Report and Community Statement

Workshop on the Eyjafjallajökull eruptions of 2010 and implications for tephrochronology, volcanology and Quaternary studies

Institute of Geography, University of Edinburgh, 5th-6th May 2011

Andrew J. Dugmore[#], Anthony J. Newton, Kate T. Smith

6th June 2011

[#]andrew.dugmore@ed.ac.uk

http://www.tephrabase.org/tiqs2011/

The first meeting of Tephra in Quaternary Science (TIQS), the new Quaternary Research Association (QRA) research group, was a very successful, dynamic gathering. As a UK research group aiming to bring together individuals and groups with wide-ranging expertise in order to promote cross-group collaborations for optimizing and advancing tephrochronology, it was most appropriate that we began with discussing the lessons that can be learned from the most recent eruption that had a major impact on the UK: Eyjafjallajökull 2010. 36 participants from a wide range of disciplines and backgrounds, from the UK, Iceland, Hungary, Germany, Switzerland and France, including 11 early career researchers and eight postgraduate students, met for two days of lively and intensive discussion on the Eyjafjallajökull 2010 eruptions and implications for tephrochronology, volcanology and Quaternary studies.

This workshop was supported by North Atlantic Biocultural Organisation (NABO) and with funding from the Quaternary Research Association and from the INTREPID project "Enhancing tephrochronology as a global research tool" of the International Union for Quaternary Research (INQUA)'s International focus group on tephrochronology and volcanism (INTAV) and the National Science Foundations of America through the Office of Polar Programmes 1042951 “RAPID: Environmental and Social Impacts of the 2010 Eyjafjallajökull Eruption”. This enabled us to support postgraduate student and early career researcher participation.

Objectives of TIQS and the Workshop

The aims and objectives of TIQS are as follows:

- Optimise the application of tephrochronology as a robust correlation tool for Quaternary science.
- Advance the extraction, quantification and geochemical techniques used in tephra studies.
- Pool developing knowledge and generate protocols for new characterisation techniques
- Establish protocols to ensure the robust correlation of tephra deposits.
- Explore opportunities for the further development of regional databases e.g. TEPHRABASE, RESET/RHOXTOR.

- Advance the use of age-modelling techniques such as Bayesian statistics in tephra studies.
- Provide a forum for (i) discussion and exploration of new ideas, (ii) mentoring and training of postgraduate and early-career researchers; and (iii) to create a platform for establishing future research initiatives.
- Build a national research group that contributes directly to the aims of the INQUA, INTIMATE and International Focus Group on Tephrochronology (INTAV).

The aim of this workshop was to discuss the key tephrochronological issues raised by the Eyjafjallajökull 2010 eruptions, exploring new ideas and connections. An important goal of the workshop was to take the first steps towards building a cohesive, mature UK-based tephra community within a broader international setting, providing a dissemination and integration platform for tephra researchers, particularly for those at the outset of their research career.

Workshop Organisation

The workshop consisted of two keynote papers and a series of round table discussions. To foster active discussion and a relaxed and friendly atmosphere the workshop was limited to 36 participants (Appendix 1: Participants). Research groups were encouraged to send small delegations and to promote postgraduate student and early career researcher participation. Everyone was encouraged to present research in poster format with a very brief oral introduction and to participate fully in the proceedings. Contributions were welcomed on work directly associated with Ey2010 as well as research which provided interesting parallels or analogues, or dealt with relevant methodological issues (Appendix 2: Programme).

Common Themes and Community Concerns

1. The need for comparable data

Tephra is studied in a wide range of disciplinary fields that investigate different research questions and require different approaches and datasets. Tephra itself can be investigated to characterise eruptions and eruptive parameters, plume/cloud processes and contribute to knowledge of eruptive histories by identifying long term trends, patterns, links and cycles. Understanding tephra is also important for assessing tephrafall hazard, vulnerability and risk, both close to and far from volcanoes. Tephra layers can be used as correlative tools, which also requires a degree of characterisation of the tephra layer to aid recognition and hence correlation between sites. Tephrochronology is widely used in geomorphology, archaeology, palaeoenvironmental studies and to assess past volcanic impacts to humans, ecology and the environment.

