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ORIGINAL PAPER

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Gigantic volcanic eruptions and climatic change in the early Eocene

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Abstract 23 layers of altered volcanic ash (bentonites) originating from the North Atlantic Igneous Province have been recorded in early Eocene deposits of the Austrian Alps, about 1,900 km away from the source area. The Austrian bentonites are distal equivalents of the "main ash-phase" in Denmark and the North Sea basin. We have calculated the total eruption volume of this series as 21,000 km^3, which occurred in 600,000 years. The most powerful single eruption of this series took place 54.0 million years ago (Ma) and ejected ca. 1,200 km^3 of ash material, which makes it one of the largest basaltic pyroclastic eruptions in geological history. The clustering of eruptions must have significantly affected the incoming solar radiation in the early Eocene by the continuous production of stratospheric dust and aerosol clouds. This hypothesis is corroborated by oxygen isotope values, which indicate a global decrease of sea surface temperatures between 1 and 2°C during this major phase of explosive volcanism.

Keywords Early Eocene · Austria · Northern Atlantic · Volcanic eruptions · Climatic change

Introduction

The North Atlantic Igneous Province (NAIP), which is one of the largest basaltic lava accumulations on Earth, formed in the early Paleogene (62–53 Ma), prior to and during the continental break-up between Europe and Greenland (Eldholm and Grue 1994; Ritchie and Hitchen 1996; Ross et al. 2005). Beside voluminous flood basalts and associated igneous intrusions, it produced widespread pyroclastic deposits. From the early Eocene Fur Formation in Denmark more than 200 ash-layers of predominantly basaltic composition have been recorded from this explosive volcanic activity (Knox and Morton 1988; Heister et al. 2001). A numbering system for most of these layers was introduced by Bøggild (1918) and is still in use: the upper, closely spaced layers constitute the "positive series," with layers numbered +1 to +140 in ascending order. The lower, more widely spaced and generally thinner layers make up the "negative series," and are numbered -1 to -39 in descending order.

The paroxysm of this volcanic activity, the positive ash–series, consists of tholeiitic ferrobasaltic layers with the exception of layer +19. In the immobile element diagram of Winchester and Floyd (1977) this layer plots at the border between trachyte and trachyandesite, whereas more detailed geochemical investigations indicate a rhyolitic composition of the original magma (Huber et al. 2003; Larsen et al. 2003). Some of the ashes of the positive series have also been found at many other sites in Denmark, the North Sea, England, the Goban Spur Southwest of Ireland, and the Bay of Biscay (Knox 1984). Based on detailed multistratigraphic and geochemical investigations, the most distal equivalents of layer +19 and 22 other layers have been identified in the Anthering and Untersberg outcrops (Fig. 1) of the Austrian Alps near Salzburg (Egger et al. 2000, 2005; Huber et al. 2003). These correlations were a prerequisite for the calculation of the eruption volumes.

It can be assumed that the ash-layers of the NAIP form important correlation horizons for lower Eocene deposits in large areas of Europe. In addition to the Austrian outcrops, reports of lower Eocene basaltic ash layers exist from Switzerland and Poland (Winkler et al. 1985; Waskowska-Oliwa and Lesniak 2002), although stratigraphic and geochemical information from these deposits is insufficient for a detailed correlation. Consequently, these ash layers have not been taken into consideration for our calculation.

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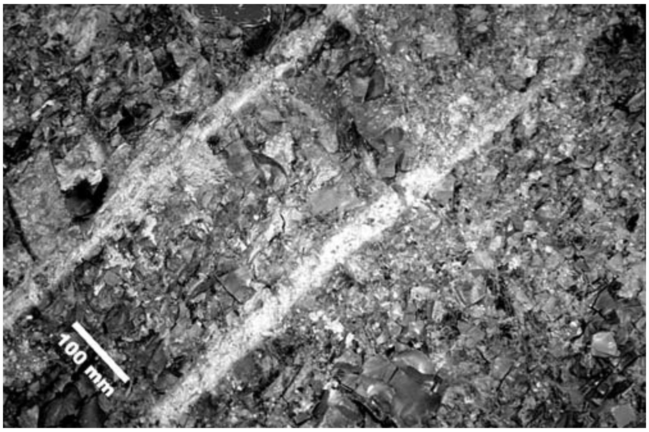

Fig. 1 Layer +19 (the *white layer* to the right of the scale) at the base of the bentonite series at Anthering (Salzburg, Austria)

The wide dispersal distance of the NAIP-ashes implies powerful phreatomagmatic eruptions, which supplied large volumes of pyroclastic material and volatile gases to the troposphere and stratosphere. In this study, we present the first calculations of the exceptional volumes of these early Eocene eruptions and we discuss the climate forcing effects of this major phase of explosive volcanism, which coincides with a short period of global climate cooling.

