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Tracking and understanding explosive volcanic emissions through cross-disciplinary integration: Findings from an ESF-supported textural working group

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Corresponding Author:	Lucia Gurioli FRANCE
Corresponding Author Secondary Information:	
Order of Authors:	Lucia Gurioli
	Daniele Andronico
	Patrick Bachelery
	Hélène Balcone-Boissard
	Jean Battaglia
	George Boudon
	Alain Burgisser
	Sarah Cichy
	Mike Burton
	Katharine Cashman
	Raffaello Cioni
	Andrea Di Muro
	Lucia Dominguez
	Claudia D'Oriano
	Timothy Druitt
	Andrew Harris
	Matthias Hort
	Karim Kelfoun
	Jean-Christophe Komorosky
	Ulrich Kueppers
	Jean-Luc Le Pennec
	Thierry Menand
	Raphael Paris
	Laura Pioli
	Marco Pistolesi
	Margherita Polacci
	Massimo Pompilio
	Maurizio Ripepe

	Olivier Roche
	Estelle Rose-Koga
	Alison Rust
	Federica Schiavi
	Lea Sharff
	Roberto Sulpizio
	Jacopo Taddeucci
	Thor Thordarson
Abstract:	A workshop entitled "Tracking and understanding volcanic emissions through cross-disciplinary integration: A textural working group." was held at the Université Blaise Pascal (Clermont-Ferrand, France) on the 6-7th November 2012. This workshop was supported by the European Science Foundation (ESF). The main objective of the workshop was to establish an initial advisory group to begin to define measurements, methods, formats and standards to be applied in the integration of geophysical, physical and textural data collected during volcanic eruptions so as to homogenize procedures to be applied and integrated during both past and ongoing events. The working group comprised a total of 35 scientists from six countries (France, Italy, Great Britain, Germany, Switzerland and Iceland). The group comprised eleven advisors from the textural analysis field, eleven from deposit studies, seven geochemists and six geophysicists. The four main aims were to discuss and define: *Standards, precision and measurement protocols for textural analysis; *Identify textural, field deposit, chemistry and geophysical parameters that can best be measured and combined; *Agree on the best delivery formats so that data can be sheared between, and easily used by, each group; *Review multi-disciplinary sampling and measurement routines currently used, and measurement standards applied, by each community. The group agreed that community-wide cross-disciplinary integration, centered on defining those measurements and formats that can be best combined, is an attainable but key global focus. Consequently, we prepared a final document to be used as the foundation for a larger, international textural working group to serve as the basis of fully realizing such a pan-disciplinary goal in volcanology. Thus, we here report our initial conclusions and recommendations.
Suggested Reviewers:	Amanda Clarke amanda.clarke@asu.edu
	Greg Valentine gav4@buffalo.edu
	Thomas Shea tshea@hawaii.edu
	Mike Ramsey mramsey@pitt.edu
	Don Swanson donswan@usgs.gov
	Jessica Larsen jflarsen@alaska.edu

Lucia Gurioli
Physicienne

Laboratoire Magmas et volcans
Observatoire du Physique du Globe de Clermont
Université Blaise Pascal
5 rue Kessler
63038 Clermont-Ferrand
France
Tel: +33 (0)473346782
Fax: +33 (0)473346744
Email: l.gurioli@opgc.univ-bpclermont.fr
WEB: http://www.opgc.univ-bpclermont.fr/

Date: 16/11/2014

Dear James and Steve,

Please find attached a manuscript we wish to submit to Bulletin of Volcanology as a review paper. It is entitled “Tracking and understanding explosive volcanic emissions through cross-disciplinary integration: Findings from an ESF-supported textural working group”, and involves 36 authors from 16 different European institutes.

The review is the result of a MeMoVolc workshop held in Clermont Ferrand in 2012. MeMoVolc is an effort funded by the European Science Foundation, and managed by Tim Druitt and Augusto Neri, with the aim of bringing together European researchers spread across multiple European countries to focus on a number of current themes in volcanology. In that regard, the aim of the review is to present the state of the art for textural characterization of volcanic products, current limits and the potential for integration of deposit, geochemical and geophysical data to enhance our understanding of systems that feed explosive eruptions. It is the result of presentations and discussions during the two day workshop held in 6-7th November 2012, and involves all contributors.

Because of its interdisciplinary nature, the review is quite long with a very long reference list that we have made complete up to 2014. We did not use figures, but have instead summarized the main points in five tables. This contribution is effectively an open dialogue where we have reported the state of the art from an European perspective with the idea of providing the reader a list of open questions, needs and recommendations.

I feel very responsible for this paper because of the large community included in it, and it has taken many months to put together with contributions and dialog from all 36 participants. We hope that Bulletin of Volcanology finds this work of value.

Suggested reviewers:

1) Amanda Clarke
School of Earth and Space Exploration Interdisciplinary Science and Technology
Tempe, AZ 85287-6004, USA
amanda.clarke@asu.edu
Phone: 1 (480) 965-6590

2) Greg Valentine
State University of New York, University at Buffalo
411 Cooke Hall
Buffalo, NY 14260-1350, USA
gav4@buffalo.edu
Phone:

3) Thomas Shea
University of Hawaii Geology and Geophysics,
1680 East-west rd POST 614B
Honolulu, HI, 96822, USA
tshea@hawaii.edu
Phone: +1 808 956 9819

4) Mike Ramsey
4107 O'Hara Street
University of Pittsburgh
Pittsburgh, PA 15260
mramsey@pitt.edu
Phone: 412-624-8772

5) Don Swanson
HVO
P.O. Box 51, HI, USA
donswan@usgs.gov
Phone: 808-967-8863 x

6) Jessica Larsen
Geophysical Institute
903 Koyukuk Drive, Univ. of Alaska
Fairbanks, AK 99775-7320
jflarsen@alaska.edu
Phone: (907) 474-7558

Tracking and understanding explosive volcanic emissions through cross-disciplinary integration: Findings from an ESF-supported textural working group

L. Gurioli[1], D. Andronico[2], P. Bachelery[1], H. Balcone-Boissard[3], J. Battaglia[1], G. Boudon[4], A. Burgisser[5], S.B. Cichy[1], M.R. Burton[6], K. Cashman[7], R. Cioni[8], A. Di Muro[9], L. Dominguez[10], C. D'Oriano[6], T. Druitt[1], A.J.L Harris[1], M. Hort[11], K. Kelfoun[1], J.C. Komorosky[4], U. Kueppers[12], J.L. Le Pennec[1], T. Menand[1], R. Paris[1], L. Pioli[10], M. Pistolesi[13], M. Polacci[6], M. Pompilio[6], M. Ripepe[8], O. Roche[1], E. Rose-Koga[1], A. Rust[7], F. Schiavi[1], L. Sharff[11], R. Sulpizio[14], J. Taddeucci[15], T. Thordarson[16]

1 Laboratoire Magmas et Volcans, Université Blaise Pascal - CNRS - IRD, OPGC, 5 rue Kessler, 63038 Clermont Ferrand, France
2 INGV, Osservatorio Etneo, Sezione di Catania, 95125 Catania, Italy
3 Sorbonne Universités, UPMC Univ Paris 06, UMR 7193, Institut des Sciences de la Terre Paris (iSTeP) and CNRS, F-75005 Paris, France
4 Institut de Physique du Globe (IPGP), Sorbonne Paris-Cité, Université Paris Diderot, CNRS UMR-7154, 1 rue Jussieu, 75238 Paris Cedex 05, France
5 ISTerre Université de Savoie CNRS, 73376 Le Bourget du lac, France
6 INGV, Sezione di Pisa, 56126 Pisa, Italy
7 School of Earth Sciences, University of Bristol, United Kingdom
8 Dipartimento di Scienze della Terra, Università degli Studi di Firenze, 50121 Florence, Italy
9 Institut de Physique du Globe (IPGP), Sorbonne Paris-Cité, CNRS UMR-7154, Université Paris Diderot, Observatoire Volcanologique du Piton de la Fournaise (OVPF), Bourg Murat, France
10 Département de Minéralogie, Université de Genève, Switzerland
11 Klimacampus, CEN, University of Hamburg, Germany
12 Ludwig-Maximilians-Universitaet (LMU), Munich, Germany
13 Dipartimento Scienze della Terra, Università degli Studi di Pisa, Italy
14 Dipartimento di Scienze della Terra e Geo-Ambientali, Università degli Studi di Bari, Italy
15 INGV, Sezione di Roma, 00143 Roma, Italy
16 Institute of Earth Sciences (IES), University of Iceland, Reykjavík, Iceland

Abstract

A workshop entitled "*Tracking and understanding volcanic emissions through cross-disciplinary integration: A textural working group*." was held at the Université Blaise Pascal

(Clermont-Ferrand, France) on the 6-7th November 2012. This workshop was supported by the European Science Foundation (ESF). The main objective of the workshop was to establish an initial advisory group to begin to define measurements, methods, formats and standards to be applied in the integration of geophysical, physical and textural data collected during volcanic eruptions so as to homogenize procedures to be applied and integrated during both past and ongoing events. The working group comprised a total of 35 scientists from six countries (France, Italy, Great Britain, Germany, Switzerland and Iceland). The group comprised eleven advisors from the textural analysis field, eleven from deposit studies, seven geochemists and six geophysicists. The four main aims were to discuss and define:

- Standards, precision and measurement protocols for textural analysis;
- Identify textural, field deposit, chemistry and geophysical parameters that can best be measured and combined;
- Agree on the best delivery formats so that data can be sheared between, and easily used by, each group;
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The group agreed that community-wide cross-disciplinary integration, centered on defining those measurements and formats that can be best combined, is an attainable but key global focus. Consequently, we prepared a final document to be used as the foundation for a larger, international textural working group to serve as the basis of fully realizing such a pan-disciplinary goal in volcanology. Thus, we here report our initial conclusions and recommendations.

Introduction

A major goal of modern volcanology is to relate conditions of magma ascent to the resulting eruption style using information preserved in volcanic deposits. Because it is impossible to directly observe magma ascent, vesiculation and fragmentation, one way of obtaining quantitative information on magma ascent dynamics is through textural quantification of the sampled products. Textural quantification involves full description of the vesicle and crystal properties of erupted products (e.g. Sparks 1978; Sparks and Brazier 1982; Whitham and Sparks 1986; Houghton and Wilson 1989; Marsh 1988, 1998; Cashman and Marsh 1988, Toramaru 1989, 1990; Cashman and Mangan 1994; Higgins 2000; 2006; Blower et al. 2002;

Burgisser and Gardner 2005; Shea et al. 2010a; Rust and Cashman 2011; Baker et al. 2012 and references therein). The relationship between the textural character of the erupted products and magma viscosity, ascent rate, vesiculation process, fragmentation style and explosion dynamic relies on the fact that these latter mechanisms imprint characteristic and measurable properties on the volcanic products, as proved through theoretical and experimental studies (e.g. Rust and Cashman 2011; Gonnerman and Houghton 2012; Degruyter et al. 2012; Nguyen et al. 2013 and reference therein). The main assumption is that most of the pyroclast properties are acquired during ascent in the conduit, with little changes occurring after fragmentation or when the products are in the atmosphere, if the pyroclasts are lapilli size, i.e., less than 2-3 cm (e.g. Houghton and Wilson 1989; Nguyen et al. 2013). Specifically, the textural parameters of the pyroclastic components have been shown to yield insights into the dynamics of explosive eruptions, as reviewed in Table 1.

