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PII: S0895-9811(08)00033-3
DOI: 10.1016/j.jsames.2008.03.001
Reference: SAMES 746

To appear in: *Journal of South American Earth Sciences*

Please cite this article as: de Oliveira, M.A.T., Behling, H., Pessenda, L.C.R., Late Pleistocene and mid Holocene environmental changes in highland valley head areas of Santa Catarina State, Southern Brazil, *Journal of South American Earth Sciences* (2008), doi: 10.1016/j.jsames.2008.03.001

Late Pleistocene and mid Holocene environmental changes in highland valley head areas of Santa Catarina State, Southern Brazil

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Abstract

Low resolution of the continental sedimentary record is a common source of skepticism about the application of geomorphology and sedimentology to Quaternary studies. In spite of this, when supported by independent proxy data, geomorphology and sedimentology may favor palaeohydrologic interpretation. This paper associates geomorphologic, stratigraphic, sedimentologic, isotopic, palynologic and geochronologic data. The research was conducted in valley head sites in southern Brazilian highlands, under mild subtropical climate. The results point to environmental changes, the ages of which coincide to Marine Isotopic Stages (MIS) 5b, 3, 2 and 1. Although late Pleistocene temperatures and precipitation were lower than those of today, the study valley heads seem to have sustained locally wetter environments, which fed shallow soil-water saturated zones. These saturated zones are believed to have expanded during transitions between stadial and insterstadial states, contributing to hillslope erosion and sedimentation regardless of the sign of the climatic change. The

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interior organization of holocenic slope wash deposits suggests that the mid Holocene climate was drier than today's and was under the influence of seasonally contrasting precipitation regimes. The predominance of overland flow-related sedimentary records suggests that an excess of precipitation over evaporation influenced local palaeohydrology. This palaeohydrologic condition seems to have been recurrent and also explains the alternating periods of pedogenesis and sedimentation.

Keywords: Geomorphology; Sedimentology; Valley Heads; Palaeohydrology; Brazil

Resumo

A baixa resolução do registro sedimentar continental é causa freqüente de ceticismo relacionado à aplicação da geomorfologia e da sedimentologia a estudos do Quaternário. No entanto, quando apoiadas em dados representativos independentes, estas disciplinas podem favorecer a interpretação paleoidrológica. Este trabalho associa dados geomorfológicos, estratigráficos, sedimentológicos, isotópicos, palinológicos e geocronológicos. Foram investigadas cabeceiras de vale localizadas em planalto do sul do Brasil, sob clima subtropical relativamente ameno. Os resultados apontam para mudanças ambientais cujas idades coincidem com os Estágios Isotópicos Marinhos (EIM) 5b, 3, 2 e 1. Apesar de temperaturas e precipitações inferiores às atuais no final do Pleistoceno, as cabeceiras de vale estudadas mantiveram ambientes relativamente úmidos ao longo do tempo, propiciando o desenvolvimento de zonas de saturação sub-superficial. Estas zonas de saturação tenderiam a expandir durante períodos de transição entre estádios e interestádios, favorecendo erosão e sedimentação independentes do sinal das mudanças climáticas. A organização interna de sedimentos de encosta indica regime climático anual com longa estação seca durante o Holoceno Médio. O predomínio de registro sedimentar relacionado com o escoamento superficial sugere regime paleoidrológico no qual a precipitação tenderia a suplantar a evaporação. Esta situação paleoidrológica parece recorrente e explica ainda períodos alternados de pedogênese e sedimentação.

Palavras chave: Geomorfologia; Sedimentologia; Cabeceiras de Vale; Paleoidrologia; Brasil.

1. Introduction

The study of the evolution of valley head areas during the early 1990's brought to light geomorphologic units of the drainage net in which mechanisms of production and preservation of continental sedimentary records should be recurrent during the Quaternary (Faulkner, 1995). Since valley head areas are places where the dynamic connection between slope and fluvial processes tends to occur, their study increased theoretical understanding of hydrologic processes at the very sources of the drainage net (Dietrich and Dunne, 1993).

Although not formulated in the same physical-based theoretical context (Dietrich and Dunne, 1993), previous sedimentologic and geomorphologic Quaternary studies in Brazilian tropical highlands had stressed the potential influence of hydrologic changes on the evolution of valley head sites (Meis and Machado, 1978; Meis and Moura, 1984). These studies emphasized the evolutionary importance of the so-called "colluvial ramps", geomorphic units preserved in valley head sites, and thus contributed to an improved understanding of the transformation from eluvium to colluvium and alluvium near the sedimentary sources of the drainage net (Meis and Moura, 1984, Moura et al., 1991).

In spite of the chronologic coincidence between the evolution of colluvial ramps and well-recognized Late Quaternary climatic change at valley head sites (Moura and Silva, 1998), some skepticism still prevails concerning geomorphology and sedimentology as sources of palaeohydrologic interpretation in tropical and subtropical continental areas (Thomas et al., 2001). Although colluvial covers are widespread in tropical and subtropical Brazil (e.g. Modenesi-Gauttieri, 2000; Melo and Cuchierato, 2004), sedimentologic and geomorphologic-based Quaternary studies also require comparison to climatic proxies and, even where proxies are available, interpretation also depends on choosing field sites at which good pieces of evidence can be found. As a result, few areas in Brazil have so far delivered geomorphologic and sedimentologic evidence that is able to demonstrate the link between landscape evolution and well-recognized global change events (e.g. Meis and Machado, 1978; Servant et al. 1989; Turck et al., 1997, Stevaux and Santos, 1998; Moura and Silva, 1998; Modenesi-Gauttieri, 2000).

This problem is not restricted to Brazilian lands and is somewhat enhanced where colluvial deposits are concerned (Bertran and Texier, 1999; Nemec and Kazanci, 1999; Bertran and Jomelli, 2000). In continental tropical and subtropical areas, most remaining doubts are attributed to the low resolution of the sedimentary record (Thomas et al., 2001). Even where sedimentary structures are preserved, pervading erosion and weathering processes tend to transform evidence into sedimentary gaps and weathering products.

Due to its continental dimensions, Brazilian lands are under the influence of several climatic regimes, ranging from equatorial and tropical, to mild subtropical climates in southern highland areas. As a result, to the extent that any geomorphologic and sedimentologic evidence is produced and preserved in Brazil, a weathering less-aggressive environment should be given precedent in any search for palaeoenvironmental evidence and palaeohydrologic interpretation (e.g. Modenesi-Gauttieri, 2000).

This paper is an attempt to associate geomorphologic and sedimentologic data with pollen and soil carbon proxies in southern Brazilian subtropical highlands, where mild climates now predominate. The discussion is based on data obtained from two sedimentary sets located at valley head sites. The results point to local environmental changes that coincide with events associated with the Last Glacial Stage, embracing a time span equivalent to Marine Isotopic Stages (MIS) 5b, 3, 2 and 1. Since the study sites are located at valley head areas, the fact that these geomorphic units are effective sources of information for Quaternary palaeohydrologic interpretation in continental areas is enhanced (Dietrich and Dunne, 1993; Oliveira, 1999).

2. Study area

The study was conducted around the so-called "Cerro do Touro" locality, situated at the southern border of the municipality of Campo Alegre, in Santa Catarina State, Southern Brazil (Fig. 1). Campo Alegre is a rural community in the "São Bento do Sul" Plateau, characterized by a rocky, stepped, hilly landscape, strongly influenced by differential weathering and erosion, developing *cuesta*-like features along the Plateau's border. Local altitudes range from 850 to 1,200 m above sea level (Santa Catarina, 1986). The study site altitude is 1,010 m. The area is drained by the Rio Negro River, an affluent of the Rio Iguaçu River, which flows to the west, from the western flank of the "Serra do Mar" range, until reaching the Atlantic Ocean along the coasts of Uruguay and Argentina, in the "La Plata" estuary.

Local climate is also influenced by the Plateau's geography, perched behind the Atlantic side of the "Serra do Mar" range. Due to the plateau's altitude and atmospheric Atlantic dampness, the climate is classified as Köppen's "Cfb" type: a wet mesothermic climate with relatively mild summers. The mean annual temperature is 16.4° C, and precipitation is well distributed along the year, with annual amounts ranging from

1,600mm to 1,800mm (Santa Catarina, 1986). Tropical and subtropical vegetation coexist in the region, forming the so-called *Araucaria* forest (Mixed Ombrophic Forest). Natural and introduced grasslands are also frequent, with gallery forests extending along topographic depressions and valleys (Oliveira and Pereira, 1998).

Volcano-sedimentary rocks of the so-called “Campo Alegre Basin” represent the local bedrock, dated as 570±30 Ma. These Neoproterozoic rocks are mainly composed of dacitic and basaltic tuffs and lavas (Citroni et al., 2001; Biondi et al., 2002). The "Campo Alegre Basin” had been divided into nine formations distributed between two groups: the "Bateias" Group and the "Campo Alegre" Group (Biondi et al., 2002). Outcrops from two formations of the "Campo Alegre" Group may be found in the study area: the "São Miguel" and "Avenca Grande" formations, composed of trachytes, rhyolites and ignimbrites (Biondi et al., 2002). Weathering of these rocks had created important clay fields, used by local and national ceramic manufacturers. As a result, morphogenesis at the study area is also influenced by the existence of deep weathering mantles.

Previous geomorphologic studies in the area brought to light a rich continental Quaternary record, mainly composed of well-preserved umbric palaeosols and colluvial sedimentary structures (Oliveira and Pereira, 1998; Oliveira et al., 2001). In spite of many fluvial deposits observed in the area, most of the Quaternary record so far explored is located in valley head sites. As discussed previously, these geomorphic units may favor spatial and temporal linkage between surface and stream flows, producing and preserving sedimentary record in transient topographic surfaces, between slopes and valleys (Dietrich and Dunne, 1993; Cosandey and Oliveira 1996) (Fig. 2).

3. Methods

Two systematic stratigraphic sections were established by field descriptions of their sedimentary units, according to color, texture, thickness, geometry and gravel content. Eighty (80) samples were taken and processed for standard textural analysis, including sieving for the coarse fraction (> 0.062 mm) and pipette sampling for the fine fraction (< 0.062 mm). These procedures were carried out at the Pedology Laboratory of the Federal University at Santa Catarina (UFSC), Brazil. Textural results were plotted in a ternary diagram, following the Flemming classification for muddy sediments (Flemming, 2000) (Fig. 3). Where gravel content was important, the Folk ternary diagram was used for sample classification (Folk, 1974). In order to consider textural variations through depth, when necessary, textural data was synthesized into a grain size ratio (<2μm / >10μm), expressed as relative percentage content (Wilson et al., 2000).

Samples impregnated with resin were optically analyzed for texture characterization (Scholle, 1979; Delvigne, 1998). When judged appropriate, analysis between macroscopic and microscopic scales was made by the use of digital images of thin lenses (De Keyser, 1999) obtained from a CanoScan-2710 slide scanner device (Oliveira et al., 2006). Scanner electron microscopy analyses (SEM), performed by Beta Analytic Inc. Services (U.S.A.), helped describe the palaeosols and detect possible plant remnants.

Soil organic matter (SOM) analysis of palaeosol samples (total organic C, ^{13}C) was carried out at the Stable Isotope Laboratory of the Centre for Nuclear Energy in Agriculture (CENA), in Piracicaba, Brazil. The organic carbon content is expressed as percentage of dry weight. ^{13}C results are expressed as δ^{13}C with respect to PDB standard using the conventional δ (‰) notations:

$$\delta^{13}\text{C}\ (‰) = [(\text{R}_{\text{sample}}/\text{R}_{\text{standard}}) - 1] \times 1000$$

where R_{sample} and $R_{standard}$ are the $^{13}C/^{12}C$ ratio of the sample and standard, respectively. Analytical precision is ± 0.2‰.