Importantly, although all these disciplines study tephra and may collect samples to investigate their particular research questions these different datasets are not always comparable (sample size, collection procedures, laboratory processing) and interdisciplinary collection protocols are not in place. Problems of misusing data can arise when misunderstanding occur about the way in which it was collected. Some techniques to prepare samples, such as vigorous sieving, washing or chemical baths, can alter their composition or characteristics thus making them unsuitable for analysis for a different purpose.

There was a general consensus of the pressing need to enhance the comparability of datasets within different disciplines and international groups through agreed analytical and data presentation protocols for both field and laboratory data.

2. Reworking and preservation of tephra in the proximal and distal records

The difficulties involved in the identification of pristine proximal tephra and the problems of reworking and preservation was a common theme throughout discussions.

Many tephra layers are not preserved. At Grímsvötn (which erupted a month after the meeting), Iceland only one quarter of all historical tephra layers have been preserved and eruptions which left no tephra in the geological record have been identified instead from ice cores or written records (Bergrún Ólafsdóttir). Similarly, at Montserrat 86% of the tephra has been washed offshore and proximal land-based tephra deposits are very poorly preserved (Costanza Bonadonna).

Reworking of tephra layers is influenced by slopes, weather conditions, vegetation, animal trampling and seasonality. In some locations reworking can be virtually immediate, and this has been observed to be the case for some of the 2010 Eyjafjallajökull tephra. Tephra surfaces can be stabilised by biocrusts and selective deflation can armour the upper surfaces but a key question is how long these periods of relative stability endure and do they last sufficiently long to see the tephra incorporated into the geological record. Participants were aware of a general lack of studies of the detailed reworking of tephra. Unless reworking occurs a long time after deposition then a layer will still represent a short enough time span to be of utility for tephrochronology, however in distal locations, with very low densities of shard deposition, interpretation and identification of the exact position of the isochron can be difficult.

Identifying primary distal tephra layers can be particularly troubled by problems of reworking, especially in marine records where ice rafting has redeposited tephra. Studies of the tephra record on the Icelandic shelf have shown that grain morphology, shard counting, grain size analysis and comparison with land records (stratigraphy, geochemistry and age models) allow identification of primary tephras in marine sediments (Esther Ruth Guðmundsdóttir: Guðmundsdóttir, et al. 2011)

In addition, reworking of a layer altering the thickness, internal structures and grain size characteristics can cause problems for studies aiming to investigate the source eruption itself. A series of 83 closely-spaced eruptive episodes deposited tephra in Montserrat and although initially distinct layers were possible to differentiate, these layers quickly took on the appearance of a single tephra layer which illustrates well how reworking could lead to misinterpretations of the geological record for eruptive reconstructions (Costanza Bonadonna). In contrast, within the Ey2010 tephra different phases are marked by colour and grain size variations. However, in areas that were snow-covered at the time of the

2010 eruption sorting has occurred in the tephra, separating fine and coarse grains and destroying primary structures (Thor Thordarson, Martin Kirkbride).
These discussions lead to the following, unresolved questions:

- What are the criteria for identifying reworking?
- How rapidly can these internal details be lost from the record?
- Why does the rate of stabilisation of tephra vary?
- Does patchiness reflect a small amount of tephra produced over a long period of time, reworking or geomorphic change? Proximity to a geomorphic threshold?

Participants agreed that prompt sampling of tephra soon after deposition is most important and where where there is a high probability of strong winds and heavy rains it is especially important to sample to record structures which could quickly be lost due to remobilisation and erosion.

3. Grain size

Throughout the workshop the grain size distribution of tephra was raised as an important issue for understanding eruption processes, for modelling tephra deposition and dispersal and for assessing hazards, especially those to health.

Grain size distribution is a key parameter for dispersal models, greatly influencing the modelled patterns of proximal deposition. Modelling of the Eyjafjallajökull plume using the NAME (Numerical Atmospheric Dispersion Modelling Environment) model was carried out with grain size distributions from single samples (not total grain size distributions). The key data used were from three eruptions, Mt. St. Helens, St. Augustine and samples from two locations near Redoubt volcano, after Hobbs et al. (1991) (Susan Leadbetter). Ideally, the dispersal model would use total grain size distributions linked to the erupting volcano, since grain size distributions vary significantly across tephra deposits and between volcanoes. However, few total grain size distributions have been published in general and none for Eyjafjallajökull in particular- hence the noted need for rapid sampling of fallout from new eruptions.

