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The ELSA tephra stack: Volcanic activity in the Eifel during the last 500,000 years

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ABSTRACT

Tephra layers of individual volcanic eruptions are traced in several cores from Eifel maar lakes, drilled between 1998 and 2014 by the Eifel Laminated Sediment Archive (ELSA). All sediment cores are dated by ^{14}C and tuned to the Greenland interstadial succession. Tephra layers were characterized by the petrographic composition of basement rock fragments, glass shards and characteristic volcanic minerals. 10 marker tephra, including the well-established Laacher See Tephra and Dümpelmaar Tephra can be identified in the cores spanning the last glacial cycle. Older cores down to the beginning of the Elsterian, show numerous tephra sourced from Strombolian and phreatomagmatic eruptions, including the $^{40}Ar/^{39}Ar$ dated differentiated tephra from Glees and Hüttenberg. In total, at least 91 individual tephra can be identified since the onset of the Eifel volcanic activity at about 500,000 b2k, which marks the end of the ELSA tephra stack with 35 Strombolian, 48 phreatomagmatic and 8 tephra layers of evolved magma composition. Many eruptions cluster near timings of the global climate transitions at 140,000, 110,000 and 60,000 b2k. In total, the eruptions show a pattern, which resembles timing of phases of global sea level and continental ice sheet changes, indicating a relation between endogenic and exogenic processes.

1. Introduction

1.1. Regional setting

The West-, Hoch- and East Eifel Volcanic Fields are situated in the western part of the Paleozoic Rhenish Massif (Fig. 1). The basement comprises Devonian sandstones, quartzites, graywackes, limestones, slates and schists, locally unconformally overlain by Triassic sand- and limestones in the West Eifel Volcanic Field. The Rhenish Massif experienced intense Tertiary volcanism, resulting in the formation of the volcanic fields of Westerwald and Siebengebirge East of the Rhine-river and Hocheifel to the West. The magmatic activity was contemporarily accompanied by an episode of uplift in the Eocene, which ceased in the late Miocene. Monogenetic volcanic activity reappeared again in the area of the Quaternary Eifel volcanic fields after 850,000 years before present (Schmincke, 2007). At the same time the Rhenish Massif was subjected to rapid domal uplift, with estimated maximum rates of about 270 m in the central region (Meyer and Stets, 2007). Both Quaternary and Tertiary volcanic fields differ significantly from each other: While the Tertiary field is comprised of sodic magmatism (Fekiacova et al., 2007; Jung et al., 2006), the Quaternary fields are more volatile-rich and potassic in nature (Mertes and Schmincke, 1985; Gluhak and Hofmeister, 2009). The West Eifel Volcanic Field includes ~240 volcanic edifices (scoria cones, tuff-rings, lava flows) including 68 maar-diatreme structures with 1.7 km^3 of total eruptive volume (Büchel and Mertes, 1982). The East Eifel Volcanic Field on the other hand exhibits only 50 volcanic edifices (dominantly scoria-cones, lava-flows and rare maars) but contains 3 larger, evolved caldera complexes of Wehr, Rieden and Laacher See volcano, totalling to 10–20 km^3 of erupted volume (Schmincke, 2007).

1.2. Previously determined phases of volcanic activity

The East Eifel Volcanic Field erupted in four relatively short intervals (each lasting about 20,000 years), beginning at around 450,000 b2k (Schnepp & Hradetzky, 1994, van den Bogaard, 1995b). From 420,000 to 400,000 b2k the Rieden Caldera and surrounding leucititic and nephelinitic scoria-cones were formed (van den Bogaard, 1995b), followed by a period of quiescence until 215,000 b2k, when the Wehr-Kessel erupted the trachytic Hüttenberg tephra (van den Bogaard et al., 1989). The basanitic to tephritic scoria-cones in the Neuwied basin, typically about 120 m high with a basal diameter of 800 m and an eruptive volume of 0.05 km^3 (Houghton and Schmincke, 1989), erupted shortly afterwards as they directly overly this evolved tephra. At 151,000 b2k the Wehr-Kessel erupted the phonolithic Glees tephra (van den Bogaard and Schmincke, 1990a, 1990b), followed by the emplacement of tephritic scoria-cones and lava flows near the villages of Ettringen and Mendig. The eruption sequence in the East Eifel Volcanic Field was completed with the eruption of the 3 km wide caldera

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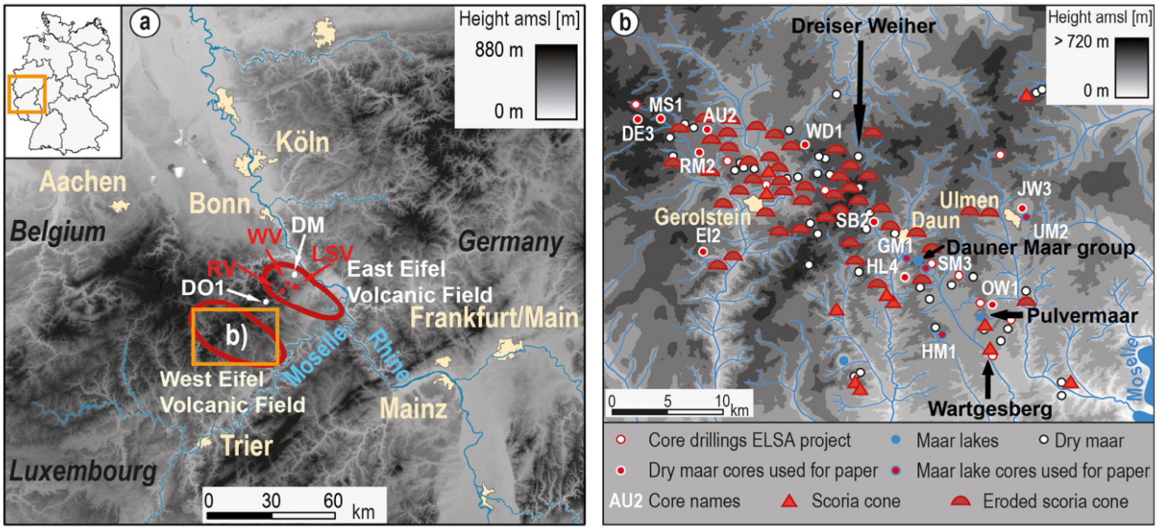