The ^{14}C analyses were carried out at the CENA ^{14}C Laboratory using the liquid scintillation counting method (Pessenda and Camargo, 1991). Radiocarbon ages are expressed as ^{14}C yr B.P. (before present) normalized to a $\delta^{13}C$ of -25‰ PDB. Other radiocarbon ages were determined at Beta Analytic Inc. (USA) and also at the Institute of Physics of the Erlangen-Nürnberg University (Germany). Thermoluminescence (TL) and optic stimulated luminescence (OSL) ages were obtained at the Glasses and Dating Laboratory, Faculty of Technology of São Paulo (Brazil).

An organic-rich deposit was sampled for pollen analysis. Sixteen (16) samples of 0.5 cm^3 were collected in plastic bags, at 10 cm intervals along the 150 cm core sample, and stored under cool (ca. +8 °C) and dark conditions, after return from the field. Samples were processed with standard pollen analytical methods, using HF (78%) and acetolysis. To determine the pollen concentration, one tablet of exotic *Lycopodium clavatum* spores was added to each sample. A minimum of 300 pollen grains was counted. For pollen identification, Behling's reference collection was used (containing about 2,000 Brazilian species) together with pollen morphologic descriptions (Behling, 1993). The total pollen sum includes herb, shrub and tree pollen grains. Moss and fungal spores were counted on the pollen slides and expressed as percentage of the total pollen sum.

For plotting of the pollen data, calculations and cluster analysis, TILIA, TILIAGRAPH and CONISS software was used (Grimm, 1987). The identified pollen taxa were grouped into Campos, *Araucaria* forest and Atlantic rain forest according to the pollen percentage diagram, to the summary pollen percentage diagram and to the cluster analysis dendrogram. This classification is based on available literature for SE Brazil (Hueck, 1966; Ururahy et al., 1983) and on the knowledge of the composition of Southern Brazilian flora (Falkenberg and Voltolini, 1994; Klein, 1978).

4. Results

The research was conducted at two sites. The first site is located near the divides, at a watershed position. The second site is located at a typical valley head position, at the footslope, where soil water tends to concentrate in topographic depressions and feed first order drainage channels (see Fig. 2). For simplicity, the results will be presented separately, according to the decreasing potential energy of the study site, from headwaters to water-soil saturated areas down slope.

4.1. Valley side slope site

Near the watershed divides (Fig. 4), the record consists of several layers of colluvium intercepted by umbric epipedon horizons (units 5 and 11 in Fig. 4). At the center of the section are channel-like features which are covered by a massive colluvium. An up to 1 m thick modern umbric cambisol tops the section. Colluvial layers display 4.3 to 12.38% gravels, and 78.25% of the samples are classified as sandy mud, ranging from very silty sandy mud (C-II) to clayey sandy mud (C-IV), with a peak mode of silty sandy mud (C-III). The palaeosols, which are of black colored (10YR2/1) mineral material (Fig.5), indicating A horizons, contain 0.41% gravels, and 68.75% of the samples are classified as silty, ranging from silty sand (B-II) and silty sandy mud (C-III), with a peak of very silty slightly sandy mud (D-II) (Fig. 6).

Radiocarbon ages for pedostratigraphic unit 5 and 11 are shown in Table 1. The radiocarbon ages indicate that the palaeosols from units 5 and 11 developed respectively during the Last Glacial Maximum (LGM) and between the LGM and the Holocene. The later period is characterized in the southern hemisphere by millennial interstadial oscillations within the warming trend that preceded the so-called Antarctic Cold Reversal (Sowers and Bender, 1995).

Pollen studies were not possible because only degraded pollen grains were found, but $\delta^{13}C$ data indicate a mixture of C_3 type (trees) and C_4 type (grass) vegetation in both palaeosol horizons at this relatively higher topographic site, near the watersheds (Fig. 7).

4.2 Valley head site

The stratigraphic section, described at the wall of a clay quarry, represents a typical valley head environment, in which episodic erosion and sedimentation alternated with soil development and slow organic matter decomposition in a water-logged environment (Fig. 8). A representative profile of the pedostratigraphic section was made (Fig. 9). Further detail on ^{14}C, OSL and TL ages is given in Table 2 and Table 3.

The deposits unconformably overlie deeply weathered Early Paleozoic pyroclastic rocks and consist of, from base to top: a) a 0.3-0.5 m thick weathered colluvium composed of sub-parallel lenses displaying crude cross stratification (Unit 1); b) a 1.5 m thick peat bog (unit 2); c) a 1.5 m thick massive muddy layer (Unit 3) with remnants of an A palaeosol horizon at the top (Unit 4); d) a lag of well-sorted coarse sand mantled by 0.75 m thick normal graded matrix-supported gravels (Unit 5); and e) a 2.65 m thick deposit consisting of a mixture of weathered gravel, sand and silt interbedded with muddy layers (Unit 6).

Unit 1 colluvium was dated by thermoluminescence to 90 ka (Table 3). The peat from unit 2 has an age apparently older than the limit of radiocarbon dating (Table 2) and consists of a lower coarser-grained interval of clayey sandy mud (C-IV) to extremely clayey slightly sandy mud (D-VI), an intermediate clay (E-VI) interval, and an upper finer-grained interval of very clayey slightly sandy mud (D-V) to extremely clayey slightly sandy mud (D-VI) (Figs. 10 and 11).

Pollen concentration and cluster analysis of samples from the peat (Unit 2) shows that the pollen diagram can also be divided into two pollen zones (Fig. 12). The pollen percentage diagram of the deposits shows that pollen taxa were grouped into Campos, *Araucaria* forest and Atlantic rain forest (Fig. 13).

Pollen zone I (150 – 45 cm, 11 samples) is characterized by abundant Campos (grassland) taxa (60 - 67%), primarily Poaceae, followed by Cyperaceae, *Baccharis,* Asteraceae subf. Asterioideae and other taxa such as Apiaceae, *Eryngium* and *Valeriana*, which occur in lower percentages. *Araucaria* forest pollen sums are moderate (25 - 32%), represented primarily by Myrtaceae, followed by *Podocarpus*, *Weinmannia,* Melastomataceae, *Myrsine, Ilex*, *Symplocos* and *Daphnopsis*. Pollen grains of *Araucaria angustifolia* except for one single grain, are missing. Percentages of Atlantic rain forest pollen taxa are low (1 - 3%) and represented only by single grains such as *Alchornea*, *Celtis* and Moraceae/Urticaceae. Aquatic pollen taxa are absent or were found only by single grains. Tree fern spores of *Cyathea* and *Dicksonia* are recorded in low percentages. Other fern spores are more frequent, primarily represented by the *Blechnum imperiale*-type and monlete psilate spores. Percentages of moss spore are rare.

Pollen zone II (45 – 0 cm, 5 samples) is dominated (60 - 70%) by Campos vegetation. Percentages of Eryngium and some other Campos pollen taxa are somewhat lower, while other taxa remain unchanged. The sum of the Araucaria forest group is similar to zone I, but the composition changed. Myrtaceae is slightly lower than in zone I, and percentages of *Podocarpus* are markedly higher. Percentages of *Weinmannia* became rare. Percentages of the group of Atlantic rain forest taxa remain at low levels

(1 – 2%), but pollen of Melastomataceae/Combretaceae decreases, while *Myrsine* increases. Tree fern spores and the *Blechnum imperiale*-type decrease in this zone.

The $\delta^{13}C$ analysis of unit 2 suggests the predominance of tree species, or C_3 type grasses such as Cyperaceae, along the entire unit (Figure 14). Total carbon content continuously decreases from the base to the top of the profile. The association of C_3 grasses and trees in unit 2, the age of which coincides at least with the MIS 3, may be explained either as a consequence of an early MIS 3 general interstadial trend, or as a consequence of the local concave topography of the buried valley head, making a transitive environment between grasslands in the summits and gallery forests in the valleys.

Units 3 and 4 mainly consist of material classified as clayey slightly sandy mud with only one sample classified as silty slightly sandy mud. The unit 4 radiocarbon age indicates that this soil epipedon had developed by the end of MIS 3 (Table 2). SOM data obtained from this unit is also displayed in Fig. 14, where more enriched $\delta^{13}C$ values indicate the presence of less dense vegetation. Unit 5 consists of weathered muddy gravel colluvium. A sample collected from the sandy lag between unit 4 and unit 5 displayed an OSL age of 6.6 ka (Table 3).

Unit 6 is classified as alternated lenses of mud and weathered gravel. If plotted in ternary diagrams for textural classification, the muddy subunits would be classified as Flemming's clayey sandy mud (C-V) and very clayey slightly sandy mud (D-V), while the gravelly subunits would classify as gravelly mud, muddy gravel and gravelly muddy sand, according to Folk’s ternary diagram (Folk, 1974).

Comparison of scanned images of thin lenses obtained from samples of unit 6 and from one sample of a present day slope wash deposit, collected after a storm in the study site’s quarry floor, shows similar structures, although some important differences may be noted (Fig. 15). The Quaternary sample (Fig. 15, A) is mainly composed of discrete massive and compacted alternating lamina of mud (units 3, 4 and 6) and sands, with some gravel (units 1, 2, 5, 7 and 8). The modern sample (Fig. 15, B) shows normal grading (units 8, 9 and 10) and cross-lamination (units 3, 4, 5, 6 and 7) in a more open packing frame, mainly made by sands and gravels, with some mud. Cycles of sedimentation may be noted in both examples (Fig. 15), alternating coarser and finer grades. The similarity of Quaternary and modern structures, created at the same site and from the same source rock, is attributed to the role played by overland flow as the main depositional agent, for both samples (Fig. 16).

5. Interpretation and Discussion

The study sites record alternating periods of sedimentation and pedogenesis, encompassing a large time span including: a) a period approximate to the onset of the Last Glacial Stage, probably MIS 5b stadial; b) the Last Glacial Stage interstadial MIS 3, or even an earlier stage; c) the Last Glacial Maximum (MIS 2); d) millennial oscillations in a period of a general warming trend, preceding the beginning of the so-called Antarctic Cold Reversal, between MIS 2 and MIS 1 (Holocene) and e) a period in about the mid Holocene.

Interpretation for the stratigraphic section near the watersheds (Fig. 4) indicates alternating periods of colluvial deposition and periods of soil development. The younger A soil horizon (Unit 11) was truncated by concentrated flows which eroded all previous stratigraphic units, suggesting palaeohydrologic changes, which may be summarized as follows:

a) Between 20-19 ka and 16-15 ka, colluvial parallel lenses, probably built up by diffusive dense gravitational flows, spread over the slope;

b) Surface pedogenetic horizons developed during the last glacial stage, building up a thick umbric epipedon during the LGM, as well as about 15 ka. Although slightly more frequent, grass was transformed into soil carbon together with organic matter from trees and bushes, suggesting the occurrence of arboreal vegetation in higher topographic levels near the watersheds;

c) Erosion by rills and gullies locally affected the site, during an undetermined period, after 15 ka. The cut-and-fill preserved sedimentary structures indicate a change from the previous-dominant diffusive gravitational flows towards concentrated flows. This change in the pattern of running water may be explained either as an isolated event, without any palaeoclimatic significance, or as a consequence of the improvement of atmospheric wetness, at the end of the Pleistocene (Oliveira e Lima, 2004; Oliveira et *al*. 2006). The age of the palaeosol eroded by this event coincides with a warming trend which had preceded the so-called Antarctic Cold Reversal, probably a period of secular climatic change in the southern hemisphere (Sowers and Bender, 1995).

Together with SEM analysis, micromorphology (Oliveira et al., 2006), general morphologic characteristics and organic matter content, most of the pedogenetic units are considered as buried A horizons classified as umbric epipedons (Lima, 2005), resulting from slow humification processes, probably under the influence of a mild local humid climate. Both C_3 and C_4 vegetation contributed to SOM content in these horizons. It is not possible to distinguish what vegetation type was dominant; suggesting that arboreal savanna (Cerrado) was established near the area's watersheds.

