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A new model for the fracture energy budget of phreatomagmatic explosions

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Abstract

The fragmentation of magma and of the hosting country rocks is a major process in explosive eruptions. It is important to quantify the mechanical energy needed for fragmentation in order to assess the physical processes of this volcanic phenomenon. This paper presents a method to calculate the fragmentation energy of country rock using granulometry data of a typical phreatomagmatic Eifel maar volcano explosion. The total fracture area of country rock fragments in one tephra layer was quantified and related to the critical fragmentation energy of these country rocks. The rock parameters critical shear stress and critical fragmentation energy were determined experimentally, whereas the pre-volcanic crack inventory was measured in the field. The paper concludes with the calculation of the energy balance (i.e. partitioning of thermal energy into kinetical energy and mechanical energy of the fragmentation) of one Eifel maar volcanic explosion.

Keywords: fragmentation; shear stress; shear strain; phreatomagmatic explosion; partitioning of energy

1. Introduction

Explosive volcanic eruptions, which release large quantities of mechanical energy in a short time period, produce large amounts of fine-grained pyroclasts (volcanic ash). Many of these eruptions are caused by the interaction of magma with groundwater and are called phreatomagmatic explosions. Pyroclasts consist of two types: (1) the fragmented magma (i.e. juvenile ashes), and (2) lithic clasts from country rocks which can make up to 90% by volume in the case of maar volcanoes (Zimanowski, 1998). Strictly speaking, an explosion results from an intensive reaction, which causes a violent expansion of a system in a surrounding medium in such a way that the mechanical limits of the surrounding medium are exceeded, i.e. the expansion velocity exceeds the speed of sound of the medium within which the expansion takes place. A phreatomagmatic explosion is defined as a short time event (timescale milliseconds) with some qualities of a detonation (i.e. supersonic character of an explosion). The thermal energy of the involved magma is converted at local rates exceeding 60% into elastic waves (seismic waves), which have the potential to disrupt surrounding magma and/or country

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rock by exceeding the critical stresses and resulting in a brittle failure of these. Usually the deposits of this kind of explosions are marked by a high content of fragmented lithics.

Quantification of the mechanical energy needed for the fragmentation of magma and country rock is essential if we are to understand their explosive power and the respective hazard in phreatomagmatic eruptions. The total energy which is available for fragmentation, transport and production of steam and sound is represented mostly by the thermal energy of the erupted magma volume. The mechanical energy which is responsible for the fragmentation of magma and hosting country rock is a part of the thermal energy that is convertible into the mechanical form on an explosive timescale. The small volume fraction of the erupted magma that was involved in the fast conversion process is represented by its specific products (i.e. interactive melt, IM). Thus the thermal energy of this small volume fraction represents the maximum kinetic energy that can drive the explosion (Büttner and Zimanowski, 1998).

The Quaternary Westeifel, Germany, volcanic field is characterized by more than 60 maar volcanoes that have been formed by phreatomagmatic explosions (Büchel, 1993; Lorenz, 2000). This is about 25% of the total number of volcanoes of this region. The resulting pyroclastic surges are low-density currents with a low transport energy so that fragmentation processes like abrasion play a subordinate role (Zimanowski, 1998). Furthermore, all granulometic distributions of Eifel maar volcanic deposits show a constant content of lithics (Zimanowski, 1985). Lorenz (2000) and Diele (2000) concluded that the explosion sites, where the magma–groundwater interaction occurs, migrate downwards so that the conduit of a maar volcano must be thinner than its diatreme. Consequently, single fragmentation mechanisms like conduit recycling are secondary in the case of maar volcano deposits and are neglected in this paper by way of a simplification. The lithic component of volcanic ash consists of Devonian sediments that were fragmented mainly by the passage of elastic waves and shock waves released during the explosions. These waves form a prominent part of the total quantity of the mechanical energy release. Another significant part is consumed by the fragmentation of magma and pyroclasts and by the eruption and the emplacement. Büttner and Zimanowski (1998) discussed the partitioning of kinetic energy in fragmentation of magma and country rock as well as transport energy. Pre-volcanic crack inventory and estimated strength of the host rocks (Atkinson, 1987) as well as their precise static and dynamic fragmentation behavior can be assessed by field measurements and laboratory experiments, following the German DIN standard (Deutsches Institut für Normung DIN: http://www2.din.de). Three of the DIN standard methodologies have been applied to the samples discussed here. These are compressive rock strength measurements, flexural bending tests and modified crushing tests. They are described in Sections 2.1, 2.2 and 2.3, respectively.

