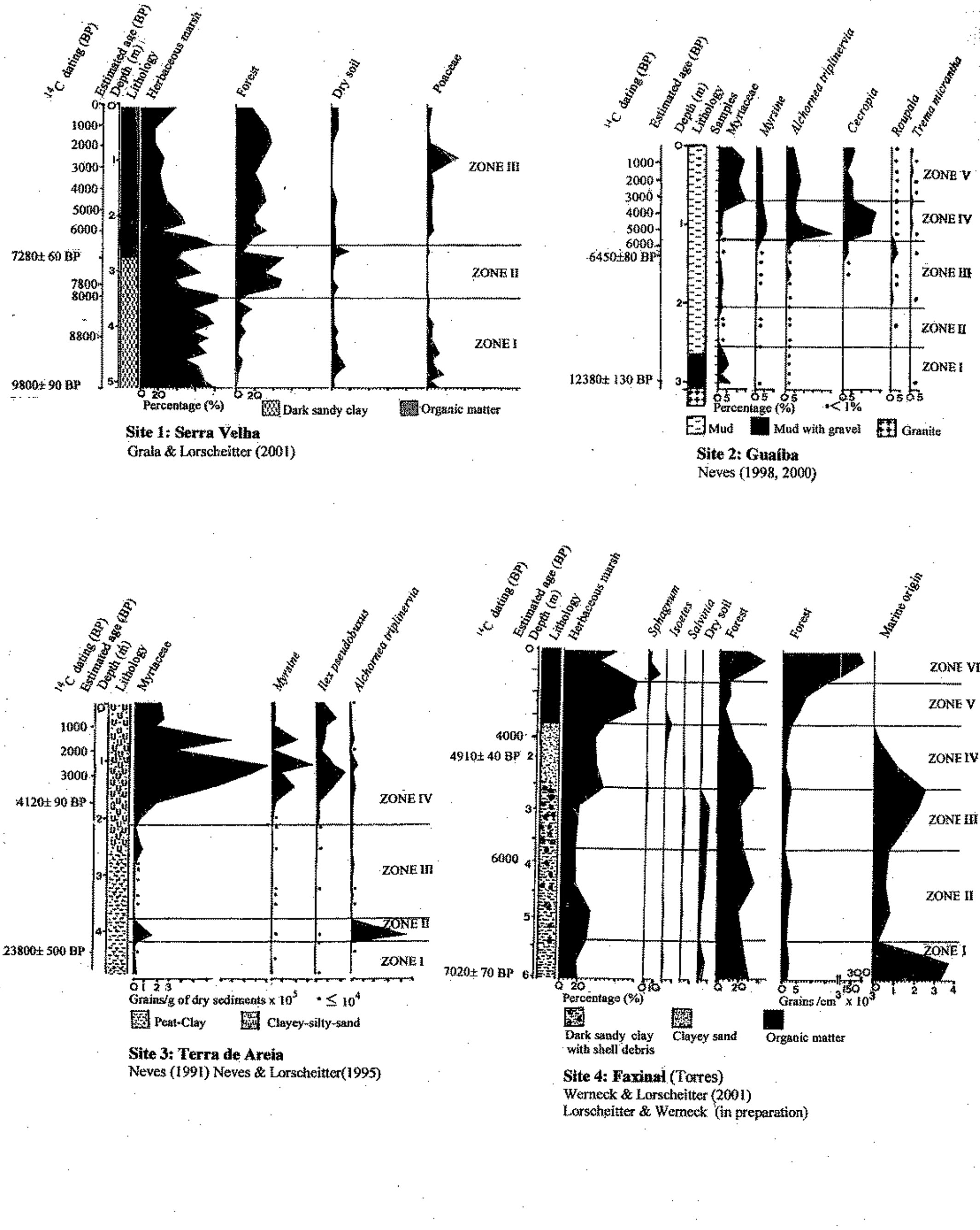
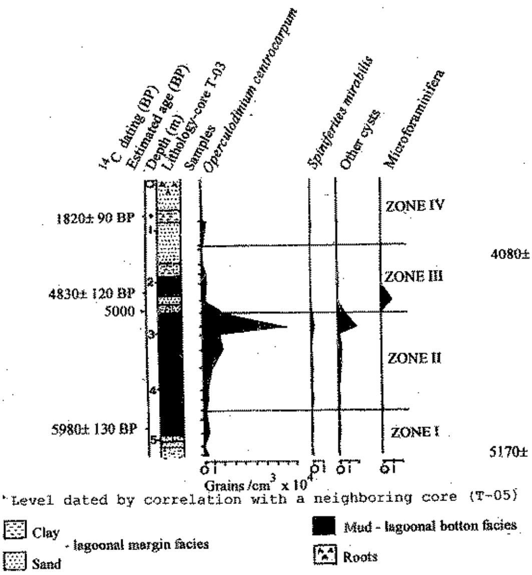
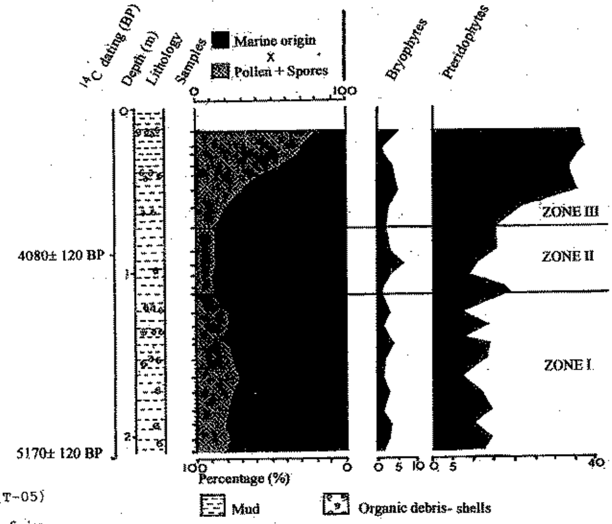


