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Climatic and land use changes on the NW of Iberian Peninsula recorded in a 1,500-year record from Lake Sanabria

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Resum

L'estudi de diversos descriptors paleoambientals com ara el pol·len, les diatomees i la sedimentologia, realitzat en sediments procedents del llac de Sanabria (NO de la península Ibèrica), ha aportat informació sobre les oscil·lacions climàtiques atribuïdes als períodes càlids tardoromà i medieval, així com a la petita edat del gel. Entre els anys 440 i 950 dC, el clima es caracteritzà per temperatures suaus i un règim de precipitacions mediterrani, malgrat l'existència de pulsacions més fredes vers els anys 530 i 700 dC. Les evidències pol·líniques dels usos del sòl indiquen l'extensió d'activitats ramaderes i agrícoles. Aquesta fase correspon al final del període càlid romà i al període càlid medieval. El canvi de condicions climàtiques es produeix entre els anys 950 i 1100 dC, moment en què els valors mínims de matèria orgànica, pol·len arbori, concentració de diatomees, nitrogen total (TN) i mida del gra indiquen temperatures més baixes i un règim de precipitacions més regular. Aquest període correspon a la petita edat del gel, que finalitzà vers l'any 1590 dC. Posteriorment, la productivitat del llac tendeix a recuperar els valors previs, malgrat que es produeixen episodis freds i curts.

Els valors de carbó orgànic total, TN i diatomees covarien amb els índexs de temperatura del NO de la península Ibèrica i posarien de manifest que, amb anterioritat a l'era industrial, el sistema lacustre de Sanabria estava controlat principalment per les condicions climàtiques. Des de l'any 1920 dC, la productivitat del llac està influenciada per l'activitat humana.

Paraules clau: variabilitat climàtica, RWP-MWP-LIA, pol·len, diatomees, sedimentologia, Holocè, NO Península Ibèrica

Abstract

This multi-proxy paleoenvironmental study from Lake Sanabria (NW Iberian Peninsula), based on pollen, diatom, and sedimentology, provides evidences of climatic oscillations attributed to the Late Roman and Medieval Warm Periods as well as the Little Ice Age (LIA). From 440 to 950 AD, the climate was characterized by mild temperatures and a Mediterranean rainfall regime, although climatic cold periods were recorded at ca. 530 and 700. Evidence from pollen indicators of land-use suggests that grazing and farming were widespread activities. This period corresponds to the end of the Roman Warm Period and the Medieval Warm Period. The onset of new climate conditions occurred between 950 and 1100 AD, as minimum values of organic matter, arboreal pollen, diatom concentration, total nitrogen (TN), and grain size indicate low temperatures and a more regular rainfall regime. This period corresponds to the LIA and ended at 1590 AD, when lake productivity tended to recover to previous values in spite of the occurrence of cool events. Total organic carbon, TN, and diatom content covary with the temperature index for the NW Iberia, suggesting that Lake Sanabria was mainly controlled by climate before the industrial period. Since 1920 AD, lake productivity has been mainly influenced by human activity.

Keywords: climate variability, RWP-MWP-LIA, pollen, diatom, sedimentology, Holocene, NW Iberian Peninsula.

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Paleoenvironmental studies on the last two millennia have provided useful data for modeling the effects of the current global warming due to anthropogenic forcing and for yielding insight into how natural forcing (such as solar and volcanic activity) triggered climate change during pre-industrial periods [1, 2, 3, 4]. Moreover, written historical sources and high-resolution paleoclimatic proxies of the last millennia (such as tree rings, ice cores, corals, and laminated sediments) have supplied accurate data to extend paleoclimatic studies to the time before the instrumental period. Recent reconstructions of temperatures in the Northern Hemisphere over the past millennium have confirmed the existence of cooler conditions, such as the Little Ice Age, approximately encompassing the period 1300–1900 AD, just after a warm period known as the Medieval Warm Period [5, 6, 7, 8, 9] or Medieval Climatic Anomaly [10].

Nevertheless, the onset of cooling and the details of decadal paleoclimatic variations account for apparent differences in the regions [11,12]. High-resolution proxy data (from year to decade) show that Late-Holocene climate evolution was more unstable and complex than previously believed [13, 9, 8]. One of the best methods to improve climate-system models is to study new high-resolution quantified paleoclimatic archives in an attempt to account for present-day regional discrepancies.

The aims of this review are to present a 1500-year paleoenvironmental record in the NW Iberian Peninsula and to reconstruct paleoenvironmental changes. This region is a sensitive area for paleoenvironmental studies, given that it is situated in the transition zone between the Atlantic and the Mediterranean bioclimatic regions [14] and is influenced by North Atlantic Oscillation variability [15]. Recent studies in the northern Iberian Peninsula have documented climatic variability in the last 3000 years [16, 17, 21]. In addition, climate reconstructions for the last 2,000 years in NW Iberia have been carried out using Hg thermal stability [18], pollen sequences [19, 20, 21], alkenones, and isotopes [22].

The lacustrine and peat sequences of the Lake Sanabria area have provided useful data, based on pollen analysis, for reconstructing environmental change for the last 14,000 years [23, 24, 25, 20], but there have been no high-resolution studies covering the last 2000 years. Lake Sanabria enables us to shed light on the paleoclimatic framework of the Roman Warm Period (RWP)-Medieval Warm Period (MWP)-Little Ice Age (LIA) interval in this region.

Site description

The oligotrophic Lake Sanabria (1000 m above sea level) is located in the NW Iberian Peninsula (42º07'3''N, 06º43'00''W) (Fig. 1) and constitutes the largest natural freshwater system in the Iberian Peninsula [26, 27]. This lake is situated in an exorrheic drainage basin (127.3 km^2) and lies in the valley of the Tera River, which is the only tributary and emissary drainage system of the lake. The basement of the catchment area is made up of granitic rocks (gneiss and granodiorite), formed during the Hercynian Orogeny [28, 29, 30], and of Quaternary deposits. These rocks have a low water solubility, which accounts for the very low ionic content of Lake Sanabria (conductivity = 14 μS/cm). The organic matter content of the lake is controlled by the rainfall regime since the organic matter is supplied by run-off [31, 32, 33]. The lake is therefore highly sensitive to both acidification and eutrophication.

Lake Sanabria is of glacial origin [34, 35] and is located in a valley blocked by a terminal moraine. The bathymetric map of the lake shows two over-excavated sub-basins (Fig. 1). The lake is located in the Atlantic margin of the Iberian Peninsula, an area where rainfall is influenced by the NAO [15]. The mean annual temperature recorded during the period 1967–1982 was 10.0ºC, and mean annual precipitation from 1942 to 1982 was 1402.3 mm.

The relief of the catchment ranges between 1000 and 2000 m above sea level (ASL). The lake's shores are covered by *Populus nigra*, *Alnus glutinosa, Fraxinus angustifolia* and *Salix* sp*.* In the watercourses at higher altitudes, these riparian trees are replaced by less thermophilous taxa, such as *Betula pubescens* ssp. *celtiberica* and *Corylus avellana*. The plant communities of the lake shore are mainly composed of *Nitella flexilis, Myriophyllum alterniflorum, Isoetes velata, Eleocharis palustris, Fontinalis antipyretica, Equisetum fluviatile, Carex* sp., *Utricularia australis*, and *Potamogeton* sp. Below 1500 m ASL, the meso-Mediterranean forest consists of *Quercus ilex*; between 1500 m ASL and the timberline (1700 m ASL), *Quercus pyrenaica* supra-Mediterranean forests dominate, with patches of *Pinus sylvestris, Juniperus oxycedrus*, *Taxus baccata*, and *Ilex aquifolium*. Between 1700 and 2000 m ASL, heathlands consist mainly of shrub taxa, such as *Erica umbellata, Calluna vulgaris, Erica australis* ssp. *aragonensis, Halimium ocymoides, Halimium alyssoides, Genista falcata, Genistella tridentata,* and *Genista sanabrensis.* In the summit areas, *Juniperus communis* ssp. *nana,* and *Genista sanabrensis* are present. High altitude grasslands develop above 2000 m ASL.

