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Impact of the Late Glacial Eruption of the Laacher See Volcano, Central Rhineland, Germany

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Within a period of a few weeks toward the end of the Allerød Interstadial, the major Plinian eruption of the Laacher See volcano produced some 20 km^3 of eruptiva, covering and preserving the late-glacial landscape in the German Central Rhineland over an area of more than 1000 km^2. Correlation of terrestrial archives with the Greenland ice-core records and improved calibration of the radiocarbon timescale permit a precise, accurate age determination of the Laacher See event some 200 yr before the onset of the Younger Dryas cold episode. Carbonized trees and botanical macrofossils preserved by Laacher See Tephra permit detailed regional paleoenvironmental reconstruction and show that open woodland were typical for the cool and humid hemiboreal climatic conditions during the late Allerød. This woodland provided the habitat for a large variety of animal species, documented at both paleontological and Final Paleolithic archeological sites preserved below Laacher See deposits. Of special interest are numerous animal tracks intercalated in Middle Laacher See deposits at the south of the Neuwied Basin. This knowledge may help to evaluate possible supraregional impacts of this volcanic event on northern hemispheric environment and climate during the late Allerød.

Key Words: **Laacher See Volcano; Laacher See Tephra; Allerød Interstadial; paleoecology; Central Rhineland Germany; Greenland ice cores.**

INTRODUCTION

The volcanic eruptiva (mainly pumice and ash deposits) today attributed to the late-glacial Laacher See Tephra (LST), have long been recognized (cf. Agricola, 1546) over the whole Central Rhineland Neuwied Basin, but only since the middle of the 19th century large-scale industrial exploitation has exposed numerous sections. Some 200 years ago the discussion of the origin of LST deposits played a role in the dispute of neptunists versus plutonists. While the former—among them J. W. von Goethe—propagated a marine origin for basaltic rocks, the latter group emphasized their origin within the Earth's interior (Schmincke, 2000, 9–10). Once its volcanic origins had been accepted, the LST was believed to have erupted from a vent submerged in today's Laacher See (Mordziol, 1931a,b), a lake named after the Benedictine monastery Maria Laach, founded in 1093 on its southwestern shore. Frechen (1953, 1959) later postulated four additional vents for different LST stages, which were discussed in the literature until the late 1970s (Windheuser and Brunnacker, 1979). Continuing research has, however, confirmed the Laacher See as the only vent for the late glacial LST eruption (van den Bogaard and Schmincke, 1984, 1985), although the center of the complex eruption with Plinian and phreatomagmatic phases repeatedly shifted between a southern and a northern crater, both of which are today submerged beneath the slightly figure-eight-shaped Laacher See.

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GEOLOGICAL SETTING

The German Central Rhineland forms part of the West European Rift system, situated on a seismotectonic belt running from the North Sea through the Rhine Valley to the Alps (Fig. 1). Since the Tertiary, the Rhenish Shield has been uplifted in the foreland of the Alpine collision front (Fuchs *et al.*, 1983; Schirmer, 1995) while the Lower Rhine Embayment and the Upper Rhine Graben have been sinking. Centered in the Rhenish Shield, the region between Koblenz to the SE and Andernach to the NW forms a geomorphological basin, the Neuwied or Central Rhineland Basin (Figs. 1, 2a and 2b). During the Quaternary, the

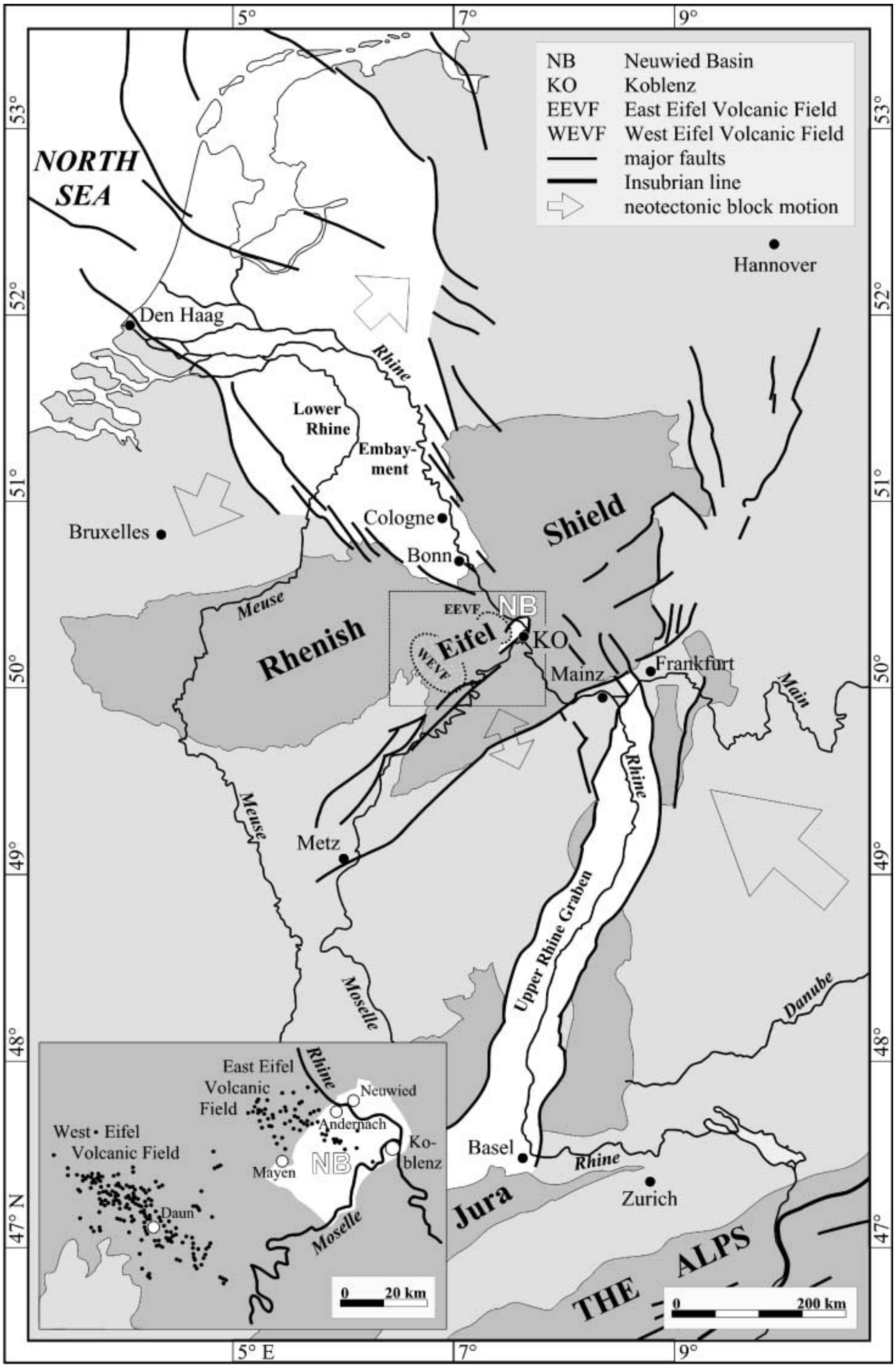

FIG. 1. The Rhineland in the central European Rift System (after Schirmer, 1995, and Illies and Fuchs in Fuchs *et al.*, 1983). Box indicates locations of West and East Eifel Volcanic Fields (cf. inlay map with the Eifel volcanic fields; modified after Schmincke, 1988).

