The impact of the Laacher See Volcano (11 000 yr B.P.) on terrestrial vegetation and diatoms *

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Abstract

Late-glacial lake sediments containing the Laacher See Tephra (LST, 11 000 yr B.P.) have been analyzed for their pollen and diatom content at three sites at varying distances from the volcano and on different bedrock geologies. The aim was to test the null hypothesis that this major volcanic eruption had no effect on terrestrial pollen or aquatic diatom assemblages. The pollen spectra at all sites show a short-lived increase in grass pollen following the LST. Partial redundancy analysis and associated Monte Carlo permutation tests suggest, however, that the LST had no statistically significant effect at two sites but it had a statistically significant impact on the pollen assemblages at the site nearest (60 km) to the volcano.

The diatom assemblages at the three sites changed individualistically after the LST deposition, with increases in *Achnanthes minutissima* at one site, an expansion of *Aulacoseira* species at another, and an increase of *Asterionella formosa* and *Fragilaria brevistriata* at the third site. Partial redundancy analysis and associated permutation tests suggest a statistically significant change in diatoms in relation to the LST and associated changes in sediment lithology at the one site situated on acidic bedrock. No significant impacts were found at the sites on volcanic or calcareous rocks. Due to the interaction between tephra and sediment lithology, it is not possible to conclude if the statistically significant diatom changes were a direct result of the LST deposition or an indirect result of lithological changes following LST deposition.

Introduction

On several occasions during the last decade, attention has focused on the environmental impacts of volcanism, as a result of the recent eruptions of Mt. St. Helens, Pinatubo, or most recently of Mayon. Volcanism has always played an important role in Earth's history. Volcanoes may destroy habitats and also create new ones. Their eruptions can also have direct and indirect impacts on the environment. Direct impacts include

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lava-flows and physical damage. Indirect impacts may consist of short-term climatic changes caused by volcano-emitted stratospheric sulphuric aerosols and fine ash particles that inhibit solar radiation and thus may lower the Earth's surface temperature.

Many volcano eruptions deposit tephra layers in lake or bog sediments. On the basis of their geochemistry and mineralogy most of these tephras can be attributed to specific eruptions. They, therefore, represent excellent stratigraphic tools for correlation purposes (see, e.g., Einarsson, 1986). In recent years several studies have equated biostratigraphical changes with tephra effects on the environment. In the present study we attempt to test the null hypothesis that a specific eruption and its subsequent tephra deposition

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had no effect on either terrestrial vegetation or aquatic diatom floras. For this purpose we have chosen three different sites at different distances from the eruption and on different geology to study possible impacts of volcanism in areas near to and far from the volcanic event and in different bedrock settings.

Laacher See Volcano

The eruption we are concerned with in this study took place in the Eifel mountains in Germany (Fig. 1) and created the Laacher See, a crater lake. This Laacher See eruption was the largest eruption in Europe since the end of the last glaciation. It produced between 10–15 km³ of phonolithic magma (Van den Bogaard & Schmincke, 1985, 1988). The Laacher See Tephra (LST) can be found as a distinct layer in lacustrine sediments between southern Denmark and northern Italy (Fig. 1). According to Van den Bogaard (1983) the eruption took place in the order of days or weeks and the tephra found in the sediments originates from one eruption. Several independent radiocarbon dates of the LST indicate an age of *ca* 11 000 yr B.P. for the eruption (see, e.g., Van den Bogaard, 1983; Ammann & Lotter, 1989).

Part of the late-glacial sedimentary record comprising the LST has been analyzed for pollen and diatoms at three different sites (Fig. 1).

The sites

Rotsee

Rotsee (419 m a.s.l., Fig. 1), a small eutrophic lake on the Swiss Plateau close to the border of the Alps is the southernmost site in this study. This area was glaciated during the last ice-age and is characterized by carbonate-rich morainic soils. The lake was formed after the retreat of the glacier *c*. 15 000 to 16 000 ¹⁴C years ago (Lotter, 1988). The LST layer lies at a sediment depth of 776.5 cm. It is 5 mm thick and occurs in a matrix of lake-marl. Rotsee lies *c*. 370 km to the south of the origin of the LST. The late-glacial sedimentary record of core RL-250 (Lotter, 1988) was re-sampled at 2.5 cm intervals, both for pollen and diatoms. The 40 cm of late-glacial sediment used in this analysis include the second part of the Allerød (II) biozone and the onset of the Younger Dryas (III) biozone. The transition between the Allerød and Younger

