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Field-based density measurements as tool to identify pre-eruption dome structure: set-up and first results from Unzen volcano, Japan

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Abstract

For an improvement in the quality of conduit flow and dome related explosive eruption models, knowledge of the pre-eruption or pre-collapse density of the rocks involved is necessary. As close investigation is impossible during eruption, the best substitute comes from quantitative investigation of the eruption deposits. The porosity of volcanic rocks is of primary importance for the eruptive behaviour and accordingly a key-parameter for realistic models of dome stability and conduit flow. Fortunately this physical property may be accurately determined via density measurements.

We developed a robust, battery-powered device for rapid and reliable density measurements of dry rock samples in the field. The density of the samples (sealed in plastic bags at 250 mbar) is determined using the Archimedean principle. We have tested the device on the deposits of the 1990-1995 eruption of Unzen volcano, Japan. Short set-up and operation times allow up to 60 measurements per day under fieldwork conditions. The rapid accumulation of correspondingly large data sets has allowed us to acquire the first statistically significant data set of clast density distribution in block-and-ash-flow deposits.

More than 1100 samples with a total weight of 2.2 tons were measured. The data set demonstrates that the deposits of the last eruptive episode at Unzen display a bimodal density distribution with peaks at 2.0 +/- 0.1 and 2.3 +/- 0.1 g/cm³, corresponding to open porosity values of 20 and 8 vol.%, respectively. We use this data set to link the results of laboratory-based fragmentation experiments to field studies at recently active lava domes.

Keywords

Field-based density measurements, Unzen Volcano, dome, explosive eruption, block-and-ash-flow, fragmentation behaviour, volcanology

Introduction

Experimental investigations and numerical modelling of explosive volcanoes require an accurate physical description of volcanic systems and the rock properties involved immediately prior to eruption or collapse (Dingwell, 1998). Ascending magmas show variable porosity in space and time, so a precise knowledge of the density distribution within complex domes or conduits is required for valid models. This can only be achieved via evaluation of a statistically reliable amount of representative samples within the eruptive products, which in the case of Unzen are dominated by block-and-ash-flow deposits. Performing density measurements in the field reduces the logistic effort enormously and if performed as soon as possible after the end of an eruption, the influence of weathering or secondary transport changes, either in size or distribution is minimized. To the best of our knowledge, this is the first extensive field-based density investigation of its kind. We demonstrate the feasibility of this method with the products of the 1990-1995 eruption of Unzen volcano (Kyushu, Japan) during two field campaigns in 2000 and 2001.

Methods of density measurements

There are various methods to evaluate the density of rocks, but most methods are not practicable for extensive investigations as they involve sample transport to the laboratory and specific sample preparation: (1) water saturation (Belikov et al., 1964; Schopper, 1982; Cas and Wright, 1987; Gardner et al., 1996) requires a very long pre-measurement preparation time (or high vacuum) and it cannot be assured that all pores are completely water-filled (especially large pores on the surface of the sample will leak immediately); (2) impregnation with a silicon spray (Houghton and Wilson, 1989), (3) coating with saran (Mayfield and Schiffman, 1998) and (4) coating with cellulose acetate (Polacci et al, 2003) require a second drying interval of the coating. As the coating is a thin film on the sample surface, the volume of broken bubbles on the surface is excluded during the volumetric measurement; (5) Mercury-intrusion porosity (Belikov et al., 1964) is not practicable for samples with large pores and can lead to structural collapse of pumiceous samples; (6) He-Pycnometry results correspond to the replaced volume of a sample. From this result and the weight of a geometrically regular sample, the open porosity can be calculated. The sample preparation in methods 2, 3, 4 and 5 is irreversible. The size of sample that can be measured in methods 5 and 6 is limited to the cell volume of the device used.

Method

We developed a robust, battery-powered device for rapid and reliable density measurements of dry rock samples directly in the field (Fig. 1). Samples are sealed in plastic bags at vacuum (250 mbar) and weighed in air and submerged. Following the Archimedean principle, the buoyancy is used to calculate the density according to

$$\rho_{sample} = \frac{m_{air}}{m_{air} - m_{water}} * \rho_{water} .$$

For more details see the appendix. For the study presented here we investigated samples with a volume range of 350-2250 cm³. Taking observed porosity features (e.g. bubble size, shape) into account, the chosen sample size range is more likely to actually represent the real porosity distribution than smaller samples measurable in the lab would do. The influence of the bags employed on the density results was demonstrated to be negligible. Therefore, we think that our method is the best approach to reveal the density distribution of complex domes. If desired, this method is applicable to any dry deposit and even smaller samples. For the purpose of investigating lapilli-sized samples with this method, several particles are placed in one bag simultaneously while avoiding contact.

Results

During two field campaigns density measurements were performed on samples from deposits of the 1990-1995 Unzen eruption. We measured more than 1100 samples with a total weight greater than 2.2 tons on the dome and in the four valleys that were most affected by block-and-ash flows (Fig. 2). Due to the time interval lapsed by between the end of the eruption and the field work, density investigations could only be performed on the uppermost deposits. The end of the emplacement time within the four valleys differs by approximately 1.5 years. Investigations of all five data sets reveal their statistical reliability (probability, randomness) and were plotted graphically (Fig. 3-8). Two data sets (dome and Senbongi valley) clearly show bimodal distribution. Histograms of Akamatsudani, Mizunashi and Oshigadani valley might be also explained unimodally. Nevertheless, there are two reasons we favour a bimodal data interpretation: 1) Small peaks/shoulders in the histograms which we take as indicator of a non-normal distribution and 2) direct observations of porosity layering in the field. Using *PeakFit*™ the distribution peaks and their fraction were evaluated. The results show concordant bimodal results for all four valleys and the dome with peaks at 2.0 +/- 0.1 and 2.3 +/- 0.1 g/cm³ but changing peak ratios. The peak ratio values correspond to the area covered by each peak curve (gaussian) as fraction of the total area. In the following we describe the results for each valley (from north to south) and the dome.