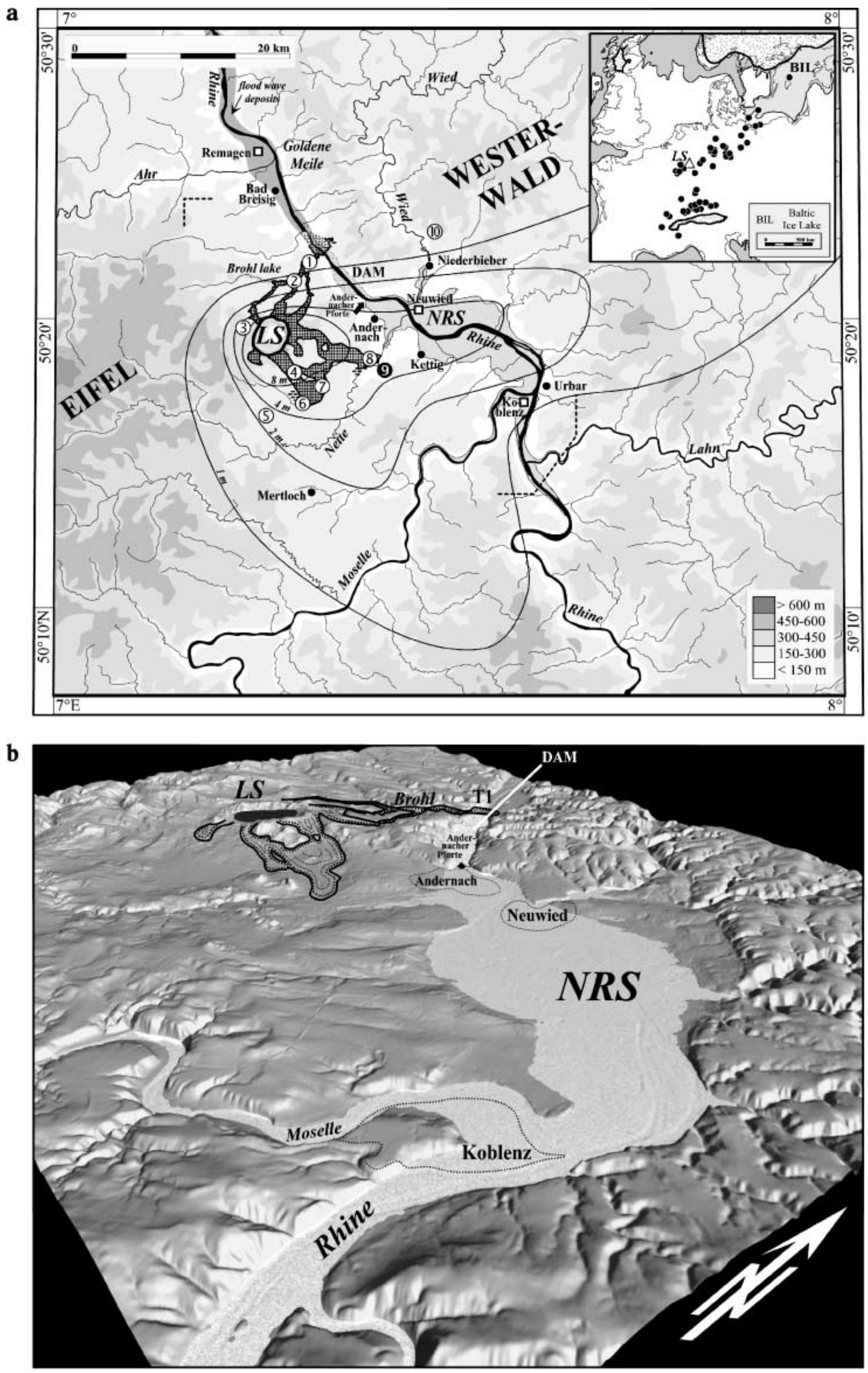

FIG. 2. (a) The central Rhineland during the Laacher See (LS) event 12,916 cal yr B.P. Isopachs show Laacher See tephra (LST) thickness in 1, 2, 4, and 8 m contours. Cross-hatched area shows ignimbrites initially damming up Rhine and Brohl to temporary lakes: Neuwied-Rhein-See (NRS; Neuwied–Rhine dam lake) and Brohl lake (cf. Schmincke *et al.*, 1990, 1999). Major archeological (Bad Breisig, Niederbieber, Andernach, Kettig, and Urbar) and paleontological sites are indicated (Mertloch, 1 = Brohl "Netzer Mühle" and "Brohltalbrücke"; 2 = Brohl 1, 2 and Bad Tönisstein "Kurpark"; 3 = Glees; 4 = Krufter Often; 5 = Thür; 6 = Fraukirch; 7 = Kruft; 8 = Miesenheim 2; 9 = Miesenheim 4; 10 = Melsbach; for further information, see text). Inlay shows paleogeography of Europe at the end of the Allerød Interstadial with reconstructed coastlines, ice shields, and Baltic Ice Lake and distal LST find spots (cf. Jöris and Weniger, 2000b). Stippled line indicates location of Figure 2b. (b) NRS dam lake in the lower Neuwied Basin as viewed from southeast looking toward the dam (hatched) between the *Andernacher Pforte* and the Brohl River mouth (vertically exaggerated by a factor of two; for location, cf. Fig. 2a). The NRS was dammed by the T1 ignimbrite of the Brohl pyroclastic flows. Prepared by Susanne Reichert and Rolf Schmidt using data from the Landesvermessungsamt Rheinland-Pfalz, Koblenz.

Rhenish Shield uplift intensified, while the uplift of the Neuwied Basin was delayed and far less pronounced. Since the Tertiary many volcanic eruptions have occurred in the Rhenish Shield lithospheric stress zone, most likely due to minor intraplate mantle plume activity (Raikes and Bonjer, 1983; Schmincke, 2000, 90–95; Ritter *et al.*, 2001). During the Pleistocene, volcanism was limited to the Eifel uplands, to the west of the Rhine and north of the Moselle, and restricted to two distinct volcanic fields (Fig. 1 inlay). The Pleistocene eruption history of the West Eifel Volcanic Field, which contains some 240 scoria cones and numerous maars, began in the early Middle Pleistocene around 0.6–0.7 myr ago. The East Eifel Volcanic Field, located at the western rim of the Neuwied Basin, also became active at around the same time, or slightly later. Here, some 100 eruption centers are known, among them four major vents of highly explosive phonolithic eruptions. The late-glacial Laacher See eruption represents merely the last and most violent one in the history of the East Eifel Volcanic Field (Schmincke *et al.*, 1990, p. 16).

LAACHER SEE ARCHIVES

Deposits of the Plinian Laacher See eruption have covered the entire Neuwied Basin (Fig. 3). Distal pumice fallout up to 1 m thick is to be found in two distinct fans more than 120 km ENE in the Westerwald uplands and beyond, as well as some 40 km SE, in all covering some 1300 km^2 (Fig. 2; Schmincke *et al.*, 1999). Laacher See ash was transported by atmospheric circulation at least as far as the nearby West Eifel region and to the south even over the western Alps, as well as being found as much as 1100 km to the NE (Fig. 2a, inlay; van den Bogaard and Schmincke, 1985). The age of the LST had been discussed since the early 19th century but, in the early 20th century, it was assigned to the late glacial Allerød interstadial on the basis of stratigraphic evidence from peat bogs and lake sediments containing Laacher See ash layers in Central and SW Germany (Mordziol, 1931b; Frechen, 1952; Firbas, 1953).

Due to its widespread deposition in central and northern Europe (Fig. 2a, inlay) the LST represents an important marker for supraregional synchronization of late-glacial climate archives (cf. Fig. 3; Broecker, 1992, p. 137). During the last decades the number of locations providing LST has increased significantly (e.g., Lotter and Zbinden, 1989; Zolitschka, 1990; Litt and Stebich, 1999; Lotter, 1999; Merkt and Müller, 1999). Studies of Swiss lake marls, in particular, have refined the relative stratigraphic position of the LST to a position after the so called Gerzensee oscillation, within the first third of the youngest Allerød temperate oscillation (Lotter and Birks, 1993) correlated with the Greenland interstadial 1a (GI 1a; Fig. 4; cf. Björck *et al.*, 1998). The LST may even have been identified in the Greenland ice cores. In the region proximal to the Laacher See volcano (Fig. 2a) numerous sites revealing paleobotanical, paleozoological, and archeological information allow a detailed paleoecological reconstruction of the Neuwied Basin for the LST time slice. These data also provide information on the seasonality of the Laacher See eruption.

SEASONALITY OF THE LAACHER SEE ERUPTION

In two German lakes, the Meerfelder Maar in the western Eifel (Zolitschka, 1988; Brauer *et al.*, 1999; Litt and Stebich, 1999) and the Hämelsee in Lower Saxony (Merkt and Müller, 1999), varve studies have shown that late spring/early summer biogenic production was interrupted by sedimentation of LST within a single varve layer. This seasonal information agrees well with paleobotanical data from the Brohl valley. Immature fruits and leaf imprints of *Prunus padus* have been found at a stage of development equivalent to that in late May today (Waldmann, 1996). The season of the eruption is also supported by foal tracks found at Mertloch (Fig. 2a) which represent neonate animals (Baales and von Berg, 1999).

REGIONAL IMPACTS OF THE LAACHER SEE ERUPTION

After 20 years of intensive volcanological research, the history of the Laacher See eruption has been summarized most recently by Schmincke *et al.* (1999). For a few weeks at most, the violent Plinian event erupted some 6.3 km^3 of magma, covering the entire Neuwied Basin with some 20 km^3 of pumice and ashes, to a thickness of up to 50 m near the vent. Generally, the LST deposits are subdivided into a lower (LLST), middle (MLST), and upper unit (ULST), topped by reworked tephras (r-LST) (Fig. 5).

During the Plinian phases, the eruption column is estimated to have reached a height of some 22–40 km (Schmincke *et al.*, 1999). More than 30 documented collapses of the eruption column during the middle phase of the eruption resulted in ignimbrite ash flows, locally named *Trass*, which filled the paleovalleys north and south of the vent (Fig. 2a). The narrow Brohl valley was filled by more than 60 m of *Trass* resulting in the formation of a small but deep lake in the Brohl valley (Schmincke *et al.*, 1990, 149). Lateral overbank facies of the pyroclastic valley flows, widespread in the Neuwied Basin and locally named *Britz*, were deposited by co-ignimbrite ash cloud lobes (Schmincke *et al.*, 1999).

Only the first ignimbrite flow (T1; Fig. 5), which dates to the B-unit of the MLST (MLST-B), rushed through the entire lower Brohl valley (Fig. 2a) and reached the Rhine (Freundt and Schmincke, 1986), blocking the river (Park and Schmincke, 1997, 524). We suggest that overloading of the Rhine by volcanic material and trees felled by blasts and base surges led to the complete obstruction of the Rhine valley over a length of 7 km between the Brohl–Rhine confluence and the *Andernacher Pforte* gorge, the northern outlet of the Neuwied Basin. The major result of this obstruction was a temporary lake in the lower Neuwied Basin between Andernach and Koblenz, while further upstream the banks of the Rhine and its tributaries were submerged (Fig. 2a and 2b).