Dryas biozones is very marked in the oxygen isotope record (Fig. 2, see also Eicher, 1987; Lotter *et al.*, 1992), whereas in pollen diagrams at this altitude it is only marked by a slight increase in NAP, especially of *Artemisia* and Gramineae (see, e.g., Ammann & Lotter, 1989). The amount of minerogenic sediment increases slightly after this transition (see Fig. 2). The Allerød/Younger Dryas transition has been radiocarbon dated at Rotsee to *c*. 10 800–10 700 B.P. (Lotter & Zbinden, 1989). Recent work on tree-rings and varved lake sediments suggest that the time-span between the deposition of the LST and the onset of the Younger Dryas biozone is in the order of 200–250 calendar years (Kaiser, 1991; Zolitschka, 1990; Lotter, 1991; Hajdas *et al.*, 1993). On the basis of this time-estimate each sample between the LST deposition and the end of the Allerød biozone (II) would represent *c*. 20–25 calendar years and between each sample there are gaps of *c*. 30–40 calendar years.

The late-glacial diatom spectra (Fig. 2) are a mixture of planktonic *Cyclotella* species and periphytic *Gomphonema, Cymbella,* and *Denticula* assemblages (see Lotter, 1988). At the transition to the Younger Dryas biozone (III) *Fragilaria* species increase substantially. The diatom pH spectra reflect the calcareous morainic soils of the catchment of Rotsee.

At the time of the LST deposition only a short-lived increase in NAP, especially in Gramineae, can be observed in the pollen diagram (Fig. 2). The LST deposition has almost no obvious effect on this coarse time-resolution in the diatom assemblages, except for an increase in *Achnanthes minutissima*.