However, the physical characteristics of individual pyroclasts must not be considered in isolation from detailed studies of (i) the deposits from which they were collected, (ii) their chemical properties, (iii) geophysical signatures of the related explosive event, and (iv) petrological and/or analogue experiments. Indeed, attempts to understand eruption dynamics have been increasingly coupled to traditional fieldwork and geophysical measurements made synchronously with sample collection. In 2004, a special issue of the *Journal of Volcanological and Geothermal Research* (Volume 137) focused on multidisciplinary approaches, proposing "*simultaneous collection of multiple geophysical data sets, such as seismic, infrasonic, thermal and deformation data, as well as sampling of ejecta and detailed mapping*". The argument was that "*complete constraint of a volcanic system is not possible using one data set, so that an integrated multiparametric approach involving simultaneous collection of multiple geophysical and petrological data sets will increase our ability to reach tightly constrained and confident conclusions regarding the mechanics and dynamics of volcanic systems and eruptions*" (Harris et al. 2004). Since 2004, numerous studies have borne these predictions out, combining textural data with:

i. Field deposits (e.g. Polacci et al. 2006a; Rust and Cashman 2007; 2011);
ii. Petrological data (e.g. Larsen 2008; Shea et al. 2009; 2010b; Burgisser et al. 2010; Bai et al. 2011);
iii. Chemical analyses (e.g. Piochi et al. 2005, 2008; Shimano and Nakada 2005; Noguchi et al. 2006; Costantini et al. 2010; Balcone-Boissard et al. 2010, 2011, 2012; Shea et al. 2012; 2014)

iv. Geophysical measurements (e.g. Burton et al. 2007; Gurioli et al. 2008, 2013; 2014; Polacci et al. 2009b; Andronico et al. 2008; 2009a; 2009b; 2013a, 2013b; Miwa et al. 2009; Miwa and Toramaru 2013; Colò et al. 2010; Landi et al. 2011; Pistolesi et al. 2011; Leduc et al. in press), and

Together these studies have delivered complete pictures of explosive eruptions and their dynamics.

In spite of this progress, we remain far from establishing the best method to sample pyroclasts, and to correlate and compare the multitude of parameters that can be measured using individual clasts and field deposits. In addition, no study has yet attempted to correlate all derivable textural parameters with the full range of multidisciplinary data available. To partially resolve these issues, a working group was set up including a mixture of experts currently active in the field of integration of textural, deposit and geophysical data, equally balanced between expertise in each of four theme areas: (i) textural studies, (ii) deposit analysis, (iii) chemistry and (iv) geophysics. Funded by the European Science Foundation, through the MeMoVolc program (http://www.memovolc.fr/), the initial grouping focused on European interests.

The final objective was to ensure that data collected in the field and laboratory can be shared effectively and be ingested in multi-disciplinary sense into experiments, modeling and monitoring. In the longer-term, the group's objective will be to publish and update standards, as well as to propose, support and organize field meetings to test integrated collection methodologies. The ultimate aim is to increase the number of open-access data-bases of standard and community-accepted quality, so as to make increasing resources available for cross-disciplinary correlations.

Methodology

Following a pre-meeting discussion and preparation of "*a list of discussion points*", the group convened on 6-7 November 2012 at the Université Blaise Pascal (Clermont-Ferrand, France). The priorities of the two-day meeting were discussion and definition of:

- Improved standards, precision and measurement protocols needed by the textural field.
- Discussion and definition of best practices for textural studies in order to have comparable datasets from different types of eruptions.

- Definition of parameters obtained from textural, field deposit, geochemical and geophysical data that need to be measured, and the best delivery format if each discipline's output is to be of use to the next.
- Review multi-disciplinary sampling and measurement routines, as well as measurement standards.

Because of the workshop time constraints, we decided to focus only on the study of explosive eruptions that generate sustained columns or fountains, and the associated fallout deposits. After a general introduction, we split into four subgroups: deposits, textural, geochemistry and geophysics. Before splitting, the core, communal issues to be explored were agreed on as follows:

1. Which are the best sampling and measurement strategies for the quantification of pyroclast textural features, and what are their precision and uncertainty?
2. Which are the best sampling and measurement strategies for pyroclastic deposits to allow textural characterization of their components?
3. How can we link chemistry, geochemistry and textural quantifications?
4. How can we link geophysical data and the textural quantification?
5. What is the best multi-disciplinary strategy to apply so as to combine output from each field in a meaningful way?

Full-group, and then sub-group break-out discussions, comprised the first day. Overnight, report-back presentations and chair notes were prepared, so that the second day began with four presentations – one from each group. This was followed by round-table brainstorming to distill global objectives and priorities for a texturally-based working group with the objective of "*tracking and understanding volcanic emissions through cross-disciplinary integration*". The reports of each sub-group are given here, as well as the report drawn up following the synthesis and post-meeting discussions.

Sampling of pyroclasts and quantification of their textural features

(i) Representative samples

It is assumed that pyroclasts from tephra deposits reflect the degassing history of the magma, from the conduit to the plume. Therefore, part of the textural signature is assumed to reflect that acquired at the fragmentation (or explosion) zone. Consequently it can be used as an indicator for magma properties (composition, porosity, connectivity, permeability, vesicle and crystal content, size, shape and distribution) at that time (Table 1). This assumption has two requirements:

i. The textural signature that we believe were quenched immediately at the fragmentation point can be distinguished by the textural effects of post-fragmentation processes, including microlite formation and bubble nucleation, expansion, collapse, coalescence and Ostwald ripening that will change clast vesicularity or vesicle size and shapes once the pyroclast has been formed (e.g. Thomas et al. 1994; Cashman et al. 1994; Herd and Pinkerton 1997; Larsen and Gardner 2000; Gurioli et al. 2008; Costantini et al. 2010; Stovall et al. 2011, 2012). The time window for post-fragmentation changes depends on magma composition, viscosity and fragmentation depth.
ii. Because clast density is also a function of clast size (Houghton and Wilson 1989), only clasts of similar sizes must be used to avoid non uniform grain-size effects on textural parameters.

We thus recommend choosing selected samples that are representative of the studied explosion, or unit, in terms of:

i. Timing: This requires sampling of narrow stratigraphic intervals (Houghton and Wilson 1989) in which juvenile clasts of similar dimensions can be assumed to represent those parts of the magma fragmented at a particular time (n.b conduit processes can change over short timescales);
ii. Distribution: This requires selection of more than one outcrop for each event;
iii. Degree of fragmentation: This requires selection of a sampling methodology that is appropriate for the whole grain size distribution;
iv. Componentry: If the juvenile fraction is heterogeneous, sampling should be done based on preliminary componentry analysis of the clast analyzed for density (e.g. Wright et al. 2011)

In previous studies, only clast sizes of 16-32 mm, i.e. coarse lapilli (e.g. White and Houghton 2006) have been considered for textural purposes. Such clasts were considered to be large enough to be easily sampled and studied, while being fully representative of the density variation of the majority of erupted pyroclasts and not having been affected by significant post-fragmentation phenomena (Houghton and Wilson 1998). These requirements are not always met. In basaltic magma, post-fragmentation effects can be a complication even for these sizes (e.g. Cashman et al. 1994; Costantini et al. 2010; Gurioli et al. 2008; Pioli et al. 2014; Pistolesi et al. 2008; 2011; Stovall et al. 2011; 2012). In these cases, the challenge is to identify, quantify and remove post-fragmentation effects in order to isolate textures generated during, or immediately, before fragmentation. For example, the original shapes of vesicles may be reconstructed artificially de-coalescencing large vesicles using the presence of residues of broken, or partially retracted, glassy septa.

However, if we study an ash-dominate or a bomb-dominated event, textural analyses need to be performed on the fine or coarse juvenile fragments. More recently ash size particles (<2 mm) has been investigated (Taddeucci et al. 2002, 2004; Cioni et al. 2008; D'Oriano et al. 2011a; b Miwa et al. 2009; 2013; Miwa and Toramaro 2013; Proussevitch et al. 2011; Genareau et al. 2012; 2013; Colucci et al. 2013). For the ash size fraction, post-fragmentation expansion can be excluded (e.g. Proussevitch et al. 2011; Genareau et al. 2012; 2013; Colucci et al. 2013). Consequently analyses allow comparison between morphological and textural features of clasts sampled in proximal and distal areas. Ash particles can record most of the information related to magma ascent dynamics (e.g. decompression-driven microlite crystallization) and fragmentation (Cioni et al. 2008; D'Oriano et al. 2010; D'Oriano et al. 2011a, b; Proussevitch et al. 2011; Genareau et al. 2012; 2013; Colucci et al. 2013). Advantages of studying ash is that it can also be statistically more representative of the variability of the magma properties and is less affected by density-driven settling within the plume. However, ash fragments record only small-scale vesicularity. The integration of observations made on the external shapes of clasts may give information about the presence and importance of a coarser vesicularity which drives magma fragmentation (e.g. Proussevitch et al. 2011; Genareau et al. 2012; 2013; Colucci et al. 2013). However, this may lack complete information about the abundance and size of the full vesicle population, if the eruptive products also include larger fragments. Furthermore, ash particles are not suitable for permeability studies, as they are often smaller than the bubbles forming the permeability network. However, the presence of coalesced vesicles in a preferred direction, and an abundance of ash clasts with an elongated shape, have been interpreted as an indication of the development of a network of permeability in the magma (D'Oriano et al. 2010a).

Bombs may represent a plethora of information for pre-eruptive degassing and ascent rate (e.g. Hoblitt and Harmon 1993; Wright et al. 2007), to timing and degree of thermal interaction of magma with wall rock material prior to ejection (Rosseel et al. 2006; Sottili et al. 2009; 2010), and post-fragmentation changes owing to bubble growth, coalescence or shape changes (e.g. Herd and Pinkerton 1997). Finally, they can also provide vesicle shape and vesicle density number N_v in the quenched samples collected directly from the plume, i.e. quenched immediately upon fall out (Gurioli et al. 2014 and Leduc et al. in press).

(ii) Bulk textural measurements

The fastest and most straightforward textural measurement of individual pyroclasts is density (vesicularity), which provides basic information on processes related to gas exsolution and escape (Houghton and Wilson 1989). Density of lapilli and small bombs are determined by comparing their weights in water and air following the Archimedes principle. Clasts can be made impermeable with silicone waterproofing spray or by immersion in cellulose acetate to seal small vesicles, or using a Parafilm™ wax. This technique is rapid and yields large arrays of data with a reproducibility within 10-30 kg m^{-3} and the accuracy within 30 kg m^{-3} (Barker et al. 2012). Following the same principles, a battery-powered device has been used to seal pumice or scoria in plastic bags at vacuum in the field (Kueppers et al. 2005).

For pyroclasts characterized by fine vesiculation (with largest vesicles smaller than 2-3 mm) the density can be measured with the glass beads method (Nakamura et al. 2008) that allows us to calculate the density as well as the volume of an object of irregular size. For large bombs (from 15 to 40 cm in diameter), the "natural waterproofing" approach was applied (Gurioli et al. 2013). Extensive tests showed that decimetric size bombs collected at Stromboli acquired a "natural waterproofing" from their quenched margins, and thus could be weighed in water without waterproofing. This represents a new easy, precise and fast strategy.

Furthermore, the derived density distributions are used as filters to select a few clasts, representative of the low, modal and high density values, from each subpopulation observed (e.g. Shea et al. 2010a). Selected clasts are then used for textural quantification.