Also, surface area measurements in combination (Section 2.4) with granulometry and volume calculations (Section 4) are used to determine the total surface area of country rock clasts of one layer representative of one Westeifel phreatomagmatic eruption. The total fragmentation energy for the production of the country rock-derived pyroclasts in the layer is calculated. With the use of energy partitioning data from MFCI experiments carried out in the past on these products (Zimanowski et al., 1997a) the total eruption energy was reconstructed and finally expressed as TNT-equivalent.

2. Field work and laboratory experiments

The critical shear stresses and resulting fragmentation energies of country rocks were experimentally determined using two different types of fragmentation tests (Fig. 1):

(1) Static fragmentation experiments were performed using a flexural bending test on sample prisms of Devonian country rocks (Fig. 1a).

(2) Dynamic fragmentation tests were carried out on a standard granulate of Devonian country rocks using a modified standard hammer crushing setup, combined with a piezoelectric force transducer system (Fig. 1b).

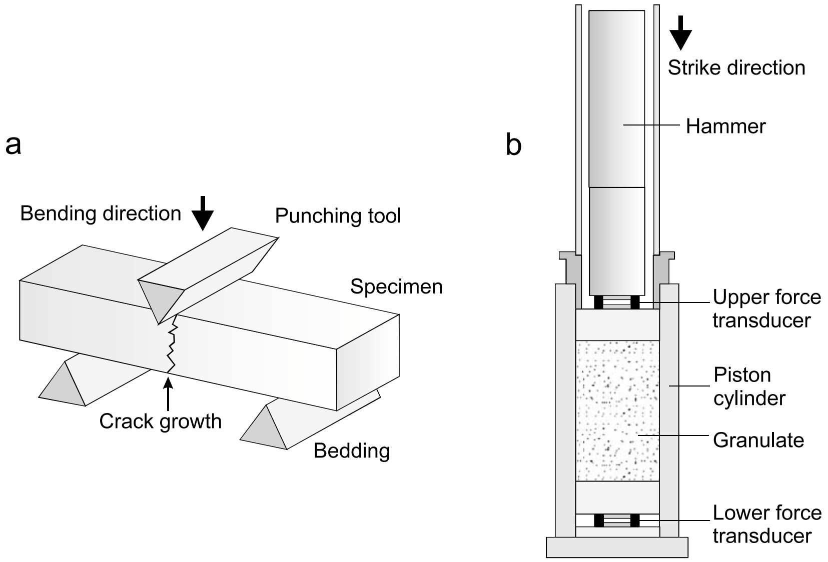


Fig. 1. Experimental setup of static flexural tests (a) and dynamic hammer crushing tests (b).

Both fragmentation tests were carried out using samples from the Devonian sediments that were affected by the phreatomagmatic explosions and represent the major component of lithics within the maar volcano pyroclastic deposits. For the following case study of the fragmentation energy budget of a typical Pulver maar volcano (PV) eruption the fragmentation behavior of location A (Fig. 2) was considered. The most affected rocks at PV diatreme are the Saxler layers (sampled at location A).