- Senbongi Valley (measurement point MP 1 and 2): This valley was affected by large block-and-ash flows after 23 May 1993, once the Oshigadani Valley had been filled to the point that the morphological barrier (Taruki Height) was overcome (Nakada et al., 1999). The outcrop situation was generally poor due to dense vegetation and dam construction. 54 samples were measured at two locations with a resulting mean density of 2.1 g/cm³ (found range is 1.6-2.4 g/cm³). The distribution is bimodal with peaks at 2.0 and

2.3 g/cm³, representing 65 and 35 %, respectively. Both peak values are at the upper end of the peak value range (Fig. 3).

- Oshigadani Valley (MP 3 to 11 and 31): This valley was affected by block-and-ash-flows from 25 August 1991 on until the end of the block-and-ash flow activity in early 1995. The deposit thickness locally exceeds 100 m (Nakada et al., 1999). The reworking activity is concentrated on a major erosional channel on the northern edge with many feeder gullies. Despite the fairly dense vegetation in this valley, a good distribution of measuring locations was possible. 298 samples at ten locations were measured with an average density of 2.0 g/cm³ (found range is 1.4–2.4 g/cm³). The highly porous samples were mainly found at MP 3, 8, 10 and 31 that were affected only at the beginning of the eruption or are situated at elevated positions and thereby protected against effective changes in original density distribution by lahars (see Fig. 2). The density distribution is bimodal with peaks at 2.0 and 2.2 g/cm³, representing 60 and 40 %, respectively (Fig. 4).
- Mizunashi Valley (MP 14 to 23): For the first three months after 24 May 1991 (onset of block-and-ash flow activity), pyroclastic flows travelled exclusively down this valley. This valley was affected until June 1993. Outcrop conditions were very good in the lower parts due to sparse vegetation. There is a large erosional channel to which most of the reworking appears to have been restricted (compare Oshigadani). The abundance of lapilli-sized particles was highest in this valley and chunks of wood were abundant, all of them carbonised exclusively on their lower sides. We take this as indicator of in-situ position with the carbonisation resulting from contact with hot block-and-ash flow deposits. As in Oshigadani Valley, a decrease in the porosity of material with increased transport distance can be discerned by comparing density distributions at locations parallel to the flow direction in this valley. The mean density of 300 samples measured at ten locations is 2.0 g/cm³ (found range is 1.3-2.5 g/cm³). The density distribution is bimodal with peaks at 2.0 and 2.3 g/cm³, representing 80 and 20 %, respectively (Fig. 5). The

percentage of dense rock samples is lowest in this valley. We show the density distribution plots at each of the ten locations in Fig. 6. These plots reveal that at some locations the amount of measured samples was not high enough to reach statistical reliability. Nevertheless, looking at all samples from this valley, the data clearly fulfil statistical requirements.

- Akamatsudani Valley (MP 24 to 30): This valley was affected by block-and-ash-flows from 19 June 1991 until 11 February 1995 (the very last block-and-ash flow during this eruptive period). Dense vegetation and ongoing Sabo-dam construction were responsible for the sampling locations not covering large proportions of the primary depositional area. Nevertheless, the results obtained in this valley show a similar density distribution to the other valleys. 210 samples were measured at seven locations, the resulting mean density is 2.0 g/cm^3 (found range is 1.6-2.4 g/cm^3). The density is distributed bimodally with peaks at 2.0 and 2.2 g/cm^3, representing 59 and 41 %, respectively (Fig. 7).
- Dome (MP 12 and 13): Measurements performed at two locations at the western edge show similar patterns, with dense rocks being the most abundant rock variety. They confirm visual estimations on the dome as access to the dome was restricted to overview surveys. 65 samples were measured at two locations at the western edge of the dome talus with a resulting mean density is 2.2 g/cm^3 (found range is 1.9-2.4 g/cm^3). The density distribution shows peaks at 2.1 and 2.2 g/cm^3, representing 62 and 38 %, respectively (Fig. 8). Bread crust bombs found west of the dome talus originate from the vulcanian eruption of 11 June 1991 and represent the least dense rock variety that can still be found (1.4-1.6 g/cm^3).

During the second campaign, we selected 23 samples covering the whole density range for laboratory correlation measurements. Rock cylinders (26 mm diameter, up to 60 mm long) drilled from these were measured using a He-Pycnometer (1330, Micromeritics). The results show that the error in field measurement is generally below 5 % (Fig. 9), and that therefore our density measurement method is fast, effective and sufficiently precise to replace existing laboratory based techniques.

He-Pycnometry measurements on cylinders from all density classes show that the density of the replaced volume is in the range of 2.5 to 2.6 g/cm^3. These values represent the matrix density, including closed porosity and crystal content. The resulting range of open porosity, averaged from 15 measurements, is calculated to be 4.0 to 34.3 vol%.

Interpretation

Due to the large number of measurements performed, good coverage of the latest block-and-ash-flow deposits of the 1990-1995 Unzen eruption was achieved. All samples within the four valleys belong to deposits of block-and-ash flows, most of which were triggered by gravitational collapse of the font of the dome lobes. The temperature of these lobes was probably considerably lower than 650 °C, the highest temperature measured at a fumarole on the dome (Umakoshi et al., 1992). Therefore, we don't expect changes in porosity (due to foaming or ductile bubble shearing-out) during block-and-ash flows or after deposition. Taking the measured sample size as being representative, an estimation of the porosity can be achieved. All five data sets reveal bimodal density distribution with similar peak values. This bimodal distribution matches very well with features in many blocks (Fig. 10) showing two main porosities. Results from Mizunashi valley show a shift to porous rock varieties. The data set shows a different peak ratio (80:20) in comparison to all other four data sets (60:40). Mizunashi valley was affected by block-and-ash flows only until mid-1993. According to Nakada (pers. comm.) the density of erupted rocks increased over the time span of the eruption. In the light of that, the Mizunashi data compared to the other four data sets show the shift in the density distribution from 1993 to1995 and allow a rough vertical resolution of the overall deposits. The peak ratio is constant (60:40) for Akamatsudani, Oshigadani, and Senbongi valley and the dome. All these areas have been affected until the end of the eruption. The influence of transport distance and secondary fragmentation after the free fall might explain higher peak values in density distribution in Senbongi valley compared to locations close or on Taruki Height (Oshigadani valley). A quantitative decrease of porous rocks with increased transport distance can be discerned by comparing density distributions at locations parallel to the flow direction. The average density is highest on the dome because samples investigated are associated with late-stage extrusion of dense degassed lava.