Rotmeer

Rotmeer (960 m a.s.l., Fig. 1) is located *c*. 250 km to the south of the Laacher See Volcano. It is an ancient, overgrown lake covered today by a raised bog. The site lies in the Black Forest mountains in Southern Germany, a region characterized by acid bedrock. This area was also glaciated during the last ice-age. After the retreat of the local glacier, probably *c*. 14 000 ¹⁴C years ago, the lake was formed (Lotter & Hölzer, in prep.). At this site the LST is 10 mm thick and is located within a clayey fine-detritus gyttja matrix. The sediment of core RO-6 has been sampled in contiguous 1 cm intervals. Each sample therefore integrates a time-span of *c*. 50–70 calendar years, assuming a uniform sediment accumulation rate and the time-span between the deposition of the LST and the onset of the Younger Dryas biozone is about 200–250 calendar years.
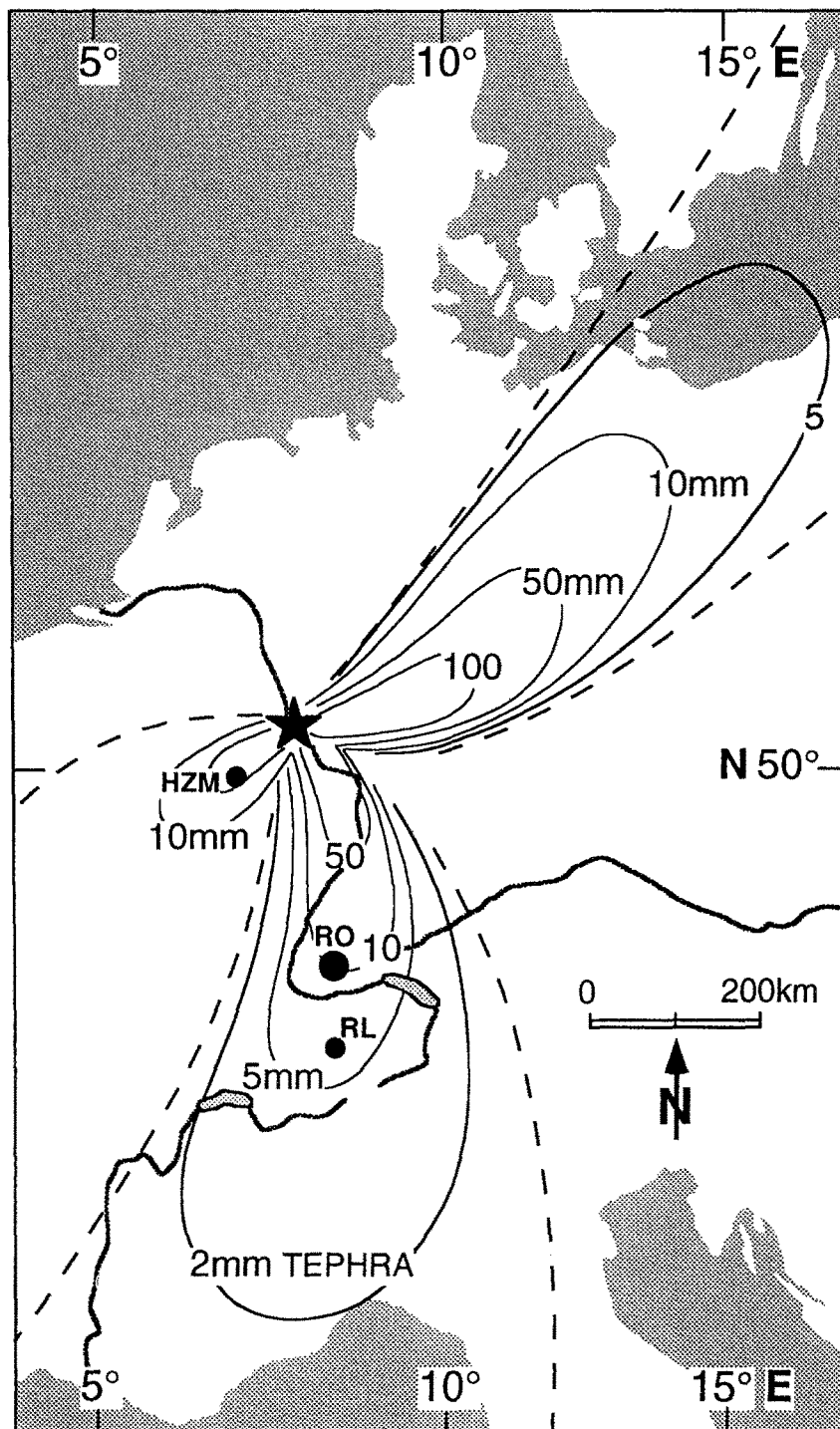
Fig. 1. Map showing the location of Laacher See (star), as well as the location of the investigated sites: RL = Rotsee (Swiss Plateau), RO = Rotmeer (Black Forest, Germany), HZM = Holzmaar (Eifel mountains, Germany). Numbers indicate the amount of Laacher See Tephra deposition in mm.
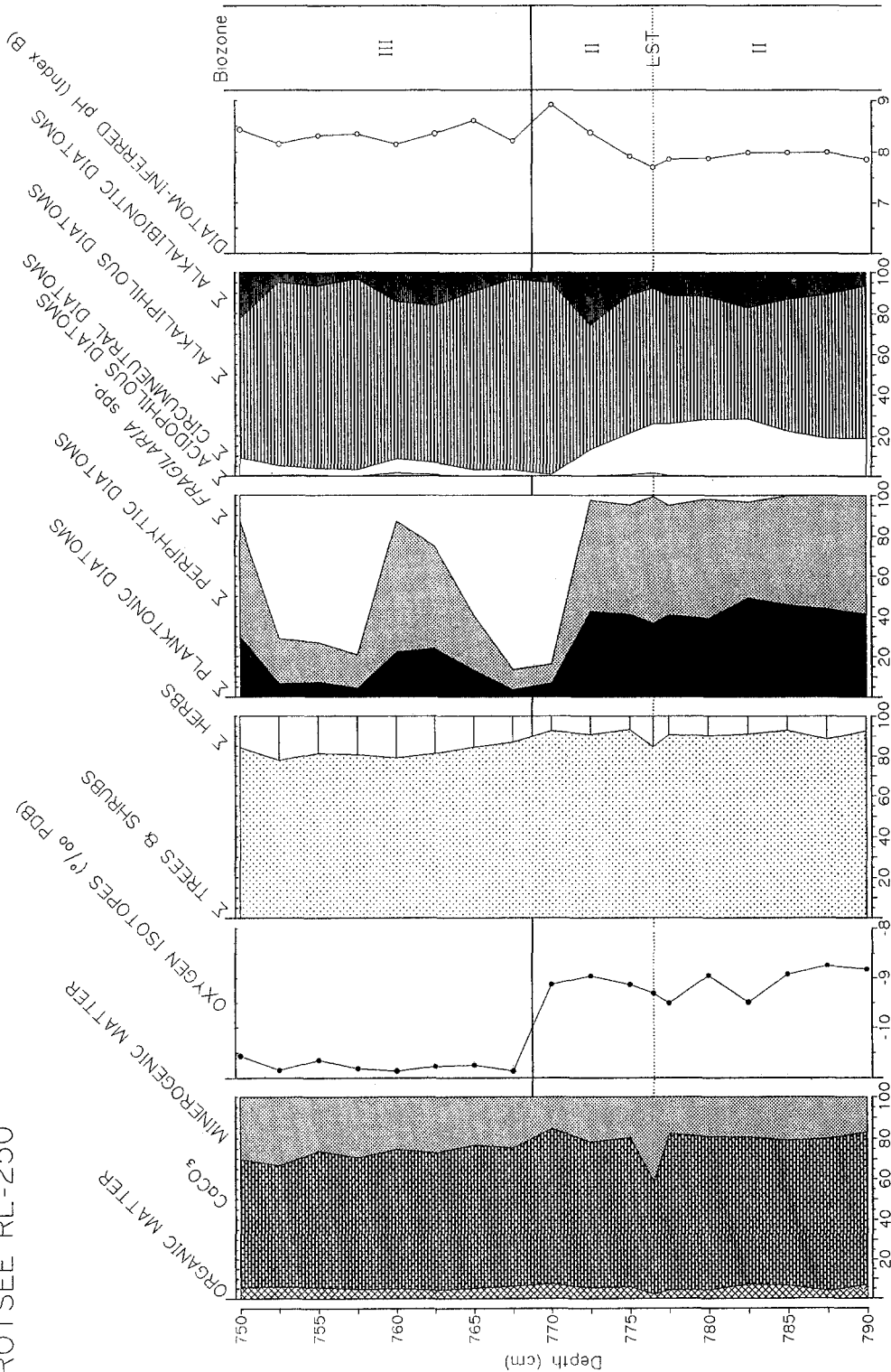
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Fig. 2. Synoptic diagram of Rotsee core RL-250, showing sediment composition (loss-on-ignition basis, % dry weight), $\delta^{18}O$ values, summary pollen diagram (100% = Σ AP+NAP), diatoms grouped according to life-form and according to pH preference as well as diatom-inferred pH reconstructions. II = Allerød biozone, III = Younger Dryas biozone, LST = Laacher See Tephra.