Fig. 1. a) Location of the Quaternary Eifel volcanic fields. b) Detailed view of the West Eifel Volcanic Field showing the locations of the drill-cores used for this paper: Ulmener Maar (UM2), Holzmaar (HM1), Gemündener Maar (GM1), Schalkenmehrener Maar (SM3), Aueler Maar (AU2), Dehner Maar (DE3), Merscheider Maar (MS1), Rother Maar (RM2), Oberwinkler Maar (OW1), Jungferweiher (JW3), Hoher List Maar (HL4), Eigelbach Maar (EI2), Walsdorfer Maar (WD1), Steinborner Maar (SB2) and Döttinger Maar (DO1).

of Laacher See Volcano (Wörner & Schmincke, 1984) at 12,900 b2k (Zolitschka, 1998) emitting 6.3 km^3 phonolithic magma (Schmincke, 2007) and dwarfing all previous eruptions of the Quaternary Eifel volcanic fields.

The eruption history of the West Eifel Volcanic Field is constrained as follows: most leucititic and nephelinitic scoria-cones are smaller in size by an order of magnitude compared to the East Eifel Volcanic Field reaching an average height of 40 m and basal diameter of 430 m (Büchel and Mertes, 1982). These cones are heavily eroded mounds without a preserved crater and were dated to 550,000–440,000 b2k (Schnepp and Hradetzky, 1994, Schnepp, 1996; Singer et al., 2008). A younger phase of activity started ca. 100,000 b2k (Schmincke, 2007) and is characterized by the formation of several foiditic maar volcanoes and large basanitic scoria-cones that reach 100 m height with basal diameters of 600 m. Mertz et al. (2015) published new $^{40}Ar/^{39}Ar$ dates of young West Eifel volcanoes. The lava flows of Wartgesberg, Papenkaule and Bad Bertrich yielded ages of 31,000 ± 11,000 b2k, 32,000 ± 13,000 b2k and 32,000 ± 11,000 b2k respectively. Most maar volcanoes, e.g. Dauner Maar group and Pulvermaar (Fig. 1) are supposed to exhibit younger ages (Büchel, 1993). The youngest volcano of the West Eifel Volcanic Field is the Ulmener Maar, which erupted 11,000 b2k (Zolitschka et al., 1995).

1.3. Tephrochronology of maar lake sediments

50 of the 68 maar structures of the Eifel have been cored since 1998 by the ELSA project, Mainz University. 22 Seilkern drill cores (Fig. 1) of between 10 and 160 m length have been dated by 320 ^{14}C dates (Sirocko et al., 2013) and Greenland ice-core tuning (Sirocko et al., 2016–this volume). The resulting multiproxy age model is used to date tephra layers of MIS 2 and 3 affinity described in this study (Table 1).

In a monogenetic volcanic field, each discrete ash layer is inferred to be linked with a pyroclastic fall derived from an eruption associated with a single volcanic vent that is likely located on a single volcanic edifice (Németh, 2010). However it cannot be excluded that single volcanic edifices may had multiple vents which erupted at times separated by periods of variable duration as demonstrated elsewhere (eg. Martin and Németh, 2005; Kereszturi et al., 2011). Here we treat individual tephra layers as indicative of an individual —"monogenetic"— volcanic event associate with a discrete volcano. Previous studies of

Table 1
Marker-tephra layers in Eifel lake sediments and corresponding ages. Ages in this study are obtained by warve-counting and ice-core tuning.

Tephra	Ages in this study	Method	Ages in literature
Laacher See Tephra (LST)	12,900 b2k	From literature	12,900 b2k (Zolitschka, 1998)
Wartgesberg Tephra (WBT)	27,900 ± 2000 b2k	Ice-core tuning (Sirocko et al., 2016--this volume)	~20,000 b2k (Eltville tephra, Juvigné and Pouclet, 2009), 31,000 b2k (Pirrung et al., 2007), 30,000 b2k (Sirocko et al., 2013) 31,000 ± 11,000 b2k (Mertz et al., 2015)
Unknown Tephra (UT1)	30,200 ± 2000 b2k	Ice-core tuning (Sirocko et al., 2016--this volume)	~28,000 b2k ("Rambach-Wallertheim Tuff", Zöller et al., 1988), 33,000 b2k (Sirocko et al., 2013)
Dreiser Weiher Tephra (DWT)	41,000 ± 2000 b2k	Ice-core tuning (Sirocko et al., 2016--this volume)	41,000 b2k (Sirocko et al., 2013)
Unknown Tephra (UT2)	43,900 ± 2000 b2k	Ice-core tuning (Sirocko et al., 2016--this volume)	45,000 b2k (Sirocko et al., 2013)
Leucite Tephra (LcT)	~60,000 b2k	Sedimentation rates	–
Dümpelmaar Tephra (DMT)	106,000 b2k	From literature	106,000 b2k (Sirocko et al., 2005) 116,000 ± 16,000 b2k (van den Bogaard and Schmincke, 1990a, 1990b)
Unknown Tephra (UT3)	~140,000 b2k	Sedimentation rates	–
Glees Tephra (GlT)	151,000 b2k	From literature	151,000 ± 11,000 b2k (van den Bogaard and Schmincke, 1990a, 1990b)
Hüttenberg Tephra (HBT)	215,000 b2k	From literature	215,000 ± 4000 b2k (van den Bogaard et al., 1989)