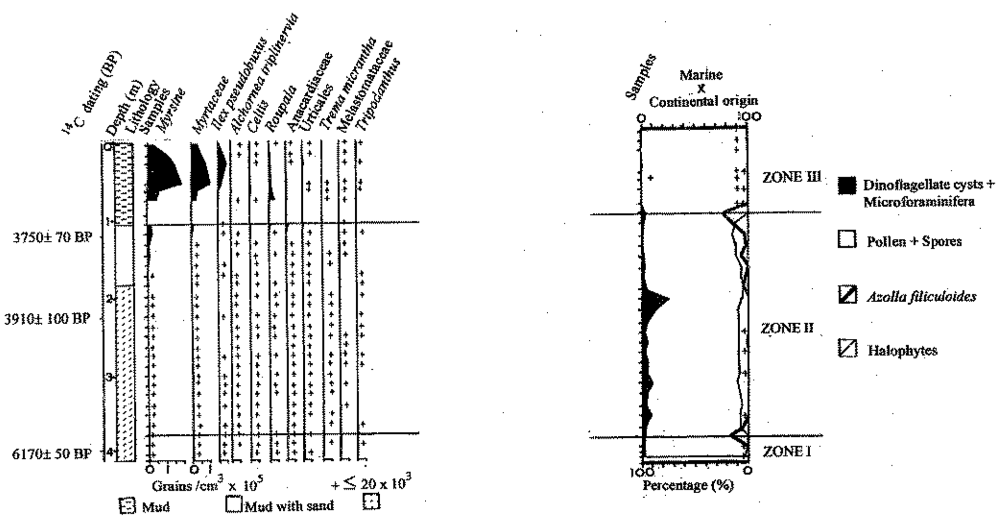
Fig. 2. Main palynological diagrams and radiocarbon ages of the seven studied sites in Rio Grande do Sul, adapted from the references: Coastal Plain adjacent low areas: 1. Serra Velha (valley of a southern foothill of Serra Geral), 2. Guaíba (Central Depression). Coastal Plain: 3. Terra de Areia, 4. Faxinal (Torres), 5. Tramandaí Lagoon, 6. Patos Lagoon, 7. Capão do Leão.



Site 5: Tramandaí Lagoon
Lorscheitter & Dillenburg (1998)



Site 6: Patos Lagoon
Cordeiro (1991); Cordeiro & Lorscheitter (1994)



Site 7: Capão do Leão
Neves (1998); Neves & Lorscheitter (1997)

36 mm

Fig. 2 (continued)