This record is interpreted as indicative of a local environment influenced by a relative surplus of water, even during the Last Glacial Maximum. Composition of colluvial materials points to poorly sorted sediments, characteristic of relatively dense solid-liquid mixtures, usually found in mud and debris flow sediments (Oliveira and

Lima, 2004). This sedimentation pattern was interrupted about 15 ka B.P. by concentrated flow processes, as gully and rill erosion, probably in a period of relative improvement of atmospheric wetness.

Results from the valley head site suggest a local wet environment in which palaeohydrologic changes had probably been influenced by soil water convergence to topographic depressions during the Last Cold Stage. The sedimentary set was divided into two sequences: lower and upper. The lower sequence suggests the predominance of a low energy depositional environment, while the upper sequence is dominated by holocenic slope wash deposits.

The lower sequence shows that most of the deposit is composed of muddy materials. The grain size ratio diagram for samples of the peat bog (Unit 2) suggests the existence of two main periods of sedimentation, implying coarser deposits during the older period (below 65 cm) and finer ones during the younger (above 65 cm). Although this is indicative of a very low energy depositional setting, as a whole, variations depicted by the grain size ratio (Fig. 11) coincide with pollen diagram zones in unit 2, suggesting usefulness of the former as a tool for interpreting ancient peat deposits.

Pollen composition of the samples suggests two periods of stable conditions (Fig. 13). The older period (pollen zone I) was somewhat warmer and drier than the younger period (pollen zone II), as suggested by the higher representation of *Podocarpus* trees and the rare occurrence of *Weinmannia* in the later. As *Weinmannia* is sensitive to colder conditions and *Podocarpus* needs sufficient moisture for growth (Behling, 1993), this pollen record suggests a change from an older period of drier and warmer climate, to a younger period of wetter and colder climate; although both periods are colder and drier than the modern climate of this region. As a result, the peat bog pollen data shows that the local increase in humidity, as recorded in pollen zone II, was not necessarily dependent upon the increase of local temperatures, as usually hypothesized for the response of tropical areas to global climatic changes.

Generally, the pollen spectra indicate the predominance of grasslands with small areas of forest during that glacial record. Subtropical *Araucaria* forests probably occurred in the form of gallery forest, in valleys along the rivers, reflecting drier and colder climatic conditions than today. In spite of some wetness improvement by the end of the deposit, *Araucaria angustifolia* itself apparently did not occur in the study region. SOM results suggest the predominance of a relatively wet local climate condition during the formation of the Last Glaciation peat bog (unit 2) (Fig. 14), which was followed by a relative local climatic degradation, probably due to increasing dryness, leading to the formation of unit 3 altered muddy material and to unit 4 ochric epipedon, usually found in dryer Brazilian environments.

The upper sequence is mainly composed of slope wash deposits spreading over a Quaternary valley head, the hollow topography of which was about 3 m below the present local topographic level. This upper sequence indicates local accumulation of alluvial-colluvial sediments. We suggest that overland flow was probably the main hydrologic mechanism affecting the area. Alternated lenses of fine (mud) and coarse (gravel) sediments suggest repeated changes in overland flow intensity during deposition. This multi-episodic pattern of the Quaternary sample, as compared to modern sedimentary conditions at the degraded quarry floor site (Figs. 15 and 16), is interpreted as evidence of a drier climate in mid Holocene times, probably under the influence of a seasonally contrasted precipitation regime, where overland flow recurrently washed out topographic surfaces in which vegetation was probably not ubiquitous around this valley head site, during the Holocene. The fact that slope deposits may conceal sedimentary structures like these, enabling detailed microscopic description and palaeohydrologic interpretation, is an interesting result, which is not completely supported by similar earlier attempts (Bertran and Texier, 1999). This is probably due to local characteristics of the sediments, related with local depositional environments and weather conditions.

Interpretation for the record preserved in this pedostratigraphic set may be summarized as follows (see Fig. 9):

a) A layer of alluvium-colluvium covers an erosive disconformity, carved over the weathered bedrock, around 90 ka B.P (Unit 1). This layer is richer in gravel at its base. Near the top, where it becomes silty and clayey, fine lamination develops, becoming gradually enriched in organic matter, which is associated with a swampy valley head environment;

b) During the Last Glacial Stage (MIS-3, or even an earlier stage) the climate was probably colder and drier than today, but swamps still developed on the study site (Unit 2), building up a peat deposit that bears the record of a drier and warmer climate in the beginning and a colder and wetter climate at the end. Vegetation was distributed as grassland along the watersheds and gallery forests along the valleys, in wetter environments;

c) This Last Glacial Stage peat was probably followed by degradation of environmental conditions, implying erosion and local sedimentation (Unit 3);

d) A period of environmental stability and pedogenesis followed near the end of EIM 3 forming the ochric epipedon of unit 4, usually characteristic of warmer and dryer conditions in Brazil;

e) Unit 4 was truncated by soil erosion dated to mid Holocene times, during a period coincident with the holocenic optimum climatic. Further sedimentation, following a pattern of fine stratified alluvial-colluvial lenses, is verified (Units 5 and 6). Comparison of microscopic holocenic sedimentary structures with modern sedimentary structures created over bare topographic surfaces suggests that overland flow was probably the main agent for Holocene sedimentation and, also, that vegetation was probably not ubiquitous during mid Holocene times.

As a result, the study site reveals peat bogs, grasslands and gallery forests evolving near a channel head during the Last Cold Stage. Grain size distribution, pollen and SOM data suggest changes in palaeohydrologic conditions about MIS 3, implying an older period of drier and warmer climate followed by a period of colder and wetter climate, associated with unit 2 deposits. Together with radiocarbon and thermoluminescence dates, proxy data suggest that the water table was probably near the surface of this valley head area during the Last Glacial Stage. Valley head aggradation took place during the mid Holocene, associated with wash slope deposits, suggesting a drier climate for the site's upper sequence.

5.1. Global environmental changes and local valley head evolution

The reported radiocarbon and luminescence ages limit the local record to time periods that coincide with the following global events (Aharon and Chappell, 1986):

a) 90 ka: Diffusive erosion and sedimentation on hill slopes, during marine isotopic stage 5b, the second stadial period at the onset of the Last Glaciation;

b) > 50 ka and 49 ka: Peat bog development at the study valley head, probably during the MIS 3 interstadial, or even earlier periods, when global temperatures, although not yet at their coldest level, were lower than present ones;

c) 37 ka: Development of ochric epipedon on valley heads and proxy isotopic evidence of local vegetation rarefaction. Dryer conditions about the end of MIS 3 (Bond et al. 1993);

d) 20-19 ka: Soil development at the last glacial maximum, during MIS 2;

e) 16-15 ka: Erosion by concentrated overland flow on valley heads, related to events at the transition from MIS 2 to MIS 1 (Holocene);

f) 6 ka: Soil erosion, slope wash deposits and local valley head aggradation, during the Holocene climatic optimum.

Also, if we take into account the alleged out-of-phase orbital driven pattern of warmer and colder oscillations recorded in Greenland and Antarctic ice caps (Bard et al. 1997; Blunier et al., 1998; Blunier and Brook, 2001; Clark et al., 2002; Weaver et al., 2003), the ages of events at the study area should correlate with the following hemispheric events:

a) 90 ka (MIS 5b): Diffusive erosion and sedimentation during a stadial period in the northern hemisphere. In the southern hemisphere, estimates for Atlantic Ocean water surface temperatures indicate a transition from warmer to colder temperatures, suggesting a change from an interstadial to a stadial condition (Cortese and Abelmann, 2002);

b) From > 50 to 49 ka (MIS 3): Peat bog development close to Bond cycle number 14 or 12, or even earlier, in the northern hemisphere, suggesting abrupt climatic oscillations during a longer-term cooling trend. According to the $\delta^{18}O$ Byrd isotopic record of the Antarctic ice cap, northern hemisphere Dansgaard-Oeschger stadials correspond to short interstadial oscillations in the southern hemisphere, leading to pulses of abrupt warming in the MIS 3 interstadial (Sowers and Bender, 1995);

c) About 37 ka: Development of ochric epipedon on valley heads. Dansgaard-Oeschger stadials (N.H.) and interstadial oscillations (S.H.) of MIS 3 (Bond et al., 1993; Peterson et al. 2000; Cortese and Abelmann, 2002). Our results suggest a relatively warm and dry local climate, probably during one of the MIS 3 southern hemisphere interstadial oscillations;

d) 20-19 ka: Soil development during the last glacial maximum (LGM) in both hemispheres;

e) 16-15 ka: Stadial period preceding the beginning of the Bölling interstadial in the northern hemisphere. In the southern hemisphere, it would correspond to pulses of secular interstadials into the warming trend that preceded the beginning of the Antarctic Cold Reversal Oscillation (Blunier et al., 1998);

f) About 6 ka: Soil-erosion and aggradation during the middle of the Holocene. Our record from the period bears evidence that overland flow was running over geomorphologic surfaces in which vegetation was probably scarce. This evidence is also supported by pollen records from Southern Brazil, which already indicated that grassland vegetation continued to be predominant from glacial to early and mid Holocene times, in spite of the change in floristic composition, suggesting a warm and dry climate.

The similar sequence of vegetation changes from different sites indicates that the change of palaeoenvironmental conditions in the Southern Brazilian highlands was regional, as suggested by the late Quaternary vegetation and climate history of "Serra Campos Gerais", in northern Paraná State, very similar to that from the highlands in Santa Catarina State (Behling 1993, 1995a, 1997a) (Fig. 17).

During late-glacial times, grassland vegetation was abundant, and scattered stands of *Araucaria* forests were probably present only in deep and protected valleys, suggesting a dry and cold climate. Interpretation for the "Serra Campos Gerais" record, suggests a Holocene palaeoclimate with a long dry season. This interpretation is an important aspect of the climate history of the Southern Brazilian highlands and may explain why the spreading of *Araucaria* forests did not take place at the beginning of the Holocene (Behling, 1997a). Only in the late Holocene, when *Araucaria* forests expanded in the highlands, did the annual dry period most likely become shorter. This may also have been the case for the study sites in Santa Catarina State, where no annual dry season occurs under modern climatic conditions. A long dry season during the early and mid Holocene explains well the sedimentologic evidence previously discussed, according to which overland flow was probably active on bare geomorphologic surfaces at the study site.

This climatic condition with a marked seasonal dry period in the early and mid Holocene could be explained by a stronger influence from dry, tropical continental air masses in Southern Brazil (Behling, 1993), which would have blocked polar cold fronts and prevented precipitation over the study area. Longer seasonal dry seasons in the early Holocene were also found in records from SE Brazil, in Lago do Pires (Behling 1995b) and Morro de Itapeva (Behling, 1997b) (Fig. 17). According to models run by Wasson and Claussen (2002) this relative mid Holocene dryness is also expected to occur elsewhere in South America, Africa and Australia.

Some of the study’s radiocarbon ages also correspond to periods during which organic-rich and water-logged soil-horizons developed in southern Brazil, around the end of the Pleistocene. Global and hemispheric events related with these periods, as well as pollen records (Behling and Hooghiemstra, 2000; Behling, 2002; Behling et al. 2004), suggest that southern Brazil was under the influence of mean temperatures lower than modern ones. As generally accepted, these global colder periods would imply drier hydrologic regimes in tropical and sub-tropical areas, while interstadials would imply a wetter climate. However, this model is somewhat difficult to conciliate with the development and conservation of the study areas' umbric and water-logged palaeosols, as these soils need conditions of water saturation for several months to fully develop. Soil water saturation requires poorly drained land surface materials in relatively wet local environments, under lower evaporation rates or relatively lower temperatures (Shotyk, 1992). Since the study site soils and deposits had developed over deep weathered mantles, far from the less permeable fresh bedrocks, the eventual existence of shallow soil-water saturated zones in topographic hollows should be attributed mainly to local wet environments, low temperatures and low evaporation rates, rather than to poorly drained land surface materials.