It is difficult to determine the range of grain sizes in the plume as it is carried away from the source. Generally this is achieved by grain size analysis of deposits. However, it would be most useful to be able to determine the grain size in the plume as an eruption occurs to be able to put real-time data into dispersal models and to assess hazard. At present LiDAR might underestimate grain size and satellite remote sensing is limited to particles less than 15 microns. However, this is a recognised development area in the field of remote sensing and may improve in future years.

Reports on tephra from Ey2010 that was found across northern Europe suggests that grain size in distal locations may be larger than initially understood. There have been observations of 20-30 micron particles in Shetland and 20 to > 50 micron grains in Norway from the Eyjafjallajökull 2010 eruption. If particles reach the troposphere, grains up to 60 microns in diameter can theoretically reach the UK. Initial estimates assumed much smaller grain sizes. Partially this is because initial sampling was concerned with health hazards and was therefore looking for particles less than 10 microns (PM_{10}) in size.

Discussions about the sampling protocols used for studying Quaternary distal tephras noted that for practical reasons it is common practise to focus on particular grain sizes in samples (e.g. 25-80 microns). These sampling windows optimise the extraction of analysable cryptotephras. This approach will miss both finer and coarser material with significant implications for modelling plume dispersal and tephra fallout. Some potentially useful cryptotephras will be missed, particularly at long distances from the source volcano, however, this very fine material is more likely to be reworked or dissolved.

The aggregation of fines was significant in Ey2010 (Costanza Bonadonna) and this affected the dispersal. Different types of aggregation can occur associated with localised atmospheric variation, ash concentration in the plume, rainfall and perhaps also residence time in the plume. The more water there is in the plume, the more aggregation occurs. The earlier stages of the summit Ey2010 eruption were particularly water-rich from a combination of melting of overlaying ice and atmospheric water. Aggregation is important because it influences tephra transport and also is, as yet, not included in most models. Also the preservation of aggregates in the geological record will be low, since they are likely to fall apart on deposition, leading to an apparent excess of fines compared to expected values with distance from the volcano. This might influence interpretations of past proximal deposits.

The possibility that the distribution of cryptotephras could be heavily influenced by the formation of aggregates was discussed. Aggregates of 100 microns with grains of up to 10 microns and possibly bonded by sulphates were found in Ey2010 samples near central England, the Western Isles of Scotland and Sweden (John Stevenson). Despite their sometimes delicate nature, aggregates can survive peroxide treatment and analysis by SEM. A less wet eruptive situation (different weather conditions and not through ice or a lake) in Iceland might reduce aggregate formation and increase the proportion of fine tephra that reaches Europe. There is the possibility that future Icelandic eruptions in a warmer world where near-vent conditions have changed due to deglaciation could generate more fine material and as a result be potentially more hazardous.

4. Protocols for tephra measurement

Tephra layers have been measured for many different reasons (from archaeology to earth science) and specific research questions have driven sampling design and measurement strategies. As research questions change (e.g. from establishing tephrochronologies to the application of tephrochronology to research questions) measurement protocols will also evolve (Bergrún Óladóttir: Óladóttir et al. 2005; Richard Streeter)

Issues:

Field measurement of tephra layers (typically grain size and maximum and minimum thickness) If there are a lot of variations then possibly dozens of measurements are needed to gain a robust and truly representative measurement. What drives layer variation? Possible factors include vegetation patterns, slopes, snow melt, animals, frost, land use and local erosion. Is maximum layer thickness the actual thickness of fallout? Some estimate fallout through the measurement of a representative thickness- but is this correct? The question of post-depositional change is key: reworking may be shown by changes in grain size and range, layer colour, bedding and other layer structures, the relation to overlying and underlying sediments, sharp or graded contacts, the presence of crystals or lithics, and specific geomorphic features.