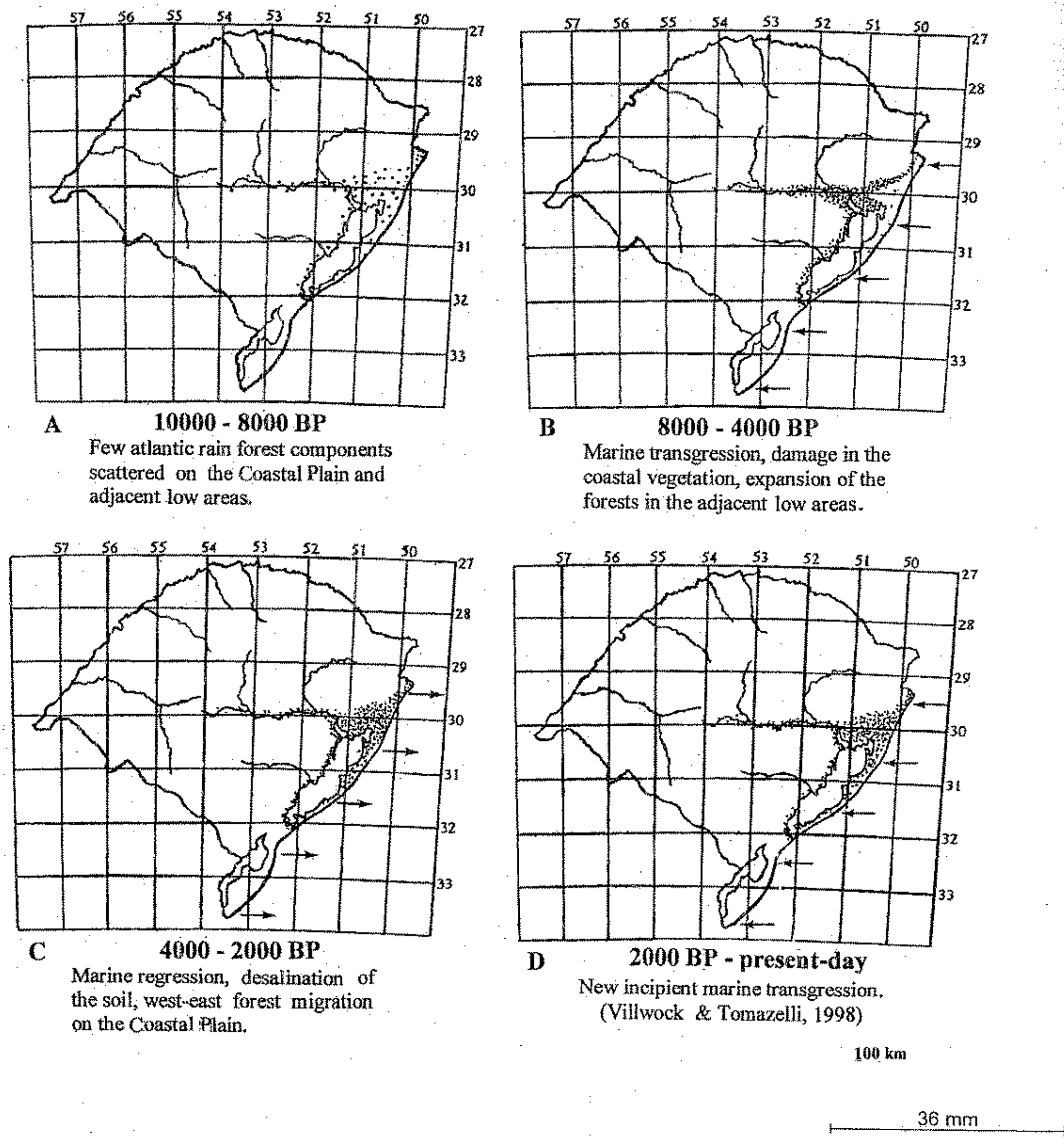


Fig. 3. Summary of the Atlantic rain forest *str. s.* history in Rio Grande do Sul during the Holocene and the marine oscillations. It is showing only the present-day seashore limits. (Dotted space according to the Atlantic rain forest *str. s.* area. Marine oscillations: (←) transgression; (→) regression).

and *Gomphrena*; Neves, 1998). Rare arboreal elements are represented in very low pollen concentrations (*Myrsine*, Myrtaceae, *Ilex pseudobuxus*, *Alchornea triplinervia*, *Celtis*, *Roupala*, Anacardiaceae, Urticales, *Trema micrantha*, Melastomataceae, and *Tripodanthus*), showing the great influence of soil salinity (Fig. 2).