The diatom pH spectra reflect the strongly acidic bedrock situation of the catchment of Rotmeer (Fig. 3). The aquatic macrophyte flora as well as the diatoms indicate nutrient-poor conditions during this part of the late-glacial period (Lotter & Birks, 1993).

The deposition of the LST seems to have triggered the expansion of acidophilous *Aulacoseira* species, maybe through the additional input of silica. In the pollen spectra a small increase in Gramineae coincides with the deposition of the LST (see Lotter & Birks, 1993).

Holzmaar

Holzmaar (400 m a.s.l., Fig. 1) is a eutrophic maar lake in the volcanic field of the Eifel mountains, located c. 60 km to the southwest of the origin of the LST. The lake was formed 40 000–70 000 years ago (Büchel, 1984). The region, which is characterized by volcanic bedrock, was not glaciated during the last ice-age. The tephra is 80 mm thick and is situated within a matrix of annually laminated diatom gyttja (Zolitschka, 1990). This sequence thus provides an extremely high time-resolution. Before the deposition of the LST each sample of core HZM contains a known number of varves, usually c. 20 varves whereas after the LST deposition each sample includes a known time-span of between 7–14 varves (Lotter et al., in prep.).

The diatom stratigraphy (Fig. 4) from Holzmaar suggests that during the late-glacial nutrient-rich, alkaline conditions prevailed. A small *Stephanodiscus* species (*S.* cf. *parvus*) dominates the assemblage.

With the deposition of the LST there is a NAP increase in three consecutive samples which corresponds to c. 20 calendar years. This increase consists mainly of Gramineae pollen. The diatoms react mainly by an increase in *Asterionella formosa* and *Fragilaria brevistriata*.

Common reactions after the Laacher See Tephra deposition

The terrestrial vegetation of the Allerød biozone (II) at all three sites consisted of open *Pinus* forests with varying amounts of *Betula*. At the onset of the Younger Dryas biozone (III) there was an opening of the pine-birch forests. After the deposition of the tephra the common pattern in the pollen records of each investigated site is an increase in NAP, especially of grasses. Absolute pollen analyses reveal that this is due to a

real increase in grasses and not the consequence of a decline in trees (Lotter, 1988 and unpubl. data).

The diatom assemblages of each site are different. After the tephra deposition there are no straightforward common patterns. Each site seems to react individualistically. Theoretically, the deposition of tephra should mostly affect the habitat of benthic organisms by covering them completely. In the littoral parts of a lake, waves stirring up tephra particles and thus generating turbid water, could inhibit light penetration for some time. Both effects would then result in a higher proportion of planktonic taxa. This is, however, not the case at the three sites investigated. There is always a slight decrease in diatom-inferred pH (based on Index B, Renberg & Hellberg, 1982) but as they all lie well within the inherent errors of this reconstruction method (±0.8 pH unit, see ter Braak & Van Dam, 1989) these slight changes are not statistically significant.