The analysis of homogeneous tephras can be simplified by sieving that isolates one grain size range.

5. Quaternary distal tephras

Discussions focussed on two key points:

Firstly there was much discussion of *where distal tephra layers are found in Europe*, their distribution and environments where they are most likely to be found. Three key points were drawn from this discussion:

- There are few studies of Holocene cryptotephras in Europe. This is a crucial gap as a better knowledge would enhance hazard prediction.
- Nobody reports where tephra has *not* been found and this is vital for establishing limits.
- The record of distal cryptotephras is primarily derived from peat bogs; is this because they are zones of preferential deposition as well as preferential preservation? Peat bogs occur in areas of high precipitation, and here there is a greater chance that during an eruption rain will be falling (with the potential to wash tephra from the atmosphere).

Secondly the *identification of distal tephra* was discussed in detail. It was agreed that databases of geochemical analyses of tephra are important reference tools (e.g. Tephrabase). The Ey2010 tephra has a big range of compositions, and this is the case with many other tephras too. Since different compositions can be produced at different times during the eruption and changing wind directions can send these different sub-sets of the tephra in different directions it is important to have a database of geochemical analyses based on proximal material that captures the full range of chemistry produced. The chemical identification of cryptotephras needs to be based on analyses of numerous separate grains; no definitive number of necessary analyses can be given as it depends on the distinctiveness of the tephra but suitable numbers range from 10-100 . Examination of microlites can usefully aid cryptotephra identification.

The distal record of basaltic Icelandic cryptotephras is limited compared to that of silicic tephra, although some has been found in London, west Ireland, NE Scotland and in Shetland (Simon Blockley, Graeme Swindles, Anthony Newton and Andy Dugmore). The weathering and dissolution of basaltic glass may explain why basaltic glass is not common, however, it was pointed out that preservation should not necessarily be a problem in Holocene records.

6. Contemporary distal tephras

The Ey2010 tephra was sampled across Europe in a wide range of ways:

- Rainwater samples (BGS, RHUL) and rainwater from gutter downpipes (Norway, Faroes)
- Samples collected on sticky tape (BGS, RHUL)
- Air quality monitoring filters (DEFRA/SEPA also Copenhagen)
- Snow samples, car roofs (Faroes)
- Samples from ships

Some problems arose with this sampling, for example city centre sampling was confusing because of urban pollution, PM_{10} air quality sampling missed the tephra signal and in some cases pollen and dust were misreported as tephra. Many people attempted to collect samples of Ey2010 tephra across the UK but not realising the particle sizes involved threw them away because 'there didn't seem to be anything'. In addition, there were difficulties in processing the wide range of samples collected. Effective public engagement programmes are needed with a combination of general information to inspire effective sampling and follow-up afterwards (eg. http://avo.alaska.edu/ashfall.php and http://scienceforcitizens.net/project/488/).

In future it is important to know mass loading, grain sizes, the geochemistry of the tephra during each phase of the eruption, grain morphology and the presence or otherwise of aggregates, for each sample at distal locations. Ideal samples would contain lots of material (100's of grains) and sample widely across the fallout footprint. Organic contamination would ideally be minimal. It is possible to remove organic contamination by a process of drying, heating and dissolving in nitric acid, treating with peroxide and then again with nitric acid, however this can break the very thin glass walls between vesicles. Heating to burn off organics can alter glass chemistry or lead to problems with soot. Flotation may be a less destructive, if problematic, technique to remove organics. Ideally, mineral contamination should be limited and questions were raised but not answered yet about how best to remove contamination and yet preserve aggregates and other delicate structures..

7. Input parameters for models

Eruption column height and tephra grain size distribution are critical input parameters for models of tephra dispersal and deposition.

Column height can be related to mass eruption rate for strong plumes by the method of Sparks (1986) or similar (e.g. Wilson and Walker, 1987; Constantini et al. 2009). The Ey2010 plume appeared to have been a weak, bent-over plume and in such cases column height and mass eruption rate cannot be directly related using this model. However, analysis of images of the eruption show that the Ey2010 eruption cloud actually consisted of pulses of tephra and steam which were carried higher by winds from the sea rising up the southern slopes of the volcano (Costanza Bonadonna, Thor Thordarson). With this interpretation using Sparks' (1986), the relationship for Ey2010 is still problematic, because the eruption consisted of a series of pulses and was not a sustained strong plume, and the height that the tephra reached in the atmosphere was due to local wind conditions rather than mass eruption rate.