Thick laminated silty deposits interstratified with sorted pumice rafts of reworked LLST are clear proof for the temporary

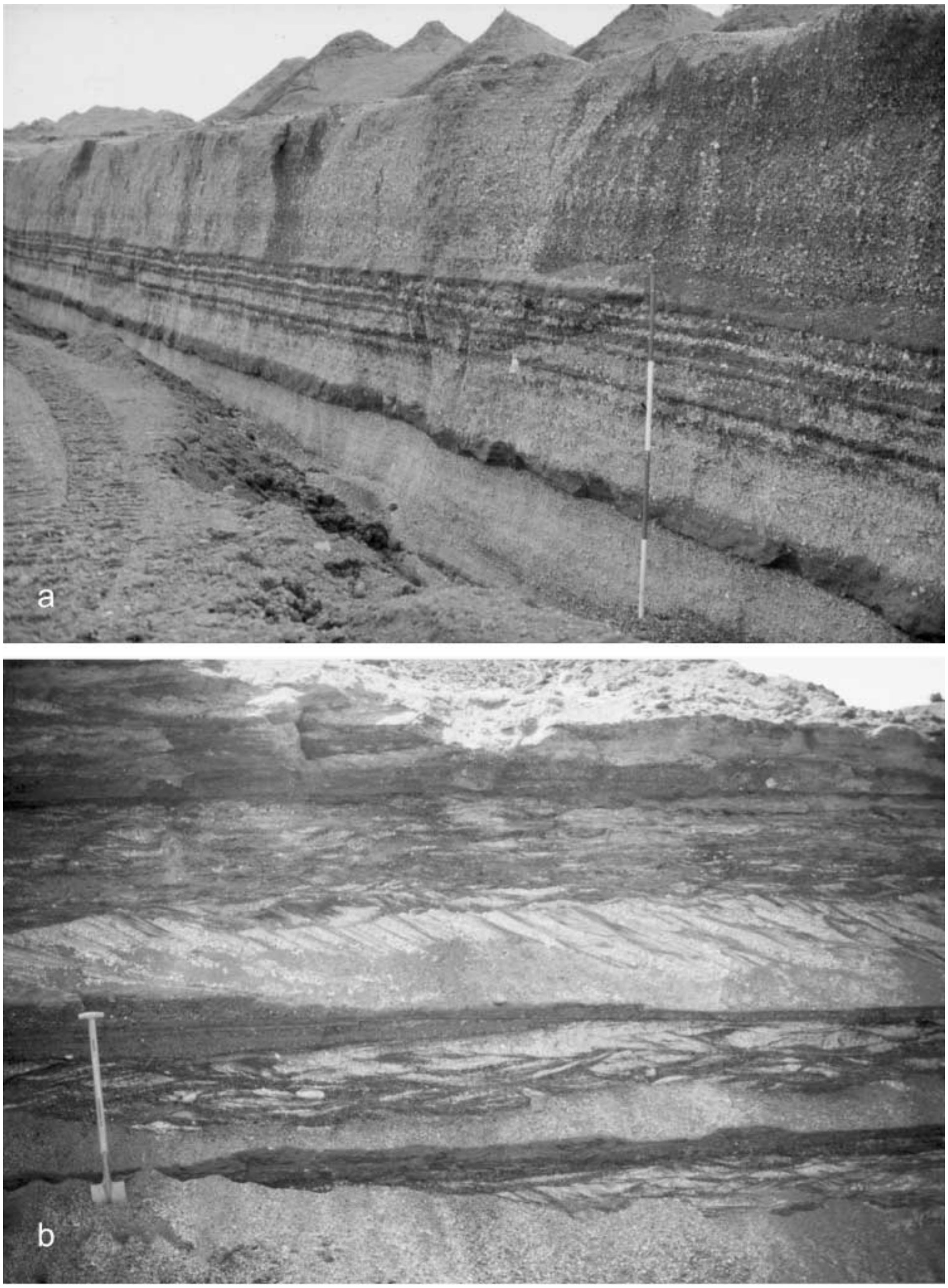

FIG. 3. (a) Deposits of fallout pumice in the Neuwied Basin during exploitation (scale: 2 m). (b) Syneruptively reworked Laacher See Tephra in cross-bedded Neuweid-Rhein-See (NRS) deposits at the southern rim of the NRS dam lake.

existence of a Neuwied–Rhine dammed lake (*Neuwied-Rhein-Stausee* = NRS). We documented water-rafted pumice at elevations of up to 71.5 m above sea level (asl) at more than 20 locations in the lower Neuwied Basin (Fig. 3b). Today's level of the Rhine in the Neuwied Basin is between 56 and 60 m asl which, referring to the 75-m asl isopach, allows a minimum estimate of around 80 km^2 for the area of the lower Neuwied Basin submerged by the NRS. This estimate is significantly less than that proposed by Schmincke and colleagues (Park and Schmincke, 1997; Schmincke *et al.*, 1999, p. 68).

Deep channels and gullies cut into LLST and silty NRS limnic phase deposits during the rapid drainage of the NRS were subsequently filled by thick fluviatile deposits of reworked LST with typical cross-bedding features (Fig. 3b). For example, channels with depths up to 10 m are known from Weißenthurm, close to Kettig and south of the Rhine today (Fig. 2a). Reworked LST sediments deposited north of the Neuwied Basin indicate that a flood wave rushed down the Rhine valley following the breaching of the NRS dam. Such flood wave sediments can be found in the so-called Goldene Meile between Bad Breisig and

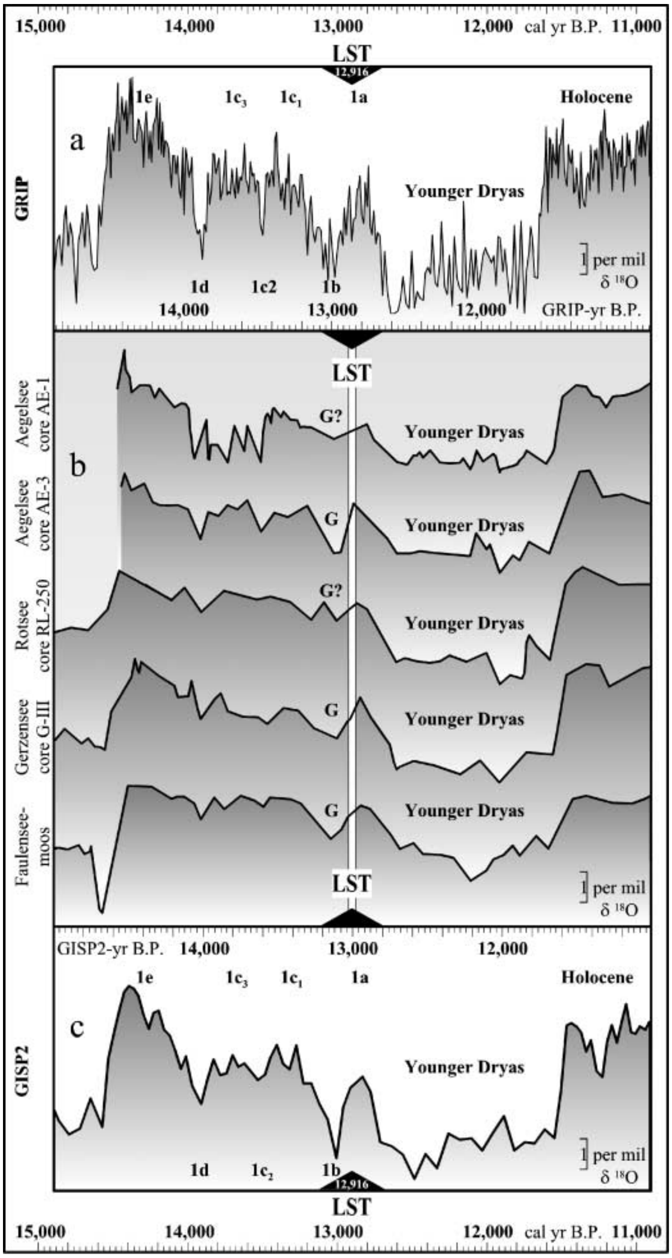

FIG. 4. Correlation of oxygen isotope records in the time window of 2000 yr within the late glacial centered around the Laacher See event showing the GRIP (a) and GISP2 record (c) as well as δ^{18}O signatures of lacustrine carbonates from Swiss lakes (b; Lotter *et al.*, 1992). The two Greenland ice cores are given with their internal chronological timescales (cf. Jöris and Weninger 2000a). G-Gerzensee fluctuation. For details, see text and Figure 9.

Remagen (Fig. 2a; cf. Schirmer, 1990), a short widening of the narrow Rhine valley in the area of the western Ahr tributary confluent.

