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High Resolution 3D Confocal Microscope Imaging of Volcanic Ash Particles

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Abstract

We present initial results from a novel high resolution confocal microscopy study of the 3D surface structure of volcanic ash particles from two recent explosive basaltic eruptions, Eyjafjallajökull (2010) and Grimsvötn (2011), in Iceland. The majority of particles imaged are less than 100 µm in size and include PM_{10}s, known to be harmful to humans if inhaled. Previous studies have mainly used 2D microscopy to examine volcanic particles. The aim of this study was to test the potential of 3D laser scanning confocal microscopy as a reliable analysis tool for these materials and if so to what degree high resolution surface and volume data could be obtained that would further aid in their classification. First results obtained using an Olympus LEXT scanning confocal microscope with a x50 and x100 objective lens are highly encouraging. They reveal a range of discrete particle types characterised by sharp or concave edges consistent with explosive formation and sudden rupture of magma. Initial surface area/volume ratios are given that may prove useful in subsequent modelling of damage to aircraft engines and human tissue where inhalation has occurred.

Introduction

Volcanic ash clouds pose significant hazard to human activates. The 2010 VEI (Volcano Explosivity Index) 4 eruption of Eyjafjallajökull, Iceland caused significant disruption to air travel over Europe and the North Atlantic, with an estimated (negative) economic impact on airline 'passenger and cargo services' of US$1.7 billion (IATA Economic briefing, 2010). Ash particles can also cause potential health conditions in humans where particles are inhaled (Lombardo et al. 2013). Explosive eruptions can send plumes of volcanic ash thousands of metres into the atmosphere that whilst buoyant can travel expansive distances in suspension (Gudmundsson et al. 2012, Stevenson et al. 2015). What is less well understood are the underlying reasons behind the damage to aircraft and health effects associated with volcanic ash in the wider environment (Moore at al. 2002, Clarkson et al. 2016, Oudin et al. 2013, Lombardo et al. 2013). Integral to mitigating these effects is a better understanding of the nature such as shape, size and roughness of the particles themselves. Furthermore measurements of volcanic particle morphology are considered important in understanding fragmentation as well as particle behaviour (Liu et al. 2015).

It has been known for several decades that volcanic eruptions could disrupt air travel locally. In 1982 two aircraft flying through an ash plume suffered engine malfunctions resulting in emergency landings (Gourgauda et al. 2000). However, since the 2010 Eyjafjallajökull eruption, awareness of this specific hazard has been heightened in part due to the fear of potentially catastrophic damage to airframes and aircraft engines (Casadevall 1994, Clarkson et al. 2016). From a respiratory health aspect, it is particles less than 10 µm in size (PM_{10}) that cause most concern as larger particles may be caught by the nose, mouth or throat (Baxter et al. 1999, Forbes et al. 2003). These small particles are also those likely to remain in suspension longest after a volcanic plume enters the atmosphere.

In view of the size of the particles, microscopy techniques form an essential component in the study of volcanic ash. Previous work in this area used conventional light microscopy (Stevenson et al. 2015) and scanning electron microscopy (Hillman et al. 2012, Fitzsimmons et al. 2013) to examine the 2D appearance of volcanic ash particles. Stereoscopic SEM techniques as well as micro-CT imaging have been applied to study the surface area to volume ratio of 63 and 125 µm ash particles (Ersoy 2010, Ersoy et al. 2010); the lateral resolution of the micro-CT imaging was 6 µm and although the resolution in stereoscopic SEM was much higher than in the micro-CT studies it could be difficult to image the complete surface with the SEM method described. We have previously applied reflection confocal microscopy to study of rock forming minerals including apatite (Petford and Miller 1993) and the 3D appearance of solid state nuclear track detectors (Wertheim et al. 2010, Gillmore et al. 2017). These studies suggest 3D confocal imaging may help to characterise and quantify the physical nature of volcanic ash particles in ways not amenable to more traditional 2D microscope techniques. Table 1 lists some of the possible methods that could be used to image volcanic dust particles. Two major advantages of using confocal microscopy in such studies are the ability to overlay a colour image and the relative ease of sample preparation not requiring coating or cutting.