Grain size distribution particularly influences modelled proximal deposition. However, few total grain size distributions have been published and different methods for determining this distribution can give quite different results (Bonadonna and Houghton, 2005). After column height and grain size, particle density is the next key factor influencing sedimentation and fallout rate, and is another important parameter to measure.

Improved co-ordination is needed between those collecting empirical data of tephra deposits and those modelling volcanic plumes and fallout. As the Met Office develops the NAME model (e.g. by smoothing the curve for mass eruption rate and by using real mass for future eruptions) it is vital that first-reponse monitoring captures data of the greatest utility.

8. The importance of preparedness

Participants recognised a pressing need to plan data collection for future eruptions, especially as there are signs of unrest in at least six Icelandic volcanoes and there is evidence that we have moved from a period of 40-60 years with low activity into a 40-60 year period with increased activity (Thor Thordarson). Being organised before an eruption is important and the following points were considered essential:

- Establishing agreed protocols for sampling distal and proximal tephra
- Developing community engagement and preparedness for coordinated distal tephra sampling
- Contingency planning for the rapid sampling of proximal tephra

Networks and links

TIQS aims to encourage cross-disciplinary, national and international dialogue, collaboration and coordination on tephrochronology. In view of the importance to society of understanding the distribution and behaviour of tephra in the atmosphere and potential distal tephra deposition across Europe in future eruptions, it is important that the tephra community collaborate and build capacity. Throughout the workshop discussions it was clear that TIQS has an important role to carry out in encouraging dialogue, collaboration, data sharing and development of agreed protocols to ensure cross-disciplinary compatibility of data. To this goal a list of networks and links was compiled by the workshop discussant, Sue Loughlin:

UK:

- Tephra in Quaternary Science (TIQS) – national dialogue, collaboration and coordination, http://www.swan.ac.uk/geography/research/environmentaldynamics/tephrainquaternarysciencetiqs/
- British Geological Survey (BGS), www.bgs.ac.uk
- Geological Society of London and the Mineralogical Society, Volcanic and Magmatic Study Group, www.vmsg.org.uk

International:

- International Union for Quaternary Research (INQUA), www.inqua.org, which includes:
  - Integration of Icecore, Marine and Terrestrial Records (INTIMATE), www.geo.uu.nl/fg/intimate
  - International Focus Group on Tephrochronology and Volcanism (INTAV), http://www.env.auckland.ac.nz/uoa/intav
- International Union of Geodesy and Geophysics (IUGG), www.iugg.org, which includes:
  - International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI) www.iavcei.org, including the following commissions and projects:
    - Explosive Volcanism (http://staff.aist.go.jp/s-takarada/CEV),
    - Tephra Hazard Modelling (http://dbstr.ct.ingv.it/iavcei),
    - Volcanogenic Sedimentation (http://www.otago.ac.nz/geology/research/volcanology/IAVCEI),
    - The International Volcanic Health Hazard Network (http://www.ivhhn.org),
    - World Organization of Volcano Observatories (http://www.wovo.org),
    - Volcano Global Risk Identification and Analysis (VOGRIPA), a volcanic hazards database (http://www.bris.ac.uk/volcanology/groups/vogripa).
  - Vhub (http://vhub.org): a website for collaborative volcano research and risk mitigation
- International Volcanic Ash Task Force (IVATF), http://www2.icao.int/en/anb/met-aim/met/ivatf/default.aspx?PageView=Shared
- Global Volcano Model: volcanic risk project funded by NERC
- European Volcano Observatory Space Services (www.evoss.eu)
- Geneva Group formed from the the „Ash dispersal forecast and civil aviation" workshop, October 2010: interdisciplinary, data acquisition and integration, modelling (http://www.unige.ch/sciences/terre/mineral/CERG/Workshop/results.html)
- North Atlantic Biocultural Organisation (NABO), www.nabohome.org
- The Global Human Ecodynamics Alliance (GHEA), www.gheahome.org