The major question is: did the eruption and the subsequent tephra deposition have a statistically significant impact on these biota, i.e. are the observed changes in pollen and diatoms statistically significant from random variations? To answer this question we followed the advice of Fægri et al. (1989), namely 'when common sense fails', we used 'statistical and numerical analyses as aids for interpretation'.

Numerical analyses

Methods

Each biostratigraphy has been treated separately. An initial Detrended Canonical Correspondence Analysis showed that the gradient lengths for all stratigraphies are short, i.e.<2 standard deviation units and therefore that linear methods of data analysis could be used (ter Braak & Prentice, 1988). We used Redundancy Analysis (RDA), a constrained or canonical form of principal components analysis. Log transformation and double centring of the samples and variables were used to allow for the closed compositional nature of the percentage biostratigraphical data. The program CANOCO 3.12 (ter Braak, 1990a) was used for all computations.

Observed changes in pollen and diatom assemblages may have been the result of late-glacial climatic change. This is modelled by the explanatory nominal (1/0) variable representing biozone. Samples from the Allerød biozone (II) were coded 1 for the class Allerød and 0 for the class Younger Dryas (see Jong-
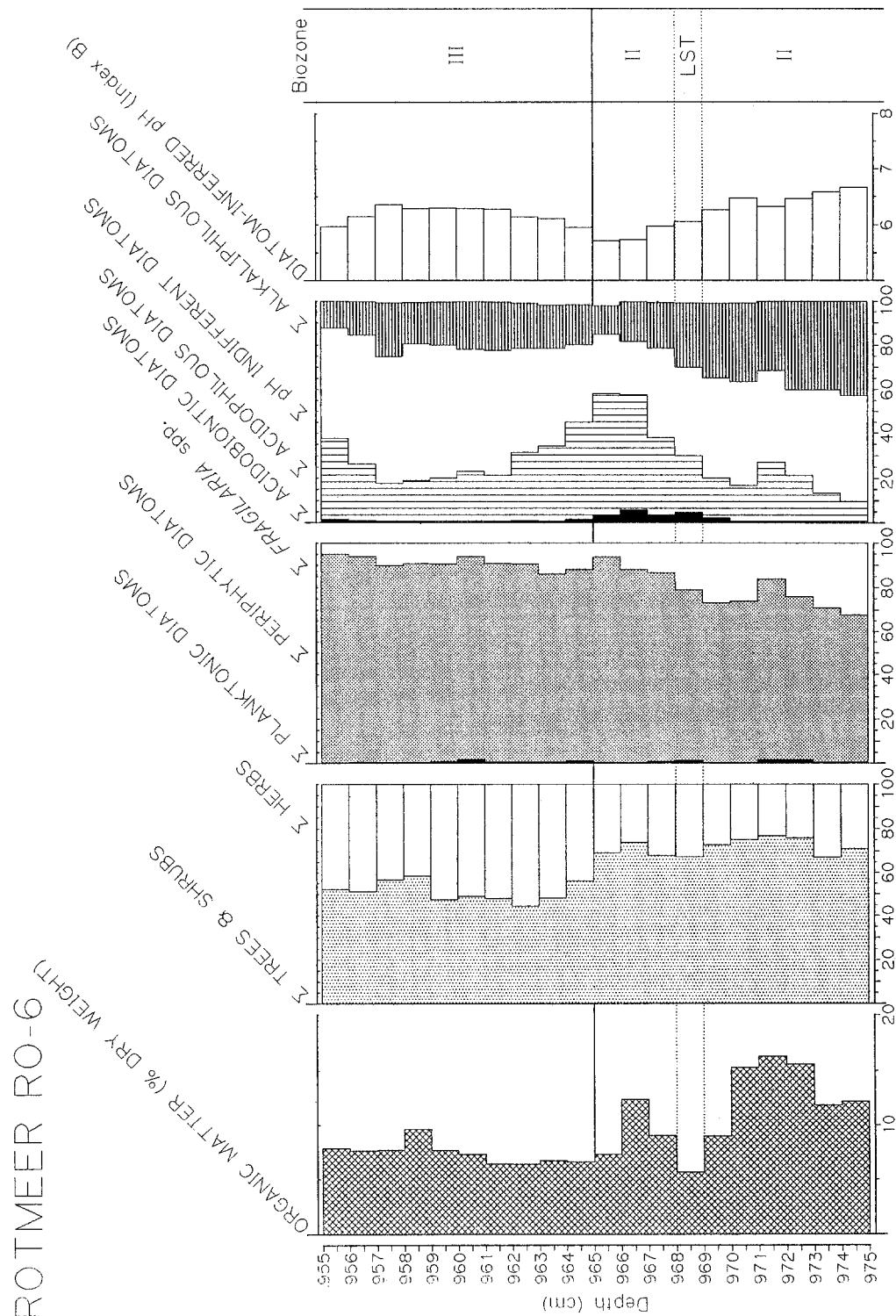
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Fig. 3. Synoptic diagram of Rotmeer core RO-6, showing contiguous data for sedimentary organic matter (loss-on-ignition, % dry weight), summary pollen diagram (100% = Σ AP + NAP), diatoms grouped according to life-form and according to pH preference as well as diatom-inferred pH reconstruction. II = Allerød biozone, III = Younger Dryas biozone, LST = Laacher See Tephra.
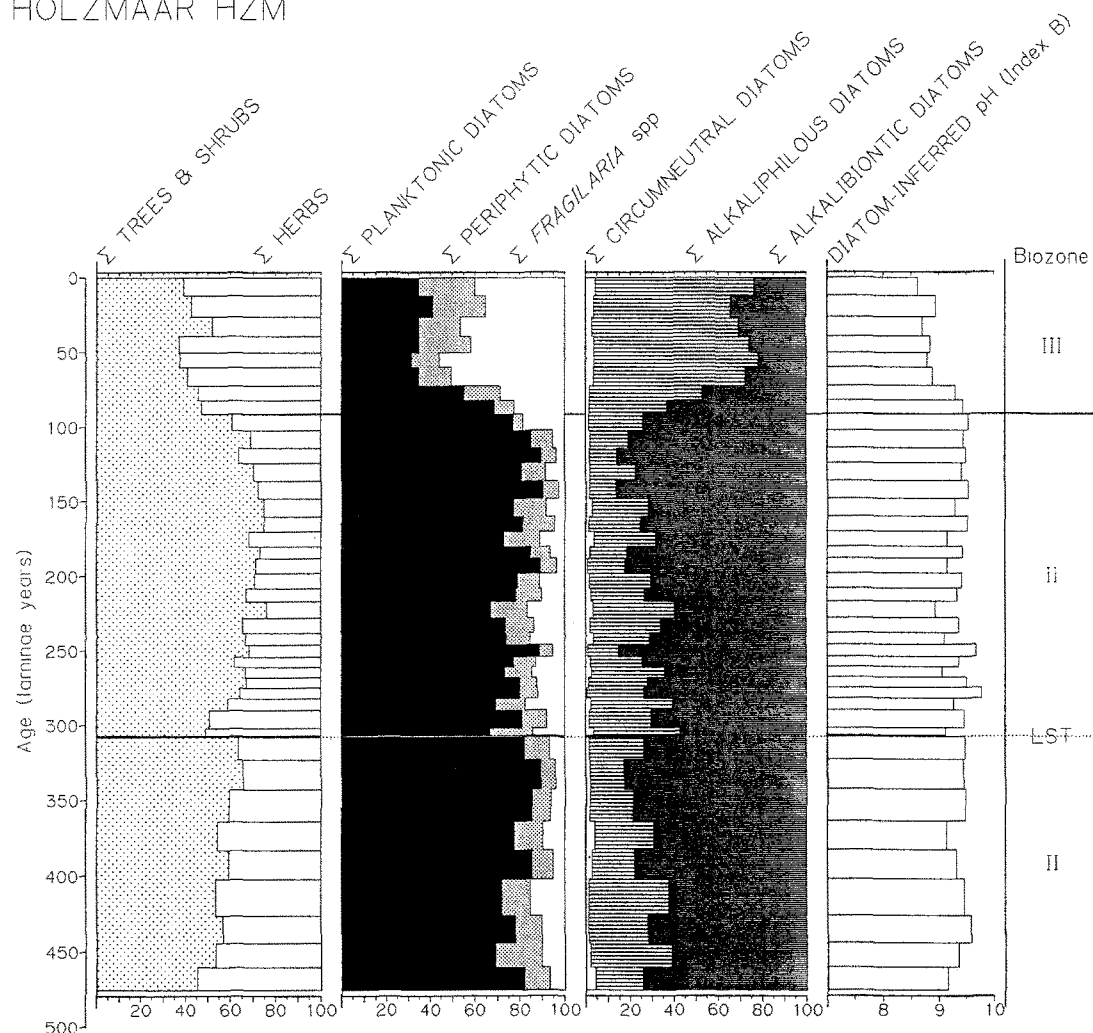
HOLZMAAR HZM