4,000 BP up to the present (upper zone II-zone III). After 4,000 BP there is an accentuated reduction of marine and dry soil taxa related to halophytes, disappearing at about 3,700 BP, when *Azolla filiculoides* has its highest frequencies (Fig. 2). Arboreal pollen has its higher concentration in zone III (especially *Myrsine*, Myrtaceae, and *Ilex pseudobuxus*), indicating the expansion of the forest after 3,700 PB (Fig. 2).

The analysis of these seven palynological records indicates the very recent age of present-day forests of the Coastal Plain, which began to develop near or after 4,000 BP. In those areas situated nearest to the shoreline forest taxa obviously appeared even later, the last ones appearing after the marine regression, as in Faxinal, parallel to the innermost vegetated dunes, at only 2 km from the shoreline. Therefore, the colonization of the present-day Coastal Plain with Atlantic rain forests occurred later than in the inner adjacent low areas and thus to have happened during the latest millennia in a gradual west-east migration from the neighboring previously forested western regions (slopes of Serra Geral and low lands). The retraction of the forest indicators near the top of the profiles is probably related to regional human activity.

There is no evidence of dry phases in the Late Holocene during this migration and the edaphic control seems to be the most important factor of the Atlantic rain forest expansion to the southern and southestern Brazil, according to Lorscheitter (1997), Prieto *et al.* (1999) and Ybert *et al.* (2001, 2003). In contrast, drier episodes were recorded in the Late Holocene for other regions of Brazil, such as at 20°S latitude (Martin *et al.*, 1993), suggesting *El Niño*-like events.

The palynological evidence of marine oscillations corroborate the geological studies of Holocene coastal evolution in Rio Grande do Sul (Villwock, 1984; Villwock & Tomazelli, 1998). According to Villwock & Tomazelli (1998) a marine transgression seems to be happening more recently (Fig. 3.D), shown by a wide-spread erosion of the seashore that in several places exposes marsh and lagune sediments directly at the foreshore or at the base of the foredunes, with sediment dated at about 2,000 BP. These lagoon marshes destroyed by the present-day incipient sea transgression would, therefore, correspond to an earlier previous formation of the marsh forests in some coastal places.

CONCLUSIONS

Comparing the results of Serra Velha and Guaíba, it becomes evident that between 10,000-8,000 BP (Fig. 3.A) taxa of the Atlantic rain forest were already present in the foothill valleys of Serra Geral and Central Depression. Taxa apparently had migrated from the northern Coastal Plain (Torres region) and subsequently migrated westward from the coast, on the lowlands adjacent areas, reaching these inner zones in a scattered way, the same occured to the south of the Coastal Plain. However, the more humid climate at the beginning of the Holocene (comparing to the semi-arid conditions at the end of the last glacial stage) was not sufficient for the development of a closed Atlantic rain forest. The direction of this migration is according to Baptista (1967) and Rambo (1950, 1951, 1961) who, however, could not determine the age of this event. There is no palynological information about marine transgression in the Coastal Plain to this phase.

At 8,000-4,000 BP (Fig. 3.B) there was a great marine influence in the Coastal Plain. At about 6,000 BP favored by temperature and humidity increase and absence of marine transgression, the expansion of Atlantic rain forest begins in low areas adjacent to the coast, with a gradual west-east migration to the Coastal Plain. Along the coast, the marine oscillations already were damaging the scarce forest taxa. At about 4,000 BP the forest expansion began in inner zones of the Coastal Plain, while a maximum marine transgression (5,000-4,000 BP) was still taking place on the rest of the coast.

At about 4,000-2,000 BP (Fig. 3.C) a marine regression and gradual desalination of the soils occurred in the Coastal Plain, with the west-east forest migration and expansion to coastal areas. According to our data, the present-day coastal Atlantic rain forests has a very recent geological history. Of these forests those closest to the shoreline are the most recent, having expanded well after the last stage of the marine regression.

According to Villwock & Tomazelli (1998) a new incipient transgressive phase occurs since 2,000 BP to present-day (Fig. 3.D), eroding the seashore.

Due to the favorable climate for forest development which is taking place during the latest millennia in the Coastal Plain and neighboring low areas of southern Brazil, water bodies tend to form marsh forests with Atlantic rain forest species in their hydrosere succession. These areas are, therefore, important for environmental conservation. In contrast to other regions of Brazil, there is no evidence of dry phases in the Late Holocene in the Rio Grande do Sul region that would suggest *El Niño*-like events. Though geologically recent and under favorable present-day climate, the Atlantic rain forest took some millennia to fully develop and must, therefore, be given especial attention with respect to environment conservation programs.

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