The magnitude of the early Eocene eruptions

The above-mentioned correlation of an ash-layer of the Austrian Alps with layer +19 at Fur and Goban Spur was the prerequisite for the calculation of the volume of this ash–fall. Layer +19 is between 2 and 3 cm thick at Goban Spur (Knox 1985) and the two Austrian sections (Egger et al. 2000, 2005) and about 20 cm thick at Fur (Andersen 1937). Using these data and a paleogeographic reconstruction of these sites, the total ash-volume has been calculated by the empirical method of Pyle (1989, 1999). Following Pyle (1999) the tephra thickness $T(A)$ at an isopach of the area A is given by the following exponential decay law:

$$T(A) = T0 \cdot e^{-k\sqrt{A}}, \quad (1)$$

where $T0$ is the ash thickness at the source location and k is the decay constant. From Eq. 1 relations for the total tephra volume V (2), the area A of the isopach with the tephra thickness $T(A)$ (3), and an estimate of the minimum total tephra volume V_{MIN}, in case tephra thickness $T1$ is only given for one isopach $A1$ and the decay constant cannot be determined (4).

$$V = \frac{2}{k^2}\, T0 \quad (2)$$

$$A = \frac{V}{2 \cdot T0} \cdot \left\{ \mathrm{In}\left(\frac{T(A)}{T0}\right) \right\}^2 \quad (3)$$

$$V_{\mathrm{MIN}} = \frac{e^2}{2} \cdot A1 \cdot T1 \approx 3.7 \cdot A1 \cdot T1. \quad (4)$$

Following the standard procedure introduced by Pyle (1999) we choose elliptical isopachs. This is a major uncertainty in the following calculation as our data cover only 25% of the total azimuth range of possible tephra transport and elliptical shape of isopachs is not proofed for 75% of the total azimuthal coverage. Deviation from the elliptical shape in this area would cause much higher errors than the +/− 10%, which can be expected in case the assumption of elliptical isopachs is true.

The shape of the isopachs may be arbitrary. We choose elliptical isopachs with the magmatic source lying at one focus (Fig. 2). The position of this source within the NAIP, and the eccentricity and the orientation of the isopachs have been determined from the available thickness data for layer +19 (Table 1). This suggests a source position at the latitude of the later Iceland which is consistent with geochemical and geodynamic considerations concerning the derivation of the magma (Larsen et al. 2003). The parameters $T0 = 1.124$ m and $k = 1/737$ km^{-1} have been estimated by fitting Eq. 1 to the tephra thickness and isopach area data. With Eq. 2 and our estimates of $T0$ and k we calculated the total ejecta volume of layer +19 as $V = 1{,}219$ km^3. From Eq. 3 follows, that an ash blanket at least 5 mm thickness covered an area of 16×10^6 km^2 (about 3% of the Earth's surface). Grain size data for ash +19 are too sparse to be used as an additional input into the eruption volume calculation. Nevertheless, the available grain size data are in accordance with the expected similar exponential decay of maximum grain size and tephra thickness (Pedersen and Surlyk 1983; Nielsen and Heilmann-Clausen 1988).

The total ash volume of about 1,200 km^3 makes the +19 events one of the largest known eruptions in geological history. Even in the case that the isopachs extend less to the NW than the assumed ellipses, the volume of the eruption would be about 1,000 km^3. Super eruptions, with more than 1,000 km^3 of ejecta, form the highest rank (VEI = 8) in the volcanic explosivity index (Rampino 2002; Newhall and Self 1982). Including the +19 ash, a total of 48 such events, ranging in age from Ordovician to Pleistocene, are identified, of which 42 eruptions are known from the past 36 Ma (see Mason et al. 2004, for a review). The truly gigantic volume of this material can be appraised from the fact that the largest eruption in historic times (Tambora, Indonesia in 1815) ejected "only" 150 km^3 and that the dense rock equivalent of the spectacular 1980 Mt. St. Helens eruption (USA) has been estimated as 0.2 km^3 (Huff et al. 1992; Simkin and Siebert 1994).