Fig. 4. Synoptic diagram of Holzmaar core HZM, showing contiguous data for pollen and diatoms. The data are plotted on an age scale (laminae). II = Allerød biozone, III = Younger Dryas biozone, LST = Laacher See Tephra.

man *et al.*, 1987 p. 58 for details of coding nominal (dummy) variables). Unidirectional short-term temporal trends such as succession and/or soil development may also account for some of the observed changes in the biostratigraphies. These have been modelled as the explanatory quantitative variable of sample depth which is a surrogate for sample age. Changes in the diatom flora may result, in part, from changes in sediment lithology. Sediment type was thus modelled as a series of nominal (1/0) variables representing each lithological type, all coded as dummy variables. The explanatory variable ash, modelled as a simple expo-

nential decay function (see Lotter & Birks, 1993), models the changing effects of tephra deposition with time.

For the pollen stratigraphies ash was used as the only explanatory variable and the effects of time and late-glacial climatic change were partialled out as the covariables depth and biozone. Sediment lithology is not considered to be an important explanatory variable for modelling the cause of changes in terrestrial pollen assemblages and hence in terrestrial vegetation. For diatoms, however, sediment lithology may be important. Furthermore, as there may also be interactions between lithology and ash that could influence aquatic organisms an ash∗lithology interaction term was intro-

duced in the RDA as an explanatory product variable. Here also, the effects of time and climate change were allowed for statistically by partialling out depth and biozone as covariables.

The test statistic of interest, namely the observed eigenvalue for the first RDA axis of the different biostratigraphies, was compared with the results of 99 permutations of a stratigraphically restricted Monte Carlo permutation test in order to assess the statistical significance of the test statistic (Table 1). The first RDA axis represents the major gradient of variation in each of the biostratigraphies constrained to be a linear function of the explanatory variables when the effects of the covariables depth (= age) and biozone are allowed for statistically in partial RDA. In practice, the residuals of the regression of the covariables on the explanatory variables are used as explanatory variables in the analysis. The first RDA axis is a weighted sum of the explanatory variables that fit the biostratigraphical data best, i.e. that gives the maximum total regression sum-of-squares. The eigenvalue measures the importance of the RDA axis and is analogous to R^2 in a regression analysis, the coefficient of determination or percentage variance explained (ter Braak, 1990a).

The permutation tests used, ter Braak's (1990b) so-called 'full model', are based on exchangeability of the species residuals after the covariables and explanatory variables have been fitted. This allows interaction terms to be validly tested and for the correlation structure between covariables and explanatory variables, including interaction product terms, to remain unchanged during the permutations. The stratigraphically restricted permutation tests are appropriate for biostratigraphical data such as these, when the data are trend-free, as they are when depth (≡ age) is used as a covariable.

The total variation in the biostratigraphical data has been partitioned into four statistically independent components, including the percentage variance explicable by LST effects independent of any other temporal or climatic changes (Table 2), following Borcard et al. (1992).

Further details of these numerical procedures are given by Lotter & Birks (1993), ter Braak (1990a, 1990b), ter Braak & Wiertz (1994), and Borcard et al. (1992).

Terrestrial pollen

For the pollen stratigraphies the RDA model used has ash as the sole explanatory variable and bio-zone + depth as covariables. Monte Carlo permutation tests (Table 1) suggest that LST had no statistically significant effect on the overall pollen assemblages and hence on terrestrial vegetation at Rotsee (probability $(p) = 0.42$) or at Rotmeer $(p = 0.09)$. There is, however, a significant effect $(p = 0.05)$ at Holzmaar near to the Laacher See Volcano after the influence of climatic change (biozone) and temporal trends (depth or age) are allowed for statistically.

Variance partitioning (Borcard et al., 1992) shows that 35–65% of the variance in the pollen data is unexplained by the explanatory variables biozone, depth, and ash (Table 2). Ash effects independent of depth and biozone account for only 3% of the variance at Rotsee and Rotmeer, and 6% at Holzmaar. Depth and biozone independent of any ash effects capture 26–57% of the total variance in the pollen data.

