Explosive silicic eruptions in Iceland: from vent to peat bog

OUTLINE
Microtephra horizons, found in soils across Scotland, contain fine ash produced by explosive eruptions in Iceland. They represent instantaneous time-markers and are vital to paleoenvironmental and archaeological studies. This project seeks to understand the eruptive and transportation processes by which they form and to evaluate the hazard to the UK presented by the eruptions that produce them.

ASHFALL IN SCOTLAND
Ash from numerous volcanoes in Iceland can be found in peat bogs and lake sediments across Scotland and the rest of Northern Europe (Figure 1; Larsen et al. 1999; A.J. Dugmore et al. 1995). Eruptions are frequent (e.g. 205 events in 1100 years; Thordarson & Larsen 2007), but vary in size and explosivity. The primary threat to Scotland from the tephra (pumice and ash) that is erupted is economic in nature. Airborne ash, even from small eruptions such as the ongoing Eyjafjallajökull eruption, causes the redirection or cancellation of transatlantic flights (Witham et al. 2007). Larger eruptions may lead to the closure of Scottish airports. Deposition of large quantities of ash harms grazing livestock by fluorine poisoning (Oskarsson 1980) and plant life by acidification of soils (Grattan et al. 1999). The eruption and weather conditions that could generate such falls in Scotland are unknown. Hemispheric changes in climate have also been associated with large eruptions in Iceland (Baillie 1989). Geologically or archaeologically speaking, tephra layers are deposited instantaneously. Furthermore, they can often be carbon dated and identified by their geochemical composition, making them extremely valuable in correlation and dating of soil horizons (Larsen et al. 1999). Microtephra studies extend the identification of key marker horizons to large distances from the source volcano, relying on just a small population of grains (Dugmore et al. 1995).

QUESTIONS
The key to the long-range dispersal of tephra is the generation of fine (<63 µm) ash. The project aims to answer the following three questions:

1) How does fragmentation of magma, in both subglacial and subaerial settings, generate fine ash?
2) How does the fine ash separate from the rest of the tephra in the plume and enter the atmosphere?
3) Under what conditions is it transported to Scotland, and in what quantities is it deposited?

Fig 1. Three historic silicic tephras from Iceland that were deposited in the Faroe Islands, Scandanavia and the British Isles (Figure from Larsen et al. 1999). The recurrence rate for eruptions such as Askja 1875 is ~200 years (Thordarson & Larsen 2007).

GENERATION OF FINE ASH
Silicic volcanism
This project will focus on explosive silicic eruptions, as these produce more fine ash (<63 µm) than basaltic eruptions (often 30-50% in the former, compared to 1-4% in the latter; Rose & Durant 2009). This fine ash can more easily be carried greater distances, as evidenced by silicic tephra making up 90% of microtephra layers, despite being produced by only 15% of Icelandic eruptions (Thordarson & Larsen 2007). Furthermore, fine ash also has a larger surface area, to which toxic volatiles such as fluorine can adsorb (Oskarsson 1980). There have been at least 50 silicic eruptions in Iceland in the last 10,000 years (Thordarson & Larsen 2007), and the source volcanoes for more than half of these eruptions lie beneath Iceland's glaciers.

Fragmentation mechanism
The fragmentation of magma is controlled by a number of factors, both internal e.g. ascent rate or dissolved volatile content, and external e.g. subaerial, subaqueous or subglacial vent conditions (Carey et al. 2009). Explosive plinian eruptions are driven by expansion of gases in vesiculating magma. The best current hypothesis is that the size of the ash relates to the size of the vesicles in the foaming magma (Rose & Durant 2009). Interaction with glacial meltwater during subglacial silicic eruptions can enhance fragmentation, leading to phreatoplinan eruption with >90% ash finer than 1 mm (Stevenson et al. 2010). Phreatomagmatic fragmentation can be recognised in the
shape of the tephra grains (Dellino & La Volpe 1996).