Consequently, the age of development of palaeosols at the study sites suggests that even during the coldest periods of the Last Glacial Stage, there was a local relative water surplus allowing the development and preservation of peat deposits and umbric epipedons in topographic hollows. This local wet soil-environment condition should also tend to maintain overland flow as an efficient and recurrent mechanism through time, explaining the dynamics of alternate periods of pedogenesis and morphogenesis at the study valley heads, implying anaerobic soil development during climatic stable periods and soil erosion and local deposition under transient climate conditions.

This palaeo-environmental interpretation implicitly assumes a hypothesis that may be summarized as follows, according to the predominance of alternated periods of erosion and pedogenesis in the study valley heads:

a) Periods of erosion: except for the event correlative to MIS 5b, erosion and deposition seems to occur during periods of adaptation of the system to transient climatic conditions, mainly during warming trends in the southern hemisphere;

b) Periods of pedogenesis: without any exception, pedogenesis occurs during periods of greater stability of the climatic system, either during stadial or interstadial states.

For each of the above environmental conditions, it must be stressed that adaptation of the study valley heads to climatic changes requires the existence of relatively wet local environments, in which overland flow and shallow soil-water saturation zones are important hydrologic agents, conditioning either erosion or pedogenesis. It also explains why the soil-carbon record suggests either the existence of composite vegetation near the hilltops, at the watershed study site, or the predominance of C_3 type plants (trees) at the valley head site. Accordingly, we may imagine, at the study area, a landscape in which topographic valley heads sustained relatively wetter environments over time, at relatively high topographic levels in the interior of drainage net systems, even during the coldest periods of the Last Glacial Stage.

6. Conclusion

The study area has preserved geomorphologic, sedimentologic, palynologic and isotopic evidence that are useful for palaeohydrologic interpretation of Quaternary events in Southern Brazil. Significant differences of the internal organization of the study slope-deposits, as shown by well-preserved detailed sedimentary structures, enabled palaeohydrologic interpretation, which is supported by independent data.

Sedimentary evidence of local pronounced dryness during the mid-Holocene, at least under contrasted seasonal regimes, was illustrated and discussed. Together with the general pedostratigraphic features and proposed interpretation, results also suggest that a colder and drier climate was probably dominant during the Last Glacial Stage. However, the need for an excess of local precipitation over evaporation was stressed in order to explain the development of water-logged soils, as well as the existence of trees at higher topographic levels, even during the Last Glacial Maximum. It is precisely that excess of precipitation over evaporation which would explain the landscape overland flow dependent pattern of evolution, in which a relative water surplus is needed either for soil development, or for erosion and sedimentation on the study's geomorphologic surfaces, during the Late Pleistocene and mid Holocene.

As emphasized in the introduction, the resolution of the tropical and sub-tropical continental sedimentary record constitutes a major problem for Quaternary palaeohydrologic interpretation (Kadomura, 1995; Thomas and Thorp, 1996; Ledru et al., 1998). Gaps in knowledge about southern hemisphere continental areas are confusing, when the apparent out-of-phase evolution of the atmosphere around Greenland and Antarctica during the last glacial cycle is taken into account (GRIP, 1993; Sowers and Bender, 1995; Bard et al. 1997; Blunier et al., 1998; Blunier and Brook, 2001).

Our study area is also limited by the same resolution constraints and by the same sources of confusion. Nevertheless, the preserved record encourages us to propose a conceptual model for the environmental evolution of some Southern Brazil highland areas, in which stadials would imply drier climate periods, but lower temperatures and lower evaporation rates still would support local shallow soil-water saturated zones. These local shallow saturated zones would tend to expand during transitions between stadial and interstadial states, improving the role played by valley head areas and contributing to overland flow and to the eventual erosion and sedimentation of local geomorphologic surfaces, whatever the sign of the climatic change, but mainly during warming trends. This recurrent concentration of hydrologic-driven processes through time is perhaps one of the most important influences of valley head areas on the adaptation of drainage net systems to environmental changes, at the study area and elsewhere (Dietrich and Dunne, 1993). Consequently, as illustrated above and predicted before, valley heads also constitute resilient environments in which the tropical and subtropical continental Quaternary record may be preserved and depicted.

Acknowledgments

This paper was supported by a research grant from the CNPq - Conselho Nacional de Desenvolvimento Científico e Tecnológico, Brazil. Funding for the project was also provided by the Programa de Pós-Graduação em Geografia, Universidade Federal de Santa Catarina, UFSC, Brazil. The paper was improved by the comments made by two anonymous reviewers.

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Figure Captions:

Fig.1. Location of the study area.

Fig.2. Typical concave slope around a valley head. Gray areas illustrate separated soil-water saturated zones. Arrows illustrate rain inputs and overland flow outputs. The figure was modified from Cosandey and Oliveira (1996).

Fig.3. Flemming ternary diagram, with different textural classes, where S: sand; A-I: slightly silty sand; A-II: slightly clayey sand; B-I: very silty sand; B-II: silty sand; B-III: clayey sand; B-IV: very clayey sand; C-I: extremely silty sandy mud; C-II: very silty sandy mud; C-III: silty sandy mud; C-IV: clayey sandy mud; C-V: very clayey sandy mud; C-VI: extremely clayey sandy mud; D-I: extremely silty slightly sandy mud; D-II: very silty slightly sandy mud; D-III: silty slightly sandy mud; D-IV: clayey slightly sandy mud; D-V: very clayey slightly sandy mud; D-VI: extremely clayey slightly

sandy mud; E-I: silt; E-II: slightly clayey silt; E-III: clayey silt; E-IV: silty clay; E-V: slightly silty clay; E-VI: clay. Based on Flemming (2000), with author's permission.

Fig.4. Schematic illustration of a portion of the watershed pedostratigraphic section, near the divides. The figure illustrates a detail of two contiguous 60-meter long stratigraphic sections. No other channel features were found elsewhere in the surveyed record.

Fig.5. Electron microscopic images obtained from a sample of Unit 5 buried epipedon. **A**: external face of the sample, showing fine and very fine silt particles. **B**: inner face of the sample, showing clays with irregular and wavy plates, organized in a somewhat crenulated pattern. There is no evidence of vegetal remnants in the sample which is mainly composed of minerals and mineralized organic matter.

Fig.6. Distribution of samples in Flemming diagram. Squares indicate samples from buried epipedons, while circles indicate those from colluvia.

Fig.7. Soil organic matter content (A) and $\delta^{13}C$ soil carbon content (B) of the watershed site buried epipedons. Generally, $\delta^{13}C$ values range from -30 to -22 for C_3 type plants (trees) and from -17 to -9 for C_4 type ones (grass).

Fig.8. General features of the pedostratigraphic section at the interior border of a clay mine. Numbers 2, 3 4, 5 and 6 indicate main units, as in figure 9. The white dotted line marks the transition between pleistocenic and holocenic materials. Orientation of the

different banks is showed. Based on dipping, the distance between the NW-SE main cut and apparent sedimentary source areas is estimated as about 25 to 30 meters.

Fig.9. Sedimentary log for the valley head pedostratigraphic sequence.

Fig.10. Flemming textural classification of materials from the buried peat bog.

Fig.11. Grain size ratio (<2µm/>10µm) estimated at 5 cm intervals for the 150 cm long peat bog. Note the two different textural zones along the diagram.

Fig.12. Summary pollen percentage diagram, including pollen concentration and the cluster analysis dendrogram, of the buried peat bog.

Fig.13. Pollen diagram for the buried peat bog, showing percentages of the major significant taxa, based on the total pollen sum. Note the variation of *Podocarpus* and *Weinmannia* (*Araucaria* forest group) along the two pollen zones.

Fig.14. $\delta^{13}C$ soil carbon values and organic carbon content of unit 2 and unit 4 in the valley head sedimentary sequence. Generally, $\delta^{13}C$ values range from -30 to -22 per thousand for C_3 type plants (trees) and from -17 to -9 for C_4 type ones (grass).

Fig.15. Scanned images obtained from thin sections of Quaternary (**A**) and modern (**B**) deposits. Images were taken under transmitted light. Numbers indicate detailed sedimentary units; the transitions are emphasized by drawn lines. The holocenic sample was collected at about 25 to 30 meters from the supposed sources of sediments, as

estimated by dipping measures. The modern sample was collected at about 40 meters from measured sources in the field.

Fig.16. Detail of a slope-wash deposit, along the floor of the clay mine studied. The deposit was formed about 40 meters from local sources of overland flow, after a two-day long 60 mm rain event. Main flow direction is to the right side of the picture.

Fig.17. Map showing the location of the study site (**X**) near Campo Alegre and those of the other sites mentioned: (**1**) "Serra Campos Gerais"; (**2**) Lago do Pires; (**3**) Morro de Itapeva. Figure adapted from Behling et al. (2004).

Table 1. Radiocarbon ages for buried epipedons at the watershed site

Lab (#)	Field (#)	Depth (m)	Stratigraphic Unit	Type of analysis	Measured age (^{14}C yr BP)	δ^{13}C (‰)
Beta- 124761	CA.24-10.A1	1,2	11	AMS	15,260 ± 80	-25.0
Beta-106474	CA.S-1	2,2	5	AMS	19,130 ± 110	-25.0

Table 2. Radiocarbon ages for the base and top of the peat horizon and for the ochric epipedon of the valley head site

Lab Code (#)	Field Code (#)	Depth (m)	Stratigraphic Unit	Type of analysis	Measured age (^{14}C yr BP)	δ^{13}C (‰)
# 953 / CENA # 520	Paleo-2	2,5	4	AMS	37.000 ± 1.425	-19.5
# 851 / CENA # 444	CA-TOPO	5.4	Top of 2	Conventional	49,300 + 9,700 – 4,250	-29.0
Erl- 5456	PH-09/02-2	6.9	Base of 2	AMS	> 50,000	-28.82

Table 3. Dose rate data, De values and optical age estimates for sandy samples of the valley head site sequence

Lab (#)	Field (#)	Depth (m)	Stratigraphic Unit	Method	Dose rate (μGy/yr)	De (Gy)	Optical age (yr BP)
LVD- 1127	CA-base-LOE	3.4	Base of 5	SOL	436 ± 40	2.89	6,625 ± 750
LVD- 662	CA-SC-73	7.5	Base of 1	TL	1,800 ± 40	150	90,000 ± 11,000

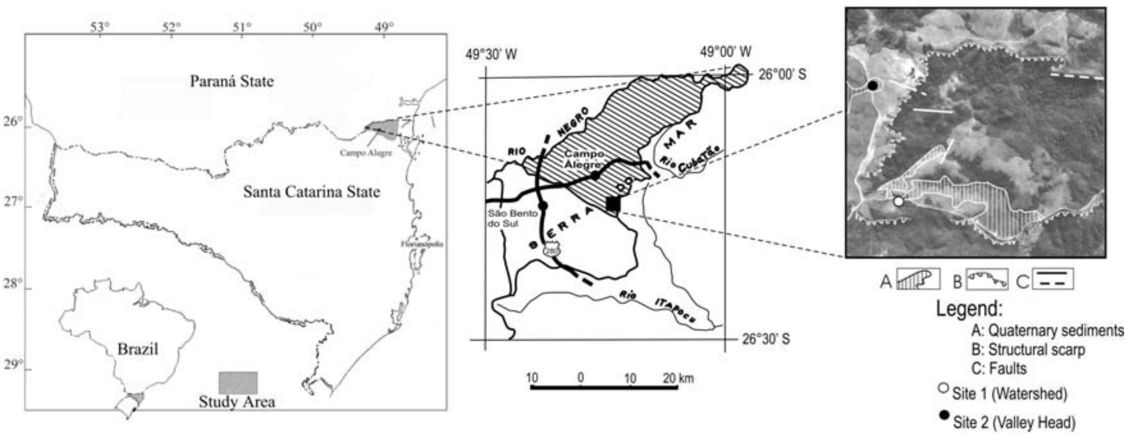
53°
52°
51°
50°
49°
26°
27°
28°
29°
Paraná State
Santa Catarina State
Campo Alegre
Florianópolis
Brazil
Study Area
49°30' W
49°00' W
26°00' S
26°30' S
RIO NEGRO
Campo Alegre
São Bento do Sul
SERRA DO MAR
Rio Cubatão
Rio Itapocu
280
10 0 10 20 km
A
B
C
Legend:
A: Quaternary sediments
B: Structural scarp
C: Faults
Site 1 (Watershed)
Site 2 (Valley Head)