2.1. Field work

Devonian quartzites and quartzitic sandstones of the Rheinisches Schiefergebirge (Fig. 2) host the Westeifel volcanic field. PV, with its well preserved pyroclastic deposits (Diele, 2000), was se-

Table 1

Compilation of scale of pre-volcanic crack inventory, compressive strength values derived by the field method of the 'Schmidt'sche Betonprüfhammer' and critical shear stresses and fragmentation energies derived by static and dynamic fragmentation tests

Locality:	A	B	C	D	E
Rock type:	gray quartzites	quartzitic sandstones	quartzitic sandstones	sandstones, quartzitic sandstones	black clays
Minimum scale of pre-volcanic crack inventory [mm]	15	10	25	10	5
Maximum scale of pre-volcanic crack inventory [mm]	180	160	220	200	210
∅ compression strength β_{Pr} [N/mm^2]	66 ± 12	33 ± 5	27 ± 7	49 ± 6	43 ± 12
∅ crit. shear stress τ_c^S (static) [kN/m^2]	1606 ± 134	710 ± 85	494 ± 30	922 ± 109	1482 ± 68
∅ crit. shear stress τ_c^D (dynamic) [kN/m^2]	3010 ± 164	2093 ± 114	2003 ± 109	1684 ± 92	–
∅ crit. frag. energy E_c^S (static) [kJ/m^2]	1.623 ± 0.334	0.222 ± 0.032	0.510 ± 0.077	1.195 ± 0.338	1.208 ± 0.253
∅ crit. frag. energy E_c^D (dynamic) [kJ/m^2]	280 ± 63	109 ± 38	78 ± 41	144 ± 32	–
recal. ∅ crit. frag. energy E_c^D (dynamic) [kJ/m^2]	3.042 ± 0.626	0.654 ± 0.094	2.068 ± 0.312	2.183 ± 0.617	–

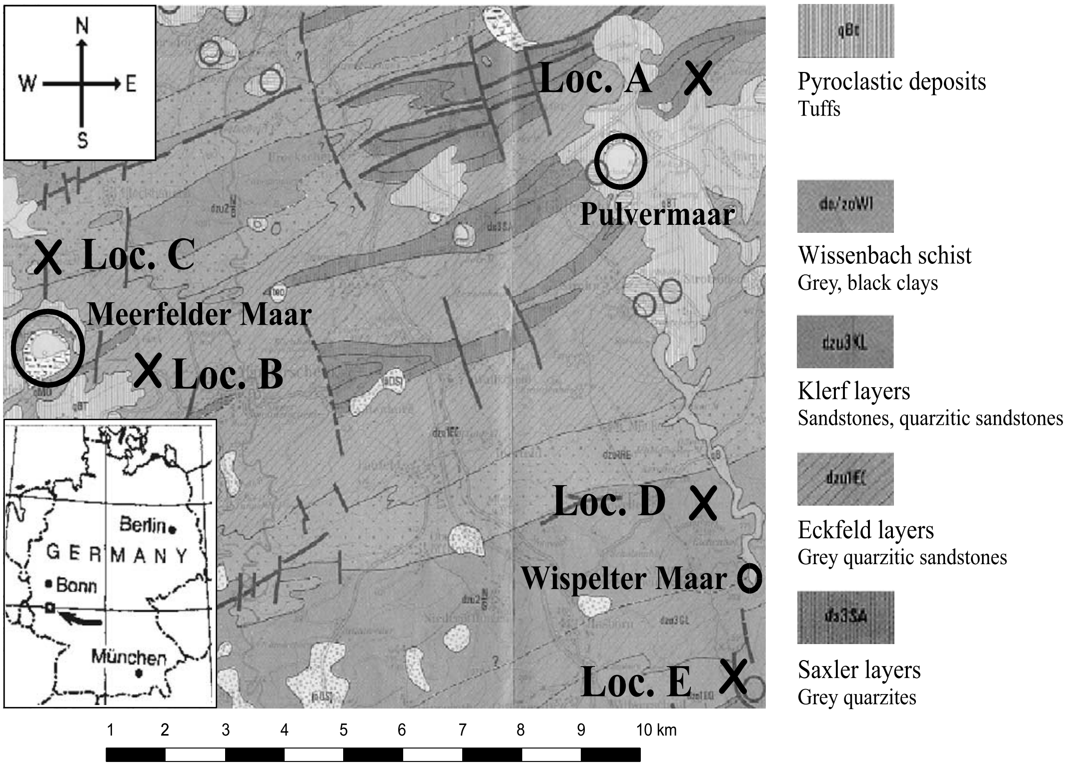


Fig. 2. Schematic geological map of the sample sites in the Westeifel volcanic field (modified after Negendank, 1983).