Here, near Bad Breisig, some 14 km north of the Laacher See, the late Allerød land surface is covered by a thin layer of greenish fallout ash (Fig. 5, layer 1). This ash—which has preserved imprints of the Allerød vegetation (Waldmann, 1996)—is most plausibly correlated with the late MLST-B. During the NRS limnic stage the Rhine largely fell dry between the confluences of the Brohl and Ahr Rivers. The subsequent flood wave took up sands from the dry Rhine bed and deposited them in a layer up to 30 cm thick, also containing white pumice debris (Fig. 5, layer 2). These sediments are overlain by a 10-cm layer of rounded lapilli (Fig. 5, layer 3) originating from a continous layer of floating LLST pumice. These rafts were sealed by a characteristic dark hardened fallout ash some 7 cm thick (Fig. 5, layer 4), which we correlate with a terminal phreatomagmatic phase attributed to the B-unit of the ULST (ULST-B; cf. Park and Schmincke, 1997, p. 523). This confirms the hypothesis of Park and Schmincke (1997, p. 525) that NRS drainage occured within the MLST–ULST transition (Fig. 5). The deposition of this characteristic fallout tephra at the Goldene Meile north of the Laacher See is remarkable since it has so far not been recognized outside the Neuwied Basin.

The Bad Breisig profile is completed by fluvially reworked LST deposits (Fig. 5, layer 5), in some cases cross-bedded and terminated by high flood sediments (Fig. 5, layer 6) containing a horizon of a late Final Paleolithic backed-point assemblage (Fig. 5, Federmesse gruppen). This new site provides important paleoecological and archeological information on the reoccupation of the central Rhineland by Final Paleolithic hunter–gatherer groups immediately following the Laacher See catastrophe (Waldmann *et al.*, 2001; Baales *et al.*, 2001; Baales and Jöris, 2002).

LATE ALLERØD ECOLOGY OF THE NEUWIED BASIN AT THE TIME OF THE LAACHER SEE ERUPTION

Tephra fossils, mainly carbonized tree trunks and leaf imprints, have been collected from LST deposits for more than 200 yr (cf. Waldmann, 1996) and are regularly observed in the *Trass* deposits of the Neuwied Basin and the Brohl valley. Today, more than 100 plant species—trees, shrubs, herbs and mosses—are known from macrofossils (Table 1). Claims for the identification of several thermophilous species such as *Corylus* and *Alnus incana* have not withstood reexamination. A postulated *Corylus* charcoal turned out to be *Betula*, and an *Alnus incana* leaf imprint was reidentified as *Betula pubescens* (Baales *et al.*, 1998).

During the 1980s and early 1990s it was possible to investigate stands of trees found in waterlogged situations below the LST, such as a large area uncovered at the site of Miesenheim 2 (Fig. 2a), south of Andernach (Street, 1986, 1995), and, the first such discovery in 1980, at Thür (Fig. 2a) some 6 km south of the Laacher See, where a small stand of birch trees (*Betula* spec.) was identified (Brunnacker *et al.*, 1982). Two tree trunks lying oriented north–south might be interpreted as having been felled either by an initial blast or by a base surge during the Laacher See eruption (Street, 1995).

Intensified investigation in the late 1990s focussed on several locations in the Nette valley near the village of Kruft some 5.5 km south of the Laacher See. Here, the Krufter Often scoria

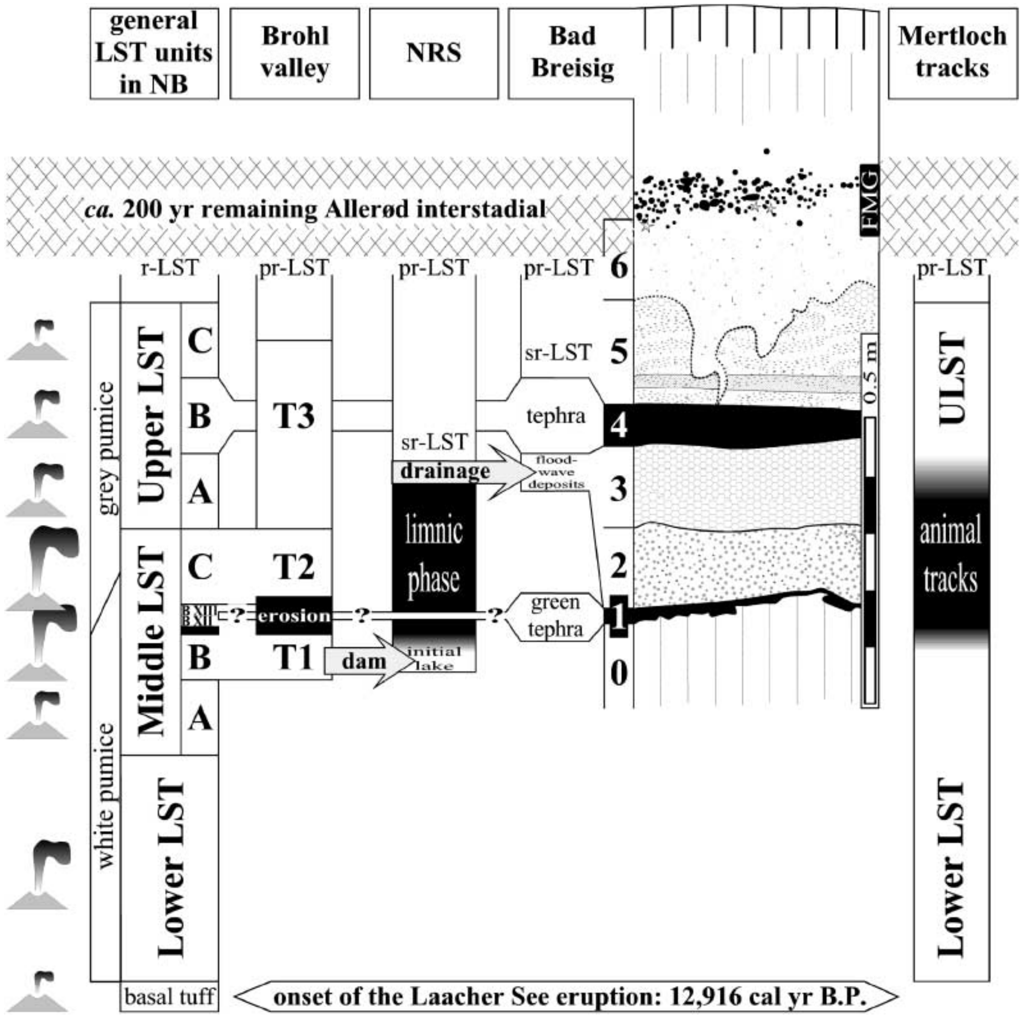

FIG. 5. Intercorrelation of the major stratigraphic units (Lower/Middle/Upper Laacher See Tephra (LST)) of central Rhineland Laacher See deposits. r-LST = reworked LST; sr-LST = syneruptively reworked LST; pr-LST = posteruptively reworked LST; T = ignimbrite phases of the Brohl valley. First two columns after Schmincke *et al.* (1990, 1999). Bad Breisig: Schematic profile containing Late Paleolithic find layer (FMG, Federmessergruppen; calcined bones and artifacts [asterisks]) overlaying LST deposits. 0 = Allerød soil; 1 = green fallout tephra of terminal MLST-B containing vegetation imprints; 2 = Rhine sands with white pumice; 3 = rafted white pumices; 4 = dark ULST-B fallout tephra; 5 = syneruptively reworked LST; 6 = high-flood sediments with posteruptively reworked LST in its basal part containing the archeological find layer. The green tephra (1) at Bad Breisig is tentatively correlated with the green tephra within silts of the limnic phase of the Neuwied dam lake (NRS) that most likely corresponds of the final phase of MLST-B.

cone (Fig. 2a) had blocked eruption blasts and thus sheltered local Allerød woodland composed of aspen (*Populus tremula*) and birch trees found standing upright in LST deposits. Alongside carbonized wood preserved in the *Trass*, further trees were documented as vertical molds left in the pumice when the wood decomposed. Most tree diameters range between 8 and 10 cm, although trees with diameters of up to 30 cm were observed, spaced at regular intervals of 5–10 m (Baales *et al.*, 1998). Further remains of wood were found in the *Trass* deposits of the Brohl and Nette valleys (Fig. 2a), mainly in allochthonous positions after transport by the ignimbrite flows, but still in place at one locality in the Brohl valley (Fig. 2a), investigated during the 1980s where wood of the bird cherry (*Prunus padus*) was also identified (Street, 1995).