Fig.1

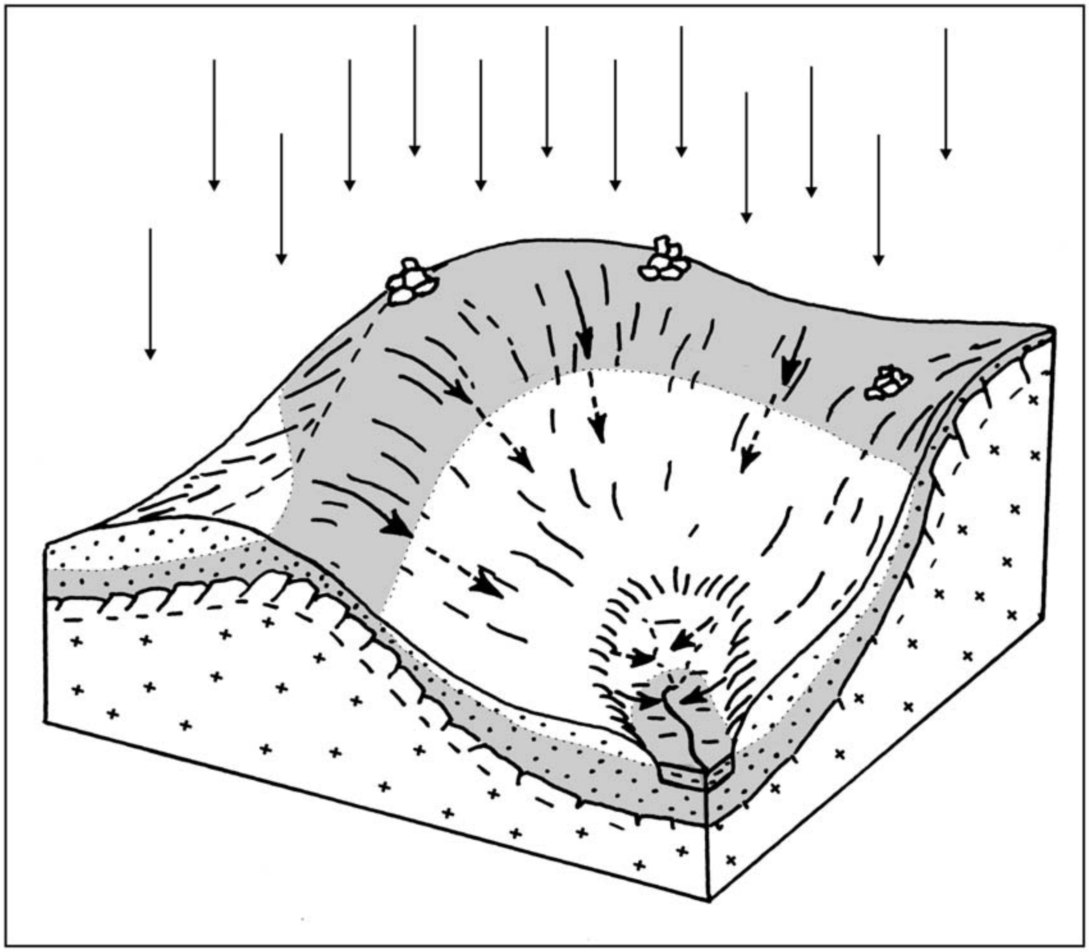

Fig.2

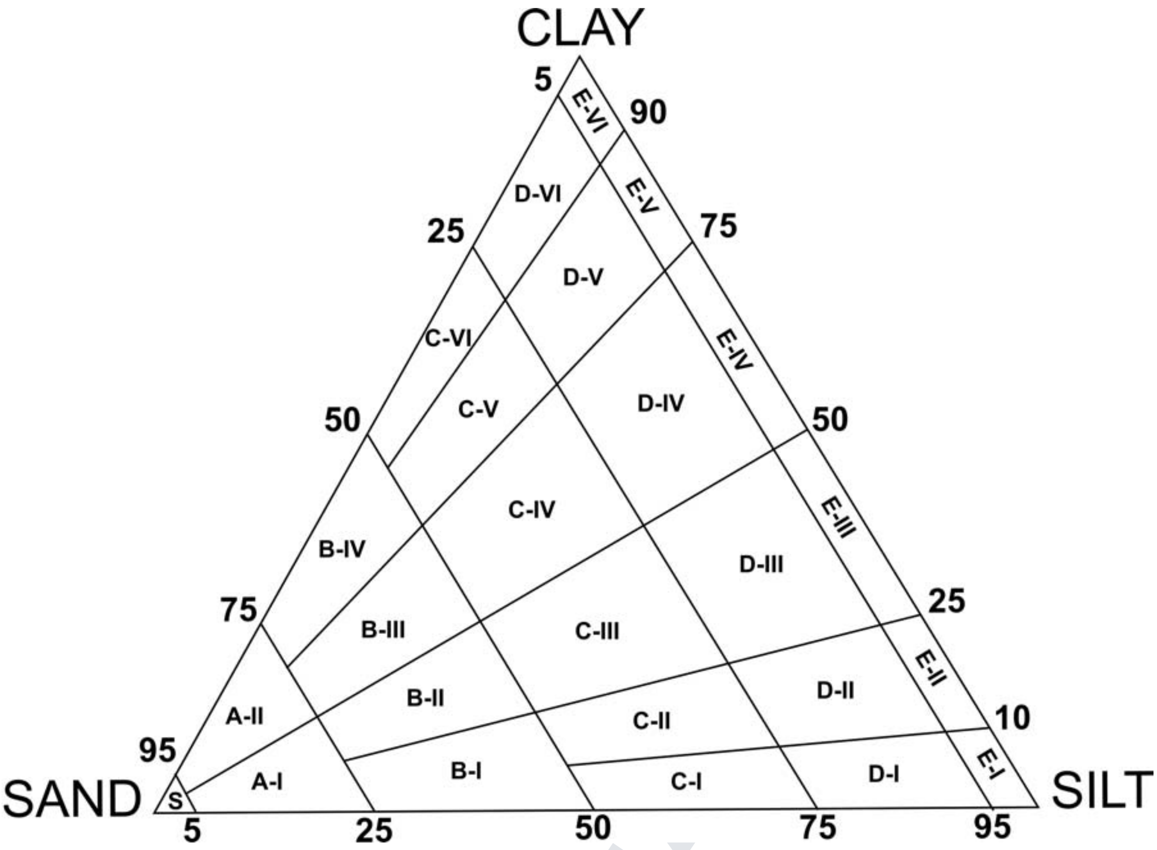
CLAY
SAND
SILT
5
90
25
75
50
50
75
25
95
10
5
25
50
75
95
E-VI
E-V
E-IV
E-III
E-II
E-I
D-VI
D-V
D-IV
D-III
D-II
D-I
C-VI
C-V
C-IV
C-III
C-II
C-I
B-IV
B-III
B-II
B-I
A-II
A-I
S

Fig.3

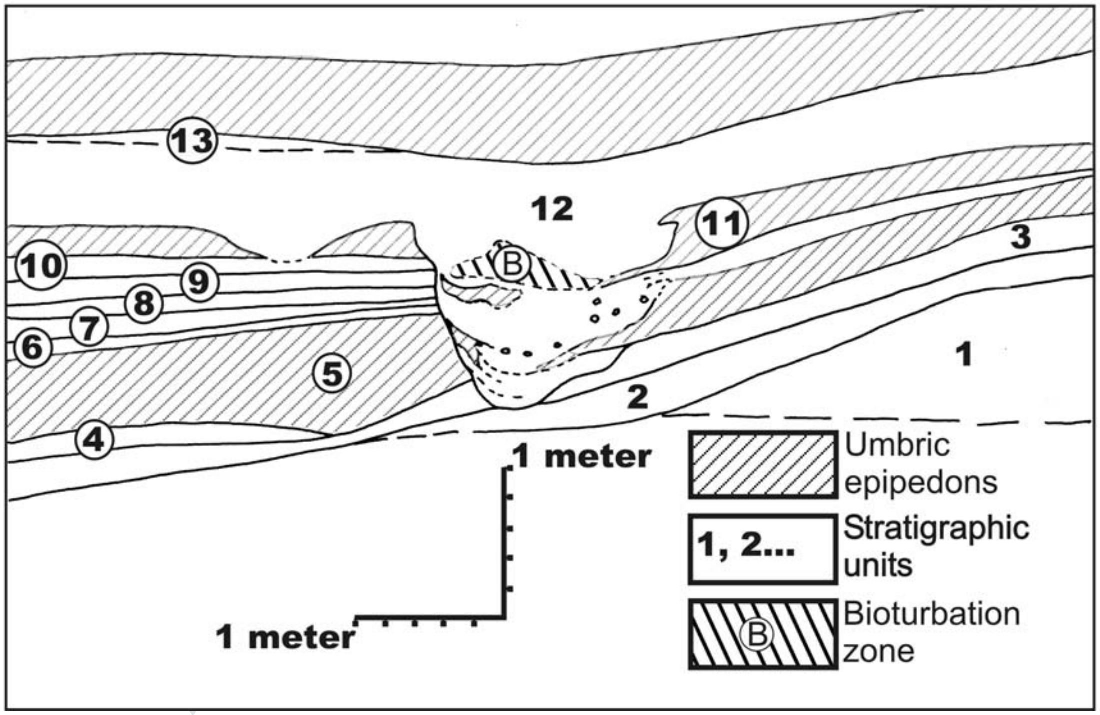
13
12
11
10
9
8
7
6
5
4
3
2
1
B
1 meter
1 meter
Umbric epipedons
1, 2...
Stratigraphic units
B
Bioturbation zone

Fig.4

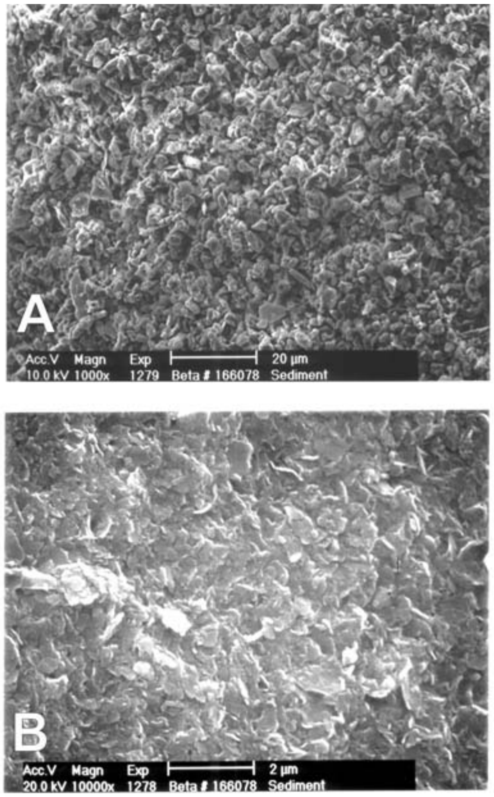
A
Acc.V Magn Exp 20 µm
10.0 kV 1000x 1279 Beta # 166078 Sediment
B
Acc.V Magn Exp 2 µm
20.0 kV 10000x 1278 Beta # 166078 Sediment