lected to be the locality for the calculation of the energy budget of a typical phreatomagmatic explosion. For both the static and dynamic fragmentation experiments it was necessary to use fresh, minimally weathered, oriented samples taken from outcrops and quarries of the Devonian sediments involved in the phreatomagmatic explosions. These rocks were penetrated and fragmented by the maar diatremes of PV (location A; Saxler layers, gray quarzites), Meerfelder Maar (locations B and C; Eckfeld layers, gray quarzitic sandstones) and Wispelter Maar (locations D and E; Klerf layers, sandstones and quarzitic sandstones; Wissenbach schist, gray and black clays) during the eruption. The layers consist of quite different types of sediments so that different fragmentation behavior was observed, as characterized by the varying scale of pre-volcanic crack inventory and different critical shear stresses and fragmentation energies (Table 1).

To determine the scale of pre-volcanic crack inventory, the population density of joints and shear planes, as well as the size of mineral aggregates were measured in the field and statistically treated. The results show that the minimum distance of joints ranges between 0.5 and 22.0 cm (Table 1).

Using the field method of the ‘Schmidtsche Betonprüfhammer’ (Prinz, 1997) a first estimation of the prevailing compressive rock strength was made feasible (Table 1). This rebound hammer equipment has to be pressed vertically onto the unweathered rock surface of each sample locality. After reaching a certain compression limit a feather-driven mass inside the equipment sends a blow on the rock surface. The energy of the blow causes a rebound of the mass, whose length is recorded. This value is positively correlated with the compressive strength β_{Pr} of the rock (Table 1). This method can be applied to drilling cores as well as directly to outcropping rocks (Prinz, 1997).

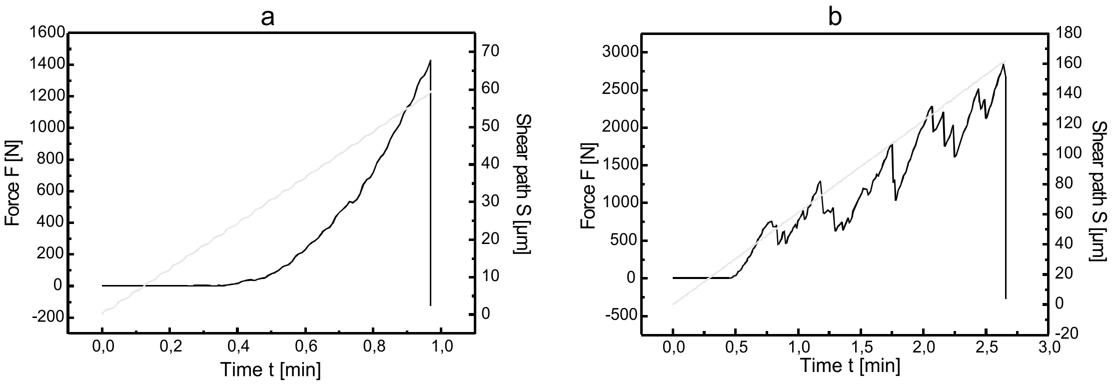


Fig. 3. Static fragmentation tests of Saxler layer material (location A). Load force (black line) and shear path (gray line) are monitored. Panel a shows a typical force ramp of homogeneous material. Panel b shows tectonic pre-affected material. The breakup behavior is characterized by many crack events that took place before the main fracture.

2.2. Static fragmentation tests

The center-loading flexural tests were performed using the static material-testing equipment of the type Zwick/1445® (Fig. 1a). The specimens (prismatic test bodies, 20×20×100 mm, cut out of Devonian sediments, were placed on two bearing edges. A punching tool of a hydraulic system applied a controlled weight on the upper surface. The compactor initiated the fragmentation test running at a velocity v of 1 mm/min, which corresponds to an increase in tension $\Delta\sigma$ of 0.2 N/mm^2. Static breaking load $F_{\mathrm{frag}}^{\mathrm{S}}$ and shear path S (i.e. the displacement of the punching tool up to the point of fracture) were detected during the experiment. After exceeding the fragmentation limit the values were recorded in [kN] and [µm]. A quasi-linear load force was monitored with a slope of approximately 0.5 (Fig. 3a).