Other bulk measurements aimed to quantify the fraction of isolated versus connected vesicles include vesicle connectivity, permeability (Klug and Cashman 1996; Klug et al. 2002; Formenti and Druitt 2003; Rust and Cashman 2004; and references in Table 1) and electrical conductivity (Le Pennec et al. 2001; Bernard et al. 2007; Wright et al. 2009; Wright and Cashman 2014) of individual pyroclasts. The connectivity measurements are mostly performed using gas displacement Helium pycnometers, and they deliver first-order information on the outgassing capacity (i.e., potential for gas loss) of the magma near fragmentation (Klug et al. 2002; Formenti and Druitt 2003; Giachetti et al. 2010; Shea et al. 2011; 2012). Permeability determines the rate at which samples can degas during decompression. Several methods exist for permeability measurements in volcanology. Rust and Cashman (2004) used a commercial permeameter to perform systematic steady-state gas-flow experiments using porous samples and the relationship between flow rate and pressure gradient was determined. They also introduced the Forchheimer equation into volcanology, which is a modified form of Darcy's law and includes the inertial effect of gas flow, and specified the importance of this effect in volcanic degassing processes. Mueller et al. (2005) used gas pressure decay with time after sudden decompression in a fragmentation bomb for the permeability measurements, without measuring gas-flow rate. A falling head permeameter developed by Burbié and Zinszner (1985) has also been used to measure the permeability of volcanic porous materials (Jouniaux et al. 2000; Bernard et al. 2007). Recently a low-cost gas permeameter was developed first by Takeuchi and Nakashima (2005) and then improved by Takeuchi et al. (2008), to measure permeability of natural samples and experimental products. Finally, electrical conductivity measures how well a material transports electric charge. Rocks, in general, are poor conductors, whereas ionic fluids are good conductors. Therefore a measurement of conduction through fluid-saturated rocks provides information about the connected pore pathway through the sample. Although the influence of pathway tortuosity and pore shape on permeability is useful for numerical simulations on gas percolation, it has been the object of only a few studies (Table 1).

(iii) Comparison between 2D and 3D textural measurements

There are two different methods currently available for extracting vesicle and crystal sizes, shapes and distributions in pyroclasts. The first is by conversion of 2D data from a planar surface (such as a thin section or photograph) to 3D data through stereology. The second method derives 3D data directly from X-ray tomographic reconstructions and visualization of clast textures without the need of stereological conversions (Song et al. 2001; Shin et al. 2005; Polacci et al. 2006b; 2008; 2009a; b; 2010; Degruyter et al. 2010b; Gualda et al. 2010; Giachetti et al. 2011; Baker et al. 2012), using computer software especially developed for geo-textural purposes (e.g. Ketcham 2005; Friese et al. 2013). Other 3D methods include serial sectioning (e.g. Bryon et al. 1995), serial focusing with optical microscope (Manga 1998), serial grinding (e.g. Marschallinger 1998a, b, c; Mock and Jerram 2005), and constructing digital elevation models of individual ash grains to calculate vesicle volume (Proussevitch et al. 2011). 2D and 3D observations have different limitations and potential, and so these two methods are becoming complementary, not competitive (e.g. Giachetti et al. 2011; Baker et al. 2011).

2D method

Standard procedures for the 2D method have been recently published for vesicles (Shea et al. 2010a) and crystals (Higgins 2000; 2006). 2D techniques can yield high-quality data in a relatively short time, and account for both vesicle and crystal sizes in the sample. They deals with relatively large numbers of samples, and the method can be applied to particle ranging in size from bombs (e.g. Gurioli et al. 2014) to ash (Miwa et al. 2009; 2013; Miwa and Toramaru 2013). These measurements are best used when there is a broad size distribution to be measured. The main limitation of the method is that is based on assumption of spherical shape of the textural objects, following Sahagian and Proussevitch (1998). When this conversion is simply obtained by dividing the number of vesicle per unit area for the median value of diameter of each size class (Cheng and Lemlich 1983) no shape assumption is made. However, the 3D conversion is more precise when a shape is defined. Empirical corrections are commonly used for crystal analyses (Higgins 2000 and 2006), although for vesicles, whose shapes are less uniform, they risk introducing systematic, uncontrolled errors in the data (Sahagian and Proussevitch 1998; Proussevitch et al. 2007a; 2007b).

3D method

X-ray computed microtomography is the only available high-resolution, non-invasive 3D technique that allows reconstruction, visualization and processing of samples. Data acquisition is generally relatively straightforward, and several scales can be examined and combined, spanning from centimeter-sized to <1 micron objects, depending on the resolution (Giachetti et al. 2011). In addition, with the use of the so-called 'local area' tomography technique (Lak et al. 2008; Mancini 2010), it is possible to reach high-resolutions even with samples larger than the field of view of the camera. However, 3D quantification of textures can also be labor intensive, depending on the size of the volume that needs to be analyzed and on the textural parameters required. The results show the internal structures of samples, highlighting how objects and apertures are linked together. This is an excellent capability for studies on vesicle size, shape and distribution, collapse, deformation, coalescence, permeability, and tortuosity as well as for determining crystal volume, size and distribution and visualizing crystal aggregates in 3D (Polacci et al. 2009a; b; 2012; Bai et al. 2010; 2011 Degruyter et al. 2010a, b; Zandomeneghi et al. 2010; Baker et al. 2012; Castro et al. 2012; Okumura et al. 2013). Vesicles with complex shapes are easily identified while they could results in two or more vesicles in a 2D section thus biasing vesicle size distribution (VSD) and number densities. The 3D method is particularly effective for determining vesicle number density if the study is focused on a specific size distribution range; vesicle number densities over a wide range of sizes is achieved with nested studies where a series of scans are done with different sizes and resolutions. However, the resolution of the reconstruction is still critical. Klug et al. 2002 showed that vesicle walls may be as thin as 0.1µm. To achieve this sort of spatial resolution using tomography requires very small samples. When the attained resolution is 5-15 µm, thin vesicle walls are not resolved.

There is currently no unique protocol for 3D measurements of different types of pyroclastic (or lava) samples; however the SYRMEP group of the Elettra Synchrotron Light Source (Trieste, Italy), together with the McGill University of Montreal and INGV Pisa (M. Polacci) is deploying protocols to be used with volcanic samples characterized by different vesicularities and crystallinities.

(iv) Crystal size distribution

Crystal size distribution (CSD) is a well-established tool for interpreting the physical processes and environmental variables that drive differentiation and crystallization in magma chambers and conduits (e.g. Marsh 1988; Cashman and Marsh 1988; Cashman 1992; Hammer et al. 1999; Cashman and McConnell 2005, Armienti 2008; also see references in Table 1). CSD coupled with vesicle distribution data yield deeper insights into the physical processes operating in the conduit (e.g. Gurioli et al. 2005; D'Oriano et al. 2005; Piochi et al. 2005; 2008; Noguchi et al. 2006; Giachetti et al. 2010; D'Oriano et al. 2011a; Vinkler et al. 2012). The CSD method has been well tested and widely applied (Table 1), so that it is now quite straightforward to quantify CSD (Higgins 2000; 2006; and references in table 1).

However, we must keep in mind that crystals are commonly anisotropic and therefore shape cannot be ignored. Most studies use the Higgins technique to account for shape. However, the Higgins method assumes that all crystals are the same shape. This is clearly not true, as small crystals are often more anisotropic than large crystals. Treating all crystals in the same way can introduce artifacts (see: Castro et al. 2003). In addition, there are still resolution issues for microlites, as well as problems in both back-scattered electron (BSE) and cathode ray tube (CRT) analyses when the crystals have a density (Z number) that is very close to that of the glass. Several methods can be used to facilitate the extraction and quantification of crystals. CSDs of larger crystals (phenocrysts, antecrysts, etc.) can be measured from transmitted light microscopy images of thin sections, and analyzed by using digital image analysis to automate and, thus speed up, the quantification process (e.g. Armienti et al. 1994; Launeau et al. 1994; Lumbreras and Serrat 1996; Goodchild and Fueten 1998; Launeau and

Cruden 1998; De Keyser 1999; Heilbronner 2000 Armienti and Tarquini 2002; Boorman et al. 2004). Tarquini and Favalli (2010) used a slide scanner to acquire input imagery in transmitted light from thin sections, and a GIS software to analyze the data.

Crystals can also be identified using a scanner and a polarizing filter placed at different angles (Pioli et al. 2014). Three pictures are then combined and their correlation allows the individual grains to be classified by their characteristic orientation. To measure smaller crystals (microphenocrysts and microlites), it is common to use a scanning electron microscope in backscattered electron (BSE) mode (Cashman 1992; Hammer et al. 1999; Cashman and McConnell 2005; Nakamura 2006; Ishibashi and Sato 2007; Salisbury et al. 2008; Blundy and Cashman 2008; Wright et al. 2012). Development of rapid x-ray mapping techniques now allows CSD analysis of x-ray element maps, which provide information on crystal compositions, textures (crystal size, orientation, shape) and modes of minerals (e.g. Muir et al. 2012; Ludovic et al. in press) to be extracted. Another new technique uses an electron backscatter diffraction detector (EBSD) attached to the SEM to obtain crystal orientations, which can provide insights into shearing, accumulation and degassing processes (Prior 1999; Prior et al. 1999; Hammer et al. 2010). Chemical mapping is now routinely and widely used (e.g. Ludovic et al. in press). In contrast, EBSD is more difficult and time consuming taking hours as opposed to a few minutes for the chemical mapping. As described in the references cited, it produces a wealth of information on various minerals, although the lack of compositional contrast between glass and feldspar can be problematic.

Crystal size distribution can also be obtained directly in 3D via X-ray computed microtomography. Using this approach it is possible to obtain the total crystal volume, as well as the crystal volume of each mineral phase present, therefore crystallinity, crystal size and shape (e.g. Zandomeneghi et al. 2010; Voltolini et al. 2011). Again, resolution can be a problem. First, crystals may span a large size range, which requires imaging at several different resolutions (e.g. Pamukcu et al. 2010; 2012). Additionally, as in BSE and EBSD analysis, the compositional similarity between some crystal phases, such as alkali feldspars, and silicic matrix glass can make automated analysis challenging (e.g. Baker et al. 2012). However, excellent results can be obtained by working in phase-contrast tomographic mode (Polacci et al. 2010) and by recently applying a procedure known as phase retrieval to the reconstructed sample volumes (Arzilli et al. 2013).

(iv) Errors in textural analyses

Uncertainties encountered in textural analysis are due to several factors. Any textural parameter, such as porosity or crystal size, has intrinsic measurement errors. These are linked to the apparatus used, and are generally easy to quantify using standards. A good practice, when a new method is introduced, is to assess its intrinsic error with synthetic samples of well-known particle content, size and distribution (e.g. see review of Rust and Cashman 2004 for permeability, and Baker et al. 2012 for 3D data from X-ray microtomography). Another type of uncertainty is linked to natural variability, which is generally approached by using the concept of Representative Elementary Volume (REV, Bear 1972). Parameters measured in small neighboring regions within a sample have a large variability. As the analyzed regions become larger, this variability decreases until a steady value is reached at the REV size. One complication is that the REV should be significantly smaller than the sample (which is not guaranteed for ash particles), and that some parameters have a REV at the deposit scale, which means that multiple clasts have to be analyzed. If the sample location is such that eruptive parameters were steady during deposition, application of REV at the deposit scale represents that of fragmentation within the conduit. Taking porosity as an example, one 2D SEM image will yield one porosity measurement with a typically small (~1 %) intrinsic error due to thresholding of the grayscale values that represent vesicles. Several 2D images of the same sample taken at different locations and/or different resolutions (larger than the REV) typically yield larger (~10 %) uncertainties that are caused by small-scale spatial heterogeneity. Finally, the density distribution of all clasts at that location indicates the variability of porosity at the conduit scale, which can be quite large (e.g. Houghton and Wilson 1998).