A major problem with the VEI scale is that it is based on estimated bulk volumes and takes no account of the deposit density. This is significant since the density of freshly emplaced tephra may vary by a factor of three (Pyle 1999). This makes the comparison of eruption magnitudes difficult. In our case, however, an overload

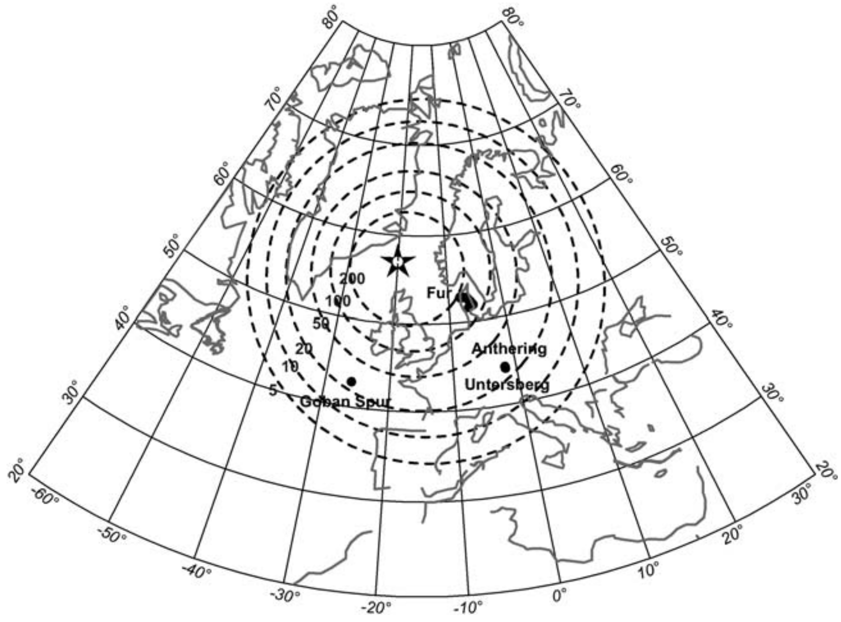

Fig. 2 Map showing the plate tectonic situation at 54 Ma (rotated present day *shore lines*), the rotated locations where layer +19 has been found (*solid spheres* and locality names), and elliptical isopachs of layer +19 (*gray contours*, tephra thickness in mm) with the assumed NAIP-source (*star*) at one focus. The plate movements have been calculated relative to a magnetic frame (Harrison and Lindh 1982) using the ODSN Plate Tectonic Reconstruction Service (http://www.odsn.de/odsn/services/paleomap/paleomap.html)

Table 1 The +19 ash layer: localities, present day and paleo-geographic coordinates, thicknesses (T) and square roots of the isopach areas ($A^{0.5}$)

Location	Present coordinates		Paleo-coordinates		$A^{0.5}$ (km)	T (mm)
	Longitude (°)	Latitude (°)	Longitude (°)	Latitude (°)		
Fur	8.6	56.9	-7.8	52.8	1,330	180
Fur	8.7	56.8	-7.7	52.8	1,338	190
Fur	8.9	56.9	-7.6	52.9	1,338	150
Fur	8.9	56.9	-7.6	52.9	1,338	180
Fur	9.0	56.8	-7.4	52.8	1,363	160
Fur	9.2	56.8	-7.3	52.8	1,371	150
Fur	9.9	56.7	-6.6	52.8	1,430	130
Fur	10.1	56.5	-6.4	52.6	1,464	150
Fur	10.1	56.4	-6.4	52.5	1,473	160
Fur	10.5	56.1	-5.9	52.2	1,541	150
Fur	10.8	55.7	-5.5	51.9	1,602	200
Fur	9.8	55.5	-6.4	51.6	1,557	170
Anthering	13.0	47.9	-1.7	44.4	2,761	25
Untersberg	13.0	47.7	-1.7	44.2	2,788	25
Goban Spur	−13.4	48.5	-25.9	42.9	2,778	25

of at least 1 km thick glaciers should have consolidated the ash layers during the Pleistocene. Consequently, it can be assumed that our calculated bulk volumes are almost identical with the dense rock equivalents.