A former shallow lake near Miesenheim (Miesenheim 4; Fig. 2a) covered by several meters of LST provided the possibility to study the hydroseral succession in detail. The analysis of plant macrofossils revealed the zonation from open water through a reed and bryophyte belt to open woodland of aspen, birch (*Betula pubescens*), and willow. Additional vegetational information is found as leaf imprints in Brohl and Nette valley *Trass* deposits (Schweitzer, 1958), in the silty NRS lake rim deposits and in the initial fallout ashes at numerous near-vent locations in the region (Waldmann, 1996). All the botanical evidence indicates the presence of relatively open woodland with a dense, species-rich undergrowth of herbaceous plants. Due to the central Rhineland topography a clear zonation of differently composed woodland can be recognized:

TABLE 1
Diaspores and Plant Macrofossils Identified below and in Laacher See Tephra (LST) Deposits in the Central Rhineland

Mosses, ferns
Amblystegium riparium
Amblystegium serpens
Amblystegium varium
Antitrichia curtipendula
Atrichum undulatum
Aulacomnium palustre
Barbula unguiculata
Brachythecium mildeanum
Brachythecium rivulare
Brachythecium rutabulum
Bryum cf. *turbinatum*
Bryum pseudotriquetrum
Calliergon giganteum
Calliergonella cuspidata
Campylium calcareum/sommerfeltii
Campylium stellatum
Cirriphylum piliferum
Dicranella cerviculata
Drepanocladus aduncus
Enthostodon fascicularis
Equisetum cf. *arvensis*
Eurhynchium spec.
Eurhynchium praelongum
Eurhynchium hians var. swartzii
Eurhynchium speciosum
Fissidens taxifolius
Funaria hygrometrica
Helodium blandowii
Homalia trichomanoides
Homalothecium nitens
Isothecium myosuroides
Plagiomnium cuspidatum
Plagiomnium ellipticum
Plagiothecium succulentum
cf. *Pseudoleskeella nervosa*
Pylaisia polyantha
Rhodobryum roseum
Rhytidium rugosum
Rhytidiadelphus triquetrus
Sphagnum imbricatum
Thelypteris palustris

Trees, shrubs
Betula cf. *pubescens/humilis*
Betula pendula
Betula pubescens
Betula spec.
Betula cf. *tortuosa*
Clematis vitalba
Daphne spec.
Pinus spec.
Populus spec.
Populus tremula
Prunus padus
Prunus spec.
Salix caprea-Type
Salix pentandra
Salix spec.
Sambucus nigra

Terrestrial herbs
Angelica sylvestris
Anthemis cf. *arvensis*
cf. *Calamagrostis arundinacea*
Campanula cf. *trachelium*
Carduus cf. *defloratus*
Carex muricata agg.
Carex umbrosa
cf. *Carum carvi*
Cerinthe glabra
Cirsium spec.
Epilobium cf. *alpestre*
Epilobium cf. *angustifolium*
Epilobium duriaei
Epilobium hirsutum-Type
Festuca cf. *altissima*
Festuca rubra agg.
Galeopsis tetrahit
Galium aparine
Galium verum
Hieracium sect. Euhieracium
Lychnis flos-cuculi
Melandrium rubrum
Mercurialis annua
Peucedanum officinale
Picris hieracioides
Pimpinella spec.
Plantago major
Poa cf. *trivialis*
Polemonium cf. *caeruleum*
Ranunculus repens
Rubus caesius
Rubus fruticosus agg.
Rubus idaeus
cf. *Rumex* spec.
Senecio erucifolius
cf. *Senecio vulgaris*
Sonchus asper
Stellaria graminea/palustris
Taraxacum spec.
cf. *Tussilago farfara*
Urtica dioica
Viola alba-Type

Aquatic, semiterrestrial herbs
Alisma plantago-aquatica
Caltha palustris
Carex acuta/elata
Carex cf. *acutiformis*
Carex appropinquata
Carex cf. *paniculata*
Carex diandra
Carex flava agg./pendula
Carex lasiocarpa
Carex pseudocyperus
Carex riparia
Carex rostrata
Ceratophyllum spec.
Chara aspera/braunii
Chara contraria-Type
Chara tomentosa
Cicuta virosa
Conium maculatum
Eleocharis multicaulis
Epilobium palustre
Filipendula ulmaria
Galium palustre agg.
Hippuris vulgaris
Lemna spec.
Myosotis palustris
Peucedanum cf. *palustre*
Phalaris arundinacea
Phragmites australis
Poa palustris
Polygonum amphibium
Potamogeton filiformis
Potamogeton gramineus/zizii
Potamogeton natans
Ranunculus sceleratus
Schoenoplectus lacustris
cf. *Schoenoplectus tabernaemontani*
Scutellaria galericulata
Senecio aquaticus
Solanum dulcamara
Sparganium neglectum
Typha cf. *angustifolia*
Typha latifolia
Valeriana officinalis agg.
Viola palustris-Type

Note. Leaf imprints (cf. Waldmann, 1996) are not considered. Locations are Miesenheim 2 (Staiger, 1988), Miesenheim 4, Fraukirch, Kruft, Brohl valley (Baales *et al.*, 1998), Melsbach, Andernach, Niederbieber, and Kettig (for location, see Fig. 2a). Pine (together with unidentifable charcoal remains of decidous trees) is also known from the Final Paleolithic find horizon at Bad Breisig located above reworked LST deposits.

1. The lower Neuwied Basin and river valleys were occupied by lower river bank woodland, mainly composed of aspen and birch (*Betula pubescens*) accompanied by willow (*Salix* spec.).
2. Somewhat higher, in elevations between 80 m and about 150 m asl, an upper river bank woodland with additional bird cherry (*Prunus padus*) was situated.
3. Up to almost 300 m asl, birch (now *Betula pendula*) and aspen woodland existed.
4. In higher elevations of the surrounding slopes and plateaux, pine (most probably *Pinus sylvestris*) joins the woodland species.

Other than a number of pine needle imprints described from the Brohl valley *Trass* (Schweitzer, 1958, p. 37) pine is so far not known as macrofossil material at paleontological sites. Pine obviously preferred drier locations and is therefore not found at the valley floor sites preserved by LST, although pine charcoal is known from Allerød archeological sites below the LST and has also been identified at Bad Breisig, postdating the Laacher See event. Pollen spectra from across central Europe show a clear presence and even dominance of pine pollen during the Allerød, reflecting both the high production and dispersal of pine pollen, and the fact that pollen of *Pinus sylvestris* is resistant to decay and easily recognized. Further information on the ecological situation is given by faunal remains found below LST deposits which have demonstrated the presence of many animal species at both archeological and strictly paleontological sites (Table 2). One example of the latter category of site is Miesenheim 4 (Fig. 2a), where much of the skeleton of a young male moose (*Alces alces*), scavenged (and also killed?) by wolves, was documented (Street, 1993, 1995). Indications for the persistence of open landscapes at higher elevations are given by the regular presence of horses which outlived the earlier steppic biotopes to survive into the hemiboreal Allerød environment. Horse remains are found at archeological sites below the LST; the species has also been documented since 1996 as ichnofossils (Fig. 6c) in the MLST deposits at Mertloch, some 16 km to the south of the Laacher See, and has recently been recovered at Bad Breisig (Baales *et al.*, 2001; Waldmann *et al.*, 2001; Baales and Jöris, 2002).

At Mertloch it was possible to document well-preserved imprints of tracks of further Allerød animal species on a short-lived surface (*Britz*) within an MLST ash layer, some 20 cm above the LLST pumice and itself covered by ULST (Fig. 5). Syneruptive rain produced a muddy ash surface which preserved the animal tracks and raindrop imprints over a surface of several 1000 m^2. The animal tracks can be attributed to predominantly female capercaillie (*Tetrao urogallus*; Fig. 6a), two brown bears (*Ursus arctos*; one track was preserved over a distance of 70 m; Fig. 6b), a red deer hind (*Cervus elaphus*) with a calf, and several horses (*Equus* sp.) with young foals (Fig. 6c; Baales and von Berg, 1997, 1999; Street and Baales, 1999).

To summarize, the ecological information for the time of the late Allerød Laacher See eruption outlines an environmental

TABLE 2

Animal Species (Except Mollusks) Identified at Archeological and Paleontological Sites below, in, and above Laacher See Tephra (LST) Deposits (for Location, see Fig. 2a)

		1	2	3
Perissodactyla				
Horse	*Equus* sp.	x	x	x
Artiodactyla				
Red deer	*Cervus elaphus*	x	x	x
Roe deer	*Capreolus capreolus*	x		x
Moose	*Alces alces*	x		
Large Bovid (Aurochs?)	*Bison/Bos primigenius*?	x		
Ibex	*Capra ibex*	x		
Chamois	*Rupicapra rupicapra*	x		
Wild boar	*Sus scrofa*	?		
Carnivora				
Bear	*Ursus arctos*	x	x	
Wolf	*Canis lupus*	x		
Dog	*Canis familiaris*	?		
Red fox	*Vulpes vulpes*	x		
Badger	*Meles meles*	x		
Weasel	*Mustela nivalis*	x		
Marten	*Martes* sp.	x		
Rodentia				
Beaver	*Castor fiber*	x		
Marmot	*Marmotta primigenia*	?		
Yellow-necked field-mouse	*Apodemus flavicollis*	x		
Common hamster	*Cricetus cricetus*	x		
Hamster	*Cricetus* sp.	x		
Large pleistocene mole	*Talpa europaea magna*	x		
Mole	*Talpa europaea*	x		
Bank vole	*Clethrionomys glareolus*	x		
Water vole	*Arvicola terrestris*	x		
Root vole	*Microtus oeconomus*	x		
Field vole	*Microtus agrestis*	x		
Voles	*Microtus arvalis/agrestis*	x		
Insectivora				
Common shrew	*Sorex* ex. gr. *araneus*	x		
Pygmy shrew	*Sorex* cf. *minutus*	x		
Water shrew	*Neomys fodiens*	x		
Chiroptera				
Noctule	*Nyctalus* sp.	x		
Long-eared bat	*Plecotus auritus*	x		
Aves				
Capercaillie	*Tetrao urogallus*		x	
Galliformes (Black grouse?)	*Terao (Lyrurus) tetrix*?	x		
Galliformes (Ptarmigan?)	cf. *Lagopus* sp.?	x		
Tit	*Parus* sp.	x		
Pisces				
Pike	*Esox lucius*	x		
Perch	*Perca fluviatilis*	x		
Chub	*Leuciscus cephalus*	x		
Cyprinids	*Leuciscus* sp.	x		
Reptilia				
Lizard	*Lacerta* sp.	x		

Note. 1 = Final Paleolithic *Federmessergruppen* and paleontological sites below LST. 2 = animal tracks in middle LST deposits at Mertloch. 3 = Bad Breisig, Final Paleolithic *Federmessergruppen* site above LST deposits (Kalthoff, 1998; Street and Baales, 1999; Waldmann *et al.*, 2001). (Aurochs? questionable identification. ? questionable context).