Nowadays, human influence over the catchment area is relatively low. Emigration commenced in the 1950s, leading to a decline in the population. The Galende municipality, where the lake is located, underwent a population density decline, from 16.2 inhabitants/km^2 to 6.5 inhabitants/km^2. Cattle-raising is the main economic activity in the area, alongside subsistence agriculture. Sheep are taken to high-altitude pastures every year along the *Cañada Real* sheep trail, but this activity has diminished in the last decades [36]. Agriculture in this zone is difficult because of the poor soil and the abrupt relief. Emigration has led to a decrease in crop cultivation. Forest exploitation has declined because of sporadic fires in recent decades (243 fires during 1995–1999). One of the main activities in the catchment area of the lake is the hydroelectric power station, which was set up in the 1950s. The sources of pollution in the area are low, since Lake Sanabria was set up as a natural park in 1978.

Materials and methods

Several sediment cores were collected from the east sub-basin (51 m water-column depth) and west sub-basin (40 m water column depth) (Fig. 1). Cores were obtained by the piston core technique. The parameters used in the paleoenvironmental reconstruction were: water content, loss on ignition (LOI), total organic carbon (TOC), total nitrogen (TN), total phosphorus (TP), grain size, diatom content, and pollen content. All parameters were studied at a 1-cm depth interval, except for TP (5 cm) and pollen content (5–10 cm). The water content and LOI analyses were carried out following standard procedures. The TOC and TN analyses were determined using a chromatograph (C.E. Instruments 2100 model). TP was analyzed by inductively coupled plasma atomic emission spectroscopy (ICP-AES). Grain size was determined by a laser Mastersizert. The value for each sample was attributed to the lower limit of the depth interval.

Four radiometric measurements were made on the sediment cores using the AMS radiocarbon method, and Pb-210 and Cs-137 profiles. Radiocarbon analyses were carried out by Beta Analytic Inc. (Miami, Florida), and the Pb-210 and Cs-137 samples were measured at the Environmental Radiation Research Laboratory (Department of Experimental Physics, University College Dublin).

Radiocarbon dates were calibrated using the CALIB 5.0. program [37]. Samples for pollen analysis were treated in the SAN235E sediment core following standard procedures [38]: KOH, 200-µm filter, HF, HCl, $Na_4P_2O_7$, and 10-µm filters. Aquatic taxa (*Ranunculus,* Cyperaceae*, Typha-Sparganium,* Nymphaceae*),* ferns, and unidentifiable palynomorphs were excluded from the basic sum. Counted pollen grains per sample ranged from 250 to 350.

Samples for diatom analysis were treated in the SAN135E sediment core following the procedures described in Julià et al. [39]. Initially, 0.2 g of wet sediment was cleaned with hydrogen peroxide, diluted with HCl, and counted under 1000× magnification using an inverted microscope. At least 400 diatoms frustules were counted per sample and counts are given as whole individuals. Diatom identifications were based upon the criteria of Du Buf and Bayer [40]. The abundance of planktonic vs. benthic diatoms was determined on the basis of diatom percentages. Planktonic flora included *Alaucoseria distans* and *Cyclotella stelligera*, whereas benthic flora included *Fragilaria*, *Tabellaria*, *Eunotia*, *Cymbella*, *Gomphonema*, *Navicula*, *Pinnularia*, and *Surirella*. Diatom, pollen, and spore assemblages were clustered using the stratigraphically constrained analysis CONISS to determine zone limits [41].

The chronology of the Hg thermal stability profiles provided by Martínez-Cortizas et al. [18] were modified according to the calibration ages obtained with CALIB, version 5.0 [37, 42].

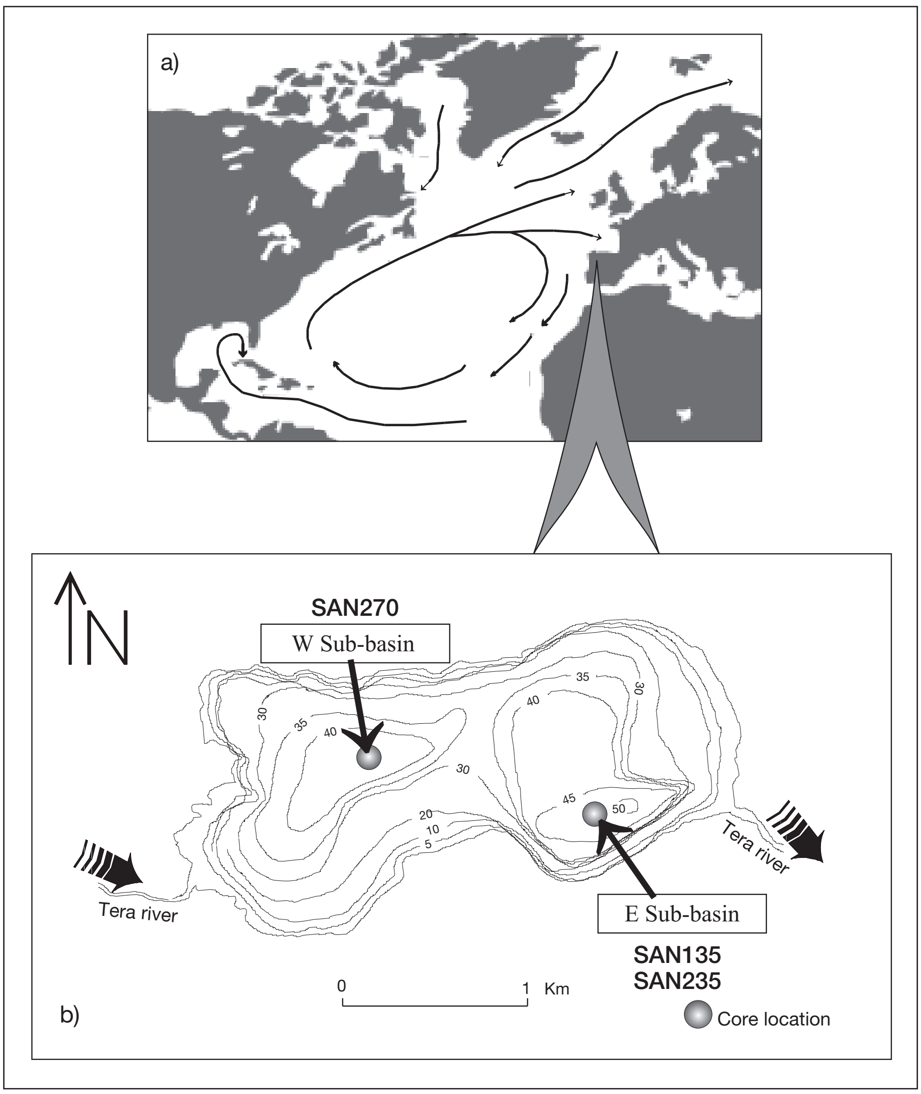

Figure 1. (a) Location of Lake Sanabria in the NW Iberian peninsula. (b) Location of the coring sites: the sediment cores were collected from two sub-basins (SAN270 at the western sub-basin and SAN235 and SAN135 at the eastern sub-basin).