Fig.5

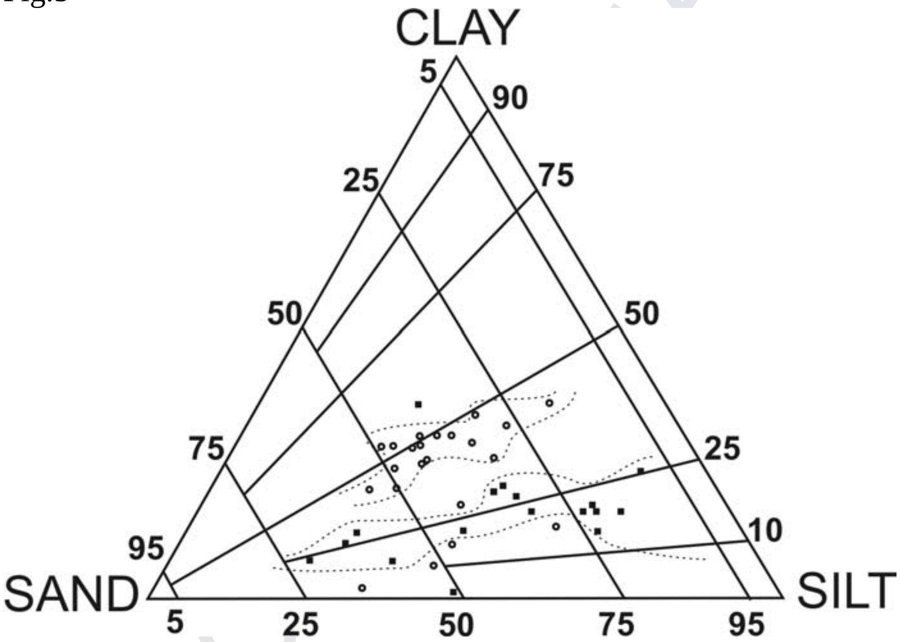
CLAY
5
90
25
75
50
50
75
25
95
10
SAND
SILT
5
25
50
75
95

Fig.6

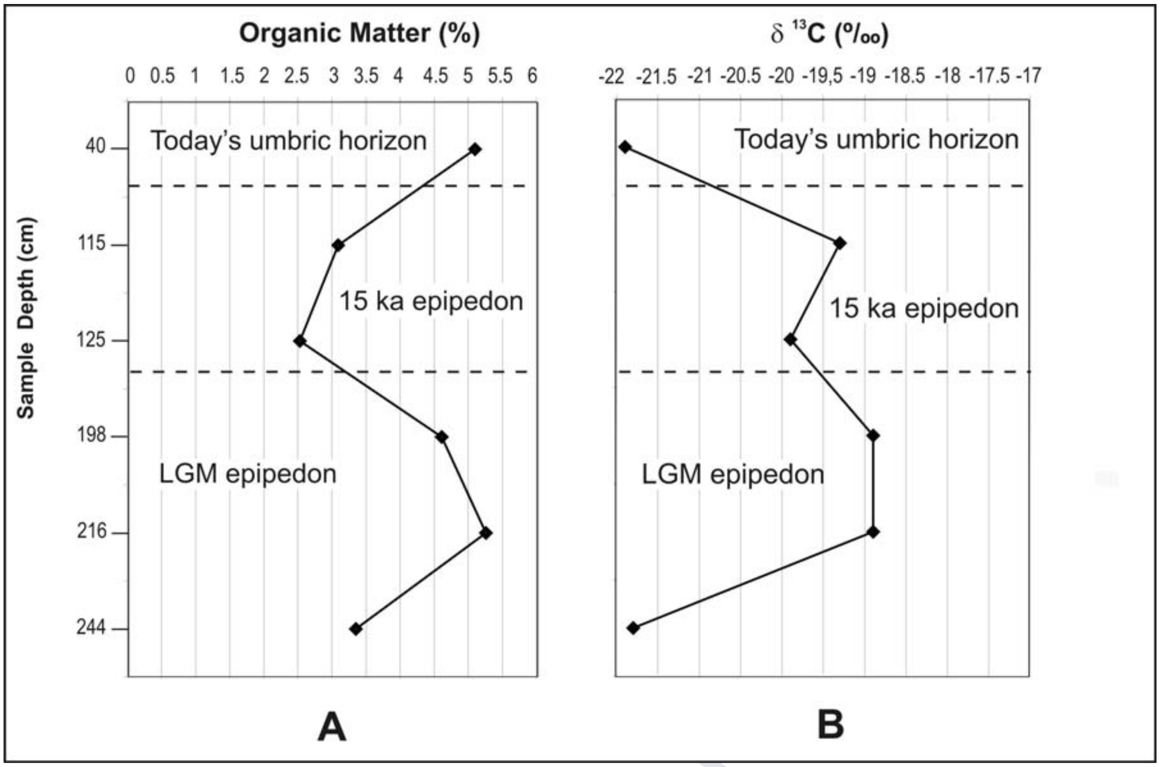
Organic Matter (%)
0 0.5 1 1.5 2 2.5 3 3.5 4 4.5 5 5.5 6
δ ¹³C (‰)
-22 -21.5 -21 -20.5 -20 -19,5 -19 -18.5 -18 -17.5 -17
Sample Depth (cm)
40
115
125
198
216
244
Today's umbric horizon
15 ka epipedon
LGM epipedon
A
B

Fig.7

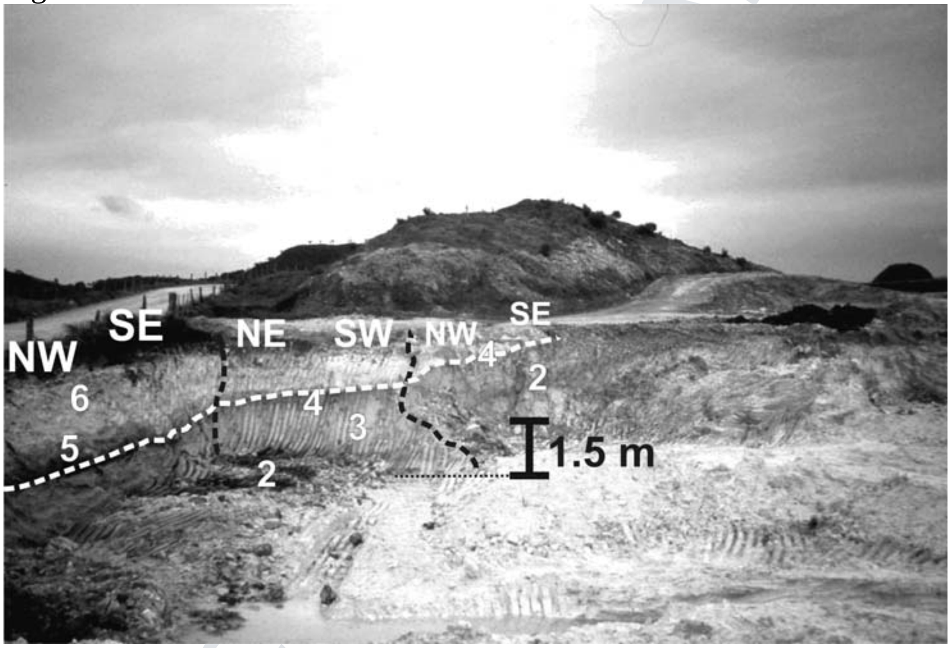
NW
SE
NE
SW
NW
SE
6
5
4
3
2
4
2
1.5 m

Fig.8

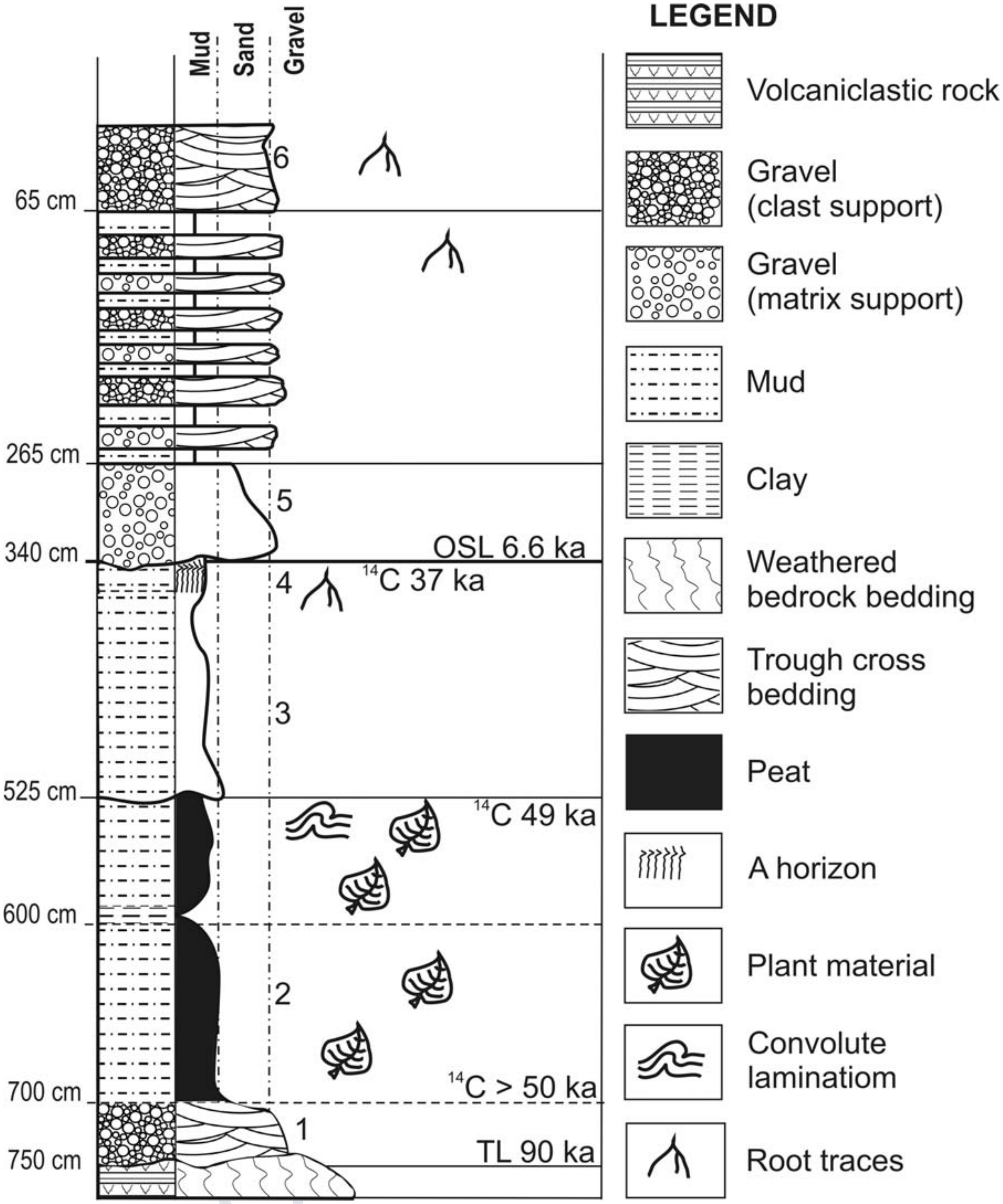
Mud
Sand
Gravel
6
65 cm
265 cm
5
340 cm
OSL 6.6 ka
4
^{14}C 37 ka
3
525 cm
^{14}C 49 ka
600 cm
2
700 cm
^{14}C > 50 ka
1
750 cm
TL 90 ka
LEGEND
Volcaniclastic rock
Gravel (clast support)
Gravel (matrix support)
Mud
Clay
Weathered bedrock bedding
Trough cross bedding
Peat
A horizon
Plant material
Convolute laminatiom
Root traces