The data provide insights into the density distribution in conduit and dome prior to eruption or collapse as differently porous rocks can be linked to features observed in the dome or in large blocks that survived transport in block-and-ash-flows. The internal structure found in the spine, many blocks on the dome (Fig. 10) and within the block-and-ash-flow deposits is sheet-like with layers of different degrees of porosity. Layer thickness is in the cm to dm range.

Three reasons might be responsible for heterogeneous porosity distribution: 1) syn-ascent mixing of two distinct dacitic magmas with different primary water content, 2) different time span available for degassing due to different ascent and extrusion rates and 3) flow-controlled vesicle collapse. It is uncertain whether mixing is responsible for the porosity heterogeneity. Petrological investigations by Nakada and Motomura (1999) show constant main element contents of lavas erupted from 1990 to 1995, while the water content was decreasing continuously over the time span of the eruption. In slight contrast, melt inclusion analyses from Botcharnikov et al (2003) indicate complex pre-eruptive magma mixing at Unzen with three melts with different major element compositions and water contents. Close field investigations reveal that layers of different porosity have a vertical alignment in the spine and are flank-parallel where dome lobes flowed down the eastern flank of Unzen. Smith et al. (2001) interpret porosity heterogeneities as mostly flow-controlled. Extrusion rates changed during the eruption and showed two major peaks (Nakada et al., 1999), resulting in repeated shifts between endogenous and exogenous dome growth. Therefore, factors 2) and 3) most probably have an influence on the development of the porosity distribution (Mastrolorenzo et al., 2001). Fast ascent rates are associated with high porosities and high residual water contents (Nakada, pers. comm.). Dense rocks are therefore most probably more efficiently degassed. In order to use density measurements results to reconstruct dome densities and thereby internal structure, experiments need to be performed to quantify the amount of porous rock destroyed by syn-block-and-ash-flow abrasion. The density measurements in the lab are in good agreement with field data and thereby serve to demonstrate the method's validity and applicability. Different values of field and lab density probably result from different sample sizes (blocks in the field, cylinder drilled from blocks in the lab). The values achieved in the field include open and closed porosity; laboratory measurements via He-Pycnometry on cylinders evaluate the open porosity, on powder the closed porosity. The distributions achieved at some locations do not show simple results of density abundance (Fig. 6). A possible reason might be an insufficient amount of samples investigated. We therefore think that 50 to 60 measurements are required per location for statistical analysis. Although the day of last emplacement of a block-and-ash flow in a single valley differed by more than 1.5 years (June 1993 in Mizunashi and February 1995 in Akamatsudani), we find constant peak values. Therefore we conclude that, although density increased during the eruption (Nakada, pers. comm.), the density distribution remains bimodal with similar peak values. This represents most probably the banding found in dome and spine. Our explanation of the origin of a bimodal density distribution is different to the results of Hoblitt and Harmon (1993). Looking at the "bimodal density distribution of cryptodome dacite from the 1980 eruption of Mt. St. Helens" they state that the dense rocks represent the more degassed outer rim of the cryptodome and the more porous rocks the cryptodome interior. We consider it likely that the differences between these interpretations reflect different emplacement processes (intrusive cryptodome at Mt. St. Helens and extrusive dome at Unzen with endogenous and exogenous dome growth).

Relevance for dome collapse

The density distribution inside a dome and the upper part of the conduit is crucial to the eruptive style of an explosive volcano. This information cannot be collected during an ongoing eruption but is important for future hazard assessment via modelling conduit flow and dome collapse/explosion behaviour. Therefore, the percentage of the mass fractions of all rock types in the primary and secondary volcanic deposits must be evaluated. For this purpose at lowest logistic effort, field-based density measurements are needed. The resultant density distribution in combination with fragmentation behaviour investigations will allow insights into a possible eruption scenario at a certain volcano or in a better understanding of explosive eruptions in general as this method allows linking both data sets. Lab investigations of the behaviour of natural samples (with crystals and bubbles) with internal overpressure have been performed in the fragmentation bomb (Alidibirov and Dingwell, 1996). Depending on the porosity, the fragmentation threshold (defined as the minimum pressure differential required to cause hot (850 °C) porous volcanic rock or magma to form pyroclasts when decompressed rapidly (Fig. 11). This is critical and defines the shift from effusive to explosive eruptions without water interaction. The most abundant rock types at Unzen have an open porosity of 8 and 20 vol%. This corresponds to a threshold of 18 and 5.4 MPa, respectively. As a volcano is not a perfectly sealed closed system and many factors play an important role in developing gas overpressure (primary gas content, magma ascent rate, magma or country rock permeability), the overpressure inside a dome is hard to quantify. Estimations of Woods et al. (2002) give a range of 5-10 MPa for the centre of the dome in the case of Montserrat with a high pressure gradient. Combining this value with experimentally derived fragmentation threshold data and the density distribution determined in the field leads to the assumption that most block-and-ash-flows at Unzen were probably mainly triggered by gravitation. Nevertheless Ui et al. (1999) often noted puffs of ash prior to block-and-ash-flows close to the resulting collapse scar, by that possibly indicating locally restricted fragmentation triggering gravitational instability. It might be that these ash puffs are the visible result of the onset of shear-induced fragmentation with associated gas-ash flux (Tuffen et al, 2003). It is a still unsolved question, to which degree a crack starting in porous rock due to overpressure-induced failure can propagate into dense rock that would still be able to withstand the overpressure and increase instabilities. Explosive events at Unzen took only place within the first weeks of lava effusion after large-scale dome collapses.