widespread tephra-layers in Central Europe examined the prominent tephra from Laacher See at 12,900 b2k and covering >10^6 km^2 (van den Bogaard and Schmincke, 1985), Eltville at 20,000 b2k (Juvigné and Pouclet, 2009) and Rocourt at 74,000–90,000 b2k (Pouclet et al., 2008). The latter two tephra covered parts in the West to South Germany, Luxembourg and Belgium spanning an area up to ~10.000 km^2. These three tephra originated from the Quaternary Eifel volcanic fields. Outcrops in which distal tephra are exposed are rare in the Eifel, as thin layers of ash are rapidly eroded. Fortunately, maar volcanoes create sheltered sedimentary archives for the deposition of tephra layers until the maars are silted up. Therefore the infilled maar craters were systematically drilled during the ELSA project, which follows previous studies of laminated maar sediments (Negendank and Zolitschka, 1993).

2. Methods

2.1. Sampling and processing tephra from drill-cores

Pleistocene sediments of infilling Eifel maar lakes are normally yellowish to brown, and have abundant quartz and clay minerals. Discrete volcanic ashes stand out in these sediments, both because of their grayish to black color and the formation of usually well-defined, >1 cm thick bands of coarser grained material in the silt to fine sand fraction (Sirocko et al., 2005, 2013). Every succession of a tephra was sampled equidistantly over its exposure in the core, achieving an average mineral composition of each eruptive event. For the tephrochronology studies 15 drill cores were analyzed from the following locations: Ulmener Maar (UM2), Holzmaar (HM1), Gemündener Maar (GM1), Schalkenmehrener Maar (SM3), Aueler Maar (AU2), Dehner Maar (DE3), Merscheider Maar (MS1), Rother Maar (RM2), Oberwinkler Maar (OW1), Jungferweiher (JW3), Hoher List Maar (HL4), Eigelbach Maar (EI2), Walsdorfer Maar (WD1), Steinborner Maar (SB2) and Döttinger Maar (DO1) (Fig. 1).

2.2. Sampling of tephra from eruption vents

In addition to the distal tephra layers that are preserved in the maar lake-sediments that have traveled 5–100 km, tephra samples were also collected from proximal deposits between 0.3–1 km from the eruption vents. The debris at the foot of the exposed tuff walls were sampled to achieve an averaged cross-section over the total eruption sequence. Tephra from proximal locations and from sediment cores was sieved to extract the 250–125 μm fraction. This tephra fraction was searched for characteristic grains of reddish and grayish sandstone, quartz, amphibole, pyroxene, scoria, pumice, sanidine, leucite and mica (Fig. 2), using a picking tray and binocular microscope with 20–40× magnification. This particular grain selection was chosen due to its high abundance in the tephra, good ease of recognition, as well as physical and chemical stability. To characterize the tephra layers, a minimum of 100 grains were counted and sorted into their groups. The grain counts are presented as the % abundances of each group and were plotted as bar graphs (Fig. 4). These histograms include the petrographic composition of the eruption site as well as all visible tephra layers in the maar lake sediment cores. The variance of different grain countings is exemplary shown in Fig. 3 whereby the diagram shows variability of the grain-counts of a tephra layer counted four times. The variability is high for country rock fragments, which are to identified by color and grain-shape, but is low for minerals that are very characteristic in appearance i.e. pyroxene, amphibole or leucite. The mostly idiomorphic sanidine crystals show a higher deviation as they are possibly fractionated when they preferentially roll into the picking tray. However this problem was minimized by using a sample divisor. The variance in counting the same tephra layer is below 15%, which is well good enough to be able to discriminate between different ^{14}C dated tephra layers. (See Fig. 5.)

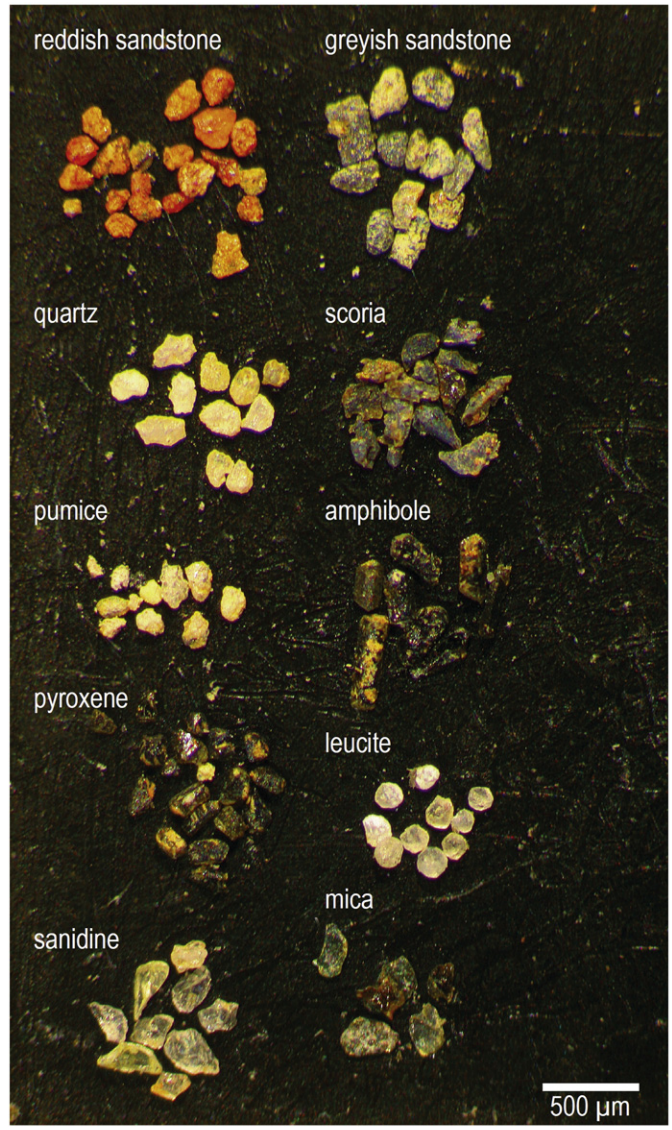


Fig. 2. Grains of the 250–125 μm fraction in tephra layers as seen in the picking tray.