Inserting average values of thickness $T1$ and isopach area $A1$ for the Fur locations into Eq. 4 results in $V_{\mathrm{MIN}} \sim V$. Based on this result, the magnitudes of the smaller NAIP-eruptions in Austria and Denmark have been assessed assuming that the ash volumes of the individual eruptions are proportional to the ash thicknesses at one location. The next largest events in the Austrian Eocene record are two ashes showing individual thicknesses of 10 mm, indicating eruptions with volumes of about 500 km^3. Most of the Austrian ashes display thicknesses of between 2 and 3 mm, indicative of eruption sizes of ca. 120 km^3. Thus all the Austrian bentonites were produced by enormous eruptions, with a VEI rank between seven and eight. Altogether, the 23 Austrian ash-layers represent a total eruption volume of about 5,000 km^3.

The Austrian ash-layers were deposited ca. 1,900 km away from the magmatic source and represent the more powerful and voluminous eruptions of the NAIP. According to the paleogeographic reconstruction, the distance between Fur and the magmatic source was only 970 km and, therefore, smaller eruptions than in Austria have been also recorded there. The thinnest of the numbered 121 layers at Fur are 10 mm thick and represent eruptions with volumes of ca. 60 km^3. The aggregate ash-thickness of the main ash-phase at Fur is 3.5 m, and thus a total eruption volume of 21,000 km^3 can be estimated. The exceptional magnitude of these eruptions indicates an extremely high magma production, which probably occurred in very shallow water depths, leading to violent explosions by the interaction of magma and water (Waagstein and Heilmann-Clausen 1995).

The periodicity of the early Eocene eruptions

For the Danish +19 ash a laser total-fusion $^{40}Ar/^{39}Ar$ age of 54.04 ± 0.14 Ma has been reported and, by the same method, the age of the older -17 ash has been determined as 54.52 ± 0.05 Ma (Chambers et al. 2003). Within this episode of 0.5 million years 0.5 m of volcanic ash and 19.5 m of diatomite were deposited (Bøggild 1918). This suggests an average sedimentation rate of diatomite of 39 mm ky^{-1}. The whole positive ash-series is 27.0 m thick and contains 3.5 m of volcanic ejecta (Pedersen and Surlyk 1983; Larsen et al. 2003). Assuming the same sedimentation rate for the 23.5 m of diatomite indicates that the positive ash-phase was deposited within c. 600,000 years.

On the base of this estimate, the mean periodicity of the more powerful eruptions (volumes > 100 km^3) of the NAIP, which are recorded in the Austrian ash-series, can be assessed as c. 26,000 years. During the same period, in Denmark 140 ash layers were deposited suggesting a mean periodicity of c. 4,300 years. The thinnest of these layers are 1 mm thick, which according to our model represent eruption volumes of about 6 km^3.

Climatic forcing of the early Eocene eruptions

Large explosive eruptions have been proposed as a triggering mechanism for global climate cooling, mainly as a result of the formation of stratospheric dust and aerosols that backscatter short-wave solar radiation (Chesner et al. 1991; Rampino and Self 1992). Estimates of paleotemperatures can be derived from oxygen-isotope ratios of foraminifera tests, where increasing $\delta^{18}O$ values correspond to decreasing temperatures. The oxygen isotope values of the Austrian sections display a strong diagenetic overprint and therefore cannot be used for paleotemperature estimations. For this reason, we have compiled data from DSDP Hole 550 at Goban Spur where the +19 ashes have been identified (Knox 1984; Aubry et al. 1996; Stott et al. 1996). There, an average increase in $\delta^{18}O$ values of 0.25‰ suggests about 1–2°C climate cooling, coincident with the major phase of explosive volcanic activity in the NAIP. The global oxygen isotope record (Zachos et al. 2001) indicates that this cooling event happened on a world-wide scale and was antagonistic to the Late Paleocene—to Early Eocene warming trend (Fig. 3).

