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Texture analysis of volcanic rock samples: Quantitative study of crystals and vesicles shape preferred orientation from X-ray microtomography data

M. Voltolini [a,*], D. Zandomeneghi [b], L. Mancini [a], M. Polacci [c]

[a] Sincrotrone Trieste, S.S. 14 - km 163.5, 34149 Basovizza (TS), Italy
[b] International Centre for Theoretical Physics, Strada Costiera 11, 34151 Trieste, Italy
[c] Istituto Nazionale di Geofisica e Vulcanologia Sezione di Pisa, via della Faggiola 32, 56126 Pisa, Italy

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ABSTRACT

In the texture analysis of volcanic rocks, the preferred orientation of the constituents can provide useful information for the interpretation of the processes involved in the rock formation. We present here a new data analysis technique, based on X-ray microtomography measurements and on shape preferred orientation analysis, to obtain the orientation distribution functions of the constituents of volcanic rocks. This procedure proved to be very suitable for volcanic samples, where diffraction-based techniques, developed for crystallographic preferred orientation studies, are of limited utilization, in addition to the fact that they cannot provide any information about vesicles or bubbles. Moreover the analysis performed directly in three dimensions (3D) overcomes the problems that usually occur when employing stereological methods for the analysis of the images obtained via microscopy-based techniques. In this study, two scoriae (from Stromboli and Etna) and a tube pumice (from Campi Flegrei) were measured via X-ray microtomography and then the resulting volumes were analyzed following the proposed procedure. Results highlight little preferred orientation for the vesicles in the two scoria samples, whereas the pumice shows a marked preferred orientation. Crystals (also divided by mineral species) were taken into account as well and in the two scoria samples there is no crystal preferred orientation, in contrast with the pumice, where crystal preferred orientation features are very similar to the ones found for the vesicles. Overall we found strong differences in preferred orientation: weak for vesicles in scoriae, showing an axial symmetry with the axis parallel to the elongation axis of the sample, and a stronger and more complex orientation texture in the pumice sample for both crystals and vesicles. The promising results obtained suggest that this procedure is potentially very useful for the analysis of preferred orientation in volcanic rocks and geomaterials in general.

1. Introduction

The formation of a volcanic rock is a complex process: many steps are involved, from magma ascent in the conduit to fragmentation and emplacement beyond the crater's rim. At the end, all these processes are somehow recorded in the texture of the rock. In particular, the products of explosive eruptions, such as pumices and scoriae, feature an arrangement of crystals and vesicles within a glassy framework. This arrangement represents the status of the magma prior to the fragmentation process; therefore a great deal of information about the history of the rock formation can be obtained by the study of its texture. Amongst the textural features of rocks, quantification of the orientation of the rock components represents an interesting field of research in the Geosciences.

Recent analyses of textures and microstructures are found in a number of works that use different techniques such as optical and electron microscopy (e.g. Schipper et al., 2010; Shea et al., 2010) or X-ray computed microtomography (micro-CT) (e.g. Mock and Jerram, 2005; Gualda and Rivers, 2006; Polacci et al., 2006, 2010; Colò et al., 2010).

The term "texture" in Earth Sciences is often used with different meanings: for example in Volcanology it is used in a more general sense, referring to all the microstructural features of the materials; in crystallography it is instead used as synonymous for "preferred orientation". In the present work we use analytical procedures commonly used in the field of crystallography to obtain quantitative preferred orientation information of the samples, so it is worth clarifying that we will use the term "texture" by its broader meaning, while "preferred orientation" will be used to refer specifically to the object spatial orientation only.

The most widespread tools used by the Geosciences community to obtain fast qualitative information about rock textures, and for the identification of the rock constituents, are optical and electron microscopy, while more quantitative information can be obtained via

* Corresponding author at: Now at: Dip. di Geoscienze, Universita' di Padova, via Giotto 1, 35137 Padova, Italy. Tel.: +39 049 8272035; fax: +39 049 8272010.
E-mail address: marco.75v@gmail.com (M. Voltolini).

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image analysis techniques. These methods have been widely applied to volcanic products to study vesicle and/or crystal size distributions, which are related to the history of the rock formation (e.g. Cashman and Mangan, 1994).

An accurate quantification of the preferred orientation of rock constituents is a less straightforward procedure, though. Microscopy-based techniques show severe limits due to the lack of information in the 3rd dimension. This is a serious issue to take into account when quantifying textural parameters, in general, using microscopy-based techniques. To overcome this problem stereological techniques have been developed to get 3D information from 2D data (e.g. Sahagian and Proussevitch, 1998). This approach proved to be reliable with isotropic samples; however, when anisotropic objects are present in the material, stereological techniques are likely to provide inaccurate results (see e.g. comments in Shea et al., 2010). It is claimed that some specific procedures work properly also when employed on strongly anisotropic samples (see e.g. the intersections probability distribution method described in Sahagian and Proussevitch, 1998; Morgan and Jerram, 2006). However this kind of approach still shows some significant limitations, the more evident being that several images of sections from the same material, cut in different directions, are needed. Given these issues, a non-destructive technique working directly on 3D data would be clearly advantageous.

In the case of very small objects, such as microlites, 3D orientation can be directly obtained by optical microscopy using series of images taken with different focus depth (Manga, 1998; Castro et al., 2003). A significant drawback of this method, in addition to the applicability on very specific samples only, is the amount of the operator effort needed to obtain a limited number of orientations.