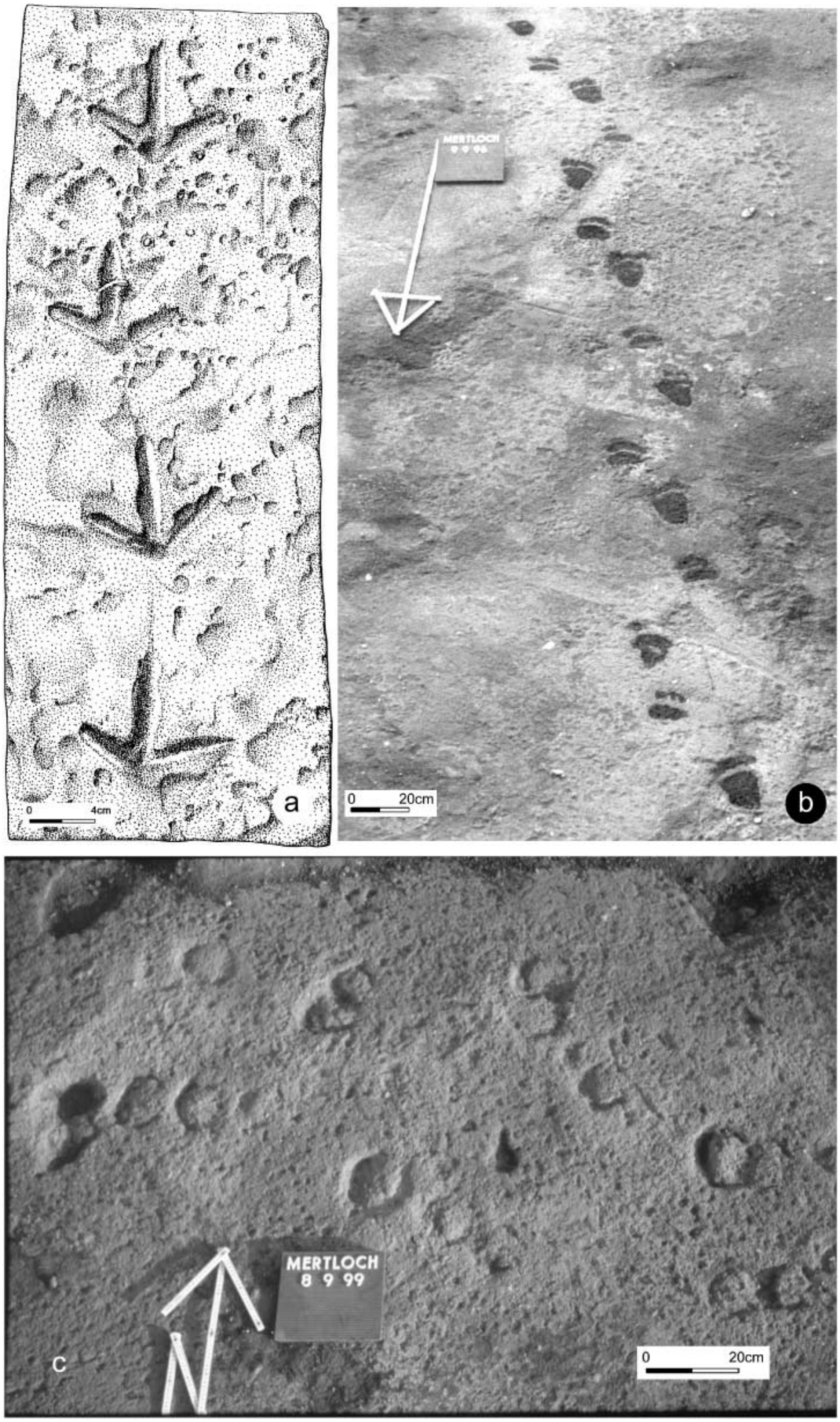

FIG. 6. Mertloch (Neuwied Basin, Germany). Tracks of three animal species preserved in a Middle Laacher See Tephra ash layer. (a) Drawing of a female capercaillie (*Tetrao urogallus*) track; note the imprints of raindrops and lapilli impacts on the ash surface. (b) Track of brown bear (*Ursus arctos*); the imprints are filled with darker sand to improve their visibility (September 1996). (c) Tracks of three horses (*Equus* sp.) (September 1999).

situation comparable to the hemiboreal conditions nowadays widespread in several regions of the northern hemisphere (cf. Waldmann, 1996). The Neuwied Basin woodland was dominated by aspen and birch (predominantly *Betula pubescens*). In the valleys, bird cherry (*Prunus padus*) and willows (e.g. *Salix pentandra*) were also present; in drier locations other willow species (e.g. *Salix caprea*) were found. In the latter situation *Betula pubescens* was to a large extent replaced by *Betula pendula*. Evidence for pine is scarce and present only from localities at the edge of the Neuwied Basin lowlands (Andernach, Urbar, possibly Niederbieber) and from Bad Breisig, postdating the LST. The situation can be described as temperate and humid. This is in accordance with paleotemperature reconstructions based on beetle studies for NW Europe, showing slightly lower annual temperatures with cooler winters for the late Allerød in comparison with today's situation (cf. Atkinson *et al.*, 1987; Coope *et al.*, 1998).

DATING OF THE LAACHER SEE EVENT

The Allerød age of the Laacher See event (Mordziol, 1931b) was first confirmed by early radiocarbon dates on peat deposits above LST from Wallensen in Lower Saxony some 240 km NE of the Laacher See, which gave an age of $11{,}044 \pm 500$ ^{14}C yr B.P. (Libby, 1952: sample C-337; Firbas, 1953). In the following years further radiocarbon measurements were obtained on charcoal from ignimbritic *Trass* deposits in the central Rhineland supporting the validity of the first data (Frechen, 1959; Rubin and Alexander, 1960).

Preliminary single-crystal laser-fusion ^{40}Ar/^{39}Ar dates obtained directly on Neuwied Basin LST material allow a broad calendric eruption age estimate of $12{,}900 \pm 560$ yr B.P. (van den Bogaard, 1995) but already in 1994 an age of 12,950 cal yr B.P. was calculated for the LST event based on radiocarbon dates using the Stuiver and Reimer (1993) calibration data curve (Street *et al.*, 1994). With the more recent INTCAL98 data set making use of the first Cariaco varve chronology, the calibrated high-precision ^{14}C data obtained from the Kruft aspen tree no. 9 range from 13,010 to 13,200 cal yr B.P. (Baales *et al.*, 1998; Kromer *et al.*, 1998; Friedrich *et al.*, 1999, 2001) and, therefore, seem to be slightly too old compared with the time range for calendric LST age estimates (cf. Andres and Litt, 1999, 1–2) derived from central European late glacial/early Holocene varve stratigraphies (cf. Litt and Stebich, 1999).

Within the proximal Laacher See region, 44 radiocarbon age determination were obtained on botanical remains, some of them high-precision (Table 3). We have distinguished between long-lived (mainly wood) and short-lived (e.g., bark, outer tree rings, charcoal) botanical samples and observe within each group three distinct clusters of data (Fig. 7). The middle cluster (Fig. 7b and c, cluster m) contains the most high-precision dates obtained on the Kruft trees (no. 8 and 9, preserved upstanding in LST) representing the most precise timing of the Laacher See eruption, with a weighted mean value of $11{,}062 \pm 11$ ^{14}C yr B.P. which is in good agreement with further high-precision data from Krumpa in Sachsen-Anhalt some 400 km to the NE of the Laacher See vent (Kromer *et al.*, 1998) but appreciably younger than the age approximation given by Hajdas *et al.* (1995). The younger cluster (Fig. 7, cluster y; weighted mean: $10{,}911 \pm 49$ ^{14}C yr B.P.) therefore represents an age inversion in the ^{14}C timescale not included in the INTCAL98 record but shown in the youngest Dättnau Allerød pine dendrochronology (DAEALCH3) in the Swiss northern Alpine foreland (Kaiser, 1993) as well as in Swedish and Polish varve chronologies (Goslar *et al.*, 2000). DAEALCH3, consisting of eight pine trees (Kaiser, 1993), shows a remarkable synchronous decline in