Discussion and conclusions

Within the last 250 million years, only about ten flood-basalt episodes occurred on a world-wide scale, each of them producing lava volumes exceeding a million cubic kilometer (Rampino and Stothers 1988). Mafic volcaniclastic deposits are known to exist in many continental flood basalt provinces (see Ross et al. 2005 for a review). The generation of explosive eruptions of basaltic magmas requires either an explosive interaction of lavas and incoming water or magma with high primary volatile concentrations and unusually high temperatures (Pedersen and Jorgensen 1981). Specific intrinsic features of the NAIP magmas are suggested by the unusually high iridium concentrations (200–400 ppt) in the ashes; such values lie in the upper end of the concentration range reported for basaltic rocks (Schmitz and Asaro 1996; Huber et al. 2003). This might indicate that the volcanism was related to magmas derived from

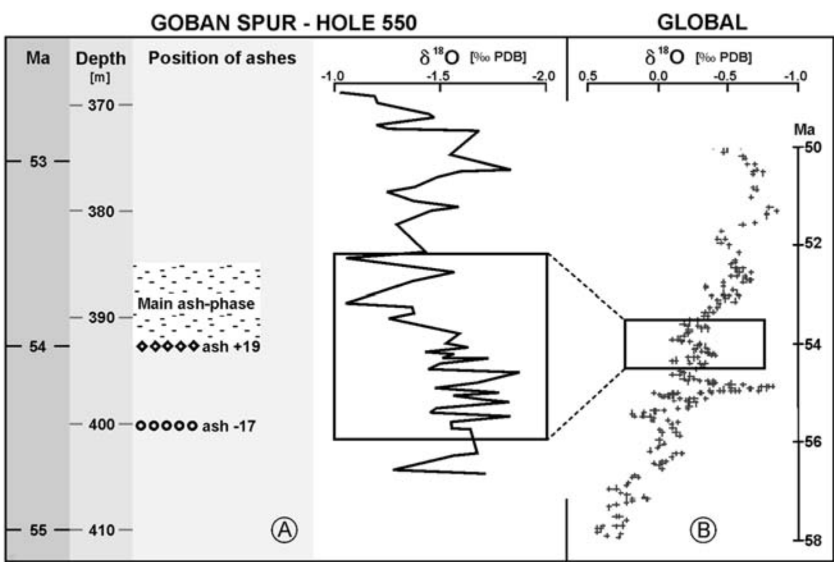

Fig. 3 *a* The temporal relationship of an increase in oxygen isotope values (Stott et al. 1996) and the main ash-phase in DSDP Hole 550 (Aubry et al. 1996) at Goban Spur. *b* Correlating isotope data from Hole 550 with the global oxygen isotope curve (Zachos et al. 2001). There is a difference in the scale of the isotope curves because for *a* planktic foraminifera have been analyzed whereas for *b* benthic taxa have been used. Note the increase in oxygen isotope values at 54 Ma. *PDB* Peedee belemnite

atypically large depths in the mantle (Fenner and Presley 1984; Elliott et al. 1992). In the NAIP, huge subaerial flood basalts and single ash-layers with high iridium concentrations already were deposited prior to the formation of the main ash-series. This indicates that the switch from effusive to explosive eruptions was not a matter of the magma composition but of a move of the magmatic source from the continent into the sea-covered opening rift of the developing Atlantic Ocean (Larsen et al. 2003; Schmitz et al. 2004). The data presented in this paper indicate that this occurrence of flood basalt volcanism in a shallow marine environment produced one of the most voluminous basaltic ash-series known on Earth.

The apparent synchroneity of this major phase of explosive volcanism with an episode of climate cooling suggests that there could be a causal link between explosive volcanic activity and global cooling. Due to the short-lived nature of volcano-induced stratospheric clouds, the long-term effects on global climate have been considered rather ephemeral (Lee et al. 2004). For example, the basaltic Laki eruption in southern Iceland in 1783 and 1784 ejected about 0.4 km^3 of ash material and caused a 1–2°C decrease in the mean northern hemisphere temperatures for three years (Thodarson and Self 1993). The NAIP-eruptions of less than 6 km^3 would not have been recorded at Fur but it can be assumed that the number of such eruptions was higher than those of the gigantic eruptions by several orders of magnitude. It has been predicted that even super eruptions of more than 1,000 km^3 of ash material and more than 1,000 million tons sulfur-rich gases, the precursors for sulfuric acid aerosols, may cause a cooling of Earth's global climate by 3–5°C for only a few years (Rampino 2002). However, it can be assumed that the long-term climate forcing effects of such a super eruption can be prolonged significantly by the continuous production of stratospheric dust and aerosol clouds from subsequent smaller eruptions of high frequency. We conclude that the climatic deterioration in the early Eocene was an effect of both, the unusual magnitude and the high frequency of eruptions, which caused a sustained stratospheric aerosol loading over a period of almost 0.6 million years.

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