Method

Three sets of volcanic ash from, the first days of the eruption in April 2010 of Eyjafjallajökull (A), another sample from Eyjafjallajökull Island mountain glacier 2010 (B) and Grimsvötn May 2011 (C) were assessed.

From each sample, a portion was sieved and washed in order to select a clean and similar particle size, thus allowing for ease of focusing. The preparation was similar to the 'Strew' slide technique and involved distributing the sieved particles on double sided tape mounted on a glass slide. Each sample was washed with propan-2-ol in an ultrasonic bath. The solution was poured onto a filter paper and allowed to dry on a hotplate at 40˚C. A small strip of double sided tape was placed on glass slides and each sample spread evenly across the surface. Crucially, sample preparation did not involve any grinding or cutting of the material, meaning the ash particles are intact and unmodified prior to imaging.

Twenty volcanic dust particles were imaged using a LEXT OLS4100 laser scanning confocal microscope (Olympus Corporation, Japan) with a 405 nm laser, in a similar fashion to that previously described (Wertheim et al. 2010). In the present studies images were taken using a x50 or x100 objective lens both having a Numerical aperture of 0.95; for 3D surface examination data were collected using the fine mode setting (60nm z-axis pitch spacing). The sieving procedure in the slide preparation was an important step in order to allow focussing in view of the working distance of the lenses (350 µm for the x50 and x100 objective lenses); it was crucial to avoid large particles greater than the working distance of both lenses. During imaging the lowest level was set by focussing slightly below the level of the double sided tape; the upper level was set at slightly above the maximum detected height on laser imaging. In this study the size of dust particles examined was similar to those expected to be seen in volcanic ash clouds and hence the maximum major axis length was about 120 µm. Particle surface area and volume measurements were made using Olympus OLS4100 software version 3.1.8 (Olympus Corporation, Japan).

Results

Volcanic ash particles were imaged successfully in 3D using the confocal microscopy technique. The appearance of particles revealed frequent, sharp, knife-like edges with some particles showing concave surfaces suggestive of remains from gas bubble inclusions (Figures 1 and 2). The true colour image which is superimposed gives further insight into the nature of the particles; the colour image shows the surface features including colour thus enabling for example crystalline structure to be detected. Examples below illustrate scatter from crystals within particles (Figures 1 and 3) as well as concave morphology reflecting breakup of bubble texture leaving apparent sharp edges (Figure 3).

Size range above 20 µm

Figures 1 to 3 show examples of images from confocal microscopy of larger particles above 20 µm. The 3D appearance of the volcanic ash particles was examined. Some particles for example showed crystalline patterns, uneven surfaces, sharp appearing surfaces or concave surfaces suggestive of reflecting breakup of bubble texture.