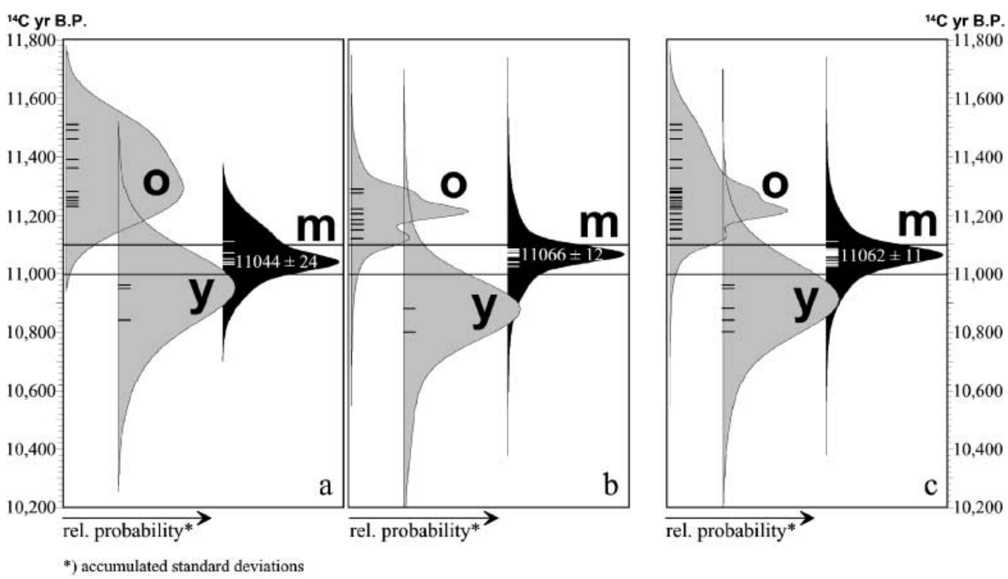

FIG. 7. Radiocarbon age distribution of vegetation samples dating the Laacher See event, distinguished as long-lived (a) and short-lived (b) and all samples (c) from the Neuwied Basin and adjacent regions. The data are sorted for their distinct age clusters (o = older; y = younger; m = middle age cluster; cf. Table 3).

TABLE 3
Radiocarbon Ages on Vegetation Samples below and in Laacher See Tephra (LST) Deposits

Site	^{14}C yr B.P.	Lab no.	Material	Location	Reference
			A		
Younger cluster (weighted mean age 10,944 ± 68 BP)					
Miesenh. 2	10 840 ± 195	Zürich	*Populus*	Below LST	Street, 1993
Thelenberg	10 950 ± 190	HD-?	Charcoal	In ULST	Frechen, 1959
Miesenh. 2	10 960 ± 110	OxA-2609	*Populus*	Below LST	Hedges *et al.*, 1993
Miesenh. 2	10 960 ± 110	OxA-2610	*Populus*	Below LST	Hedges *et al.*, 1993
Middle cluster (weighted mean age 11,044 ± 24 BP)					
Miesenh. 2	11 030 ± 110	OxA-2611	*Populus*	Below LST	Hedges *et al.*, 1993
Kruft	11 037 ± 27	Hd-18648	*Populus* 1 rings 31–40*	In MLST	Baales *et al.*, 1998
Thür	11 050 ± 110	KN-2868	*Betula*	Below LST	Brunnacker *et al.*, 1982
Miesenh. 2	11 070 ± 100	KN-3520	*Populus*	Below LST	Street, 1986
Thür	11 110 ± 90	KN-2869	*Betula*	Below LST	Brunnacker *et al.*, 1982
Older cluster (weighted mean age 11,351 ± 30 BP)					
Miesenh. 2	11 230 ± 95	KN-3516	*Populus*	Below LST	Street, 1986
Brohi valley	11 240 ± 100	KN-3800	*Populus*	In MLST	Street, 1993
Thür	11 250 ± 95	KN-2870	*Betula*	Below LST	Brunacker *et al.*, 1982
Brohl valley	11 260 ± 95	KN-3801	*Populus*	In MLST	Street, 1993
Brohl valley	11 280 ± 100	KN-3802	*Populus*	In MLST	Street, 1993
Miesenh. 2	11 360 ± 110	KN-3534	*Populus*	Below LST	Street, 1986
Miesenh. 2	11 390 ± 90	KN-3532	*Populus*	Below LST	Street, 1986
Miesenh. 2	11 460 ± 100	KN-3531	*Populus*	Below LST	Street, 1986
Miesenh. 2	11 490 ± 90	KN-3533	*Populus*	Below LST	Street, 1986
Brohl valley	11 510 ± 90	KN-3803	*Populus*	In MLST	Street, 1993
			B		
Younger cluster (weighted mean age 10,876 ± 70 BP)					
Glees	10 680 ± 85	GrN-?	Charcoal	In MLST†	Schweitzer, 1958
Nette valley	10 800 ± 300	W-525	Charcoal	In MLST	Frechen, 1959
Nette valley	10 880 ± 95	?	Charcoal	In MLST	Bogaard and Schmincke, 1985
Miesenh. 2	10 880 ± 110	OxA-2612	Charcoal	Below LST	Hedges *et al.*, 1993
				† rejected.	
Middle cluster (weighted mean age 11,066 ± 12 BP)					
Tönisstein	11 025 ± 90	GrN-?	Charcoal	In MLST	Frechen, 1959
Miesenh. 4	11 040 ± 60	UtC-4815	Wood	Below LST	K. van der Borg pers.comm.
Miesenh. 2	11 040 ± 110	OxA-2613	Charcoal	Below LST	Hedges *et al.*, 1993
Miesenh. 2	11 040 ± 220	KN-3519	*Populus* bark‡	Below LST	Street, 1986
Miesenh. 2	11 060 ± 120	OxA-2614	Charcoal	Below LST	Hedges *et al.*, 1993
Kruft	11 063 ± 30	Hd-19098	*Populus* 9 rings 1–20	In MLST	Baales *et al.*, 1998
Kruft	11 065 ± 22	Hd-18438	*Populus* 8 outer rings	In MLST	Baales *et al.*, 1998
Kruft	11 066 ± 28	Hd-19092	*Populus* 9 rings 21–30	In MLST	Baales *et al.*, 1998
Kruft	11 073 ± 33	Hd-18622	*Populus* 9 rings 31–40	In MLST	Baales *et al.*, 1998
Kruft	11 075 ± 28	Hd-19037	*Populus* 9 rings 41–50	In MLST	Baales *et al.*, 1998
Brohl valley	11 075 ± 185	Hv-11774	plant remains	In MLST	Heine, 1993
Miesenh. 2	11 080 ± 220	KN-3518	*Populus* bark‡	Below LST	Street, 1986
Brohl valley	11 085 ± 90	?	Charcoal	In MLST	Schweltzer, 1958
			‡identical sample.		
Older cluster (weighted mean age 11,210 ± 11 BP [3 σ])					
Brohl valley	11 121 ± 28	Hd-17101	Tree 5b, ca. 50 rings	In MLST	Kromer *et al.*, 1998
Tönnisstein	11 150 ± 200	W-528	Charcoal	In MLST	Street *et al.*, 1994
Miesenh. 4	11 170 ± 100	OxA-3587	Green moss on antler	Below LST	Hedges *et al.*, 1993
Miesenh. 4	11 185 ± 90	?	?	Below LST	Schimer, 1995
Brohl valley	11 206 ± 20	Hd-17100	Tree 1a, ca. 50 rings	In MLST	Kromer *et al.*, 1998
Brohl valley	11 223 ± 22	Hd-17145	Tree 3a, ca. 50 rings	In MLST	Kromer *et al.*, 1998
Brohl valley	11 277 ± 26	Hd-17900	Tree 1/4, rings 1–38	In MLST	Kromer *et al.*, 1998
Miesenh. 2	11 290 ± 95	KN-3517	*Populus* bark	Below LST	Street, 1986

Note. A = "long-lived" (mainly wood). B = "short-lived" plant remains (mainly found in LST deposits). Compare Figure 7. ULST = Upper LST; MLST = Middle LST.

* Wood with insect bore holes standing upright in LST.

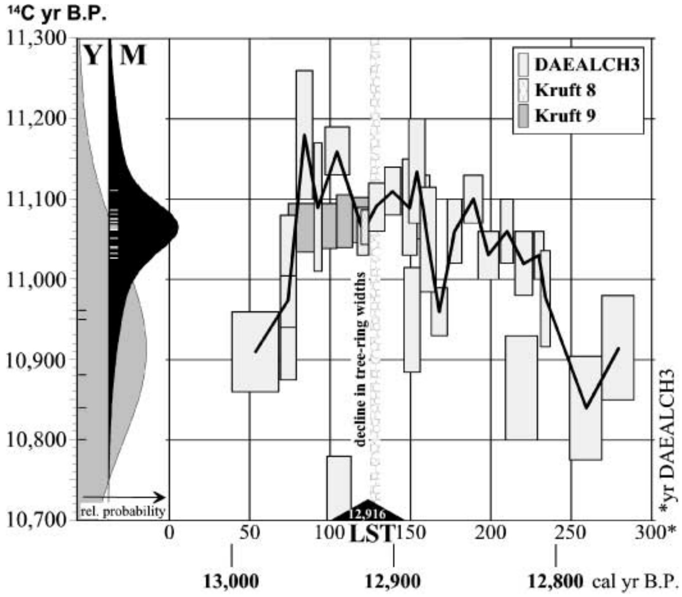

FIG. 8. High-precision dendrochronologies from the Swiss site of Dättnau (DAEALCH3; Kaiser, 1993) and Kruft in the Neuwied Basin (Tree no. 9; Baales *et al.*, 1998) showing late Allerød fluctuations in atmospheric ^{14}C concentration compared with the younger (Y) and middle (M) radiocarbon age clusters of central Rhineland vegetation samples (cf. Fig. 7 and Table 3). The data prove an ^{14}C age inversion prior to the Laacher See event which is marked in the DAEALCH3 sequence. The weighted mean of the middle ^{14}C age cluster fits perfectly with the ^{14}C age of DAEALCH3 shortly before the decline in tree-ring widths. Calibrated ("calendric") ages (cal yr B.P.) follow the age model explained in the text.

tree-ring widths, indicating an environmental impact that is most likely caused by the Laacher See event (Fig. 8).