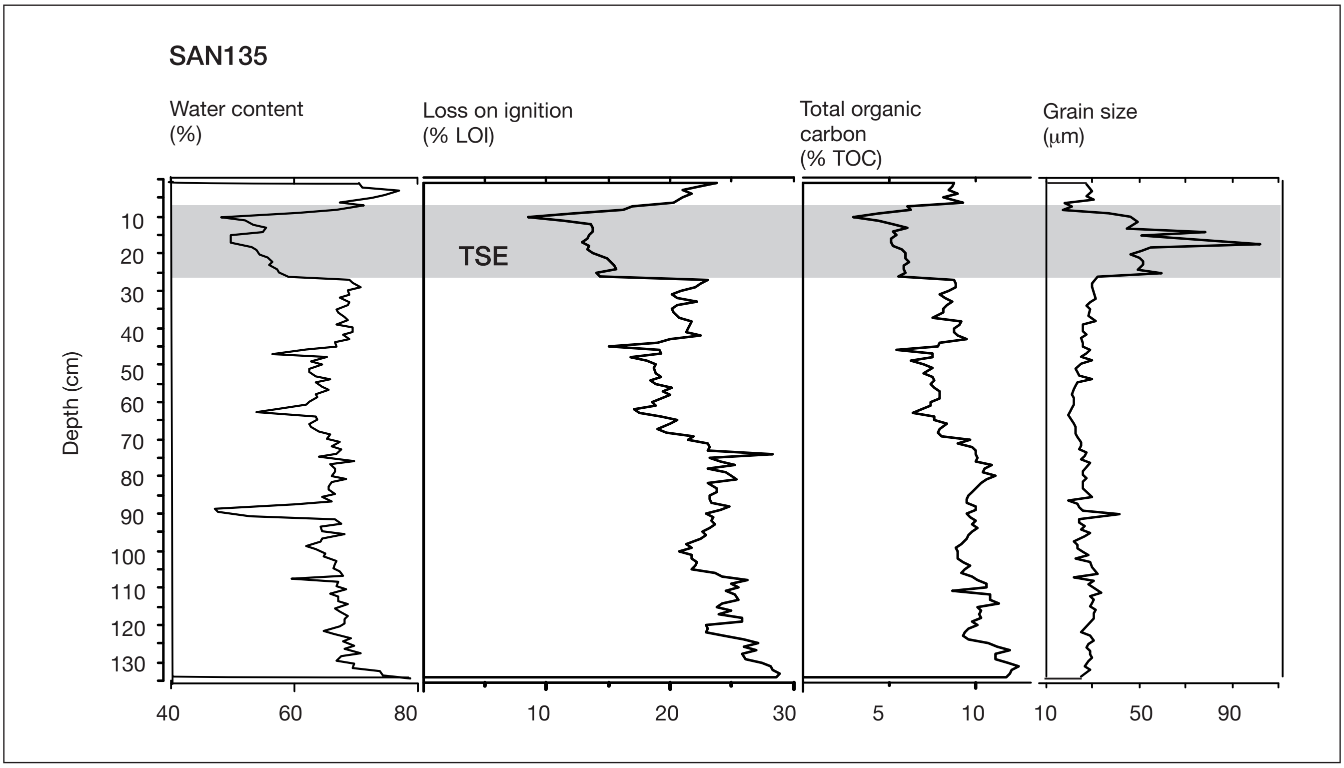

Figure 2. Sediment lithology of SAN135. Sampling was carried out at 1-cm resolution. The terrigenous sedimentary episode (TSE) resulted from the break of the Vega de Tera dam on 9 January 1959.

Table 1. Radiocarbon results from cores SAN135 and SAN235

Core	*Depth (cm)*	*Lab. reference*	*Material*	*Conventional radiocarbon age*	*13C/12C (‰)*	*Cal age (BC/AD) (2 sigma)*	*Age BC/AD used for chronological model*
SAN135	69	Beta-216166	Bulk sediment	1030+/-40 BP	–24.5	960-1030 AD	995 AD
SAN135	104	Beta-216167	Bulk sediment	1380+/-40 BP	–26.3	630-710 AD	670 AD
SAN135	134	Beta-139809	Bulk sediment	1630+/-40 BP	–26.0	350-535 AD	442 AD
SAN235	234	Beta-139810	Bulk sediment	2360+/-40 BP	–26.8	515-380 BC	447 BC

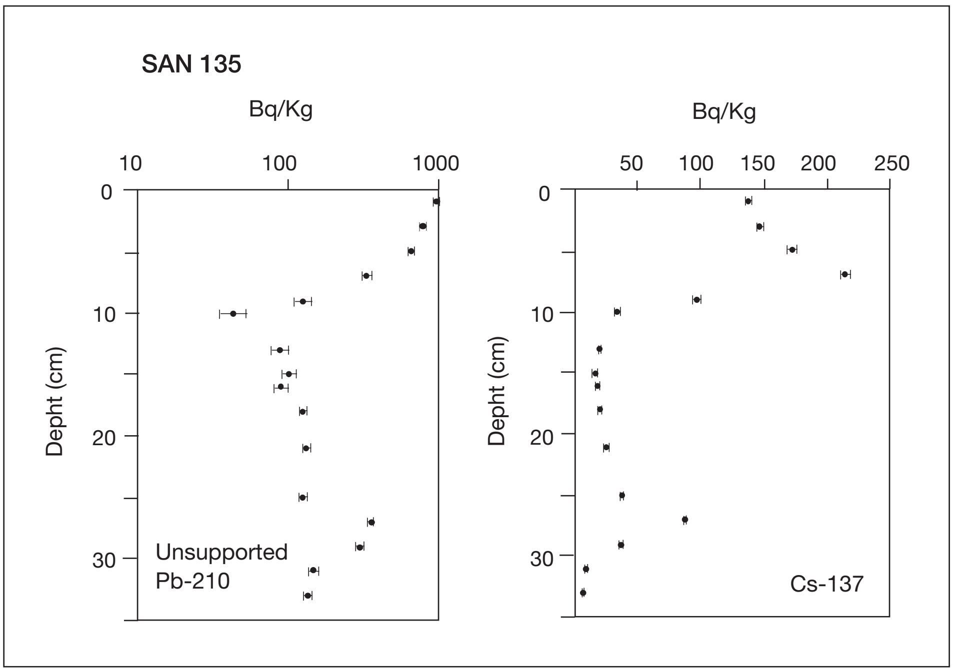

Figure 3. Unsupported Pb-210 and Cs-137 activity profiles obtained from SAN135. The Cs-137 chronology was deduced by assuming the presence of the 1963 peak. The Pb-210 chronology was calculated according the CIC model (details in Luque and Julià, 2002).

Results

Lithology

The sediment is mainly composed of homogeneous dark organic-rich silt (Munsell color: 5YR 2/1, brownish black). Sporadically, inorganic sedimentary facies exist at different depths (Munsell colors: 7.5YR, 10YR, 2.5Y). A sedimentary level located in the upper stratigraphy of each sediment core was noted. This was characterized by a coarser grain size (from sandy silt to sand) and by a lower organic matter content (Fig. 2). The specific features of the sedimentary level resulted from it being much more terrigenous than the dark brown silt and it was thus termed the Terrigenous Sedimentary Episode (TSE) [43].

Organic matter content

The organic matter content in the sediment of Lake Sanabria could be deduced from the LOI, since the crystalline catchment area of the lake excludes inorganic carbon from the sedimentary system [43]. Figure 2 shows the high correlation between water content, LOI, and TOC, allowing one layer of low organic matter content, corresponding to the TSE layer, to be distinguished.

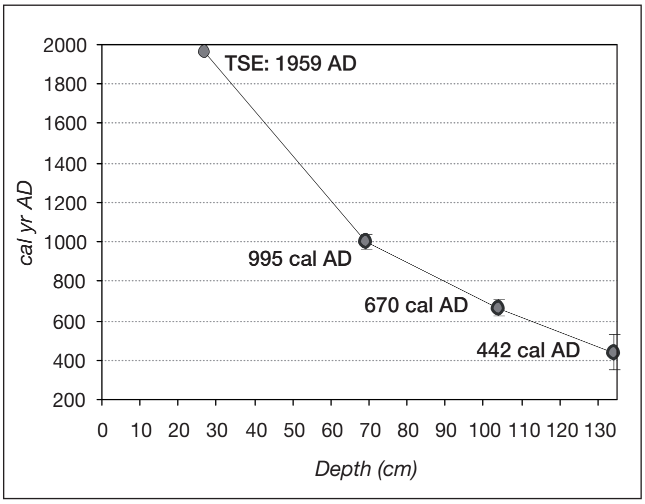

Figure 4. Age-depth plot for core SAN135.

Radiometric dating

The results of radiocarbon dating and calibrations are shown in Table 1. The age used for the chronological model of each core corresponded to the mean value of the 2-sigma interval after