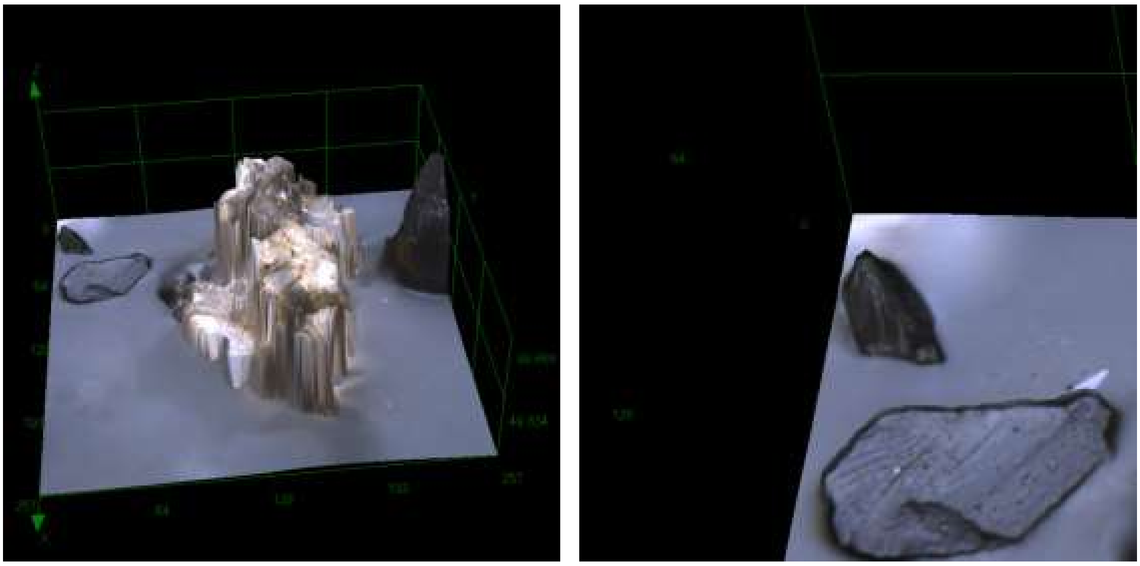

Figure 1: 3D confocal microscope image of volcanic ash (glass) particles from sample C Grimsvötn eruption with centre particle showing light scatter from inclusions within in Figure 1a. The concave morphology reflects breakup of bubbly texture leaving apparent sharp edges. One small fragment of about 16 x 28 x 10 µm is also seen in the upper left corner. Objective lens x50, image size 260 by 260 by 100 µm. A zoomed image of the small sharp appearing fragment is shown on right.

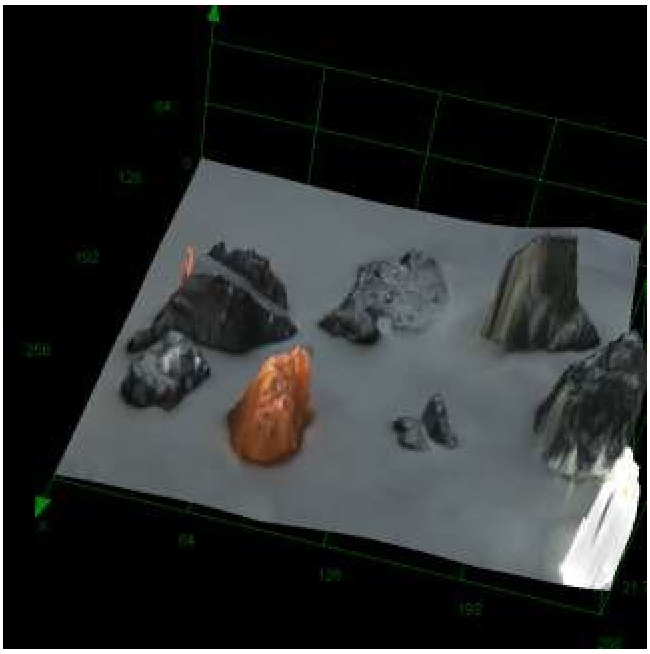

Figure 2a: 3D view showing a diverse range of particle sizes and colours, x50 objective lens, image size 260 x 260 x 128 µm from sample A (Eyjafjallajökull eruption).

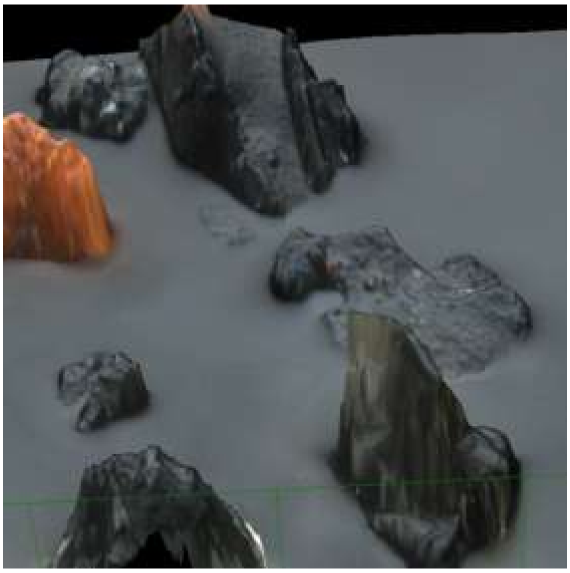

Figure 2b: Close-up view of specimen in Figure 2a showing sharp edges associated with various sizes of fragments including small particles of sample A (Eyjafjallajökull eruption).