Although the age discrepancies of radiometric and varve data reflect problems in the correlation of high-resolution archives for the time window discussed, an LST age determination of highest precision and accuracy is desired due to its potential use as an ideal "zero year" reference in the synchronization of annual-layer counted archives (cf. Broecker, 1992, p. 137), among them the Greenland ice cores GRIP and GISP2 which—at present—represent the most continuous records with highest resolution in time.

While the Greenland ice cores are among the most important records of northern hemispheric climate change, their timescales differ during the late glacial period by up to a few centuries (Fig. 4; cf. Grootes *et al.*, 1993). Comparison of the duration of the Younger Dryas (YD) shown by ice-core chronologies and by anually layered European lake sediments gives a mean value of 1143 yr (Table 4), which clearly shows that the GISP2 age model stretches the YD cold episode for a few decades (cf. Jöris and Weninger, 2000a,b).

We have taken the age of the onset of the Holocene as 11,570 cal yr B.P., which can be seen most precisely in the remarkable supraregional increase of tree-ring widths observed in the continuous central European YD–Holocene dendrochronology established during the last several years (Friedrich *et al.*, 1999, 2001). To this we have added the mean duration of the YD (1143 yr) from several paleoclimatic archives to arrive at an age of 12,713 cal yr B.P. for the Allerød–YD transition.

After the first third of GI 1a the Greenland ice cores show a significant increase in electrical conductivity measurement (ECM) values and an extraordinarily high amount of volcanic SO_2 content (Fig. 9). The relative chronological position of this volcanic event some 200 yr before the onset of the YD in the Greenland ice cores is in overall agreement with that of the LST deduced from numerous annually counted varved lakes in central Europe (Fig. 4; Jöris and Weninger, 2000a). We therefore trace both signals in the ice cores back to the Laacher See event.

It is suggested that the Laacher See impact was delayed by some 1–2 yr, as indicated by the DAEALCH3 dendrochronology (Kaiser, 1993; Friedrich *et al.*, 1999, 2001; cf. Fig. 9 and Jöris and Weninger, 2000a). With this hypothesis the δ^{18}O signatures of both ice cores perfectly synchronize over the entire duration of GI 1a. Furthermore, the Greenland δ^{18}O signals correlate roughly with changes in tree-ring growth recorded in year 126 of the youngest Dättnau Allerød sequence (DAEALCH3; cf. Kaiser, 1993). If we accept these correlations, the onset of the remarkable decline in tree-ring widths some 192 + ca. 5 yr before the end of the Swiss dendrochronology (Kaiser, 1993) correlates with the ECM peak and the peak of volcanic sulphur in the Greenland ice cores. With this synchronization the Laacher See event predates the onset of the YD by some 203 yr on average

TABLE 4
Approximation of the Time Interval between Laacher See Tephra (LST) Event and Onset of the Holocene

	1 MFM	2 SOP	3 LGO	4 GRIP	5 GISP2	Avg. 1–5	Avg. 2–4
Duration of the YD	1090	**1139**	**1140**	**1150**	1180	1140	**1143**
LST to start of YD	200	**213**	**203***	**193**	217	205	**203**
LST to end of YD	1290	**1352**	**1343***	**1343**	1397	1345	**1346**

Note. YD = Younger Dryas; MFM = Meerfelder Maar (Brauer *et al.*, 1999); SOP = Soppensee (Hajdas *et al.*, 1993, 1995); LGO = Lake Gosciaz (Goslar *et al.*, 1995); GRIP (Johnsen *et al.*, 1992); GISP2 (Alley *et al.*, 1993); (cf. Jöris and Weninger, 2000a). *Interpolated on basis of synchronization of the δ^{18}O signature with Greenland ice cores.

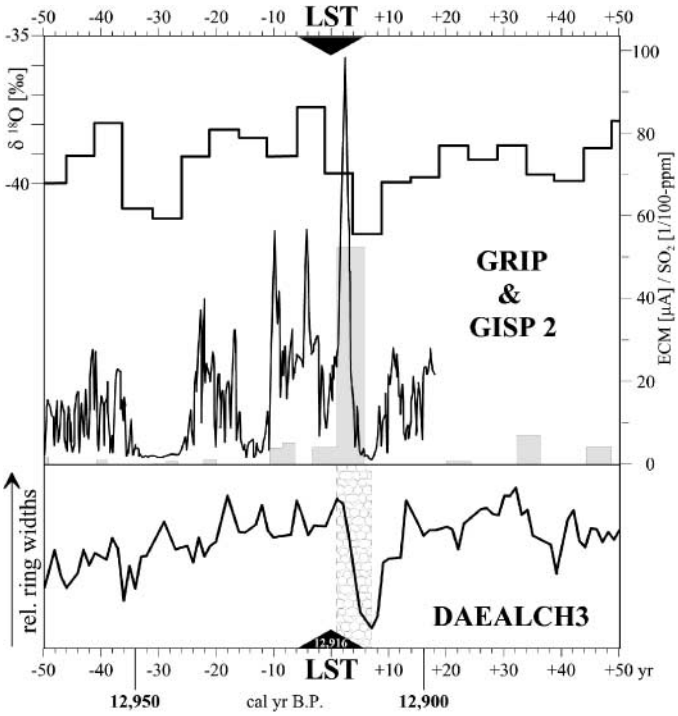

FIG. 9. Time window of 100 yr within the Late Allerød centered around the Laacher See event showing the DAEALCH3 dendrochronology (bottom) with marked decline in tree-ring widths (shading; cf. Kaiser, 1993) in comparison with combined GRIP and GISP2 data that are calibrated by the assumption that an extraordinary marked peak of sulphur in both ice cores can be traced back to the Laacher See event. Ice core data show electrical conductivity measurement (bold line; Taylor *et al.*, 1993) and total volcanic sulphur (shaded histogram; Zielinski *et al.*, 1996) in relation to $\delta^{18}O$ signature of the GRIP record (Johnsen *et al.*, 1997) to the top of the diagram. Calibrated ages (cal yr B.P.) follow the age model explained in the text.

(Table 4) which is in good agreement with counting of organic matter laminae in the northern German Hämelsee (Kaiser, 1993, 164–165; cf. Merkt and Müller, 1999). Thus, we finally arrive at an age of 12,916 cal yr B.P. for the onset of the Laacher See event.

Taking this date as the "zero year" of late glacial archives for this specific point, the GRIP record has to be shifted by 23 yr to an older age, while the GISP2 record has to be shifted by 121 yr to a younger age (Jöris and Weninger 2000a).

SUPRAREGIONAL IMPACTS

A total of approximately 150 megatons of sulphur (max. estimate) may have been released prior to and during the Laacher See eruption, a value significantly larger than those for comparable large-scale volcanic explosions (Schmincke *et al.*, 1999, p. 70). Taking into account the presumed height of the eruption column during the Plinian phases of the Laacher See eruption, one must assume that major sulphur emissions into the stratosphere by LST aerosols probably caused increased albedo and most likely a lowering of northern hemispheric average temperatures.

Following the chronological correlations suggested above, the ECM and volcanic SO_2 signals in the Greenland ice cores coincide to within ±2 yr with the most prominent drop in $\delta^{18}O$ values during GI 1a (Fig. 9; cf. Fig. 4), indicating a short-term climatic deterioration, possibly representing a "volcanic winter" in the northern hemisphere, most likely triggered by the Laacher See event.

Although pollen and diatom analysis of some central European varve lakes shows no significant impact of the LST on local biogenic production (Lotter and Birks, 1993; Birks and Lotter, 1994), it is possible that ash falls, acid rain, and lowered temperatures following the LST eruption might have significantly injured the late Allerød ecology (Schmincke *et al.*, 1999, 70). Acidification, in particular, may have seriously damaged ecosystems sensitive to external changes such as diatoms in aquatic environments or on terrestrial vegetation. On the other hand, these effects are largely confined to local situations and dependent on intensity of precipitation. However, the temporal resolution of most LST archives does not allow us to establish definitively the possible ecological impacts of the eruption as opposed to "regular" natural variability.

Nevertheless, the drop of $\delta^{18}O$ values in the Greenland ice cores suggests that environmental damage in the northern hemisphere due to the Laacher See event may have been on a much larger scale than is indicated by the minor ecological alterations of diverse parameters observed in local limnic archives.

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