In Earth Sciences, besides conventional microscopy techniques, there are a number of methods routinely used for preferred orientation analysis, usually aimed at obtaining information about the preferred orientation of crystal lattices as the Crystallographic Preferred Orientation (CPO).

Specific techniques have been developed and can be used in very particular cases, e.g. Heilbronner and Tullis (2006) obtained quartz *c*-axis, crystal lattice orientation from petrographic microscopy data.

Electron Back-Scattering Diffraction (EBSD) is perhaps the most widespread technique used to obtain the CPO of mineral species in the sample; given this characteristic, in Volcanology it is commonly used with fully crystalline samples (e.g. to study exsolution mechanisms as by Feinberg et al., 2004 or to study xenolites texture as by Vonlanthen et al., 2006). This technique is used on polished sections to obtain 3D information about crystals orientations on selected surfaces (no volume data); moreover, relying on crystal lattices only, it cannot provide any information about voids and amorphous phases. While this limitation is usually not important for crystalline samples, in volcanic products voids represent a large percentage of the volume and can provide a great deal of information about magmatic processes (see e.g. Rust and Manga, 2002, where shear rates and stresses from bubble shape and orientation in lava flows are obtained). Pole figure X-ray diffraction is another technique commonly used to measure the CPO of mineral species. This technique shows many drawbacks since it is time-consuming, and, as it can only analyze up to ~1 mm thick sections, in transmission geometry (because of adsorption problems), or surfaces (reflection geometry), the effective analyzed volume is very small. In addition, as the analyzed volume must provide a statistically significant number of diffracting domains to avoid grain-ness problems in the data analysis, it is limited to very fine-crystalline samples. Grain-ness problems arise when there are either too few grains or a limited number of grains much bigger than the average: this situation provides data extremely difficult to analyze. More recently hard X-rays from synchrotron sources have been used for CPO studies. Larger volumes can be studied (usually slabs about 1–2 mm are used and analyzed in transmission geometry), data collection is faster, but still grain-ness problems can be encountered. For more coarse-grained samples, neutron diffraction is required, since centimeter-sized samples have commonly to be used. In any case, all techniques based on diffraction are excellent for the preferred orientation of the crystals in the sample, but cannot provide information about the sample voids, and this is a strong limitation in studies concerning volcanic products such as pumices and scoriae.

Anisotropy of Magnetic Susceptibility (AMS) is also used for preferred orientation studies and is strictly related to crystal lattice orientation as well. This technique is useful in describing the magnetic anisotropic properties of large samples, but advanced data interpretation, such as separating different mineral contributions to the sample anisotropy, is not a trivial task (see e.g. Pioli et al., 2008 for a study on tuff). Ultrasonic velocities are also used to study the global anisotropic properties of rocks (including contributions from CPO, voids and grain contacts), but no information about single phases is obtainable. An example showing the importance of taking both voids (including their orientation) and microstructural parameters into account when calculating anisotropy of ultrasonic velocities from CPO data (in shales) can be found in Wenk et al. (2008).

X-ray computed microtomography (micro-CT) proved to be a very suitable technique to overcome the problem of deriving 3D results from 2D data, typical of microscopy-based techniques. Another advantage of the X-ray micro-CT technique with respect to conventional microscopy is the easy sample preparation. In fact, small samples (from millimeter- to-centimeter sized samples) can be used without preparation, while the preparation of thin sections of extreme fragile material (e.g. pumices with very thin vesicle walls) could be very troublesome. X-ray micro-CT is an extremely useful technique for material structure analysis, including rock samples: conventional X-ray micro-CT has been successfully applied to the investigation of volcanic sample microstrucures, with a focus on vescicularity (e.g. Nakashima and Kamiya, 2007; Degruyter et al., 2009; Polacci et al., 2009a; Zandomeneghi et al., 2010). Synchrotron X-ray micro-CT has been used for the analysis of volcanic rock samples, to obtain quantitative parameters about volcanic rocks textures, used to speculate about the magma properties, and the community of volcanologists recognizes it as a very valuable tool. (see e.g. works of Song et al., 2001; Gualda and Rivers, 2006; Polacci et al., 2006; Andronico et al., 2008; Polacci et al., 2008, 2010).

There are different methods to quantify microstructure and anisotropy of materials studied with micro-CT and some software tools have been developed (e.g. Lindquist, 1999; Ketcham, 2005a,b; Brun et al., 2010). Despite this effort, little work has been done in the field of quantitative analysis of Shape Preferred Orientation (SPO) taking advantage of micro-CT data (Ketcham, 2005b). However, there have been some notable examples of using micro-CT data to quantify preferred orientation: the distribution of the elongation axis of metal particles in meteorites has been used to discuss the impact strength of the sample (Friedrich et al., 2008). Kinney et al. (2005) provided a more advanced analysis, where an Orientation Density Function (ODF) is calculated and used for data interpretation on trabecular bone samples.

In this work we present a generalized method to perform SPO analysis from micro-CT data followed by a discussion about its potentials and reliability. This method has been used to study the preferred orientation of *both* crystals and vesicles in complex volcanic rock samples and it proved to be a reliable and useful method for texture analysis. Obtaining preferred orientation information about both crystals and vesicles is of primary importance in the study of volcanic rocks since they both record events involved in the rock formation, such e.g. stress fields. Another significant advantage is that one single micro-CT measurement can supply the whole preferred orientation information. In particular this is the first time that an 3D SPO study is performed on volcanic products using micro-CT data. Quantitative SPO parameters are obtained and the preliminary results and interpretation are given, together with a comparison with other