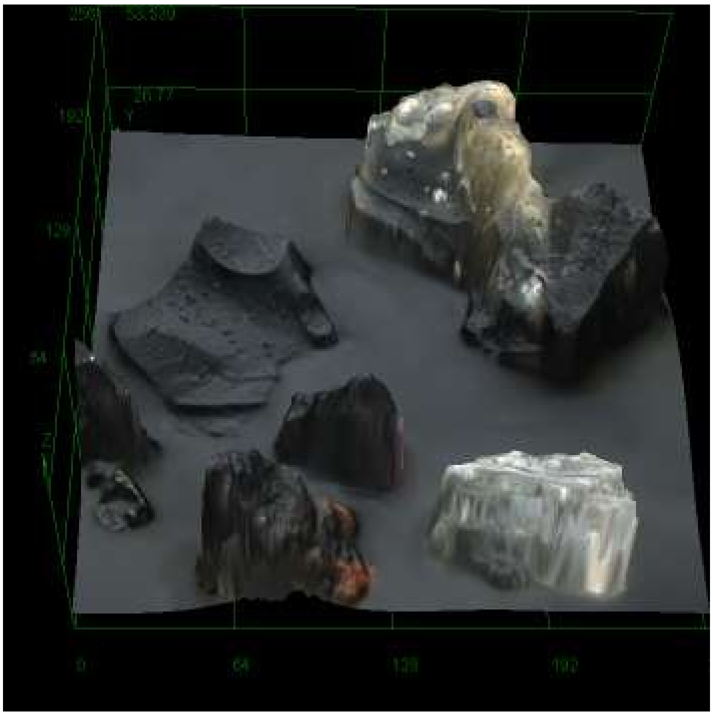

Figure 3: Further examples showing the wide and striking variation in shape, colour, transparency and surface roughness of volcanic ash particles, x50 objective lens, image size 260 x 260 x 54 µm from sample A (Eyjafjallajökull eruption). The top left particle shows a concave structure which is suggestive of the remains of a bubble.

Size range PM_{10}

Six small particles with longest axis between 5 and 15 µm were imaged using the x100 objective lens. Overall two patterns of 3D surface appearance were observed: 1. scatter type undulating uneven surface (Figure 4) and 2: an appearance characterised by sharp edges (Figure 5).

Surface area/volume ratios

For the right hand particle in Figure 4 the volume was 112 μm^3 , the surface area (excluding the lower surface) was 135 μm^2 with the lower surface having an area of approximately of 112 μm^2 . Thus the surface area to volume ratio was 2.2 μm^{-1} with an equivalent diameter for the lower surface area of 12 µm. The particle in Figure 5 had a volume of 38 μm^3 , the surface area (excluding the lower surface) was 71 μm^2 with the lower surface having an area of approximately of 53 μm^2 . Thus the surface area to volume ratio was 3.3 μm^{-1}. The surface area to volume ratios are different as the sharp surface in figure 5 has a higher relative surface area to that in figure 4, however the difference is not as much as might be expected as the surface in figure 4 is not smooth.