Conclusion

As magma in the conduit or lava in the dome are heterogeneous in their physical state, density data are – amongst others – an important input-parameter for realistic models of conduit flow or volcanic eruptions. As shown above, these data can be achieved precisely and used to reveal the density distribution. The method also provides accurate and fast laboratory measurements. The results for the last Unzen eruption show flow-parallel porosity banding with a bimodal distribution with peaks at 2.0 +/- 0.1 and 2.3 +/- 0.1 g/cm^3 with a corresponding open porosity of 20 and 8 Vol.%, respectively. Initial overpressures of 5.4 and 18 MPa are required to fragment such samples by rapid decompression. As most volcanic activity at Unzen was effusive, these pressure values are unlikely to have been reached within the dome. The relatively few vulcanian eruptions at the beginning of the eruptive episode were triggered by large block-and-ash-flows that unloaded the conduit.

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Appendix:

The density measurements performed directly in the field are based on the Archimedean principle. That way, knowledge of the weight and the volume of a sample is necessary. As the evaluation of a sample's volume is usually very time-consuming if achieved via a water-saturating process, we changed the measuring procedure. The weight of a dry sample - evacuated in a plastic bag - in air and under water is determined and used to calculate the density according to

$$\rho_{sample} = \frac{m_{air}}{m_{air} - m_{water}} * \rho_{water} .$$

with m_{air} being the weight of the sample evacuated in a plastic bag in air and m_{water} being the weight of the same sample submerged. For the calculation, ρ_{water} was assumed to be 1.

Two people are needed for the evacuation procedure. With these values, the buoyant force of the sample is quantified and the density can be calculated. The apparatus (overall weight below 20 kg) consists of: (1) a battery-powered vacuum pump (Metzger, Germany) that allows a vacuum of up to 250 mbar; (2) a precise battery-powered digital balance (Ohaus, Germany) with a maximum load of 4.1 kg; (3) an aluminium tripod with a holding device for the balance; (4) a water-proof bag or a bucket; (5) 10 litres of water; (6) minor consumable items (plastic bags, glue). The energy for the vacuum pump and the balance is delivered by rechargeable AA-batteries, making the measurements independent of direct power supply in the field.

Set-up: The balance is fixed on top of the tripod with three adjustment screws guaranteeing a horizontal position. The waterproof bag is fixed centrally below the balance, from where a holding device leads down to the sample holder. The measurements are performed on samples contained in the waterproof bag acting as a screen. No pre-evacuation sample preparation is required. For every sample, we determine two weights, (1) the weight of the dry sample in air and (2) under water evacuated in a plastic bag. Depending on the roughness of the sample surface, one of three different types of plastic bags with different wall thickness was chosen in order to avoid bag failure. The buoyancy of the used plastic bags, sealed with silicon glue and evacuated, is determined to be negligible and has no influence on the results. For evacuation, we place the sample inside a bag, squeeze a line of silicon-based glue on the bag rim and close the bag along this line after inserting a plastic tube connected to the vacuum pump. The highly viscous glue is used to avoid energy-consuming melting procedures. During the evacuation, the bag becomes tight to the rock sample but only partially sucked into the broken-up bubbles at the sample surface. Therefore even this outermost part of a sample is taken into account during the measurement. The vacuum remains stable for more than 15 minutes after the plastic tube was removed from the bag. To exclude any influence of the wind on the weighing, a special measuring program of the balance is used, taking the average weight over a 30 seconds period.

The time needed per sampling location is about 3 hours, consisting of 15 minutes for collecting 30 samples at a single location, 15 minutes for the set-up of the apparatus and approximately 5 minutes per sample for evacuation procedure and measurement. The measurements should generally be performed as soon as possible after the end of an eruption in order to minimize (1) reworking of the deposits by secondary influences such as erosion, weathering, or human processes (sabo dam constructions, quarry work) and (2) the growth of vegetation that can make the deposits inaccessible. There are some limitations of this method with our set-up: 1) Sample size that can be used (max. 20cm). 2) Climatic situation (dry samples are needed). During our field campaigns, measurements have only been performed on the surface of the deposits. We assume that we can ignore any possible impact on the results if covering big parts of the depositional area with resulting different run out distances and deposition times. If taking any possible reason for sample alteration or other influence on the results into account, this method is capable to result in large and reliable data sets in a short time period. Further on, this method is applicable to all dry deposits and can as well be adapted to lapilli-sized samples. For this purpose several particles are placed in one bag simultaneously while avoiding contact. To investigate samples from older deposits and ensure their dryness, sample selection and their exposure to sun at least one day prior to measurements ensured sample dryness.

Figures:

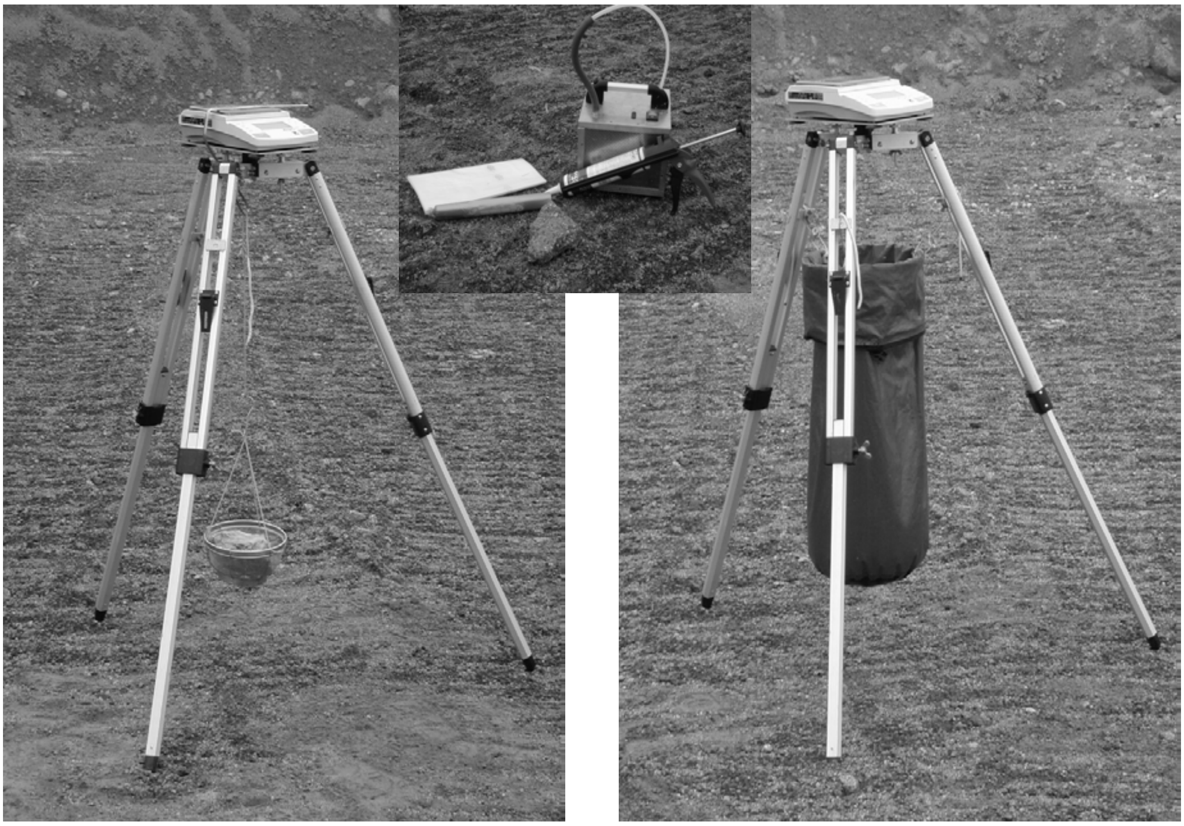

Figure 1: The field apparatus with the battery-powered balance fixed on an aluminium tripod and the holding device for the sample (left) inside the waterproof bag (right). The inset (above) shows the battery-powered vacuum pump, the silicon injection device and various bags.

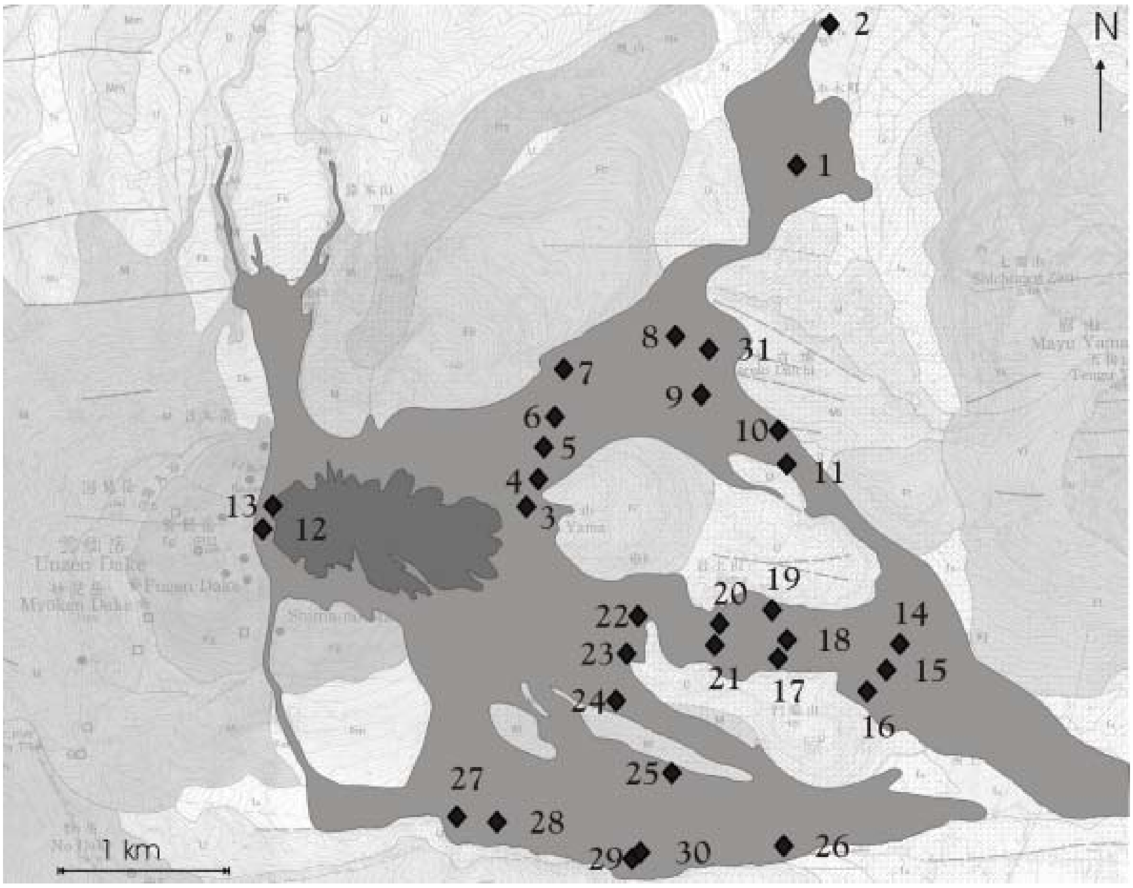

Fig. 2: Distribution of density measurement locations at Unzen. Dome in dark grey, block-and-ash-flow deposits in bright grey.