The observed bar-plot pattern is influenced by the magma composition and style of eruption: mafic minerals like amphibole and pyroxene crystalize early in the differentiation series and a high abundance of these minerals is therefore typical of a basic magma composition. Scoria and pumice occur as glassy, vesicular particles, originating from quenched lava fragments. Sanidine is a mineral that is typically associated with evolved magma composition, when it dominates the bar-plot

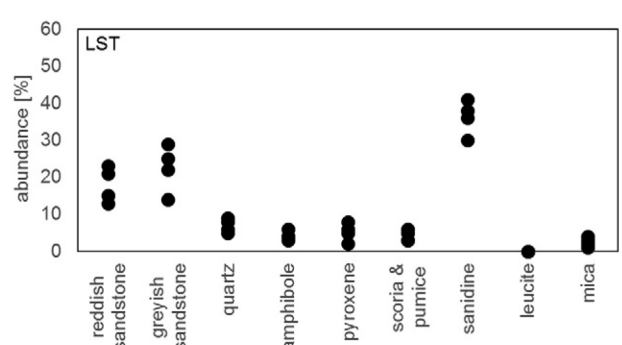


Fig. 3. Variance in grain-ratios after four time counting of the same tephra layer.

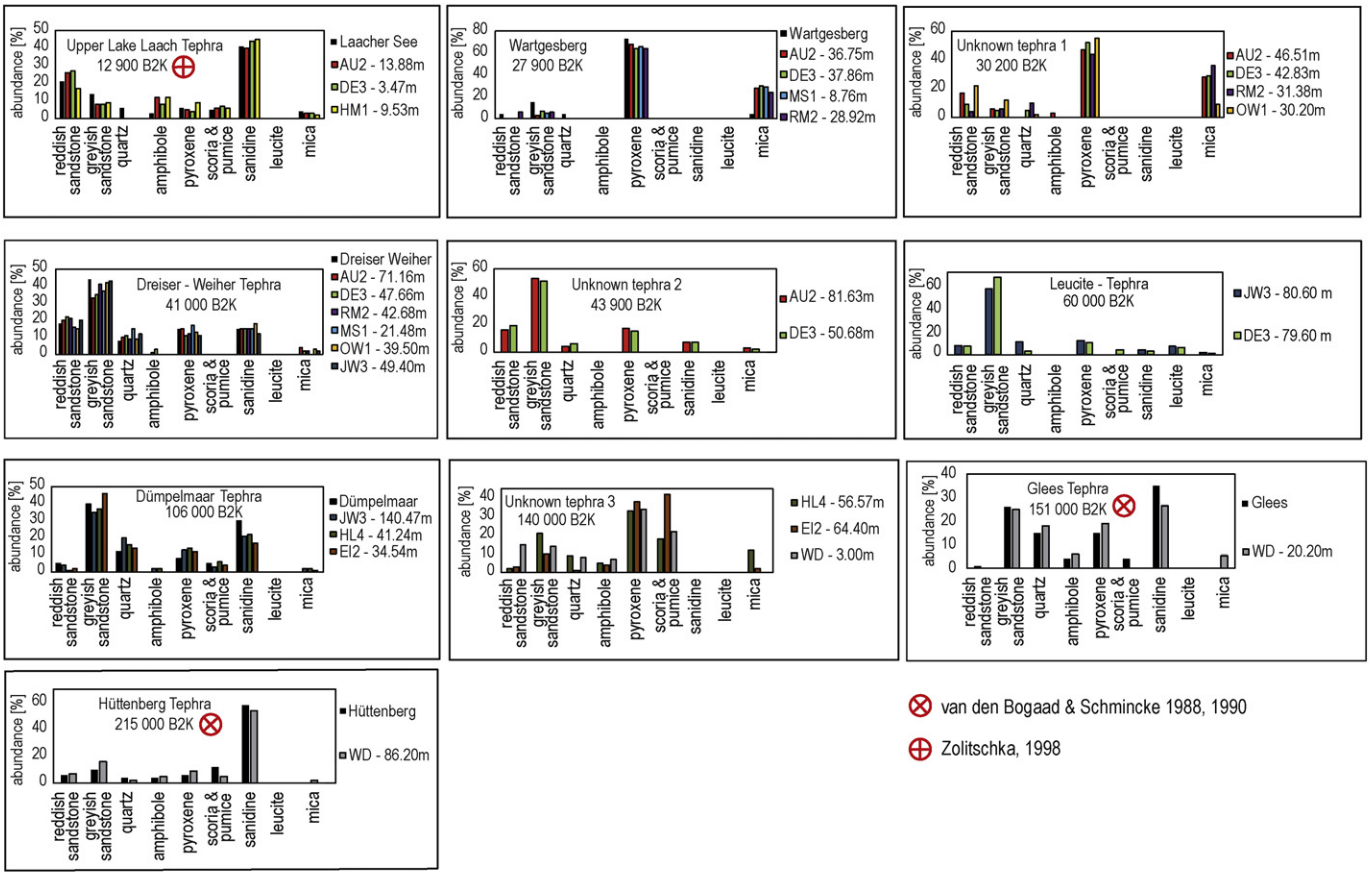


Fig. 4. Grain count ratios of the marker layers from Laacher See, Wartgesberg, Dreiser-Weiher, Dümpelmaar, Glees and Hüttenberg and the layers of unknown origin UT1–UT3. The ages for the marker layers are derived from the literature for the $^{40}Ar/^{39}Ar$ dated sites, the ages for all other cores are from ^{14}C dates and ice core tuning (Sirocko et al., 2013).