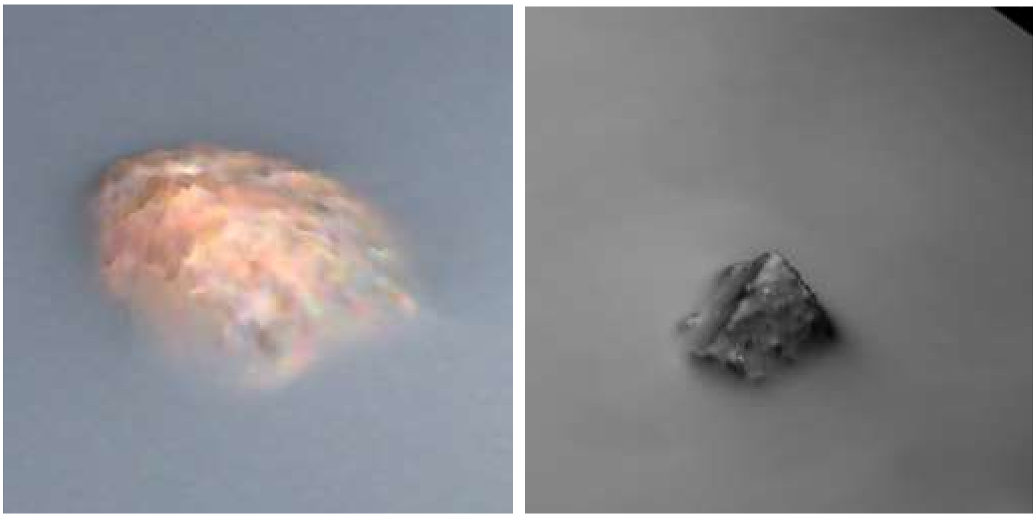

Figure 4. Examples of particles in the general PM10 range showing a highly undulating surface (left image) and a more polygonal structure with sharp sides (right image) sample B (Eyjafjallajökull eruption Island mountain glacier)..

Figure 5. Example showing two views of the same sharp volcanic fragment (6 by 12 µm) from sample C Grimsvötn eruption.

Conclusions

Previous studies of volcanic ash particles have mostly used light microscopy or SEM imaging which mainly only provide 2D visualisation and data of 3D structures. Stereoscopic SEM imaging can be of use but the technique could be limited in its imaging capacity because of occlusions (Ersoy 2010). Micro-CT is another possible imaging modality that has been applied to give the outline appearance of volcanic particles (Ersoy et al. 2010). Atomic Force Microscopy (AFM) has been used in atmospheric aerosol particle studies (Li et al. 2016) however, the study suggests this approach is more applicable to particles less than about 2 µm. AFM has also been used together with transmission electron microscopy (TEM) to study sea salt aerosols (Chi et al. 2015).

To obtain a true record of particle geometry in 3D quickly and non-destructively, confocal scanning laser microscopy provides an optimal solution. This non-destructive technique maintaining original sample geometry, not only provides high resolution image height data it also allows a colour optical image to be superimposed. Incorporating a colour image with height allows the identification of structures on the surface of particles to be easily made and as seen detection of crystalline structure as well as helping to detect concave morphology reflecting breakup of bubble texture leaving apparent sharp edges. Applying this method, it is apparent the particle edges are frequently sharp across all size ranges investigated. Our approach also allows calculation of volume, surface area and shape thus enabling calculation of surface area/volume ratio.

Particles of the order of 10 µm (PM_{10} size) with sharp edges were also observed. These images may help understand better the increase in respiratory and cardiovascular symptoms associated with inhalation of air contaminated with volcanic ash particles (Gudmundsson 2011, Lombardo et al. 2013, Hlodversdottir et al. 2016).

Further Work

Damage to aircraft engines in flight that inject volcanic ash can result from melting of particles in the temperature range of aircraft engines 1200 to 2000 ˚C (Song et al. 2016, Dean et al. 2016). Particle size and its relationship to melting point has an important bearing here as experimental work on grain size and melting point show (Volcanic Ashfall Impacts Working Group, 2014). Our results suggest damage may also occur as a result of mechanical abrasion by sharp particles, consistent with observations of turbine blade damage as well as paint being stripped from one plane travelling through a volcanic ash cloud (Casadevall 1994, Weinzierl et al. 2012). The surface area/volume ratio of ash particles is considered of value when assessing volcanic plume dynamics, shape and particle interactions, transportation and deposition of ash particles (Ersoy, 2010). Potentially the confocal technique could be complemented with SEM to also provide information about the composition of particles; such an approach may facilitate understanding the underlying reasons for different particle colours and appearances that we observed. The confocal technique outlined here can obtain these data easily and offers promise to further advance this important aspect of modelling volcano plume-atmosphere interactions. Finally, further studies are required to see if such sharp features are present in other types of PM_{10} particles that impact negatively on human health when inhaled.