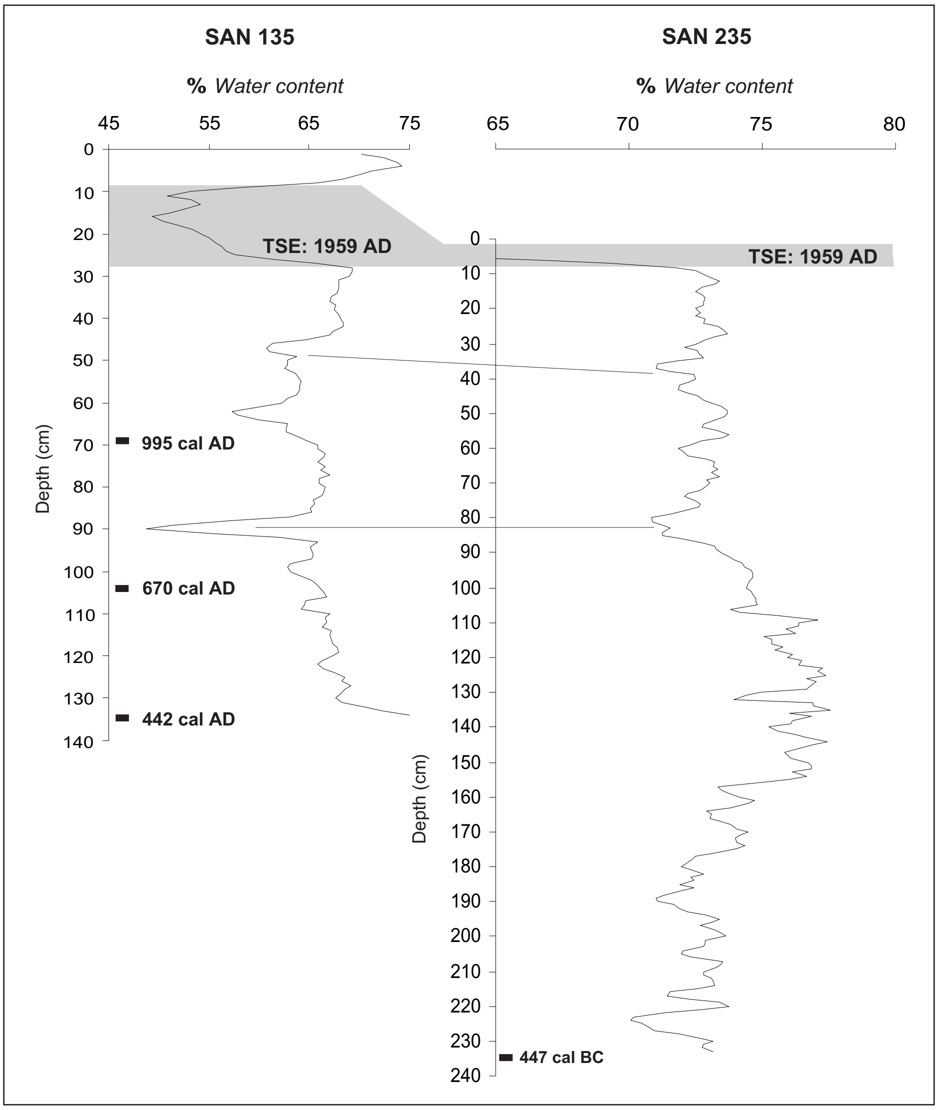

Figura 5. Correlation between the cores SAN 135 and SAN 235, based on water content.

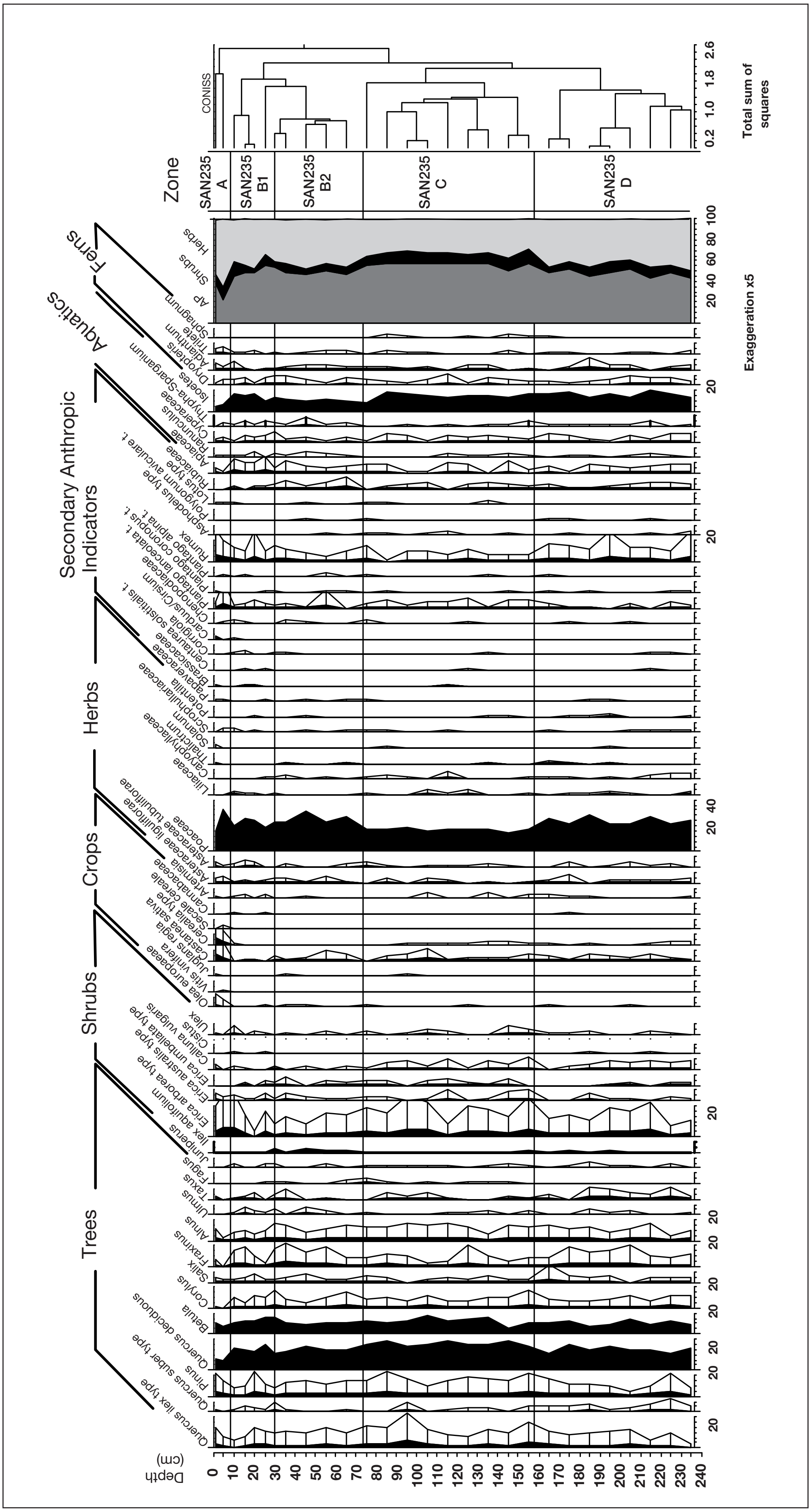

Figure 6. Pollen diagram at Lake Sanabria (SAN235 core). The results are expressed in percentages. The pollen sum includes all terrestrial pollen, excluding aquatics.

date calibration. Unsupported Pb-210 and Cs-137 profiles of the core SAN135 [43] were used to establish the chronology and sedimentation rates for the uppermost sediments (Fig. 3).

The profile of unsupported Pb-210 of SAN135 did not follow an exponential decline and recorded a second, deeper peak at 27 cm depth. The low values of Pb-210 activity between both peaks fit the TSE layer. Measured Cs-137 activities also revealed two peaks, a maximum at 6–7 and a second one at 26–27 cm depth. The highest Cs-137 activities were associated with the nuclear weapons tests in 1963. These data indicated that TSE layer was deposited before 1963 and after 1950, as suggested by the deepest peak of Cs-137 activities, which could correspond to the beginning of the nuclear tests. The sedimentology and radionucleide dilution, therefore, enabled us to establish the chronology of the TSE layer between 1950 and 1963 AD, associated with a high sedimentation rate. This layer corresponds to the collapse of the Vega de Tera dam on January 9, 1959, which resulted in a 35-m-high catastrophic flash flood [44, 43].

Chronological model

The chronological framework for SAN135 was obtained by assuming a constant sedimentation rate between two dated contiguous samples (Fig. 4). An age-depth model for the core SAN235 was established using the radiocarbon date at a depth of 234 cm and the correlation with SAN135 based on the sedimentological data (Fig. 5)

Pollen analysis

Pollen analysis was carried out in SAN235 (eastern sub-basin) and in SAN270 (western sub-basin). SAN270 was used to complement the vegetation change for more recent times. It recorded pollen deposition in the TSE layer and the evolution of the land until the present. Pollen diagrams with almost all the identified taxa are shown in Figs. 6 and 7. The latter includes the LOI and pollen concentration values to provide a better understanding of the pollen spectra of the TSE flash-flood layer.

Cluster analysis differentiated four pollen zones in the SAN235 profile. The SAN270 pollen diagram was subdivided into pre-TSE, TSE, and post-TSE samples.