pattern. Leucite is a feldspathoid, typically found in potassium-rich magmas such as leucitites or leucite-phonolithes (Schmincke and Mertes, 1979, Mertes and Schmincke, 1985, Wilson and Downes, 1991). Micas typically occur in distal ash layers, as they are concentrated by aeolian-transport whereby heavy minerals drop out. Sandstone was selected because it monitors, together with quartz, important information about the basement and therefore regional position of the eruption vent (Fig. 1).

2.3. Grain count ratios

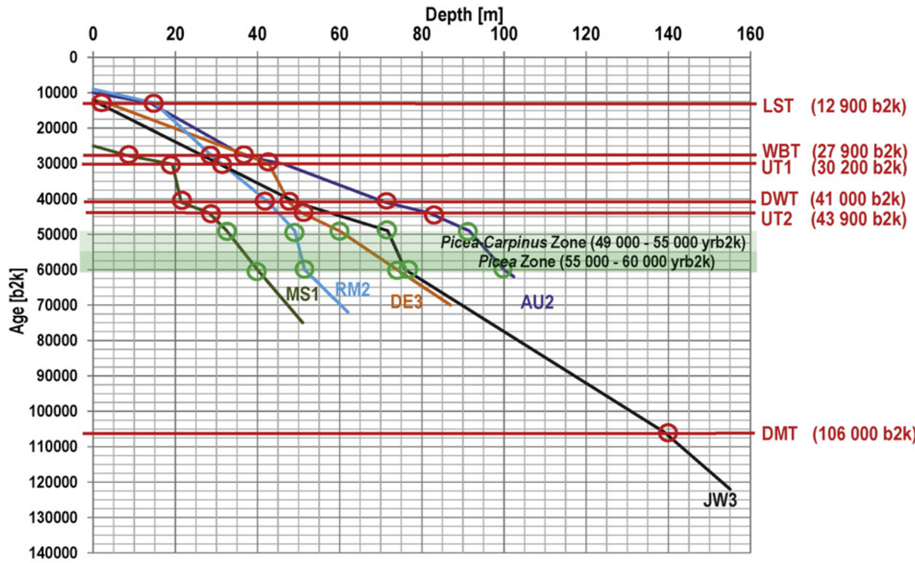
The bar-plot pattern of grain-counts results in three principal groups of tephra:

1. The first group is dominated by sandstone and quartz, which can add up to 90% of the tephra by volume. These tephra layers are well defined and distinctly coarser grained than the laminated lake sediments. They are dominated by angular country rock fragments, excavated by subterranean steam explosions within the growing diatreme of a maar volcano (Lorenz, 1986, 1987; White and Ross, 2011, Valentine and White, 2012, Kereszturi et al., 2013). Magmatic minerals and glassy particles like scoria are reduced to a minimum of 10–30%. This dominance of non-magmatic rock fragments marks this kind of tephra as sourced from phreatomagmatic eruptions. The percentage of reddish to grayish sandstone fragments varies with the geographic position of the diatreme, as the Eifel is dominated by grayish Devonian basement, locally overlain by reddish Triassic sandstone.
2. Tephra layers rich in clinopyroxene and scoria belong to a second group which is sourced from Strombolian activity. The dominance of volcanogenic particles suggests a dry eruption whereby the melt is fractionated by the exsolution of magmatic gases to form vesicular scoriaceous particles (Houghton and Wilson, 1989, Mangan and Cashman, 1996). These dark scoriaceous particles, in combination with the mafic mineralogy suggest a mafic to intermediate magma composition. Typically, scoria-cones erupt this kind of tephra and comprise of a mafic to intermediate magma composition (Schmincke and Mertes, 1979, Mertes and Schmincke, 1985). Country-rock fragments are reduced to less than 20% of the total or are absent. There is also a broad range of transitional tephra, varying between the pure end-members of phreatomagmatic and Strombolian composition. This is not uncommon as scoria cones are known to have an initial phreatomagmatic phase in their early development stage (White and Ross, 2011) as well as destructive phreatomagmatic eruptions, that can occur through the entire history of the volcanic activity (Kereszturi and Németh, 2012).
3. The last group of tephra appears very light in color and is dominated by pumice and sanidine. These grains are erupted from evolved, silicic magma-chambers usually during Plinian eruptions. The mafic content of these magmas is reduced or absent due to fractionation processes which leads to phonolithic magma compositions in the Quaternary Eifel Volcanic Fields (Wörner and Schmincke, 1984).

Beside these three main types, some tephra show certain enrichments of grains of grayish sandstone, pyroxene, sanidine or leucite (Fig. 2).