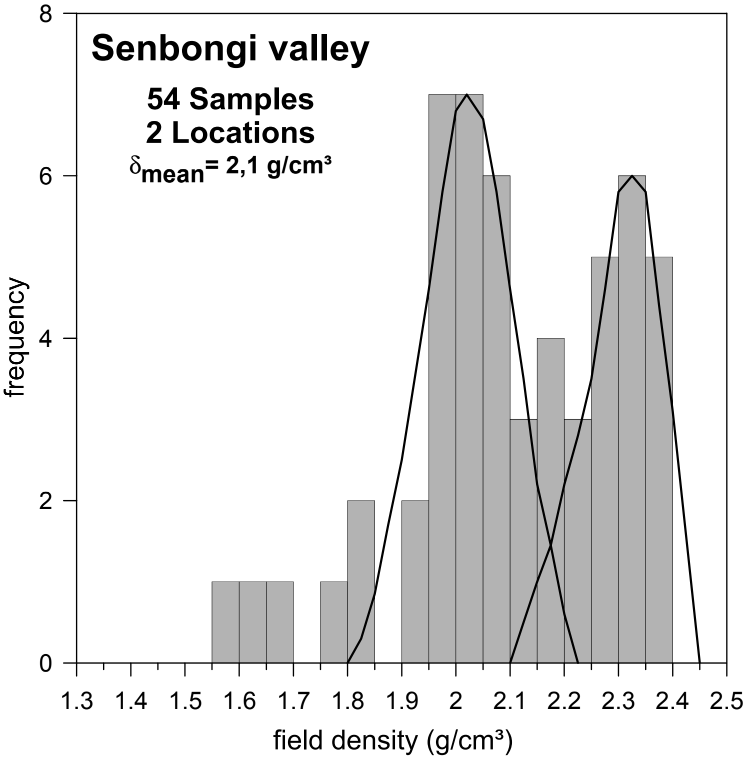

Fig. 3: Results from 54 density measurements in Senbongi valley. Densities range from 1.6 to 2.4 g/cm^3 with an average value of 2.1 g/cm^3. The bimodal density distribution can be clearly seen and is indicated by the two black curves.

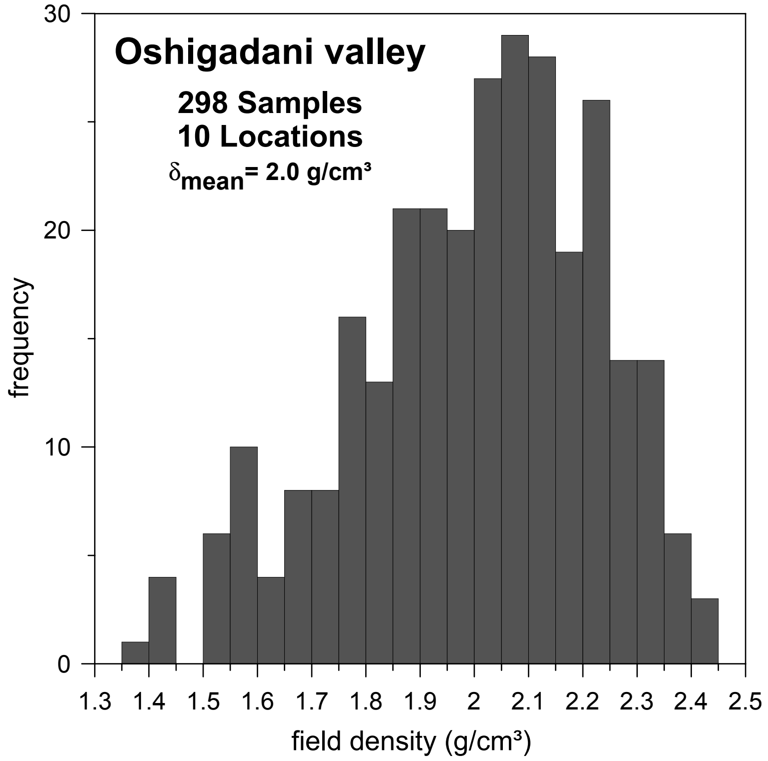

Fig. 4: Results from 298 density measurements in Oshigadani valley. Densities range from 1.4 to 2.4 g/cm^3 with an average value of 2.0 g/cm^3.

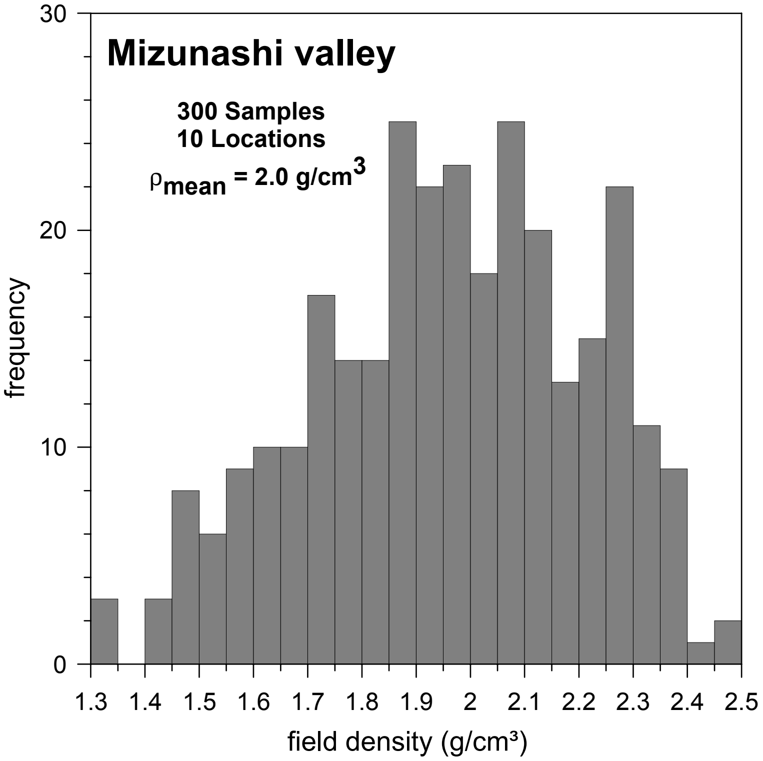

Fig. 5: Results from 300 density measurements in Mizunashi valley. Densities range from 1.3 to 2.5 g/cm^3 with an average value of 2.0 g/cm^3.