SAN 235 pollen diagram (Fig. 6)

Zone D (depth of 235–158 cm) was characterized by relatively low percentages of arboreal (42–50%) and shrub (7–12%) pollen whereas the percentages of herbaceous pollen reached 38–45%. The arboreal pollen was dominated by deciduous trees, such as *Quercus*, which had pollen values up to 20–25%, *Betula*, with values of 7–15%, and *Ulmus*. *Quercus ilex* type was present while the highest values in the sequence were recorded for *Quercus suber* type and *Taxus baccata*. *Fraxinus, Salix* and *Alnus* constituted the riparian forests. *Erica arborea* type was the main shrub-pollen taxon, together with the continuous presence of *Calluna vulgaris.* Poaceae and *Rumex* pollen occurred at high percentages, up to 38 and 5%, respectively, whereas pollen of the *Plantago lanceolata* type occurred sporadically. Lacustrine macrophytes, such as *Isoetes*, were abundant (17–24%). Regarding the cultivated taxa, the presence of the *Cerealia* type was noteworthy.

Zone C (depth of 158–75 cm) exhibited higher percentages of arboreal pollen (50–57%), whereas herbaceous taxa showed the lowest values in the entire sequence (28–32%). High values were recorded for the shrub pollen in the beginning of the zone (up to 14%), with intermediate percentages in the rest of the zone (10%). Pollen values of deciduous *Quercus* (25–30%) and *Betula* (13–18%) increased. Percentages of *Quercus ilex* type and *Pinus* rose slightly whereas the values of *Quercus suber* type diminished. In this zone, pollen of *Fagus* made its first appearance but *Taxus baccata* percentages declined. Values of riparian trees, such as *Salix* and *Fraxinus*, were reduced*.* Moreover, the shrub-pollen taxa (especially *Erica arborea* type, but also *Ulex* type, *Erica australis* type, *Erica umbellata* type, and *Calluna vulgaris*) increased and *Ilex aquifolium* decreased. *Plantago lanceolata* type values expanded whereas percentages of Poaceae and *Rumex* (15–20% and 2–3%, respectively) decreased. In addition, the occurrence of *Artemisia, Asphodelus* and Papaveraceae was noted. *Isoetes* recorded the same percentages as in zone D, between 18 and 25%. Percentages of cultivated taxa, such as *Cerealia* type, increased.

Subzone B2 (depth of 75–30 cm) initially showed a decrease in arboreal pollen percentages (44–48%) as well as an increase in herb-pollen values (38–45%), both attaining percentages similar to those in zone D. Pollen percentages of deciduous *Quercus*, *Betula, Quercus ilex* type*, Quercus suber* type, *Pinus* and *Taxus baccata* diminished. The values for riparian trees, such as *Salix* and *Fraxinus*, were higher than those in the previous zone. The following pollen features of this subzone should be noted: (a) high percentages of Poaceae, attaining the highest values in the entire sequence (35–40%); (b) low values of shrub-pollen taxa, such as *Erica arborea* type and *Calluna vulgaris*; (c) an increase in *Ilex aquifolium* percentages; (d) an increase in percentages of other herbs, such as *Rumex* and Rubiaceae; and (e) low values of *Isoetes* (8–10%) and a predominance of pollen of hydrophytes, such as *Ranunculus* and *Typha-Sparganium*. Moreover, *Olea europaea* pollen values rose whereas *Cerealia* type was no longer found.

In subzone B1 (depth of 30–7 cm), arboreal pollen values recovered up to 40–50%. Deciduous *Quercus* and *Betula* attained high percentages whereas the values of *Corylus* and *Fraxinus* slightly increased. There was a decrease in shrub-pollen values, mainly those of *Erica arborea* type. The percentages of some ruderal pollen herbs, such as *Plantago lanceolata* type and *Rumex*, expanded whereas *Artemisia*, Brassicaceae, and *Centaurea cyanus* type, were present. *Isoetes* recovered to the values recorded in zones D and C (up to 17–20%).

Pollen percentages of cultivated tree taxa such as *Olea europaea* decreased whereas the first occurrences of Cannabaceae pollen must be noticed.

Zone A (depth of 7–0 cm). Zone brought about a marked change in the pollen sequence: (a) an abrupt diminution in the percentages of arboreal-pollen percentages, such as deciduous *Quercus* (10%), *Quercus suber* type, *Betula, Corylus, Ul-*

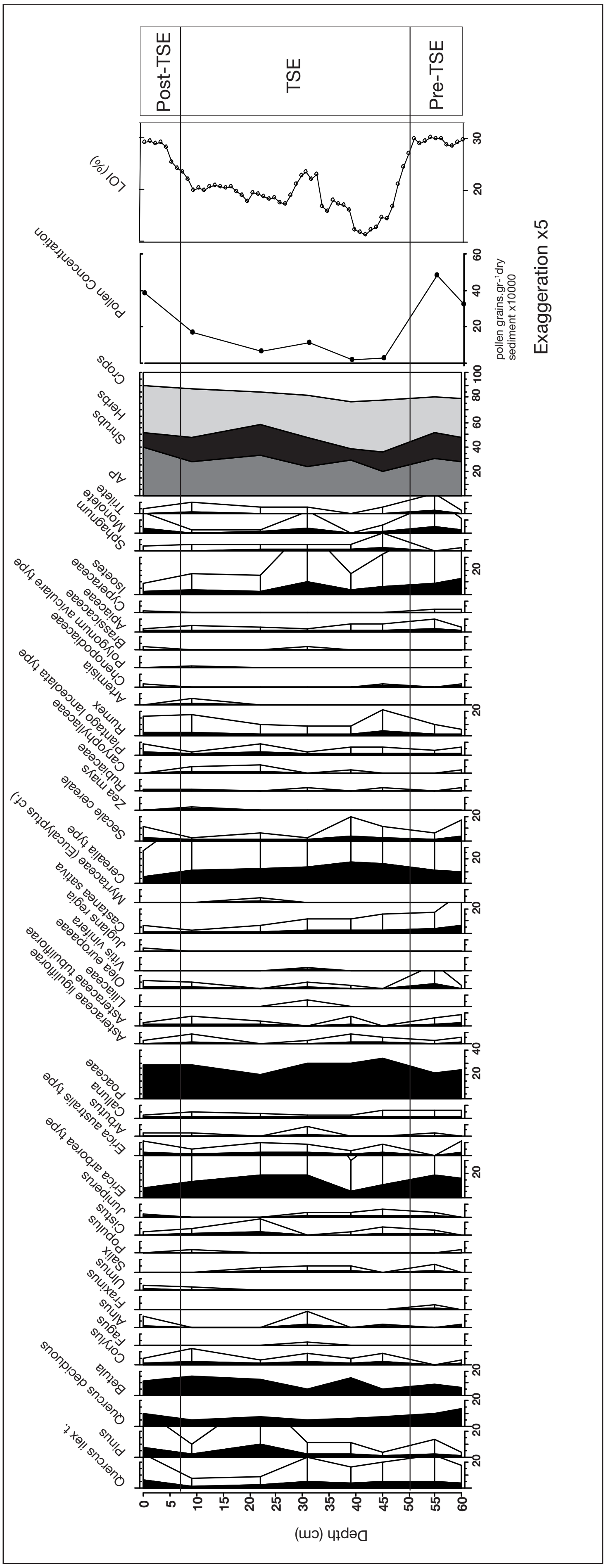

Figure 7. Pollen diagram at Lake Sanabria (SAN270 core) showing pollen changes produced by the catastrophic TSE event. The results are expressed in percentages. The pollen sum includes all terrestrial pollen, excluding aquatics.

mus, Taxus baccata and the riparian trees (*Fraxinus* and *Alnus*); (b) a slight increase in the pollen percentages of meso-Mediterranean trees, such as *Quercus ilex* type; (c) high pollen percentages of *Erica arborea* type (up to 7–10%); (d) high percentages of cultivated taxa, such as *Olea europaea*, *Cerealia* type, and *Secale cereale*, and the first occurrence of *Vitis*; (e) low values of aquatic plants, such as *Isoetes*; and (f) a rise in percentages of ruderal taxa, such as *Plantago lanceolata* type and *Rumex*.

SAN 270 pollen diagram (Fig. 7)

Pre-TSE samples (60–47 cm depth)

The total pollen concentration was high. This zone was characterized by low levels of arboreal pollen (25%) mainly dominated by deciduous *Quercus* (15%), with *Betula* and *Quercus ilex* type also present. Pollen of *Erica arborea* type accounted for up to 20% and Poaceae was the main herb taxa (25%). Cultivated taxa, such as *Cerealia* type (10%), *Castanea sativa* (7%), *Olea europaea*, and *Secale cereale*, were well-represented. The recorded percentages of *Isoetes* and fern spores (Monolete and Trilete) were high.