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References

Baxter PJ, Bonadonna C, Dupree R, Hards VL, Kohn SC, Murphy MD, Nichols A, Nicholson RA, Norton G, Searl A, Sparks RS, Vickers BP. Cristobalite in volcanic ash of the Soufriere hills volcano, Montserrat, British West Indies. Science. 1999; 283(5405): 1142-1145

Casadevall TJ. The 1989-1990 eruption of Redoubt Volcano, Alaska - impacts on aircraft operations. Journal of volcanology and geothermal research. 1994; 62: 301-316.

Chi, J. W., Li, W. J., Zhang, D. Z., Zhang, J. C., Lin, Y. T., Shen, X. J., Sun, J. Y., Chen, J. M., Zhang, X. Y., Zhang, Y. M., and Wang, W. X.: Sea salt aerosols as a reactive surface for inorganic and organic acidic gases in the Arctic troposphere, Atmos. Chem. Phys., 2015; 15: 11341-11353.

Clarkson RJ, Majewicz EJE and Mack P. A re-evaluation of the 2010 quantitative understanding of the effects volcanic ash has on gas turbine engines. Proc IMechE Part G: J Aerospace Engineering 2016; 230: 2274–2291.

Dean J, Taltavull C and Clyne TW. Influence of the composition and viscosity of volcanic ashes on their adhesion within gas turbine aeroengines. Acta Materialia 2016; 109: 8–16.

Ersoy O, Şen E, Aydar E, Tatar I, Çelik H. Surface area and volume measurements of volcanic ash particles using micro-computed tomography (micro-CT): A comparison with scanning electron microscope (SEM) stereoscopic imaging and geometric considerations. Journal of Volcanology and Geothermal Research. 2010; 196: 281–286.

Ersoy O. Surface area and volume measurements of volcanic ash particles by SEM stereoscopic imaging. Journal of Volcanology and Geothermal Research. 2010; 190: 290–296.

Fitzsimmons KE, Hambach U, Veres D, Iovita R (2013) The Campanian Ignimbrite Eruption: New Data on Volcanic Ash Dispersal and Its Potential Impact on Human Evolution. PLoS ONE 8(6): e65839. doi:10.1371/journal.pone.0065839

Forbes L, Jarvis D, Potts J, Baxter PJ. Volcanic ash and respiratory symptoms in children on the island of Montserrat, British West Indies. Occup Environ Med. 2003; 60:207-211.

Gillmore G, Wertheim D, Crust S. Effects of etching time on alpha tracks in solid state nuclear track detectors. Sci Total Environ. 2017; 575: 905-909.

Gourgauda A, Thoureta J.-C, Bourdier J.-L. Stratigraphy and textural characteristics of the 1982±83 tephra of Galunggung volcano (Indonesia): implications for volcanic hazards. Journal of Volcanology and Geothermal Research. 2000; 104: 169-186.

Gudmundsson G. Respiratory health effects of volcanic ash with special reference to Iceland. A review. Clin Respir J. 2011; 5: 2-9.

Gudmundsson MT, Thordarson T, Höskuldsson Á, Larsen G, Björnsson H, Prata FJ, Björn Oddsson, Magnússon E, Högnadóttir T, Petersen GN, Hayward CL, Stevenson JA, Jónsdóttir I. Ash generation and distribution from the April-May 2010 eruption of Eyjafjallajökull, Iceland. Scientific Reports 2, Article number: 572 (2012) doi:10.1038/srep00572

Hillman, S.E., Horwell, C.J., Densmore, A.L. Damby D. E., Fubini B, Ishimine Y and Tomatis M. Sakurajima volcano: a physico-chemical study of the health consequences of long-term exposure to volcanic ash. Bull Volcanol. 2012; 74: 913. doi:10.1007/s00445-012-0575-3

Hlodversdottir H, Petursdottir G, Carlsen HK, et al. Long-term health effects of the Eyjafjallajökull volcanic eruption: a prospective cohort study in 2010 and 2013. BMJ Open 2016;6:e011444. doi:10.1136/bmjopen-2016-011444

IATA Economic briefing (2010). The impact of Eyjafjallajokull's volcanic ash plume. https://www.iata.org/whatwedo/Documents/economics/Volcanic-Ash-Plume-May2010.pdf (accessed 30th November 2016).