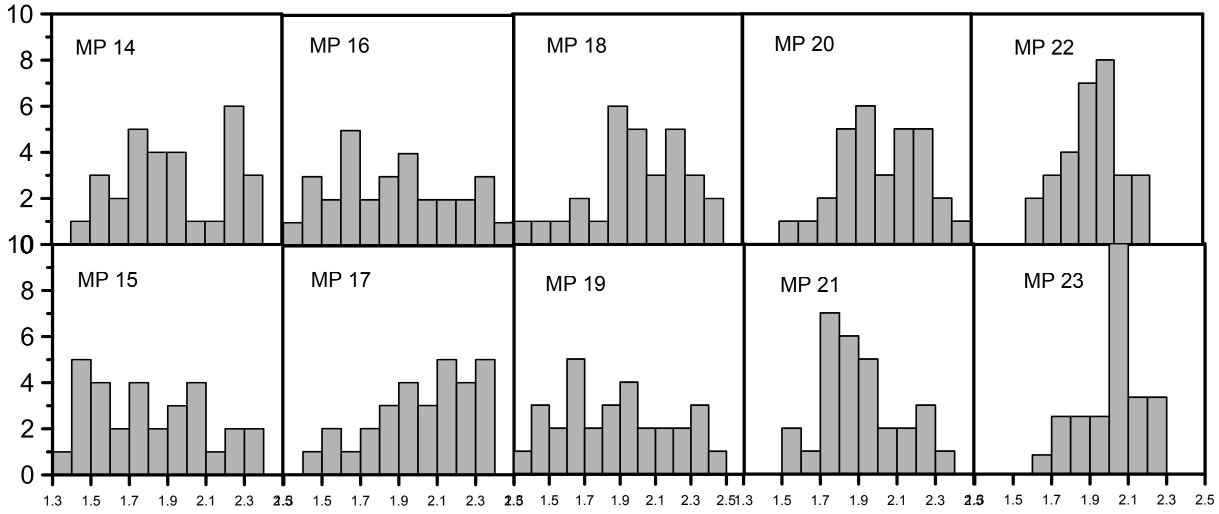

Fig. 6: Density distribution of all ten measurement points (MP 14-23 in Fig.2) inside Mizunashi valley. It becomes obvious that at some MP the amount of samples measured does not allow any statistical conclusions. X-axis covers the 1.3-2.5 g/cm^3 density range for each single MP, y-axis shows the amount of samples.

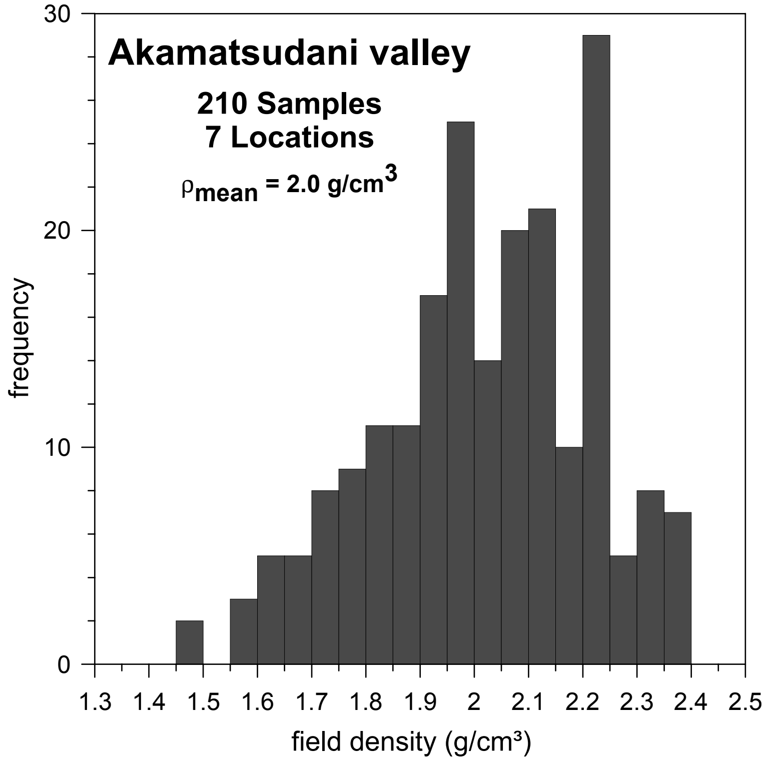

Fig. 7: Results from 210 density measurements in Akamatsudani valley. Densities range from 1.6 to 2.4 g/cm^3 with an average value of 2.0 g/cm^3.

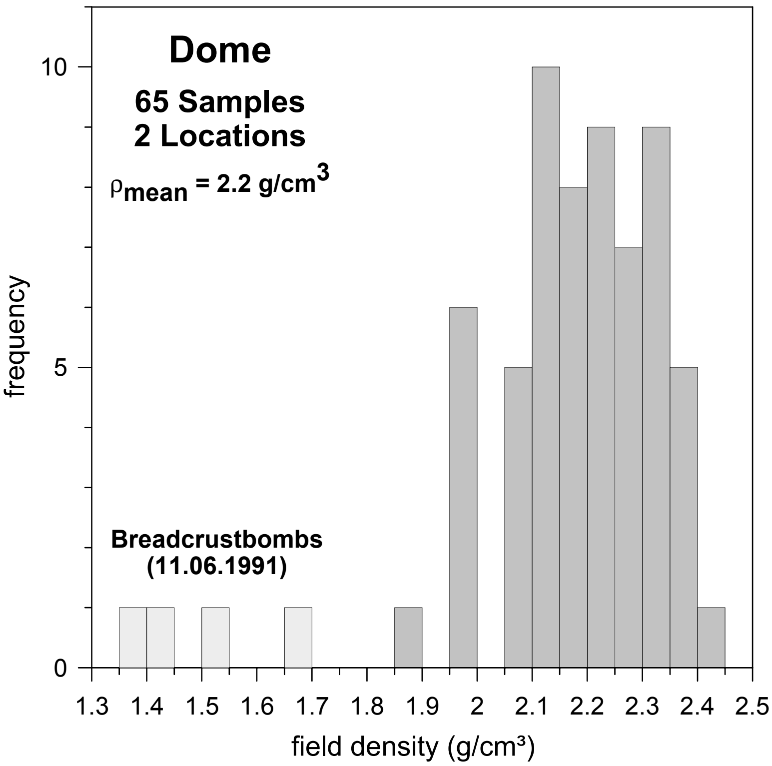

Fig. 8: Results from 65 density measurements on the dome. The found densities of dome lavas range from 1.9 to 2.4 g/cm^3 with an average value of 2.2 g/cm^3. Bread crust bombs from 11 June 1991 vulcanian eruption show densities in the range of 1.3-1.7 g/cm^3.