Proposals and projects

Projects in progress:

1. Holocene tephra in Europe: Simon Blockley and European Network (TIQS)
2. Ey2010 transformation and redeposition: comparison with primary layer and stratigraphy: Andy Dugmore and Thor Thordarson

Proposed projects:

1. Determination of a distal sampling protocol across UK and Europe for airborne tephra and tephra on the ground: John Stevenson and Claire Horwell

Post workshop note: This was promptly tackled by Sue Loughlin, BGS and John Stevenson when Grímsvötn started erupting on 21st May 2011, setting up a protocol for sample collection across the UK (http://www.bgs.ac.uk/research/highlights/GrimsvotnAshCollection.html), a questionnaire for reporting ashfall, or lack of, (http://www.quakes.bgs.ac.uk/questionnaire/VolQuest.html), the resultant map (http://www.quakes.bgs.ac.uk/recent_events/volcanic_ash/map.html) and initial observations and information (http://all-geo.org/volcan01010/).

2. Ey2010 database observation: Claire Horwell
3. Contingency planning for proximal sample collection: John Stevenson.
   This requires a sampling protocol that maximises data utility and the capability to undertake rapid sample collection. Local communities are key and it was recommended that a working group be set up to discuss ways to develop proximal sampling capacity in coordination with other groups, such as the IAVCEI Tephra Group which is working on standardising collection techniques for proximal and medial deposits.
4. Enhancement of the UK Meteorological Office NAME model using tephra data: Improved input parameters for modelling tephra dispersal and grain aggregation. Susan Leadbetter.

Other ideas:

1. A database of where distal tephras have and *have not* been found, a possible application of GIS – a TIQS paper: Simon Blockley, Jane Boygle
2. The monitoring of tephra reworking following future eruptions: Andy Dugmore
3. Reference samples: Bank/library of samples for geochemical analysis for comparison with distal samples and for comparisons between different labs and analytical techniques. INTAV results for EPMA show variability (Edinburgh and Oxford labs are statistically indistinguishable, INTAV Inter-comparison of Tephrochronology Laboratories: http://www.env.auckland.ac.nz/uoa/intercomparison-of-tephrochronology-laboratories; Kuehn et al. 2010)
4. Determining the scales of variations in a tephra deposit: Martin Kirkbride
5. Network map of all organisations, interested parties: Simon Blockley

TIQS Spring 2012 (Two and a half to three days):

Topics to include: Proximal and distal correlations (chemistry, stratigraphy, age); using tephra as a chronological tool; review progress from TIQS 2011

Acknowledgements and Thanks

We would particularly like to thank Siwan Davies, Simon Blockley (TIQS) , David Lowe (INQUA) and the North Atlantic Biocultural Organisation (NABO) for their support. Cathy Campbell, Laura Comeau, Kirsty Maclean and Richard Streeter provided invaluable practical assistance. This workshop was supported by funding from the Quaternary Research Association, from the INTREPID project "Enhancing tephrochronology as a global research tool" of INQUA's International focus group on tephrochronology and volcanism (INTAV) and the National Science Foundations of America through the Office of Polar Programmes 1042951 "RAPID: Environmental and Social Impacts of the 2010 Eyjafjallajökull Eruption".

References

Bonadonna, C. and Houghton, B.F. (2005) Total grain-size distribution and volume of tephra-fall deposits. *Bulletin of Volcanology,* 67:441-456

Costantini, L.**,** Bonadonna, C.**,** Houghton, BF and Wehrmann, H. (2009) New physical characterization of the Fontana Lapilli basaltic Plinian eruption, Nicaragua. *Bulletin of Volcanology*, 71(3): 337-355.

Gudmundsdóttir, E.R**.,** Eiríksson, J., Larsen, G. 2011: Identification and definition of primary and reworked tephra in Late glacial and Holocene marine shelf sediments off North Iceland. In press. *Journal of Quaternary Sciences*

Hobbs, P. V., Radke, L. F., J. H. Lyons, R. J. Ferek, D. J. Coffman and T. J. Casadevall. "Airborne Measurements of Particle and Gas Emissions from the 1990 Volcanic Eruptions of Mt. Redoubt." *J. Geophys. Res*., *96*, 18,735-18,752.