Diatoms

A series of RDA models of progressively increasing complexity were fitted to the diatom data (Table 1). Initially the model was simply ash as the sole explanatory variable but with depth + biozone as covariables. The probabilities obtained were all non-significant (Holzmaar 0.09, Rotsee 0.71, Rotmeer 0.16). When lithology is added as an explanatory variable (model = ash + lithology, covariable = biozone + depth), the probabilities remain non-significant (Holzmaar 0.06, Rotsee 0.47, Rotmeer 0.17). However, when an interaction term is introduced (model = ash + lithology + ash∗lithology, covariables = biozone + depth), the probability drops to 0.03 at Rotmeer but remains non-significant at Holzmaar (0.22) and Rotsee (0.34). The introduction of interaction terms amongst explanatory variables should be approached with some caution (ter Braak, 1990a). In this case the first eigenvalue of the RDA, the test statistic in this study, at Rotmeer is considerably larger (0.086) than in the absence of the ash∗lithology interaction term (0.057), suggesting that the effects of ash on the diatom assemblages at Rotmeer depend, in part, on lithology. Because of this significant interaction we cannot ascertain if the observed diatom changes at Rotmeer are due to ash deposition directly or if they are indirectly due to lithological changes.

Using the RDA model with the ash∗lithology interaction term, LST explains 15% of the variance in the diatom data at Rotmeer independent of depth and biozone but only 8% at Holzmaar and 12% at Rotsee (Table 2). A high proportion of the variance is unex-

Table 1. Results of (partial) redundancy analysis of the pollen and diatom stratigraphical data sets of Holzmaar (HZM), Rotsee (RL-250), and Rotmeer (RO-6) for different models of explanatory variables and covariables. Entries are significance levels as assessed by restricted Monte Carlo permutation tests (n=99). *=0.01<p≤0.05

Site	Explanatory variables	Covariables	Data set	
			Pollen	Diatoms
HZM	Ash	Depth + biozone	0.05*	0.09
RL-250	Ash	Depth + biozone	0.42	0.71
RO-6	Ash	Depth + biozone	0.09	0.16
HZM	Ash + lithology	Depth + biozone	—	0.06
RL-250	Ash + lithology	Depth + biozone	—	0.47
RO-6	Ash + lithology	Depth + biozone	—	0.17
HZM	Ash + lithology + ash*lithology	Depth + biozone	—	0.22
RL-250	Ash + lithology + ash*lithology	Depth + biozone	—	0.34
RO-6	Ash + lithology + ash*lithology	Depth + biozone	—	0.03*

Table 2. Results of partitioning the variance in the pollen and diatom stratigraphical data sets of Holzmaar (HZM), Rotsee (RL-250), and Rotmeer (RO-6) under the most appropriate model of explanatory variables. Entries are sum of squares (=variances) expressed as percentages of the total variance in each data set. The models used are as follows: pollen - depth + biozone + ash; diatoms - depth + biozone + ash + lithology + ash*lithology

Source of variance	Pollen			Diatoms		
	HZM	RL-250	RO-6	HZM	RL-250	RO6
Temporal and climatic changes independent of any LST effects	25.7	49.7	57.0	12.9	27.7	12.0
LST effects independent of temporal and climatic change	6.4	3.0	3.0	8.4	11.5	15.0
Depth- and biozone-structured LST effects	3.2	5.4	5.0	18.5	25.1	46.0
Unexplained variance	64.7	41.9	35.0	60.2	35.7	27.0

plained at Holzmaar (60%), whereas at Rotsee 36% remains unexplained and at Rotmeer 27% is unexplained. Depth and biozone independent of any LST effects explain 28% of the diatom variance at Rotsee but only 13% at Holzmaar and 12% at Rotmeer.

Conclusions

The Laacher See eruption was the major volcanic event in Europe during the last 15 000 years. In this study of three different sites, its effect on terrestrial vegetation was only significant at Holzmaar. This may, on one hand, be due to the proximity of this site's pollen catchment to the origin of the volcano. On the other hand, this site also has the highest time-control (5–7 years) because of its laminated sediments. Recent stud-

ies after the Mt. St. Helens eruption have shown that the affected vegetation outside the actual blast zone rapidly recovers within years. If there are any short-term effects of volcano eruptions on vegetation they can probably only be traced with a very fine stratigraphical temporal-resolution (Lotter & Birks, 1993).

The statistical analyses of the diatom assemblages indicate only a significant impact of the tephra or its associated change in the lithology in the Black Forest region. This might be due to either the supplementary nutrient and silica input into a nutrient-poor aquatic system or due to a lowering of the pH through atmospheric sulphur input originating from the eruption (Lotter & Birks, 1993). However, because of the interaction between tephra and lithology it is not possible to conclude if the observed diatom changes were primarily caused by the volcanic eruption or were due to changes in sediment lithology influenced, in part, by the inwashing of tephra.

Acknowledgments

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