To achieve reproducible results the sample prisms of the Devonian country rock may not include stratification joints. Fig. 3 compares the fragmentation of a homogeneous specimen (Fig. 3a) with that of a specimen that contains numerous stratification joints (Fig. 3b). The latter is essentially useless because the fracturing of the calcite-filled stratification joints precedes the main fracture event, leading to enormous fluctuations in the gradient of the load force. Seven homogeneous prisms from each sampled locality were measured both parallel, and another seven perpendicular to their stratification.

A thin metal foil was used to create an inprint of the fracture plane. The circumference of the imprint was digitized using an optical scanner. Afterwards the area of the fracture plane was obtained from the digital image using standard graphic software. Then the critical static shear stress $\tau_{\mathrm{c}}^{\mathrm{S}}$ is given by:

$$\tau_{\mathrm{c}}^{\mathrm{S}} = \frac{F_{\mathrm{frag}}^{\mathrm{S}}}{A} \tag{1}$$

and gives the force (breaking load) per area A of newly built fracture, acting parallel to the fracture surface.

The critical static fragmentation energy $E_{\mathrm{c}}^{\mathrm{S}}$ follows from:

$$E_{\mathrm{c}}^{\mathrm{S}} = \tau_{\mathrm{c}}^{\mathrm{S}} S \tag{2}$$

with the critical static shear stress $\tau_{\mathrm{c}}^{\mathrm{S}}$ and the shear path S. The term *critical fragmentation energy* E_{c} is defined in this paper as the product of the shear stress τ and the respective shear path. The result represents the fragmentation energy needed to build new surface.

2.3. Dynamic fragmentation tests

The dynamic fragmentation tests were performed using a standard hammer and a piston cylinder (Fig. 1b). This setup was modified by adding a piezoelectric force transducer system (Kistler™ 9031 A) at the bottom and the top of the piston cylinder, which documents input and

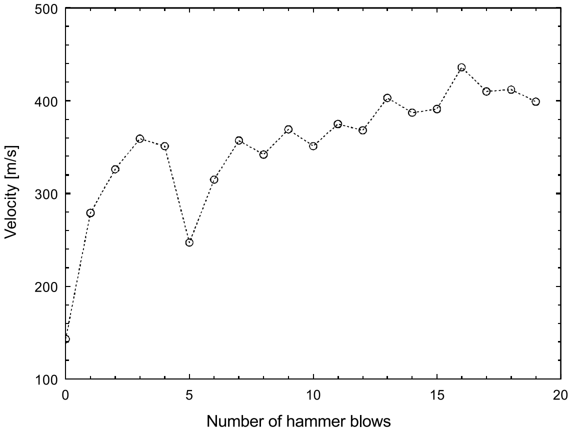


Fig. 4. Dynamic fragmentation test. Speed of sound plotted against hammer blow numbers of Saxler layer material (location A). After four blows the speed of sound (i.e. the debris density) inside the piston cylinder remains relatively constant. This means that the coupling of each hammer blow is reproducible.

output forces of a hammer blow. In addition, the speed of sound in the sample was monitored (Fig. 4) from the time interval between the signals to provide information on the granulate density in the piston cylinder (i.e. to ensure that the hammer blows are reproducible). In this way the fragmentation energy and the damping characteristics of the rock material were determined.

An artificially crushed granulate of the Devonian country rocks with a grain size between 1 and 2 mm mesh was filled into the piston cylinder apparatus and stressed by 20 blows of a standard hammer. Input and output forces of each blow were recorded. Using:

$$F^{\mathrm{D}}_{\mathrm{frag}} = \sum_{1}^{20}(F_{\mathrm{in}} - F_{\mathrm{out}}) \tag{3}$$

the dynamic fragmentation force $F^{\mathrm{D}}_{\mathrm{frag}}$ was expressed in kN. The critical dynamic shear stress $\tau^{\mathrm{D}}_{\mathrm{c}}$ in kN/m^2 then results from:

$$\tau^{\mathrm{D}}_{\mathrm{c}} = \frac{F^{\mathrm{D}}_{\mathrm{frag}}}{A} \tag{4}$$

where A represents the newly built fracture area during 20 hammer blows.