Raw data in terms of size (area, long axis, short axis, perimeter) and orientation of crystals and vesicles yield negligible intrinsic errors because they are computed with programs on 2D binary images with high resolution (>10^6 pixels). The greatest source of intrinsic error here is thresholding, which is set by the operator (Baker et al. 2011). When converting 2D data to a 3D projection, however, the error depends on the stereological model used (i.e. particle shapes have to be assumed, Cashman 1988) and is thus harder to estimate.

Most 2D textural parameters have well-established techniques and protocols to quantify intrinsic errors: porosity and vesicle size distribution, including:

- VSD (Toramaru 1990; Mangan et al. 1993; Klug and Cashman 1994; 1996; Klug et al. 2002; Adams et al. 2006b; Shea et al. 2010a),
- CSD (Higgins 2006), fabric indicators (Launeau et al. 1990),
- vesicle shape (Moitra et al. 2013),

- clast shape (Marshall 1987; Capaccioni and Sarocchi 1996; Dellino and Liotino 2002; Riley et al. 2003; Ersoy et al. 2006).

However, conversion from 2D to 3D distributions introduces errors linked to stereological assumptions. The Cheng and Lemlich (1983) method does not involve assumptions of object shape, but it still does not take into account the truncation effect (e.g. Pickering et al. 1995). Left-hand (small-scale) truncation is related to the sensitivity of the measurement process; small objects are increasingly difficultto detect as their size decreases. Right-hand (large-scale) truncation occurs under several circumstances, that in general imply the difficulty of sampling of the large objects. The Sahagian and Proussevitch (1998) conversion assumes spherical shapes, but corrects for the cut effect. Giachetti et al. (2011) found that N_v obtained from the two methods from the same lapilli were the same to within 15 %, and that VSD were also very similar. They recommended the first method for vesicle analysis, as the second method may generate negative values for some size classes.

In terms of parameters that we can derive from textural analyses, decompression rate is probably one of the most important to quantify due to its implications for eruption dynamics. To achieve this, microlite shape, number density and size distribution have been used in combination with experimental data for low-mass flux, effusive eruptions (Couch et al. 2003; Cashman and McConnell 2005; Szramek et al. 2006; Clarke et al. 2007; Martel 2012; Wright et al. 2012). That different generations of microlites (nucleated pre-eruptively in the reservoir or syn-eruptively formed in the conduit) can be distinguished on the basis of chemical composition (Martel et al. 2006) confers a high degree of reliability in this method. Decompression rates deduced from vesicle number density (e.g. Toramaru 2006), however, tend to be maximum estimates because there could be more nucleation events during ascent that add to the signature left by decompression. Maximum decompression rates associated with the final, rapid, stages of ascent could be calculated directly from the smallest bubbles formed during the final fragmentation event (Shea et al. 2011; 2012). However, the relationships between bubble shape, nucleation, coalescence, deformation and/or breakup is not well established.

Quantification and sampling of pyroclastic deposits for the textural characterization of their components

The sub-group discussion focused on all types of pyroclastic fall deposits, as studied for textural purposes, identifying four main needs or issues, as listed next.

(i) Preliminary field studies and sampling strategy

Field-based studies of pyroclastic deposits aim to relate both the whole deposit characterization (thickness and grain size), and the physical properties of the constituent particles, to the eruption conditions. Textural studies are time consuming, especially when they provide complete size distributions of the vesicle and crystal population. For these measurements the choice of a limited number of "representative" clasts selected for the analysis is critical, particularly when using these data to model eruption processes and their variability in time and space. Obtaining such clasts requires a cautious sampling strategy with well-defined scientific goals during field work. These studies are best performed only on well-documented deposits, supported by a robust stratigraphic reconstruction and correlation, as well as an accurate compositional stratigraphy framework. When not familiar with the deposit, a preliminary survey at different locations is useful for the evaluation of the significance of the case-type outcrops used for analysis. Well defined sublayers (or Units) should be identified in the deposit on the basis of clear, unequivocal lithological/sedimentological features and cross-correlated over the whole dispersal area of the deposit. Stratigraphic data are critical for placing each studied layer within an appropriate temporal framework within the stratigraphic sequence.

Pyroclasts can be collected after the eruption/explosion, from fall deposits of ancient (unobserved) or recent (observed) eruptions, preferably within hours to days of the event (e.g. Gurioli et al. 2008; 2013). Sampling may also take place during eruptive activity, with samples collected directly with a specific device placed inside the fallout field. Three simple collection methods that can be applied to active fallout, as currently used, were listed: (1) the hand collection method involves collecting (and quenching) bombs or lapilli as they fall out of the plume by people standing in the active fall out field (e.g. Lautze and Houghton, 2007, 2008; Gurioli et al. 2014); (2) the "tarp", "space blanket" or "cleaned surface" strategy whereby plastic sheets are laid out close to the vent, or preexisting antropical or natural surfaces are considered. In both cases the pyroclasts falling in a known area are collected (e.g. Rose et al. 2008; Swanson et al. 2009; Andronico et al. 2009a; 2013; Eychenne et al. 2012; Houghton et al. 2013, Harris et al. 2013b); (3) the bucket strategy by which a large number of buckets are distributed across a discrete area of fallout for a certain period of time (e.g. Yoshimoto et al. 2005; Bustillos and Mothes 2010). When possible, the aim it is to collect a sufficient number of samples to estimate the magnitude of the explosive event through extraction of the mass load per unit area; and to obtain a sufficient number of clasts for chemical and textural characterization. Other promising methods are just coming on-line, such as automatic ash sampling collectors (e.g. Bernard 2013; Shimano et al. 2013).

(ii) Definition of essential, basic physical properties of the deposit to the study

Most textural studies aim at characterizing magma heterogeneity and ascent dynamics, and at understanding the fragmentation process, beginning from the quantification of the juvenile componentry within the deposit (Table 1). Therefore, the clasts are usually sampled in a deposit at single locations (reference sections). It is important to bear in mind that variability across the deposit is filtered by transport and sedimentation, which primarily depends on eruption intensity, along with related plume dynamics and other properties such as wind direction and velocity. Therefore, clast properties can vary both in time (from the base to the top of a vertical sequence) and in space (from the main axis of dispersal to lateral outcrops at the edge of the fall out zone across the cloud, and from proximal to distal sites). Volcanic plumes (and clouds) are thus complex systems, whose properties do not vary linearly with the main eruption parameters. They are also affected by external variables, such as wind direction and intensity. This latter variability adds additional complexity to the clast type distribution. For this reason, the deposit should be preliminarily characterized at least in terms of stratigraphy, dispersal, thickness variation and volume (e.g. Fisher and Schmincke 1984; Cas and Wrigth 1987; Thordarson et al. 2009; Cioni et al. 2011). Estimation of plume height, eruption duration, volume and magma eruption rate can then also be derived for past eruptions from such analyses (e.g. Carey and Sparks 1986; Pyle 1989; Fierstein and Nathenson 1992; Sparks et al. 1997; Bonadonna et al. 1998; Freundt and Rosi 1998; Bonadonna and Costa 2012; Fagents et al. 2013).

(iii) Selecting the outcrop

Basic criteria for sample outcrop selection can be reduced to three points. First: minimize the effect of wind direction. Outcrops located along the main dispersal axis are preferred to lateral exposures, unless the effect of wind is the target of study. For this reason, in the case of changes in wind direction or eruption intensity during different phases of the same eruption, it is more appropriate to sample each tephra layer at different ‘equivalent’ locations rather than to collect all samples at a single type outcrop. If sampling is restricted to a single location, the inferred dispersal pattern and distance from the main dispersal axis of each layer should be noted and taken into account when analyzing clast variability among different layers.

Clear textural variations among the juvenile clasts, in terms of color, general morphology, vesicularity, vesicle shape, crystallinity should be evaluated in the preliminary field survey, so that any lateral and vertical variability within the deposit is already defined following field reconnaissance. This ensures that, when clast types are chosen in the laboratory, the main textural types are easily identified and separated. It is also important to avoid excessive subdivisions, which can unnecessarily complicate interpretations and lead to redundant measurements.

Finally, if one of the goals of the study is quantification of the proportion of distinct textural clast types, it is important to remember that sedimentation from the volcanic plume is affected by clast density, shape and size (Bonadonna et al. 1998; Pfeiffer et al. 2005; Barsotti et al. 2008; Eychenne et al. 2013, and references therein). This is especially relevant when a single explosion produces a juvenile population with a wide range of physical and textural features: their relative distribution within the deposit can vary laterally in the deposit as well as with distance from the vent. Thus, at any single site, the sample is not necessarily representative of the abundance within the eruption mixture. This is especially true in the case of small plumes and mid-intensity eruptions (e.g. Rose et al. 2008; Cioni et al. 2008; 2011; D'Oriano et al. 2011a; Andronico et al. 2013a and references therein). While the textural features of the different clast types can be studied at a single outcrop, the relative proportions between clast types need to be determined across the whole deposit by integrating componentry data on samples collected at outcrops at differing azimuths and distances from the source.

(iv) Sampling

After identification of the "type locality/ies", where the deposit shows the best and most complete exposure, a suitable approach is random collection of a statistically relevant number of clasts from a single layer. Several techniques can be used, ranging from sieving in the field to find the dominant clast size (for coarse clasts), or sampling the bulk deposit for later clast selection in the laboratory (for small clasts). In the case of fine-grained deposits, it can be useful to apply sampling techniques that preserve structural and textural characteristics of the whole deposit. Samples can be retrieved using tubes or boxes manually pressed into the deposits, or carfully carved out and surround-wrapped deposit blocks. In situ and/or laboratory impregnation techniques of deposits exist for a broad range of grain sizes and compositions (Bouma 1969), some of which are applicable to fragile or loose volcanic deposits. The applicability of such techniques to fine-to-medium grained volcanic deposits should be tested, since they would allow both 2D (e.g. X-ray radiography and thin section analysis) and 3D analysis (X-ray tomography and anisotropy of magnetic susceptibility) to be applied, as frequently used for hard rocks or single clasts (e.g. Lanza and Meloni 2006).

The number of samples collected should be defined depending on the purpose of the study. Fixing the number of samples per stratigraphic layer based on the layer characteristics dynamics (e.g. extent of zoning/fluctuations in grain-size, componentry, etc.) for characterizing eruption dynamics, or focusing on the layer thickness for conduit dynamic characterizations are two examples of such pre-selection decisions. Before selecting clasts, basic grain-size studies (when the bulk deposit is collected) on each sampled layer (median and sorting of grain-size distribution) and componentry analysis should be carried out to ensure effective sub-sampling for textural studies. Componentry analysis is the subdivision of the sample into three main components: juvenile and non-juvenile materials and crystals. Following Fisher and Schmincke (1984), juvenile components are vesiculated or dense fragments that represent the primary magma involved in the eruption; non-juvenile material includes accessory and accidental fragments that are not related to the fresh magma. The free crystals in the deposits can be juvenile or not. Finally, after choosing the size intervals of the clasts for physical and textural measurements (i.e. bulk and solid density, vesicularity, microtextures, permeability), it is useful to compare the grain-size distribution of each interval with the total grain-size distribution of the sampled layers, especially when the grain-size distribution is highly variable within the sampled stratigraphy. This strategy allows checking of sample representativeness. For example, sampling may be from (i) bimodal or complex multimodal distributions, or (ii) anomalous, poorly sorted deposits. In the second case, features that can be indicative of contamination from other sources, such as ballistic components, elutriated ash from pyroclastic density currents or from reworking (e.g. Fierstein et al. 1997, Eychenne et al. 2012). It is useful, whenever possible, to show variance, or invariance, of the textural features by comparing data collected in the selected size class with textural data appositely made on different size classes. This should, at-least, be carried out for a few selected cases.