Kuehn, S., Froese, D., Shane,P., Davies, S., & Alloway, B. 2010. The INTAV intercomparison of tephrochronology laboratories, Presentation at International Field Conference and Workshop on Tephrochronology, Volcanism and Human Activity: Active Tephra in Kyushu, 2010; Kirishima (Kagoshima Prefecture), South Kyushu, Japan, May 9-17, 2010.

Lowe, D.J. 2011. Tephrochronology and its application: A review. Quaternary Geochronology, 6, 2, 107-153.

Manville, V., Hodgson, K.A., Houghton, B.F., Keys, J.R. (H.), White, J.D.L. 2000. Tephra, snow and water: complex sedimentary responses at an active snow-capped stratovolcano, Ruapehu, New Zealand. *Bulletin of Volcanology*, 62, 278-293.

Óladóttir, B. A., Larsen, G., Þórðarson, Þ., Sigmarsson, O., 2005. The Katla volcano S-Iceland: Holocene tephra stratigraphy and eruption frequency. Jökull, 55, 53-74.

Sparks RSJ (1986) The dimensions and dynamics of volcanic eruption columns. *Bulletin of Volcanology,* 48:3-15

Wilson, L. and Walker, G.P.L., (1987) Explosive volcanic eruptions: VI. Ejecta dispersal in plinian eruptions: the control of eruption conditions and atmospheric properties. *Geophys. J. R. Astron. Soc.* **89**, 657–679

Appendix

Appendix 1: Participants List

Peter Abbott	Swansea University	p.abbott@swansea.ac.uk
Simon Blockley	Royal Holloway, University of London, UK	Simon.Blockley@rhul.ac.uk
Christel van den Bogaard	Leibniz Institute of Marine Sciences, IFM-GEOMAR, Germany	cbogaard@ifm-geomar.de
Costanza Bonadonna	University of Geneva, Switzerland	Costanza.Bonadonna@unige.ch
Jane Boygle	Manchester Metropolitan University, UK	j.boygle@mmu.ac.uk
Dale Cameron	University of Edinburgh, UK	s0678878@sms.ed.ac.uk
Andrew Casely	University of Edinburgh, UK	Andrew.Casely@ed.ac.uk
Mike Church	Durham University, UK	m.j.church@durham.ac.uk
Laura Comeau	University of Edinburgh, UK	L.E.L.Comeau@sms.ed.ac.uk
Andy Dugmore	University of Edinburgh, UK	andrew.dugmore@ed.ac.uk
Kingsley Gale-Sides	EPCC, University of Edinburgh, UK	Kingsley@Gale-Sides.net
Esther Ruth Guðmundsdóttir	University of Iceland, Iceland	estherrg@raunvis.hi.is
Jónas Guðnason	Lyngheiði 8, 810 Hveragerði, Iceland	jonasjard@simnet.is
Thor Hansteen	Leibniz Institute of Marine Sciences, IFM-GEOMAR, Germany	thansteen@ifm-geomar.de
Szabolcs Harangi	Eötvös University, Hungary	szabolcsharangi@gmail.com
Chris Hayward	University of Edinburgh, UK	chris.hayward@ed.ac.uk
Gabi Hegerl	University of Edinburgh, UK	gabi.hegerl@ed.ac.uk
Carley Iles	University of Edinburgh, UK	s1057777@sms.ed.ac.uk