Assuming fully elastic coupling of the hammer into the system, the kinetic energy input E_{kin} is obtained from the potential energy of the hammer ($E_{\mathrm{pot}} = E_{\mathrm{kin}}$). Furthermore, assuming that the partitioning of kinetic energy is analog to the partitioning of the forces:

$$D = \frac{F_{\mathrm{in}}}{F_{\mathrm{out}}} \tag{5}$$

the dynamic fragmentation energy $E^{\mathrm{D}}_{\mathrm{frag}}$ [kJ/m^2] is described by:

$$E^{\mathrm{D}}_{\mathrm{frag}} = E_{\mathrm{kin}} - (E_{\mathrm{kin}} D) \tag{6}$$

in which D is the damping coefficient of the system, which was approximated before using a sandstone calibration cylinder with nearly ideal elasticity and low seismic impedance. In general the damping of a system represents the value of energy which is lost by friction and the attenuation of a seismic wave.

The progress of critical fragmentation was monitored via the production of finer grain sizes. In the case of the natural material used, self-similar daughter fragments were generated (suggesting homogeneous material and singularity of fragmentation process) and sieved out.

2.4. Surface measurements of experimental products of dynamic fragmentation tests

To determine the surface area of the generated particles the multipoint Brunnauer–Emmett–Teller (BET) method (Sing et al., 1985; Allen, 1990) and the fundamental BET equation:

$$\frac{1}{W\frac{P_0}{P} - 1} = G + H\frac{P}{P_0} \tag{7}$$

was used, where W is the mass of gas adsorbed at a relative pressure P/P_0. $G = 1/(W_{\mathrm{m}}J)$ and $\mathrm{H} = (\mathrm{J}\text{-}1)/(\mathrm{W_m J})$ are constants, with W_{m} the weight of an adsorbed monolayer, and J the BET constant. The gas sorption analyzer NOVA-1200® (Quantachrome Corp.) uses nitrogen as adsorbant and coolant. Thus W_{m} can be obtained by combining G and H:

$$W_{\mathrm{m}} = \frac{1}{G + H}. \tag{8}$$

In the next step the total surface area A_t of the sample was calculated using:

$$A_t = \frac{W_m N A_{CS}}{M} \tag{9}$$

where N is Avogadro's number, A_{CS} is the molecular cross-sectional area, and M is the molecular weight of nitrogen. Finally, the specific total surface area A was calculated:

$$A = \frac{A_t}{w} \tag{10}$$

where w is the sample weight.

The measurement of the granulate surface area has to be done before and after the dynamic fragmentation process. The difference between the two values represents the new surface area A_n created by the fracturing process. Using the equation:

$$E_c^D = \frac{E_{frag}^D}{A_n} \tag{11}$$

the dynamic fragmentation energy E_{frag}^D can then be assigned to A_n and expressed as the critical dynamic fragmentation energy E_c^D.

3. Results

The two modes of brittle fragmentation used in the tests describe the most important ones (i.e. elastic rebound and passage of shock waves) in order to produce the lithics in the base surge deposits of Eifel maar volcanoes. Fragmentation mechanisms like abrasion and conduit recycling are secondary in the case of maar volcano deposits.

The static shear stresses represent average values among measurements done parallel and perpendicular with respect to the stratification of the specimen. The samples of location E were not used for the dynamic fragmentation tests because of their platy grain shapes (producing non-self-similar daughter fragments). The variability between different samples (Table 1, more than a factor of two) results from the distinctive rock parameters of quartzites, quartzitic sandstones, sandstones and clays. Their values correspond to the estimations of the rock strength in the outcrops (Table 1). A comparison of the critical shear stress values derived from static and dynamic fragmentation experiments (Table 1) shows that they are in good agreement. However, numerous static fragmentation tests combined with several dynamic fragmentation experiments per sample would help to reduce the total error reported in Table 1. In general, a dynamic fragmentation process should need a higher shear stress than a static fragmentation process, reflecting a higher radiation of the mechanical energy (Chau et al., 2000).