TSE samples (47-8 cm depth)

Total pollen concentration was lowest in the five pollen samples from the TSE layer. Of the three lowest samples, from a depth between 47 and 22 cm, arboreal pollen percentages sharply decreased. Deciduous *Quercus* values diminished whereas *Betula*, *Corylus* and *Alnus* increased. Pollen of *Erica arborea* type declined whereas the values for other shrubs, such as *Cistus*, increased. Pollen percentages of herbs rose, – mainly Poaceae (30%), *Asteraceae liguliflorae*, *Rumex*, and *Plantago lanceolata* type. Values of tree crops, such as *Olea europaea* and *Castanea sativa*, declined but pollen percentages of annual crops (*Cerealia* type and *Secale cereale*) increased. The percentages of *Isoetes* and fern spores were low, whereas spores of *Sphagnum* were more abundant.

In samples acquired at a depth between 22 and 8 cm, corresponding to the upper part of the TSE layer, the recovery of arboreal pollen was up to 30%. *Pinus* and *Betula* were the main tree taxa and pollen of *Eucalyptus cf.* was present. Pollen values of deciduous *Quercus* remained low whereas those of *Quercus ilex* type decreased further. Cultivated taxa, such as *Castanea sativa*, *Cerealia* type, and *Secale cereale*, were only scarcely represented. The percentages of herbs, mainly those of Poaceae, *Rumex*, *Plantago lanceolata* type, and *Artemisia*, increased.

Post-TSE sample (top of the sequence)

The pollen concentration of the uppermost sample was consistent with that of the pre-TSE samples. Arboreal pollen increased up to 40%, mainly as a consequence of a rise in deciduous *Quercus*, *Q. ilex* type, and *Pinus* percentages. The crop taxa *Olea europaea*, *Castanea sativa*, *Cerealia* type, and *Secale cereale*, remained low and did not recover to their earlier levels.

On the basis of sedimentological features, SAN270 pre-TSE samples record the vegetational landscape before the TSE and, as a consequence, correspond to SAN235 zone C1. The pollen spectra were similar, indicating a relatively forested landscape dominated by deciduous oaks and birches. The expansion of Ericaceae indicated human activity at higher altitudes. However, whereas crops were scarce in SAN235-C1, they were well-represented in SAN270 pre-TSE. This discrepancy could be attributed to the sampling resolution because the sedimentation rates between these two cores were very different.

The TSE clastic layer was characterized by reductions in total pollen concentration and in arboreal pollen, especially, of deciduous oaks. Poaceae and cereal crops increased whereas *Isoetes* diminished. Since the TSE layer, at a depth between 46 and 8 cm, resulted from a sudden flash flood, the pollen spectra cannot be interpreted in terms of landscape changes because the pollen grains were supplied by eroded soils. The post-TSE sample of SAN270 indicated a decline in farming, forest recovery at least after the Cs-137 peak, partial forest regeneration, and anthropic reforestation with *Pinus* and *Eucalyptus*.

Diatom analysis (Fig. 8)

Figure 8 is a diagram showing the percentage of diatom from the SAN135 core. The most abundant species in the sediment are *Aulacoseira distans*, *Cyclotella stelligera*, *Tabellaria*, and *Fragilaria*. The 81.0% of the total valves corresponds to planktonic diatoms, mainly *Aulacoseira distans*. Cluster analysis differentiated four zones.

Zone D (depth of 135–55 cm) had the highest total diatom concentration. The diatom assemblage was dominated (>90%) by the planktonic *Aulacoseira distans*. Three phases could be distinguished in this zone on the basis of diatom concentration: (a) between a depth of 135 and 107 cm (SAN135-D1), the total diatom concentration was the highest (up to 10^9 valves gr^{-1} dry sediment), (b) between a depth of 107 and 75 cm (SAN135-D2), the diatom concentration decreases to 6×10^8 valves gr^{-1}, and c) between a depth of 75 and 55 cm (SAN135-D3), total diatom concentration diminished to 10^8 valves gr^{-1} , coinciding with a slight increase in benthic diatoms.

In zone C (depth of 55-42 cm), the total diatom concentration was relatively low (6.3×10^7 valves gr^{-1}). This zone was characterized by an increase in benthic diatoms. The proportion of *Aulacoseira distans* decreased to ca. 66% while the percentages of *Fragilaria* (ca. 15%), *Tabellaria* (ca. 10%), *Eunotia, Navicula* (ca. 10%), *Gomphonema* and *Pinnularia* increased.

Zone B (depth of 42–27 cm) evidenced recovery of the total diatom content, which peaked at 7×10^8 valves gr^{-1} at a depth of 29 cm. Planktonic *Aulacoseira distans* predominated whereas lower values of benthic diatoms, such as *Fragilaria, Tabellaria, Eunotia*, and *Navicula*, were recorded. The first occurrence of *Cyclotella stelligera* was observed.

Zone A (depth of 27–0 cm) corresponded to the TSE layer, between 26 and 9 cm deep and to the post-TSE samples, between 9 and 0 cm deep. The zone was characterized by a progressive decrease in the percentage of *Aulacoseira distans*, an

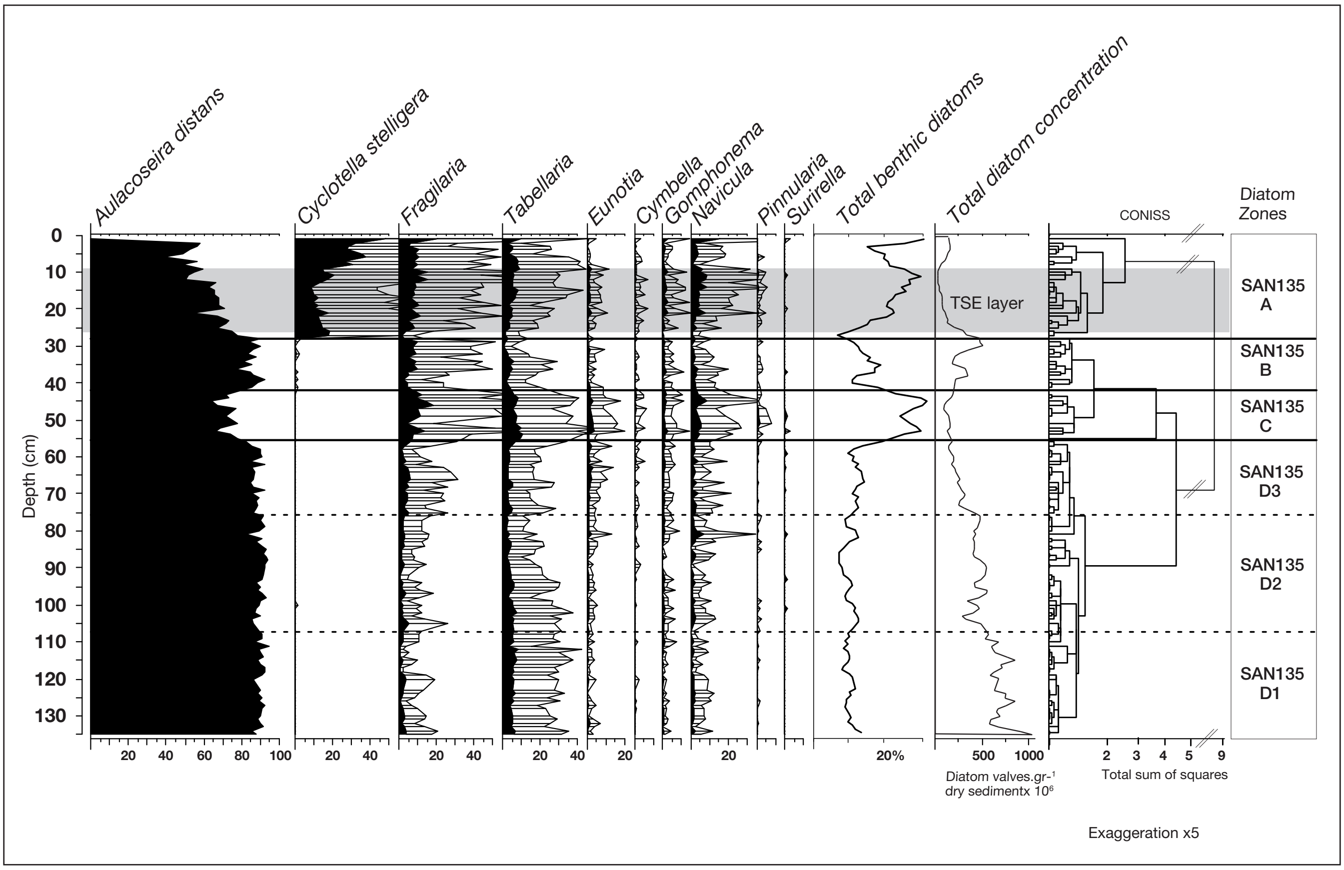

Figure 8. Diatom diagram at Lake Sanabria (SAN135 core). The results are expressed in percentages. Total diatom concentration values, expressed in million of valves/g dry sediment, are included after 3-point centered smoothing.

expansion of *Cyclotella stelligera*, and a slight increases in benthic *Fragilaria, Tabellaria*, and *Navicula*. The high sedimentation rate of the TSE layer was confirmed by the low diatom concentration. Post-TSE samples showed an increase in both total valve concentration and planktonic diatoms, mainly due to the expansion of *Cyclotella stelligera.*

Discussion

Proxy data and climate relationship

The low representation of arboreal pollen in the entire diagram (45–60%) suggests an open landscape during the last 2500 years (Fig. 6), with ample development of grasslands and heathlands. The long pollen sequences studied in the Lake Sanabria area indicated a landscape little-disturbed before ca. 3000 years BP, when arboreal pollen percentages reached 80–90% [25, 20].