Martin Kirkbride	University of Dundee, UK	m.p.kirkbride@dundee.ac.uk
Susan Leadbetter	Met Office, UK	susan.leadbetter@metoffice.gov.uk
Sue Loughlin	British Geological Survey, UK	sclou@bgs.ac.uk
Réka Lukács	Eötvös University, Hungary	reka.harangi@gmail.com
Dave McGarvie	The Open University in Scotland, UK	d.mcgarvie@open.ac.uk
Kirsty Maclean	University of Edinburgh, UK	k.s.maclean@sms.ed.ac.uk
Ian Matthews	Royal Holloway, University of London, UK	I.P.Matthews@rhul.ac.uk
Anthony Newton	University of Edinburgh, UK	anthony.newton@ed.ac.uk
Bergrún Óladóttir	University of Iceland, Iceland	bergrun@hi.is
Joe Parsons	University of Edinburgh, UK	s0791760@sms.ed.ac.uk
Maxim Portnyagin	Leibniz Institute of Marine Sciences, IFM-GEOMAR, Germany	mportnyagin@ifm-geomar.de
Andrew Schurer	University of Edinburgh, UK	a.schurer@ed.ac.uk
Kate Smith	University of Edinburgh, UK	ksmis1@staffmail.ed.ac.uk
John A Stevenson	University of Edinburgh, UK	john.stevenson@ed.ac.uk
Richard Streeter	University of Edinburgh, UK	r.t.streeter@sms.ed.ac.uk
Graeme Swindles	University of Leeds, UK	g.t.swindles@leeds.ac.uk
Thorvaldur Thordarson	University of Edinburgh, UK	thor.thordarson@ed.ac.uk
François De Vleeschouwer	Laboratoire Ecologie Fonctionnelle et Environnement, France	fdevleeschouwer@gmail.com

Appendix 2: Workshop programme

DAY 1: Thursday 5th May

Introductions and the Ey2010 eruption

10:00 – 10:30 Introduction:	Andy Dugmore, Anthony Newton and Kate Smith
10:30 – 11:00 Keynote lecture:	Thor Thordarson (School of GeoSciences, University of Edinburgh), The 2010 Eyjafjallajökull eruption. Chair: Andy Dugmore
11:00 - 11:30	Coffee and Tea

Relevant Research

11:30 – 13:00 Round table discussion 1:	5 minute (max) introductions to current research projects relevant to the workshop theme; 3 minute (max) poster introductions Chair: Anthony Newton
13:00 - 14:00	Sandwich lunch and posters

The Ey2010 eruption: from vent to atmosphere

14:00 – 15:30 Round table discussion 2:	Ey 2010 and the wider lessons to be learnt from the eruption? The nature of the eruption, parallels and analogues. Chair: John Stevenson
15:30 - 16:00	Coffee and Tea

Proximal tephra characterisation

16:00 – 17:30 Round table discussion 3:	Proximal tephra (Ey2010 and others, ancient and modern): methodological issues (of sampling, identification, characterisation etc); consequences for applications. Chair: Mike Church
17:30 - 19:00	Wine Reception and posters
Dinner	Meal at B’est Restaurant, Drummond Street (2 minutes walk)

DAY 2: Friday 6th May

Monitoring and modelling tephra dispersal	
9:00 – 9:15 Taking stock:	Andy Dugmore, Anthony Newton and Kate Smith
9:15 – 9:45 Keynote lecture:	Susan Leadbetter (Atmospheric Dispersion Research and Response, UK Met Office) Atmospheric modelling and Ey 2010, Chair: Kate Smith
9:45 – 11:00 Round table discussion 4:	Tephra dispersal: remote sensing, monitoring and modelling.Chair: Thor Thordarson
11:00 - 11:30	Coffee and Tea
Proximal tephra distributions	
11:30 – 13:00 Round table discussion 5:	Monitoring proximal tephrafall during eruptions, determining proximal tephra distributions and modelling tephrafall from eruption plumes. Chair: Susan Leadbetter
13:00 - 14:00	Sandwich lunch and posters
Distal tephra distributions	
14:00 – 15:30 Round table discussion 6:	Distal tephra distributions ancient and modern: Ey2010 distal deposition and implications for understanding tephra in Quaternary Science. Chair: Costanza Bonadonna
15:30 - 16:00	Coffee and Tea
Looking to the future	
4:00 – 5:00 Round table discussion 7:	Taking stock and looking forward- where next? Chair: Dave McGarvie
17:00 – 17:30 **Conclusion**	Susan Loughlin (British Geological Survey), workshop discussant.
Dinner	Gathering at pre-arranged venue where delegates can make their own dinner arrangements