Central to this project is the detailed mapping of the distribution of both mass per unit area and grainsize of tephra from the target eruptions. This allows calculation of erupted mass, including the proportion of fine ash, and of the total deposit grainsize distribution (TGSD), which is a crucial source parameter for tephra dispersal and sedimentation models (Mastin et al. 2009). Information on deposit structure and the presence of lithic clasts will help constrain the eruption history. Vesicle growth and conduit dynamics are explored by measuring pumice density and microtextures. The latter are analysed by sectioning clasts and taking images at a range of magnifications with a scanning electron microscope. Image analysis software is used to calculate a vesicle size distribution that can identify subpopulations formed during different stages in the ascent of the magma (e.g. Carey et al. 2009). The shape of ash grains will be analysed to identify features such as blocky shards, or the presence of adhering grains. These features are associated with phreatomagmatic fragmentation and would indicate the involvement of external water during fragmentation (Dellino & La Volpe 1996).

FIELD STUDIES

Field locations

Three field areas have been targeted for this work, focusing on individual eruptions of Hekla and Öræfajökull volcanoes, and older deposits at Kerlingarfjöll. They allow a comparison between subaerial and subglacial eruptions, including extremely proximal deposits of subglacial rhyolite eruptions.

- **Hekla H-3 eruption.** Hekla is the second most active volcano in Iceland, with 23 eruptions in 900 years (Thordarson & Larsen 2007). The H-3 eruption was a subaerial eruption carbon dated at 1150 +/- 50 B.C. and produced 12 km$^3$ (uncompacted volume) of rhyolite tephra (Baillie 1989). Despite its size, very little work has been done on these deposits and this study will shed new light on an important eruption and tephrochronological marker.

- **The Öræfajökull 1362 eruption** was subglacial, erupting a volume of 1.2 km$^3$ DRE through the ice-filled caldera. It caused widespread destruction and fatalities via the pyroclastic density currents, tephra fall and the jökulhlaups (powerful floods caused by melting of ice) that it produced. Some recent work has been done on this eruption (e.g. Sharma et al. 2008), but these studies are lacking the detail necessary for the analysis proposed here. For example, they don't include careful examination of the extensive proximal deposits that are present on the volcano slopes above 500 m.

- **Rhyolite tuyas at Kerlingarfjöll** are the remains of older (50-400 kyr) subglacial rhyolite eruptions and represent the material that was trapped beneath the ice (Stevenson et al. 2010). They therefore give insight into deposits that are inaccessible at Öræfajökull. The deposits are massive, poorly sorted to very-poorly sorted, lapilli tuffs that were deposited en-masse within a cavity in the glacier. The deposits are extremely rich in fine ash, indicating that phreatomagmatic fragmentation took place.

- **New mapping technology**

 Measurement of the TGSD requires large amounts of spatially-registered data to be analysed in a GIS, and new methods of electronically collecting field data using smartphone technology will be trialed, to evaluate how they can aid geologists in their fieldwork. This work will be carried out in collaboration with Dr Colm Jordan, head of the Earth and Planetary Observation and Monitoring team within the British Geological Survey, who will also advise on the preparation of digital elevation models from aerial photographs and the visualisation of three dimensional models.

**BEHAVIOUR OF TEPHRA IN THE PLUME**

Computer models of tephra dispersal will be used to relate the mapped deposits of the Hekla and Öræfajökull eruptions the plume from which they fell. TEPHRA is an advection-diffusion model for sedimentation of tephra through a series of horizontal atmospheric layers with distinct wind vectors and particle-size dependant turbulent horizontal diffusion (Bonadonna et al. 2005). It predicts the mass per unit area and grain size distribution of deposits at given locations on the ground at relatively close range to the volcano (<200 km). TEPHRA can be used both in the forward mode (e.g. Bonadonna et al. 2005) to compile hazard assessment, or in the inversion mode (e.g. Connor and Connor 2006) to infer eruptive parameters from field data of mass/area. Given the TGSD of an eruption and estimates for wind speed, wind direction and column height (estimated using the model of Carey & Sparks 1986), internal parameters of TEPHRA such as the diffusion coefficient and mass distribution model can be calibrated by minimising the misfit between predicted and observed deposit isopachs.