How to link chemistry, geochemistry and textural quantifications: the rock (bulk, glass, crystal) geochemistry group report

This group based their discussion on three fundamental observations:

1. all procedures required to acquire geochemical data and run high petrological experiments are well defined;
2. all measurements have associated error and error propagations which can be dealt with systematically;
3. internet databases are already available (e.g. Georoc and Germ) and incremented on a regular basis (e.g. GeoReM: http://georem.mpch-mainz.gwdg.de/; Earth: http://earthref.org/; GEOROC: http://georoc.mpch-mainz.gwdg.de/georoc/).

Therefore, the approach undertaken was to

(1) list what geochemistry can provide in terms of initial parameters and conduit processes,
(2) identify the potential areas of textural study where geochemistry can be of help, and
(3) discuss a few contentious points.

(1) Initial parameters and conduit processes

Geochemical and petrological analysis of pyroclastic products can constrain the initial conditions operating in the shallow crustal holding chamber through to the surface via the conduit system. In transit through this system, the textural features of the pyroclasts quenched upon eruption are imprinted. These were listed as*:*

- Defining magma pre-eruptive storage conditions (in terms of pressure and temperature) from mineral-melt equilibria or disequilibria (e.g. Rutherford et al. 1985; Scaillet and Evans 1999; Pichavant et al. 2002; Blundy and Cashman 2008);
- Assessing initial viscosity, temperature, melt composition and volatile, budget including input of gases from deeper sources (e.g. Wallace 2001; Blundy and Cashman 2008; Métrich et al. 2010);
- Defining the evolution of volatile contents (specifically CI, F, S, H_2O, CO_2) using electron probe, ion probe (SIMS), Raman and FTIR in melt inclusion and host minerals, while combining results with vesiculation studies and gas relsease measurements (e.g. Wallace 2005; Métrich and Wallace 2008). In such a way we can determine whether the magma was saturated, over-saturated or under-saturated at a certain depth, and how these conditions affect vesiculation in the conduit (e.g. Anderson 1991; Hurwitz and Navon 1994; Dixon 1997; Roggensack et al. 1997);

- Measuring residual volatiles in glasses and bulk-rock samples to reveal how degassed the magma is (Newman et al. 1988; Villemant and Boudon 1998; Shea et al. 2014);
- Providing variable diffusion of stable elements (^{6}Li, ^{7}Li, H/D, ^{10}B, ^{11}B) or radiogenic isotopes (^{210}Pb-^{226}Ra), which are used as tracers for degassing and interaction with hydrothermal fluids (e.g. Berlo et al. 2004; Kent et al. 2007; Humphreys et al. 2008b; Schiavi et al. 2010; Berlo and Turner 2010; Vlastélic et al. 2011);
- Measuring mineral diffusion profiles and deriving pre-eruptive residence times, ascent rates and cooling rates (e.g. Kahl et al. 2011);
- Providing crystal shapes, zoning schemes, and dissolution stages, while determining which magmatic process and physical parameters control crystal shape/zoning (e.g. Hammer and Rutherford 2002; Rutherford and Devine 2003; Blundy et al. 2006; Costa et al. 2008; Streck 2008);

In addition, petrological investigations can provide:

- Experimental observations on phase equilibria (mineral-melt-vapor), crystallization paths and liquid line of descent (e.g. Hammer and Rutherford 2002; Couch et al. 2003; Blundy et al. 2006; Hammer 2008);
- Calibration of decompression rates. While this has been carried out for rhyolitic systems (e.g. Mourtada-Bonnefoi and Laporte 2002, 2004; Mangan and Sisson 2005; Gardner 2007; Cichy et al. 2011; Cluzel et al. 2008) and phonolitic systems (e.g. Larsen 2008; Shea et al. 2010b), there are ongoing studies on basaltic systems (Bai et al. 2008; Lesne et al. 2011; Pichavant et al. 2013);
- Diffusion coefficients of relevant chemical elements, including volatiles, to improve kinetic modeling (Dohmen et al. 2007; Chakraborty 2008);
- Relationships between crystal morphologies, cooling rates and degree of undercooling (e.g. growth of crystals with hopper and swallow tail shapes experiencing rapid late-stage crystallization; Faure et al. 2003, 2007);
- Surface flux of volatiles (i.e. what leaves the system; see reviews by Fischer 2008; Pyle and Mather 2009) compared with melt inclusion data (i.e. what is in the system initially; e.g. Le Voyer et al. 2010; Rose-Koga et al. 2012; Schiavi et al. 2012).

2) Where geochemistry can help textural study

Measurements of volatile contents in quenched, phenocryst-hosted melt inclusions provide estimates of initial (shallow crustal) values (e.g. Kent 2008). These are minimum estimates, because H_2O can leak from melt inclusions during ascent by intracrystalline diffusion as the far-field environment of the crystal evolves (Chen et al. 2011, 2013). Melt inclusion volatile contents can be inverted to equivalent saturation pressures using multi-species (e.g., H_2O-CO_2; H_2O-Cl) solubility laws (using, for example, VOLATILCALC, MELTS). These, in turn, can be used to calculate total pressures (and hence depth) by assuming volatile saturation, or minimum pressures if the sample is under-saturated in volatiles. Progressive closure of melt inclusion networks in growing phenocrysts can result in zone-dependent melt inclusion volatile contents that record the evolution of pressure conditions as magmas migrate form depth (Blundy and Cashman 2008, and references therein). Combining melt major element and volatile compositions with phenocryst contents allows calculation of initial magma physical properties (viscosity, density, surface tension, etc.). Derivations of such parameters are necessary for modeling of magma ascent, vesiculation and groundmass crystallization.

Pre-ascent storage conditions can also be inferred from phase-equilibria studies of natural compositions. Comparison of natural and experimental phase abundances and compositions, combined with constraints of volatile content (from melt inclusions) and temperature (from e.g. Fe-Ti oxides) allows estimation of total pressure if the degree of volatile saturation is established through use of mixed-volatile experiments (Pichavant et al. 2007; Cadoux et al. 2014).

Residual volatile content (H_2O, CO_2, SO_2, Cl, F … … …) measured in the glass or directly from gases emitted at the vent, can be correlated with textures (e.g. Piochi et al. 2005; 2008; Balcone-Boissard et al. 2011, 2012; Shea et al. 2012, 2014; Burton et al. 2007; Polacci et al. 2009b; Miwa and Toramaru 2013). They can also be compared with pre-eruptive volatile contents obtained from melt inclusion investigations to evaluate both the extent and efficiency of syn-eruptive degassing (e.g. Shimano and Nakada 2005; Noguchi et al. 2006, Métrich et al. 2001; 2010). Residual water content or Cl content (when Cl partitions into a H_2O vapor phase, so that it can thus be used as an indicator of degassing processes; Balcone-Boissard et al. 2010) is typically plotted against Vg/Vl, where Vg is the volume of vesicles corrected for phenocrysts and Vl is the volume of melt and microlites (Villemant and Boudon 1998, Balcone-Boissard et al. 2011, 2012). An important issue is to assess the extent of post-eruption hydration. Recently, thermal gravimetric studies have proved to be quite effective in alowing this correction; a correction based on oxygen or hydrogen isotopic compositions (e.g. Giachetti and Gonnerman 2013; Shea et al. 2014). Recent studies on hydrogen isotopes, correlated with SEM glass textures permit us to identify magmatic water from meteoric water generated by re-hydratation (Kyser and O'Neil 1984). Hydration can also be assessed from the ratio between water species (molecular H_2O vs. OH) in residual glass, as determined by FTIR data or Raman analyses (Hammer et al. 1999; Le Losq et al. 2012).

Ascent and decompression in the conduit can result in chemical changes that can be quantified by a range of microbeam analytical techniques (EPMA, LA-ICPMS, FTIR, μ-Raman). As the pressure drops, H_2O will migrate out of melt inclusions and crystals (Le Voyer et al 2010; Hamada et al 2010), and light elements (Li, B) will try to re-establish equilibrium between crystals, host melt and any vapor or brine phase present (Berlo et al. 2004). At the same time, H_2O and CO_2 will migrate out of melt inclusions to be apparent as re-entrant tubes at the edges of crystals (Liu et al. 2007; Humphreys et al. 2008a). Each of these processes will establish diffusive gradients frozen into the pyroclast. These can be measured and modelled using experimentally determined kinetic laws to infer decompression rates during ascent (e.g. Gonnermann and Manga 2013). These decompression rates can then be compared with those derived from other approaches, including those based on analyses of microlite sizes and shapes, vesicle number densities, and hornblende-breakdown reactions (e.g. Martel 2012; Cluzel et al. 2008; Giachetti et al 2010; Shea et al. 2011).

3) Contentious points

Care needs to be taken when converting decompression rate to magma ascent rate, and especially when comparing decompression rates obtained using different methods. Pressure gradients in conduits are highly nonlinear due to the strong effect of dissolved H_2O on magma viscosity, particularly at low H_2O contents (Gonnermann and Manga 2013). Moreover, different processes will likely record different decompression rates, according to the time available for the process to take place. For example, microlite growth is relatively slow, so that microlite size and shape distributions are likely to record an average decompression rate during ascent (Martel 2012). Bubble nucleation and growth, on the other hand, can occur very rapidly, so that Nv may record just the peak decompression rate immediately beneath the fragmentation zone (Cluzel et al. 2008; Giachetti et al 2010). Comparison therefore requires caution. However, integration of decompression rates as obtained from different textural and chemical characterizations, when combined with mass eruption rate estimation from deposit analysis or direct observations, can provide quantitative insights into the processes involved in magma ascent from the deep source to the surface.

Another outstanding issue is the role of dense clasts. That is, did they originate from (i) magma quenched at depth prior vesiculation, (ii) vesicle collapse phenomena, or (iii) volatile-poor magma? It is important to provide a correct interpretation because each conclusion relates to very different mechanisms. In several eruptions it has been found that the densest clasts can be depleted in water through syneruptive bubble collapse and coalescence (Rust and cashman 2007; Piochi et al. 2008, Shea et al. 2014). In Plinian eruptions at Vesuvius (Pompeii and Avellino) the densest clasts have been interpreted as being due to magma that has lost water during transition from closed-to open-system degassing (Balcone-Boissard et al. 2011; 2012). Water depletion can also result from syn-eruptive processes, such as clast recycling at magmatic temperature and intrinsic magmatic redox conditions, as shown by the experiments of D'Oriano et al. (2012).