Fig.9

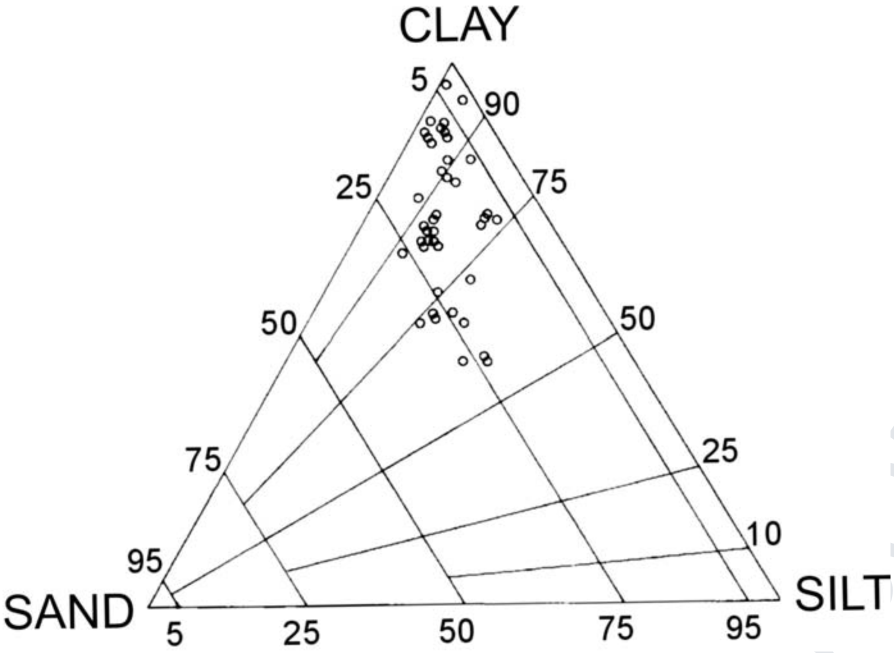

Fig.10

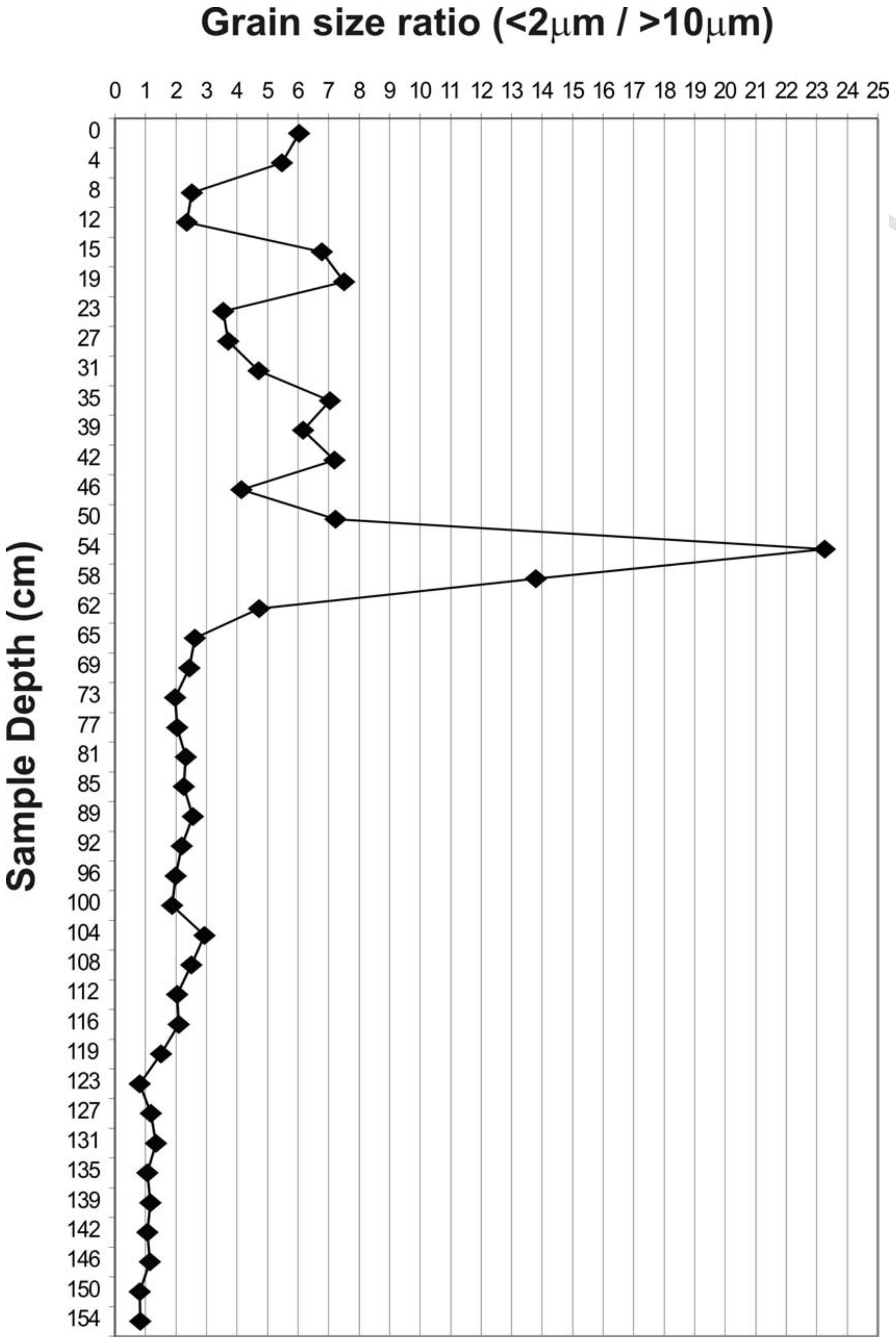
Grain size ratio (<2µm / >10µm)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
Sample Depth (cm)
0
4
8
12
15
19
23
27
31
35
39
42
46
50
54
58
62
65
69
73
77
81
85
89
92
96
100
104
108
112
116
119
123
127
131
135
139
142
146
150
154

Fig.11

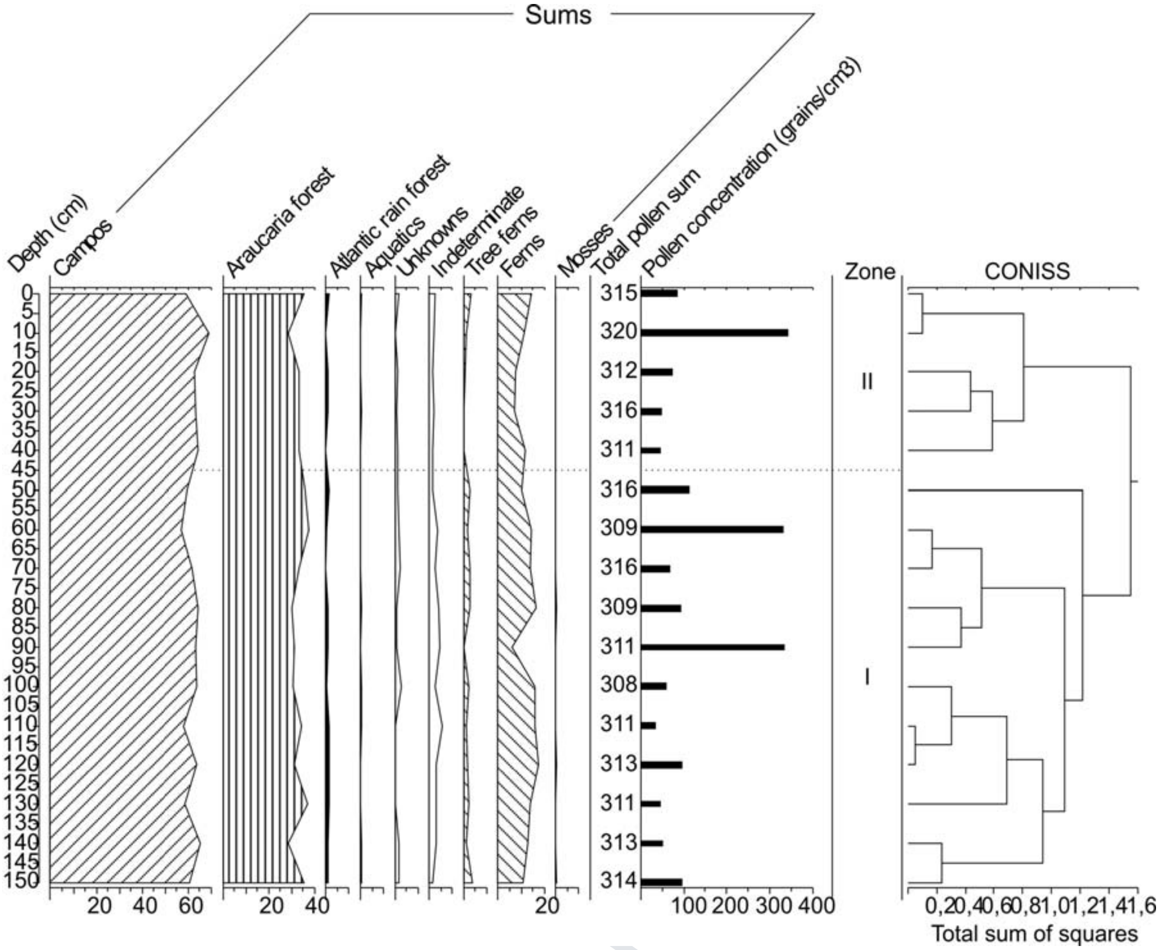
Sums
Depth (cm)
Campos
Araucaria forest
Atlantic rain forest
Aquatics
Unknowns
Indeterminate
Tree ferns
Ferns
Mosses
Total pollen sum
Pollen concentration (grains/cm3)
Zone
CONISS
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
95
100
105
110
115
120
125
130
135
140
145
150
315
320
312
316
311
316
309
316
309
311
308
311
313
311
313
314
II
I
20
40
60
20
40
20
100
200
300
400
0,2
0,4
0,6
0,8
1,0
1,2
1,4
1,6
Total sum of squares

Fig.12

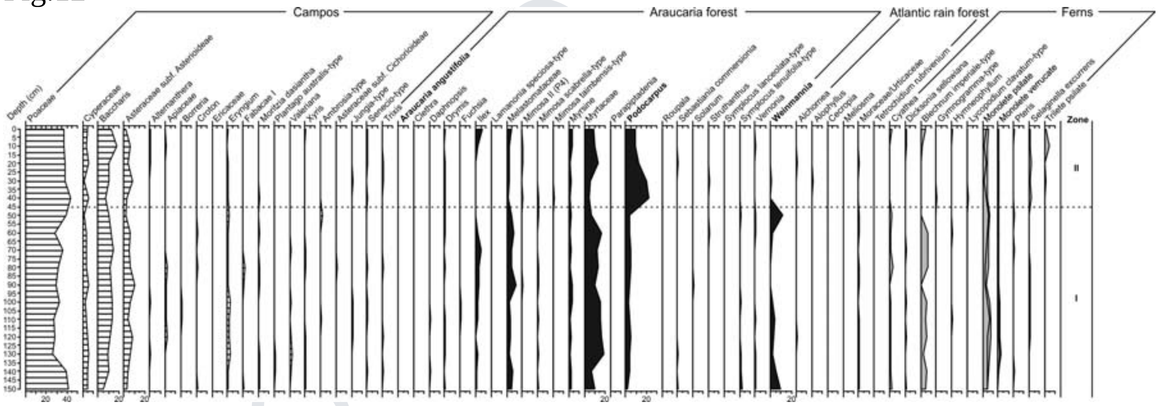
Campos
Araucaria forest
Atlantic rain forest
Ferns
Depth (cm)
Poaceae
Cyperaceae
Baccharis
Asteraceae subf. Asterioideae
Alternanthera
Apiaceae
Borreria
Croton
Ericaceae
Eryngium
Fabaceae I
Moritzia dasiantha
Plantago australis-type
Valeriana
Xyris
Ambrosia-type
Asteraceae subf. Cichorioideae
Jungia-type
Senecio-type
Trixis
Araucaria angustifolia
Clethra
Daphnopsis
Drymis
Fuchsia
Ilex
Lamanonia speciosa-type
Melastomataceae
Mimosa II (P4)
Mimosa scabrella-type
Mimosa taimbensis-type
Myrsine
Myrtaceae
Parapiptadenia
Podocarpus
Roupala
Sebastiania commersionia
Solanum
Struthanthus
Symplocus lanceolata-type
Symplocus tenuifolia-type
Vernonia
Weinmannia
Alchornea
Alophyllus
Cecropia
Meliosma
Moraceae/Urticaceae
Tetrochidium rubrivenium
Cyathea
Dicksonia sellowiana
Blechnum imperiale-type
Gymnogramma-type
Hymenophyllum
Lycopodium clavatum-type
Monolete psilate
Monolete verrucate
Pteris
Selaginella excurrens
Trilete psilate
Zone
II
I
20
40
20
20
20
20
20