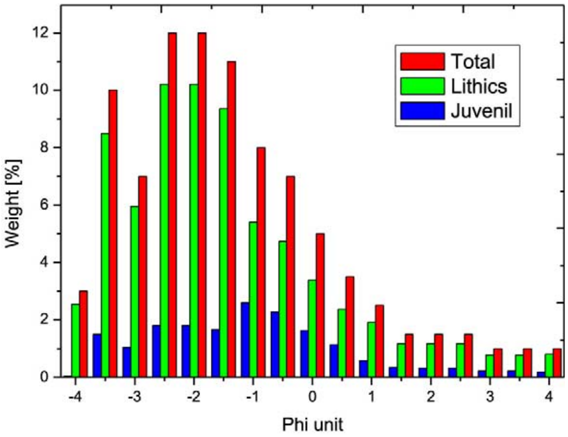
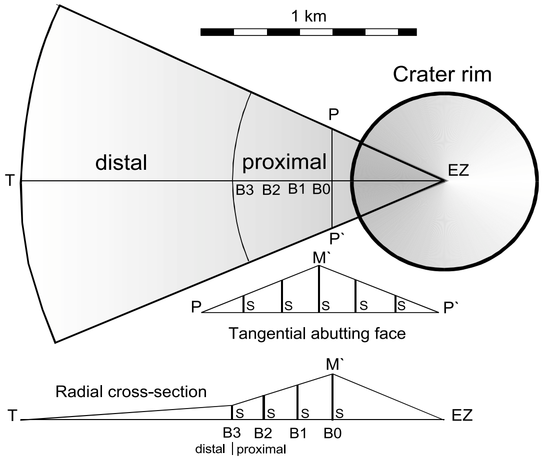


Fig. 5. Grain-size and component histogram of a PV tuff (after Zimanowski, 1985). The diagram documents the high content of lithics (80% by volume, averaged over all grain size fractions).

The critical fragmentation energies, as obtained by dynamic fragmentation tests, however, result in unrealistically high values. This behavior results from the assumption that the potential energy of one hammer blow is transformed completely into kinetic energy (i.e. fully elastic coupling assumed). However, much of the initial energy is lost due to damping and only a fraction is coupled into the fragmentation process. The ratios of static and dynamic shear stresses, which are experimentally measured, can be used to recalibrate the critical fragmentation energies derived from dynamic fragmentation tests (Table 1) using:

$$\mathrm{recal.}E_c^D = \frac{E_c^S}{\tau_c^S / \tau_c^D} \tag{12}$$



Lateral dispersion	proximal: 0.2 km^2	distal: 0.9 km^2
Radial cross-section	proximal: 230 m^2	distal: 37 m^2
Tangential abutting face	proximal: 76 m^2	distal: 20 m^2
Normalized thickness	proximal: 18 cm	distal: 3 cm
Specific volume	proximal: 35 500 m^3	distal: 29 400 m^3
Total specific volume	64 900 m^2 (therefrom 13 000 m inside the crater)	

Fig. 6. Geometric fan model used for the volume calculations of PV deposits and the resulting specific volume of one individual tephra layer (after Zimanowski, 1985). The model is based on drill holes and excavations (s). Lateral dimensions and variations in thickness are calculated as triangles and trapezoids via the profiles (B0–B3). Between the maxima the values were linearly interpolated. EZ = eruption center, T = tuff boundary, B0–B3 = profiles, P–P′ = measured dilatation in the outcrop, EZ–T = lateral dilatation of tuff.