Li W, Shao L, Zhang D, Ro C-U, Hu M, Bi X, Geng H, Matsuki A, Niu H and Chen J. A review of single aerosol particle studies in the atmosphere of East Asia: morphology, mixing state, source, and heterogeneous reactions. Journal of Cleaner Production. 2016; 112: 1330–1349.

Liu EJ, Cashman KV & Rust, AC. Optimising shape analysis to quantify volcanic ash morphology. GeoResJ 2015; 8: 14–30.

Lombardo D, Ciancio N, Campisi R, Di Maria A, Bivona L, Poletti V, Mistretta A, Biggeri A, Di Maria G. A retrospective study on acute health effects due to volcanic ash exposure during the eruption of Mount Etna (Sicily) in 2002. Multidiscip Respir Med. 2013;8: 51.

Moore KR, Duffell H, Nicholl A and Searl A. Monitoring of airborne particulate matter during the eruption of Soufrière Hills Volcano, Montserrat. Geological Society, London, Memoirs. 2002; 21: 557-566.

Oudin A, Carlsen HK, Forsberg B and Johansson C. Volcanic Ash and Daily Mortality in Sweden after the Icelandic Volcano Eruption of May 2011. Int. J. Environ. Res. Public Health 2013; 10: 6909-6919.

Petford N and Miller JA. The study of fission track and other crystalline defects using confocal scanning laser microscopy. Journal of Microscopy, 1993; 170: 201–212.

Song W, Lavallée Y, Hess K-U, Kueppers U, Cimarelli C and Dingwell DB. Volcanic ash melting under conditions relevant to ash turbine interactions. Nature Communications 2016; 7, Article number: 10795 (2016).

Stevenson JA, Millington SC, Beckett FM, G. T. Swindles GT and Thordarson T. Big grains go far: understanding the discrepancy between tephrochronology and satellite infrared measurements of volcanic ash. Atmos. Meas. Tech., 2015; 8: 2069–2091.

Weinzierl B, Sauer D, Minikin A, Reitebuch O, Dahlkötter F, Mayer B, Emde C, Tegen I, Gasteiger J, Petzold A, Veira A, Kueppers U, Schumann U. On the visibility of airborne volcanic ash and mineral dust from the pilot's perspective in flight. Physics and Chemistry of the Earth, Parts A/B/C. 2012; 45-46: 87–102.

Wertheim D, Gillmore G, Brown L, Petford N. A new method of imaging particle tracks in solid state nuclear track detectors. J Microsc. 2010; 237: 1-6.

Volcanic Ashfall Impacts Working Group (2014). https://volcanoes.usgs.gov/volcanic_ash/ (Accessed 29th November 2016).

Table 1: Comparison of expected potential advantages and suitability (✓) of different techniques for imaging volcanic dust particles. The standard implementation of techniques listed are for 2D brightfield light microscopy, micro-CT, scanning electron microscopy (SEM), atomic force microscopy (AFM) and confocal microscopy. Chemical composition refers to the ability in certain techniques to obtain details of chemical composition, e.g. for AFM in combination with infrared spectroscopy. Suitable scanning area and height refers to whether these are likely to be appropriate for imaging the wide range of particle sizes seen with volcanic dust particles. Colour imaging refers to the ability of the technique to provide a visual colour image of the particles' appearance.

Method	**3D imaging**	**Chemical composition**	**Suitable scanning area**	**Suitable scanning height**	**Colour image**
2D Brightfield light microscopy			✓		✓
Micro-CT	✓		✓	✓	
SEM	stereo ✓	✓	✓	✓	
AFM	✓	✓			
Confocal microscopy	✓		✓	✓	✓