2.4. Definition of marker tephra

Six tephra layers from the drill-cores were identified as belonging to the eruption centers of Wartgesberg and Dreiser-Weiher, located in the West Eifel Volcanic Field and Laacher See, Dümpelmaar and Wehrer-



Core ID	Depth (m)	Age (b2k)	Material	Fraction
AU2	16.0	17830	Ranunculaea seeds	base residue
	16.0	15080	Ranunculaea seeds	base residue
	16.0	18330	Ranunculaea seeds	base residue
	23.5	17860	Ranunculaea seeds	base residue
JW2/JW3	26.5	34250	Ranunculaea seeds	base residue
	28.5	27920	Ranunculaea seeds	base residue
	30.0	32730	Ranunculaea seeds	base residue
	30.0	32430	Ranunculaea seeds	base residue
	34.5	25430	Ranunculaea seeds	base residue

Fig. 5. Age vs. depth calibration of the cores MS1, RM2, DE3 and AU2. The stratigraphy for these cores was already presented and is now extended by 12 new ^{14}C dates from a zone with ranunculaceae enrichment in the late MIS 3 sections of the cores.

Kessel with Glees- and Hüttenberg tephra, located in the East Eifel Volcanic Field (Fig. 2). Common to all of them is a recognizable pattern of grain types, wide regional distribution of >1000 km^2, and thickness of >2 cm. These three distinctive features are necessary to be able to characterize a tephra layer as a marker layer. The marker tephra identified in this study are visible in the following cores: Holzmaar (HM1) contains the Laacher See ash layer. Dehner Maar (DE3) and Aueler Maar (AU2) contain the Laacher See, Wartgesberg and Dreiser-Weiher ash layers. The Rother (RM2) and Merscheider Maar (MS1) contain the Wartgesberg and Dreiser-Weiher ash layers. Jungferweiher (JW3) and Dehner Maar (DE3) also contain a leucite bearing tephra. The Dümpelmaar tephra is found in the cores of Jungferweiher (JW3), Eigelbach Maar (EI2) and Hoher List Maar (HL4). The Walsdorfer Maar (WD1) core contains the Glees- and Hüttenberg tephra that originated in the Wehr volcano (Fig. 1). In addition, the drill-cores are also connected by 3 marker-layers that lack a specific eruption center but also show characteristic distributions. These marker-layers of unknown origin are denoted as UT1-3.

2.5. The tephrochronologic “bar code”

In addition to visible marker tephra layers, maar lake drill-cores can also be correlated by identification of successions of tephra. This is most clearly seen by comparison of the JW3 (Jungferweiher) and EI2 (Eigelbach) drill-cores sequences (Fig. 1). Both cores exhibit a succession that starts with an evolved tephra layer, followed by five phreatomagmatic tephra layers and end with a Strombolian ash (Fig. 6). This succession lies at a depth of 124.50 m–139.10 m at Jungferweiher and 23.76 m–34.54 m at Eigelbach Maar and allows, in combination with the ages of the geochemical distinct sanidine-rich phonolithic Dümpelmaar tephra at the basis of this succession, a robust correlation of these cores.

3. Discussion

3.1. Correlation of the drill-cores

UM2, HM1, GM1 and SM3 are the youngest drill-cores of largely Holocene MIS 1 age, covering the time interval from 15,000 b2k until present. AU2, DE3, MS1, RM2 and OW1 cover MIS 2-4, starting around 60,000 b2k and are connected to the Holocene cores by the Laacher See Tephra which is visible in each of these cores (Fig. 6). However MS1, RM2 and OW1 were silted up rapidly at the Last Glacial Maximum and are ending around 20,000 b2k. These cores are connected by the thick Wartgesberg and Dreiser-Weiher tephra layers that appear in each. The 150 m long JW3 core extends from 130,000 b2k to 30,000 b2k when the maar lake infilled, thus covering MIS 2-5. JW3 contains the Dreiser-Weiher Tephra in its upper part and the Dümpelmaar Tephra near the base of the core (Fig. 6). The Dümpelmaar Tephra was already identified in cores HL4 and EI2 and geochemically correlated by micro X-ray spectroscopy to the cores JW3, HL4 and EI2 (Sirocko et al., 2013). The HL4 core spans from 140,000 b2k to 95,000 b2k, whereas