4. Modeling the energy budget of a typical maar volcano explosion

The pyroclastic deposits (base surge deposits) outcropping at PV (sample location A) are the result of multiple phreatomagmatic explosions (Büchel, 1993). The good state of preservation of the tephra ring demonstrates that PV is one of the youngest maar volcanoes of the Westeifel volcanic field (Diele, 2000). The maximum diameter of the crater amounts to approximately 1 km, the maximum height of the tephra ring to approximately 40 m. Intensive digging in this area allows an estimate of the total of approximately 500 (Zimanowski, 1985). The energy needed to produce one individual tephra layer can be calculated and expressed in a complete fragmentation energy budget by using the results of the fragmentation tests. The grain size distributions and component data (Fig. 5) as well as the volume calculations (Fig. 6) were taken from Zimanowski (1985). In that paper the total volume of a representative tephra layer was found to be 64 900 m^3 (1.73×10^8 kg, using a mean density of 2670 kg/m^3) and a volume of lithics of 51 920 m^3, (1.39×10^8 kg) was calculated resulting from a lithic content of 80% by volume (averaged across all grain size fractions).

The critical fragmentation energy necessary to produce 1 m^2 of fracture area in the host rock of PV (locality A), was quantified by the laboratory experiments of the present paper (Table 1): static (s): 1.623 kJ/m^2; dynamic recal. (d): 3.042 kJ/m^2). The total fracture area of the country rock volume (51 920 m^3) fragmented and erupted in a single explosion is $1.9 \times \times 10^8$ m^2 using a mean density of 2670 kg/m^3, BET measuring and the granulometric data (Zimanowski, 1985). Pre-volcanic crack inventory was checked (Table 1) and its scale represents the lapilli and block fraction, which is negligible for the total surface of lithics (less than 1%). A total fragmentation energy of

3.083×10^8 kJ (s) and 5.780×10^8 kJ (d) results as the product of the critical fragmentation energy and the total fracture area of the studied tephra layer. This is the energy needed to explain the fragmentation of country rock via static and dynamic mechanisms.

An alternative method for the calculation of the mechanical energy release of thermohydraulic explosions is described in Büttner and Zimanowski (1998) and in Büttner et al. (2002). The authors addressed the question of how much energy is released by the interaction of 1 kg of IM with water. In the case of basaltic andesites, 1 kg of IM produces up to 500 kJ/kg of shock wave energy.

Typically, one single explosion of PV contains 13 000 m^3 of juvenile material (Zimanowski, 1985). Only a small part of this volume represents IM. This fraction can be quantified using methods of particle analysis (Zimanowski et al., 1997a; Büttner et al., 1999). In the case of PV the result is a value of 870 m^3 of IM. Taking into account the information of Büttner and Zimanowski (1998) and Büttner et al. (2002) a volume of 218 m^3 (s) and 409 m^3 (d) of IM is needed to produce the fragmentation energy (3.083×10^8 kJ (s); 5.780×10^8 kJ (d)) that generated the country rock clasts in one single explosion. During a phreatomagmatic explosion a dynamic fragmentation process (fragmentation caused by passage of shock waves) is by far the most effective fragmentation process. Thus the value of 409 m^3 of IM needed to trigger such a process represents nearly 50% of the total IM volume calculated by the method used by Büttner and Zimanowski (1998) and Büttner et al. (2002). Considering that additional amounts of mechanical energy (i.e. IM) are needed to explain the fragmentation of magma, the eruption and transport of pyroclasts and the production of steam and sound, the results are in agreement with the physics of thermohydraulic explosions.

The TNT-equivalent of available energy of 1 kg of IM amounts to 4.2 MJ/kg (Büttner and Zimanowski, 1998). Thus, the fragmentation energy of country rock of 5.780×10^8 kJ of a typical PV eruption corresponds to an explosive power of 138 000 kg of TNT.

5. Conclusions

A new approach to quantify the fragmentation energy release of a phreatomagmatic explosion is presented in this paper using a newly created surface area of fragmented lithics. This procedure calculates energy partitioning of volcanic eruptions that produce a high amount of lithics (i.e. phreatic and phreatomagmatic explosions). In this way the amount of kinetic energy released during a specific explosion can be recalculated using field data of the total volume of pyroclasts deposited by the eruption. Now the energy needed to produce the granulometric characteristics of these deposits per unit mass can be assigned. Finally, this energy value is useful to scale numerical models of the eruption and to improve the quality of hazard assessment in vulnerable regions like the Westeifel volcanic field.

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