Fig.13

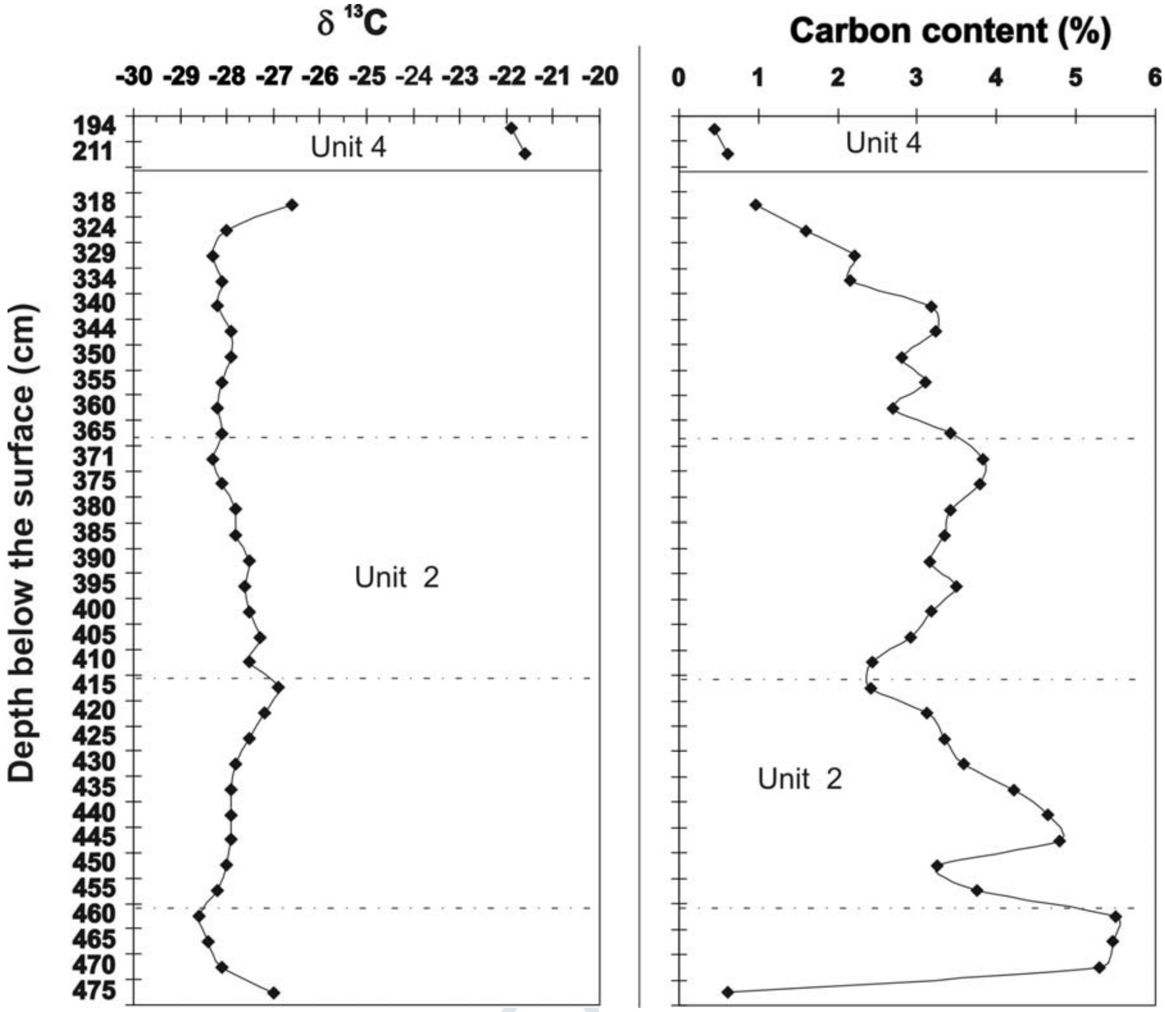
δ ¹³C
Carbon content (%)
-30 -29 -28 -27 -26 -25 -24 -23 -22 -21 -20
0 1 2 3 4 5 6
Depth below the surface (cm)
194
211
318
324
329
334
340
344
350
355
360
365
371
375
380
385
390
395
400
405
410
415
420
425
430
435
440
445
450
455
460
465
470
475
Unit 4
Unit 2
Unit 4
Unit 2

Fig.14

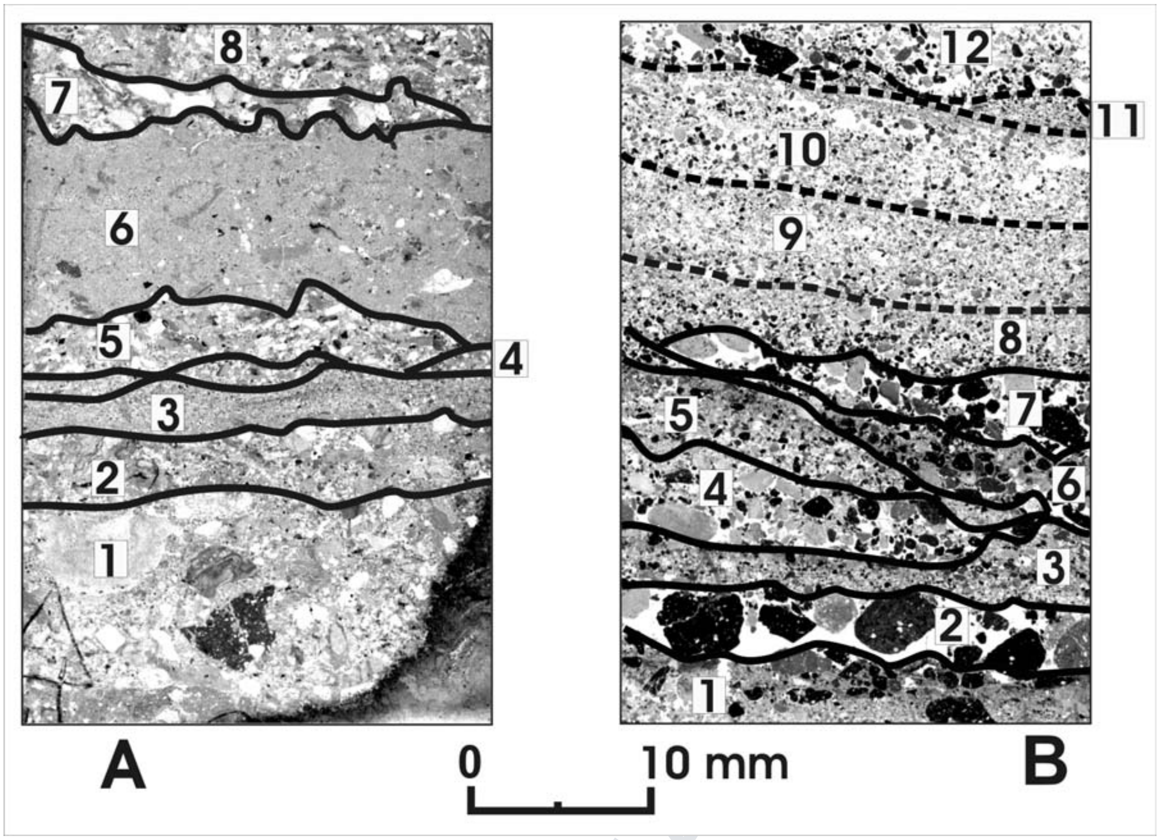

Fig.15

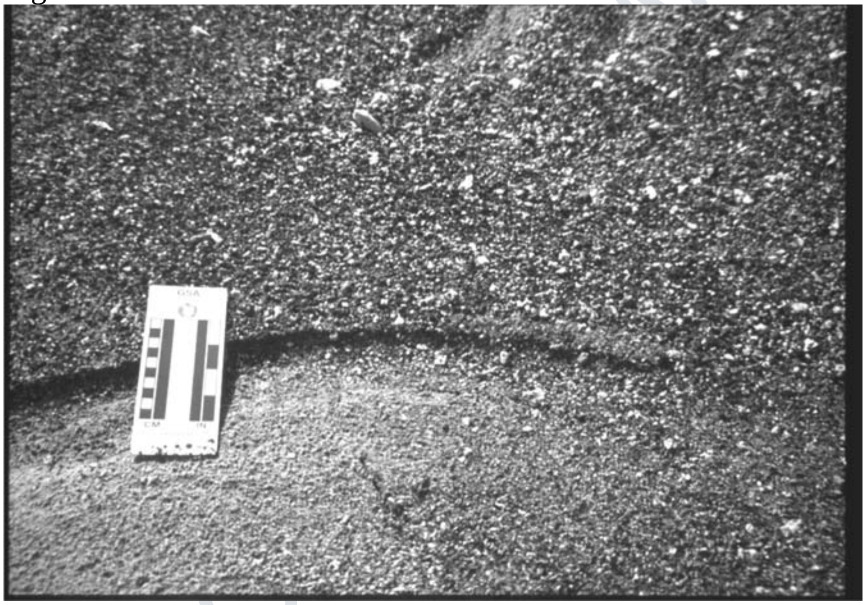

Fig.16

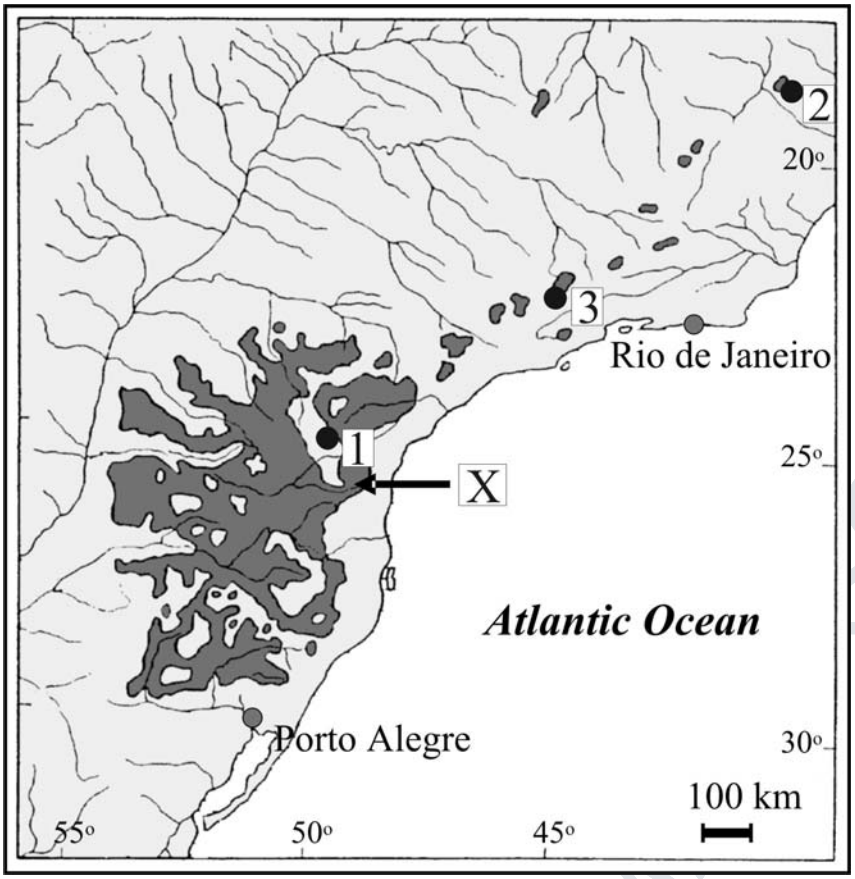
2
20°
3
Rio de Janeiro
1
25°
X
Atlantic Ocean
Porto Alegre
30°
100 km
55°
50°
45°

Fig.17