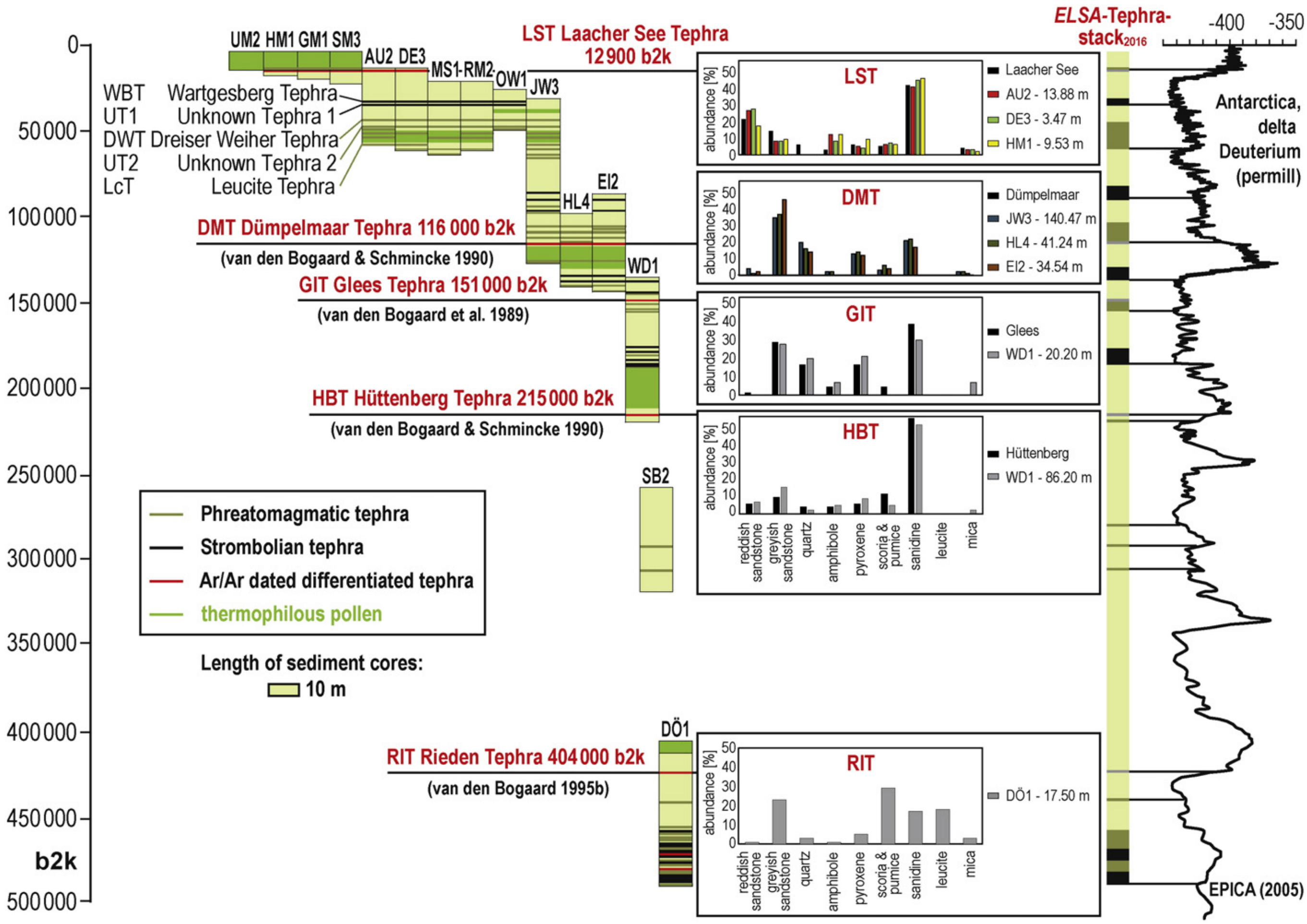


Fig. 6. The tephrochronology of the Eifel Volcanic Fields showing all correlated drill-cores and their tephra layers. Evolved marker layers are highlighted in red with corresponding $^{40}Ar/^{39}Ar$-ages. All tephra layers are combined in the ELSA-Tephra-Stack on the right. The beginning of each eruption cluster is projected on the EPICA (Lisiecki and Raymo, 2005) stack.

EI2 sediment covers from 145,000 b2k to 85,000 b2k, thus belonging to MIS 5 and end of 6 (Sirocko et al., 2005). Both cores contain an amphibole-rich Strombolian-type tephra near their base, which is also found in the uppermost part of the WD1 core. WD1 contains the Glees Tephra at the top, and the Hüttenberg Tephra at the base of its succession. Thus, the WD1 core spans from 220,000 b2k at its base to 140,000 b2k at the top of the sequence, covering the complete MIS 6 and much of MIS 7 (Fig. 6).

The SB2 core lacks tephra layers and is considered to span a period of volcanic quiescence that lasted from 400,000 to 220,000 b2k. It is filled with glacial-stage sediments and therefore fits to the MIS stages 8 or 10. The Döttinger Maar (DO1) succession, palynologically dated to the Holsteinian/Elsterian-stage (Diehl and Sirocko, 2007), contains a leucite and sanidine bearing evolved tephra layer at a depth of 17.50–18.70 m. This tephra layer has a thickness of 1.20 m, and most likely originated from a voluminous volcanic event nearby. The Rieden caldera is the only evolved volcano near the Döttinger Maar, located only at 10 km distance and therefore the only possible source for this thick tephra layer. The lower 30 m of the Döttingen-core contains 44 Strombolian and phreatomagmatic eruption origin-type tephra layers, with 3 phreatomagmatic-type tephra layers containing significant amounts of reddish sandstone and therefore originating in the West Eifel Volcanic Field, where flat lying Triassic reddish sandstones unconformably overlies the grayish slates and sandstones of the metamorphic Devonian basement. If these 44 tephra belong to the first eruption phase of the West and East Eifel Volcanic Fields, lasting from 850 to 400,000 b2k (Schnepp and Hradetzky, 1994, van den Bogaard, 1995b; Schnepp, 1996; Singer et al., 2008), then the DO1 succession has its top at ~400,000 b2k and base at ~500,000 b2k (Fig. 6). Accordingly, this aligns the Holsteinian to MIS 11 and the Elsterian to MIS 12.

3.2. The eruption history of the Eifel

The oldest eruption series from the Eifel Volcanic Fields dates from 550,000 b2k until 400,000 b2k (van den Bogaard and Schmincke, 1990a, 1990b, Schnepp and Hradetzky, 1994, van den Bogaard, 1995b; Schnepp, 1996; Singer et al., 2008) and were found in the DO1 drill-core (Fig. 6). From 400,000 b2k until 100,000 b2k a proposed hiatus (Schmincke, 2007) in volcanic activity is in accord with the lack of tephra layers in the SB2 sequence. However, volcanism in the West Eifel resumed with the formation of the Walsdorf maar at ~220,000 b2k, as its sediment infill starts at the beginning of the MIS 7. This eruption was followed by the ejection of the Hüttenberg tephra at 215,000 b2k from the Wehr Volcano in the East Eifel Volcanic Field (van den Bogaard et al., 1989). Here it is proposed, that the cluster of Strombolian-type tephra layers from 200,000 to 180,000 b2k in the WD1 succession belong to basanitic to tephritic scoria cones of the East Eifel Volcanic Field as their eruptions are dated by $^{40}Ar/^{39}Ar$ close to 200,000 b2k (van den Bogaard, 1995b). From 180,000 to 155,000 b2k no ash layer is recognized in WD1 for this time interval. The Glees tephra was ejected by a second eruption of the Wehr volcano and was $^{40}Ar/^{39}Ar$ dated to 151,000 b2k by van den Bogaard and Schmincke (1990a, 1990b) and is clearly visible in WD1 at 20.20 m depth. This tephra is preceded by phreatomagmatic-type tephra layers at 155,000 b2k and followed by