Despite the different resolutions of the pollen and diatom diagrams, it could be deduced that zones of forest extension (zone SAN235-C and SAN235-B1) corresponded to a high diatom content (SAN135-D1-D2 and zone SAN135-B), and vice versa. This relationship was consistent, given that in the catchment area of this oligotrophic lake, the greater the forest expansion, the higher the contribution of nutrients to the lake. A limnological survey carried out between 1987 and 1989 indicated that the abundance of phytoplankton was controlled by nutrient availability (P and N), temperature (or radiation), water turbidity, and water residence time [31, 33, 26]. In wet periods, the low water residence dilutes nutrients and reduces the stratification period of the lake water, with the result that phytoplankton productivity is lower. Consequently, water renewal determines the limnological system, which is highly sensitive to the rainfall regime [31, 33].

The TN content and TOC had a high correlation coefficient ($r^2 = 0.96$), indicating that organic matter supplied the nutrients (Fig, 9a). The organic matter is introduced into the lake by runoff; as a consequence, organic carbon and nitrogen content are increased, triggered by the rainfall regime [31].

Figure 9b shows the correlation ($r^2 = 0.64$) between total diatom content and TN for the pre-industrial period. The best fit between the two parameters followed an exponential distribution, suggesting that temperature, water turbidity, and water renewal also play a role in phytoplankton productivity, in addition to nutrient availability.

Lacustrine proxy data from Lake Sanabria showed a pattern similar to that of the temperature index reported by Martínez-Cortizas et al. [18] for NW Iberia (Fig. 10), suggesting that major changes recorded in the Sanabria sediments were triggered by climate regime. The paleoenvironmental study carried out by Diz et al. [22] in the estuarine deposits of the Ría de Vigo (NW Iberian Peninsula) reconstructed the sea-surface temperature (SST) during the last 3,000 years on the basis of $U^{K'}_{37}$ index and variation in the oxygen-isotope signal from benthic foraminifers (*Cibicides* spp.). The cold phase recorded in Sanabria between 650 and 725 AD correlated with a decrease

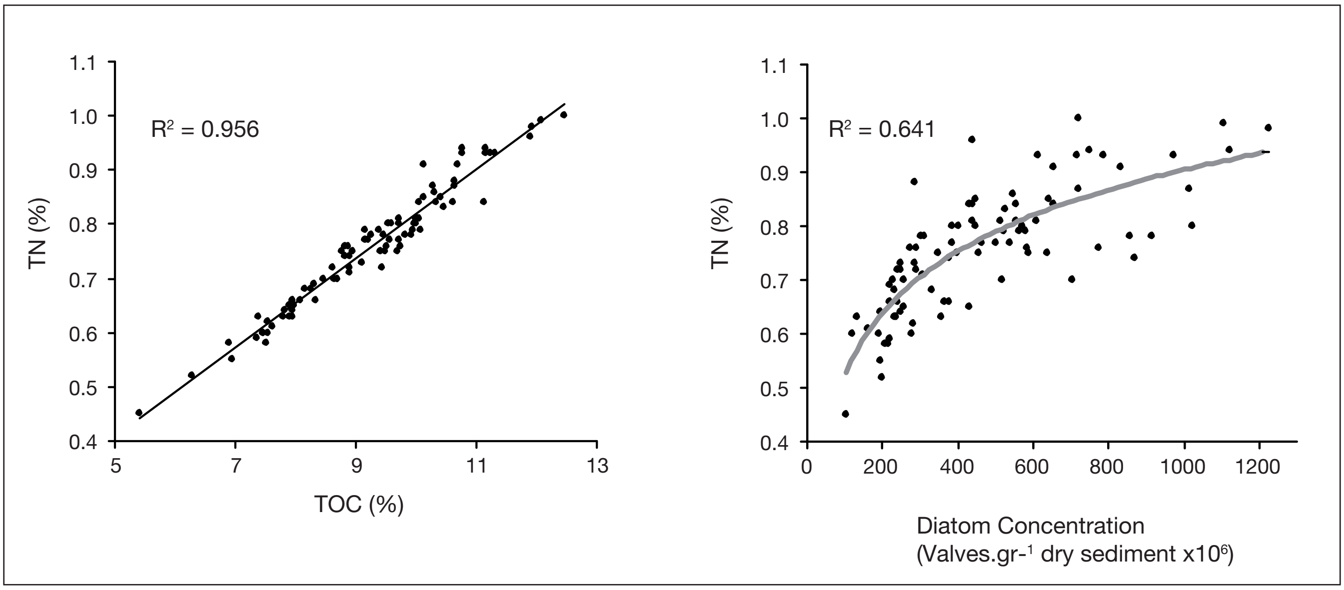

Figure 9. Relationship between diatom concentration and organic matter in SAN135 core. (**a**) Plot of total organic carbon (TOC) *vs.* total nitrogen (TN), and (**b**) plot of TN *vs.* total diatom content. Interval used in both plots corresponds to the pre-industrial samples (96 samples).

in SST. The data supplied by Diz et al. (2002) showed a decrease in the SST (ºC) and an increase in $\delta^{18}O$ (‰) values around 1450–1500 calendar years AD, resembling the response detected in TOC, TN, and diatom profiles from Lake Sanabria from 1310 to 1590 calendar years AD (Fig. 10). These climatic changes recorded in both inland mountains and the littoral indicated that they were not local in origin.

Environmental phases (Figure 10)

Comparison of the studied proxies allowed us to identify five main phases of environmental change from 440 AD to the flash flood that occurred in 1959 AD.

Phase I extends from 440 to 650 AD and includes the lower part of the SAN235-C pollen zone and the SAN135-D1 diatom zone. This phase represents a productive lacustrine ecosystem, as indicated by high concentrations of phytoplankton and an abundance of macrophytes, as evidenced by the high percentages of *Isoetes*. Woodlands reached maximum development in the catchment area that supplied large amounts of N and P to the lake via runoff. The altitudinal rise of deciduous forests at the expense of high-altitude vegetation belts (heathlands and grasslands) suggests warmer conditions, whereas the large grain size and high organic matter content indicate an effective runoff under a Mediterranean rainfall regime. In the lake system, this type of precipitation induces a long residence time of water, favoring a longer lapsed time of water stratification and, consequently, higher lake productivity [33].

During this phase, a short period of environmental change occurred between the years 520 and 550 AD, which was characterized by a decrease in lake productivity resulting from less input of organic matter. This climatic event was also identified in the Hg-lability-based temperature index reconstruction for the NW Iberian Peninsula [18].

Pollen indicators suggested the presence of human activities during this phase, in accordance with the foundation of the San Martin de Castañeda monastery during the 6th century AD. The continuous presence of *Plantago lanceolata* type, *Artemisia*, and *Asphodelus* suggests that grazing activities developed near the lake, whereas the values for cereals and chestnuts corroborate the expansion of farming.

Phase II extends from 650 to 950 AD and includes the upper part of the SAN235-C pollen zone and the SAN135-D2 diatom zone. This phase was characterized by a slight diminution of lake productivity, as attested to by decreases in diatoms and macrophytes. The reduction in grain size, organic matter, and nutrients (N and P) indicates low erosion, probably due to a more regular rainfall regime. Reduction of the deciduous oak forest and the altitudinal descent of heathlands and grasslands suggest a decrease in temperatures, as also recorded by Hg lability for NW Iberia [18] and by $\delta^{14}C$ [42]. During this phase, there was a slight increase in nutrient levels between 850 and 950 AD that corresponded to the warmer pulse of the MWP [18].