Another key question in the geochemical investigation of volcanic rocks is whether it is possible to assume that the compositions (including volatile content) that we measure (whether it be in the bulk rock, glass, minerals) represents equilibrium or disequilibrium processes and/or if equilibrium or disequilibrium conditions pertain to local subsystems or to the whole magmatic body that we are investigating (see for example Pichavant et al. 2007). Chemical species with different diffusivities, for example, record equilibrium or non-equilibrium conditions (De Campos et al. 2008). Equilibrium kinetics is also composition dependent because it is dictated in part by melt viscosity which, itself, is related to viscosity. This issue will generally affect silicic to intermediate magmas more than basaltic compositions. However, we note that even for basaltic systems crystal-fluid-bubble magma mixtures can achieve viscosities that range over six or seven orders of magnitude, up to 10^6 Pa s (e.g. Gurioli et al. 2014), depending on the degree of cooling, degassing and crystallization. Such rheological variation even within a single composition, and its effect on eruption mechanisms, deserves equal attention.

How to link the geophysical data and the textural quantification: the geophysics group report

There are a wide array of remote sensing and geophysical approaches that can be used to parameterize an explosive event both within the conduit and outside of the conduit. Within the conduit geophysical signals, are generated by fluid and gas flow in the magma-filled part of the conduit and during fragmentation. Magma-gas ascent dynamics and supposed conduit conditions, extracted from geophysical data for this part of the system, are particularly difficult to validate because the processes cannot be directly observed. They are thus effectively "invisible" to direct observation. By outside of the conduit we mean measurements of the emitted mixture of gas and particles as it (i) exits the vent, (ii) ascends above the vent as a plume, and then (iii) drifts away from the vent as the cloud. Models and dynamic parameters extracted for geophysical and remote sensing data for this part of the system are a little easier to validate because they can be directly observed.

The invisible part of the system is the realm of studies using seismic, pressure (infrasonic), and deformation data. All three data sets have long been shown capable of detecting the geophysical signature of explosive events spanning weakly explosive Hawaiian-to-Strombolian events through Plinian events. Seismic data sets are available, for example, for gas-pistoning events, puffing, fountains, and strombolian eruptions at mafic systems (e.g., Goldstein and Chouet 1994; Ripepe et al. 1996; Sciotto et al. 2011; Ripepe and Braun 1994); as well as events that generate somewhat larger plumes generated during silicic eruptions as at Santiaguito, Soufriere Hills, Redoubt to name a few. Associated pressure impulses (as typically recorded by infrasound and barometers) have long been recorded for such energetic events, famous examples include the pressure response to the 1883 eruption of Krakatoa and the 1967 caldera-forming eruption of Fernandina (Simkin and Howard 1970). Magma-gas ascent has also been shown to generate rapid, but recordable, deformation signals detected by tiltmeters (Aoyama and Iguchi 2008; Genco and Ripepe 2010; Iguchi et al. 2008; Zobin et al 2007).

The measurement of velocities, masses and size distributions of particles leaving the vent have typically been measured by visible and thermal video (e.g., Chouet et al. 1974; Ripepe et al. 1993; Harris et al. 2012; Delle Donne and Ripepe 2012; Taddeucci et al. 2012; Bombrun et al. 2014; Gaudin et al., 2014a,b) and Doppler radar (e.g., Dubosclard et al 1999; Hort and Seyfried 1998; Vöge et al 2005; Gouhier and Donnadieu 2008; 2011; Gerst et al 2013). While infrasonic array methods are also available to location of the emission in x,y space (Ripepe and Marchetti, 2002). Plume front velocities, density and entrainment rates have also been successfully tracked using visible and thermal cameras, as well as radiometers, for a few stronger, ash-rich, buoyant plumes at Stromboli, Santiaguito and Eyjafjallajökull (Patrick 2007; Sahetapy-Engel and Harris 2009; Bjornsson et al. 2013; Valade et al. 2014); See Chapter 9 of Harris (2013) for review.

Satellite remote sensing has long been used to track and measure cloud properties as the cloud drifts and disperses. These data are available for all cloud sizes, from those associated with small Strombolian and fountaining events (e.g. Heiken and Pitts 1975; Dehn et al 2000;

2002) to sub-Plinian and Plinian events (e.g., Holasek and Self 1995; Koyaguchi and Tokuno 1993; Holasek et al. 1996). Cloud dispersion dynamics are especially well revealed by geostationary satellite data with nominal imaging of one image every 15 minutes, and higher. Basic cloud properties that can be measured by satellite data include cloud dimensions, drift velocity and height (e.g., Robock and Matson 1982; Denniss et al. 1998; Aloisi et al. 2002; Zakšek et al 2013); with Prata (1989) and Wen and Rose (1994) having introduced a method to potentially extract particle size distribution and mass from "split window" (10-12 μm) thermal data. In the last five years, while especially modified ground-based thermal cameras have been adapted to extract ash particle size and plume mass (Prata and Bernardo 2009) newly available technology such as LiDAR and PLUDIX were shown of value in detecting, tracking and measuring fine particles in the Eyjafjallajökull's cloud (e.g. Bonnadonna et al. 2011). Disdrometers and ash collectors, however, currently show greater potential for measuring particle size and terminal velocity (Marchetti et al. 2013; Shimano et al. 2013) than PLUDIX, which was designed more for meteorological applications (Caracciolo et al. 2006; Prodi et al. 2011).

For the gas content of the cloud, satellite-based sensors such as TOMS, AIRS, OMI, MODIS, GOME and IASI, and have been used to obtain SO_2 content in the far field; that is once the gas cloud has decoupled from the ash cloud (e.g. Krueger et al. 1990; Carn et al. 2003; 2005; Watson et al. 2004; Yang et al. 2007; Thomas et al. 2011; Rix et al. 2012; Walker et al. 2012). Ground-based sensors, such as COSPEC, FLYSPEC and DOAS (e.g. Caltabiano et al. 1994; Horton et al. 2005; Oppenheimer et al. 2011), have been used to measure SO_2 fluxes relatively close to the source, see Williams-Jones et al (2008) for full review. These approaches have been recently supplemented by SO_2 camera systems, which allow 2D images of SO_2 concentrations to be collected at ~1 Hz rates (Mori and Burton 2006). Such studies have, though, tended to focus on passive degassing and gas-puffing systems, because the presence of ash interferes with UV-light transmission on which the technique relies, making measurements problematic. Recently, however, SO_2 cameras have been used to measure the gas masses and fluxes involved in discrete explosive events (Mori and Burton 2009; Holland et al 2011; Barnie et al. 2014).

However, none of these techniques directly collects or makes contact with the magma or particles they measure; this is, after all what defines these techniques as "remote sensing". They thus the need for quality ground truth data to validate particle velocities and sizes extracted from what is, basically, an electronic response, as well as to test the assumptions and models used to convert received "power" to a more meaningful and useful parameter (such as mass). At the same time, any single data set can be inverted to support a conduit or plume dynamic model; but results need to fall within constraint provided by ground truth data. In this case, ground truth is provided by analyses of the magma and particles themselves to extract parameters such as magma temperature, chemistry, density, crystallinity and vesicle content, plus vesicle shape and size, as well as particle density, size, shape and roughness. Geophysical-data-derived magma ascent, explosion-source and fragmentation models likewise need to be consistent with independent (physical-volcanology-data-derived) measurements for the same processes if they are to be valid. We explored these needs through mostly focusing on weakly explosive, basaltic cases; these being the cases usually targeted, because they provide a reliable and easy-to-measure source for testing new technology, methods and algorithms for ground-based geophysical enquiry.

The basic need: Realistic assumptions and validation

The basic response of a remote sensing instrument is a voltage which, through calibration, can be converted a higher level physical value, such as spectral radiant intensity or power. To convert this value to higher level and more volcanologically-useful parameters (such as particle size distribution, mass flux or plume density) requires an increasingly complex system of assumption stacking. Thus, to adequately reduce geophysical data, a number of input parameters are required and many assumptions need to be made all of which can be provided by the physical volcanological community. Data sets from the physical volcanological community, especially if provided simultaneously with geophysical data collection during an active event, or provided as a library typical of that event, can also be used to “ground truth” or check the precision and reality of the geophysically applied input and output.

(i) Seismic and infrasonic data

Seismic signals that accompany explosions are primarily short period (high frequency > 1 Hz) signals which are typically termed “explosion quakes”. These usually have high amplitudes and mostly include frequencies up to a few hertz, with a possible higher frequency acoustic phase (McNutt 1986, Mori et al 1989, Braun and Ripepe, 1993). Below these frequencies, short period (SP) signals are often hidden by Very-Long Period (VLP) components with much lower amplitudes (Neuberg et al., 1994; Kaneshima et al. 1996). In-spite of an enormous amount of work, it remains unclear as to how we can explain the VLP seismic component, which itself is only one part of the seismic signal. It also remains unclear as to whether, and/or how, SP and VLP components are related to the magnitude and intensity of an explosion, although attempts have been made using tremor (Brodsky et al 1999; Nishimura and McNutt 2008; Prejean and Brodsky 2011). Clearly, coupling with the physical volcanology community could help narrow down much uncertainty, and allow progress towards better models to untangle the seismic signal associated with discrete explosive events.

Delay times in the arrival of seismic, infrasonic and thermal signals have been commonly used for assessing the depth at which various physical processes occurring in explosive basaltic systems (e.g. Ripepe and Braun 1994; Ripepe et al. 2001; 2002; Harris and Ripepe 2007). However if, for example, the thermal-infrasound delay is to be used to obtain the fragmentation depth, then sound speed in the conduit needs to be assumed. This will be highly variable with conditions in the empty portion of the conduit, including mixture density, gas-to-particle ratio, and temperature of the mixture through which the sound is propagating. Thus we need to know these variables if we are to provide a realistic sound speed value and hence a plausible depth. For geophysical modelling of the shallow explosion mechanism and depth we thus need to constrain two fundamental parameters. First, the magma crystal and bubblecontent (as well as size, shape and distribution), plus fluid chemistry and temperature, to define magma rheology properties and bubble ascent dynamics. Second, the exact mix and character of the mixture of gas and particles that ascends the final section of the conduit to exit the vent and feed the emission.

(iii) Plume emission parameterization

Velocities, mass fluxes and particle size distributions (PSDs) for lapilli through bomb sized particles have been derived from high spatial and temporal resolution video data obtained using both near-infrared and thermal cameras (Chouet et al., 1974; Ripepe et al., 1993; Harris et al., 2012; Delle Donne and Ripepe 2012; Bombrun et al., 2014).

Generally, these studies have focused on Stromboli. In such camera data, the lower limit of a particle size that can be extracted is limited by pixel size. This is typically centimeter in dimension, depending on the detector instantaneous field of view and distance to the target (Harris 2013). A pixel mixture model can be applied to obtain the size of a sub-pixel particle, but it needs to assume a temperature for the particle and then uses the pixel-integrated temperature to solve for pixel portion occupied by that particle (Harris et al. 2013a). Symmetry then needs to be assumed to convert from particle area to particle volume, and a density needs to be assumed to derive particle mass (Bombrun et al. 2014). For ash-rich plumes, methods have been applied to extract total plume mass and air entrainment properties from ascent dynamics of buoyant thermals (Wilson and Self 1980; Patrick 2007; Valade et al. 2014). However, all methods need particle shape, particle density, plume density and/or size distribution data to: (i) determine whether the input assumptions are valid; and (ii) ground truth the remote-sensing-data derived size and mass data (Harris et al. 2013). The advantage is, if a validated method can be developed, particle size distribution, mass and mass flux data for the vent leaving plume can potentially be provided multiple times per second using camera data. (e.g. Taddeucci et al. 2012; Bombrun et al. 2014).