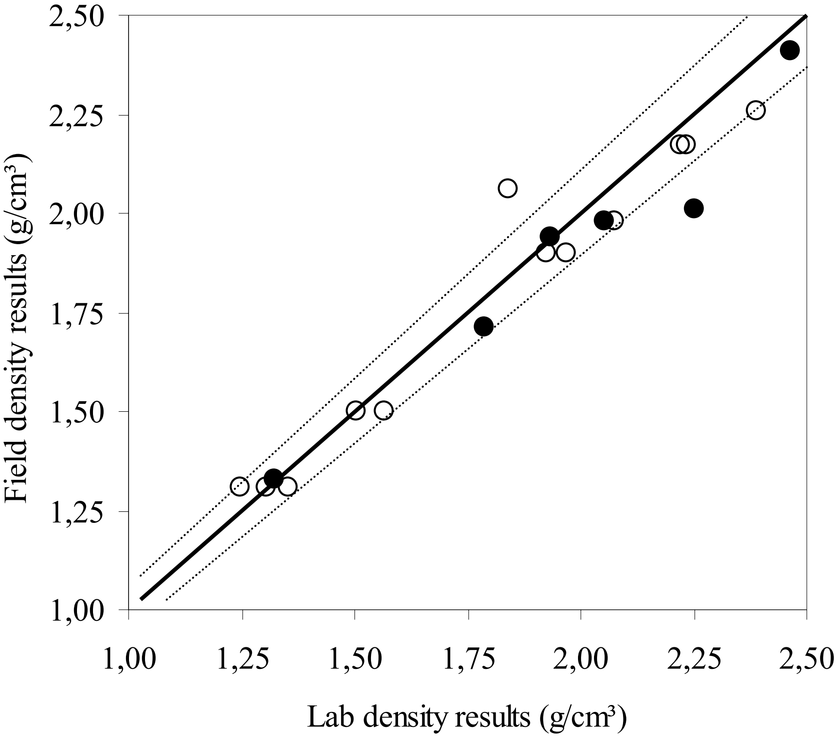

Fig. 9: Laboratory vs. field results of density measurements from 2000 (full circles) and 2001 (open circles) samples. The results show a good agreement between the two data sets. Dashed lines mark the 5 % error line. 23 data points represent 96 correlation measurements.

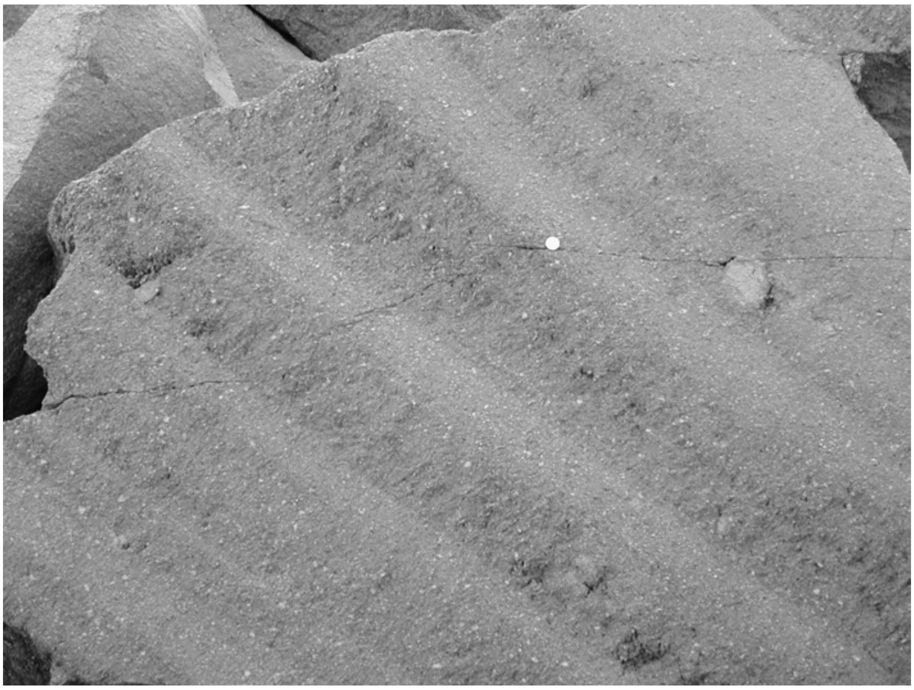

Fig 10: Layers of different porosity in blocks on the dome. Layer thickness is in the cm to dm range. (picture width approx. 1m)

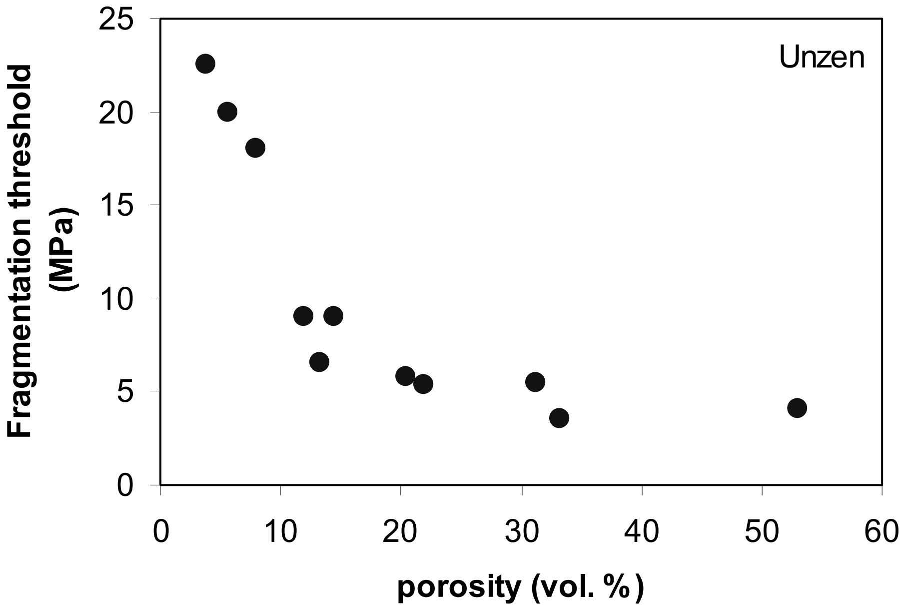

Figure 11: Plot of fragmentation threshold (MPa) vs. porosity of samples from Unzen volcano, Japan. A non-linear dependency is clearly visible.