A possible anthropogenic origin of this vegetation change was ruled out, given that the decrease in crop pollen suggests a decline in arable farming, in spite of the population increase during the 9th and 10th centuries [45].

The fine grain size and fall in lake productivity related to the low nutrient content (N and P) between 650 and 730 AD suggest a short period of more regular rainfall and lower temperatures [18].

P*hase III* extends from 950 to 1590 AD and corresponds to the SAN235-B2 pollen zone and the SAN135-D3 and SAN135-C diatom zones. The features of this phase are the low diatom concentration and low levels of planktonic diatoms, organic matter and nutrients (N and P), fine grains, and arboreal pollen. Depleted lake productivity, as indicated by the low diatom concentrations, resulted from the wash-out of nutrients [31, 33]. These findings are indicative of a regular rainfall regime. Moreover, wet conditions contributed to the reduction of water residence time and to the minimization of lake-water stratification, which resulted in low phytoplankton production [33]. The expansion of grasslands suggests the descent of the

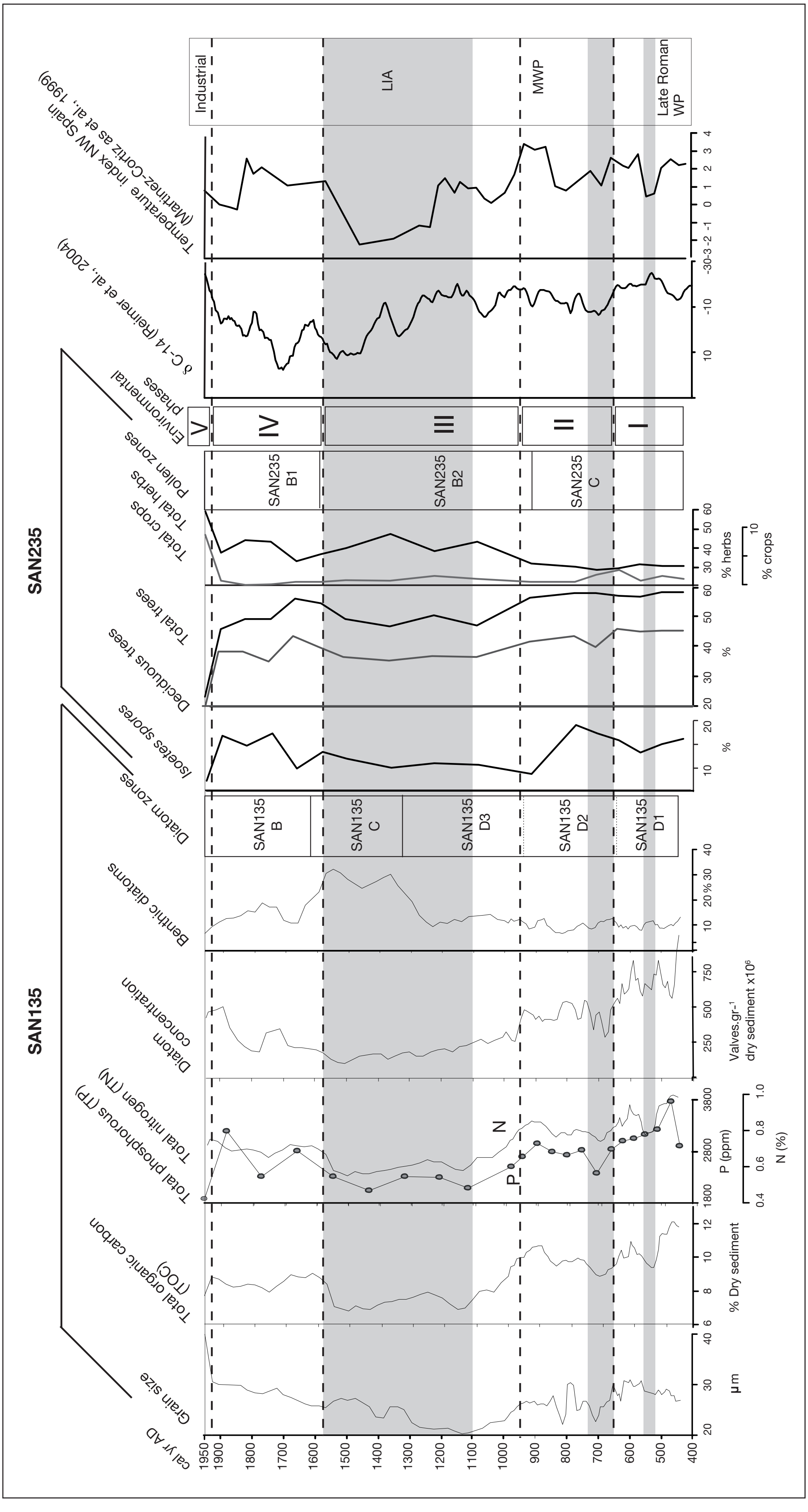

Figure 10. Selected proxies of SAN 135 and SAN235 cores used to establish the environmental phases. Temperature index for NW Iberia (Martínez-Cortizas et al., 1999) and δ14C (Reimer et al., 2004) are included for comparison with the Sanabria data.

mountain vegetation belt as a result of cooler conditions, as was also indicated by the decrease in the temperature index [18] and in $\delta^{14}C$ [42].

The expansion of benthic diatoms mainly after 1300 AD might be explained by lower lake-water turbidity as a consequence of the low content of particulate organic and inorganic matter. This period of minimum lake productivity corresponds to the lowest temperatures attributed to the LIA [18].

Pollen indicators of anthropogenic activity, such as farming and grazing, decreased, consistent with low human activity in the area.

Phase IV, from 1590 to 1920 AD, includes the SAN235-B1 pollen zone and the SAN135-B diatom zone. This phase was characterized by the recovery of plankton and macrophyte productivity. The coarse grain size indicates a more effective runoff that supplies more nutrients into the lake, suggesting a more irregular rainfall characteristic of a Mediterranean climate. The recovery of the forest and the altitudinal rise of sub-Mediterranean vegetation suggest milder climatic conditions, as confirmed by the temperature index [18]. The first occurrence of the diatom *Cyclotella stelligera* indicates human influence, despite the absence of pollen indicators of farming activities.

Phase V extends from 1920 to 1959 AD and corresponds to the SAN135-A diatom zone and the SAN270 pre-TSE pollen samples. Agricultural development after 1900 AD coincided with the expansion of *Cyclotella stelligera,* indicating a change in the lake status. Furthermore, the catchment area of the lake was drastically modified during the 1930s, with the construction of several dams associated with the Moncabril hydroelectric complex. These activities led to a considerable input of eroded soil into the lake, which therefore no longer serves as a natural environmental sensor.

Since 1960 AD, the landscape evolution has been characterized by a decline in farming as a result of population migration, and reforestation of the area with *Pinus* and *Eucalyptus*.

Conclusions (Fig. 10)

According to the chronological framework, environmental phase I, ranging from 440 to 650 AD, corresponds to the end of the so-called Roman Warm Period [18, 21]. During this period, the sub-Mediterranean vegetation belt progressed towards higher altitudes due to milder temperatures, whereas the Mediterranean rainfall regime triggered the soil erosion that supplied organic matter to the lake. Consequently, the increased availability of nutrients led to high lake productivity.

The episode between 520 and 550 AD suggests cooler temperatures and a more regular rainfall. Human activity expanded, especially in the 6th century AD, consistent with the presence of monastery foundations and with signs of repopulation of the area.

A change in climate occurred between 650 and 730 AD, at the beginning of phase II, when lake productivity decreased as a consequence of more regular rainfall and cooler temperatures [18, 42]. Between 730 and 950 AD, organic matter and lake productivity recovered but remained lower than in phase I. The increase in lake productivity between 850 and 950 AD could have been due to the warmer pulse of the MWP [18].

During environmental phase III, between 950 and 1590 AD, nutrients and lake productivity decreased, suggesting a more regular rainfall and lower temperatures. Lowest lake productivity occurred between 1300 and 1590 AD. A similar chronology for the LIA was established by the temperature index for NW Iberia [18].

Phase IV corresponds to the end of the Little Ice Age, after 1590 AD, and the return to milder climate, with a more irregular rainfall regime supporting an effective runoff.

Lastly, Phase V, from 1920 onwards, is characterized by anthropogenic influences on the lake system.

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