Deducing the erupted mass from Doppler radar data, requires the assumption of a particle size distribution for the eruption. Because this particle size distribution is unknown, an average particle size can be constrained from the Doppler radar measurement, typically using the eruption velocities themselves using either terminal fall velocities (Hort et al 2003) or by discriminating between ballistics (larger than a few millimeters or 1 cm, depending on the radar wavelength) and fine ash particles (<1 mm) using their temporal velocity evolution (Valade and Donnadieu 2011). Both methods can be used to obtain an estimate for the erupted mass of ballistics. We thus need to know whether the constrained average particle size can be used for mass retrieval, whether the assumption is a good approximation, and what the difference between the derived value and true value is.

The radar is able to measure particles of all sizes, provided there are enough particles available to return a signal. The relationship between particle size and number of particles required for a signal that exceeds the noise level, however, is not linear. It also depends on the radar wavelength and the distance between the radar and target. The smaller the radar wavelength, and/or the smaller the distance between the radar and target, the smaller the number of fine particles needed for a return signal. For particles <1 mm, halving the particle size increases the number of required particles by a factor of 64. Doubling the size of particles to >1 cm means that only ¼ of the number of particles are needed to return the same signal amplitude. In addition, radar can measure at points (gates) across the entire plume thickness. Currently, the radar's best role is to provide radial velocity measurements, with well-stated limits as to the particle size to which these data relate, through the entire plume thickness.

Questions, points and issues

In short, the question from the geophysical to the textural community is: "*Just what does the magma look like at the point of fragmentation?*" Then, we need to know everything possible (physically) about those fragments if we are to reduce and model our data correctly. To help with this, the geophysics group concluded that:

- Basic measurements of geophysical parameters (such as seismic energy, acoustic energy, energy partitioning, spectral radiance, radar power) are the most straightforward geophysical measurements to consider for correlations with parameters derived from physical volcanology.
- By completing multi-disciplinary correlations we improve our understanding of explosion dynamics, and only with a complete set of measurements can we have a complete and well-constrained understanding of the system (e.g., Gurioli et al. 2013; 2014; Leduc et al 2014).
- There is a wealth of textural and geophysical data for Strombolian events, and some data for larger events. These have been used to define the characteristic geophysical and textural signatures that allow us to distinguish each event type (e.g. Patrick et al. 2007; Leduc et al 2014). Focus on such eruptive phenomena is a result of low energy events being more frequent, more approachable, and thus easier to capture as at the case type location: Stromboli (Harris and Ripepe 2007).
- There is an unfortunate, but understandable, lack of multi-disciplinary data for larger (Vulcanian-to-Plinian) events; because they are rarer. With multi-disciplinary approaches becoming more routine, this situation is improving.

Thermal and SO_2 sensor arrays are becoming increasingly common components of permanent monitoring arrays at many persistently active sites (Harris 2013). However, it is extremely unlikely that such technology will ever be installed on every potentially active volcano; all of which will give seismic and pressure signals detectable by distant stations. Thus, from an operational point of view, it is more realistic to push forward with operational correlations between seismic-infrasonic metrics and textural deliverables to understand the ongoing progression of global volcanic events. In doing this, we must remember that many geophysical signals tend to be time-averages (e.g. tremor amplitude). Thus, we need to consider geophysical measurements that describe single, discrete explosions if we are to reasonably compare with textural variations between many individual emission events, or emission phases, that characterize the total eruption, total energy being one prime example (e.g. Marchetti et al 2009).

In terms of progress, we are at an exciting point in our ability to track and understand explosive volcanic emissions through true cross-disciplinary integration of deposit, geochemical, textural and geophysical data. Studies are increasingly bringing together multiple approaches in the field (e.g. Rosi et al. 2006), in the laboratory (Clarke et al. 2009), at large-scale artificial experiments (Sonder et al. 2013) and during field deployments (Harris et al. 2013b). As a community we appear to be converging on the correct, multi-disciplinary approach around which we are uniting. This can only be aided by further funding, and contribution to, pan-disciplinary workshops, meetings and working groups with the objective of totally understanding the system and constraining measurements with the least amount of uncertainty.

If we are to progress further with our understanding of fragmentation and plume ascent processes, we must develop a new multi-disciplinarily mentality. This requires us to break the borders between different disciplines, to move beyond combining simple geophysical interpretations and to bring in constraint that spans the entire community. We are, today, just at the beginning of this new age; an age which links texture to seismology (Miwa et al. 2009; Miwa and Toramaru 2013; Gurioli et al. 2014) and infrasound (Colò et al. 2010, Landi et al. 2011); as well as petrology to geophysics (Saunders et al. 2012; Martí et al. 2013).

Questions, needs and recommendations

In terms of issues that need to be resolved, if we are to improve our understanding of volcanic emissions through a truly cross-disciplinary integration (with a focus on textural metrics), we sum up in Tables 3, 4 and 5. While Table 3 summarizes the main open questions identified by this working group, Table 4 collates the needs, in terms of work that needs to be done, to attempt to address these questions. Finally, Table 5 provides recommendations as to how we may move forward to begin to solve these, currently, recognized gaps in our capability.

The list of key issues and questions defined by each sub-group, as complemented by the final round-table discussion and follow up discussion allows us to distil the following community-wide points and initiatives as priorities:

1. We need to define, and adhere to, standard sampling, data collection, experimental and methodological procedures to allow full integration of the four disciplines;
2. In doing this we need to understand each other needs, and then follow each other's well-recognized sampling etiquette if we are to work together as a truly integrated team.
3. We have to collate all data and measurements that can be provided by each discipline and evaluate what do we need more from each field at some central host site;

4. Always, quantification and statement of the precision on the measurements must be made, and a set of standards produced to allow data quality control has to be adhered to;
5. The community needs to explore and discuss the best means to improve quality measurements and the amount of data available, while collecting "missing" data;
6. Guidelines need to be agreed on regarding essential key parameters that need to be extracted (versus those that are less important), and common standards need to be fixed that allow these key parameters to be exported from one group to another.
7. Central to this is creation of an open access data bank to support essential geophysical, deposit, textural and geochemical data integration and sharing. This means creation of a repository of data grouped by eruptive style and/or geographic location into which members can make deposits and withdrawals;
8. All of this should be ideally be integrated into a GIS platform to allow for easy cross-correlation and comparison of different type of parameters.

To an extent, points one through three (listed in the recommendations section) have been addressed here; we now need to turn to the final four points as our next step.

DynVolc: an integrated database

Inspired by this effort, a database – DynVolc (Dynamics of Volcanoes) – is now operative at http://wwwobs.univ-bpclermont.fr/SO/televolc/dynvolc/index.php. This data base is part of an observation system within the services provided by Observatoire de Physique du Globe de Clermont-Ferrand (OPGC). It is an attempt to provide a much needed integration, and accessible, library for all multi-disciplinary data sets for explosive eruptive events described herein. This database is an integrated collection of data from physical and geophysical observations of dynamic volcanic processes.

Inspired and supported by this group effort, the –DynVolc database spans the full range of explosive, and effusive, activity types. Its intent is to provide a library of standards for case type eruptive styles. For each eruptive style, the data base provides, and links (among other things):

- field data (i.e., results of field mapping, outcrop and sample descriptions);
- key deposit features (thickness, areal dispersion, sedimentary structure, grain size);
- clast characterization (componentry, morphology, density, porosity, permeability);

- clast texture (connectivity, vesicle and crystal size and size distributions);
- chemical analyses of samples (bulk and glass chemistry);
- associated geophysical measurements (e.g., fragmentation depth, ejection and ascent velocity, fragment and gas mass, seismic and acoustic energies).

Integration of these data does not only allow improved, and better constrained, insights into the dynamics driving each eruptive style, but also it also allows improved definition of the rheological and degassing conditions associated with each activity style. At the same time it provides a library of key physical parameters that need to be assumed by geophysical data reduction methods, as well as during model-based enquiry.

Central to this initiative will be the transformation of this database in a communal databank, involving a web-based GIS platform to allow huge amounts of cross-correlation, and comparison between parameters relating to different processes and cross-correlation between same events. It is intended as an open data base into which all can input, and withdraw, citable cross-disciplinary information for scientific analysis. At the same time, through this library, we can provide cross-community time series, baseline and monitoring data for the full range volcanic activity.

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Table

Table 1 Quantification of explosive dynamics from textural parameters of the pyroclast components

Textural parameters	*Quantification*		*References*
Clast shape, morphology and size	Discriminate between different fragmentation mechanisms		Wohletz 1983; 1986; 1987; Heiken and Wohletz 1985; Sheridan and Marshall 1983; 1987; Dellino and La Volpe 1996a; b; Palladino and Taddeucci 1998; Büttner et al. 1999; 2002 Kueppers et al. 2006 Dellino et al. 2001; 2012 Zimanowski et al. 2003
	Conduit stratigraphy and processes		Taddeucci et al. 2002; D'Oriano et al. 2005; Cioni et al. 2011 Perugini et al. 2011 Andronico et al. 2009b; 2013a; Lautze et al. 2012; 2013
	State of the magma at the fragmentation		Carey et al. 2000; Dellino and Liotino 2002; Maria and Carey 2002; 2007; D'Oriano et al. 2011 Ruth and Calder 2014
	Link between vesicularity and particle morphology, and particle morphology with cloud dispersal and sedimentation		Wilson and Huang 1979 Dellino et al. 2005; Alfano et al. 2011; Mele et al. 2011
Clast density and vesicularity	Lateral variability of magma within the conduit		Houghton and Wilson 1989; Kennedy et al. 2005 Kueppers et al. 2005 Mueller et al. 2011 Barker et al. 2012
	Dense juvenile	Presence of outgassed magma	Sable et al. 2006; Lautze and Houghton 2005; 2007; 2008; Polacci et al. 2008; 2009a; b; 2012; Gurioli et al. 2005; 2014; Shea et al. 2011; 2012; 2014 Cimarelli et al. 2010
		Presence of a plug	Hoblitt and Harmon 1993 D'Oriano et al. 2005; Sable et al. 2009; Adams et al. 2006a; 2006b Giachetti et al. 2010; Barker et al. 2012; Lavallée et al. 2012
Clast permeability and connectivity	Degassing history experienced by the magma		Eichelberger et al. 1986 Klug and Cashman 1996; Saar and Manga 1999; Jouniaux et al. 2000 Blower 2001a, b Klug et al. 2002 Melnik and Sparks 2002; Rust and Cashman 2004; 2011; Mueller et al. 2005; 2008 Wright et al. 2006; 2007; 2009; Plats et al. 2007 Bernard et al. 2007; Takeuchi et al. 2008; Nakamura et al. 2008 Bouvet de Maisonneuve et al. 2009; Yokoyama and Takeuchi 2009; Bai et al. 2010; 2011; Degruyter et al. 2010a; 2010b; 2012 Vinkler et al. 2012 Polacci et al. 2012; 2014 Nguyen et al. 2014 Pioli et al. 2008