Once calibrated, the model will be run forwards to simulate eruptions from Hekla and Öræfajökull, using a range of wind fields and plume heights chosen stochastically from a predetermined distribution. The Eruption Range Scenario hazard map produced will show the possible impact of similar eruptions in the future (Bonadonna et al. 2005) and identify settlements at risk of roof collapse or damage to agriculture. Predictions of the grainsize distribution of fine ash within the column will be used to provide source parameters for far-field simulation models e.g. PUFF, or NAME, which divides ash of 1-30 μm into 5 size-class bins (Witham et al. 2007).

Tephra dispersal associated with phreatomagmatic eruptions such as that of Öræfajökull is typically characterised by aggregation of fine particles, which is not yet implemented in the model. The approach of Bonadonna et al. (2002) will be used to describe particle aggregation. This work will be carried out in collaboration with Costanza Bonadonna, a Professeur-Adjoint in the Centre d'Étude des Risques.
Géologiques, Université de Genève, and who has worked extensively with tephra-fall deposits including the estimation of total grainsize distributions. She is the developer of the TEPHRA software and will advise on its implementation in this project.

TRANSLANTIC TRANSPORT OF TEPHRA

- Analysis of microtephra horizons

Microtephra horizons from carefully selected sites in Scotland will be sampled and the tephra grains isolated using the method of Dugmore et al. (1995). Ground-truth for modelling results and insight into ash sedimentation processes such as aggregation will be derived from measurements of grain abundance, size and shape.

- Electron microprobe analysis

The composition of both distal and proximal tephras will be determined by electron microprobe. Major element chemistry will allow distal tephras to be correlated with their source volcanoes (Larsen et al. 1999). The volatile budget of each eruption, including F, which poisons livestock (Oskarsson 1980), and SO₂, which is linked to soil acidification and climatic effects (e.g. Sharma et al. 2008), will be estimated from proximal tephras by comparison of the concentrations of volatile elements in melt inclusions with those in the matrix glass. Large areas of Scotland have soils which are already acidic and therefore have a low critical load factor and are susceptible to even small additional acidification (Grattan et al. 1999).

- Particle tracking models

To investigate the transport of ash to Scotland, volcanic ash transport and dispersion (VATD) models are required, such as Puff, HYPLIT, and NAME (Witham et al. 2007). The models are primarily used by Volcanic Ash Advisory Centres (VAACs) and were developed to allow aircraft to avoid plumes. Each has been validated against the ETEX tracer experiment and remote sensing data. They can be used for very low particle concentrations (e.g. limit of ash visibility is 10⁻⁴ g m⁻³) and large distances (~2000 km). The current source parameters are simple: ash is dispersed evenly in a vertical line or area source between the vent and the top of the plume; the grainsize distribution can be changed, as can the release rate. Current models take no account of buoyancy, momentum or sedimentation due to aggregation or hydrometeors, but more complex models are in development (Webley and Mastin 2009).

Combining our new data with data from the literature, a more detailed source parameter database for Icelandic volcanic eruptions, as a refinement of the effort of Mastin et al. (2009), will be prepared. This provides 'best guess' values to be used in preparation of hazard warnings in the absence of other information. Particle tracking software will then be used to simulate a number of likely eruption and weather scenarios, including different seasons from years characterised by high and low North Atlantic Oscillations, and their effects on Scotland and the UK. These will be the first simulation of rhyolite eruptions from Iceland, and the only simulations of a subglacial eruption anywhere. The conditions that could result in damage to livestock or plants would be identified, and this information will passed to policy-makers via the BGS along with a series of 'trigger' thresholds for which recommended measures e.g. bringing in of livestock, can be prepared.

REFERENCES