Strombolian-type layers until 135,000 b2k (Fig. 6). According to the tephra succession in our cores, the Jungferweiher maar erupted close to 130,000 b2k and followed the eruptions of Eigelbach and Hoher-List maars. These events preceded a large cluster of maar eruptions from 115,000 to 100,000 b2k early in the last glacial cycle (Fig. 6). The Dümpelmaar erupted in the East Eifel Volcanic Field at 106,000 b2k (Sirocko et al., 2005) or 116,000 ± 16,000 b2k (van den Bogaard and Schmincke, 1990a, 1990b). The cluster of maar eruptions was closely followed by the eruption of three Strombolian-type tephra layers at 95,000, 90,000 and 85,000 b2k. The 90,000–74,000 b2k Rocourt tephra fits to this time period (Pouclet et al., 2008) and is most likely represented by one of these mafic, Strombolian-type tephra layers. From 85,000 b2k until 60,000 b2k volcanic activity paused, as no tephra layer is recognized during this time period. From 60,000 b2k until 27,900 b2k a second cluster of phreatomagmatic-type tephra layers documents a period of intense maar formation. During this time the maars of Dehner, Auel, Merscheid, Roth, Oberwinkel, Daun, Dreiser-Weiher, Meerfeld, Mosbruch and the maar volcanoes around Gillenfeld were formed. This cluster was followed by the eruption of the scoria cones of Wartgesberg that erupted at 27,900 b2k. The Papenkaule-group near Gerolstein and Bad Bertrich-group also erupted at this stage, as they are dated to 32,000 ± 11,000 and 32,000 ± 13,000 b2k by Mertz et al. (2015). The "Rambach-Wallertheim Tuff" was dated by Zöller et al. (1988) to ~28,000 b2k and possible represents the Wartgesberg tephra. The 20,000 b2k Eltville tephra (Juvigné and Pouclet, 2009) was not identified in all young maar-lake sediments, possibly a consequence of the prevaling westerly winds (Kasperski, 2002). However, there is also a possibility that the Wartgesberg tephra resembles the Eltville tephra, but that would shift their age from 20,000 to 27,900 b2k (tab. 1). Then the "Rambach-Wallertheim Tuff" may be represented by Unknown Tephra 1 (UT1) at 30,200 b2k and both tephra layers are preserved in the maar drill-cores but are older than previously dated. From 27,900 b2k onwards, the volcanic activity paused again, only interrupted by the eruption of the Ulmener Maar at 11,000 b2k (Zolitschka et al., 1995) and the huge eruption of Laacher See Volcano at 12,900 b2k (Zolitschka, 1998) in the East Eifel Volcanic Field. The Laacher See eruption is visible as a 5–20 cm gray, pumice-rich layer in the cores HM1, GM1, RM1, SM3, DE3 and AU2.

4. Episodic vs. continuous volcanism in the quaternary Eifel volcanic fields: conclusions from the ELSA-tephra-stack

The tephra layers encountered in Eifel maar lake sediments suggest a strongly episodic, volcanic activity with long dormant intervals. Németh (2010) showed that prolonged activity is typical for monogenetic volcanic fields, while individual eruptions are smaller in volume compared to polygenetic volcanoes but numerous over the entire life time of the field. By analyzing the tephra-fall record in the Eifel maar sediment cores a strong clustering of eruption events is apparent from 550,000 to 400,000 b2k in the West and East Eifel Volcanic Field, 215 to 180,000 b2k, 151 to 130,000 b2k and 12,900 b2k in the East Eifel Volcanic Field and from 140 to 130,000 b2k, 110 to 80,000 b2k and 60 to 27,900 b2k in the West Eifel Volcanic Field. There is no evidence for volcanism in the West Eifel Volcanic Field between 27,900 b2k and 11,000 b2k, so that all maars with the exception of the 11,000 b2k Ulmener Maar are older than previously described. Phases of young, intense phreatomagmatic activity in the West Eifel Volcanic Field were concentrated in three episodes starting at 140,000, 110,000 and 60,000 b2k. The volcanism is most intense in times of climate change prior and after interglacials, but seems to be nearly absent during glacial maximas and interglacials (Fig. 6). However, thin tephra layers (crypto tephra) could also be masked by minor bioturbation effects and mixing, which are most intense in shallow maar lakes just before they are infilled by sediment and lack anoxic bottom waters. Furthermore, slumping processes of the steep inner slopes can cause the complete erosion of a tephra layer and their re-deposition mixed with lake-sediments in a deeper part of the maar-lake. A volcanic eruption adjacent to an open maar lake may cause significant changes to the lake sediments by intensive slumps, triggered by volcanic earthquakes or base surges. However, studying different maar lake sediment sequences that cover the same time intervals minimize these disturbing effects as the tephra layers were multiply deposited.

Fig. 6, demonstrates the remarkable clustering of tephra layers to times of significant climatic change. A relation between volcanism and global sea level and ice sheet dynamics can therefore be confirmed, a connection which was earlier proposed by van den Bogaard and Schmincke (1990a, 1990b) and Nowell et al. (2006). Future work will resolve paleo wind-directions in mid-Europe by comparing thicknesses and grain size distributions of the tephra layers in the maar lake sediment records. Also, thin tephra layers of <1 cm thickness will be investigated to resolve the complete eruption history of the Eifel Volcanic Fields.

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Appendix A. Supplementary data

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