		Formenti and Druitt 2003; Giachetti et al. 2010; Shea et al. 2011; 2012
Clast conductivity	Input parameters for numerical percolation simulations	Le Pennec et al; 2001 Bernard et al. 2007 Wright et al. 2009 Wright et Cashman 2014
Vesicle shape and size	Bubble coalescence, ripening or collapse signatures	Klug and Cashman 1996; Mangan and Cashmann 1996; Gurioli et al. 2005; Shin et al. 2005 Sable et al. 2006; Polacci et al. 2008; Castro et al. 2012
	Shear conditions in the conduit Convection in the conduit	Marti et al. 1999 Polacci et al. 2001; 2003; Rust et al. 2003; Okumura et al. 2006; 2008; Bouvet de Maisonneuve et al. 2009; Wright and Weinberg 2009; Laumonier et al. 2011; Shea et al. 2011; 2012 Carey et al. 2013
	Eruptive style	Moitra et al. 2013
Vesicle size distributions (VSDs)	Vesicle nucleation processes and growth in magmas	Klug and Cashman 1994; Shea et al 2010a; LaRue et al. 2013, and references therein
	Total number of nucleation, coalescence or ripening events	Gaonac'h et al. 1996a; b Klug and Cashman 1996; Herd and Pinkerton 1997; Blower et al. 2001; 2002; Gaonac'h et al. 2003; 2005; Lovejoy et al. 2004, Yamada et al. 2008; Bai et al. 2008 Costantini et al. 2010
	Post-fragmentation evolution as indicator of : i) fountaining mechanisms ii) transportation and dispersal of the pyroclasts in submarine environment	Polacci et al; 2006a Gurioli et al; 2008 Stovall et al. 2011; 2012 Schipper at al. 2010 Rotella et al. 2013
Vesicle Number density (Nv)	Link with magma mass eruption rate (MER), link with column height	Polacci et al. 2006b Toramaru 2006; Gurioli et al. 2008; Carey et al. 2009; Houghton et al. 2010 Rust and Cashman 2011; Alfano et al. 2012
	Magma decompression rate	Mangan and Sisson 2000; Toramaru 2006; Cluzel et al. 2008; Shea et al. 2010b; 2011; 2012 Wright et al. 2012
	Link vesicularity with external trigger mechanisms (crystallinity, pressure changes)	Belien et al. 2010 Carey et al. 2012 Gurioli et al. 2014
Crystal size distribution (CSD)	Crystal size (mean, modal, and maximum crystal size), crystallization kinetics (nucleation and growth rates), annealing, crystal accumulation, and fractionation	Cashman and Marsh, 1988; Marsh 1988; 1998; 2007 Cashman 1993; Armienti et al. 1994; Higgins 2000; 2002a;b; 2006; 2011; Wilhelm and Worner, 1996; Bindeman 2003; Gualda 2006; Gualda and Rivers 2006 Mock et al. 2003; Simakin and Bindeman, 2008 Spillar and Dolejs 2013

	Magma ascent rate	Cashman 1992 Rutherford and Hill 1993; Rutherford and Devine 2003; Noguchi et al. 2008 D'Oriano et al. 2011
	Pre-eruptive decompression paths	Hammer et al. 1999; Szramek et al. 2006; Clarke et al. 2007 Innocenti et al. 2013
	Magma storage conditions prior to eruption and residence times	Mangan 1990; O'Driscoll et al. 2007; Cigolini et al. 2008 Simakin and Bindeman 2008; Magee et al. 2010; Shea et al. 2009
	Water exsolution rate meter	Toramaru et al. 2008
	Magma mixing	Morgan et al. 2007; Jerram et al. 2003
Crystal+Vesicle size and percentage	Three phases magma rheology, fluid mechanical behavior of magma	Gurioli et al. 2014; Noguchi et al. 2006

Table

Table 2 Working groups

Deposits group (chair: Jean-Luc Le Pennec; secretary: Laura Pioli)
Daniele Andronico, Raffaello Cioni, Jean-Christophe Komorosky, Ulrich Kueppers, Dominique Lafon, Jean-Luc Le Pennec, Raphael Paris, Laura Pioli, Marco Pistolesi, Roberto Sulpizio
Textural group (chair: Alan Burgisser; secretary: Alison Rust)
Hélène Balcone-Boissard, Pierre Boivin, Georges Boudon, Alan Burgisser, Sarah Cichy, Lucia Dominguez, Claudia Doriano, Lucia Gurioli, Alison Rust
Geochemistry group (chair: Thor Thordarson; secretary: Estelle Rose-Koga)
Patrick Bachelery, Francesca Forni, Didier Laporte, Estelle Rose-Koga, Olgeir Sigmarsson, Thor Thordarson
Geophysics Group (chair/secretary: Andrew Harris)
Jean Battaglia, Andrew Harris, Karim Kelfoun, Jean-François Lenat, Thierry Menand, Lea Scharff

Table

Table 3 Open questions

Is it possible to derive the total grain size distribution, and how?
How much information do we lose in sampling (for textural purpose) along main axes of dispersal, rather than lateral?
How representative are different types of pumice (tubular, non-tubular, dense)?
When we focus, for textural quantification, on some narrow grain size interval which information do we lose from the bigger and the smallest fragments?
Which is the inter-relationship between bubbles and crystals?
Why do vesicle number densities (Nv) from single explosions show such wide ranges?
How can we isolate the contribution to Nv due to decompression processes from the contribution due to prior gas exsolution or post fragmentation vesicle expansion?
Because Nv can vary over orders of magnitude during single eruptions, which Nv values do we consider representative of the event, and how can we narrow down the variability?
Nv can correlate with magma decompression rate, but keeping in mind the three previous points, which Nv has to be chosen if such correlations are to succeed?
Is there a direct correlation between Nv and magma decompression rate for mildly explosive activity?
How does rheology change? Which rate of change will affect eruption intensity and transitions in the style of eruptive activity?
Is microlite content sensitive to the glass composition?
How to define microlite in a standard way?
How does microlite crystallisation affect rheological evolution and the composition of the melt and bubble nucleation +residual volatile concentration? And vice-versa
How to compare estimations of decompression rate obtained by different techniques?
What controls the diffusion of Li in crystals, and what is the effect of a brine phase?
Can we estimate pressure at the instant before fragmentation (to allow better interpretation of velocity data)?
Can we estimate strain rate at the fragmentation time?
Can we extract anything about conduit shape, dimensions and geometry?
What is the most relevant geophysical parameter that can be correlated with vesicle number density and other textural measures?
What measure of explosion "energy" can we extract from seismic data to add to the integration? Integration of what?
How does the time-varying velocity and mass flux distribution relate to the vesicle number density, vesicle size distribution, and gas flux, and are we able to really explain the link in a confident way?
Is the geophysical community ready for measuring a large Vulcanian, Sub-Plinian, Plinian eruption?
Is it possible for a geophysical group located far from an active volcano, to have the funds and logistical means to quickly reach the site and deploy in case of a sudden large eruption?

Table

Table 4 Needs

Quantify error/variability of all the field data
Provide the field measurements techniques for a correct comparison with existing databases
Improve sample collection in active fallout field for bombs, lapilli and ash
Make machines capable of collecting pyroclasts from single explosions
Find a standard method to determine the total grain size distribution for fallout deposits
Make analogue experiments long enough to reproduce bubble growth or coalescence, and evolving magma physical and rheological properties
Build a synthetic library for analog and high temperature experiments
Set up a working group to define and solve outstanding problems for the deposit community
Definition of the representative elementary volume: (i) at the deposit scale (inter clast); (ii) at the sample (ash, lapilli, etc.); (iii) at the microscale for image analyses (for VSD and CSD)
Provide a standard procedure for the 3D tomography analyses
Increase links between texture and: (i) total grain size distribution of the related deposits (ii) clast morphology (iii) glass chemistry (iv) water, CO2, SO2, HCL, HF (depending on the composition) analyses; (v) geophysical parameters of the related explosion/eruption
Complete more detailed sampling and textural studies of selected eruptions to increase the breadth and depth of the available textural data base.
Increase textural data for: (i) pyroclastic density current deposits (ii) lava flows
(i) Define pumice types (e.g., tube vs normal, crystals vs no crystals), (ii) their abundance (iii) identify pumice end members and make a classifications of types
Produce more data of: (i) permeability (ii) connectivity (iii) tortuosity
Provide a dataset of raw and elaborated images, of primary and secondary parameters high resolution chemical mapping in order to extract what you are interest in as elements
Cross-correlation, and comparison of textural parameters relating to different processes, and cross-correlation between same events (e.g. gas jetting versus impulsive events explain the difference), may allow us to understand which measures work together under certain conditions; and those that do not.
Link what we see and measure at the surface of remote sensing (geophysical) instruments through the unknown "empty", but hot gas and particle filled, conduit section to the magma conditions in the filled (and/or fragmenting) part of the column
Check if the source condition and explosion mechanism models are valid for all sets of measurements
Geophysical data for sub-Plinian and Plinian events are rarer, and we need to think how we are to build a statistically significant geophysical data base for the Vulcanian field upwards
For each event type we need thousands of geophysical measurements and coincident samples, for individual, well-defined, explosions. This will built a statistically robust data set
Define an integrated response method that allows simultaneous geophysical measurement and a sample return, which (for crisis response) can ideally run in near-real time

Table

Table 5 Recommendations

Textural studies should be performed on well constrained deposits (in terms of stratigraphy, dispersal, thickness variation, volume)
Develop a sampling strategy based on the goal of the study. For example, when the purpose of the study is the characterization of magma properties during different eruption phases it could be more appropriated to sample each tephra layer at different locations rather than selecting a single type outcrop
To minimize the effect of wind direction, outcrops located along the dispersal axis should be preferred to lateral exposures, but it is necessary to analyze what to expect outside this main axis and in distal locations
Check density juvenile variation with distance. If there is variation, then it is recommended to weight the proportion of each clast type
After having selected the outcrop, it is necessary to get a statistically relevant number of clasts collected at random from the deposit
For textural purposes, the sample has to be defined in terms of: • Grain size • Componentry • Morphology
Sample the dominant grain size (bombs, lapilli, ashes) representative of the explosion/eruption. If all the components are presents , it is recommended to perform textural analyses at different grain scale
Differentiate the primary vesiculation quenched at the fragmentation/explosion level from syn-eruptive expansion and coalescence and post-expansion features
Gain knowledge of the global (total) variability of the juvenile population
Crystals and vesicles should always been studied together to understand the relationships between them and them and matrix
Vesicle number density and total grain size distribution correlation should be performed at eruptions with different distributions of vesicles
Standard methods and derived parameters should be made available through a web-based data base, or repository of material attached to articles.
Combine textural and geochemical analyses on the same samples so as to properly link texture and geochemistry
Correlate degassing (initial volatile budget versus surface gas measurements+residual content to make the total budget) with textures
Combine integrated textural and geochemical study with experimental petrology to derive key parameters (e.g. partition coefficients, decompression rates, etc.)
Contribute to understanding textures over differing timescales by using, for example, diffusion profiles in zoning of mineral and melts
Because seismic and acoustic arrays are extensive, and arrays of gas spectrometers are now present on several volcanoes, we recommend, for a global, operational coupling to concentrate on, and validate, correlations with seismic and acoustic data.
In terms of seismicity, RMS integrates multiple pulses and is dominated mostly by background tremor, and not specific explosions, it is thus not a good metric to correlate, unless at specific volcanoes as Mt Etna (Alparone et al. 2003).
Assuming a constant size and shape in geophysical inversions, and not incorporating existing textural data is irresponsible
Sensitivity of model has to guide texture researchers to measure the key and most important parameters, thereby reducing the errors on the most important inversion parameters.
Design and execute a community-wide experiment at a key, case-type volcano, or (initially) using a synthetic, controlled explosion.
Make a larger-scale experiment that brings all groups together